Accelerating the Development of Polymer Composites: Modeling & Scalable Manufacturing

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Outline

- Past & Current Research
- Future Research Lab
- Teaching Philosophy

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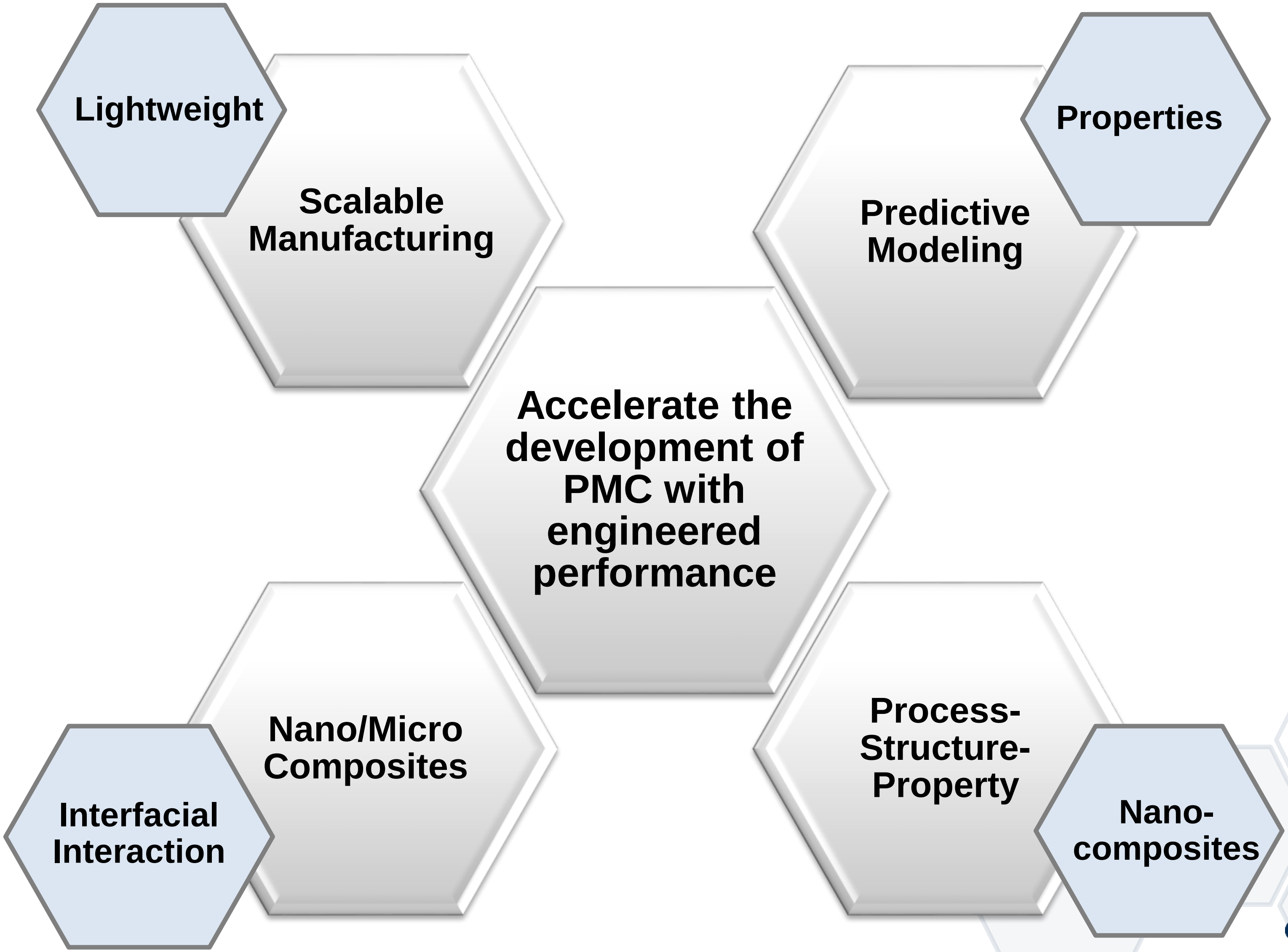
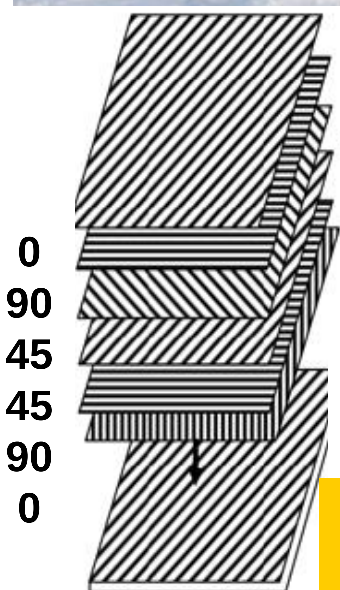
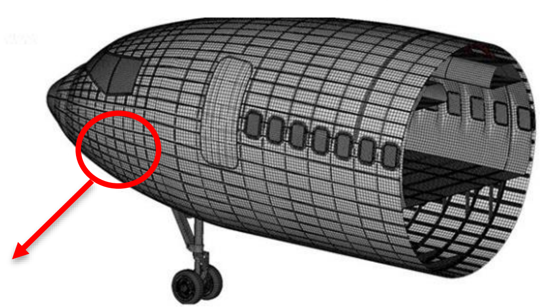
Research Background



Challenges/Opportunities in Development of Polymer Composites

World's largest autoclave by ASC





Composites

Models to reduce the experimental trials and cost of development

How to achieve the desired properties with a reduced process cycle?

Accelerated development of PMC

1. **Modeling:** Understanding/prediction the mechanical behavior
2. **Manufacturing**

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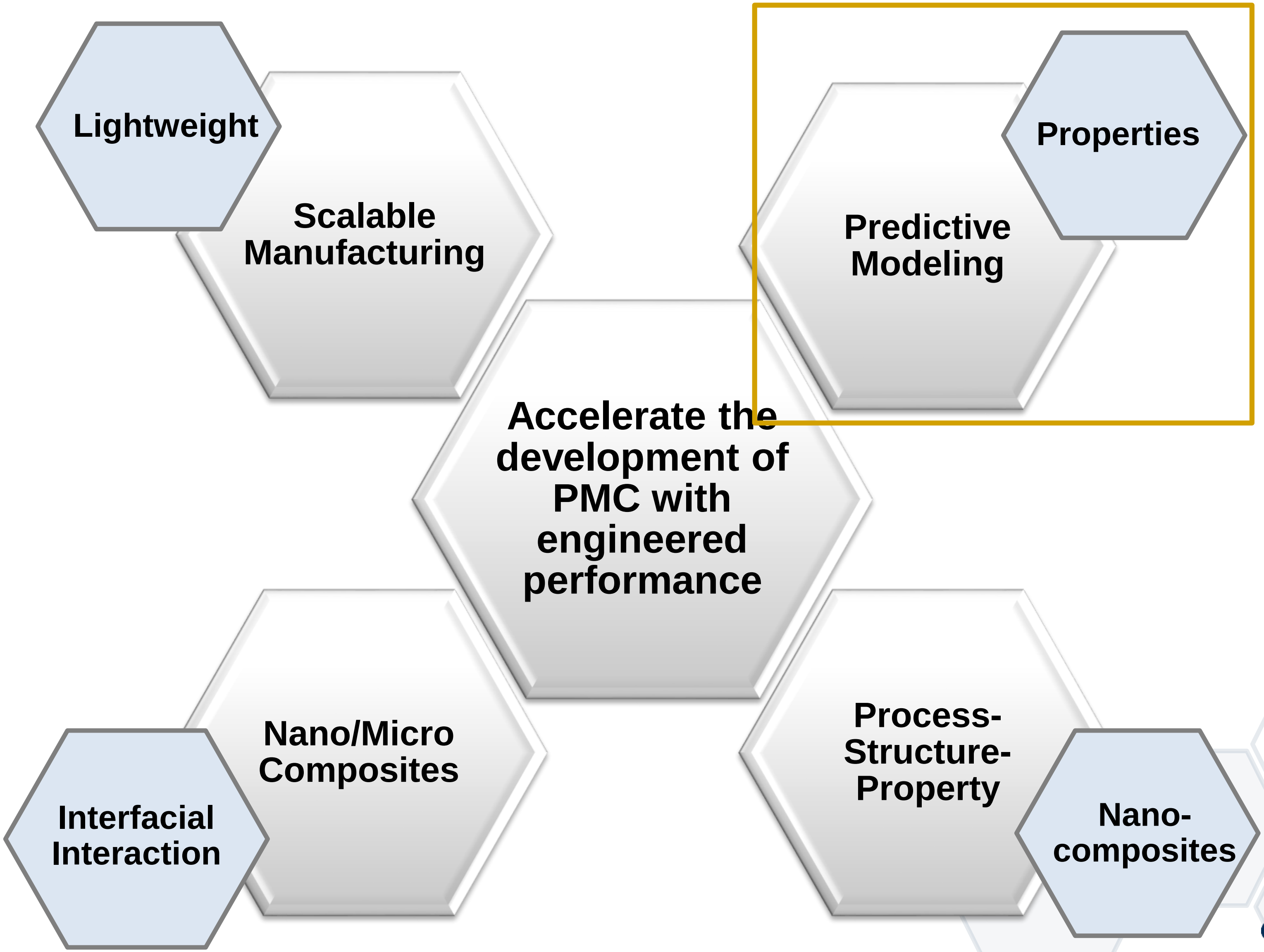
Research Outline

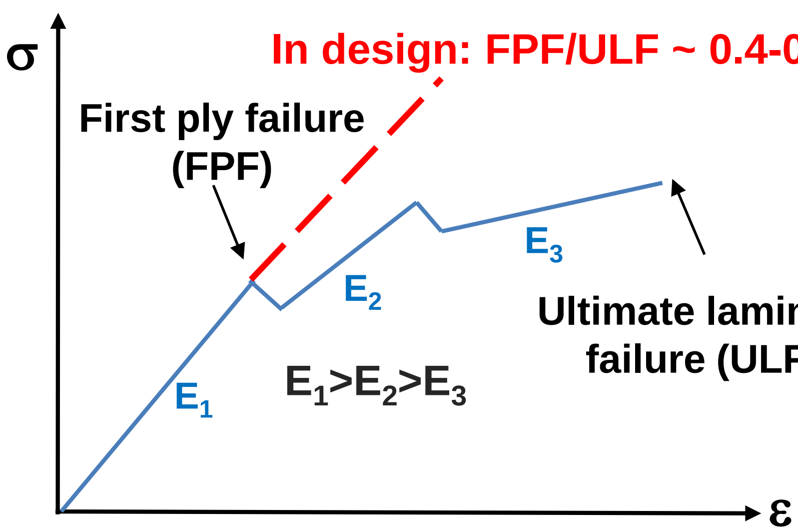


Application Concern of PMC

- ❑ Long-term modulus degradation: Creep
- ❑ Long-term strength degradation: Creep- rupture

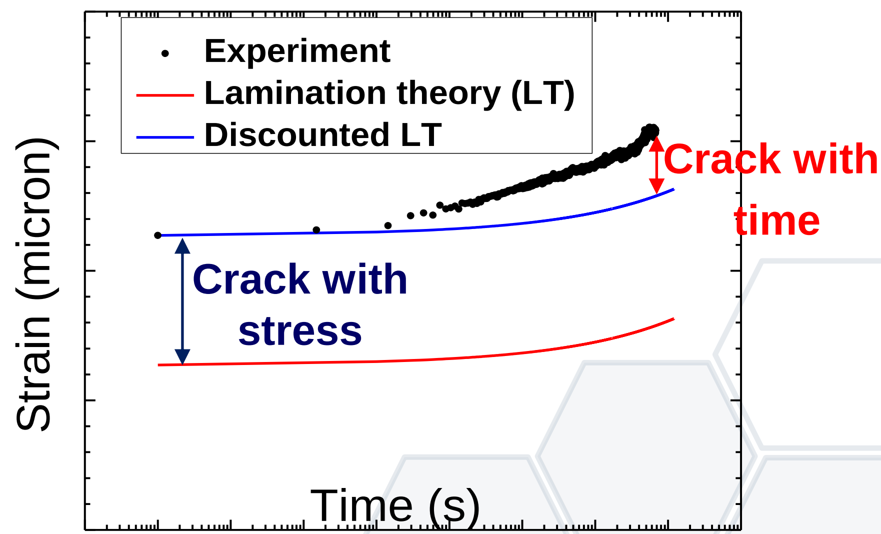
} Viscoelasticity of Polymer Matrix + Damage

Damage progression with stress



Modulus degradation with cracking

Damage evolution with time



Creep strain with cracking

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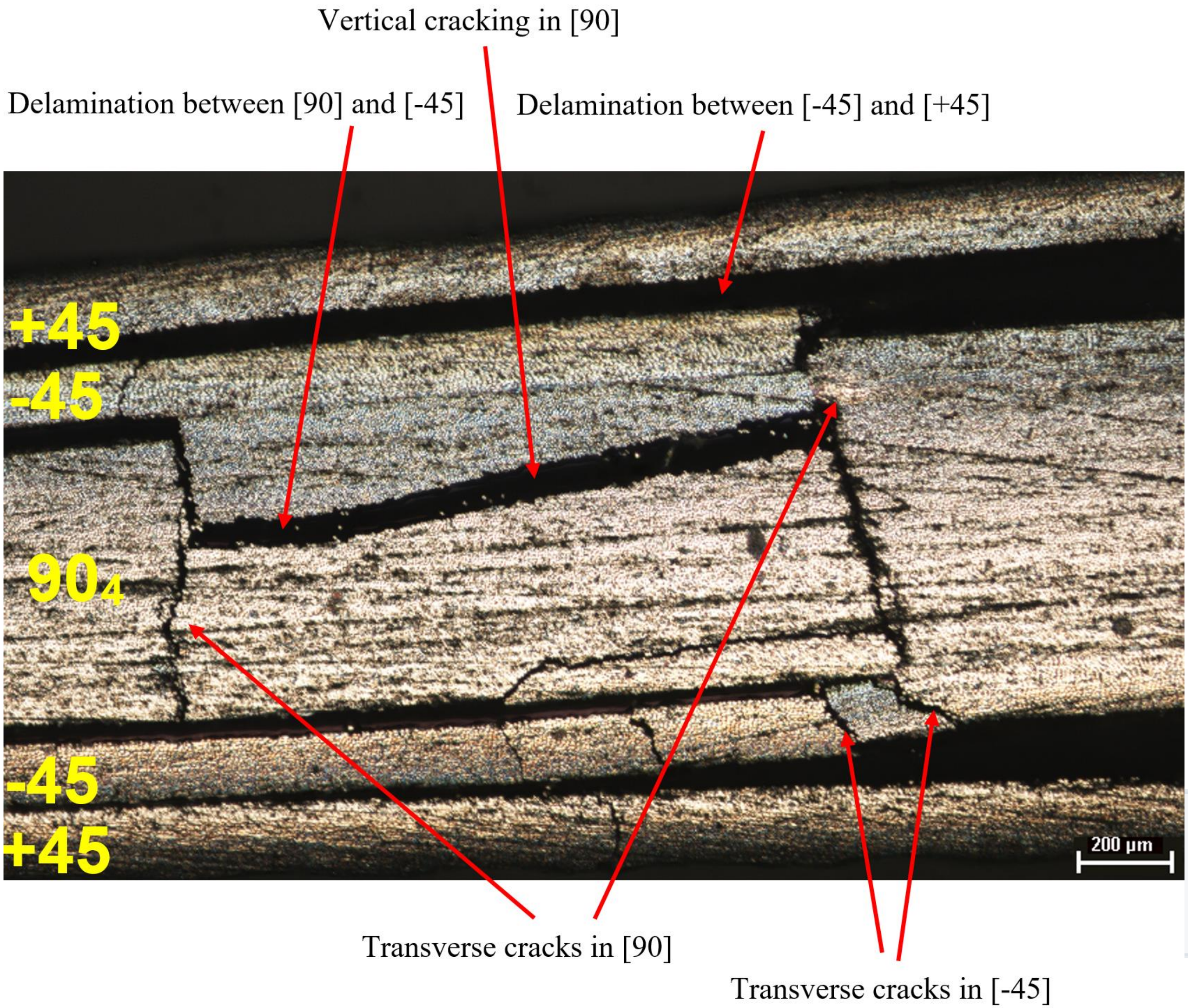
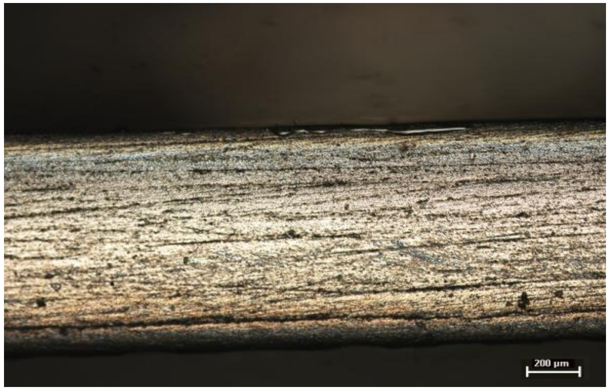
Damage in Multidirectional Laminates

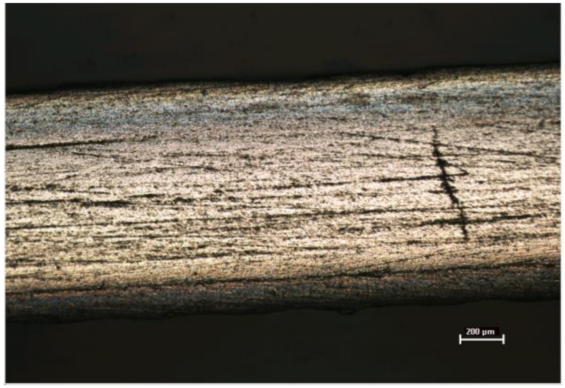


Evolution of Damage in Multidirectional Laminates

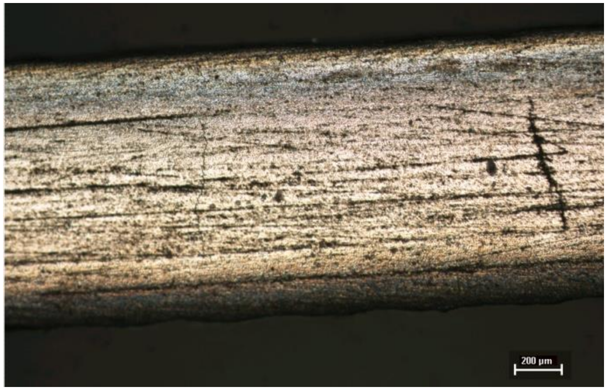
Damage evolution with stress and time



0 MPa

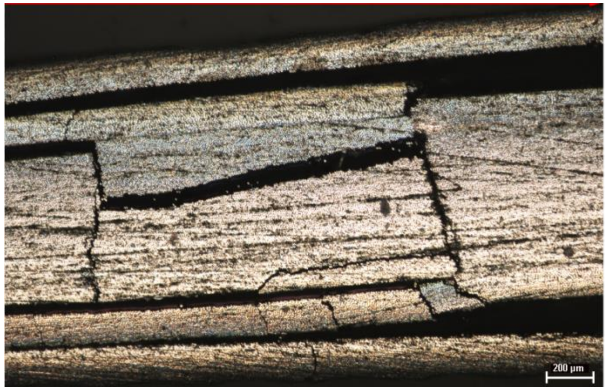


50 MPa



70 MPa

90 MPa



100 MPa

Asadi et al., Composite Structures, 2015,132:665

State of the Art

Model	How it works		Pros & Cons	Prominent studies
Ply discounting	Reduces the modulus of the cracked ply to near a zero value		+ Simplicity - Artificial chang... st...	Hinton (2002), Anand (2006)
Continuum dam... mechanics				...994), Talreja ...arna (1999)
Elastic analysis-...	...g ...nd strai... and find the new stress and strain	a...	a... (e.g. ... function)	...54), McCartney ...), Barbero (2010)
			... assumptions - Complexity	Hashin (1985, 2010)

Multiple ply cracking analysis

Simulating crack evolution

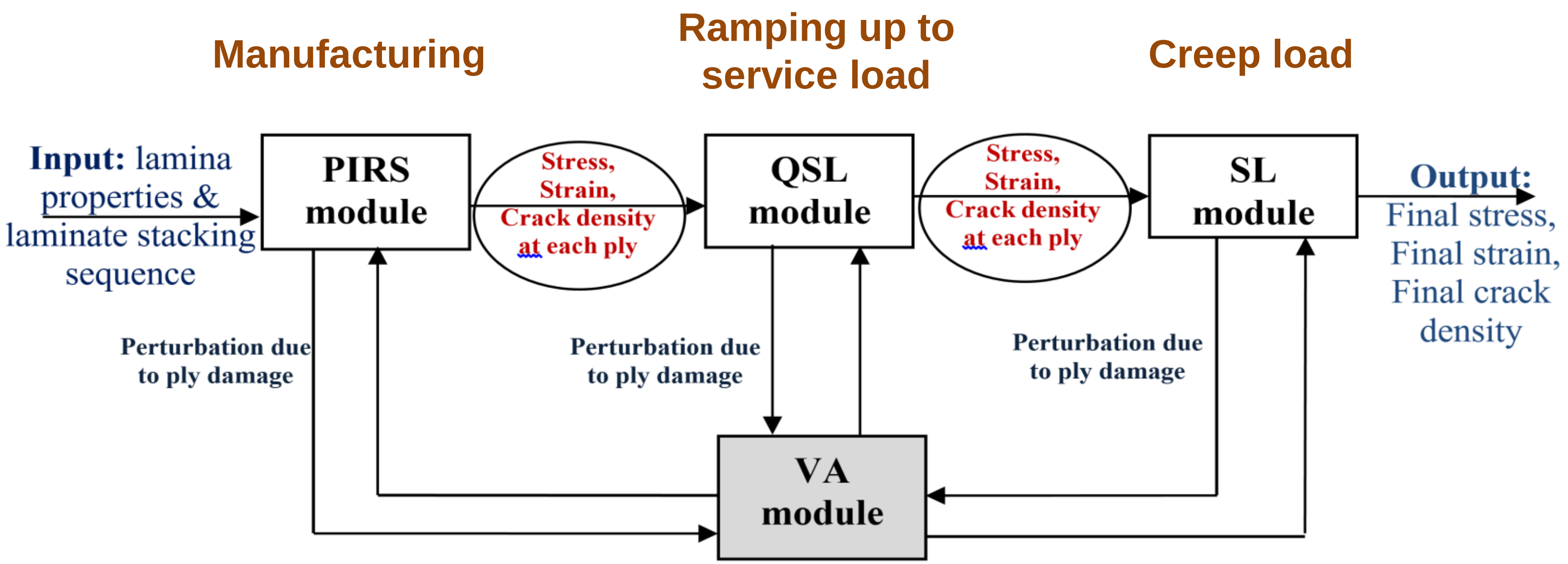
Effect of damage on creep

My approach:

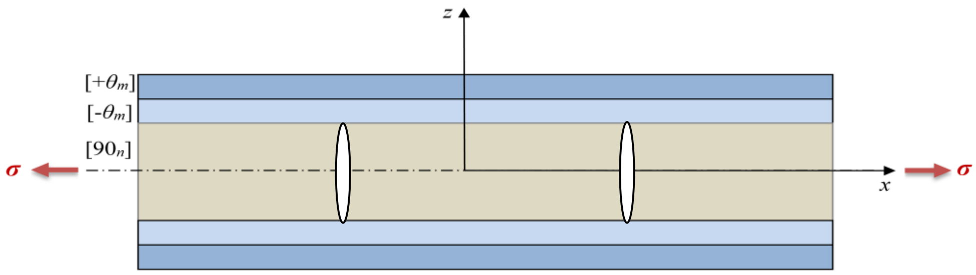
Variational analysis-based model in a lamination theory model framework to predict the cracking evolution and its effect on creep

Creep Model

A successful creep-damage model should consider the history of loading

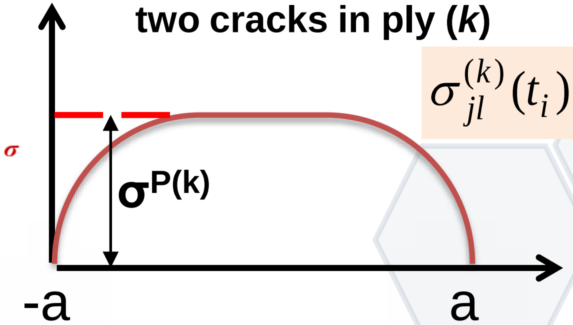


Variational Analysis (VA): Finds an admissible stress state in each ply by determining the perturbation in stresses due to cracking in plies of a laminate

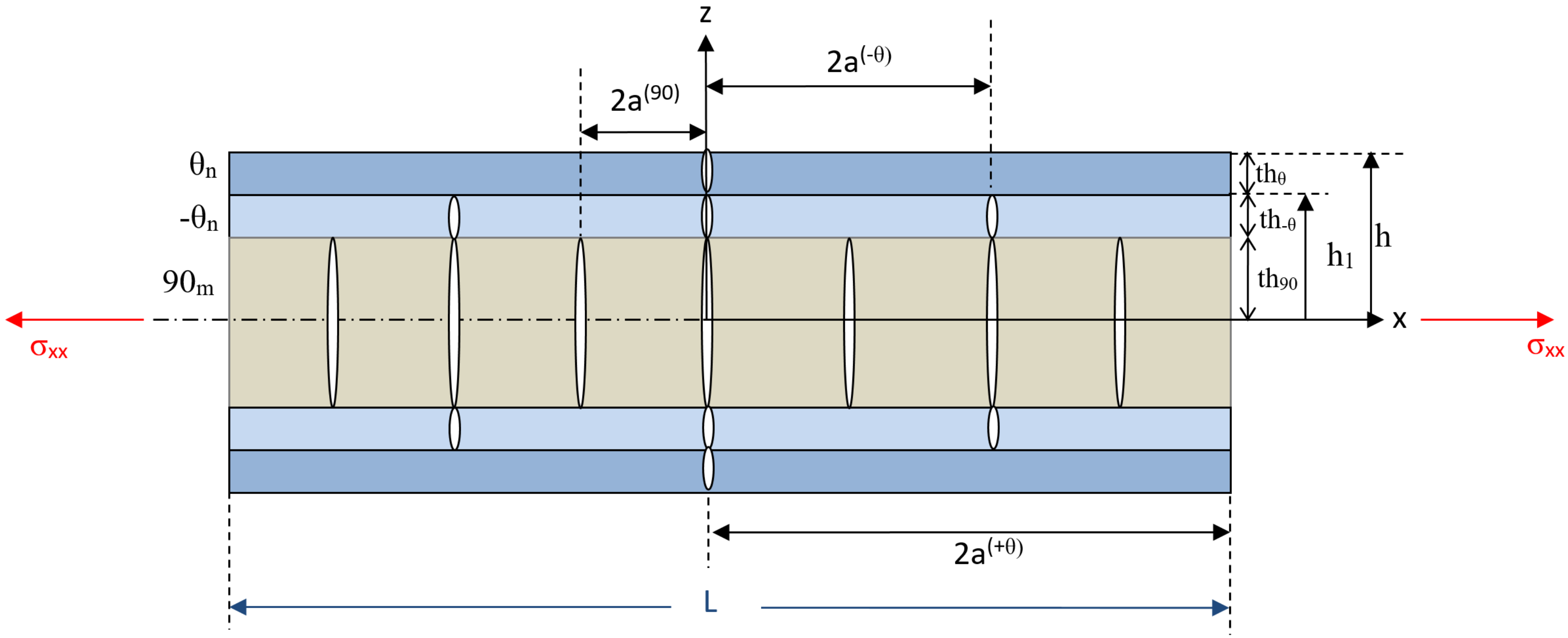


Stress distribution between two cracks in ply (*k*)

$$\sigma_{jl}^{(k)}(t_i) = \sigma_{jl}^{(k)}(t_{i-1}) - \sigma_{jl}^{P(k)}$$



Variational Analysis for Multiple Cracking



$$\sigma_{xx}^{(k)}(t_i,x)=\sigma_{xx}^{(k)}(t_{i-1})-\varphi^{(k)}(x)$$ → **Axial stress perturbation**

$$\sigma_{yy}^{(k)}(t_i,x)=\sigma_{yy}^{(k)}(t_{i-1})-\eta^{(k)}(x)$$ → **Transverse stress perturbation**

$$\sigma_{xy}^{(k)}(t_i,x)=\sigma_{xy}^{(k)}(t_{i-1})-\psi^{(k)}(x)$$ → **Shear stress perturbation**

How Variational Analysis Solves for Cracking?

Complementary energy for each ply

Euler-Lagrange Equations

Equilibrium Eqn. & B.C

Principle of minimum complementary energy: First variation (minimizing) of complementary energy to each perturbation stress

$$A_1 \frac{d^4}{dx^4}\varphi^{(90)}(x) + A_2 \frac{d^2}{dx^2}\varphi^{(90)}(x) + A_3\varphi^{(90)}(x) + A_4 \frac{d^4}{dx^4}\varphi^{(-\theta)}(x)$$

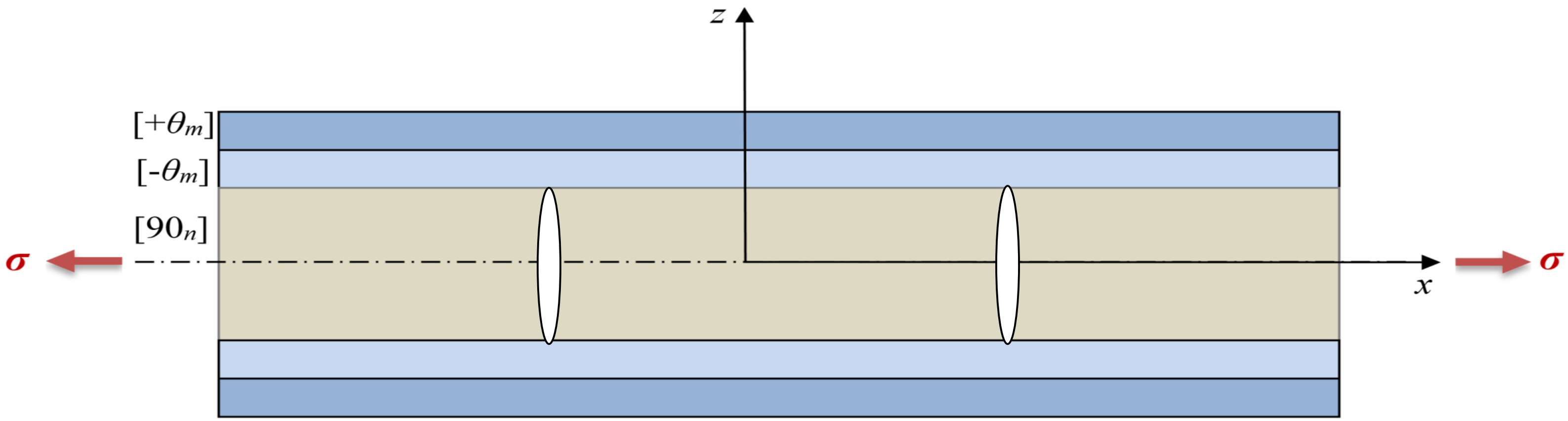
$$+ A_5 \frac{d^2}{dx^2}\varphi^{(\theta)}(x) + A_6 \frac{d^2}{dx^2}\eta^{(90)}(x) + A_7\eta^{(90)}(x) = 0$$

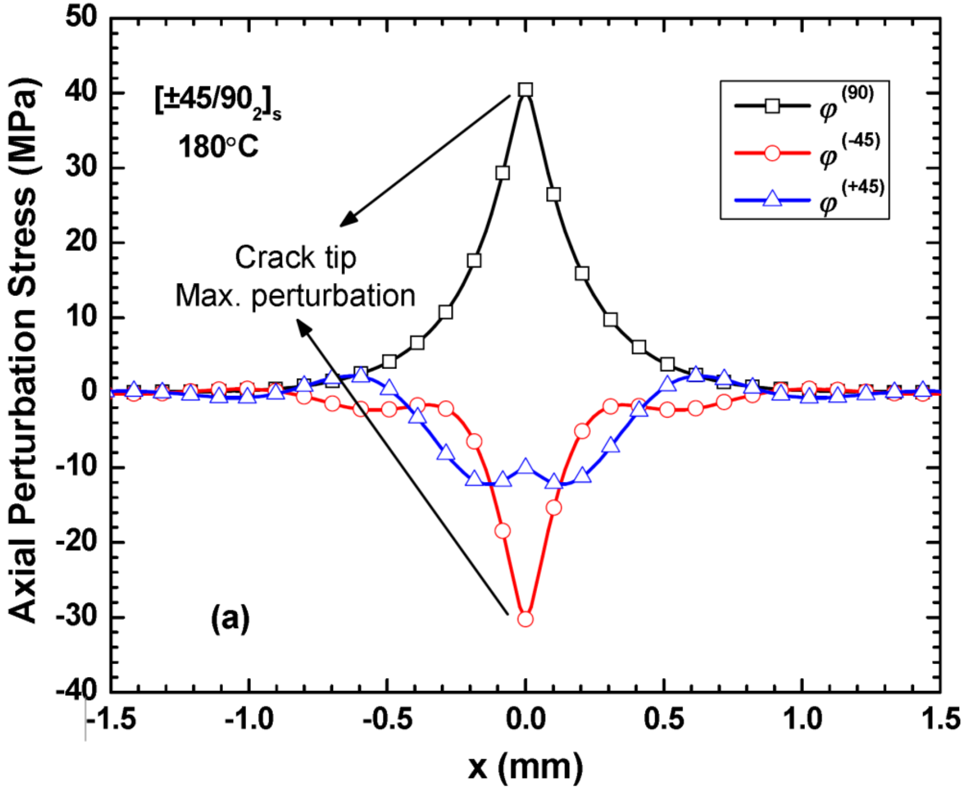
$\sigma_{xy}^{(90)}(t_i,$ …

$\sigma_{yy}^{(90)}(t_i,$ …

$$\sigma_{xz}^{(90)}(t_i, x, z) = \frac{d\varphi^{(90)}(x)}{dx} z$$

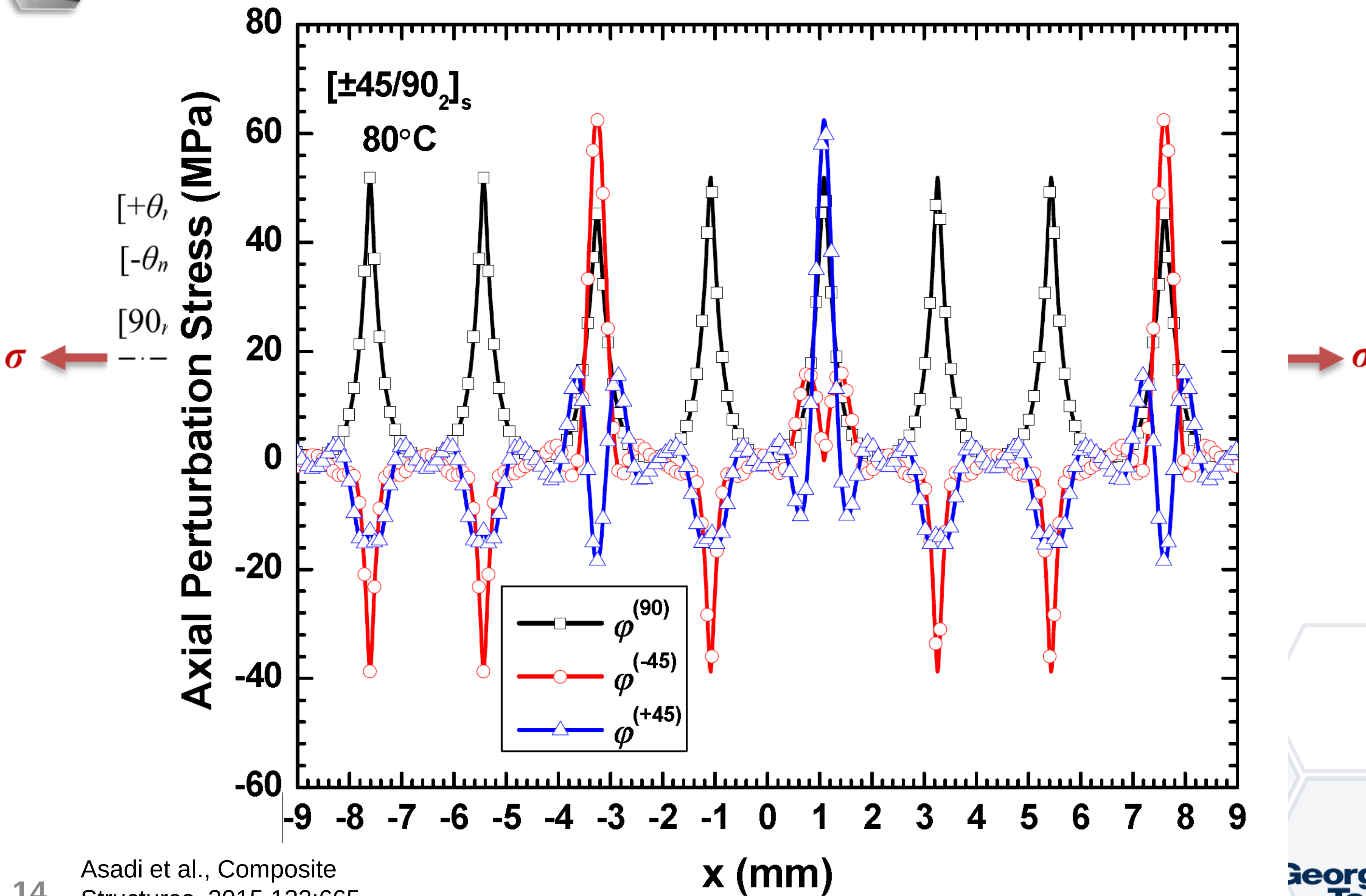
Single-Ply Cracking: Perturbations





Asadi et al., Composite Structures, 2015,132:665

Multiple-Ply Cracking: Perturbation



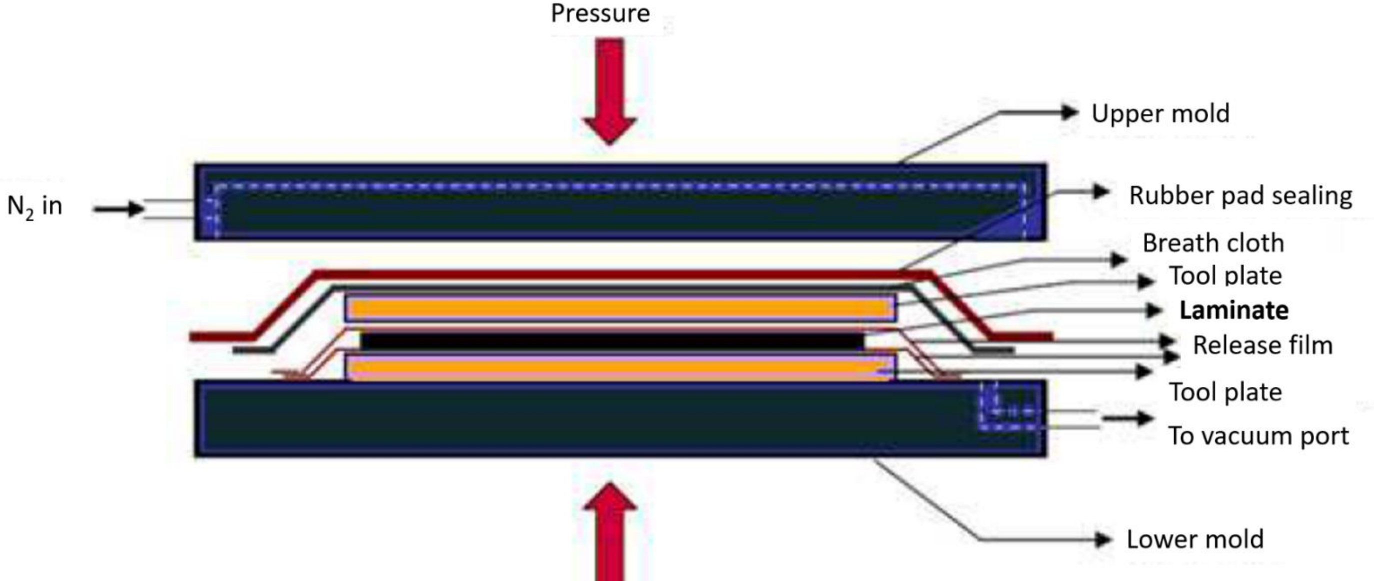
Asadi et al., Composite Structures, 2015,132:665

Experimental Validation of the Model

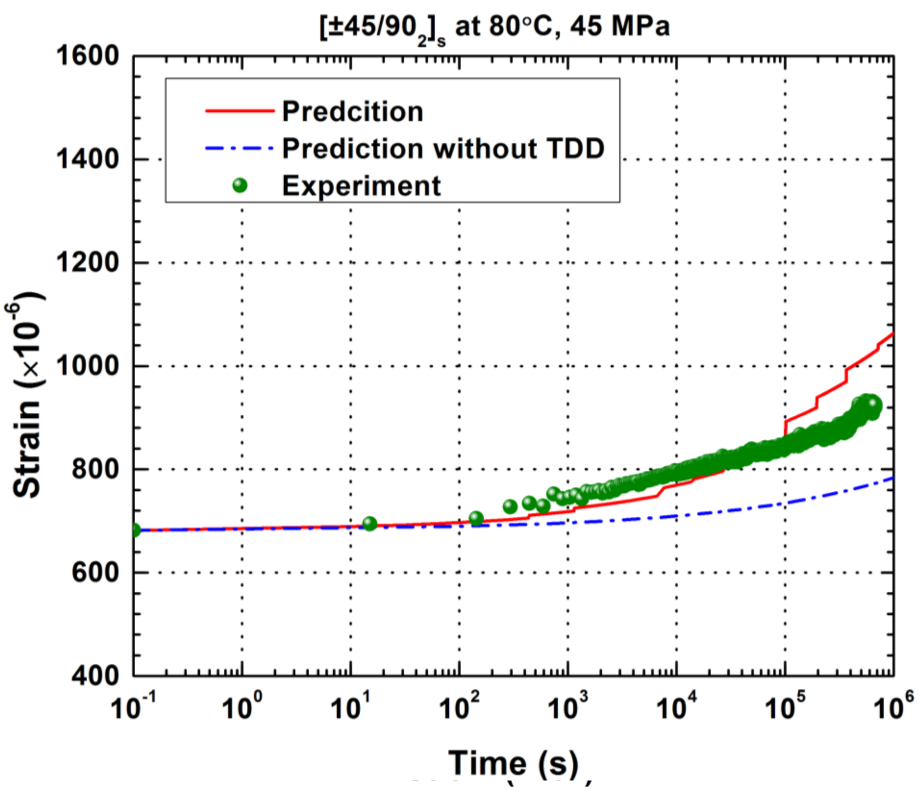
Composites made with:

- ❑ **Hexcel F263-7 Epoxy/Toho G30-500 carbon fiber prepreg.**

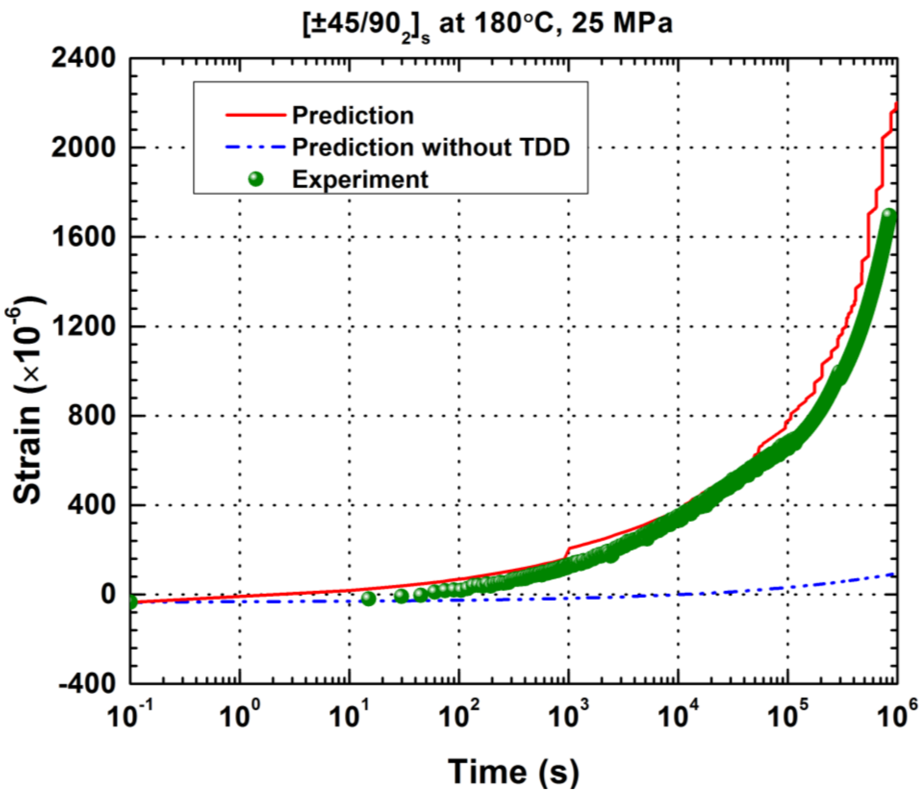
- ❑ **Autoclave manufacturing for unidirectional [0], [90], [45] and multidirectional [$\pm 45/90_2]_S$ laminates.**



Predictions: Effect of Cracking on Properties and Behavior



Creep behavior prediction with damage evolution (moderate temperature)



Creep behavior prediction with damage evolution (high temperature)

Asadi et al., Composite Structures, 2015, 132:665

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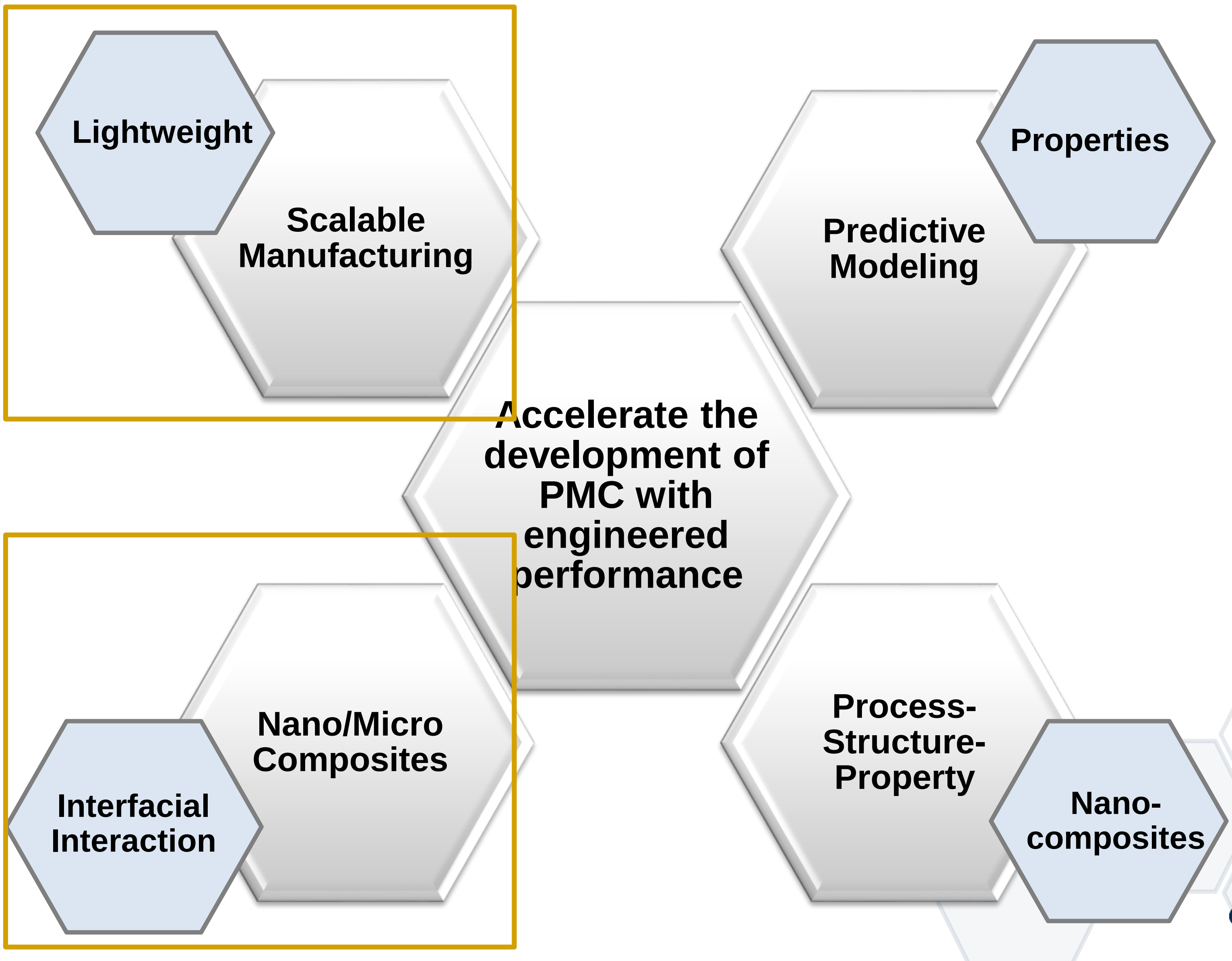
Research Outline



Why Lightweight?

71% of US total petroleum

17% of total CO_2 emission

10% weight reduction

6-8% increase in fuel efficiency

28.5 mi/gal in 2012 → 54.5 mi/gal by 2025

U.S. Department of Energy, Annual Energy Review, 2012.
M. Van der Hoeven, CO2 Emissions From Fuel Combustion-Highlights, International Energy Agency: Paris, France, 2011.
U.S. Department of Energy, Quadrennial Technology Review, 2011.

Ways to Lightweight

- **Surface**

  Change the part design, so less material is used.

- **Thickness**

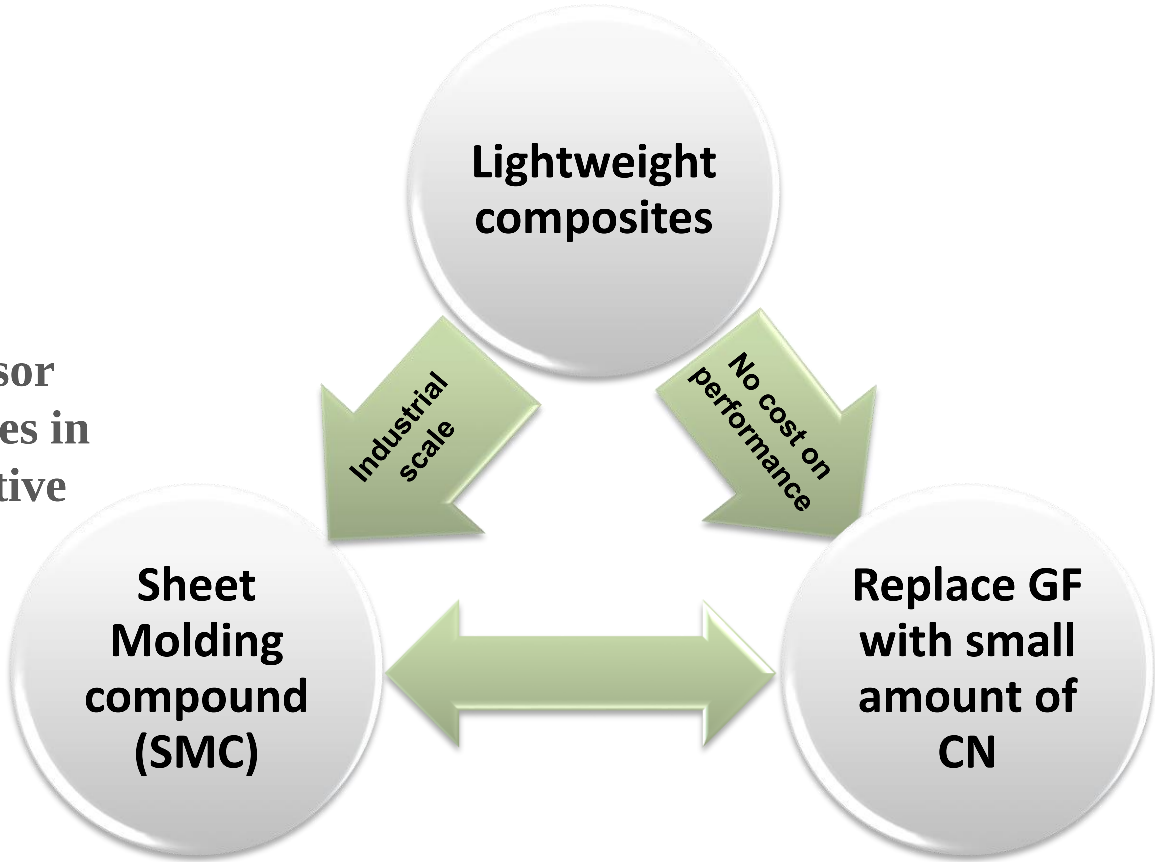
  Use a stronger material so a thinner part can support the required loads.

- **Density**

  Replace the material with a lighter one of at least equal performance.

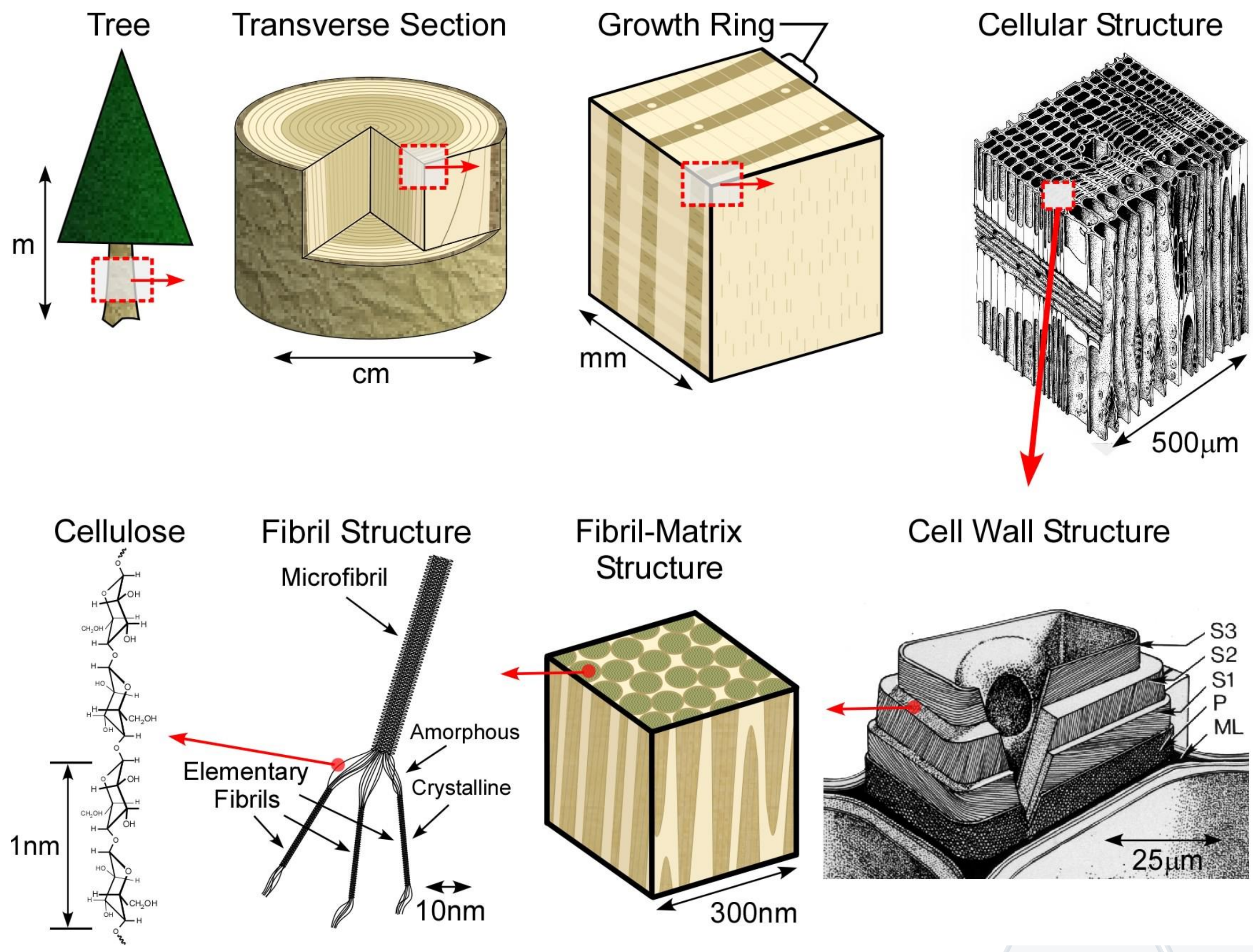
Our Approach to Make Polymer Composites Lighter

Precursor composites in automotive



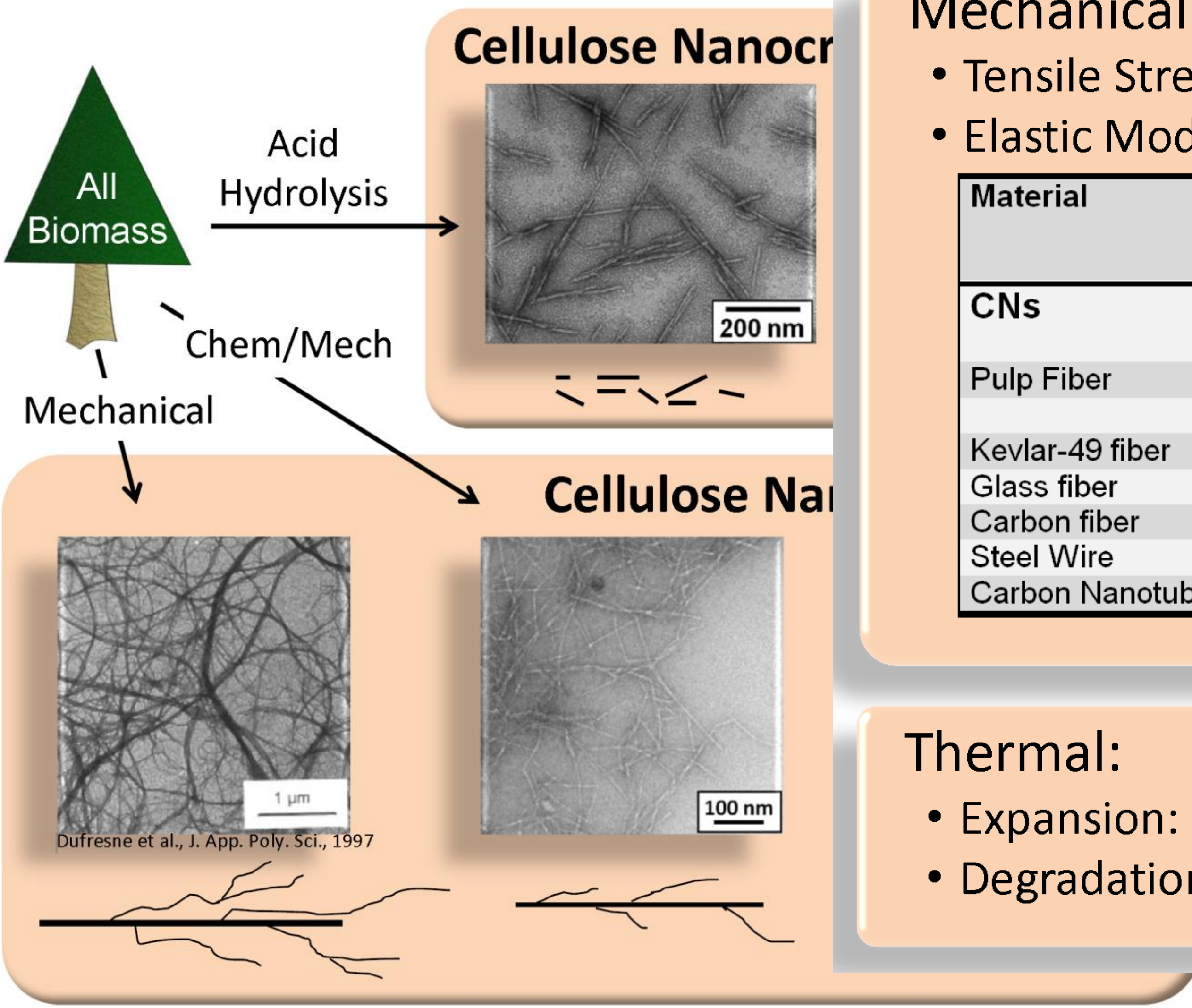
Challenge: Scalable techniques to introduce nanocellulose (CN) into SMC lines

What is Cellulose?



Moon et al. Chem. Soc. Rev. 2011; 40, 3941

Cellulose Nanoparticles



Mechanical Properties:

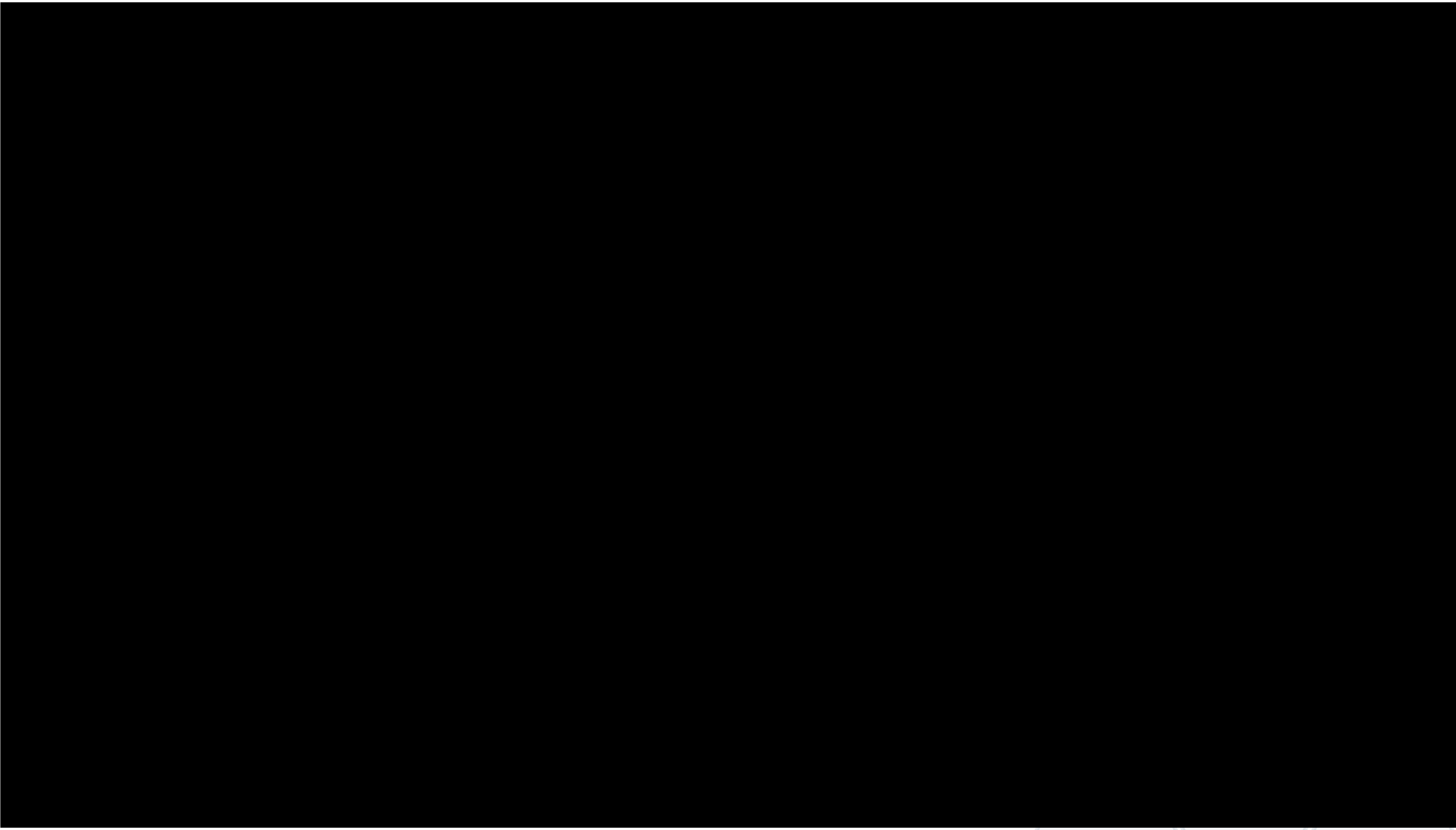
- Tensile Strength: 2-7.5 GPa
- Elastic Modulus: 120-220 GPa

Material	Density (g/cm^3)	Tensile Strength (GPa)	Elastic Modulus (GPa)
CNs	**1.6**	**2 - 7.5**	**120-220**
Pulp Fiber	0.8-1.2	0.3-1.4	5-45
Kevlar-49 fiber	1.4	3.5	124-130
Glass fiber	1.5	4.8	86
Carbon fiber	1.8	1.5 - 5.5	150-500
Steel Wire	7.8	4.1	210
Carbon Nanotubes	--	11-63	270-950

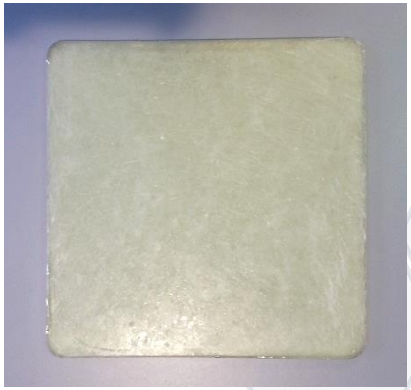
Thermal:

- Expansion: 4-6 x 10^{-6}/K
- Degradation: 200-300 C

Sheet Molding Compound (SMC) Manufacturing: Thermoset Polymers

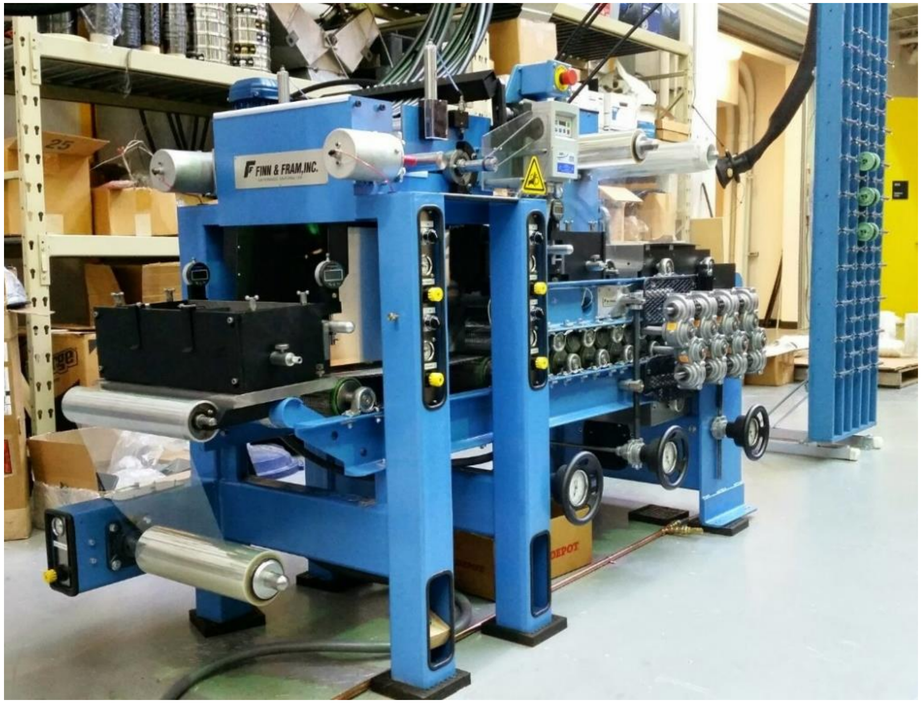


SMC Processing



GATECH SMC & Materials

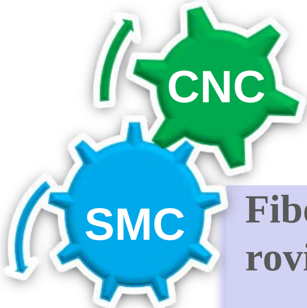
A unique SMC at Georgia Tech:
1) Similar to industrial SMC machine but in a smaller scale (12” wide products)
2) Capable of manufacturing of
   a) short glass fiber composites
   b) continuous carbon fiber composites
   c) fiber mat composites



Glass fibers roving rack

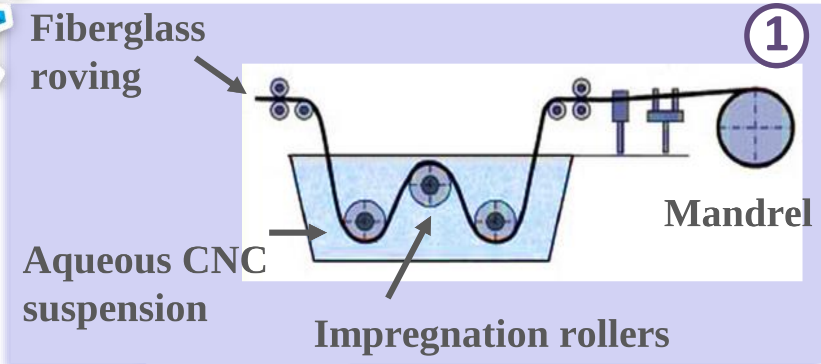
Materials
1. Owens Corning ME 1510 glass fibers: suitable for SMC and epoxy
2. US Composites epoxy 150+polyamide
3. Cellulose Nanocrystals (CNC):Freeze-dried & aqueous suspension: US Forest Service

Scalable Techniques to Introduce CNC in SMC

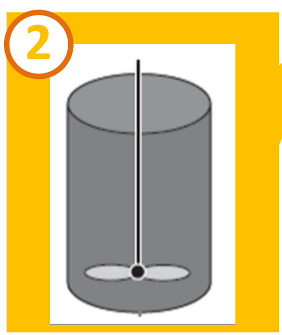


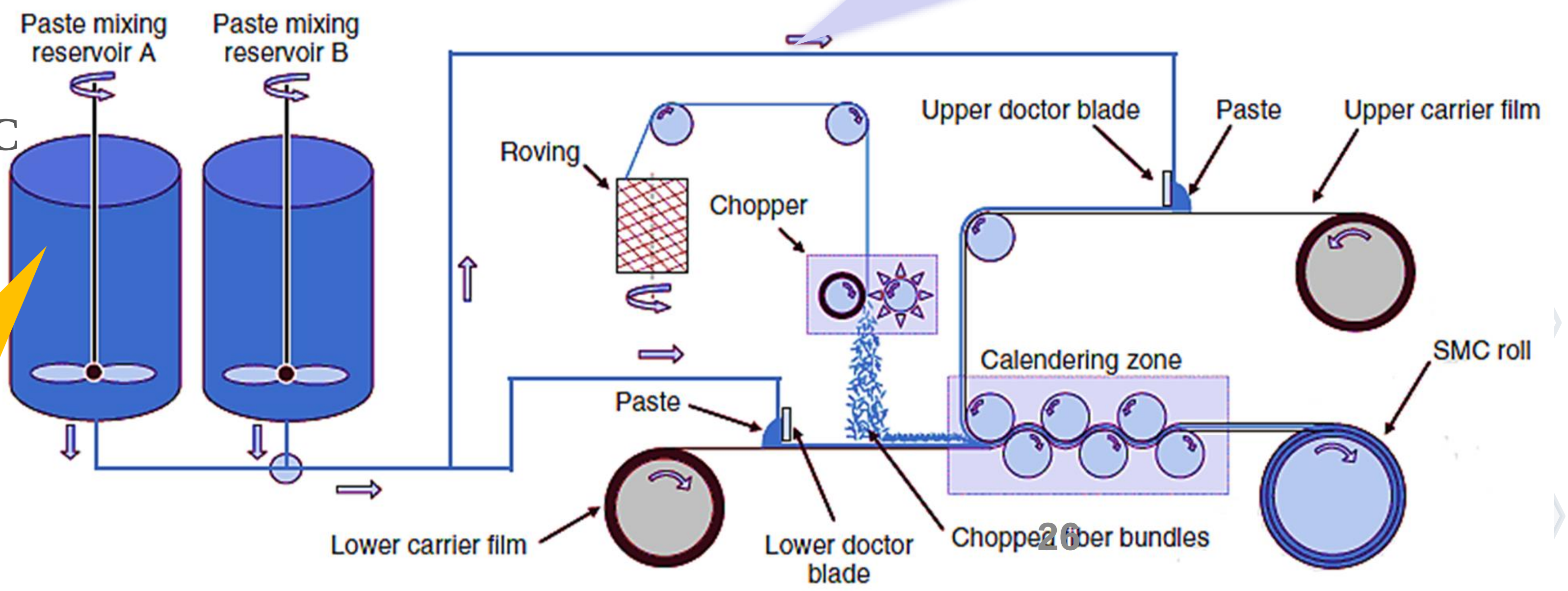
i. Coating glass fibers with CNC

ii. Dispersing CNC in polymer matrix

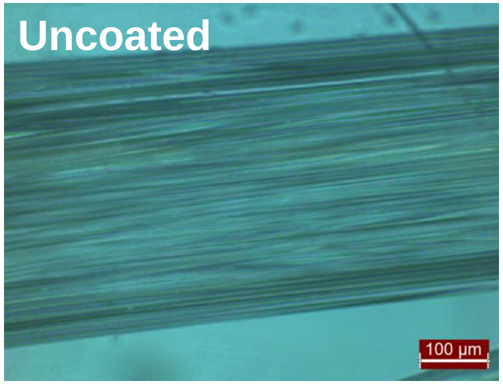


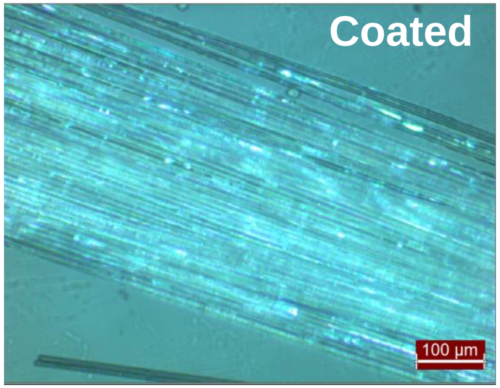
Dispersing CNC in the resin

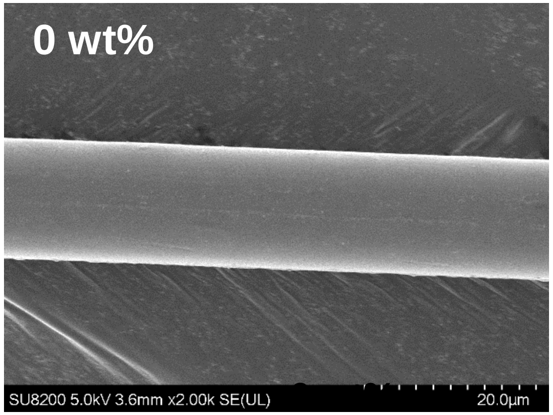


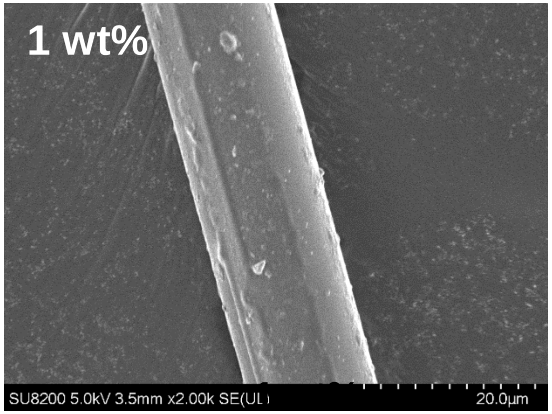


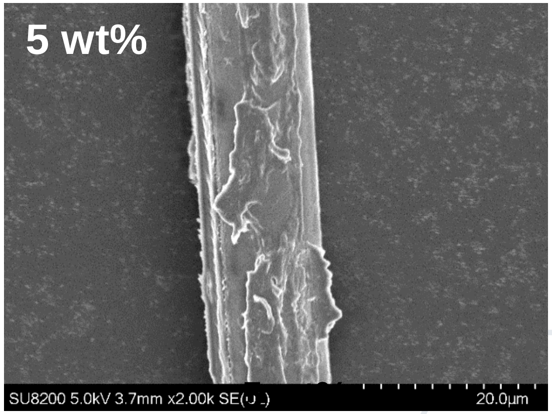
I. Coating Glass Fibers with CNC











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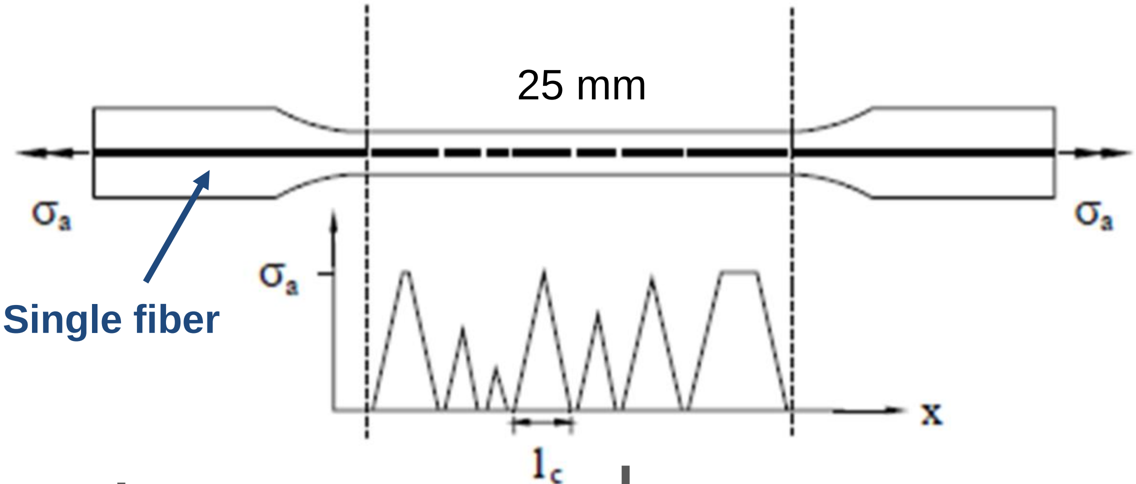
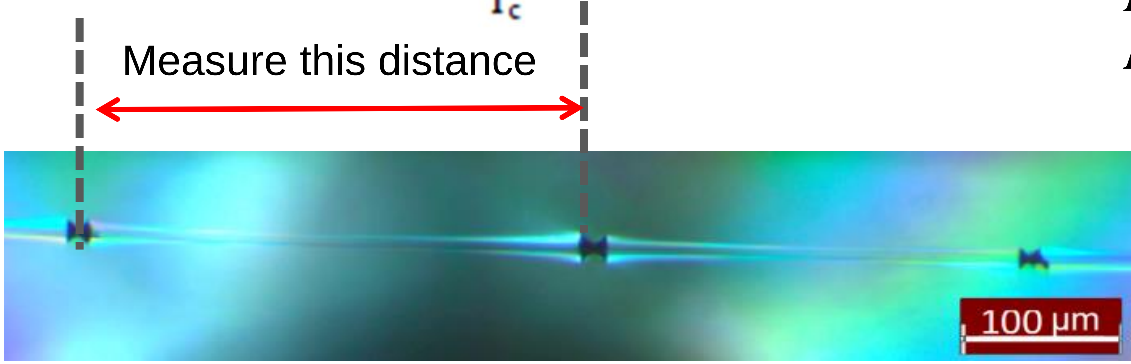
I. CNC Effect on Interfacial Shear Strength

Load transfer efficiency from matrix to GF

Single Fiber Fragmentation (SFF) Test





Polarized light micrograph of single GF after SFF test

$$\tau_i = \frac{d_f \sigma_f}{2 l_c} = \frac{3 d_f \sigma_f}{8 \bar{l}}$$

τ_i: IFSS;
d_f: fiber diameter;
σ_f: fiber strength
l_c: fiber critical fragment length
$\bar{l}$:average length of fragments

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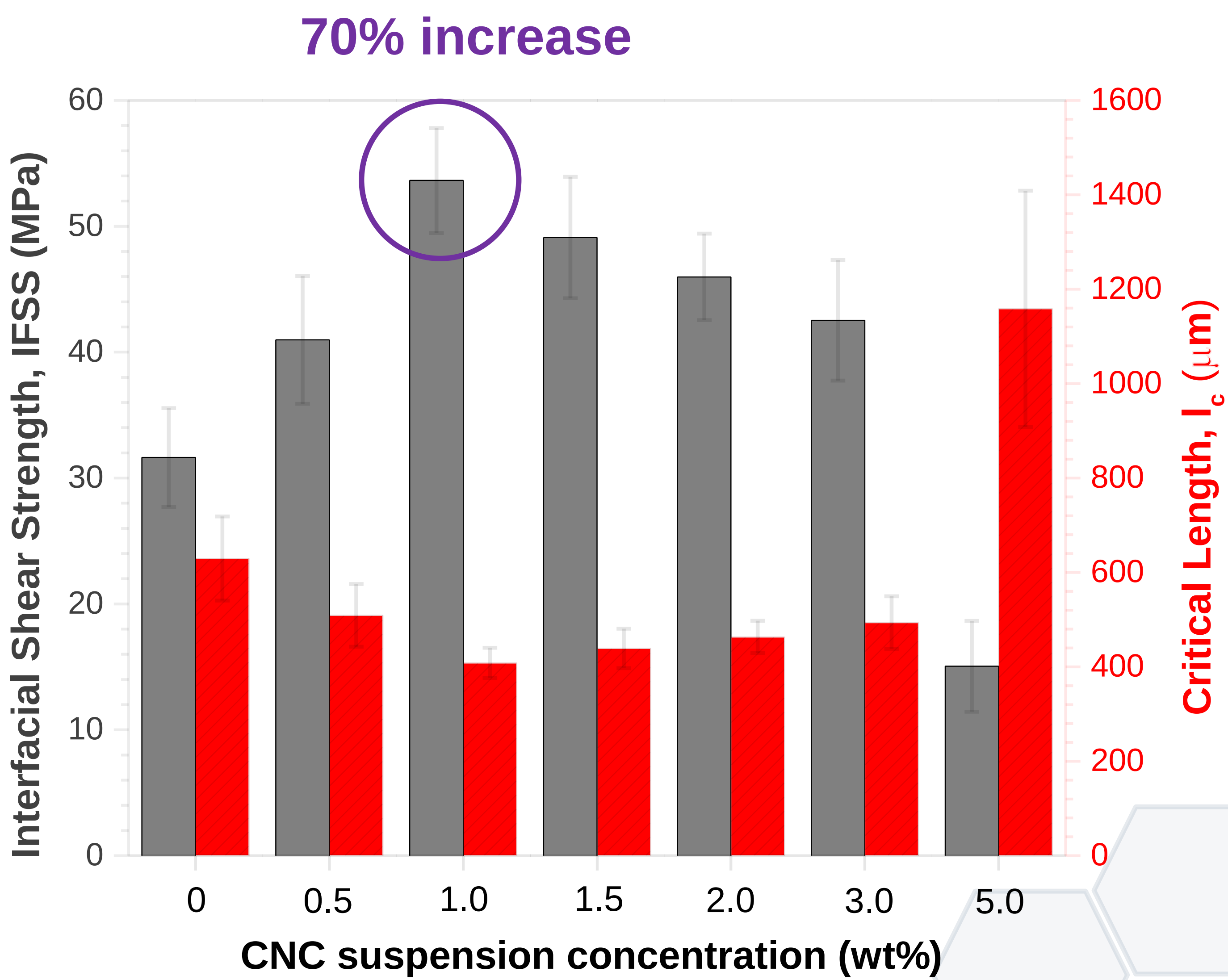
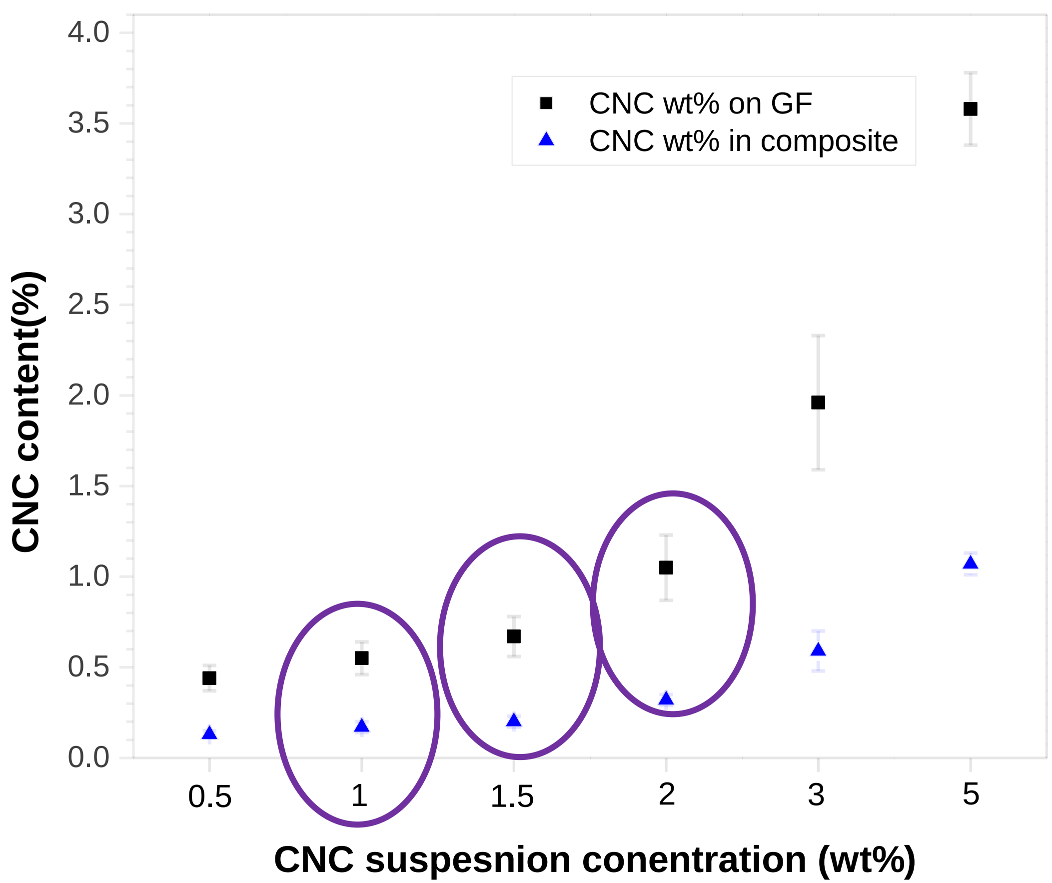
I. CNC Effect on Interfacial Shear Strength



Asadi et al., Express Polymer Letters 2016,10(7):587

I. CNC Content on GF and Composite

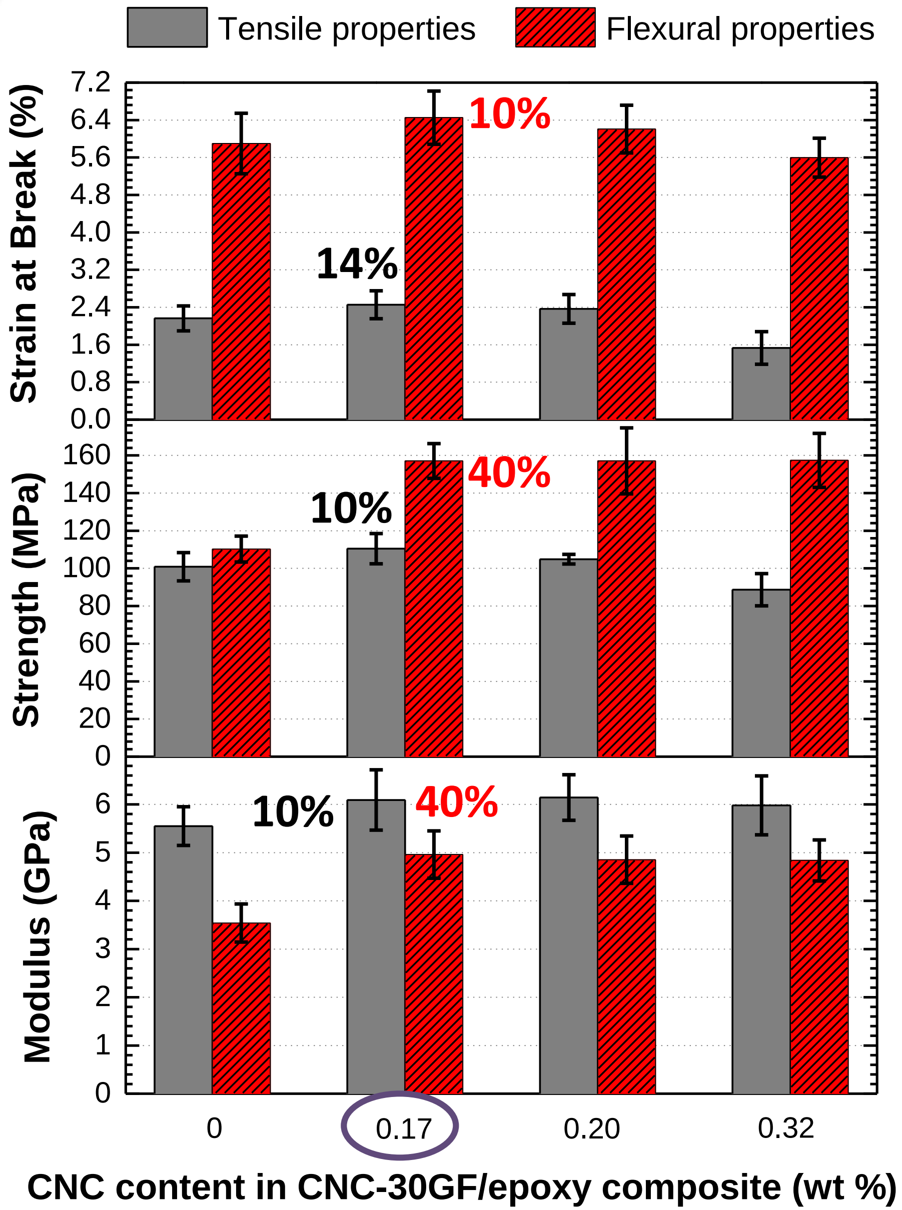
Thermogravimetry (TGA) results

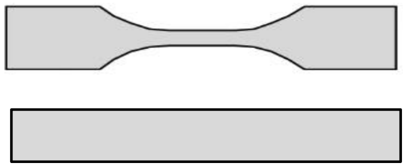


CNC wt% in aqueous suspension	CNC wt% in a 30GF/epoxy composite
0.5	0.13
1	0.17
1.5	0.2
2	0.32
3	0.59
5	1.07

Highest IFSS to make composites

I. Tensile and Flexural Properties of CNC-30GF/Epoxy Composites





Tensile Properties

- ↑ or – Modulus
- ↑ or – Strength
- ↑ or – Strain at break

Flexural Properties

- ↑ Modulus
- ↑ Strength
- – Strain at break

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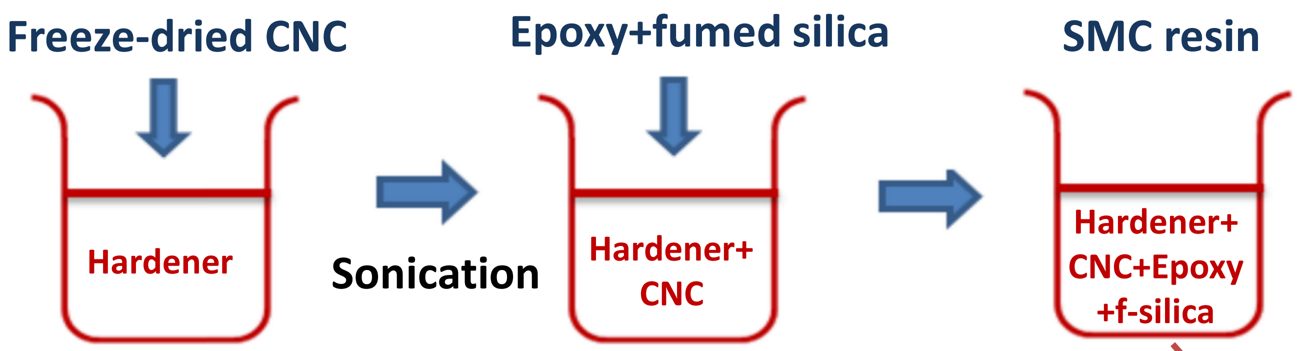
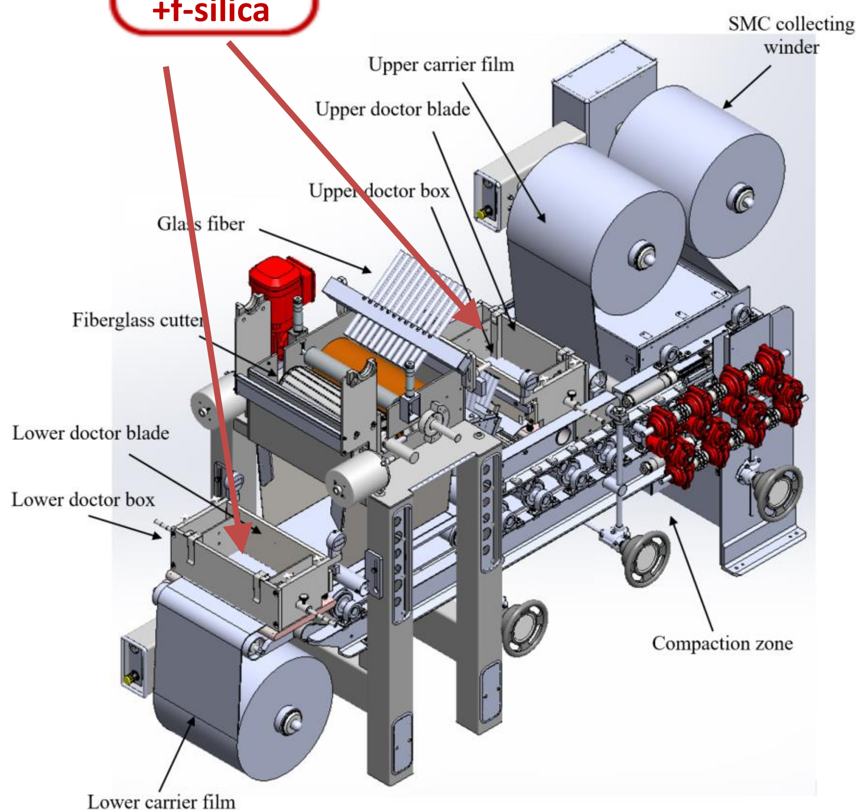
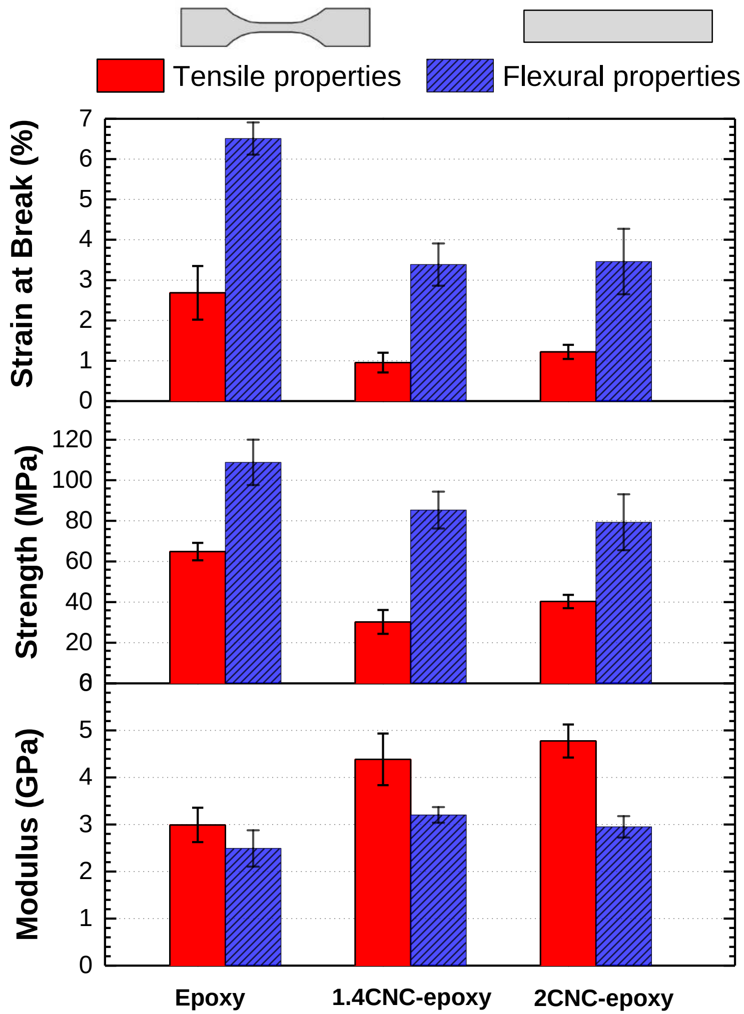
II. Reinforcing Polymer Matrix with CNC prior to Use in SMC

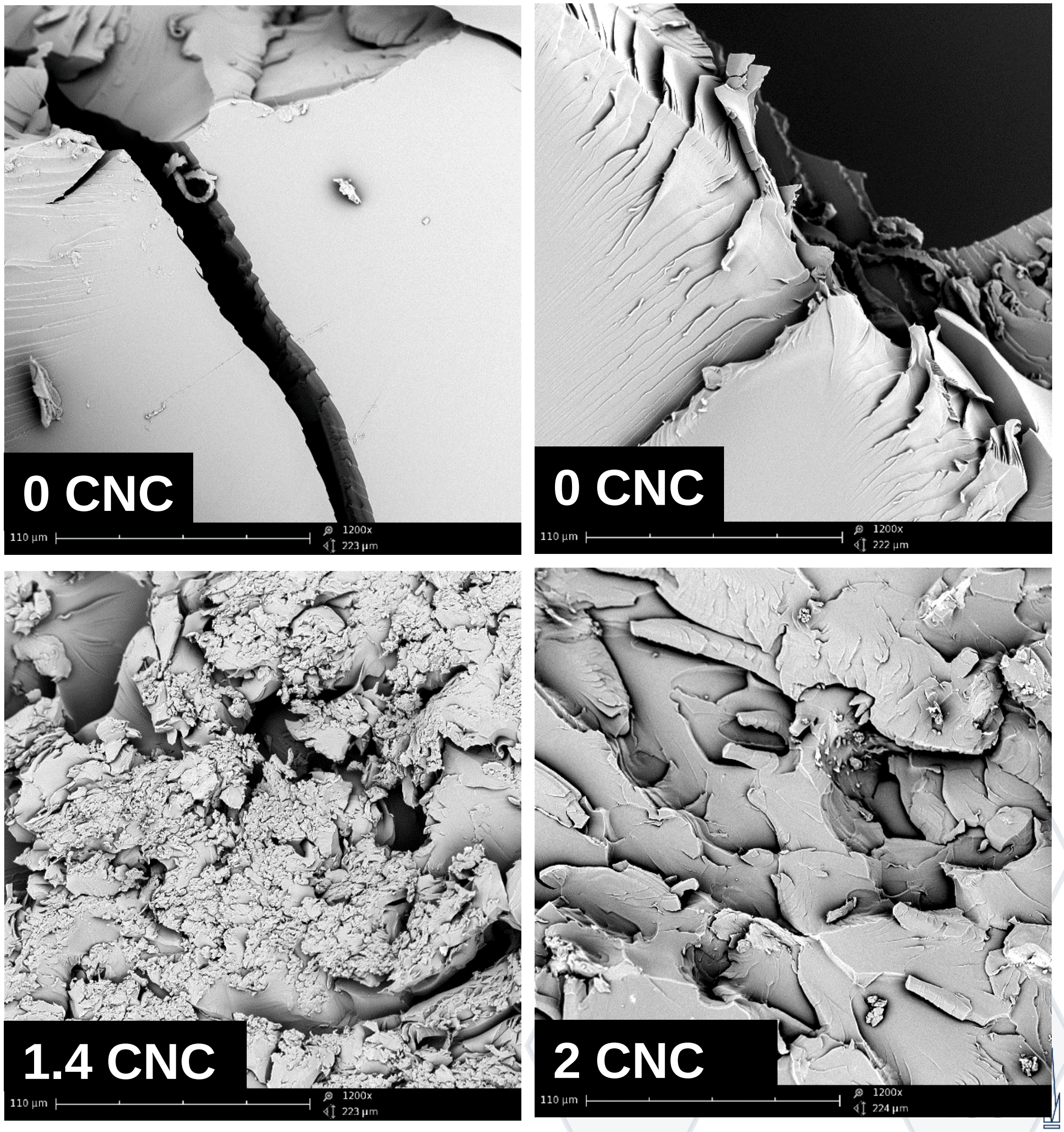


CNC wt% in the neat resin	CNC wt% in a 35GF/epoxy composite
0	0
0.2	0.15
0.4	0.3
0.7	0.5
1.4	0.9



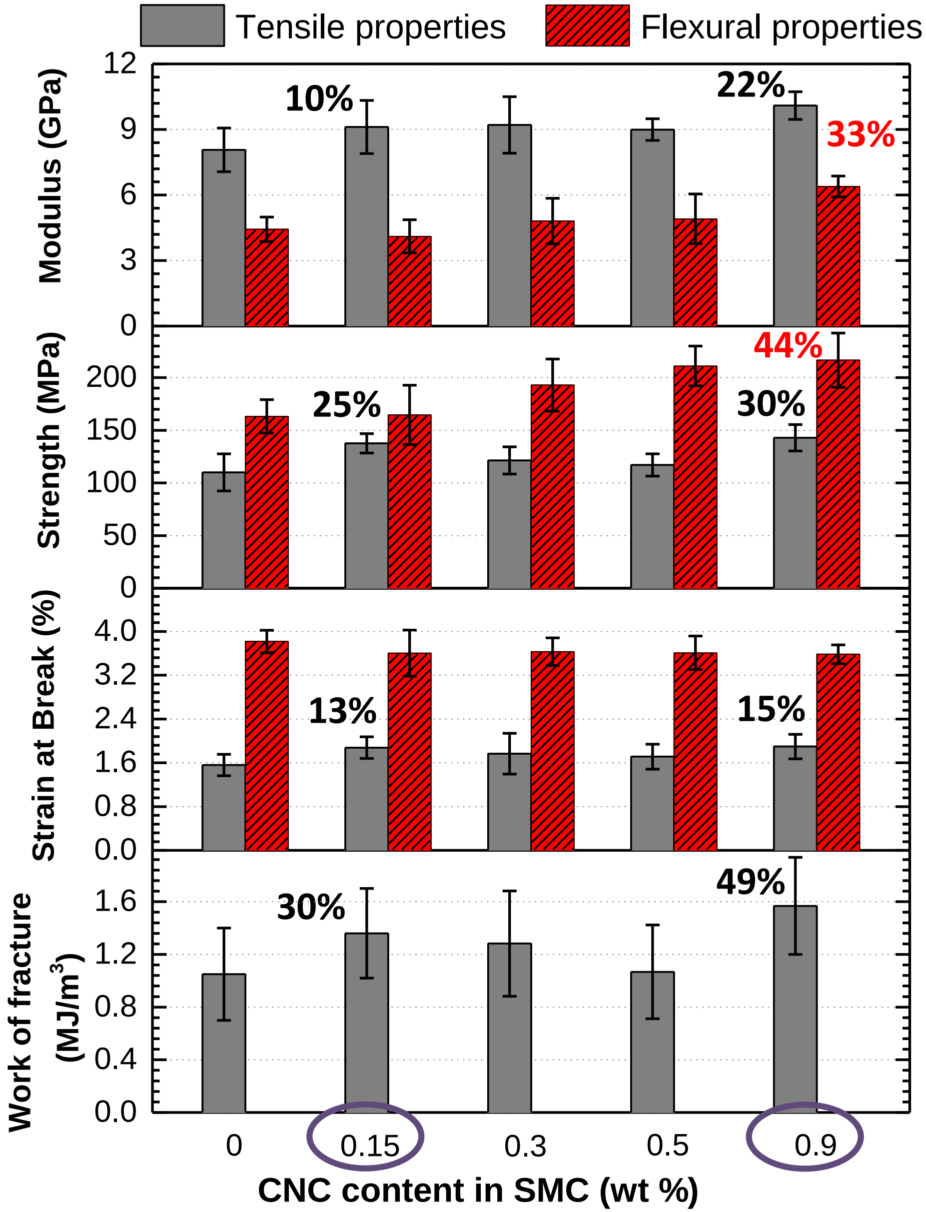
II. Tensile and Flexural Properties of CNC-epoxy Composites

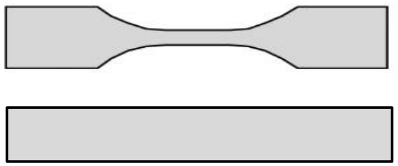




Asadi et al., Composite Structures 2017,160:211

II. Tensile and Flexural Properties of SMC 35GF/CNC-epoxy Composites

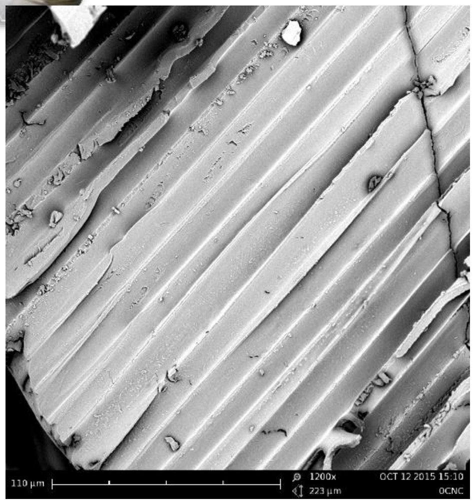




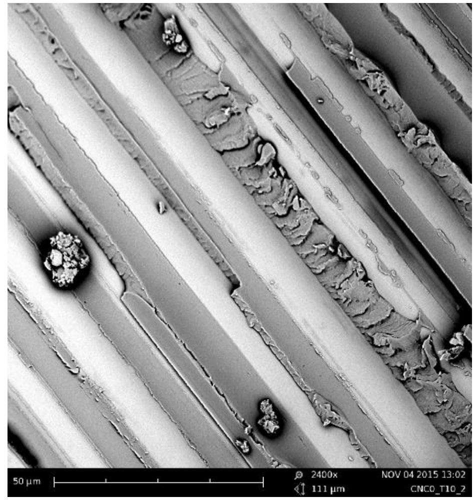
ANOVA Verified

Asadi et al., Composites Part A 2016,88:206

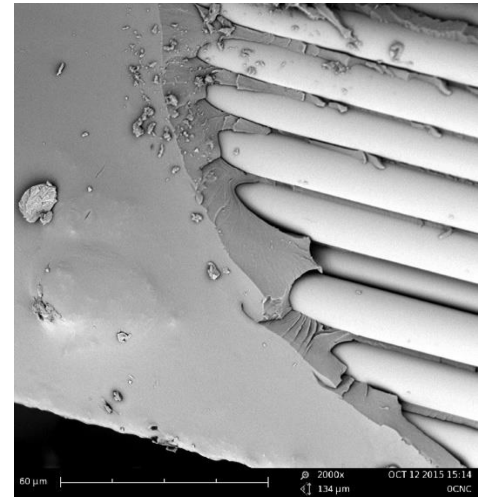
II. Tensile Fracture Surface Morphology of SMC 35GF/CNC-epoxy Composites



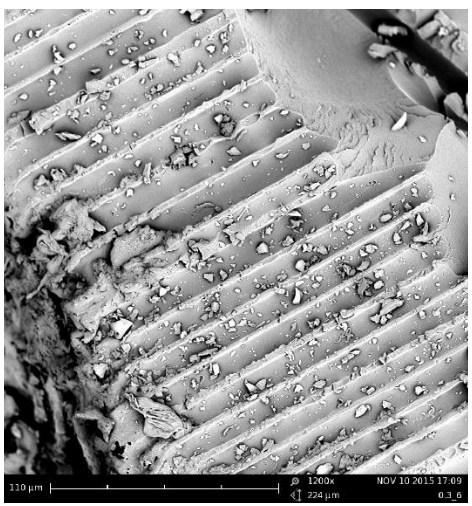
0 CNC wt%



0 CNC wt%



0 CNC wt%

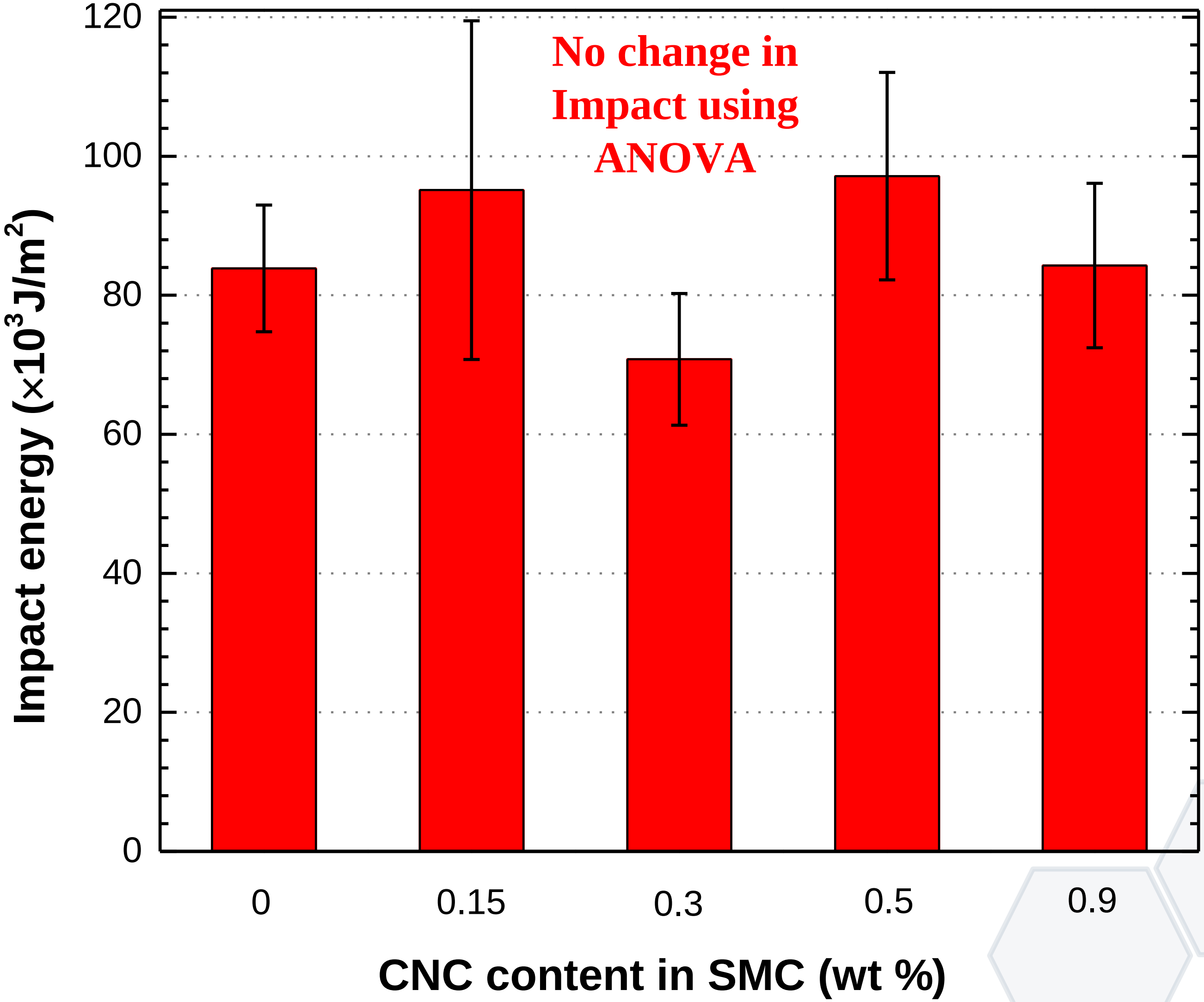


0.3 CNC wt%

0.15 CNC wt%

0.9 CNC wt%

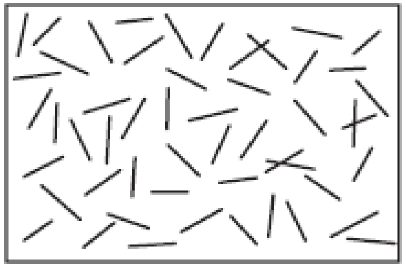
II. Impact Properties of SMC 35GF/CNC-epoxy Composites



II. Theoretical Guidelines for Light Weighting

Goal: Determine the CNC and GF content of a GF/CNC-epoxy composite so that is has the same specific modulus with 35 wt% GF/epoxy composites

Discontinuous randomly distributed fiber/composite



$$E_{Composite} = \frac{3}{8}E_{11} + \frac{5}{8}E_{22}$$

$$E_{11} = E_m\left(1 + 2\frac{l_f}{d_f}\eta_L v_f\right)/\left(1 - \eta_L v_f\right)$$

$$E_{22} = E_m\left(1 + 2\eta_L v_f\right)/\left(1 - \eta_L v_f\right)$$

$$\eta_L = \left(\frac{E_f}{E_m} - 1\right)/\left(\frac{E_f}{E_m} + 2\frac{l_f}{d_f}\right)$$

$$\eta_T = \left(\frac{E_f}{E_m} - 1\right)/\left(\frac{E_f}{E_m} + 2\right)$$

Density: $\rho_c = \frac{1}{(w_f/\rho_f) + (w_m/\rho_m)}$

Sample	E_c (GPa)	ρ_c (g/cm^3)	$E_{c,\ specific}$
25GF/epoxy	6.3	1.37	4.6
25GF/1CNC-epoxy	7.4	1.37	5.4
25GF/1.5CNC-epoxy	7.8	1.37	5.7
35GF/epoxy	8.0	1.46	5.5

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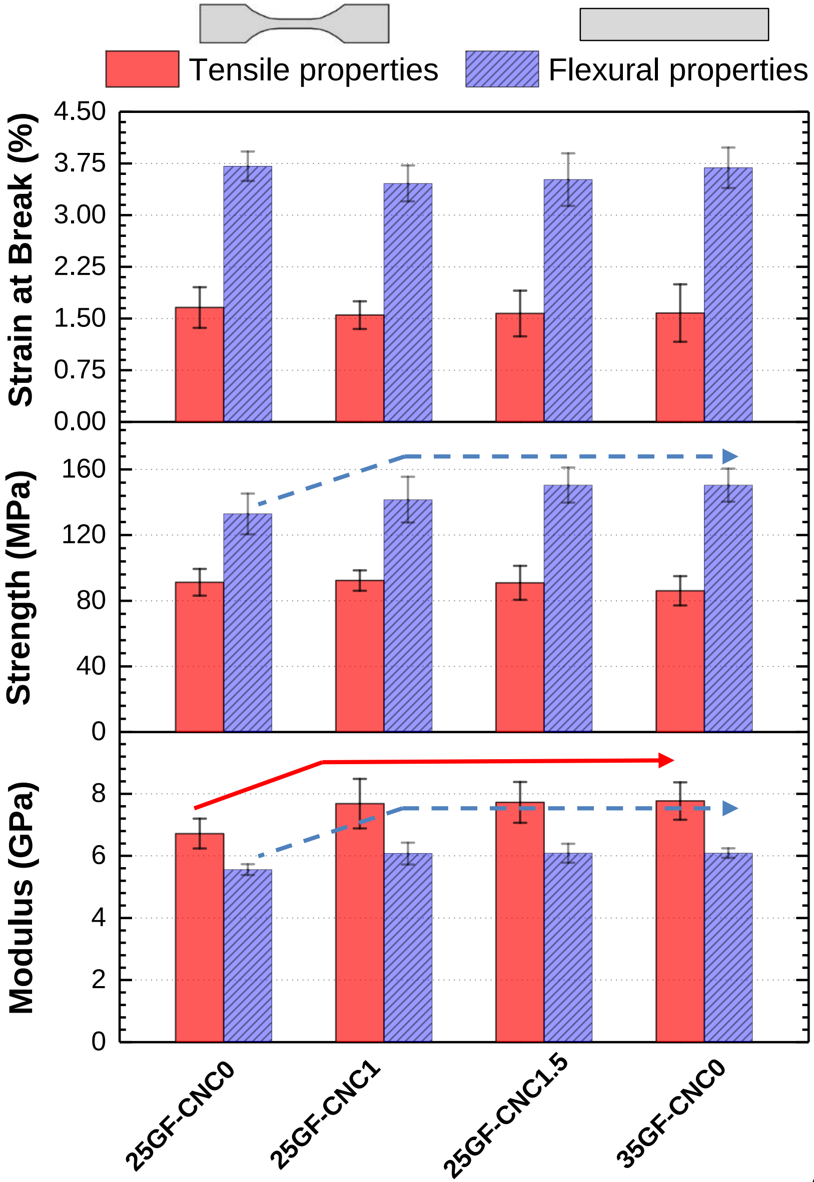
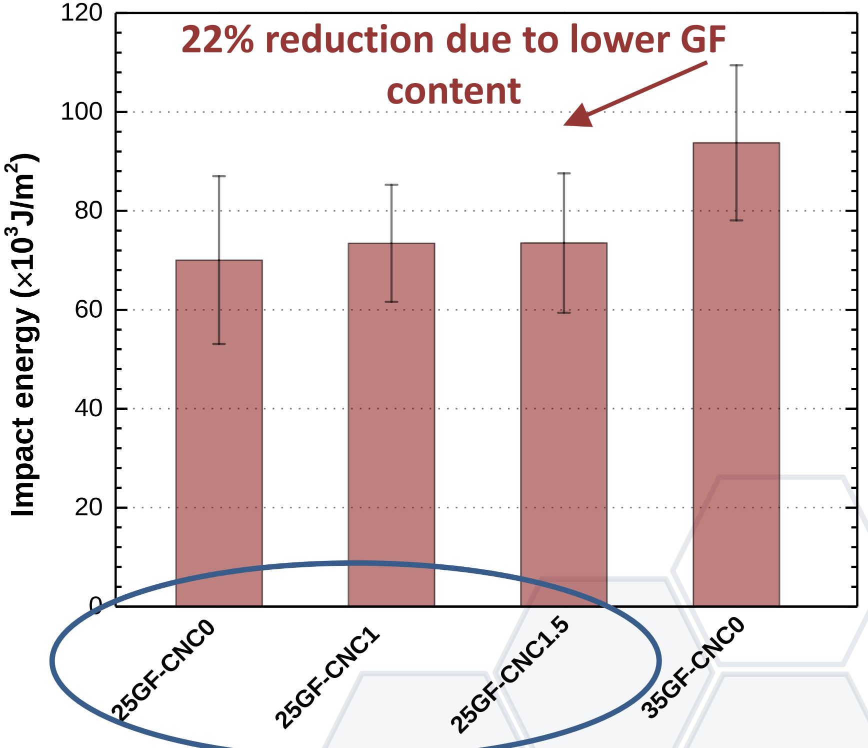
II. Light Weighting Achieved



10% reduction in GF wt%

8% reduction in density



No effect of CNC on Impact

Asadi et al., Composite Structures 2017,160:211

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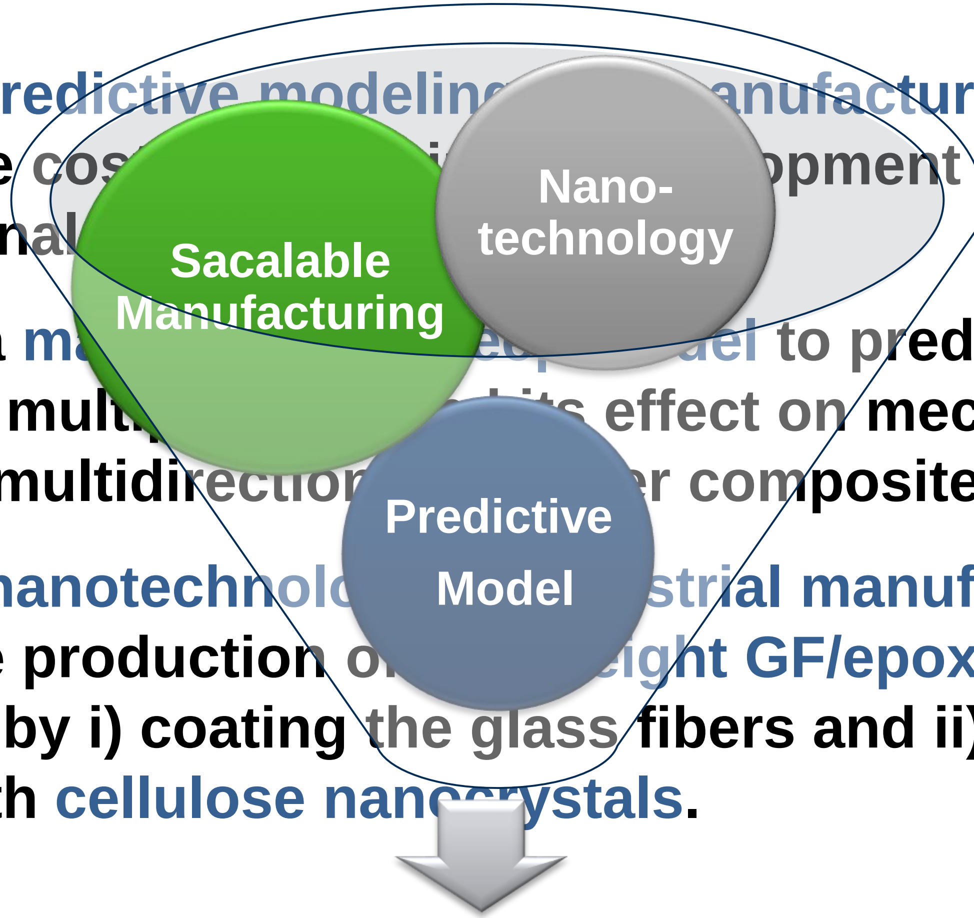
Summary

- **Combined predictive modelin[…]anufacturing to minimize the cos[…]opment of multifunctional[…]**
- **Developed a ma[…]el to predict the damage evolution in mult[…]its effect on mechanical behavior in multidirection[…]er composite laminates.**
- **Introduced nanotechnolo[…]strial manufacturing for high volume production o[…]eight GF/epoxy SMC composites by i) coating the glass fibers and ii) reinforcing the resin with cellulose nanocrystals.**



Accelerate the development of multifunctional (hybrid and nano) composites with engineered performance

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Research Lab in 2032

Manufacturing and Mechanics of

Applications

- Automotive
- Aerospace
- Marine
- Wind Energy
- Biomedical and tissue engineering
- Electronics and heat transfer

Collaborations

- National labs
- Government agencies
- Industries
- Public-Private Partnership
- Universities

Nanomaterials into industrial manufacturing

New synthesis and sintering methods

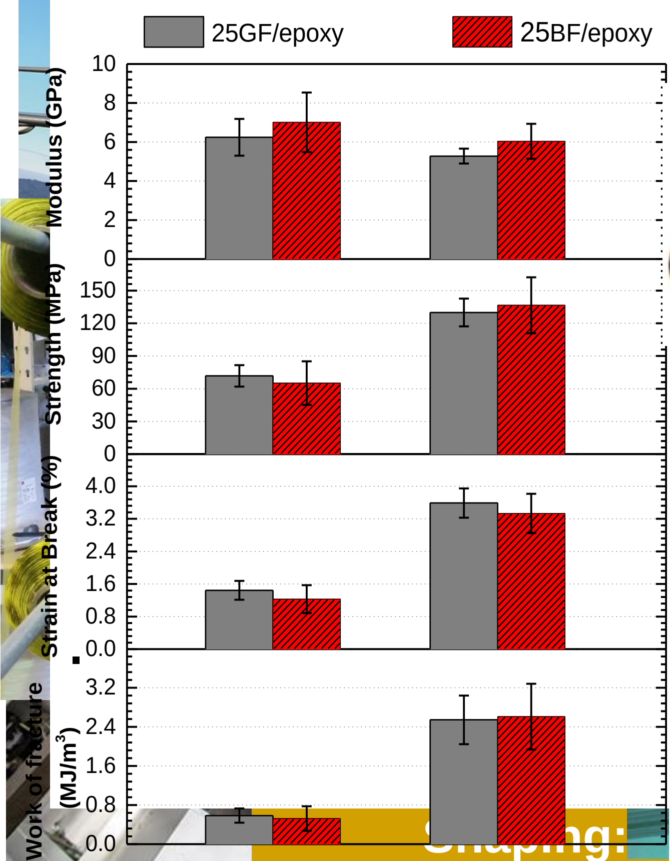
Additive manufacturing of thermoset nanocomposite

Automation in composites manufacturing

MMC Lab by 2022

Cellulos… an… | **Basalt fibers in SMC** | …ynthesis …ion

Extension of the current work to add nanomaterials for light weighting, the optimum process conditions, e.g. time, temperature and pressure for fast production



+

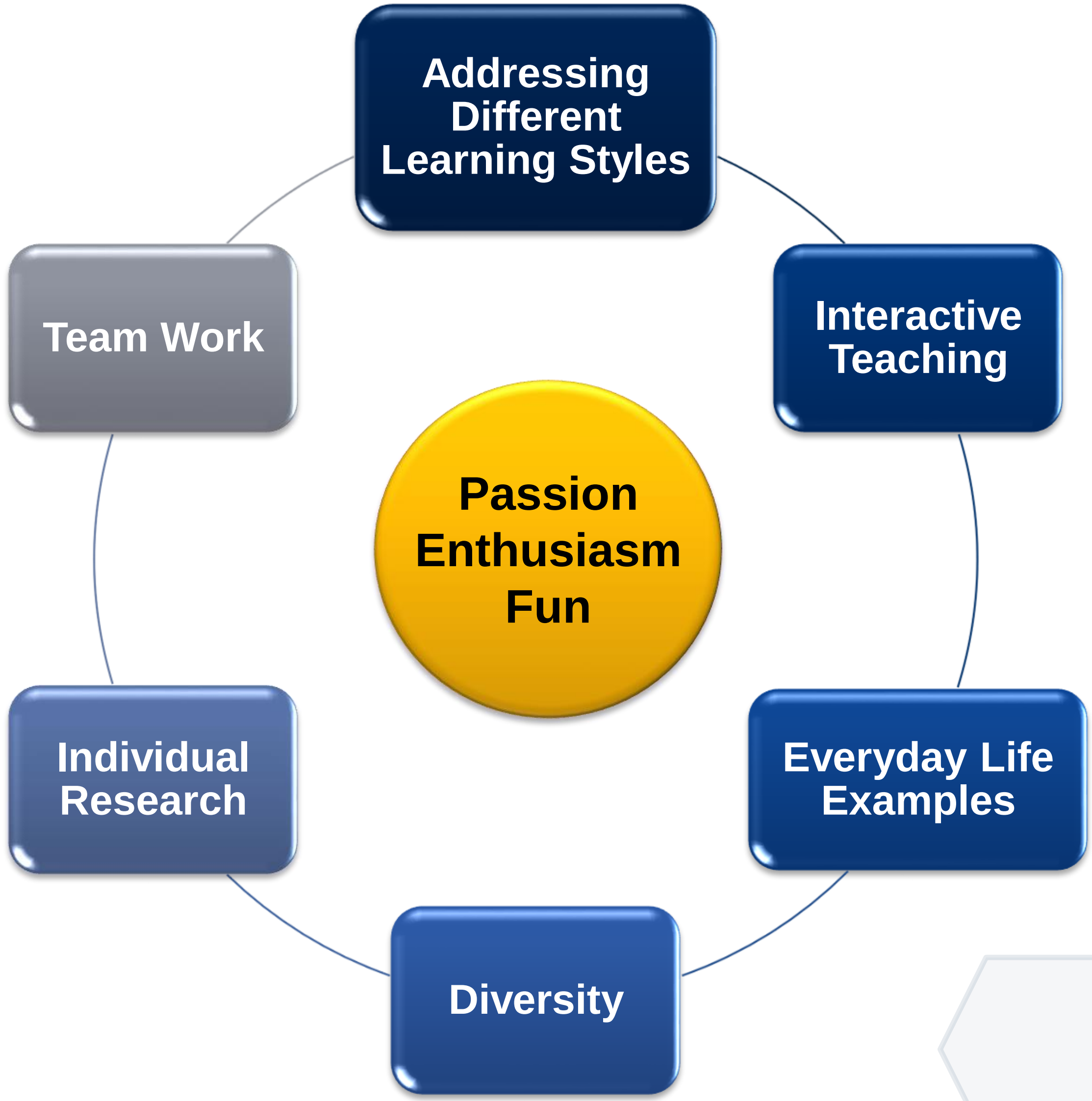
Glass/epoxy SMC composite

Basalt/epoxy SMC composite

Funding Targets

- Department of Energy
- National lab
- US Forestry
- NSF
- Automotive Industries
- Aerospace Industries
- Fiber Manufacturer
- Biomedical Industries

Teaching Philosophy



Courses

Taught Courses

- ✓ Composite Materials (GA Tech)
- ✓ Engineering Materials (UofM)
- ✓ Introduction to Thermal Sciences (UofM)

Interested to teach at ASU

MET 418: Composites Materials Manufacturing
MFG 482: Materials Science in Manufacturing
MFG 385: Design for Manufacturing
MET 300: Applied Material Science
MET 345: Advanced Manufacturing Processes
EGR 343: Mechanics of Solid Materials
EGR 218: Materials and Manufacturing Processes
MET 230: Introduction to Engineering Materials
MET 213: Applied Mechanics of Materials

New Graduate-Level Courses

Process-structure-property in nanocomposites[1]

Providing a roadmap to design the compounding and shaping to achieve the desired properties

A. Asadi, K. Kalaitzidou. A book chapter on "Process-Structure-Property Relationship in Polymer Nanocomposites", Elsevier, 2017

Acknowledgement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NSERC
CRSNG

P3Nano

U.S. Endowment
for Forestry and Communities

Volkswagen

BOEING

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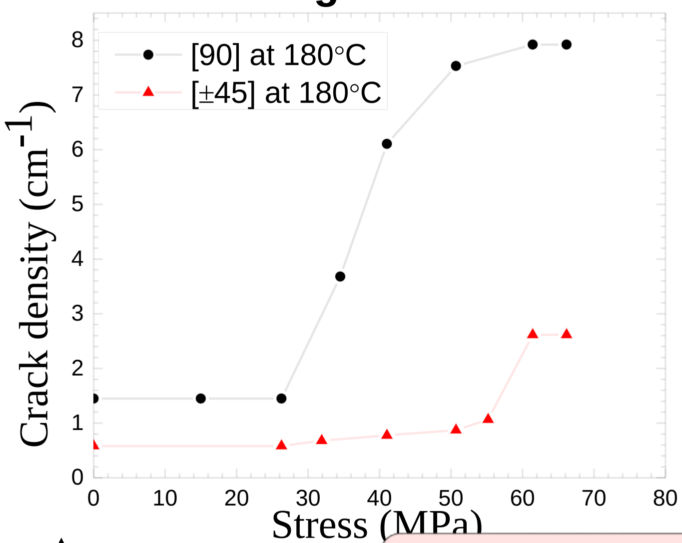
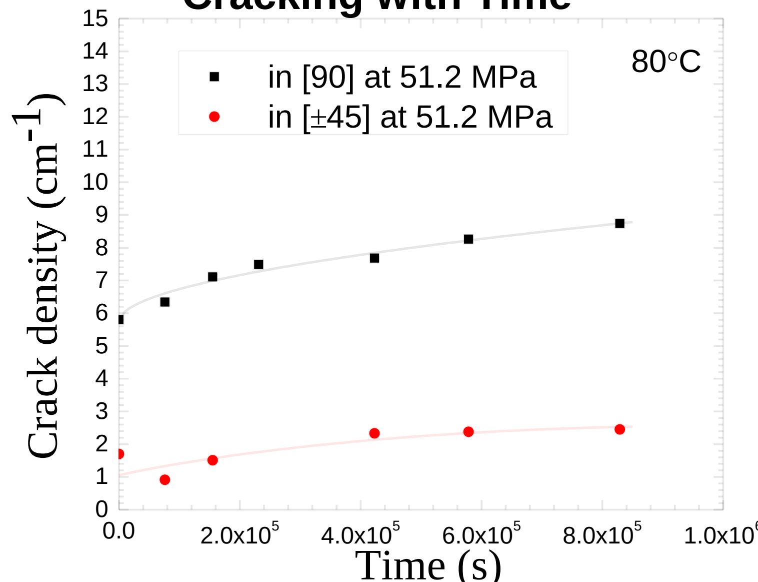
Thank You!

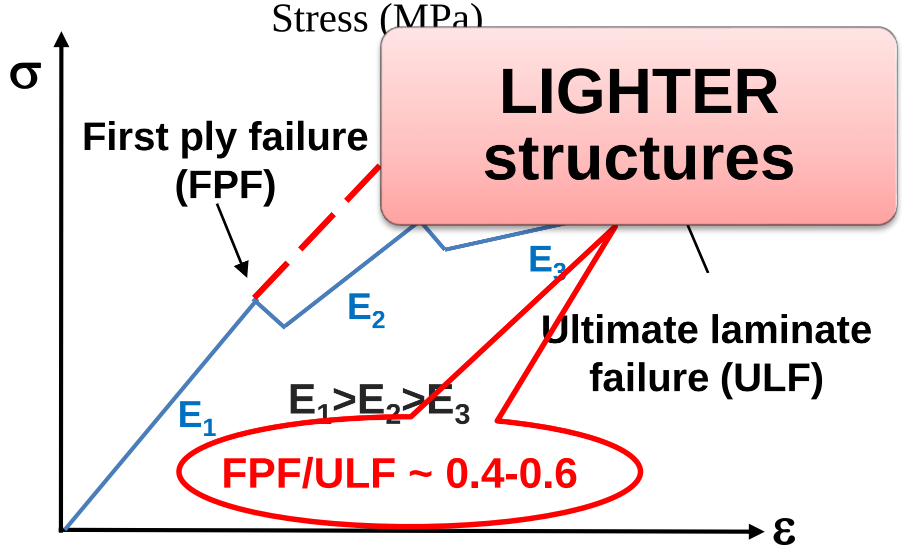
Effect of Damage on Composite Behavior

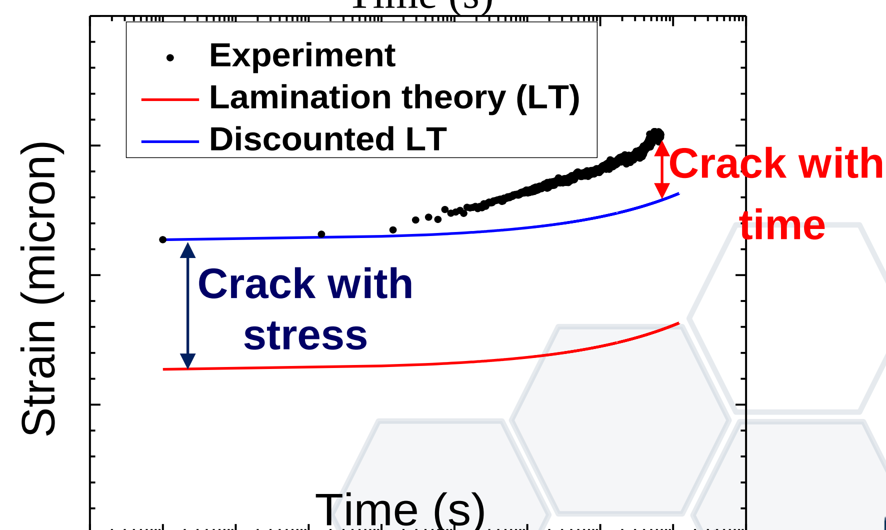
Cracking with Stress



Cracking with Time







Modulus degradation with cracking

Creep strain with cracking

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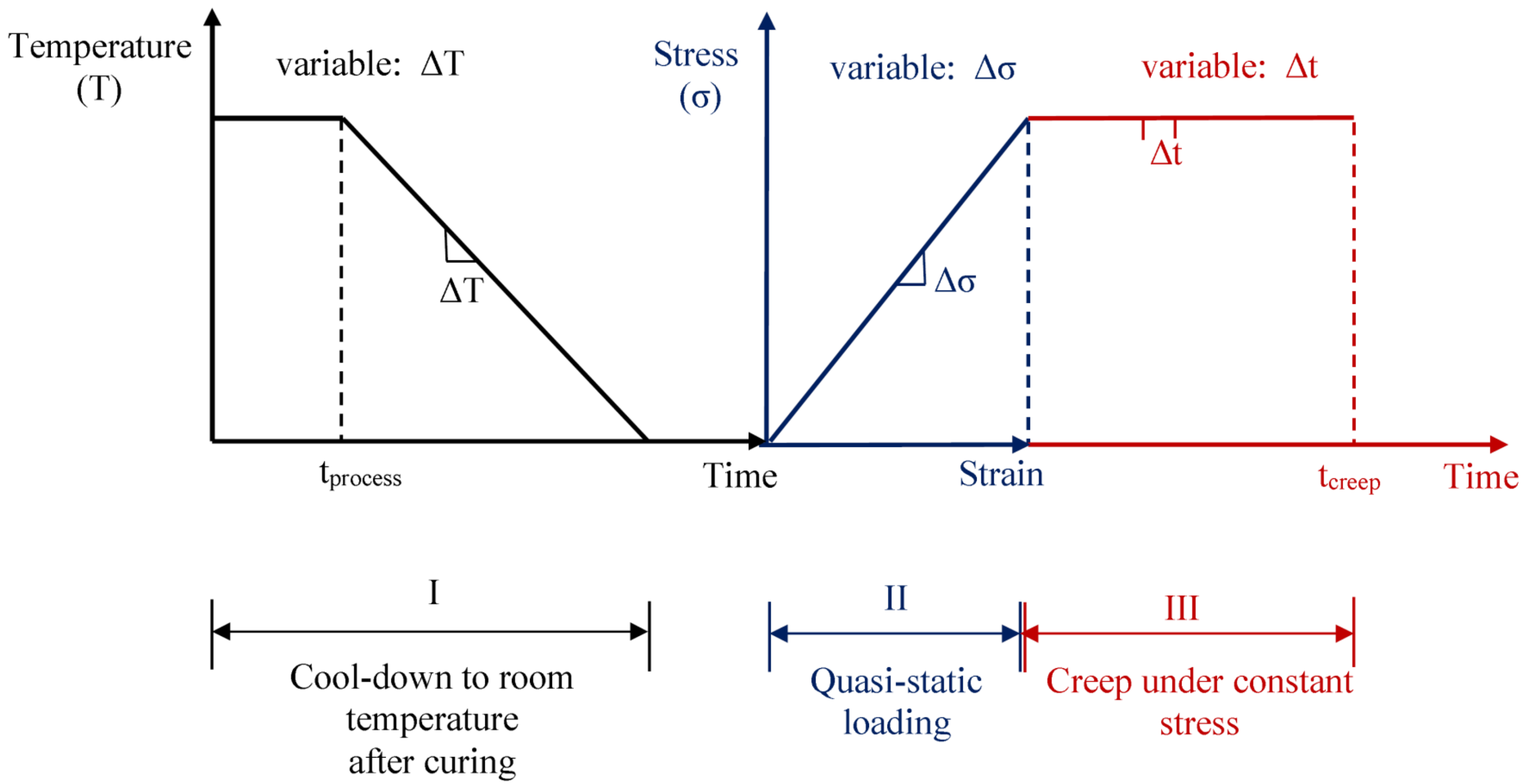
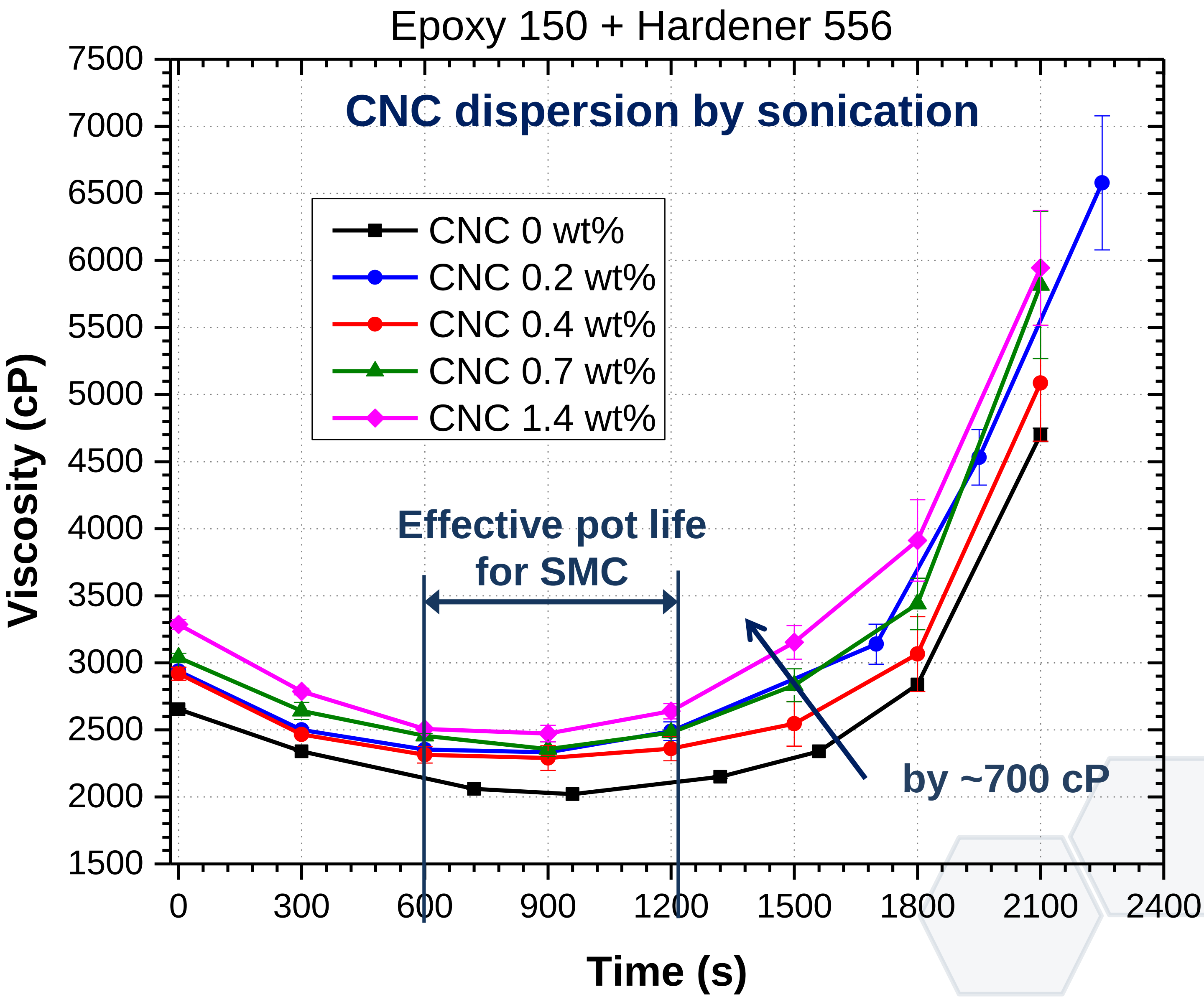
What is Important in a Creep Model?

A successful creep-damage model should consider the history of loading



Manufacturing **Ramp up** **Service**

CNC Effect on the Viscosity of Epoxy



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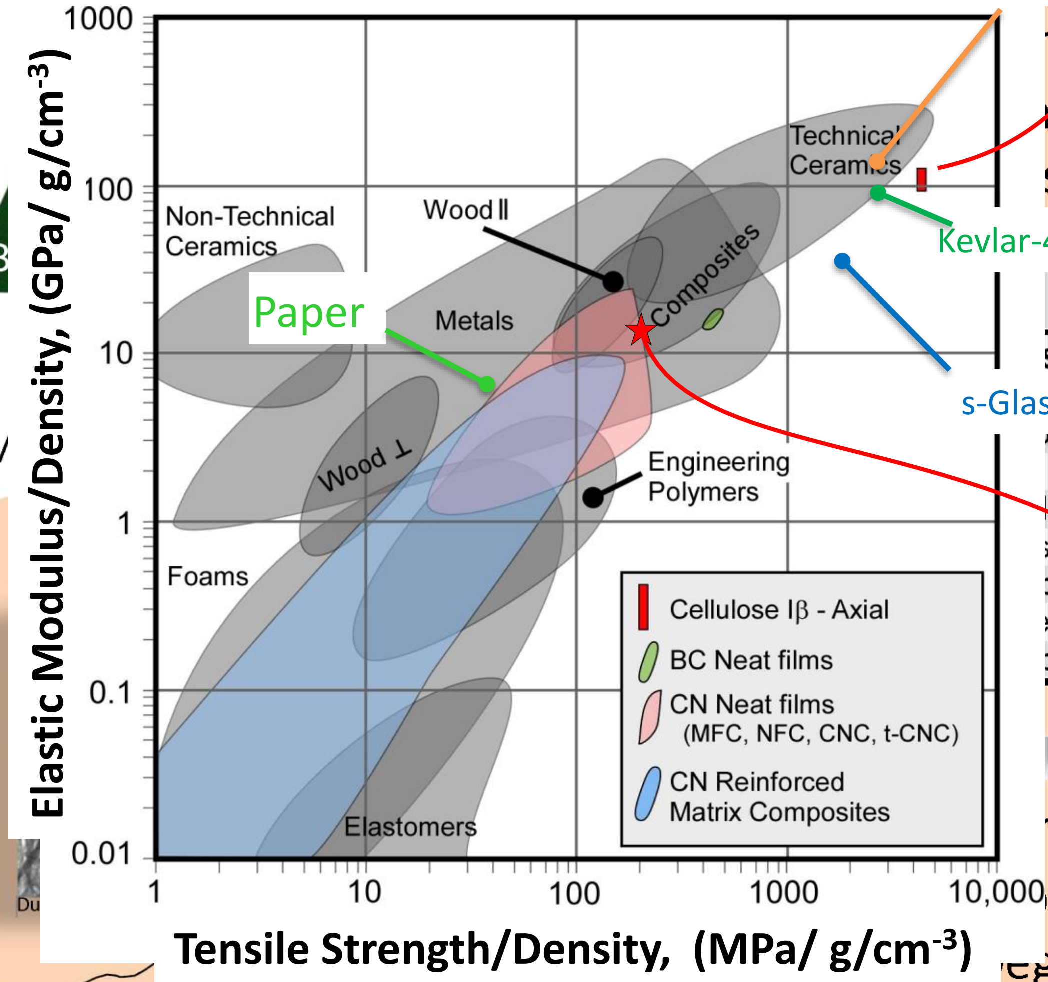
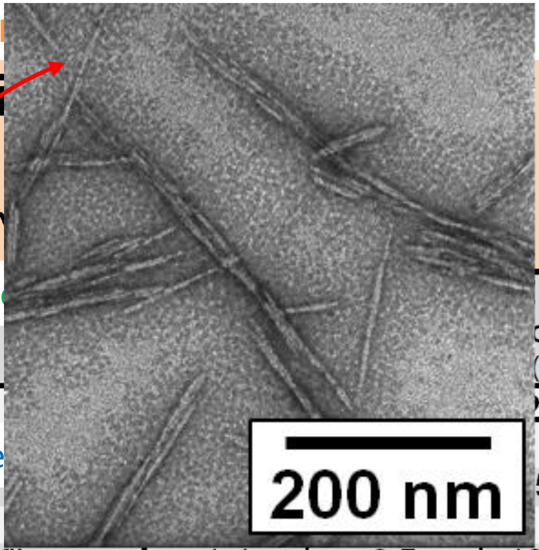
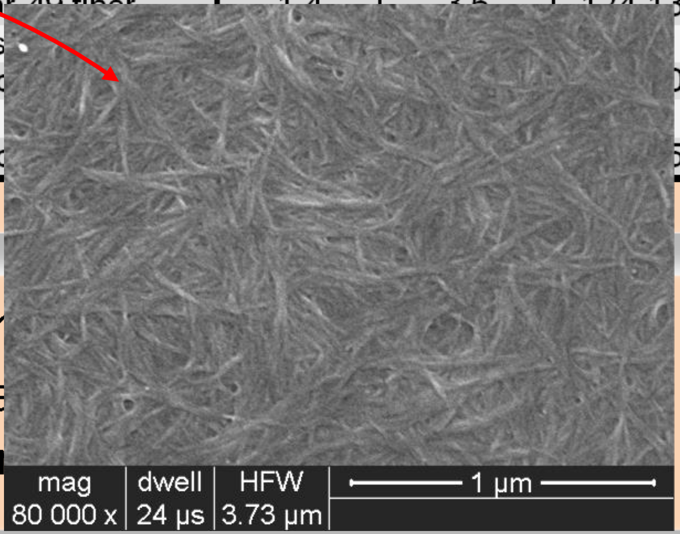
Cellulose Nanoparticles

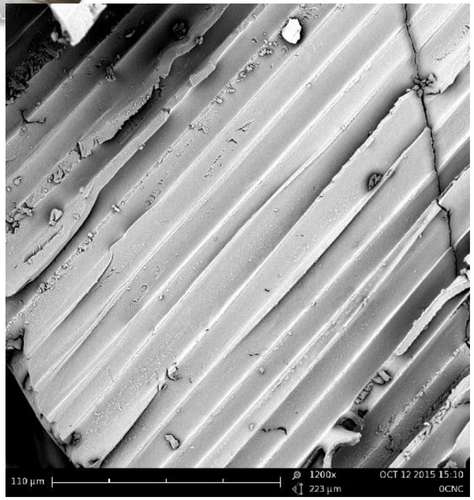




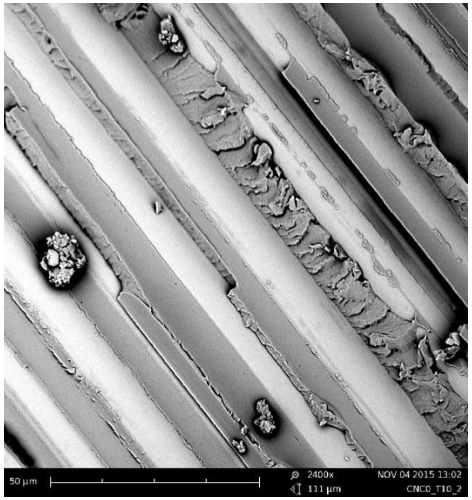


Moon et al. Chem. Soc. Rev. 2011; 40, 3941

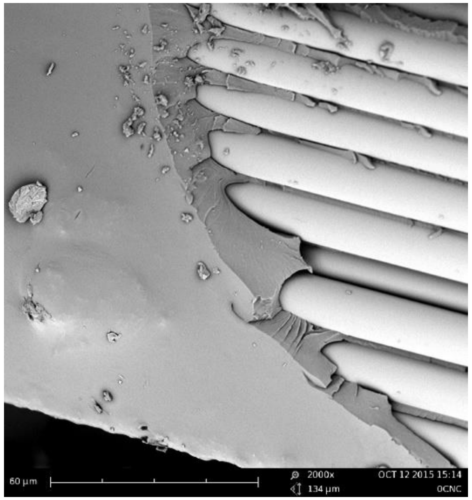
II. Tensile Fracture Surface Morphology of SMC 35GF/CNC-epoxy Composites



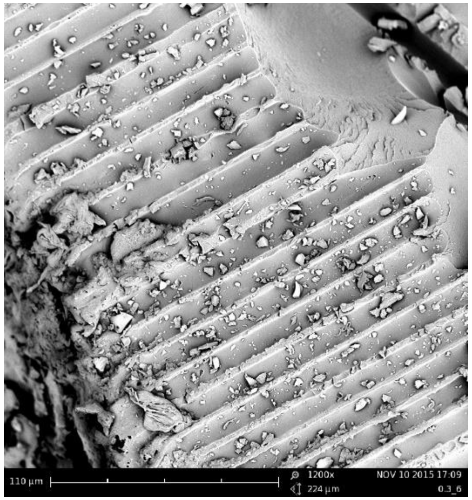
0 CNC wt%



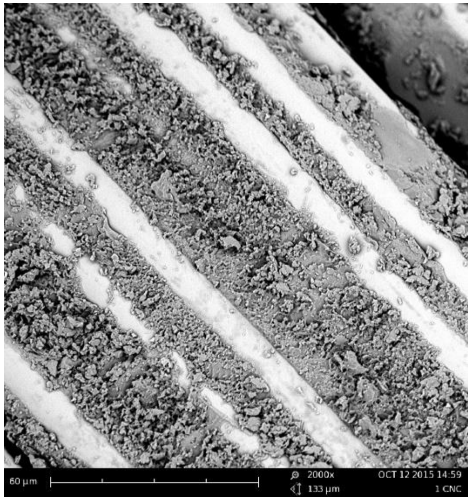
0 CNC wt%



0 CNC wt%



0.3 CNC wt%



0.15 CNC wt%

0.9 CNC wt%

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