A Natural Alternative to Glass Fibers in Composite Laminates: Challenges and Opportunities of Silk Fibers

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15th International Symposium on Bioplastics, Biocomposites and Biorefining
July 24th, 2018
Guelph, ON, Canada

The UNIVERSITY of OKLAHOMA
School of Aerospace and Mechanical Engineering

ISBBB

Natural Fiber Composites

Environmental awareness
Stricter environmental policies

Industries pursuing eco-friendly materials

Interest in natural fiber composites

Natural fibers:

Plant-based fibers:
- Sisal, Jute, Hemp,...
- Significant commercial use
- Mostly non structural parts

Animal-based fibers:
- Limited commercial use
- Less scientific interest



Natural Fiber Composites

Environmental awareness
Stricter environmental policies

↓

Industries pursuing eco-friendly materials

↓

↑ Interest in natural fiber composites

↓



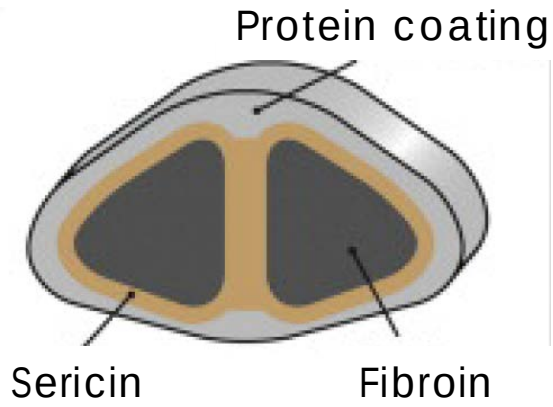
Monteiro et al. Revista Matéria, v. 15: 488 - 505 (2011)

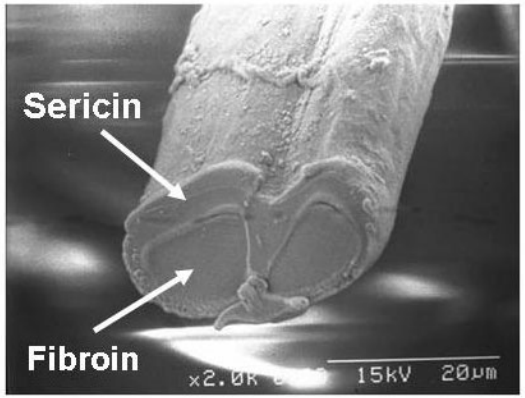
To fabricate a natural fiber/polymer composite

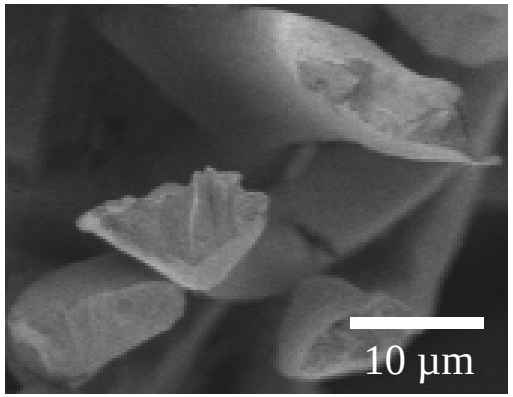
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- Cost
- Availability
- Processing methods
- Performance - Properties
- Durability/Environmental/Thermal stability

Silk Fibers



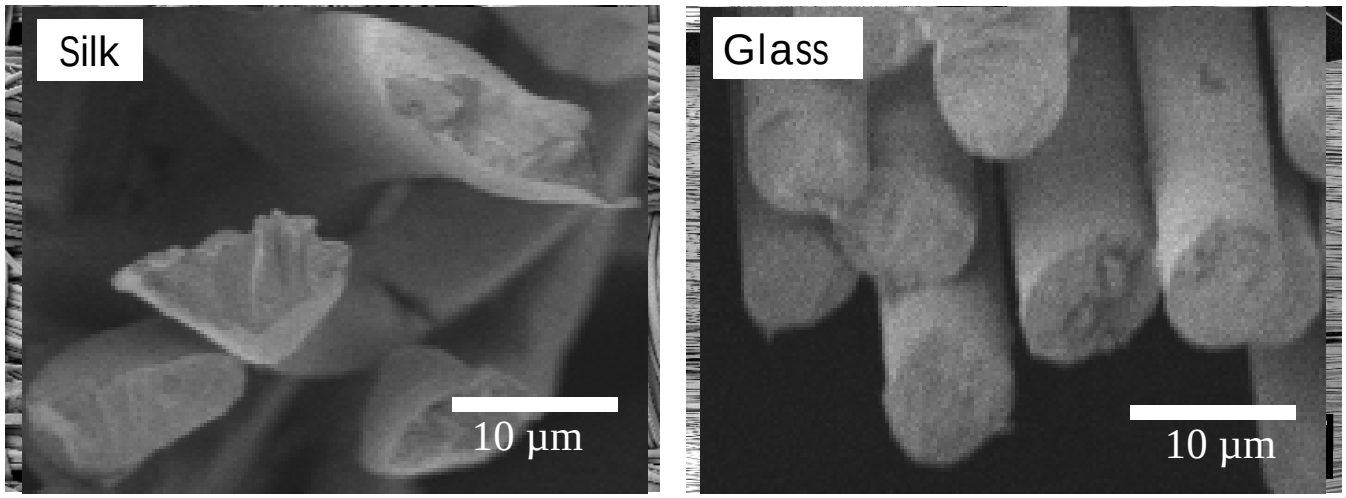




As a reinforcement, silk fibers offer:

- Higher mechanical performance than plant fibers
- Lower density than inorganic fibers/plant fibers
- Specific properties comparable to glass fibers
- Higher toughness/Higher breaking energy

Silk vs Glass Fiber

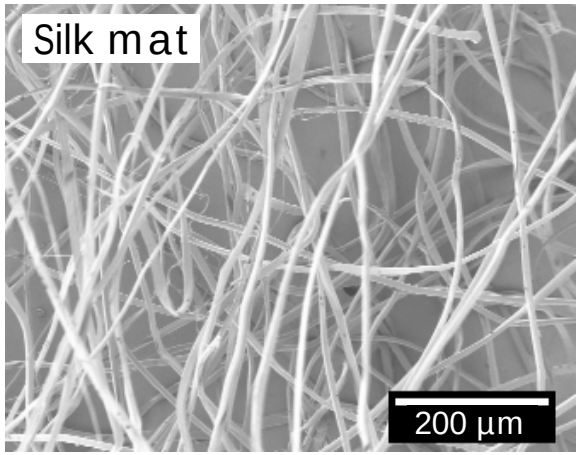


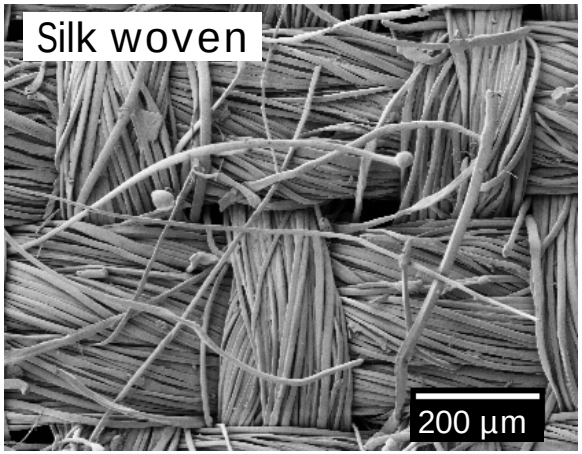
Silk fibers can be the natural alternative to E-glass:

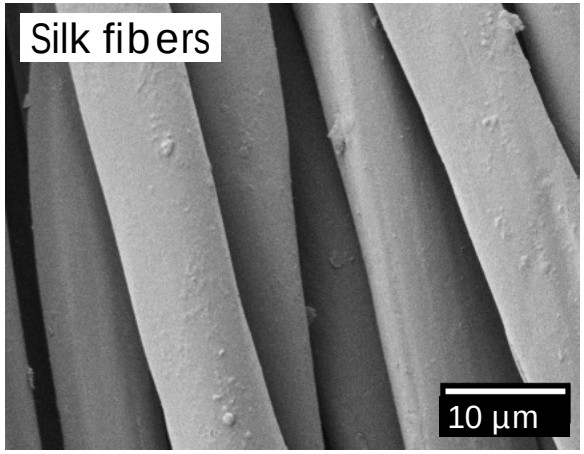
	Silk	E-Glass
➢ Silk density (g/cm^3):	1.24-1.37	2.5
➢ Tensile strength (MPa):	100-1500	2000-3000
➢ Tensile stiffness (GPa):	5-25	70
➢ Failure strain:	15-21%	2.5%
➢ Specific tensile strength (MPa cm^3/g):	100-1500	800-1400
➢ Specific tensile stiffness (GPa cm^3/g):	4-20	29

Yang et al. Materials and Design (2016)
Pickering et al., Composites A (2016)

Silk/Epoxy Laminates: Objective







- Preform architecture
- Manufacturing process

- Process-induced microstructure
- Mechanical performance
- Silk moisture effects

Silk/Epoxy Laminate Fabrication

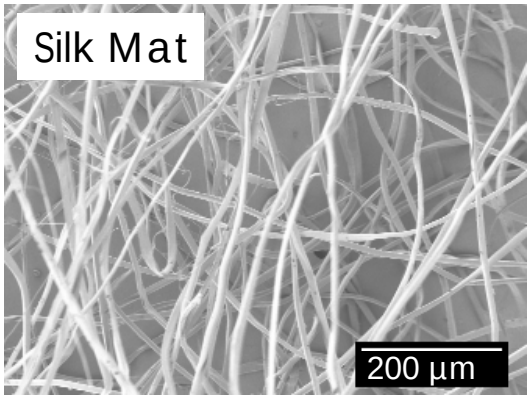
Silk Preform Architecture:

Random silk mats

- Easily produced
- Cheaper

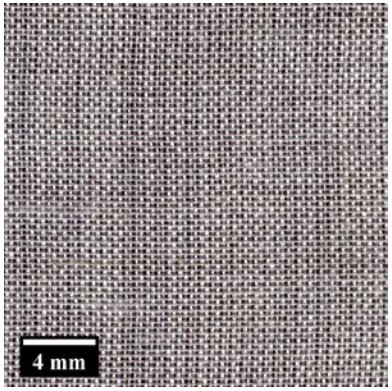
Bombyx mori, mulberry silk
Paradise Fibers, Inc.
Spokane, WA

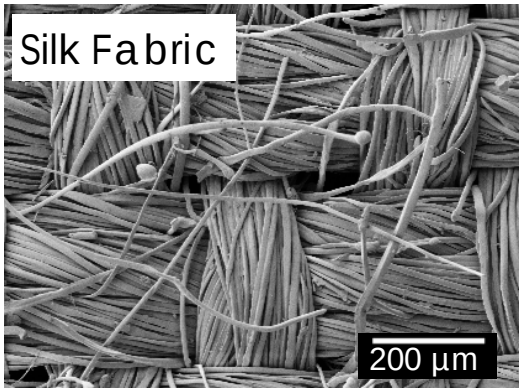




Woven silk fabric

Bombyx mori, mulberry silk
Aurora Silk, Inc.
Portland, OR



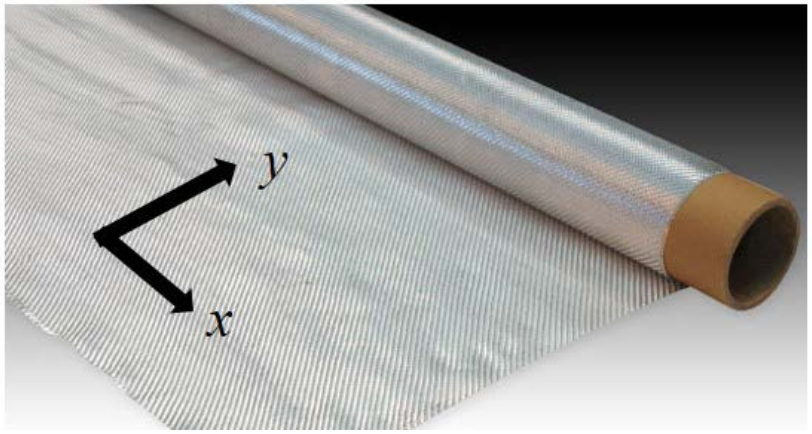


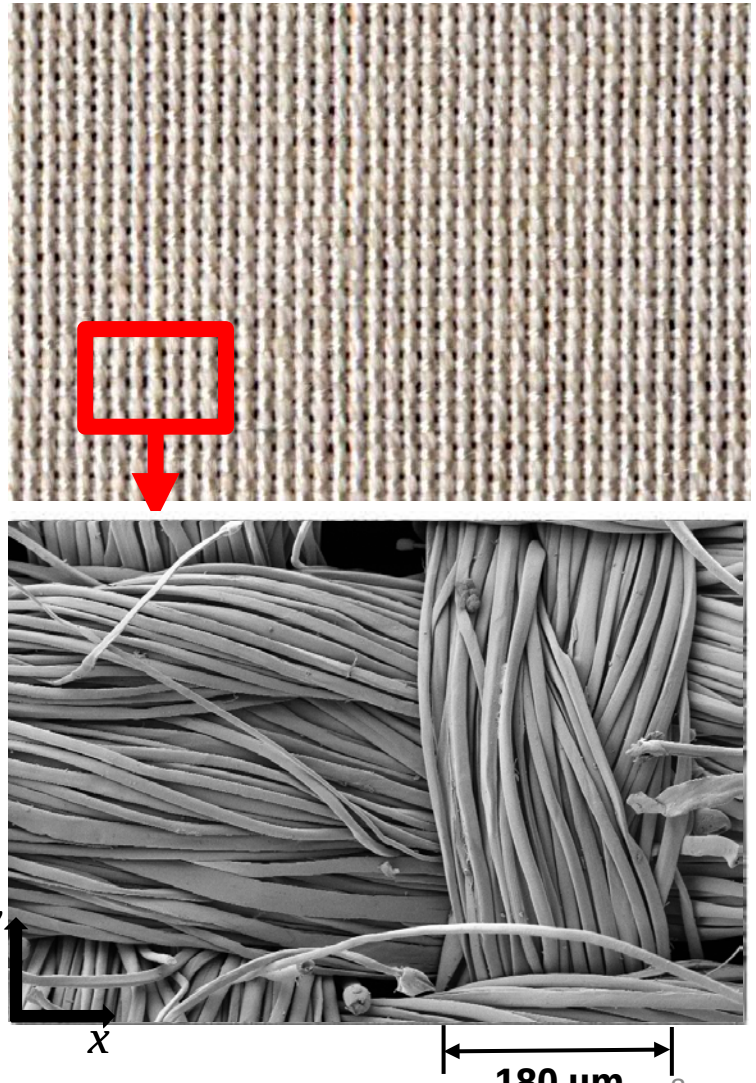
Handling random silk mat is more challenging

Silk/Epoxy Laminate Fabrication

Woven Silk Architecture:

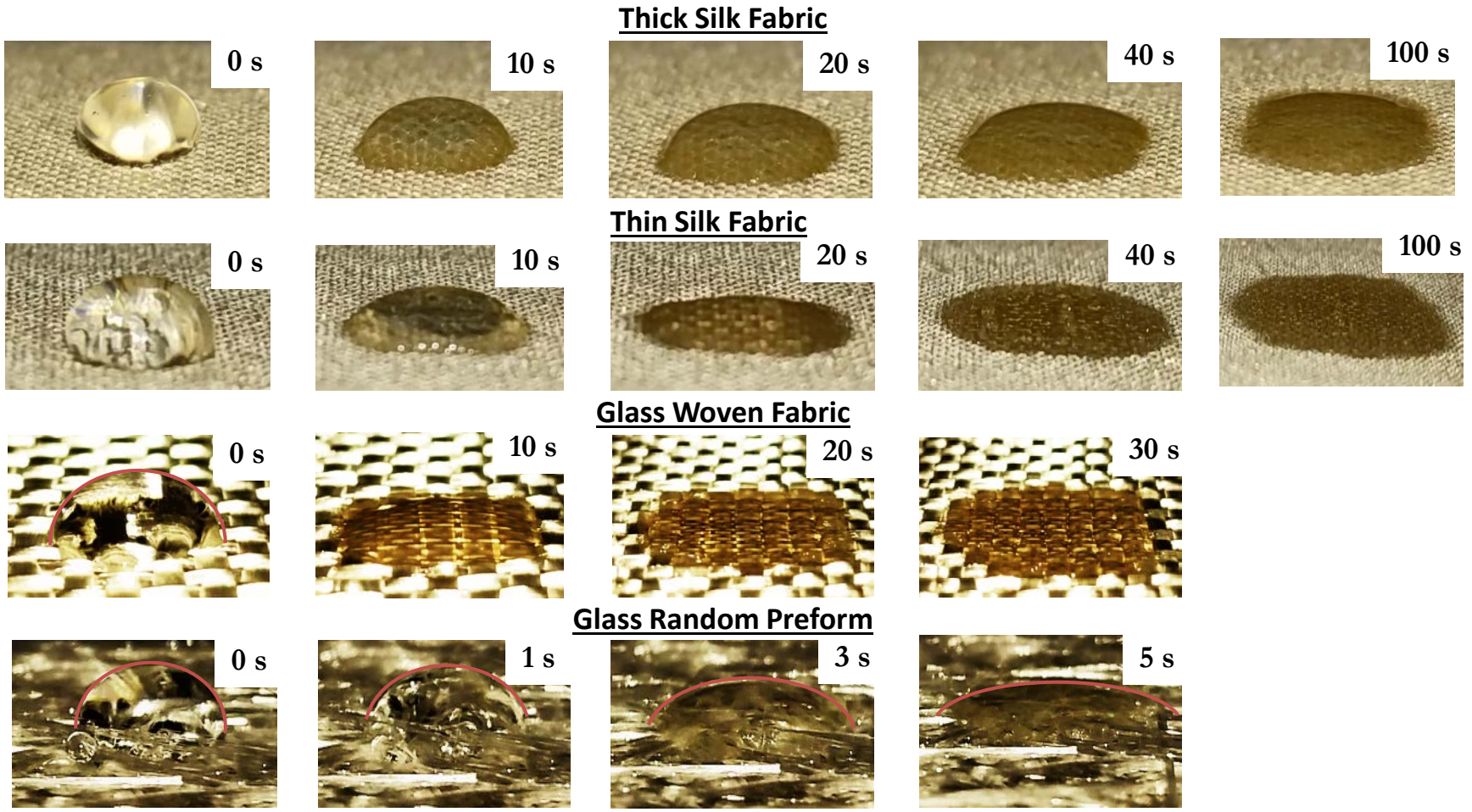
- Unbalanced weave pattern
- *x* / *y* anisotropy:
  - Affects fabrication (flow, permeability)
  - Anisotropic mechanical performances





Silk/Epoxy Laminate Fabrication

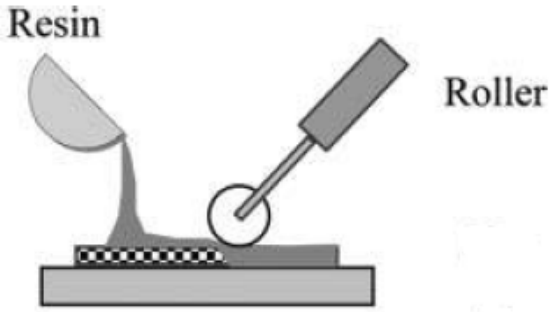
Fiber type/architecture yields different fiber/epoxy affinity:



Silk/Epoxy Laminate Fabrication

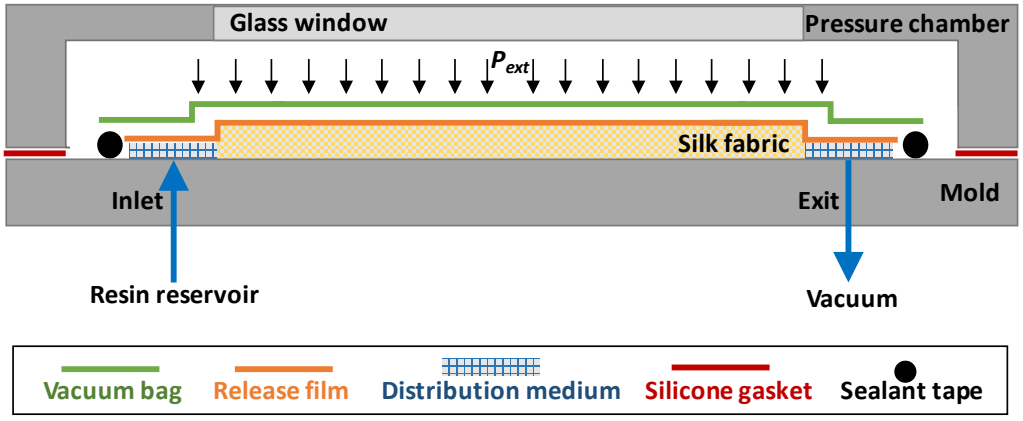
Manufacturing Processes: Open mold-cost effective

- Vacuum bag/wet lay-up



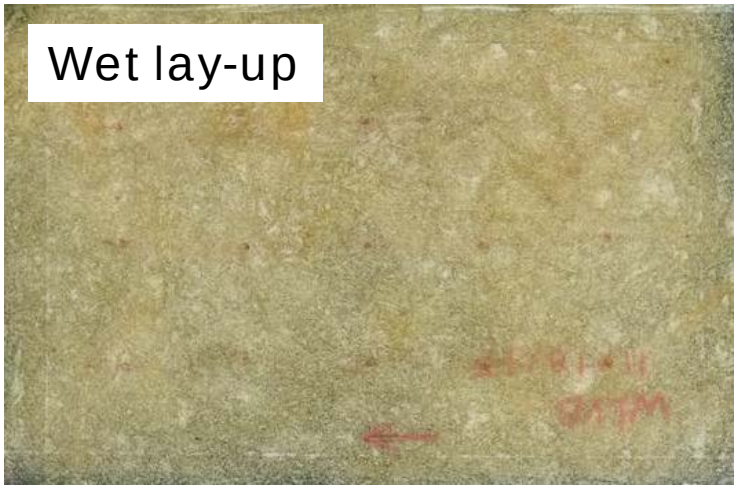
- VARTM (vacuum-assisted resin transfer molding)

- Pressurized VARTM: Lower pressure than press forming or RTM, and lower cost



Silk/Epoxy Laminate Fabrication

Manufacturing Processes:



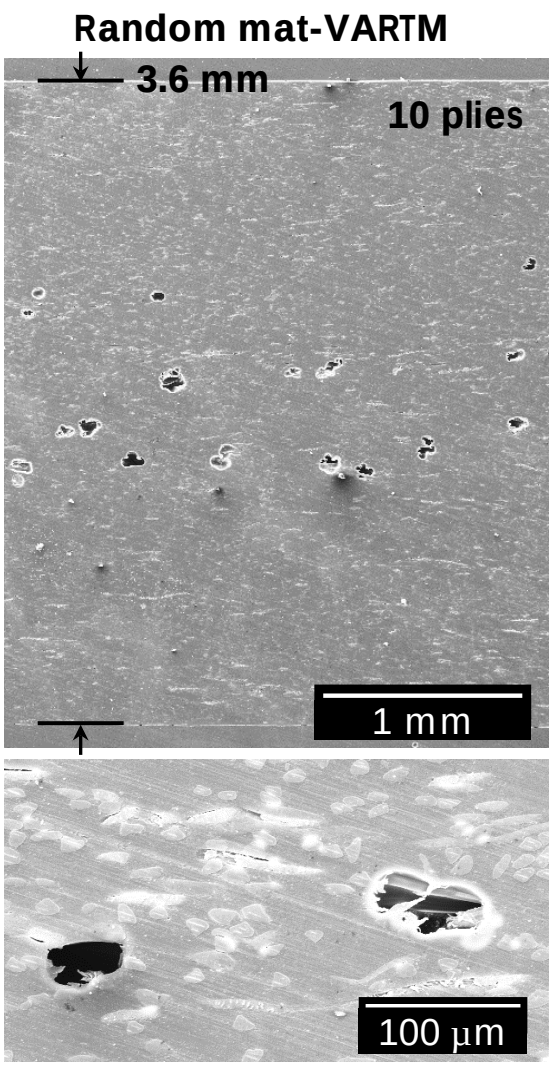
- Difficult fiber wetting
- Excessive void content

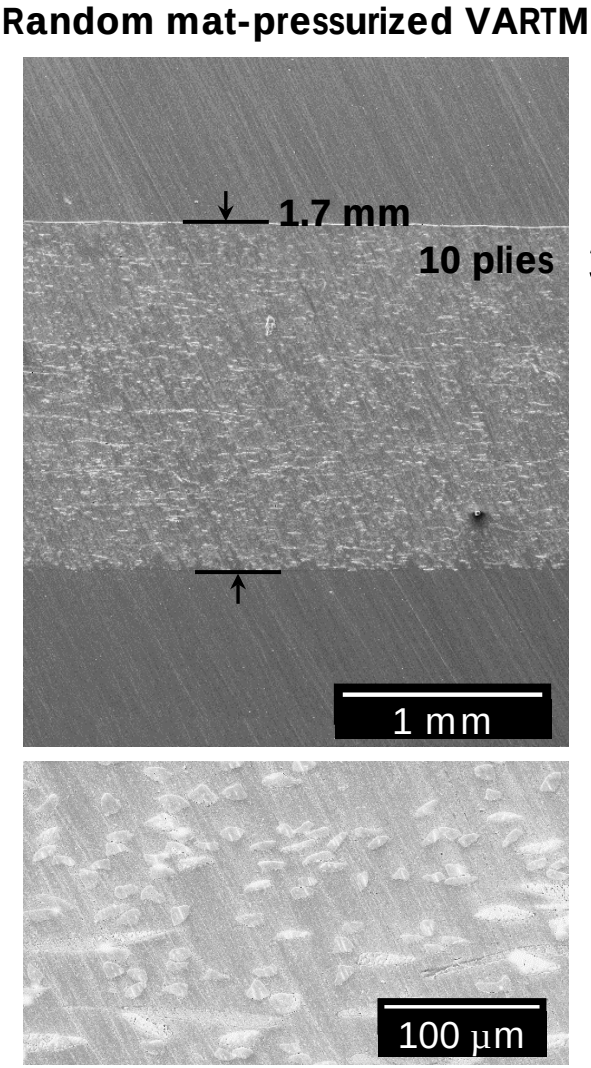


- Uniform impregnation
- Higher fiber content
- Higher part quality

VARTM more appropriate for silk/epoxy fabrication

Process-Induced Microstructure



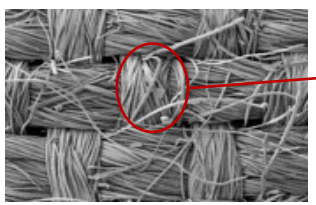


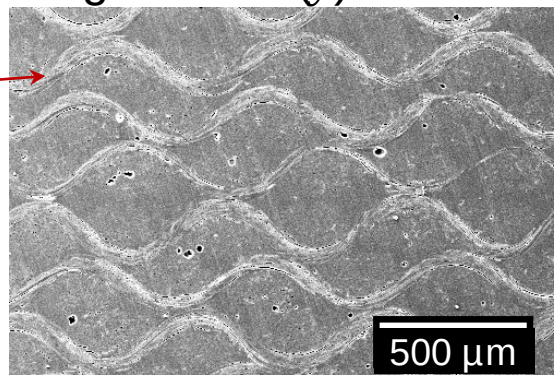
30-psi external pressure:

- ↓ voids
- ↑ fiber content
- ↓ thickness

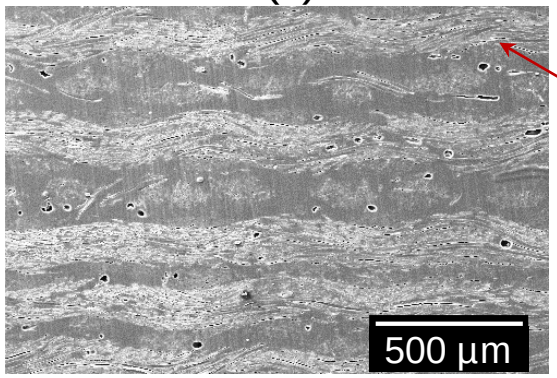
Process-Induced Microstructure

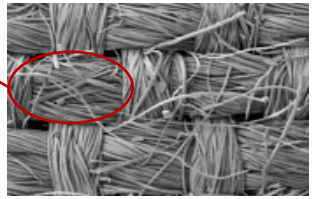
Woven-VARTM
Longitudinal (y) direction



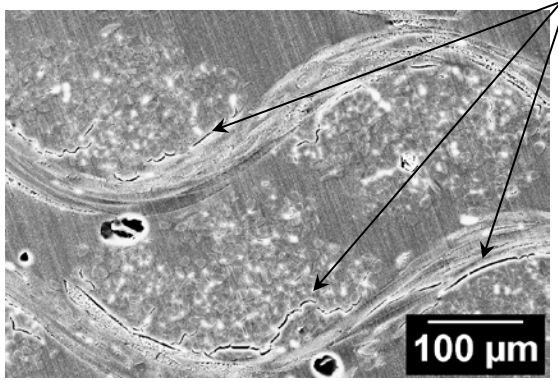


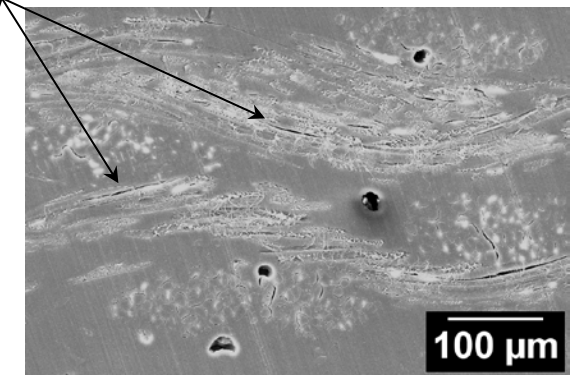
Woven-VARTM
Transverse (x) direction





Fiber/matrix debonding

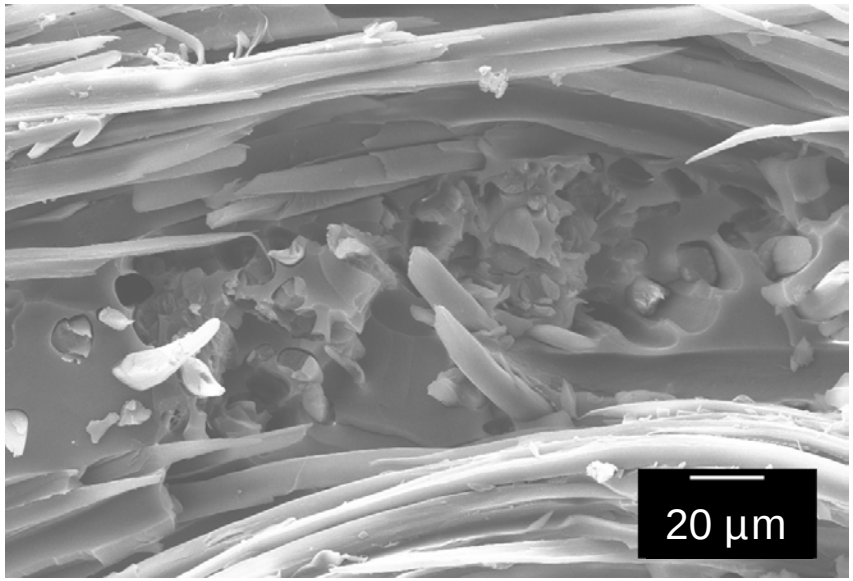




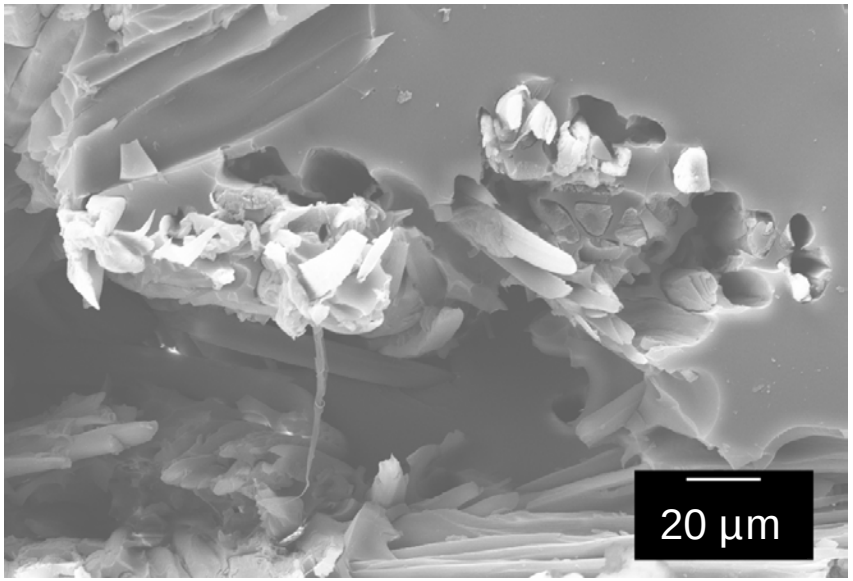
Weaker silk/epoxy adhesion when fabricated without pressure

Fracture Surface Microstructure

Woven-VARTM



Woven-Pressurized VARTM



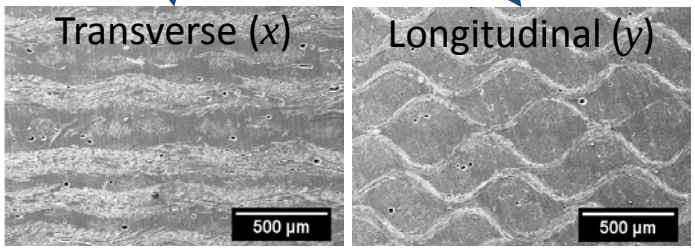
- Pullouts are often observed even in woven silk/epoxy laminates molded with external pressure
- An appropriate surface treatment needed for silk fibers

Mechanical Performance

Woven silk/epoxy: Anisotropy effects

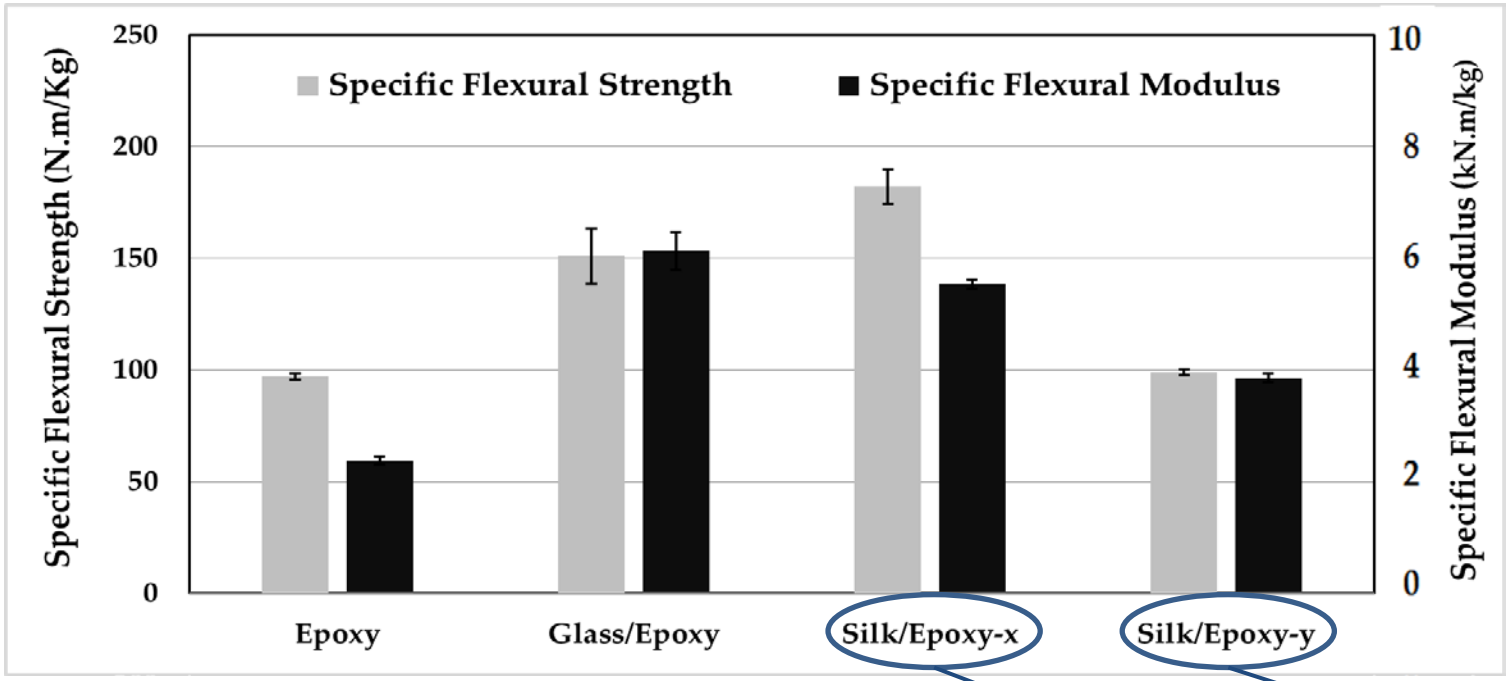


- Longitudinal vs. Transverse:
  - ~46% ↓ in flexural strength
  - ~30% ↓ in flexural modulus

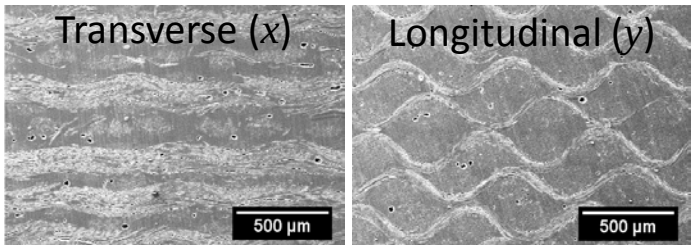


Mechanical Performance

Woven silk/epoxy: Anisotropy effects

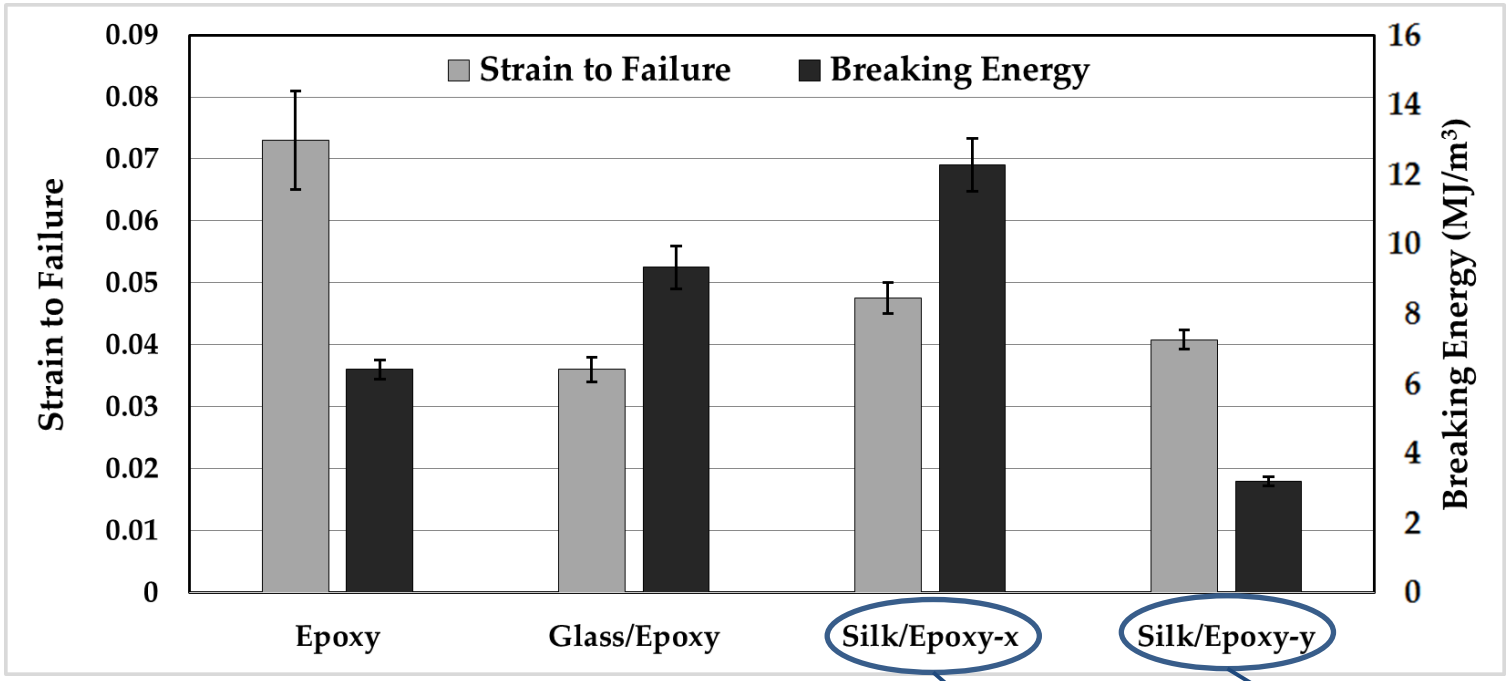


- Specific properties:
  - Transverse strength: ~25% ↑ than glass/epoxy
  - Transverse modulus: comparable to glass/epoxy

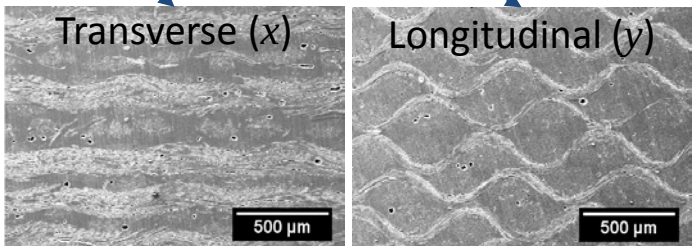


Mechanical Performance

Woven silk/epoxy: Anisotropy effects

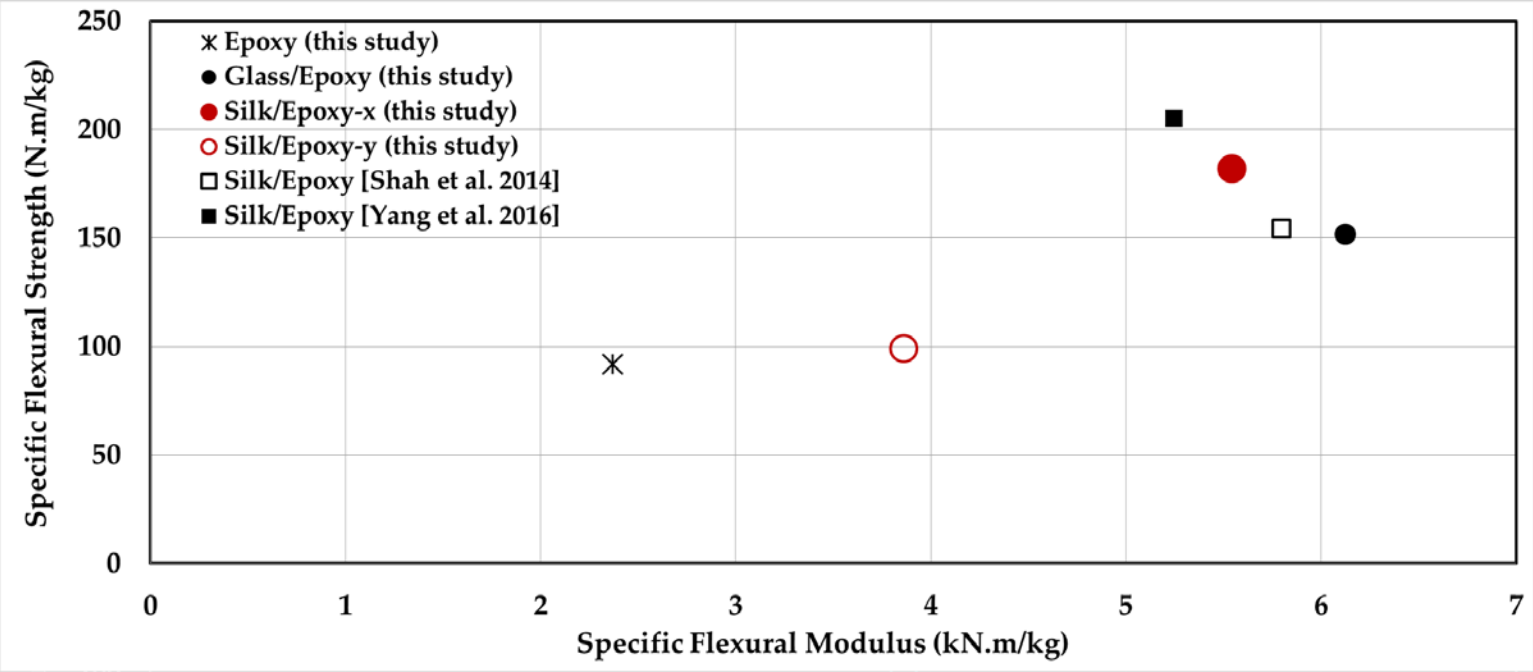


- Longitudinal vs. Transverse:
  - ~74% ↓ in breaking energy
  - ~14% ↓ in strain to failure



Mechanical Performance

Woven silk/epoxy: Specific properties

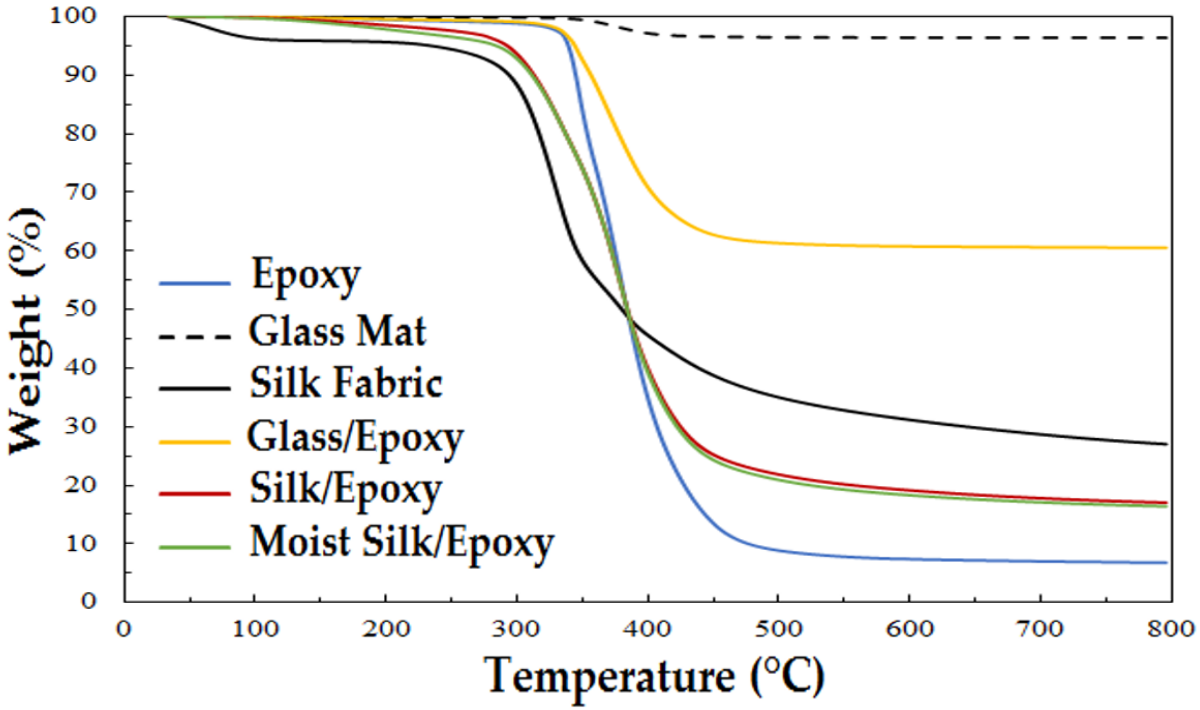


Transverse (x) specific properties
- Comparable to glass/epoxy

Longitudinal (y) specific properties
- Comparable or better than epoxy

Thermal Stability

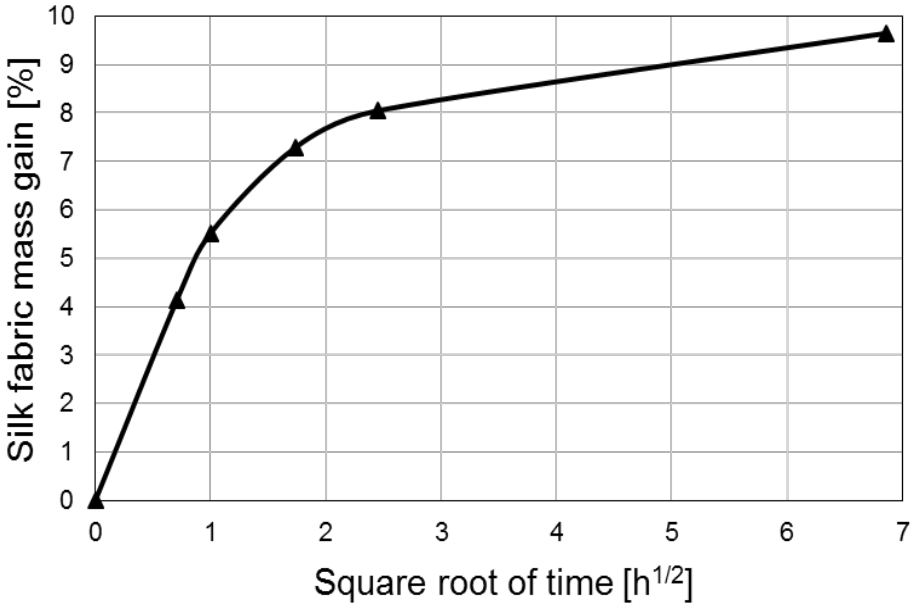
Thermal Analysis: TGA thermograms



- Epoxy and Glass/Epoxy thermal decomposition starts ~350°C
- Silk and Silk/Epoxy thermal decomposition starts ~300°C

Silk Moisture Effects

Silk fibers absorb moisture (Clearly non-fickian)



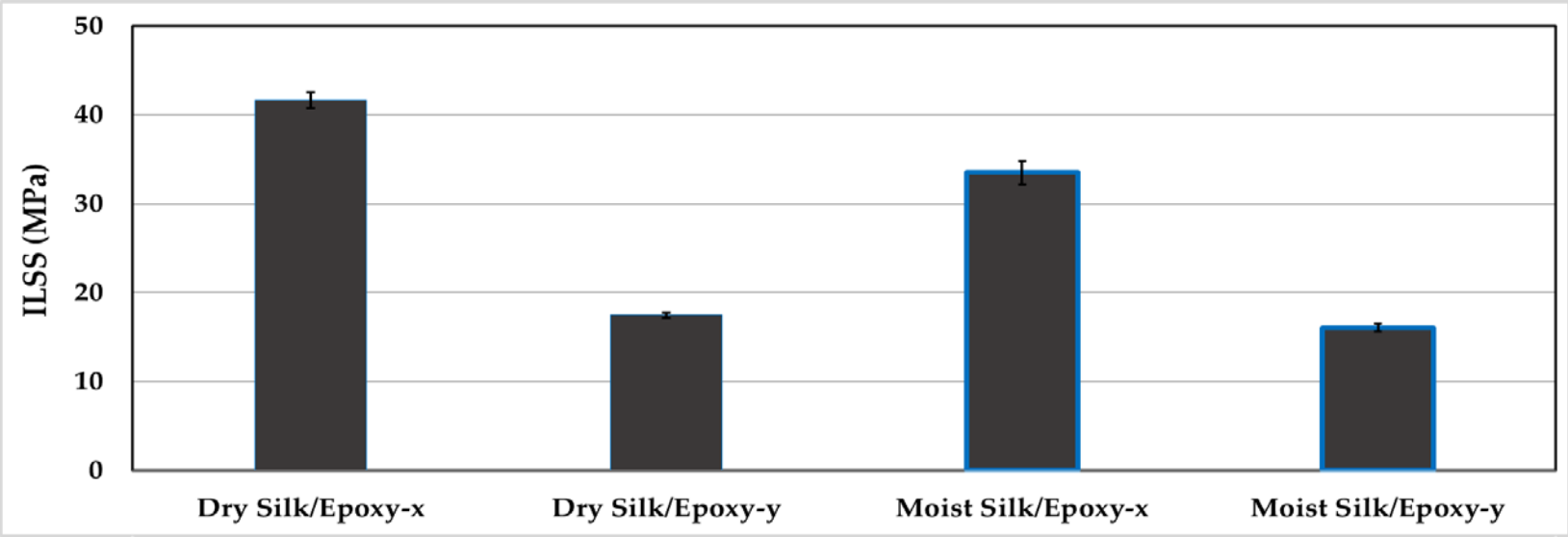
Laminates fabricated with:

- **Dry silk fabric**: ~ 0% moisture
- **Moist silk fabric**: ~ 10% moisture

- Presence of fabric moisture affects fabrication:
  - Slower fill time: from 20~25 min up to ~37 min
  - Possible causes:
    - Accelerated crosslinking of resin
    - Resin viscosity change
    - Swelling of silk fibers: decreased preform permeability

Silk Moisture Effects

Mechanical performance:



- Moisture in silk fibers ⇒ Reduction in laminate performance:
  - ~25% ↓ in specific strength
  - ~8% ↓ in strain to failure
  - ~20% ↓ in ILSS
  - ~22% ↓ in specific modulus
  - ~30% ↓ in breaking energy
  - ~3% ↓ in T_g

Silk storage conditions affect laminate performance

Concluding Remarks

- Preform Architecture: Woven
- Manufacturing Process: VARTM; applying pressure helps
- Silk Fabric Anisotropy: 140~190% difference in properties along principal fabric directions
- Silk/Epoxy vs. Glass/Epoxy: Comparable specific properties
- Moisture in silk fibers: Up to 30% performance reduction
- To enhance silk/epoxy performance:
  - Silk fiber surface treatment/sizing
  - Higher fiber content
  - Dry storage conditions/or dry before fabrication

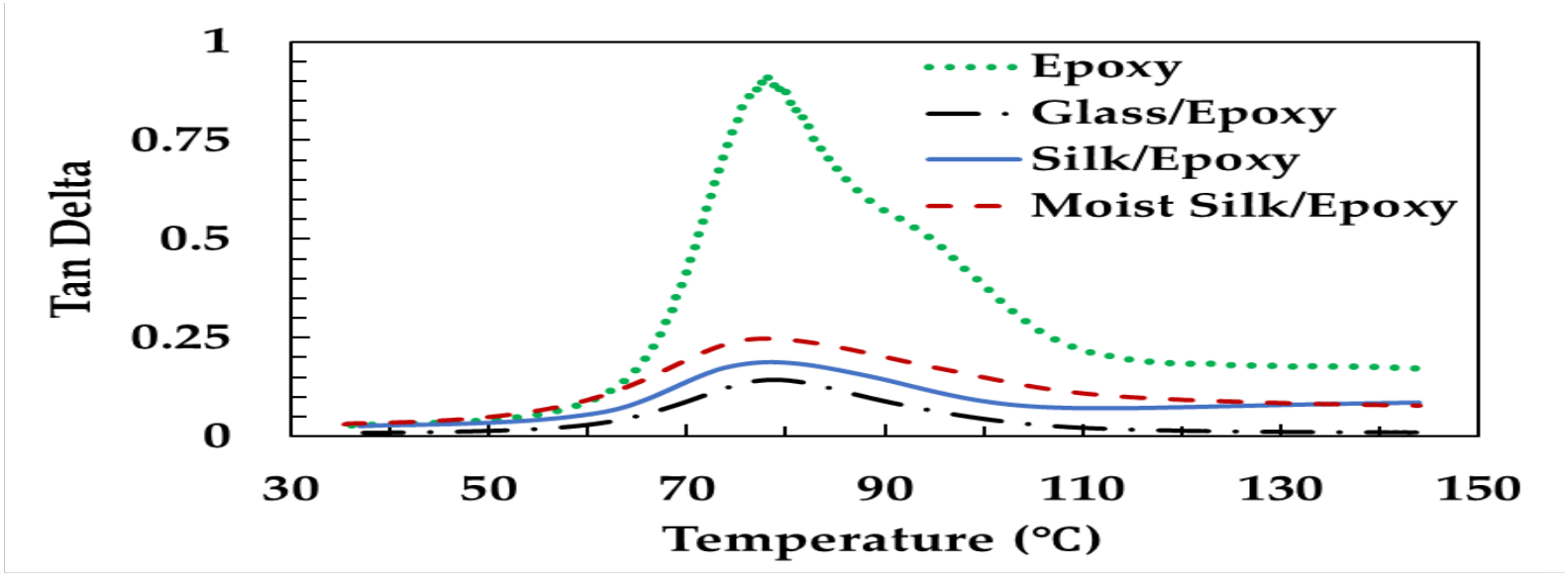
Thank You

Presentation Outline

- Natural Fiber Composites
- Silk/Epoxy Laminate Fabrication
- Process-Induced Microstructure
- Mechanical Performance
- Silk Moisture Effects
- Concluding Remarks

Mechanical Performance

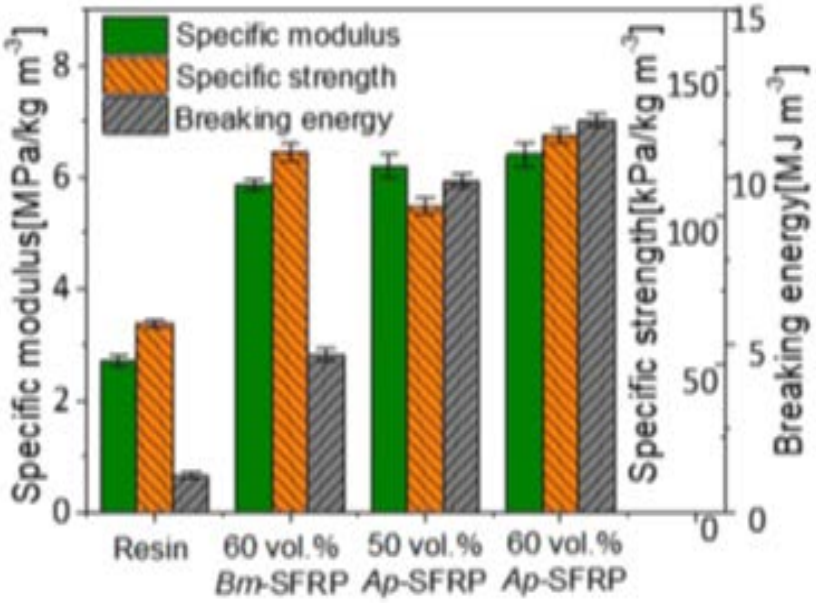
Dynamic mechanical Analysis:



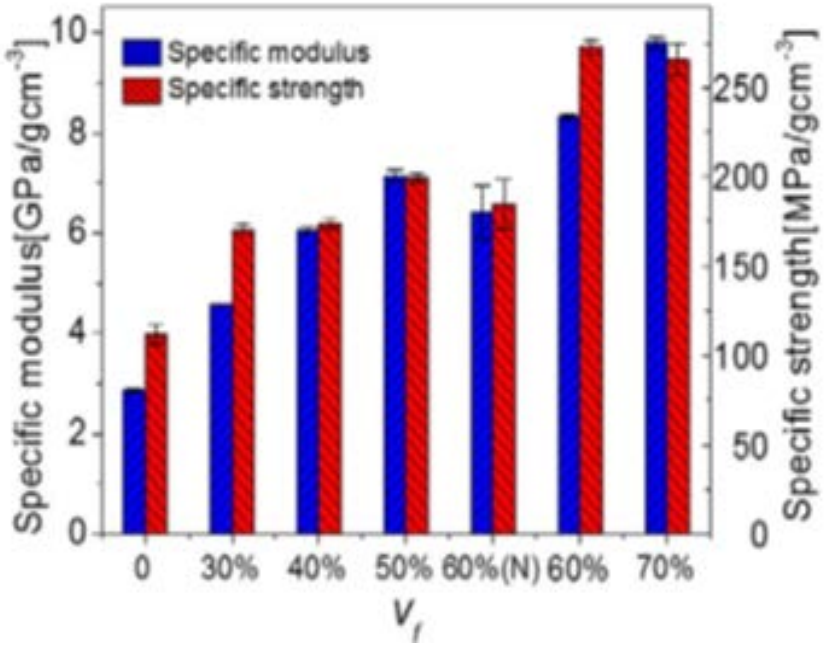
- Glass/epoxy vs. silk/epoxy:
  - Higher storage modulus
  - Higher loss modulus peak
  - Comparable T_g

Silk Reinforced Composites

Yang et al. Scientific Reports 7: 11939, 1-9 (2017)



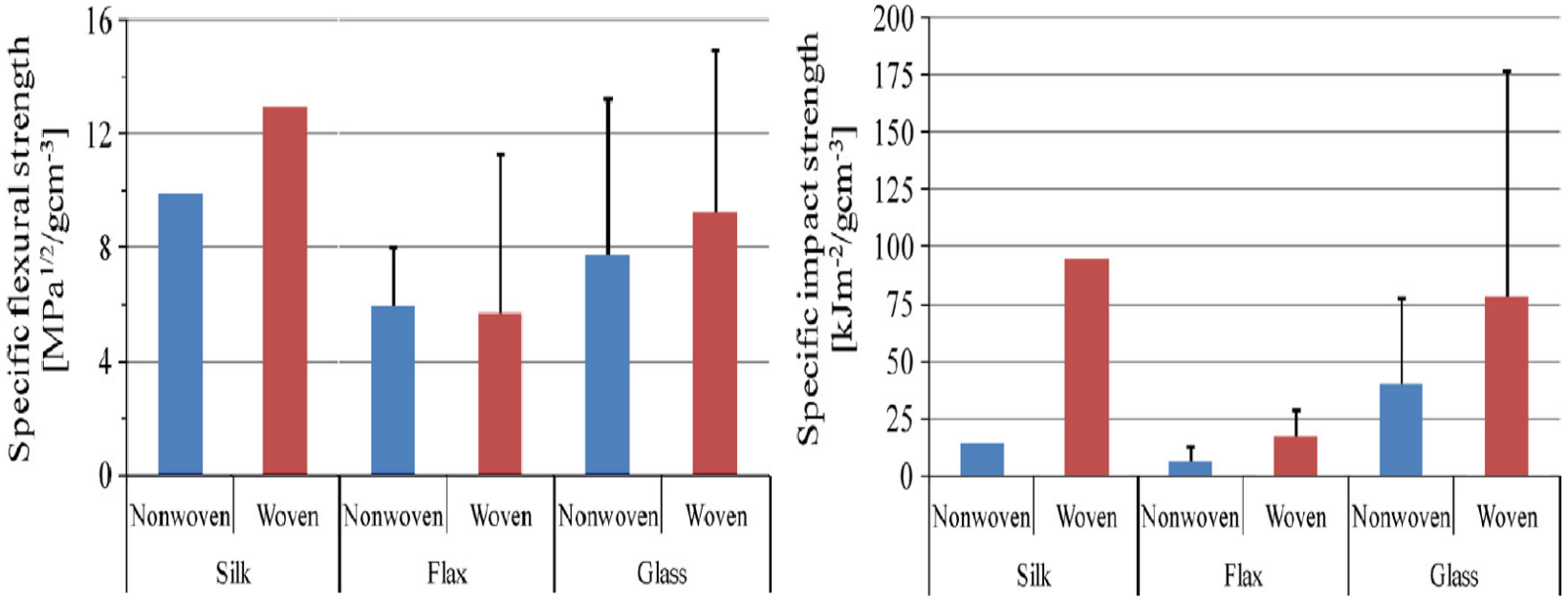
Yang et al. Materials and Design 108 470–478 (2016)



Yang et al. (2016, 2017) investigated silk/epoxy laminates:

- Optimal properties obtained at 60% fiber content
- Ap-silk fibers observed to yield better properties than Bm-silk fibers
- Specific properties comparable to glass/epoxy

Silk Reinforced Composites



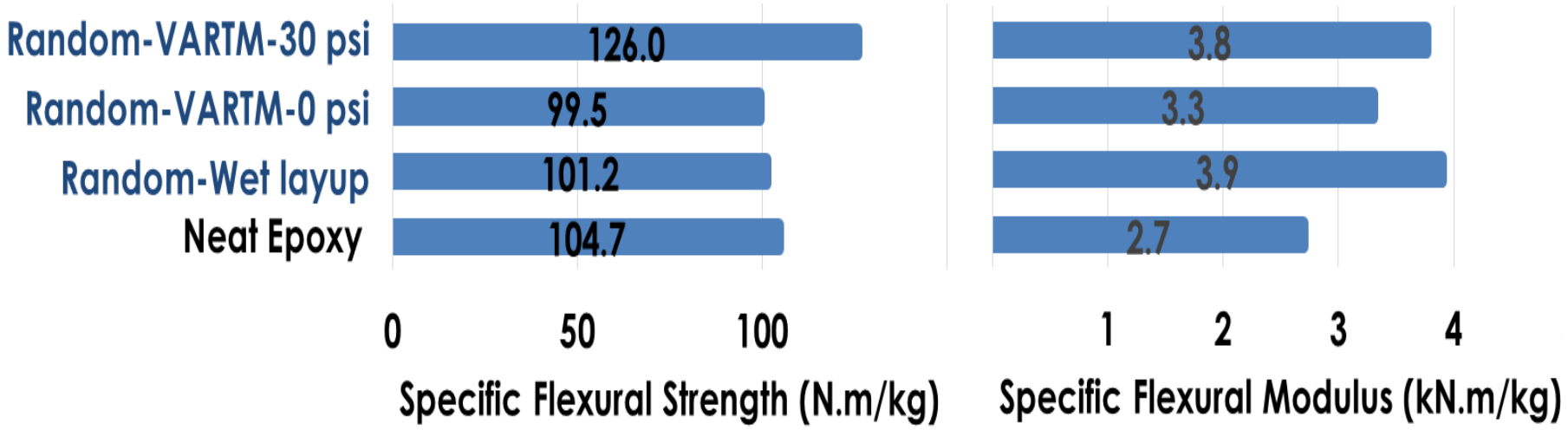
Shah et al. Compos. Sci. & Tech. 101, 173-183 (2014)

Shah et al. (2014) compared silk/epoxy performance to flax/epoxy and glass/epoxy:

- Best properties obtained for woven silk fabric
- Specific properties comparable to glass/epoxy
- Specific properties higher than flax/epoxy

Mechanical Performance

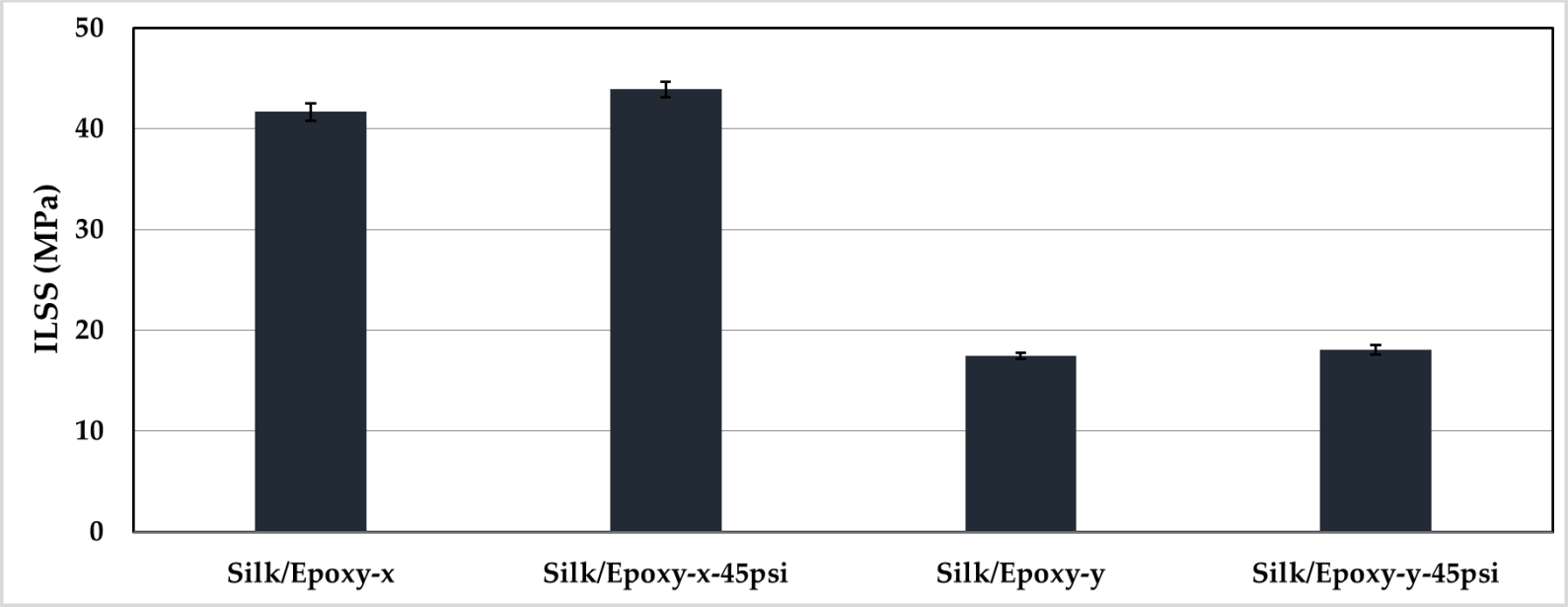
Random Mat Silk/Epoxy:



- Random silk/epoxy shows limited improvement over epoxy
- Improvements in specific strength only for pressurized VARTM
- Possibly due to:
  - Lower voidage
  - Higher fiber content (*from 17 to 21%*)
  - Reduced fiber/matrix debonding

Mechanical Performance

Post-fill external pressure effects:



- Flexural strength and modulus ➡ no observed effect
- ~25% ⬆ in breaking energy (transverse direction)
- ~8% ⬆ in ILSS (transverse direction)