FABRIC FORMING:
HOW IT AFFECTS DESIGN AND PROCESSING AND HOW SIMULATION CAN ADDRESS THIS

CO-HOSTED BY:

Composites Knowledge Network

sampe Canada

compositeskn.org

nasampe.org

INVITED SPEAKER

Prof Abbas Milani, PhD, PEng

- *CRN Techanical Director, MMRI Director, Killam Laureate, Member of Royal Society of Canada (RSC); Lead of UBC Biocomposites Reserach Cluster*
- Expertise: **Textile Fiber-Reinforced Composites- Fabrication, Testing, Modeling & Simulation, AI-based Optimization**
- Related interest: Polymer matrix composites and their manufacturing; Micro-CT 3D visualization and in-situ characterization of defects
- Web: http://crno.ok.ubc.ca

CRN Composites Research Network

HOSTED BY: CKN Composites Knowledge Network

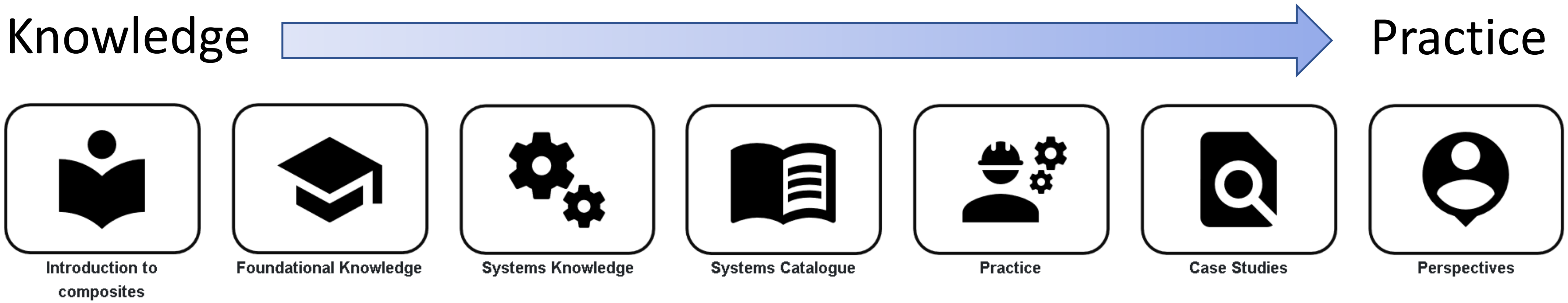
HOSTED BY: sampe Canada

KNOWLEDGE IN PRACTICE CENTRE (KPC)

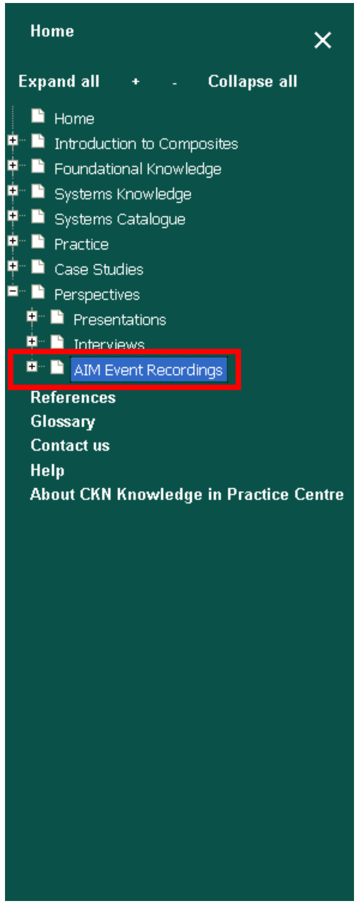
- A freely available online resource for composite materials engineering:

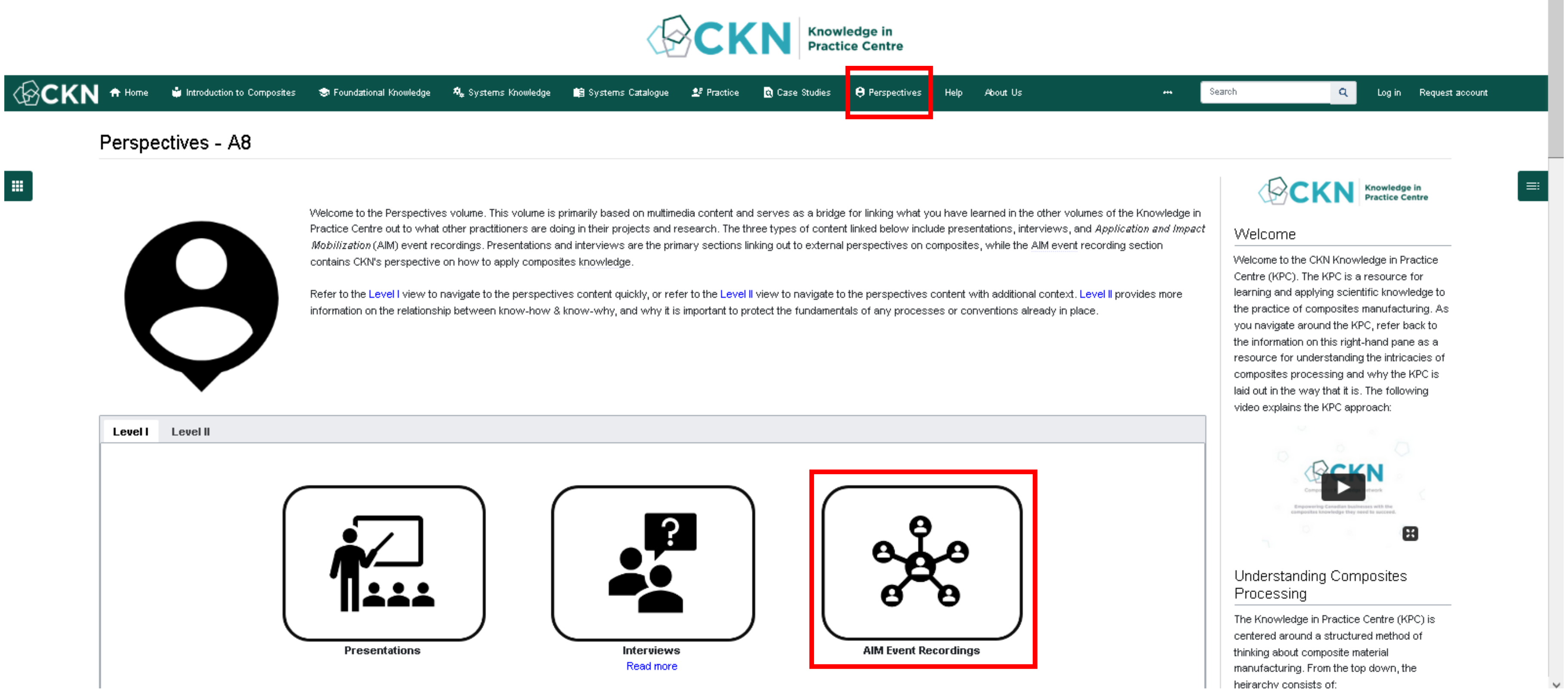
compositeskn.org/KPC

- Focus on practice, guided by foundational knowledge and a systems-based approach to thinking about composites manufacturing



PAST WEBINAR RECORDINGS AVAILABLE





Composites Knowledge Network

Fabric Forming: how it affects design and processing, and how simulation can address this

Invited speaker:
Prof. Abbas S. Milani

CKN Seminar Series
B.C., Canada, November 2021

UBC

CRN Composites Research Network

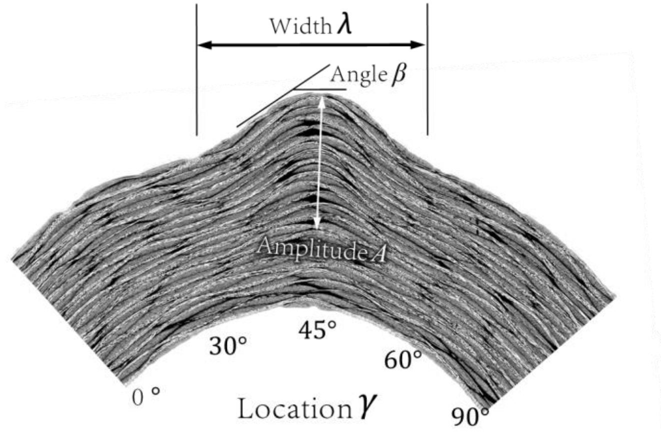
Materials & Manufacturing Research Institute
Experience Innovation with Us

Reminder: Quality Management in Composites Manufacturing

Input Parameters → Process → Quality outcomes

Input Parameters	Process	Quality outcomes
Forming Temperature	Forming + Curing	Fiber misalignment
Geometry		Porosity
Ply count		Under-cured/over-cured
Ply sequence		Low interface strength
Forming method		…
Bagging quality		
…		

Fiber-path Defects

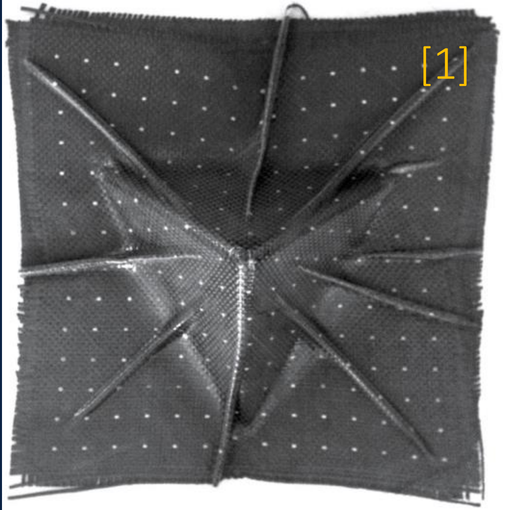


Impact of Process Conditions

Defect-free Parts

A Typical Process & Fibre Geometrical Defects

Receiving 2D Fabric Product → Cutting & lay-up → Forming & Heating — Bagging & Debulk → Post-processing 3D Product



Fiber Misalignment

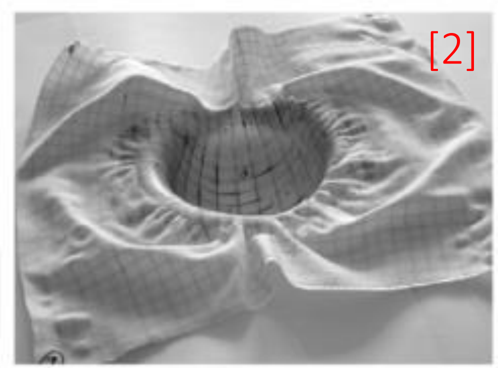
- Deviation from the nominal intended fiber direction specified in the design

Fiber waviness

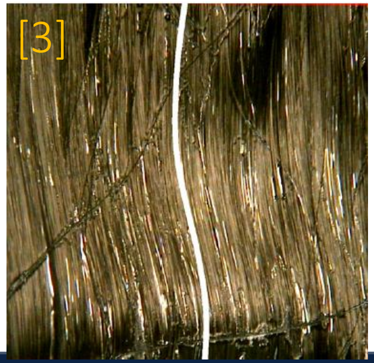
- Refers to in-plane curviness of tows

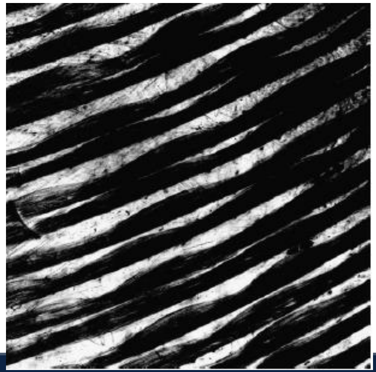
Wrinkling

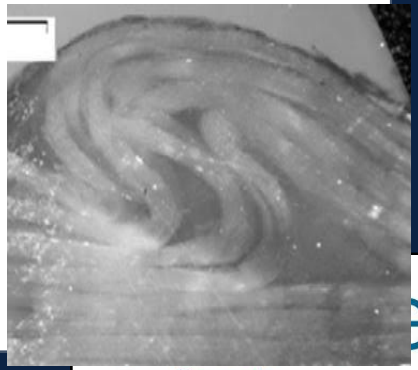
- Refers to out-of-plane misalignment, i.e. occurring in the through thickness direction



[1] Thompson A.J. et al., *Materials and Design*, 2020
[2] Boisse P. et al., *Composites Part B: Engineering, 2018.*
[3] Potter K. et al., *Composites Part A: Applied Science and Manufacturing* 39.9 (2008): 1343-1354.
[4] Bloom L.D. et al., Composites Part B: Engineering 45.1 (2013): 449-458



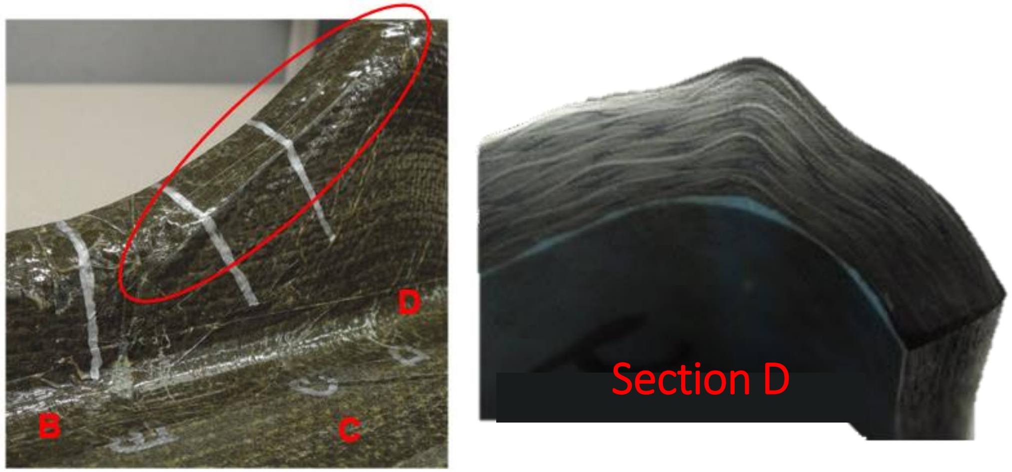




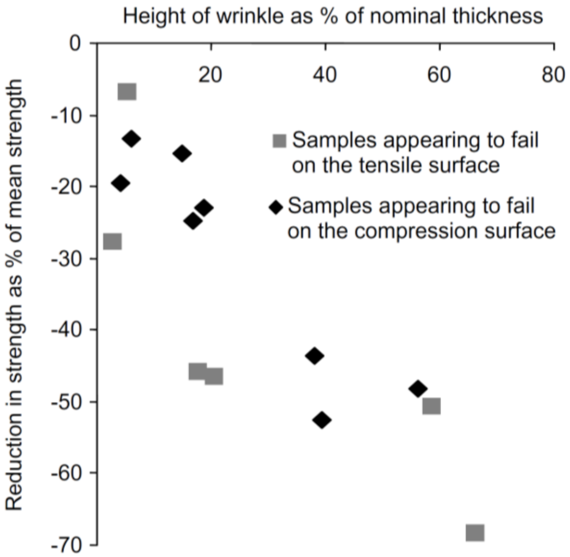
Why Wrinkling Particularly Matters in Design?

Wrinkling:

- Compromises the structural integrity of the final part → Expensive wholesale rejection.
- Increases through-thickness stresses, triggering failure at significantly reduced loads.
- Results in a drastic reduction in compressive strength of the laminates **(Up t 70%).**



Wrinkling in a textile carbon fiber laminate
[Image Courtesy of Boeing Winnipeg]



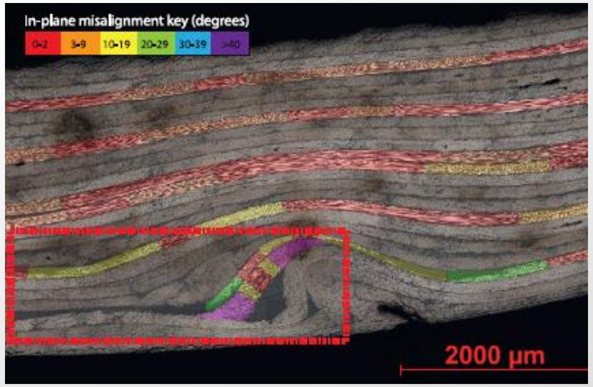
[Potter et al., 2008]

HOSTED BY: CKN Composites Knowledge Network

HOSTED BY: sampe Canada

Distinguishing between Types/Sources of the Defect

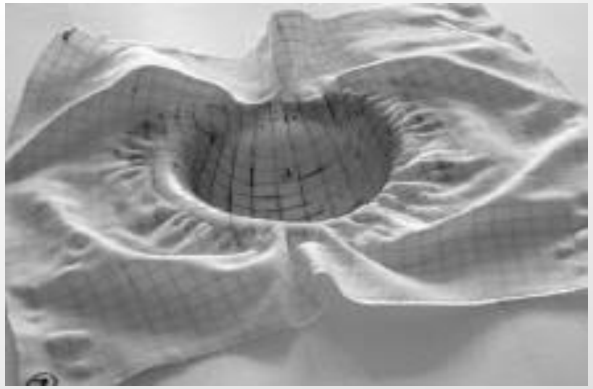
Process (curing/consolidation)-induced wrinkling



(Lightfoot et al., 2013)

- Ply slippage occurring during consolidation of laminates near the mould surface
- Non-uniform interaction of plies
- ...

(Dry) Forming-induced wrinkling



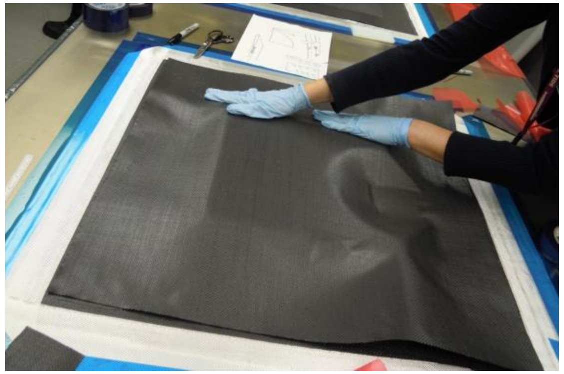
(Boisse et al., 2012)

- Excessive relative motion of fibers during draping
- High coefficient of friction between plies (in multi-ply forming)
- ...

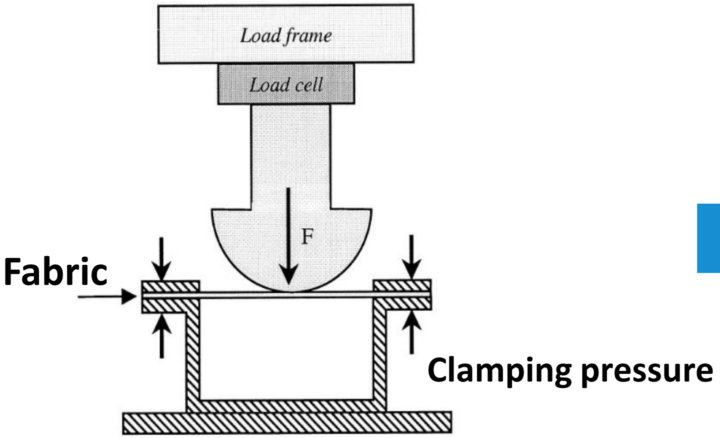
Part I:
Forming-induced Wrinkling

How does wrinkling occur during forming stage

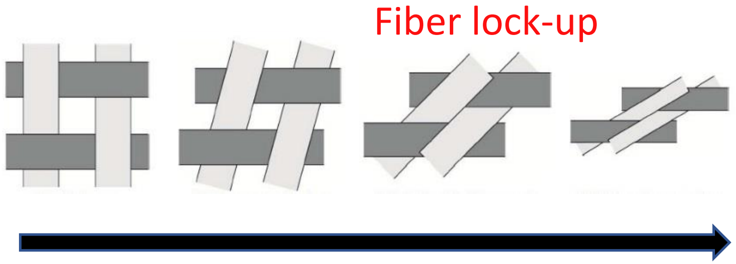
- Highly depends on the type of fabric, part geometry, friction, and boundary condition.
- To develop full simulation capabilities, we need to better understand the fundamentals of the fabric deformation mechanisms.



Manual



Semi-automated



As forming progresses

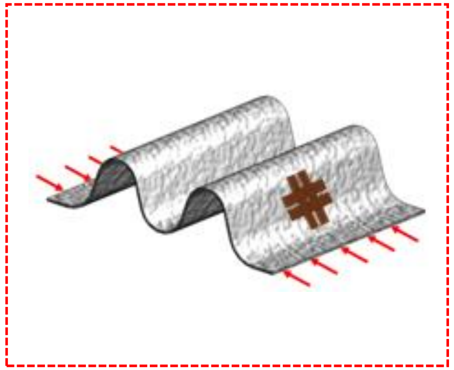
e.g. Ballistic Helmet

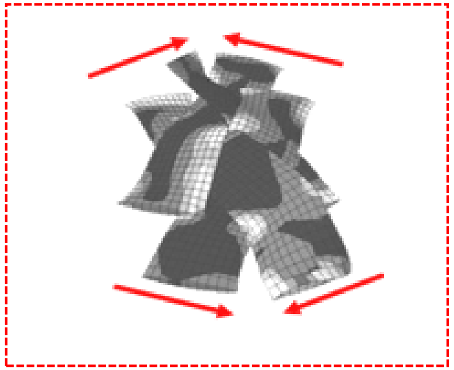
A Closer Look to the Sources of Forming-induced Wrinkles

In-plane compression (Type I)

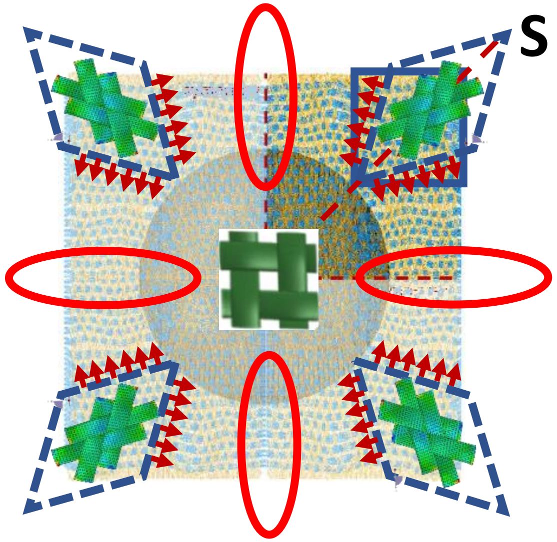
In-plane shear (Type II)

(global) Macro-scale wrinkles



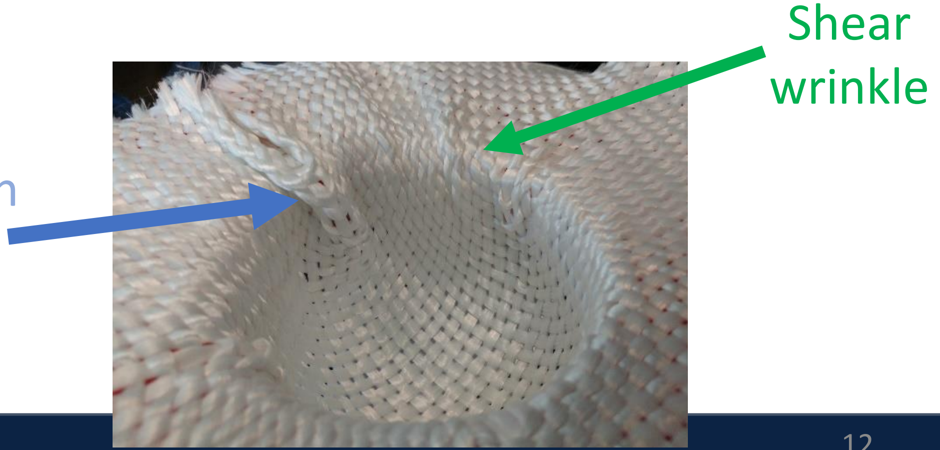


Meso-scale wrinkles



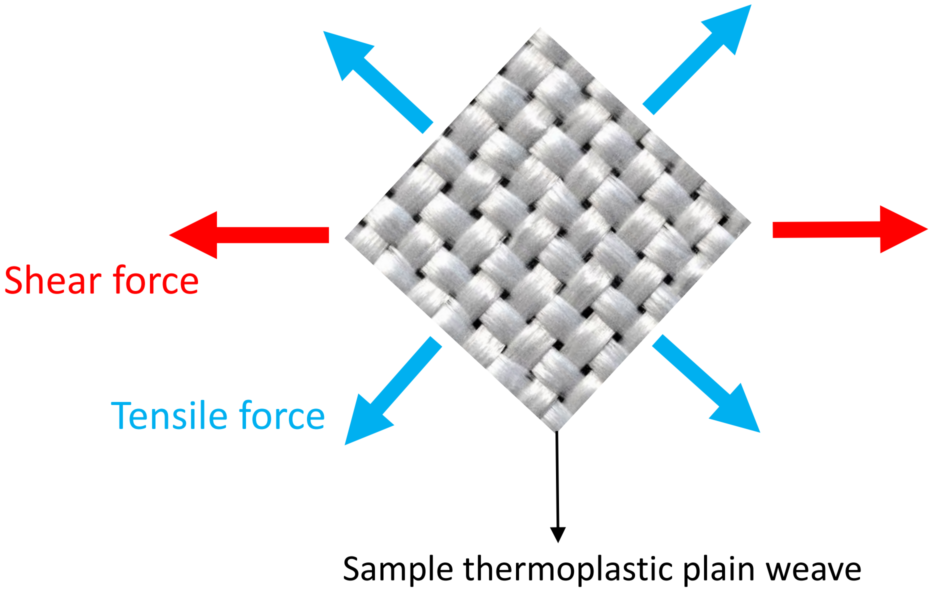
Region *C* (four locations): dominantly *Compression* deformation (vulnerable to wrinkling due to Compression)

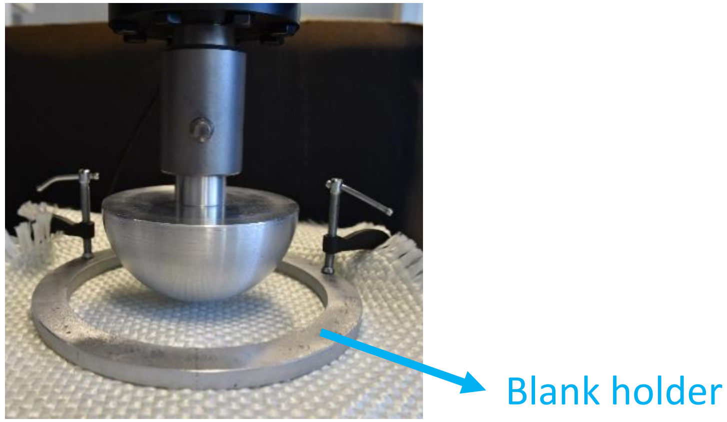
Region *S* (four locations): dominantly *Shear* deformation (vulnerable to wrinkling due to *Shear* deformation)



How to Combat such Wrinkling?

- Inducing tension to the yarns, blank holders can effectively mitigate wrinkling.





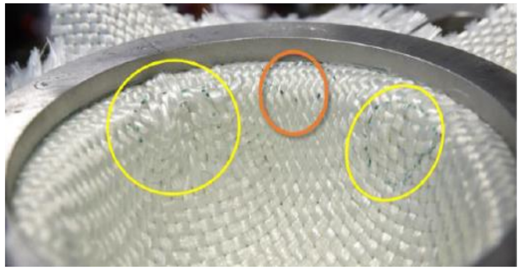
- The relationship between shear compliance and membrane stresses should be closely investigated to arrive at:
  - accurate numerical simulations; and
  - optimum amount of blank holding forces/forming conditions.

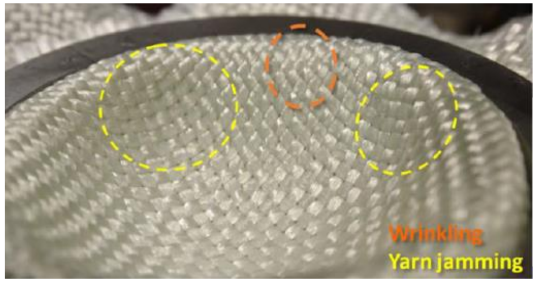
Inherent Shear-Tension Coupling in the Deformation of Fabrics

Forming without tension

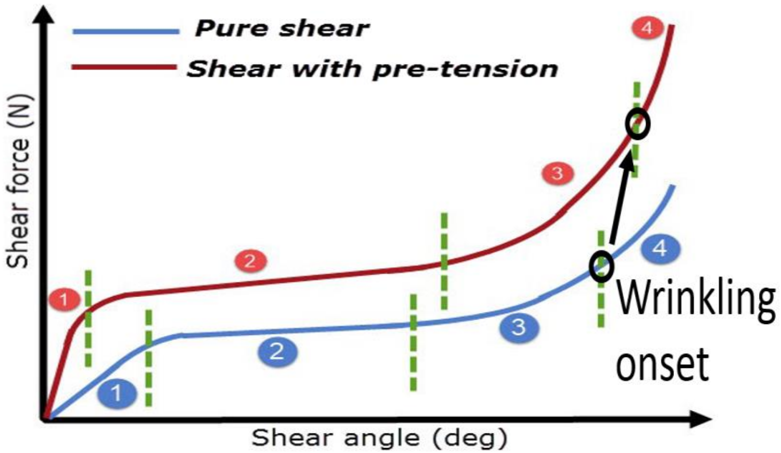
Forming with tension

Technical/Industrial level (Practical outcome of inherent coupling)

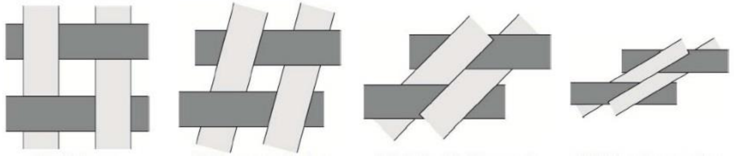




Academic/Scientific level (Mathematical/mechanical complications/modeling of inherent coupling)



For a typical material without coupling, the two curves would have to be the same, but not for fabrics!



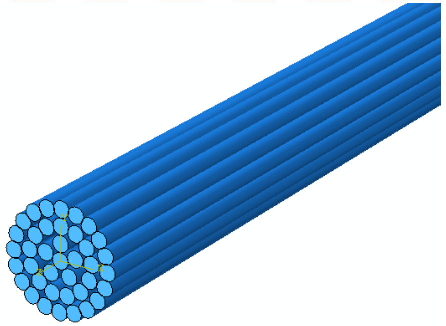
- **A non-linear non-orthogonal behavior including four different phases: 1- shear with static friction at meso-level, 2- shear with dynamic friction, 3- locking, and 4- wrinkling.**

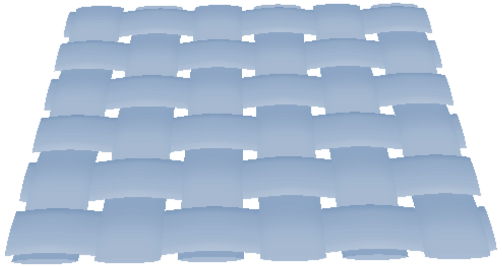
Multi-scale Nature of Reinforcing Woven Fabrics

Micro-level	Meso-level	Macro-level
fibers	yarns	part
~10^{-6} m	~10^{-3} m	~10^{0} m

Physical

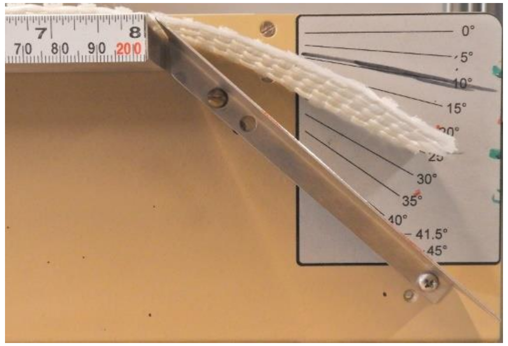
Simulation

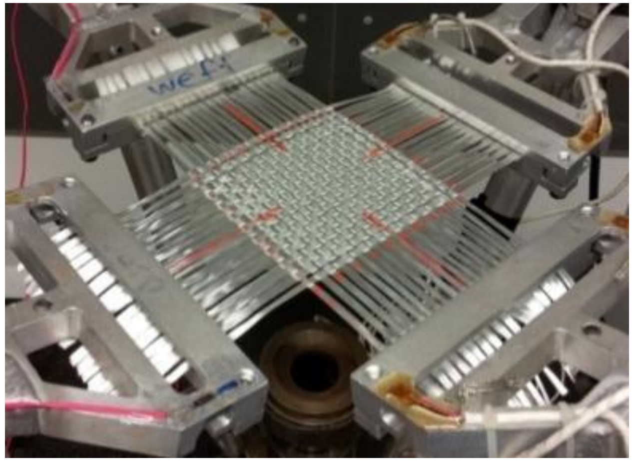


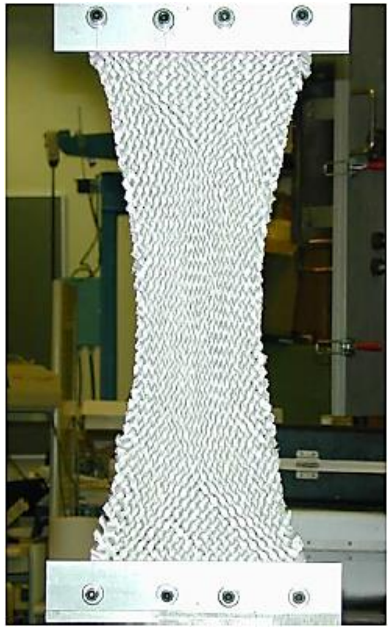


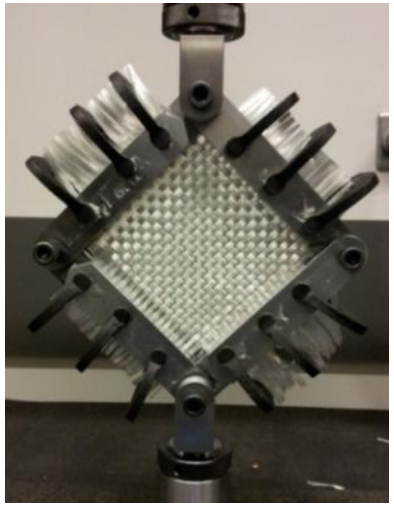
Typical Characterization Tools for Fabrics

- Uniaxial tension
- Biaxial tension
- Trellising shear (bias-extension and picture frame)
- Bending

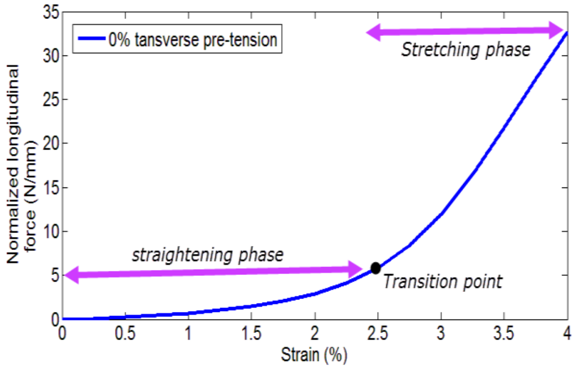


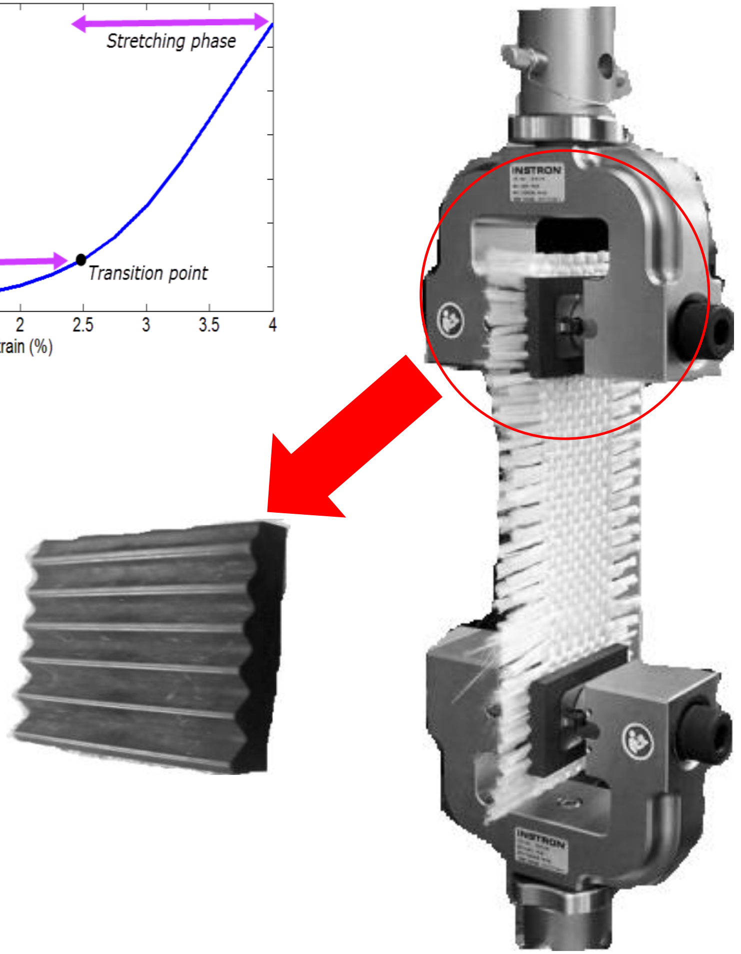


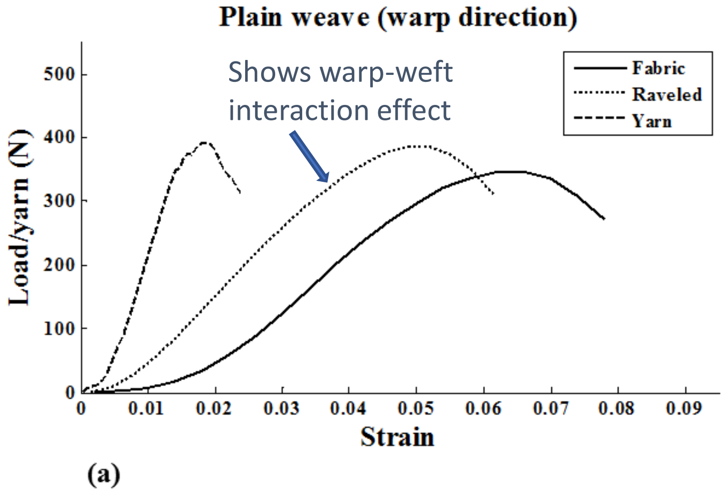


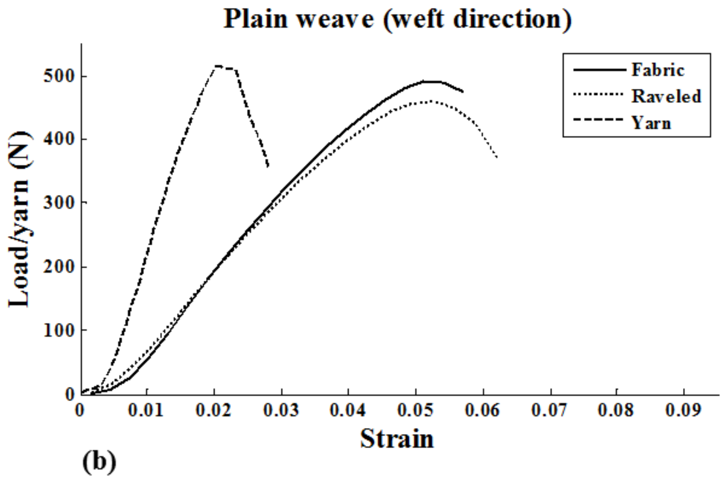


Typical Response/Examples under Uniaxial Tension







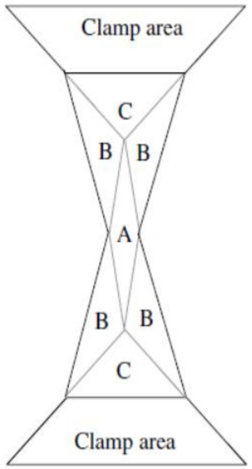


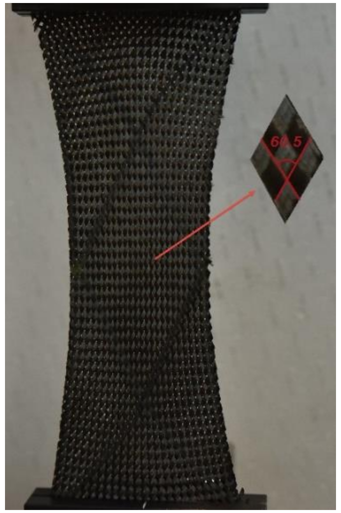
Notice unbalanced weft/warp responses!

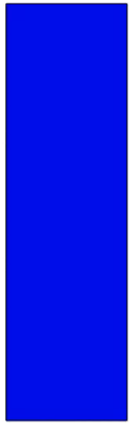
Comparing Standard Shear Characterization Methods for Fabrics

1- Bias extension testing

- Simple to preform
- No unintentionally induced tension within sample
- Heterogeneous deformation field within sample; along with potential yarn slippage



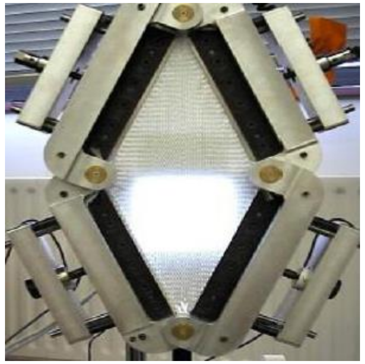


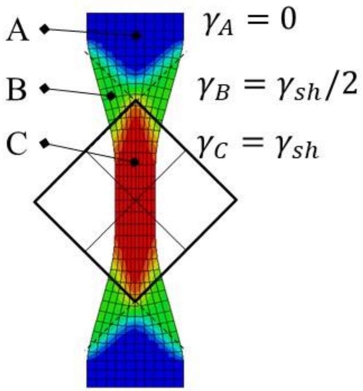


Simulation

2- Picture frame testing

- Uniform deformation field
- Need more advanced fixtures
- Problems with sample alignment
- Clamping can cause tension





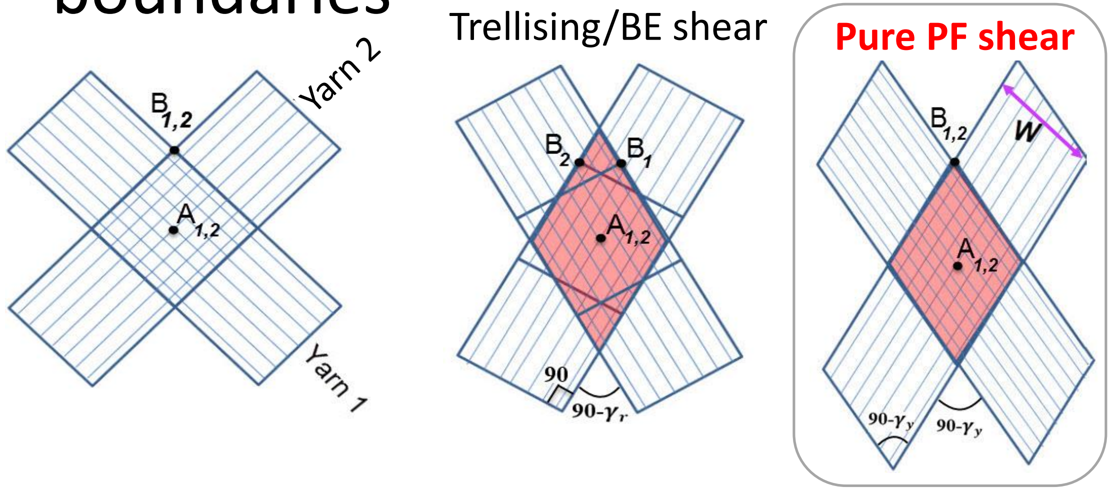
Are the characterization results the same in the A-zones?
If Not, which one is more similar to actual forming?

HOSTED BY: CKN Composites Knowledge Network

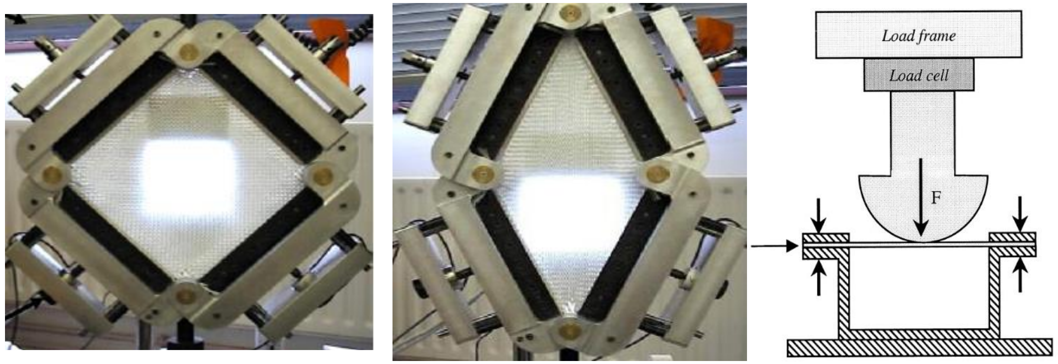
HOSTED BY: sampe Canada

Critical Effect of Intra-yarn Shear

- Resulting from continuity at fixture (blank holder) boundaries



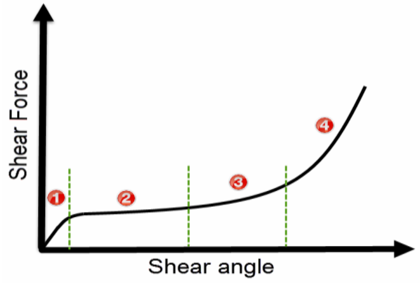
Analytical evidence



Experimental evidence
(delayed wrinkling, beyond locking)

Intra-yarn shear mechanisms:

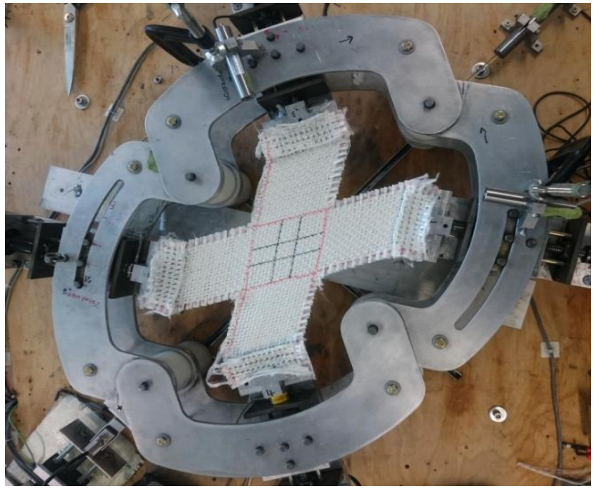
Undeformed | Intra-filament shear | Inter-filament slippage

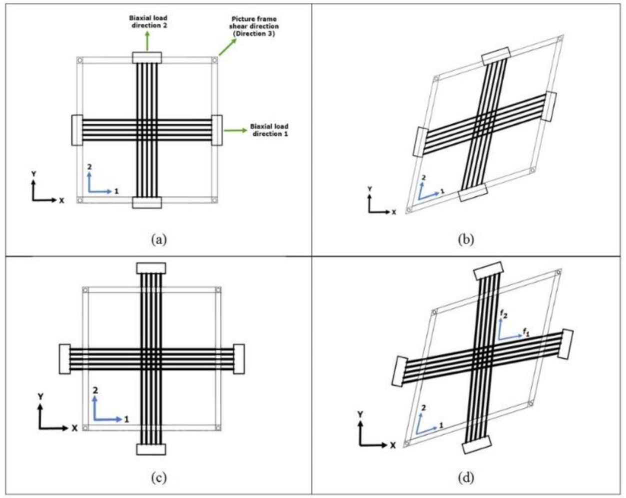


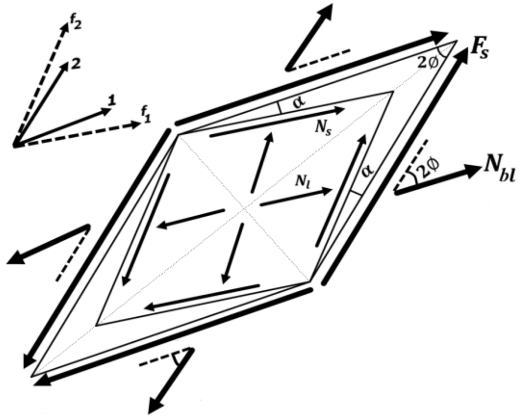
Similar to picture frame tests

Similar to bias extension tests

Advanced Combined Biaxial Tension-Shear Characterization Tool





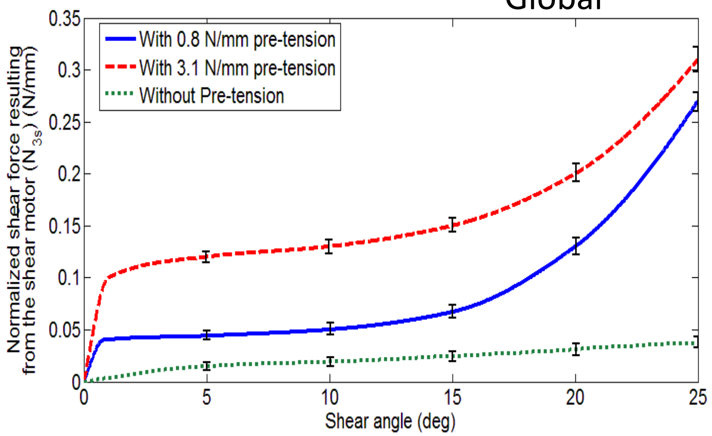


$$N_s = \frac{\sin(2\emptyset+\alpha)}{\sin^2(2\emptyset+\alpha)-\sin^2\alpha}\left[N_{bl}\sin\alpha\,(1+\sin 2\emptyset) + F_s\left(\sin(2\emptyset+\alpha) + \frac{\sin^2\alpha}{\sin(2\emptyset+\alpha)}\right)\right]$$

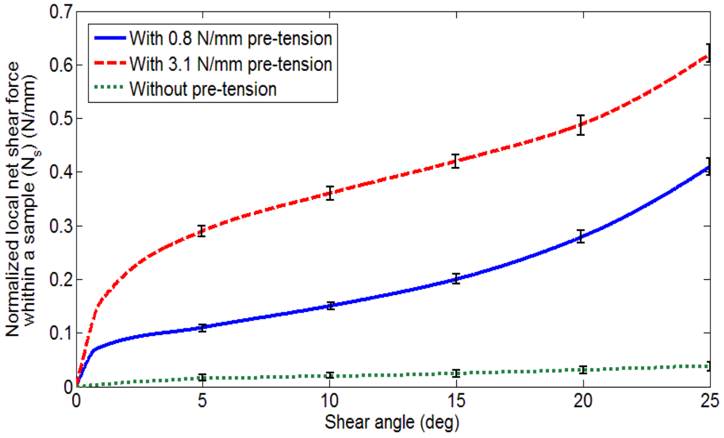
Local

Global

- Coupling effects can be modeled.



Comparison of global normalized response

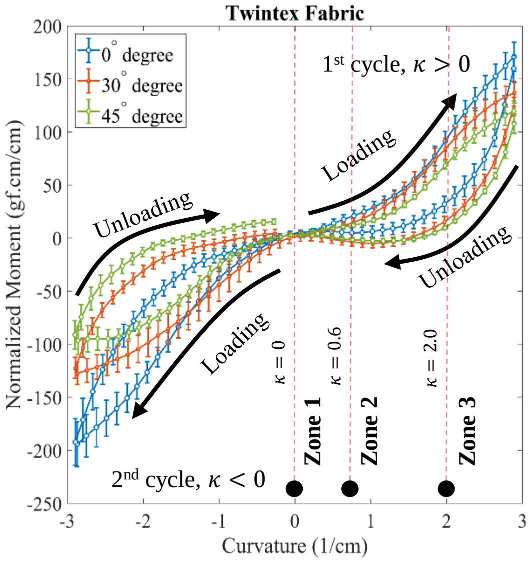


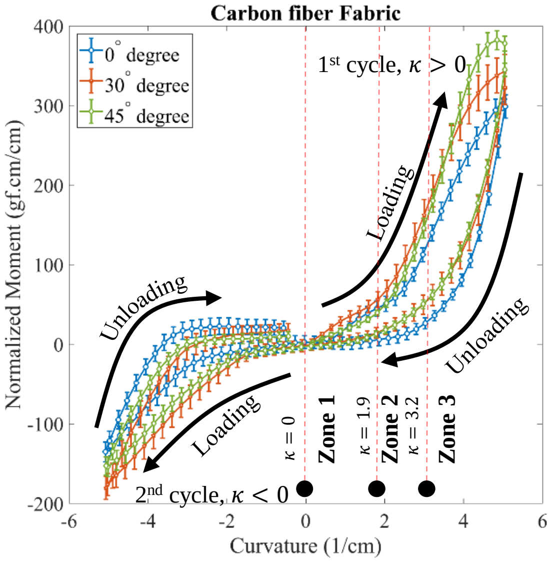
Comparison of local normalized response

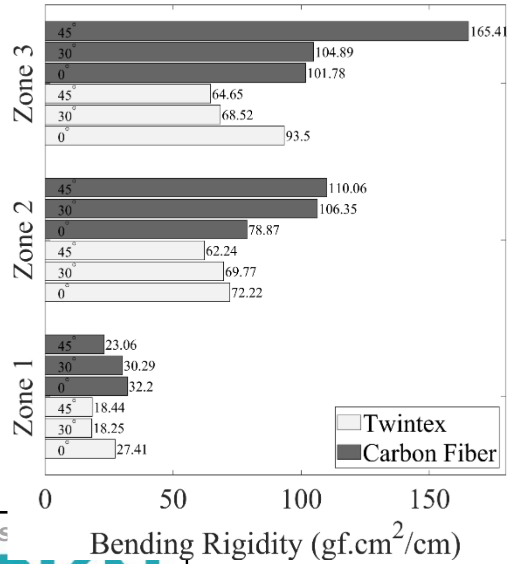
HOSTED BY: CKN Composites Knowledge Network

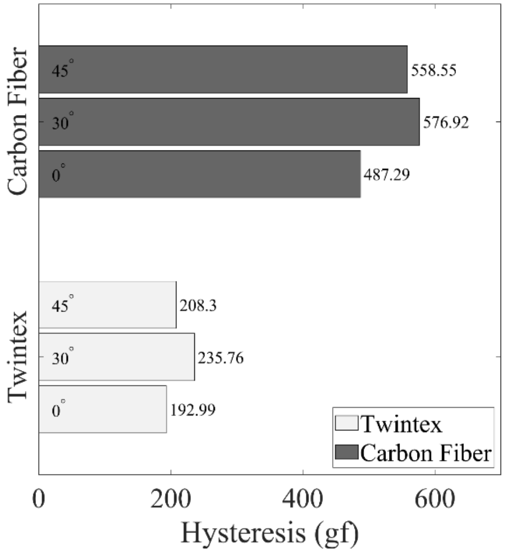
HOSTED BY: sampe Canada

Out-of-Plane Bending Characterization

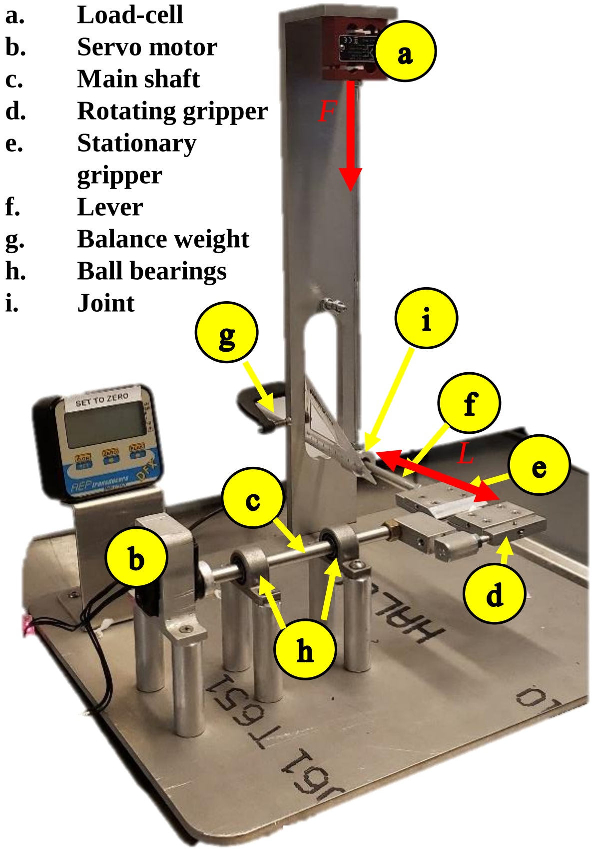


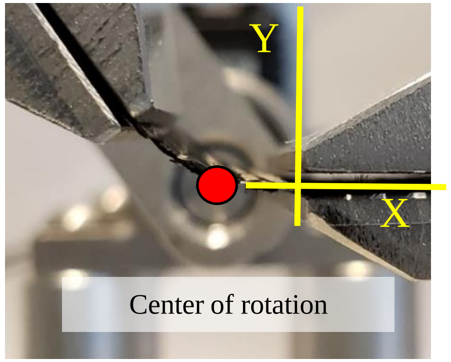


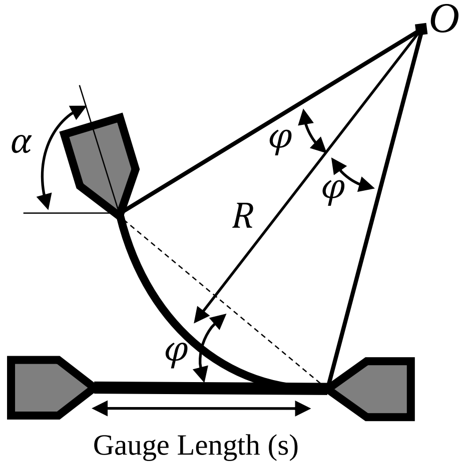




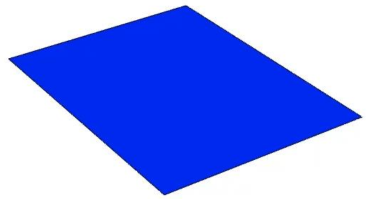
a. Load-cell
b. Servo motor
c. Main shaft
d. Rotating gripper
e. Stationary gripper
f. Lever
g. Balance weight
h. Ball bearings
i. Joint



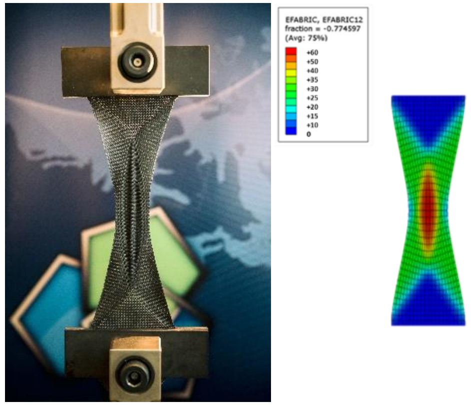




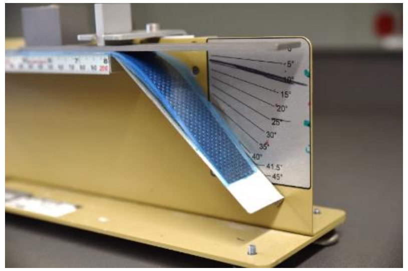
Simulation model

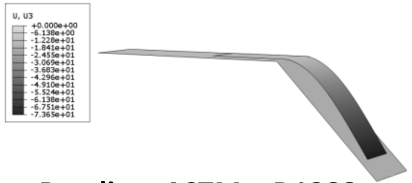


Example of Full-Scale Macro-Simulation: Hemisphere Forming

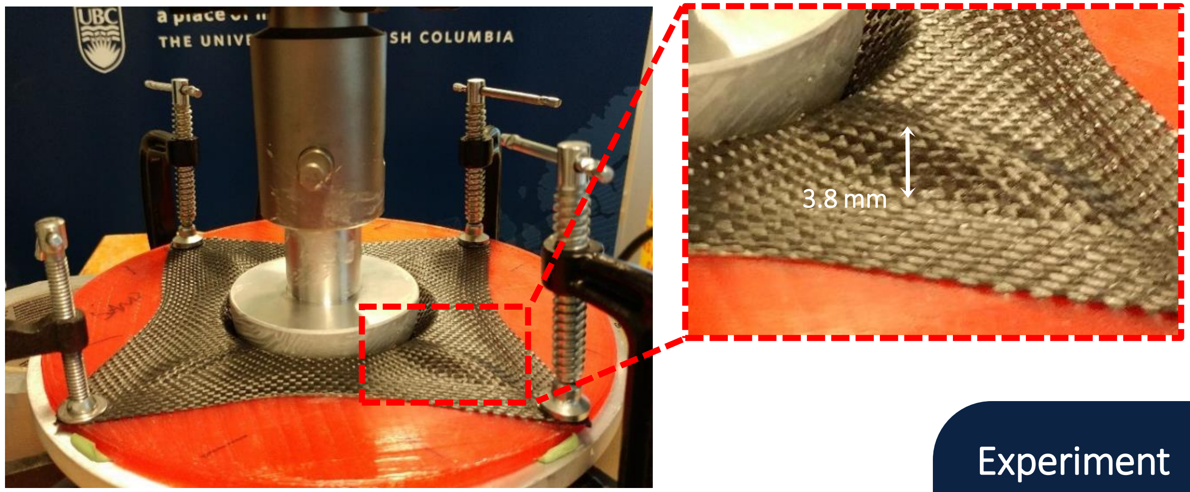


Intra-ply shear: Bias-extension test

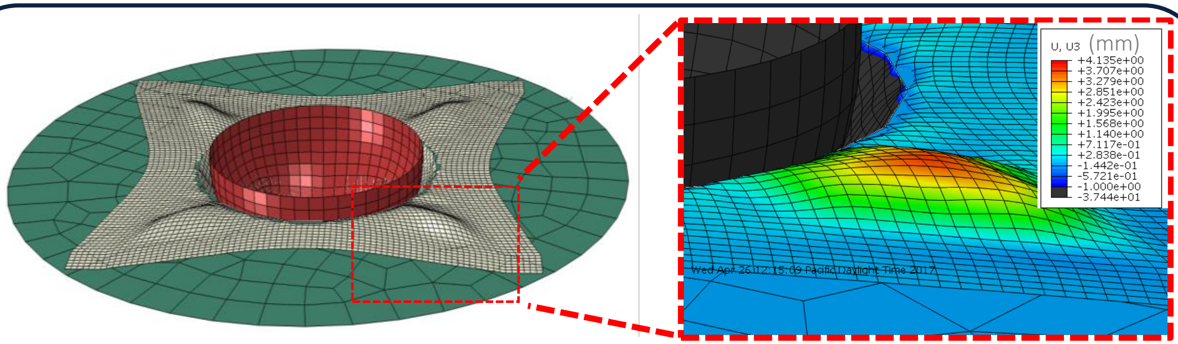




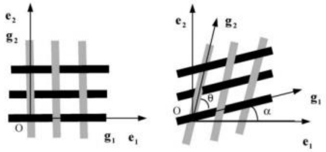
Bending: ASTM – D1388 Modified for Prepreg testing



Experiment

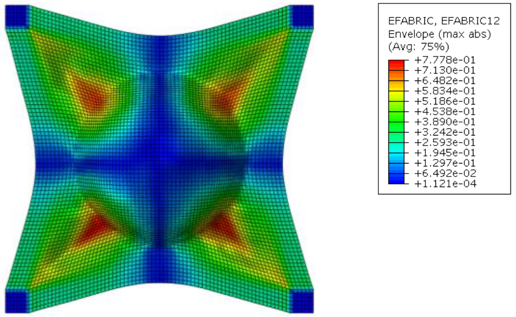


FEM



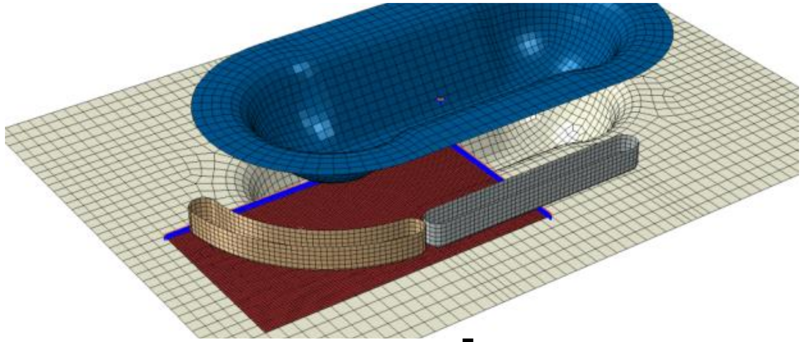
Hypo elastic non-orthogonal Material Model

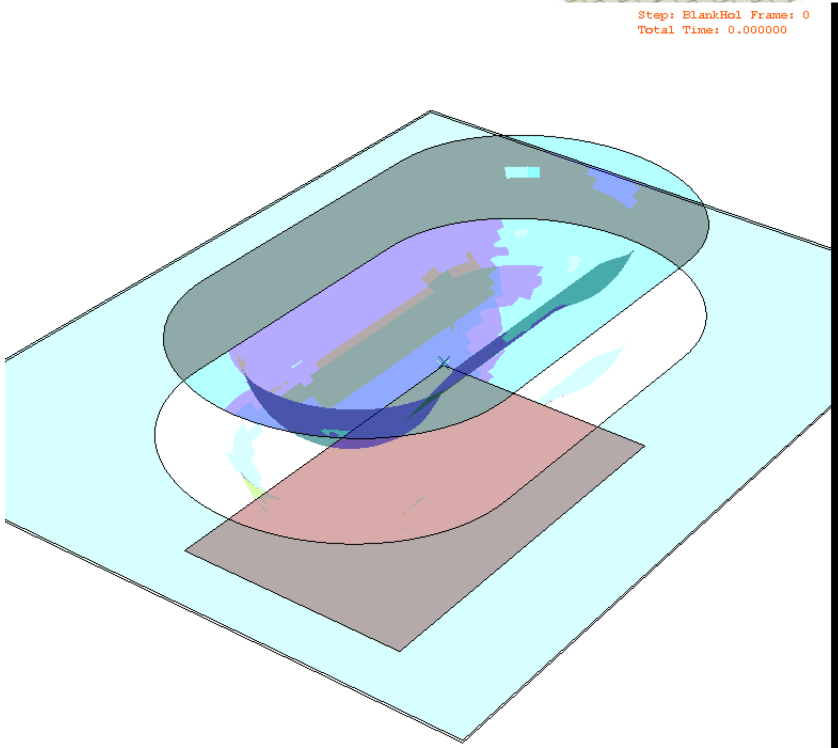
$$\begin{Bmatrix} d\tilde{\tau}^{11} \\ d\tilde{\tau}^{22} \\ d\tilde{\tau}^{12} \end{Bmatrix} = \begin{bmatrix} \tilde{D}^{11}(\boldsymbol{\varepsilon}) & \tilde{D}^{12}(\boldsymbol{\varepsilon}) & 0 \\ \tilde{D}^{12}(\boldsymbol{\varepsilon}) & \tilde{D}^{22}(\boldsymbol{\varepsilon}) & 0 \\ 0 & 0 & \tilde{D}^{33}(\boldsymbol{\varepsilon}) \end{bmatrix} \begin{Bmatrix} d\tilde{\varepsilon}_{11} \\ d\tilde{\varepsilon}_{22} \\ d\tilde{\gamma}_{12} \end{Bmatrix}$$

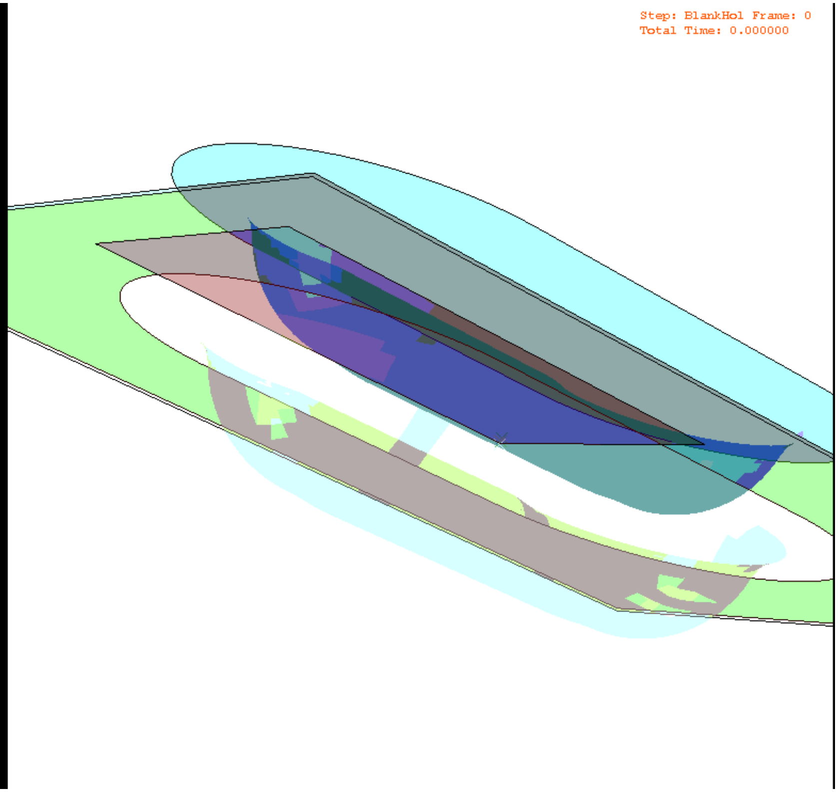


Shear angle contour
Top-down view

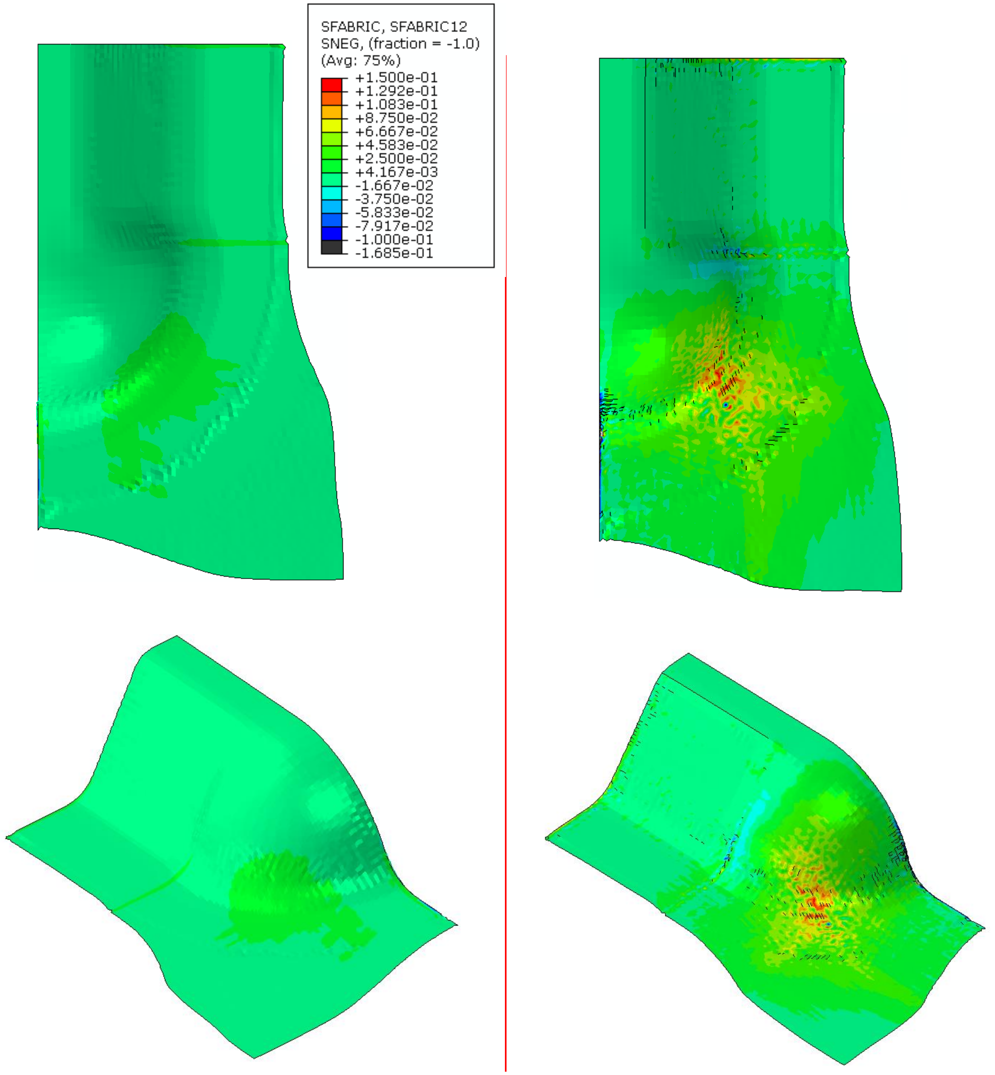
Example Macro-Simulation: Double Dome Forming







100 N Blank holder force; Resulting shear stresses τ_{12}



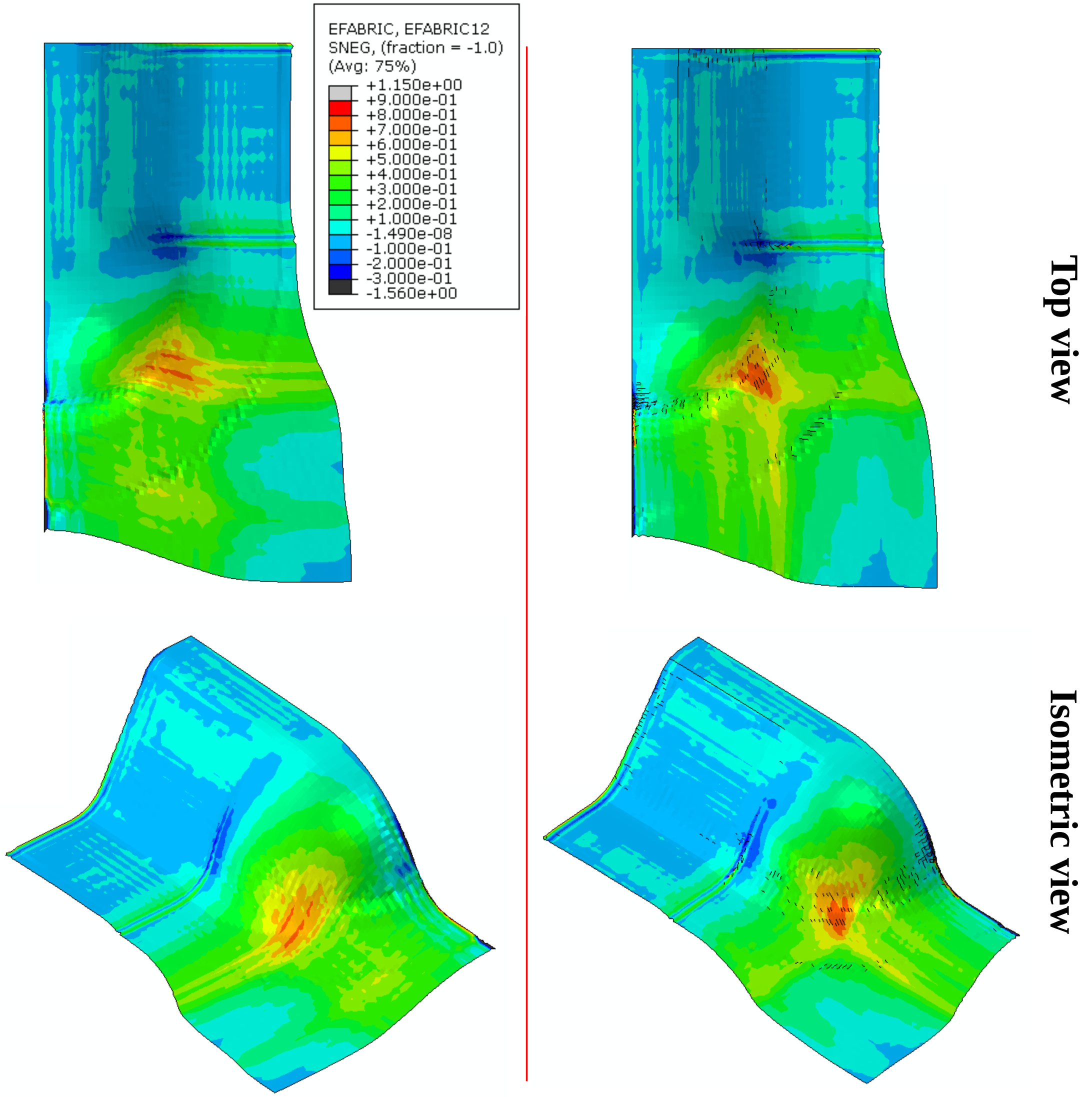
Top view

Isometric view

Uncoupled tension-shear

Coupled tension-shear

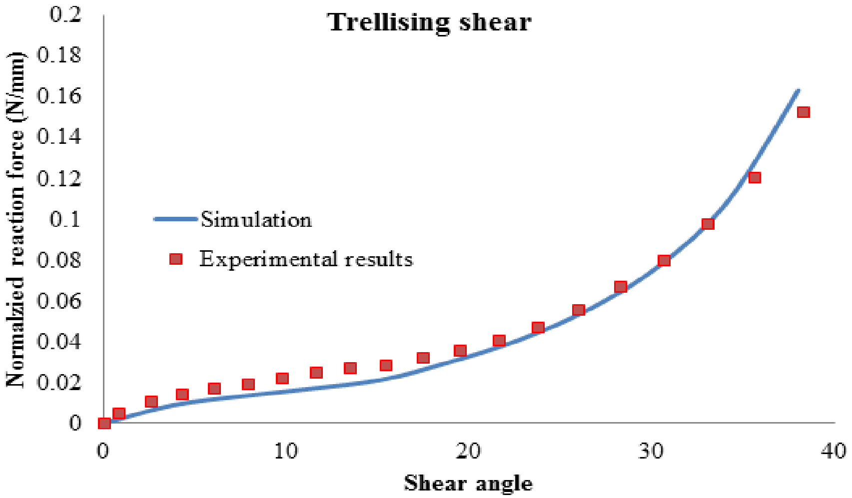
100 N Blank holder force; Resulting shear strains γ_{12}

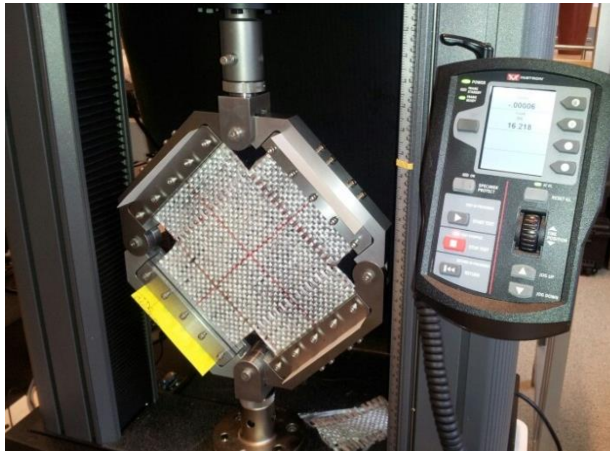


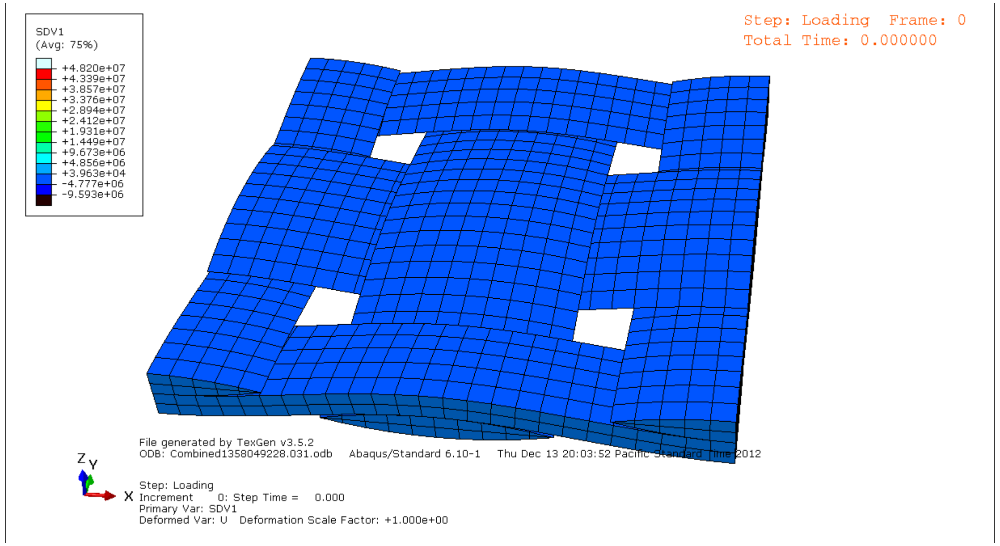
Uncoupled tension-shear

Coupled tension-shear

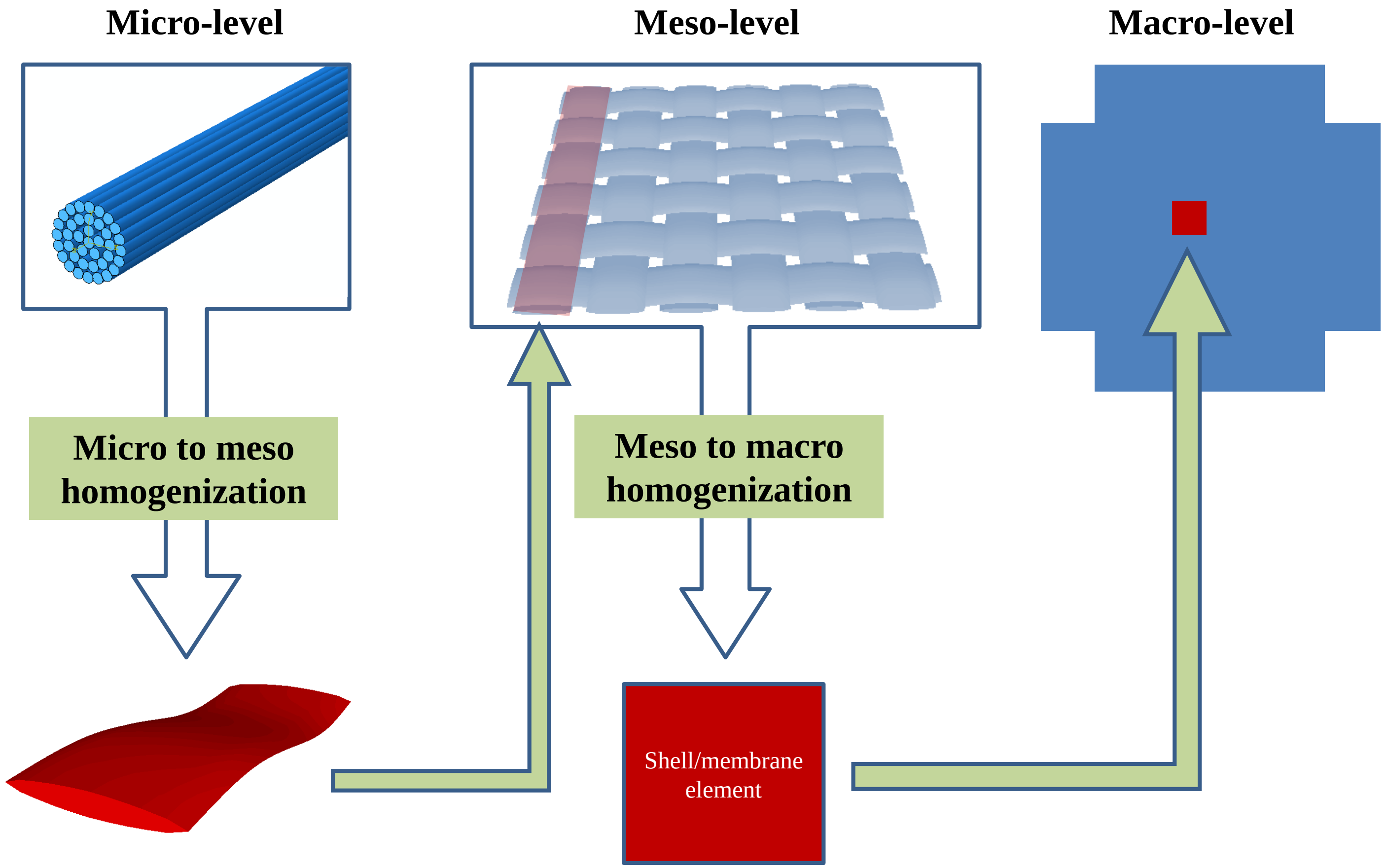
Example Meso-Simulation: PF Shear



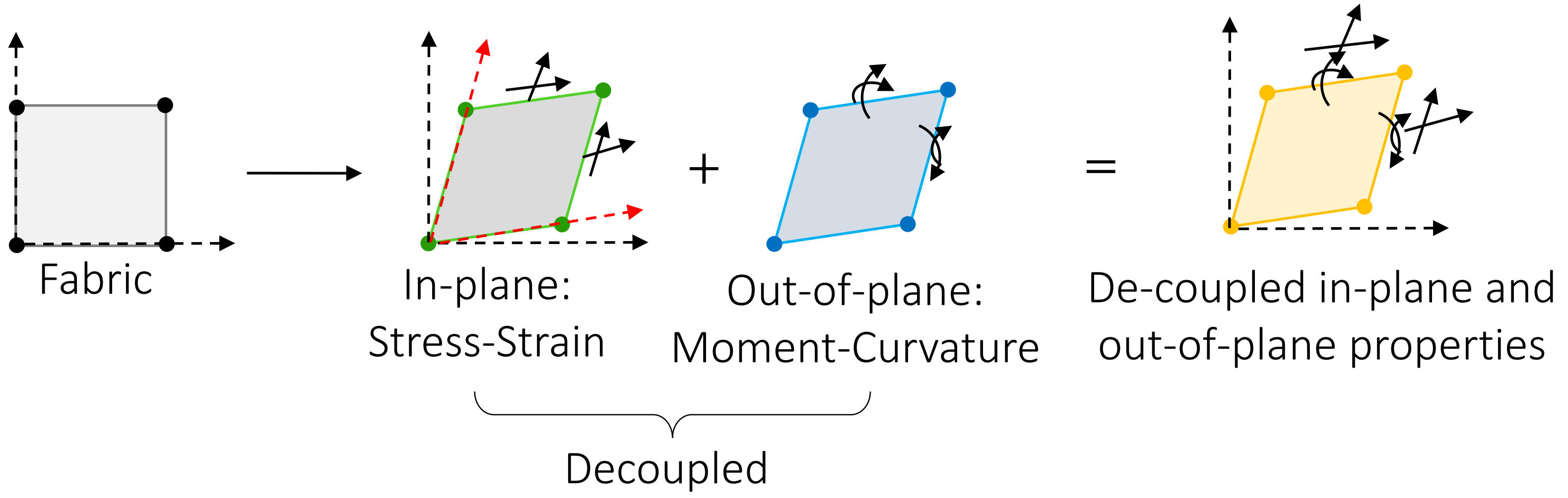




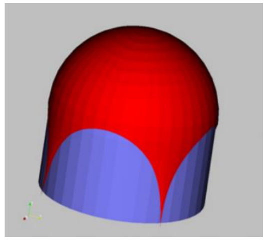
Homogenization



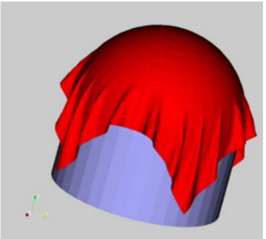
Summary of Fabric Forming (Take-home Messages)



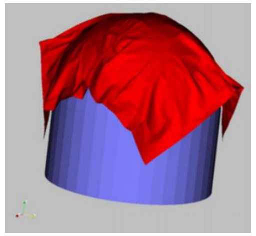
- **Woven fabrics have superior forming capabilities owing to significantly low shear modulus:**



$G = 0$
Shear angle close to 90°;
No wrinkles



G is very low, but not zero
(similar to woven fabrics)
Some wrinkles

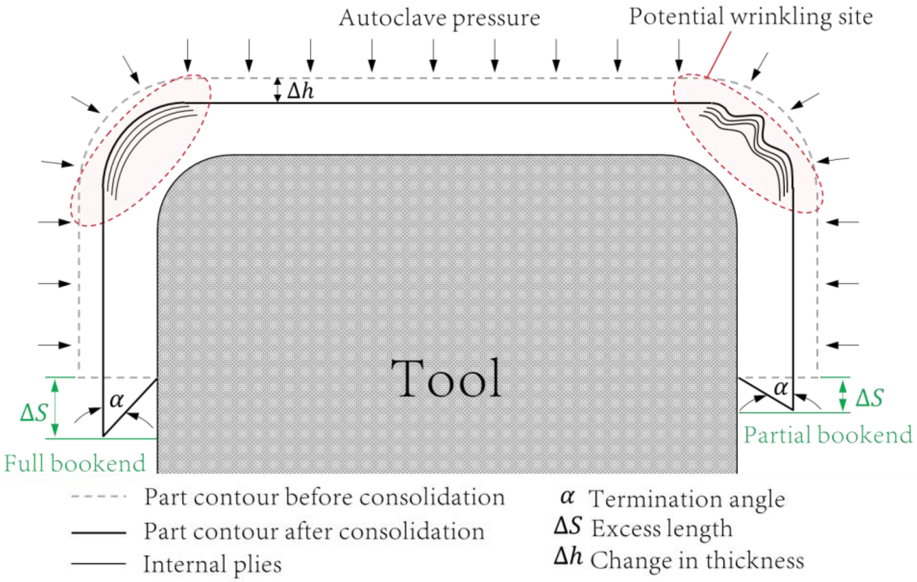


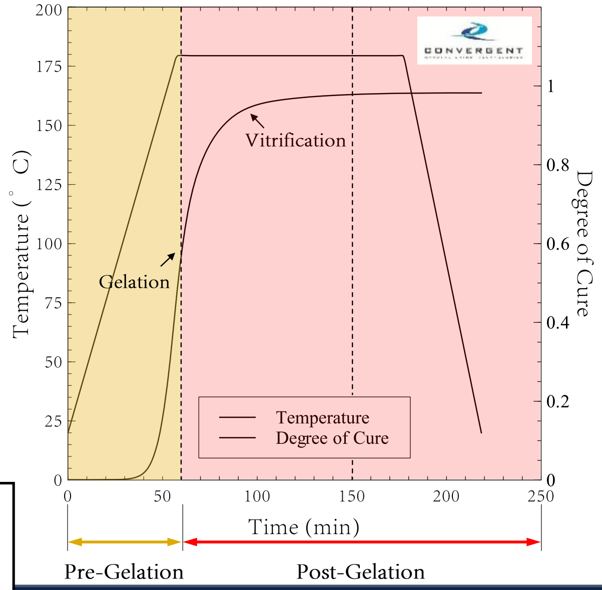
Isotropic material (G comparable to E)
Significant tension-compression within sample,
causing many wrinkles

- **Yarn tensioning postpones wrinkling (owing to inherent coupling), but the level of tension should be optimized.**

Part II:
Process-induced Wrinkling

Example: Autoclave Manufacturing



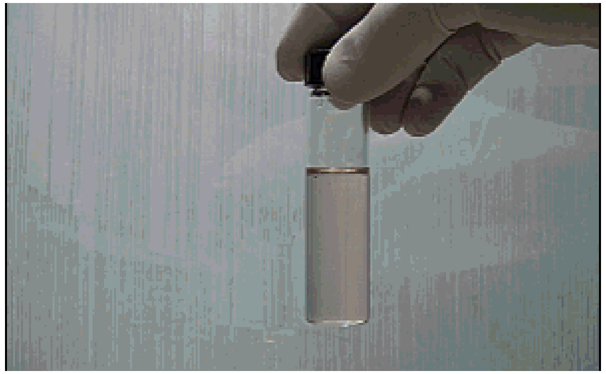


- Consolidation over complex tooling → Wrinkling
- Curved geometry → Reduced path length → Excess length!
- Ply slippage → Pre-gelation stage of the cure cycle.

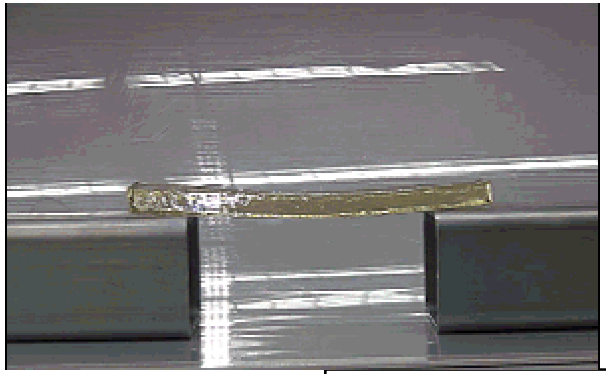
To date:

- Limited numerical investigations on process-induced defects in fabric prepregs.

Liquid state

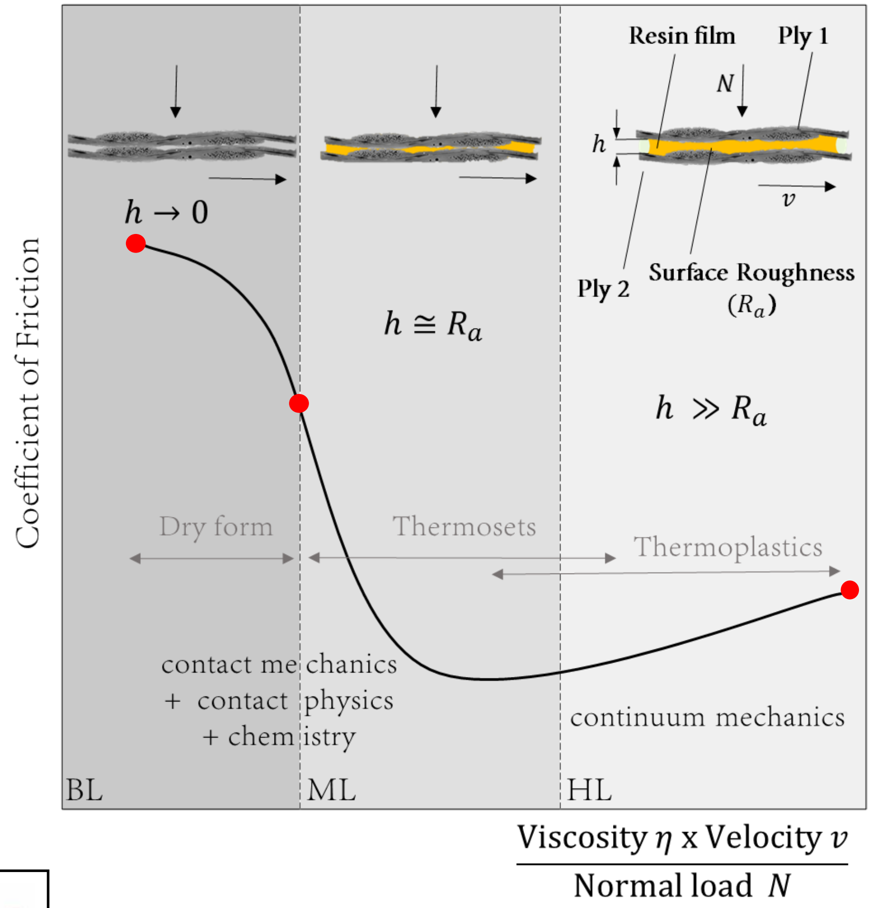


Gel state



Inter-ply Friction/Lubrication Modes Occurring during Processing

The Stribeck curve represents the general characteristic of lubricated moving surfaces:



Boundary lubrication (BL)
Load is carried solely by the asperities.
Friction becomes of a Coulomb nature.

$$\tau_a = \mu.\sigma_n$$

Mixed lubrication (ML)
Load is partly carried by the asperities.
The remaining part by the fluid film.

$$\tau_a + \tau_f$$

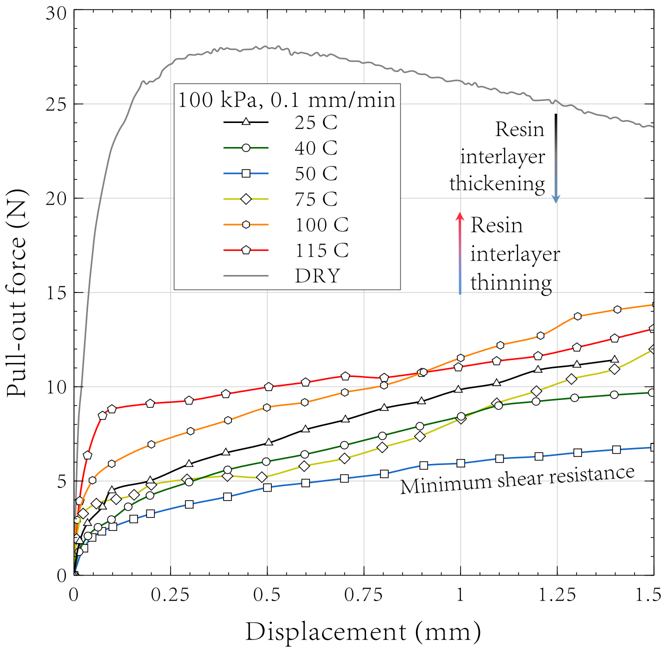
Hydrodynamic lubrication (HL)
Load is totally carried by the fluid.
No asperity contact occurs.
Surfaces are fully separated by a fluid film.

$$\tau_f = \eta.\dot{\gamma}$$

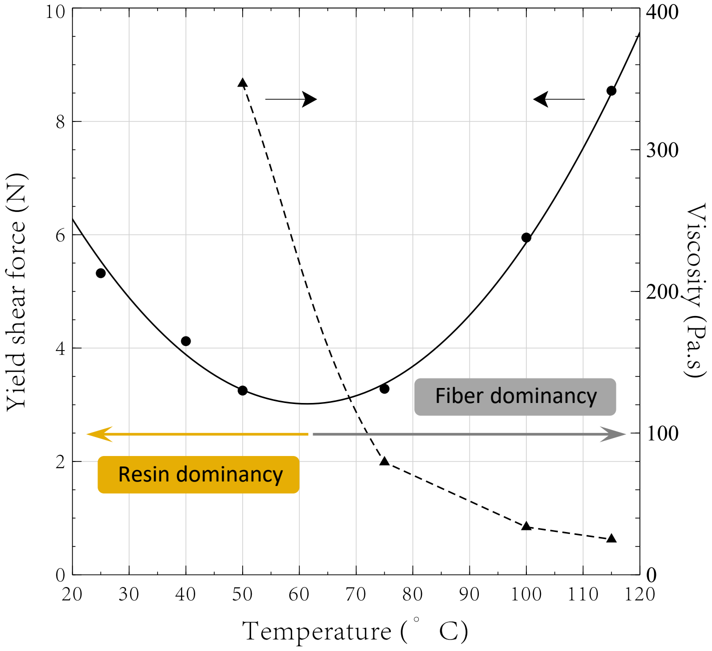
Example Ply/Ply Friction Experimental Characterization

Dry fabric

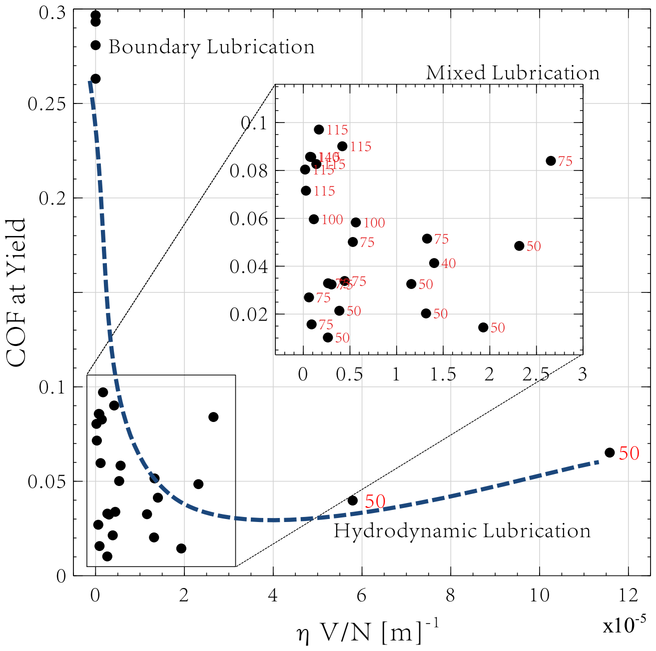
Prepreg



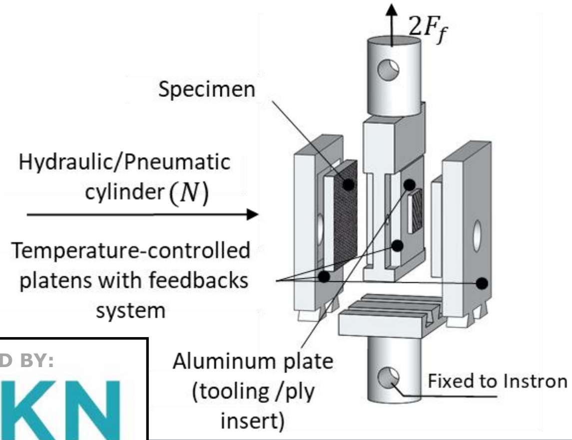
Frictional Behavior @ various temperatures

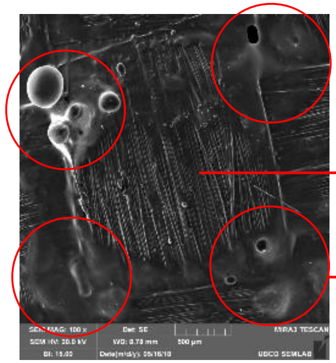


Shear stress & Viscosity vs. Temperature



Stribeck curve

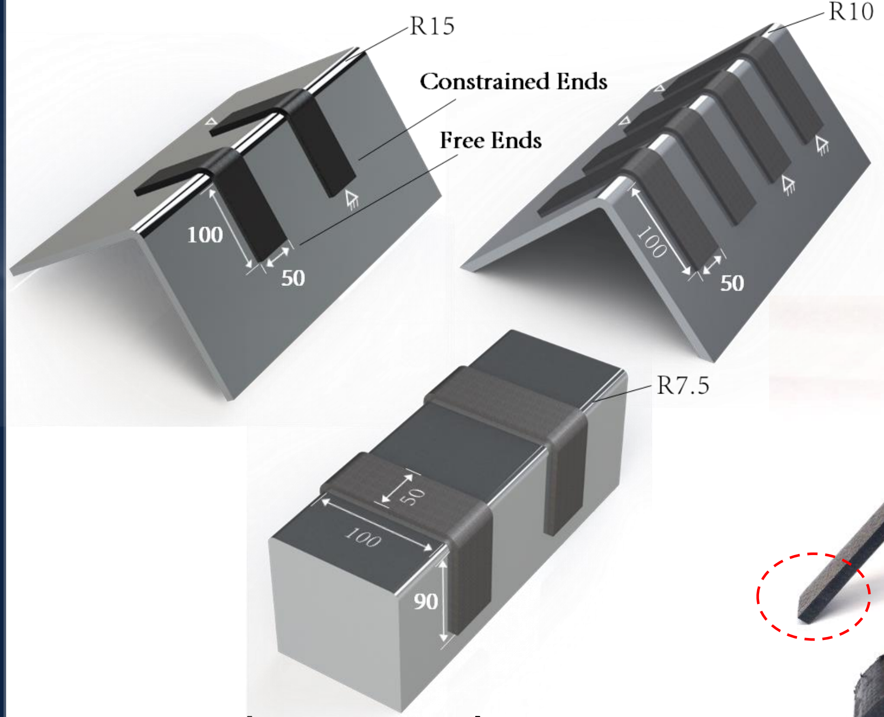




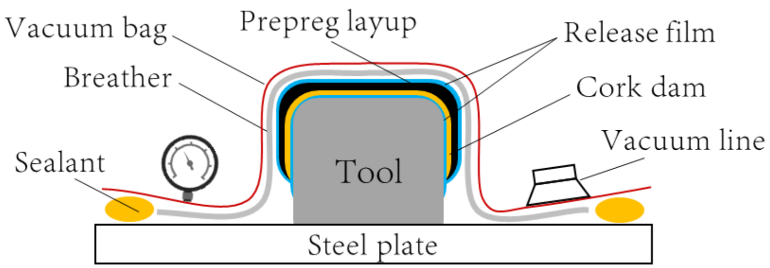
- Frictional forces increase as surface resin is worn away.
- The softening matrix promotes increasing roughness.

Wrinkling Case study: Manufacture of L-Sections & C-Sections

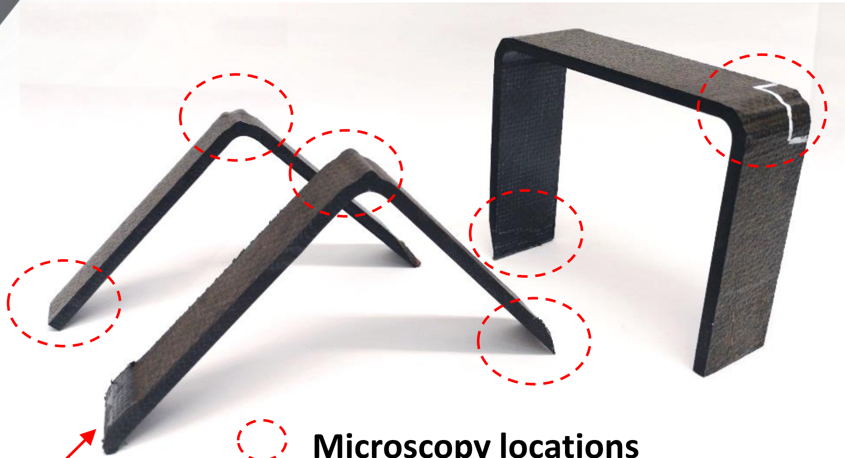
- $[90/0]_{18}$ & $[90/0]_{24}$
- Tool Radii: 7.5 mm (C-Section) – 10 & 15 mm (L-Section)
- BC: Free ends & Constrained ends
- CYCOM 970's Standard MRCC



[Dimensions in mm]



Bagging arrangement



Microscopy locations

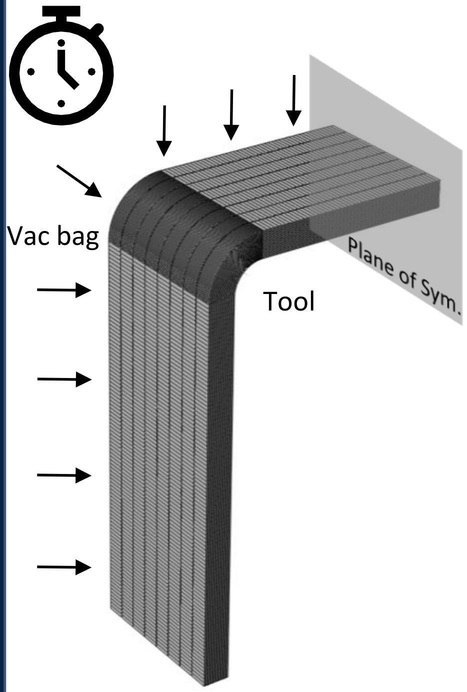
Constrained ends

Autoclave

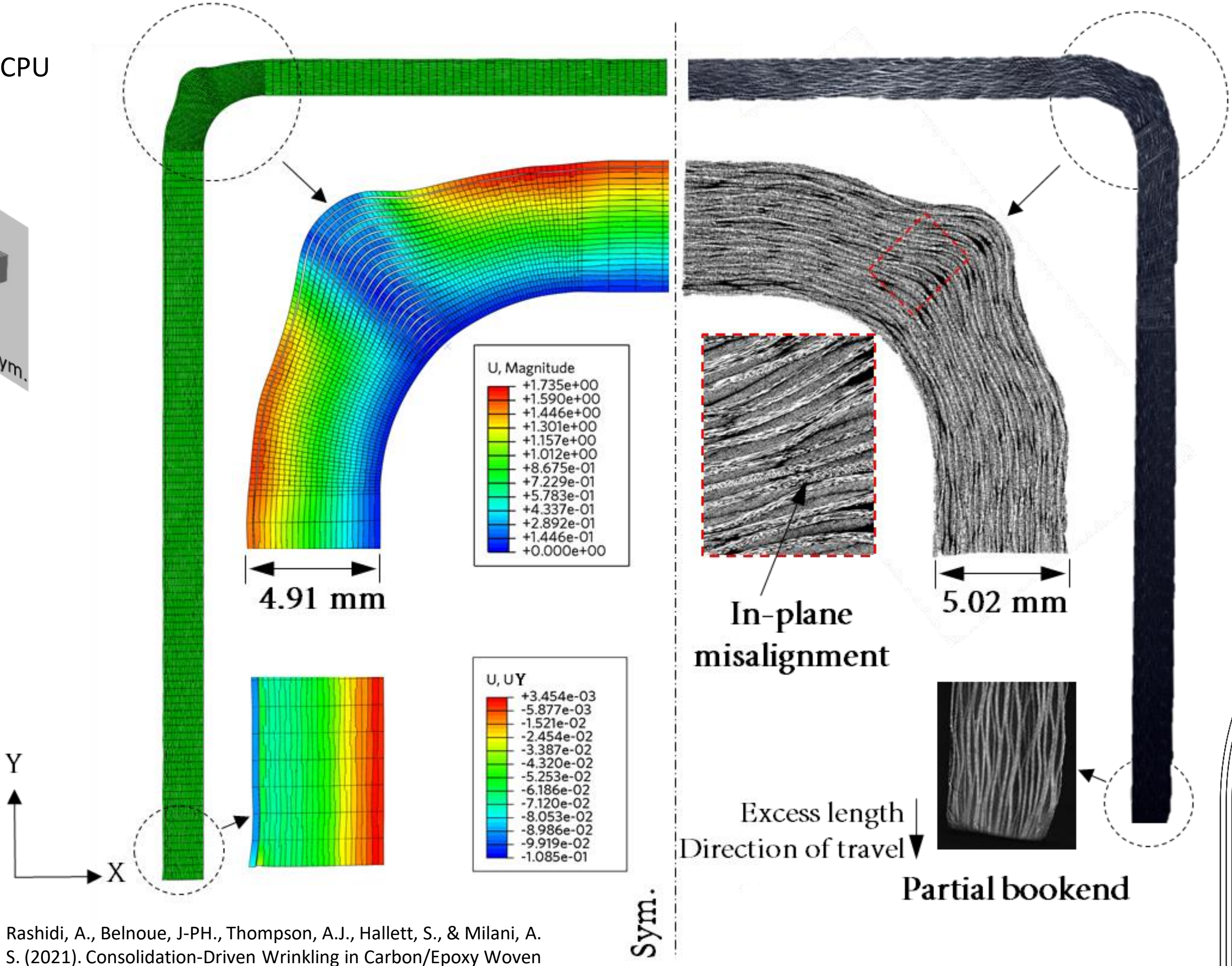
Simulation results: C-Section geometry

Ply-by-ply FEM model:

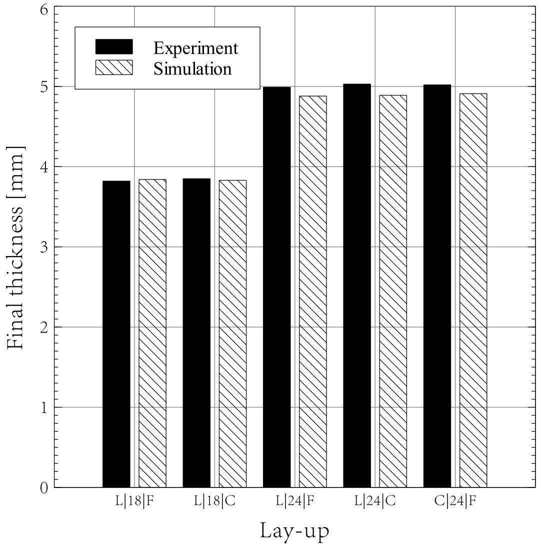
- **Run time: ~4 hr**
- 15 cores - Dual 2.20 GHz CPU



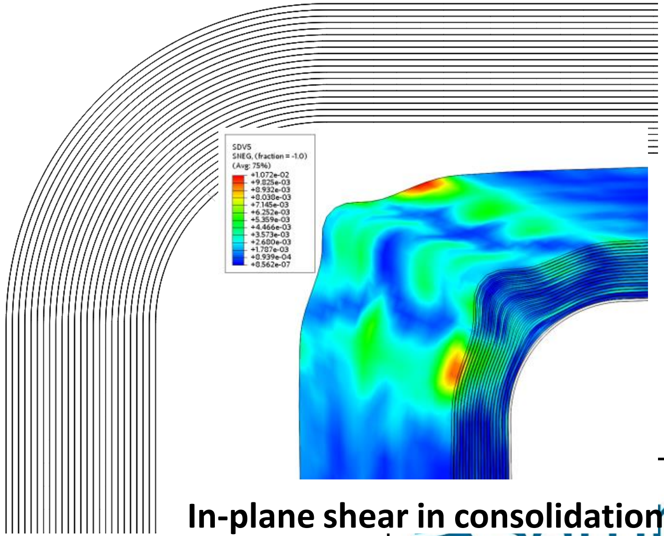
24-ply | C-Section | Free ends



Rashidi, A., Belnoue, J-PH., Thompson, A.J., Hallett, S., & Milani, A. S. (2021). Consolidation-Driven Wrinkling in Carbon/Epoxy Woven Fabric Prepregs: An Experimental and Numerical Study. ***Composites Part A: Applied Science and Manufacturing***, 106298.



Final thickness – Sim. Vs. Exp.



In-plane shear in consolidation

Acknowledgments

Research Assistants (>80) & CRN Colleagues:

Funding Agencies (>$15M):

Natural Sciences and Engineering Research Council of Canada / Conseil de recherches en sciences naturelles et en génie du Canada

Canada

Western Economic Diversification Canada

INNOVATION.CA
CANADA FOUNDATION FOR INNOVATION | FONDATION CANADIENNE POUR L'INNOVATION

NRC·CNRC Canada
NRC Industrial Research Assistance Program | Programme d'aide à la recherche industrielle du CNRC

Mitacs

Industry Partners (>300):

Performance BioFilaments, solus, Tetra Tech, PRE Labs, EMTEQ, Cooledge, Harwood Custom Composites, G3, Whitewater, MDT, Magellan, FoldTech Innovations, HGE Marine Engine Products, International Water-Guard, ASL Environmental Sciences, Crescent Custom Yachts, MacDon, beachcomber Hot Tubs, Structural Composites, axine Water Technologies, Nabtesco, AS Composite Inc., RSI, Trinity Aviation, Nicholson, PCM, waterplay Solutions Corp., Viking, Versatile, MAAX, Valid Manufacturing Ltd., Westport Fuel Systems, SHOXS, Velometro, Campion, Solegear, Arktos Developments Ltd., Helios Global Technologies, Meggitt Training Systems, Hover Collective, Redflagdesign, New Flyer, sepro mineral systems, exo, Brican Flight Systems Inc., Metropolitan Community College, plascon plastics, nanozen, urthecast, Ronin 8, beyond closed loop, Dynamic Structures, KF Aerospace, Polyrap, Fort Garry Fire Trucks, BionicPower, wesgar, Big Foot Manufacturing Company, ecofab, Hempco, FormaShape, Heli-One, Cascadia Windows & Doors, Instream Energy Systems, lululemon, Agility Blades, Axys Technologies Inc., Carlson Engineered Composites Inc., Viking, Twin Anchors Houseboats, LVM, Axalta, Kohler, ShawCor, Starboard Aerotech, PREDL systems, Structa Wire Corp, Canadian Sport Institute, Sandvik, Arrow Truck Caps, Giatec Scientific, Rhinokore Composite Solutions, Reforus, Rigel Marine Services, MTU Aero Engines, Backun Musical Services

Thank you!


UBC MMRI
Contact:
Abbas S. Milani, Director
abbas.milani@ubc.ca
Killam Laureate, Member of
Royal Society of Canada College
mmri.ubc.ca

Thank you for joining us!

The next AIM event will be January 23, 2022

And don't forget to visit the KPC for more information:

https://compositeskn.org/KPC

Questions?

For more information on future dates and times visit:

compositeskn.org

HOSTED BY: CKN Composites Knowledge Network

HOSTED BY: sampe Canada