A Comprehensive Framework for Characterization and Simulation of Forming Processes

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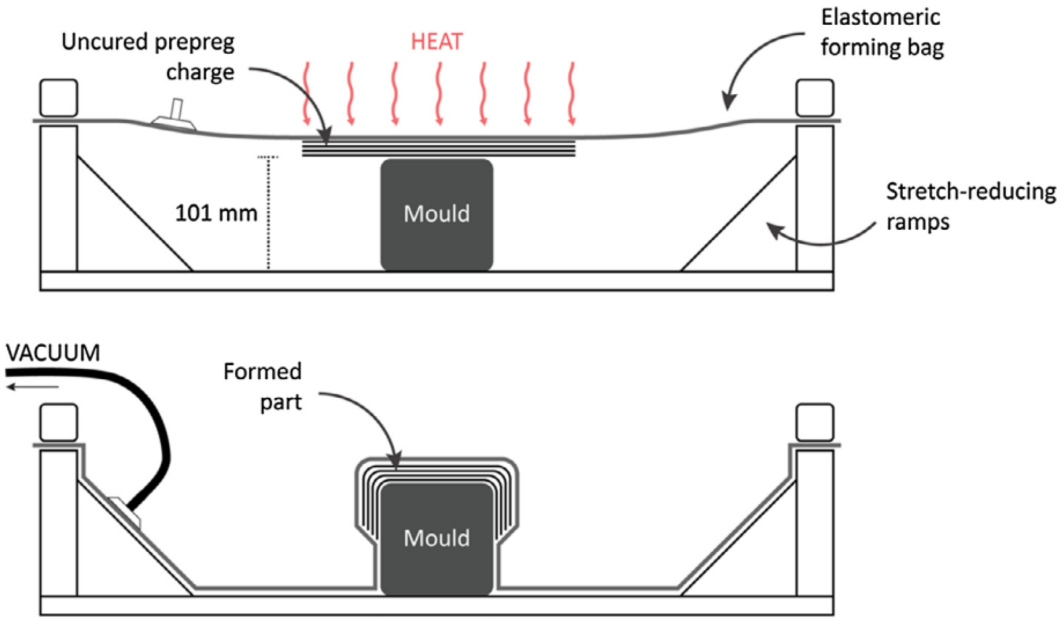
Composites Forming Simulation Challenges

In automated deposition processes such as forming:

- The material undergoes large deformations
- There may be a large number of parts with evolving interactions (such as contact) between them:
  - Mould
  - Material layers
  - Diaphragm or punch
  - Grip holders
- Unlike sheet metal forming, the workpiece (laminate) is composed of multiple orthotropic material plies with different fibre orientations

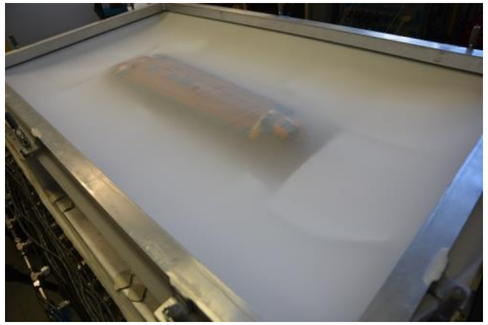


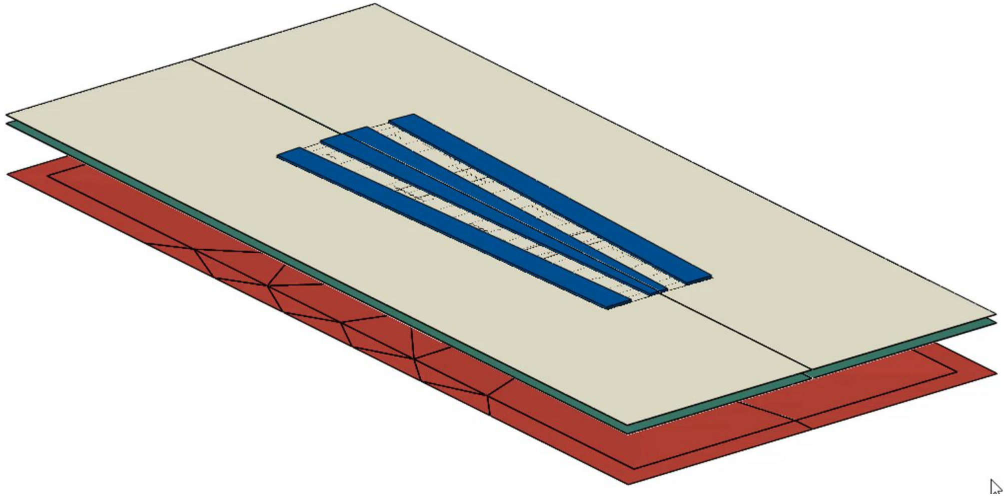
*Farnand et al (2017)**

* Farnand et al (2017), Micro-level mechanisms of fiber waviness and wrinkling during hot drape forming of unidirectional prepreg composites, Part A: Applied Science and Manufacturing. ;103:168–77.

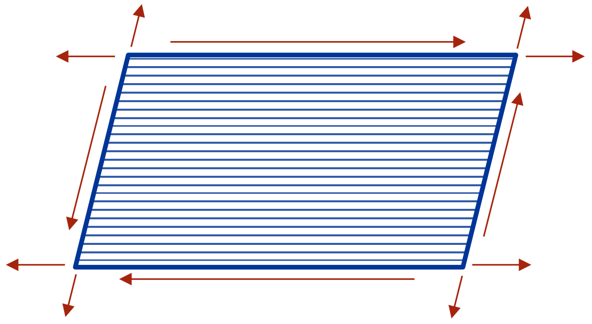
Physics-Based Forming Simulation

- Physics-based modelling is founded on our understanding of *causality* of events.
- The phenomena of interest are modelled using mathematical representations
- In Process Simulation, a physics-based model needs to include representations of:
  - **Material** being processed: its incoming state, its evolution when subjected to process conditions
  - **Process**: Sequence of events and boundary conditions
  - **Equipment**: Interaction of the equipment with material and its effect on process conditions

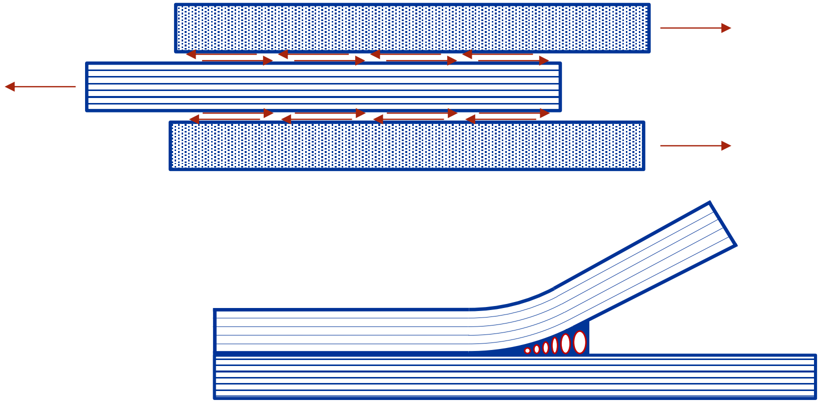




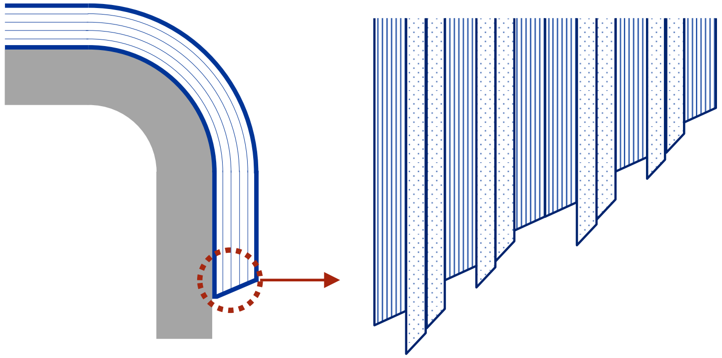
Key Deformation Mechanisms



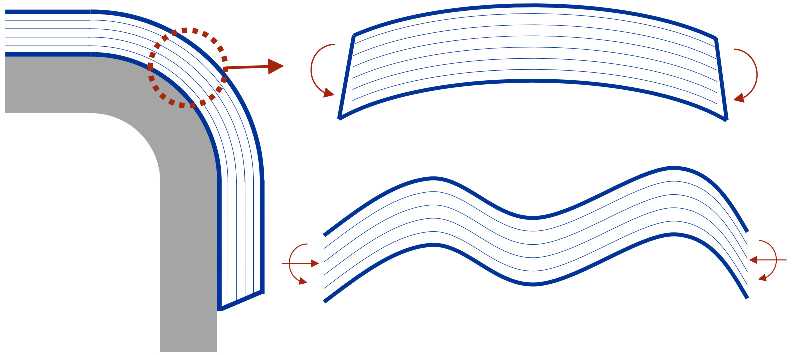
Ply In-plane (axial, shear, locking)



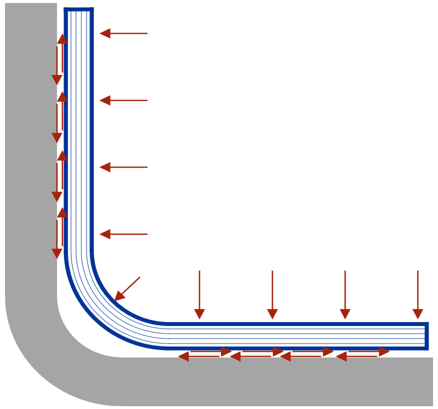
Interlaminar (shear/friction, stick-slip, tack)



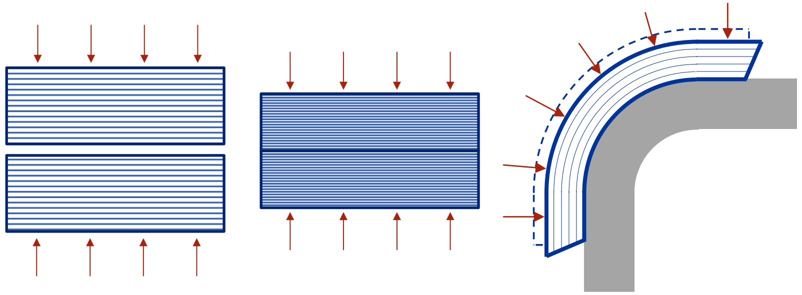
Ply Transverse Shear & Logrolling



Ply Bending & Buckling



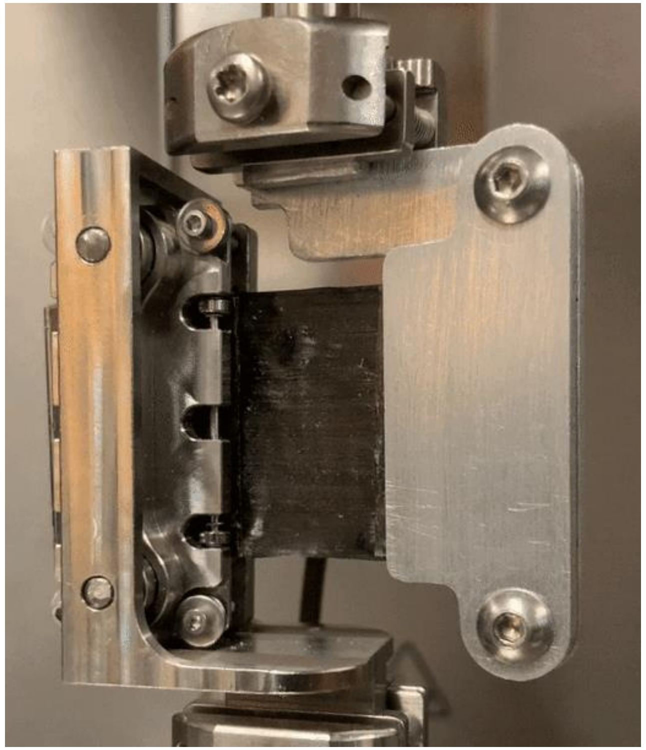
Tool-Part interaction



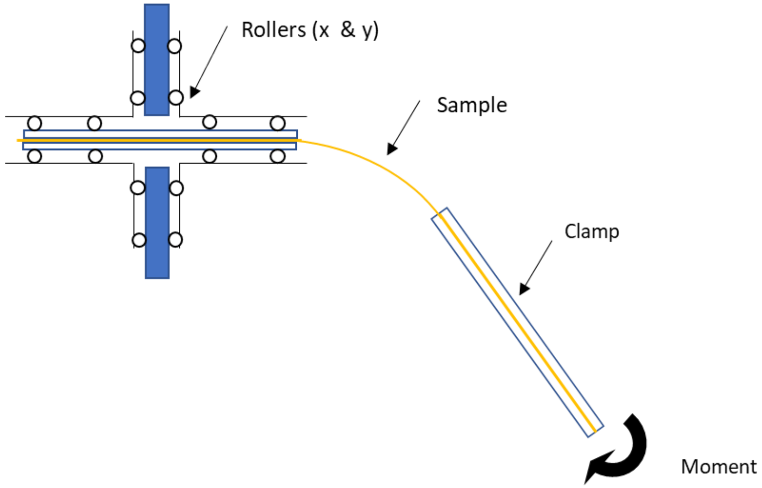
Debulk & Consolidation

Prepreg Bending

Characterization Test



Bending characterization fixture installed in a rheometer



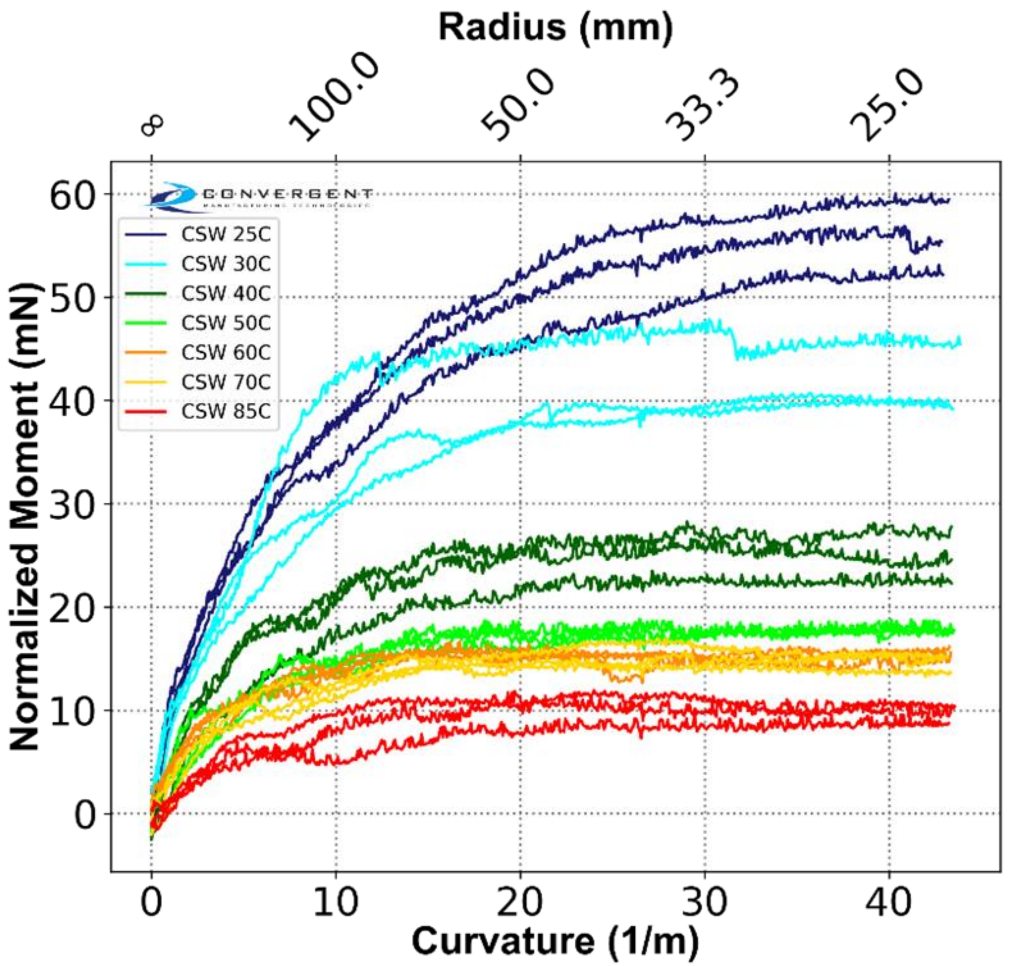
Top view of the double-roller design

- Fixture inspired by original Sachs(2014)* design
- Fixture features:
  - Double roller design: minimizing frictional effects and providing uniform bending moment
  - Fixed sample length
- Fully definable test conditions:
  - Temperature
  - Bending Rate
  - Bending Angle and Radius of curvature
  - Loading/Relaxation/Unloading

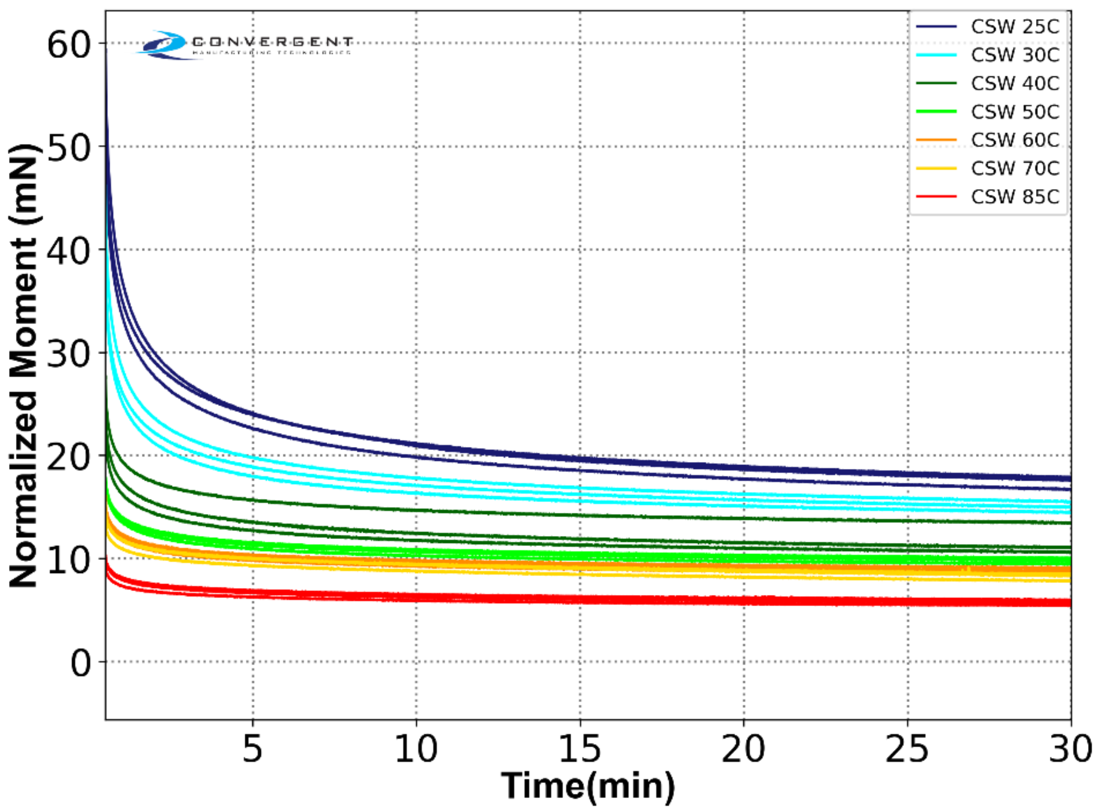
* U. Sachs (2014), Friction and bending in thermoplastic composites forming process, PhD Dissertation, Universiteit Twente.
For more information see: Lane et al (2023), Characterization testing of un-cured prepreg fabrics for forming process. Proceedings of SAMPE Seattle

Prepreg Bending

Loading

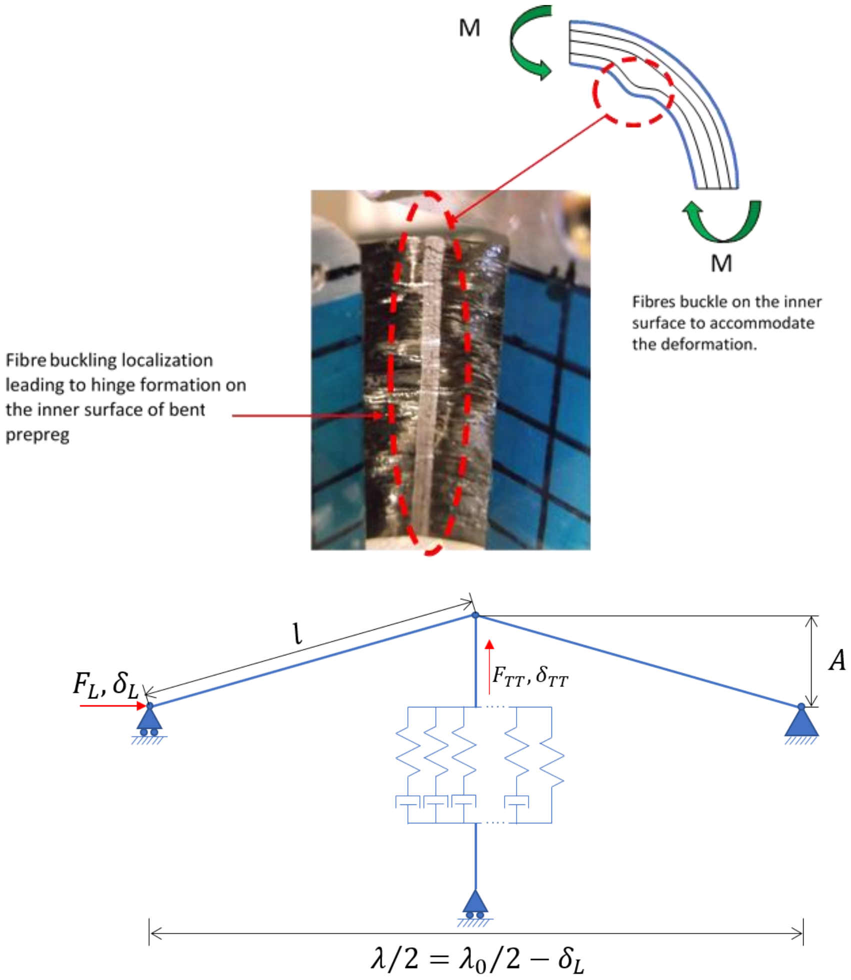


Relaxation

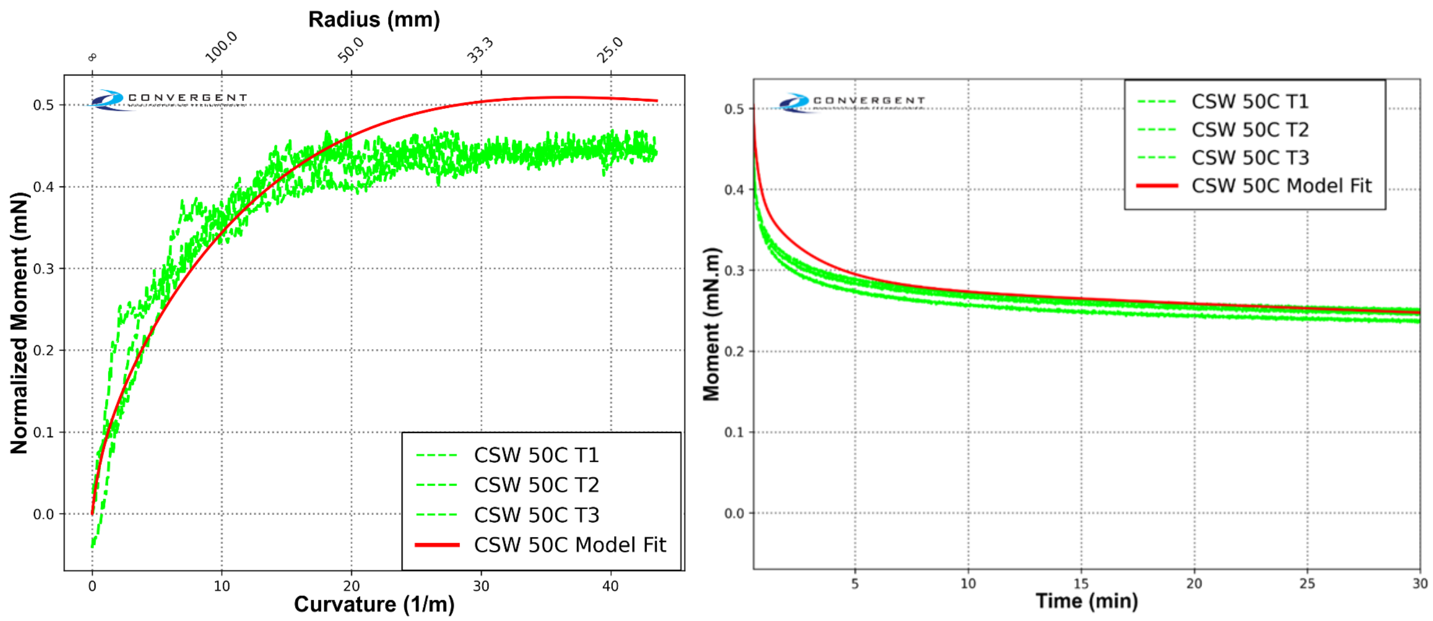


Prepreg Bending

Constitutive Modelling: Non-linear Viscoelastic



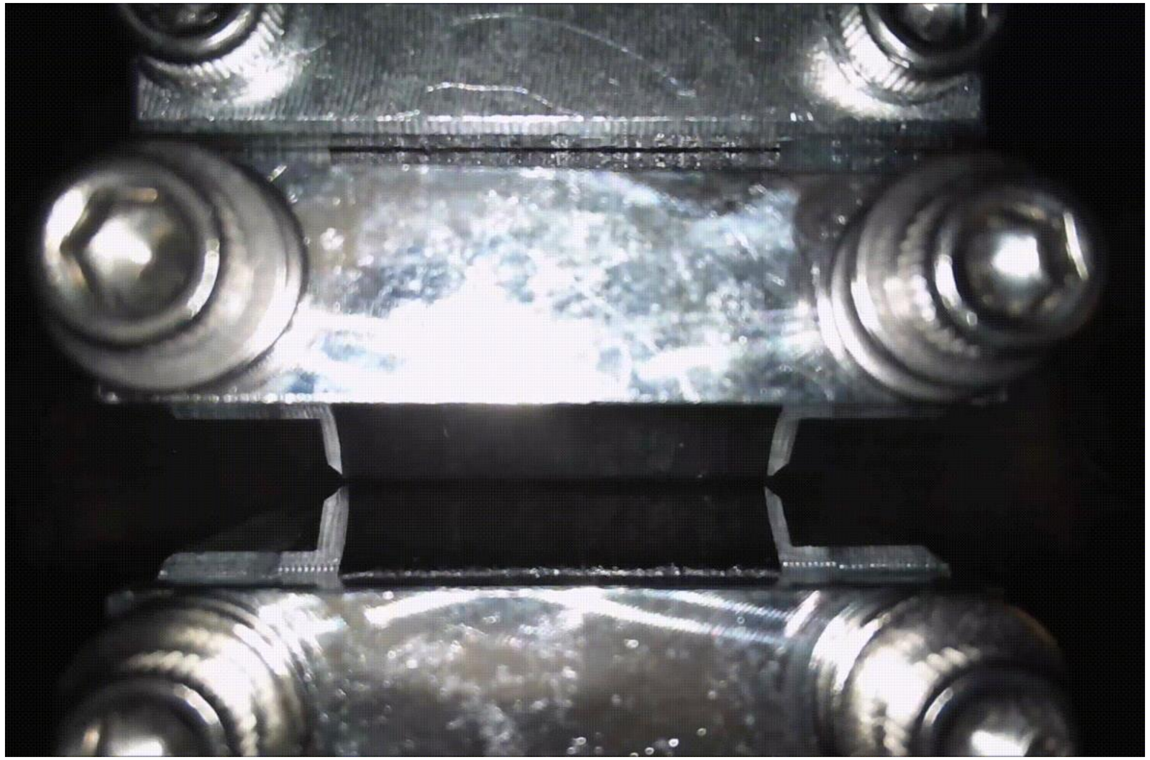
- Fiber micro buckling is observed in bending samples
- This inspired development of a non-linear viscoelastic model that is schematically represented as a hinge on a viscoelastic bed



Model fit examples

Prepreg Tack

Characterization Test



- Tack is the measure of the resistance to separation of two surfaces
- A prepreg-to-prepreg probe tack test fixture was developed in house:
  - Relatively large contact area (1”x1”)
  - UD or Fabric testing
  - Testing prepregs at relative angles (0-0, 0-90, 0-45, …)
  - Control over process parameters:
    - Temperature
    - Cohesion Pressure
    - Dwell time
    - Separation rate
    - Moisture
    - …

For more information see: Lane et al (2023), Characterization testing of un-cured prepreg fabrics for forming process. Proceedings of SAMPE Seattle

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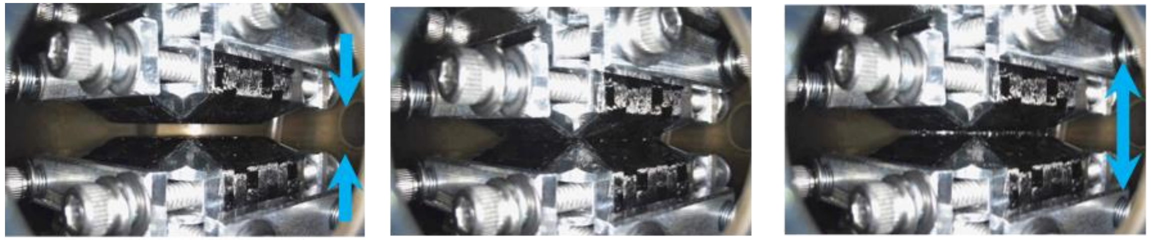
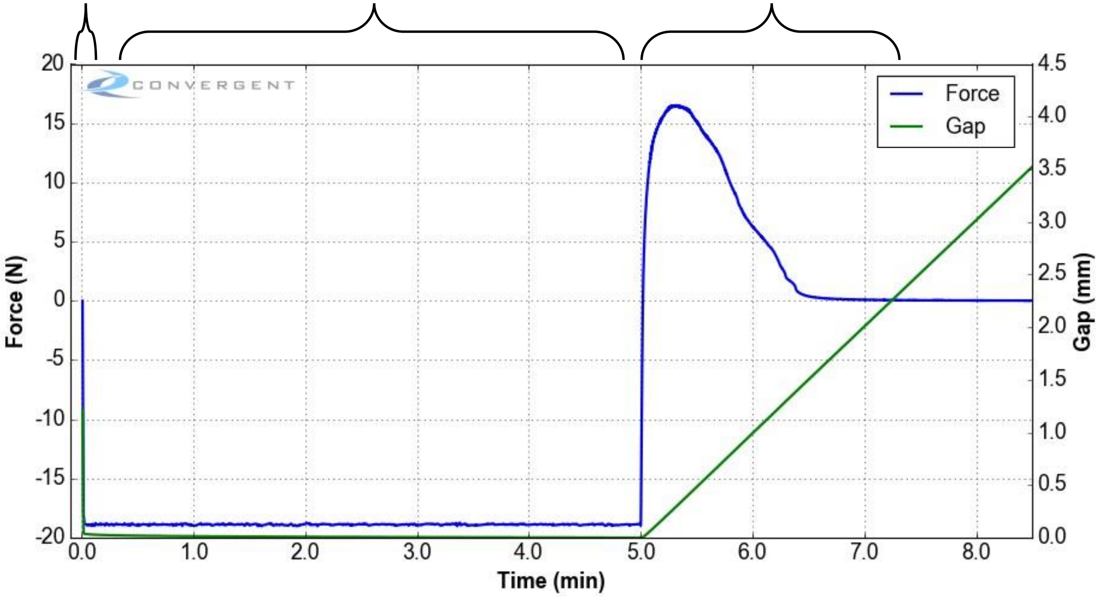
Prepreg Tack

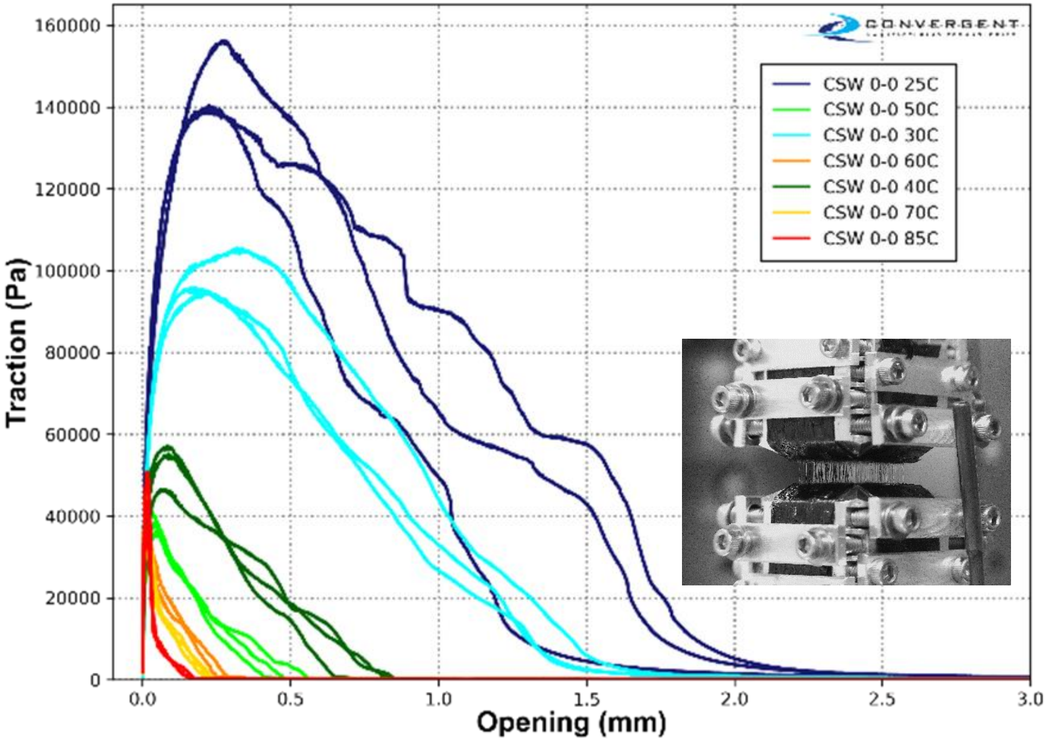
Characterization Tests



Approach Force Controlled | **Dwell** Constant Pressure & Temperature | **Separation** Displacement Controlled

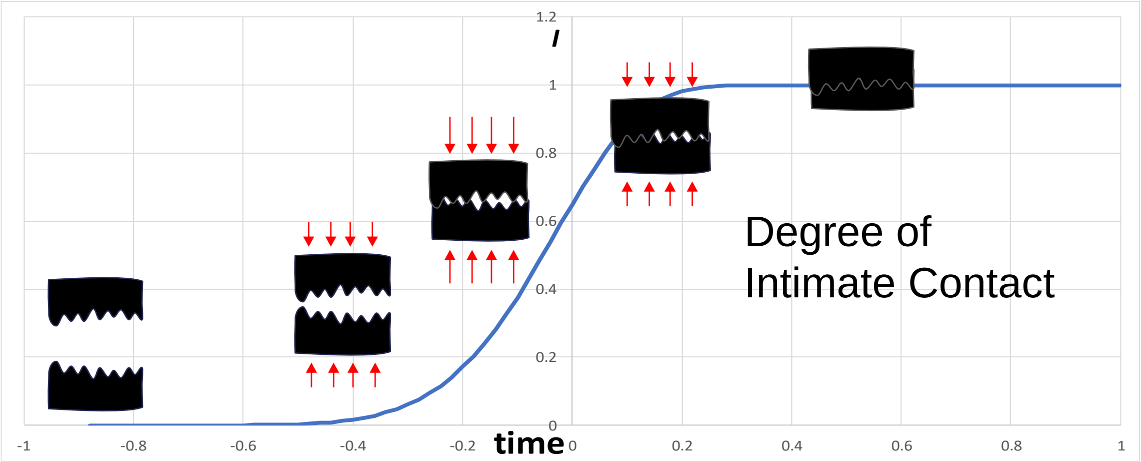
Approach Force Controlled | **Dwell** Force Controlled | **Separation** Displacement Controlled





Prepreg Tack Constitutive Model

Cohesion Model



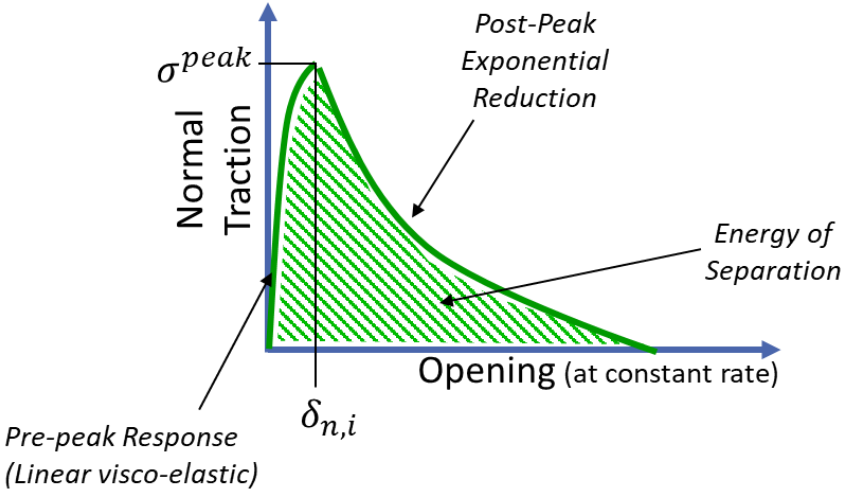
Degree of Intimate Contact:

$$I = e^{-\frac{\log\left(\frac{F}{F_{max}}\right)}{2I_{SD}^2}}$$

where F is the pressure flow index

$$F = \int \frac{P(t)}{\mu(X,T)} dt$$

Decohesion Model



$$\sigma_1 = R\sigma_{1VE}$$

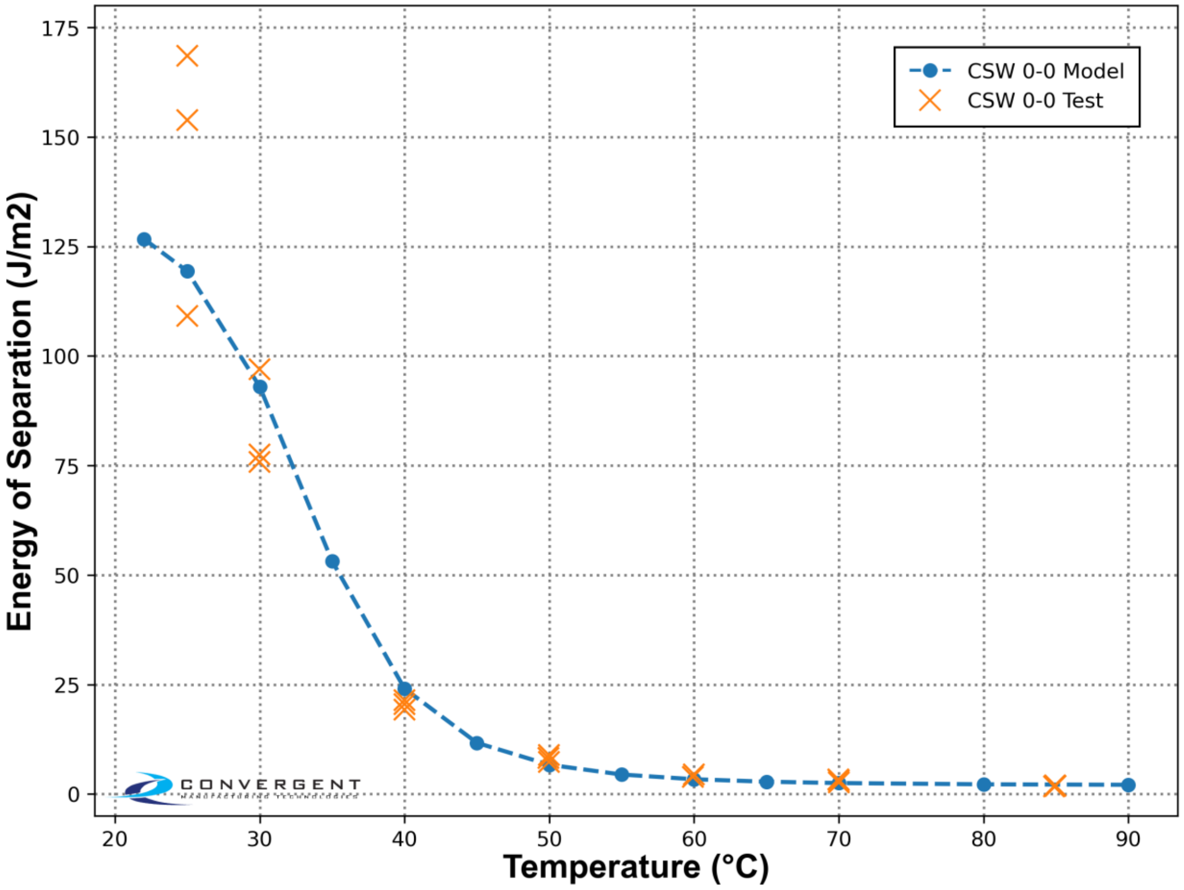
Viscoelastic Cohesive model for decohesion stage

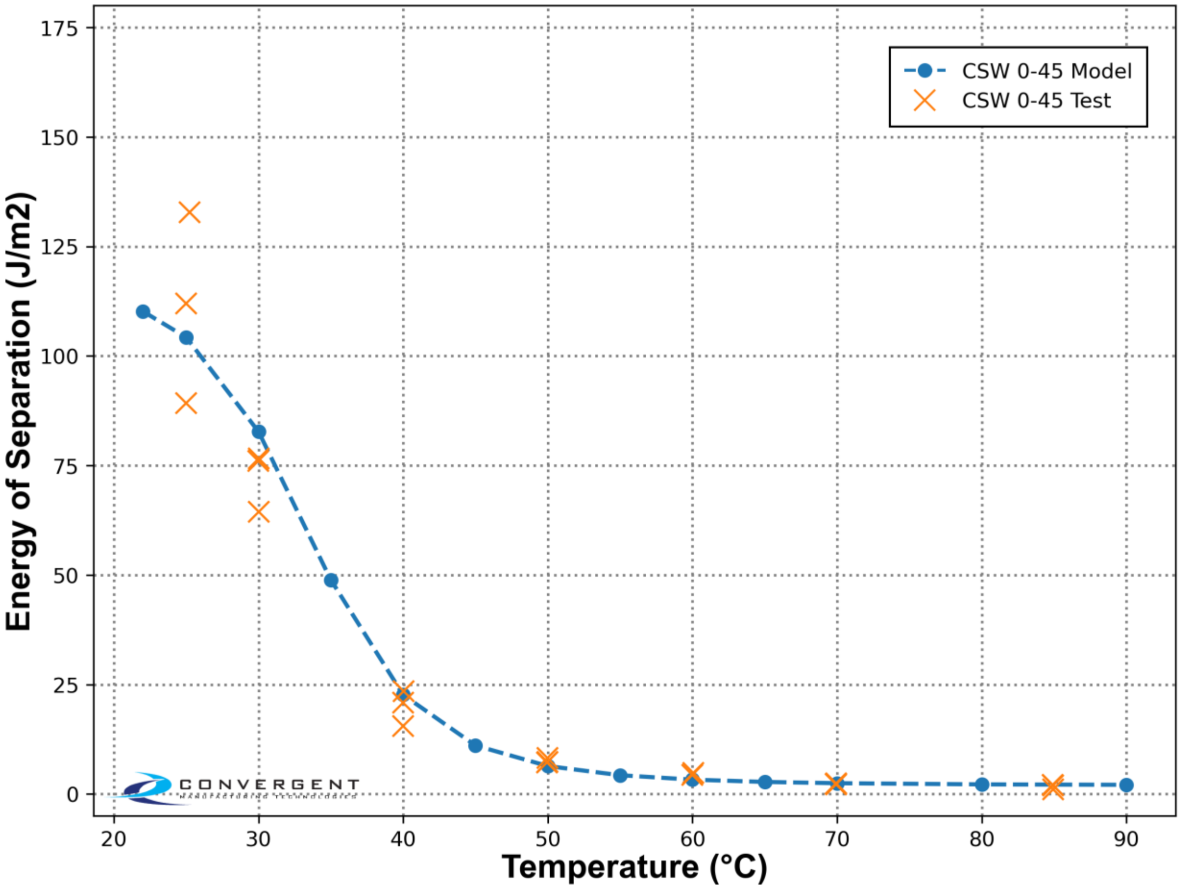
$$\sigma_{1u-r} = \sigma_{1u-r} e^{-\left(\frac{\Delta t}{\tau}\right)} + I(E_u - E_r)\left(\frac{\delta_n}{h}\right)\left(\frac{\tau}{\Delta t}\right)\left(1 - e^{-\left(\frac{\Delta t}{\tau}\right)}\right)$$

$$R = e^{-\left(\frac{(\delta - \delta_i)}{\delta_c}\right)^{\gamma}} \leq 1.0$$

Probe Tack

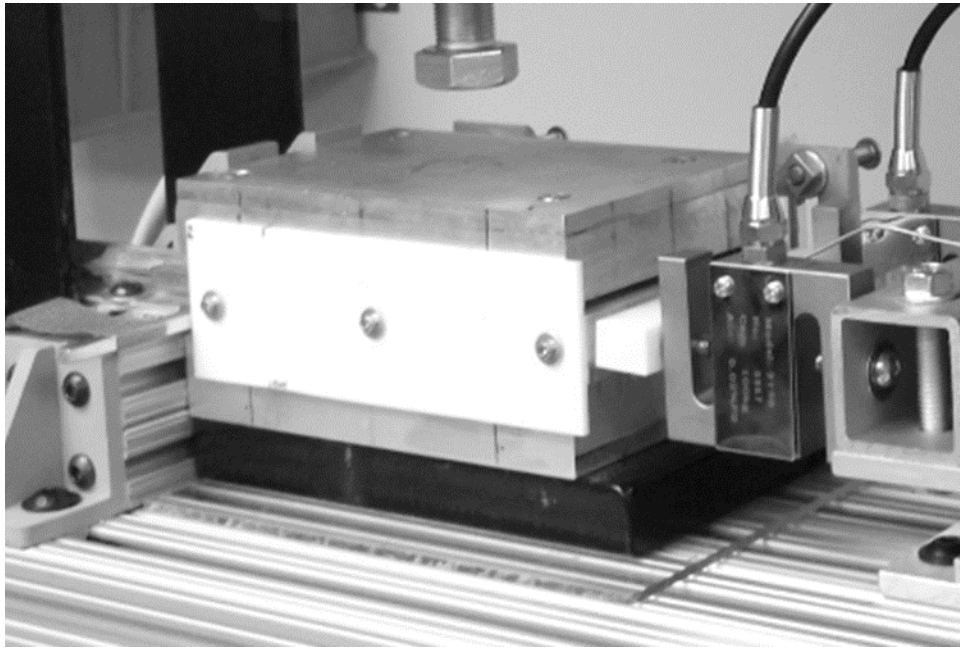
Model Fit Example

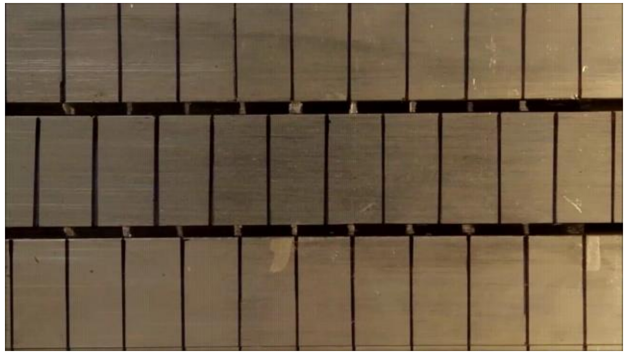




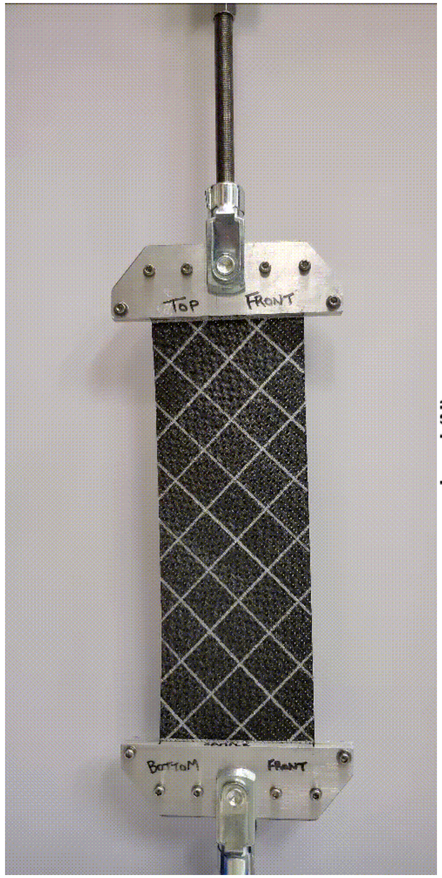
Shear Mechanisms

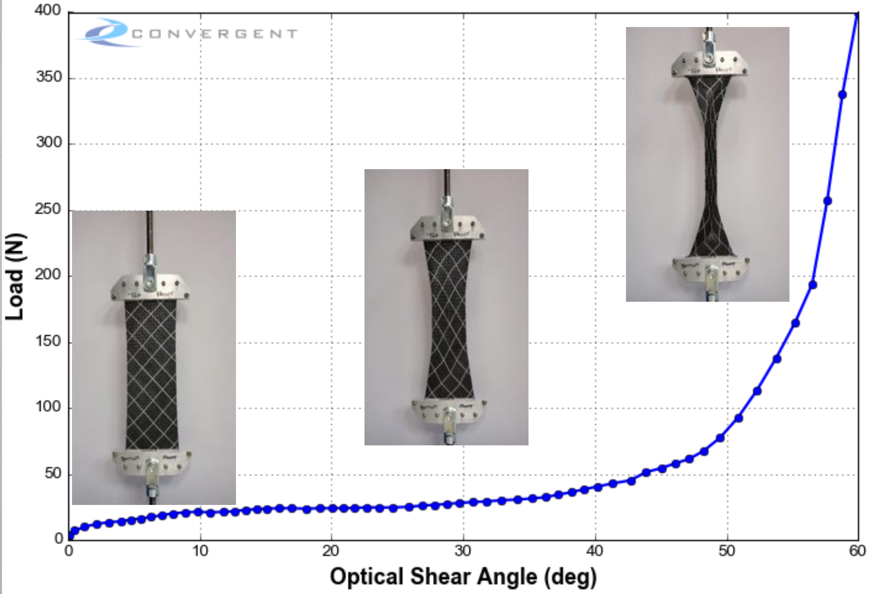
Transverse Shear





In-plane Fabric





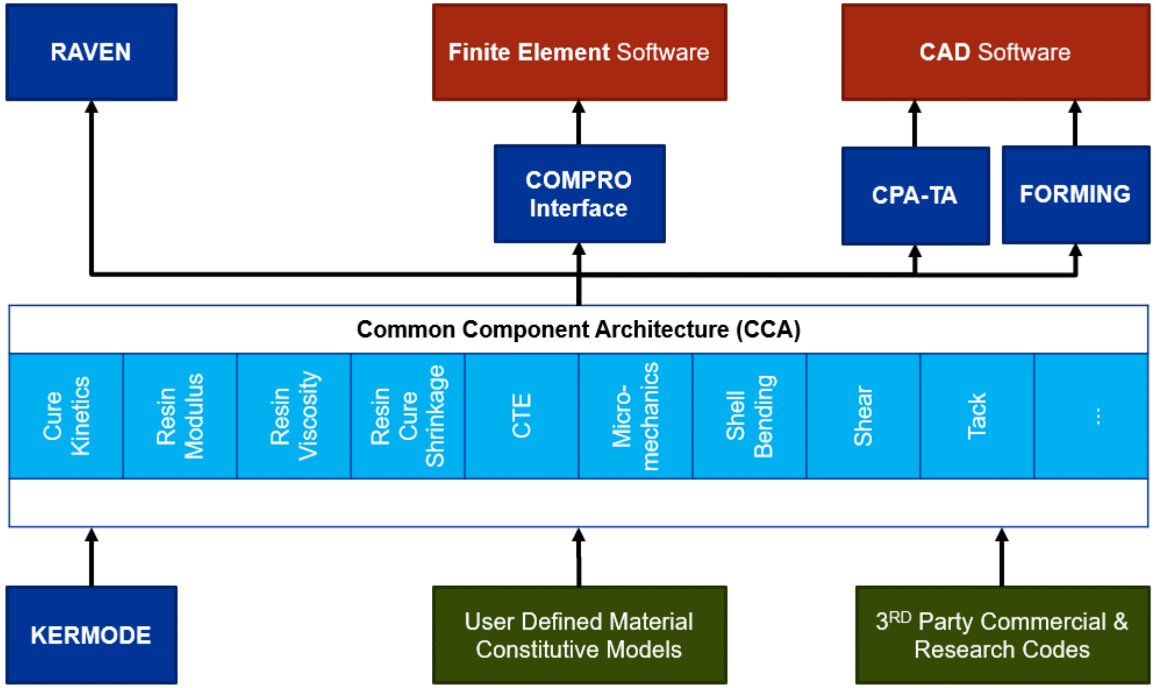
Common Component Architecture (CCA)

Comprehensive Library of Material Constitutive Models

State-variable based, expandable material model database

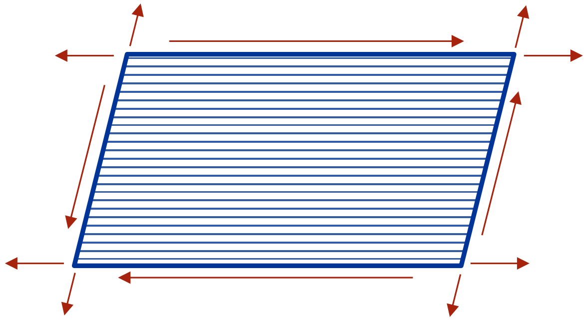
Integrated ***MATERIAL PROPERTIES***

- **140+** constitutive models
- Largest high-fidelity process simulation composite materials library anywhere:
  - **30+** open data sets
  - **10+** Distribution C data sets (created for and managed on behalf of the US Government)
  - **Many more** proprietary data sets created for customers
- Interlinked process parameters
- User-defined Constitutive Models

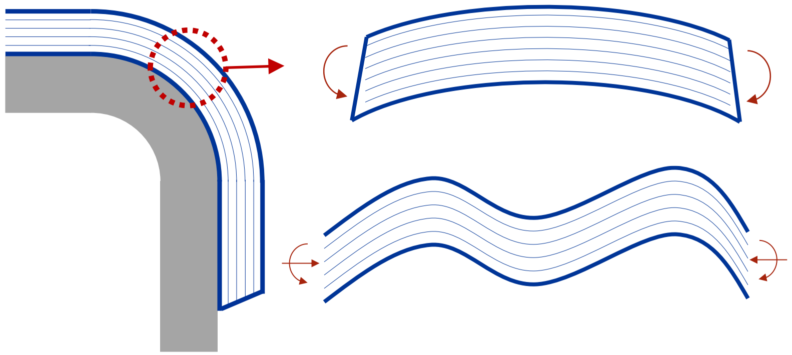


Simulation Framework

Shell Element

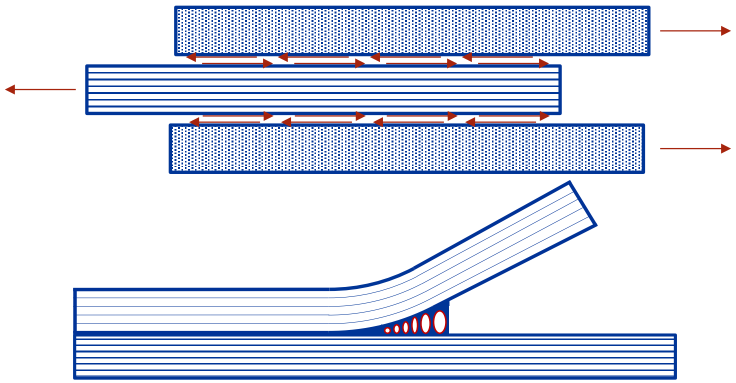


Ply In-plane: *A* stiffness

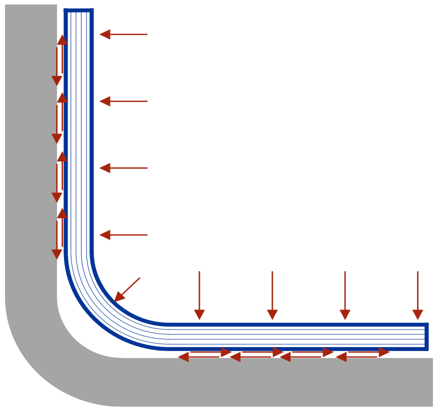


Ply Bending: *D* stiffness

Contact Algorithm

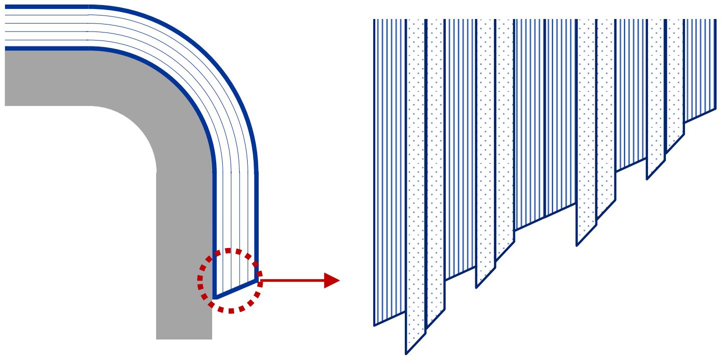


Interlaminar (friction, stick-slip, tack)

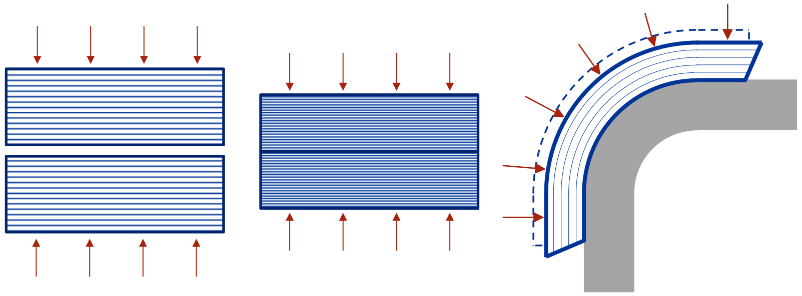


Tool-Part interaction

Solid + Shell Element †



Ply Transverse Shear & Logrolling



Debulk & Consolidation

† Silva et al, *Defect prediction during forming and consolidation of composite materials using finite element analysis,* ASC 34th Technical Conference, 2019

Forming Simulation Solution Levels

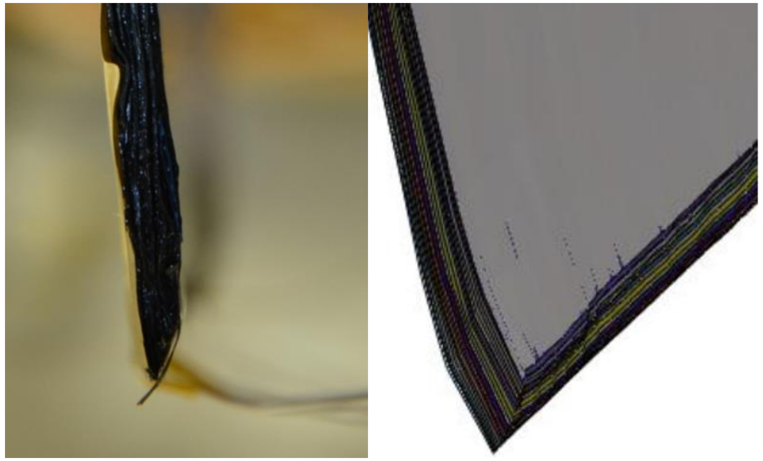
Solution Level	FE Representation	Application	Features	Solver	Computational Cost
1	Single Membrane	Dry fabric forming	Shear locking	Explicit	Fast
2	Ply-wise Shell	Hot Drape Prepreg Forming • Effect of temperature and evolving degree-of-cure/crystallization • Effect of forming rate	Level 1 + • In-plane / bending decoupling • Elastic/Viscoelastic behaviour • Temperature and DoC dependencies	Explicit	Fast to Moderately Expensive
3	Ply-wise Shell + PU Solid (optional thermal analysis coupling)	Cross-section Prepreg Forming • Level 2 + • Consolidation & wrinkling • Non-uniform temperature/cure	Level 2 + • Debulk and consolidation • Resin flow • Thermal predictions	Implicit Dynamic	Expensive

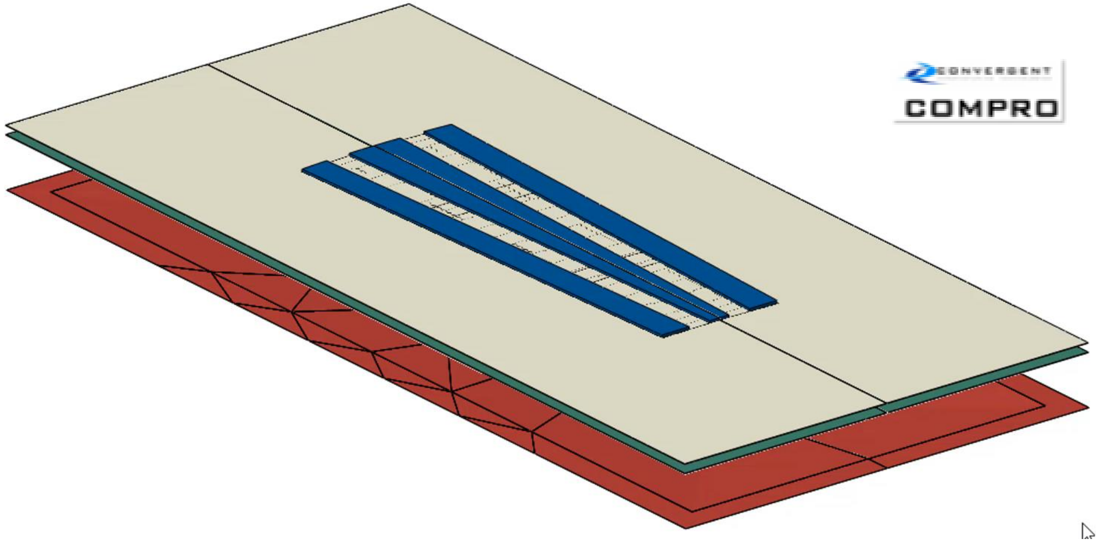
Shell-based Simulation

C-Channel Example

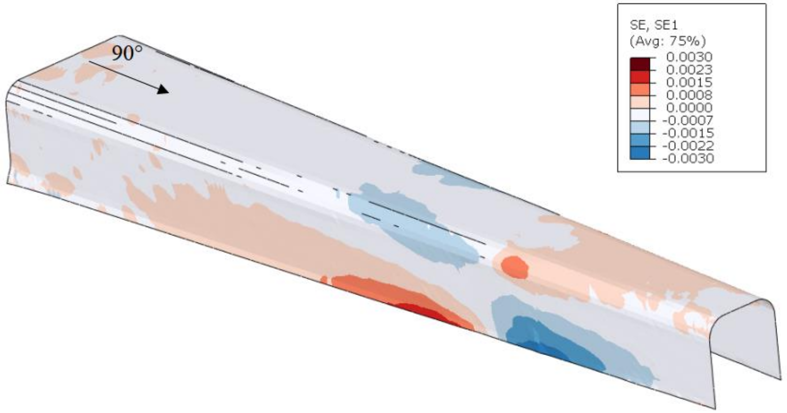
- Plies modelled using shells
- Inter-ply interaction through contact
- Representation of the tool, double bag/membrane, and stiffening elements

Bookending Effect





Fibre Axial Strains show tension and compression in joggle area



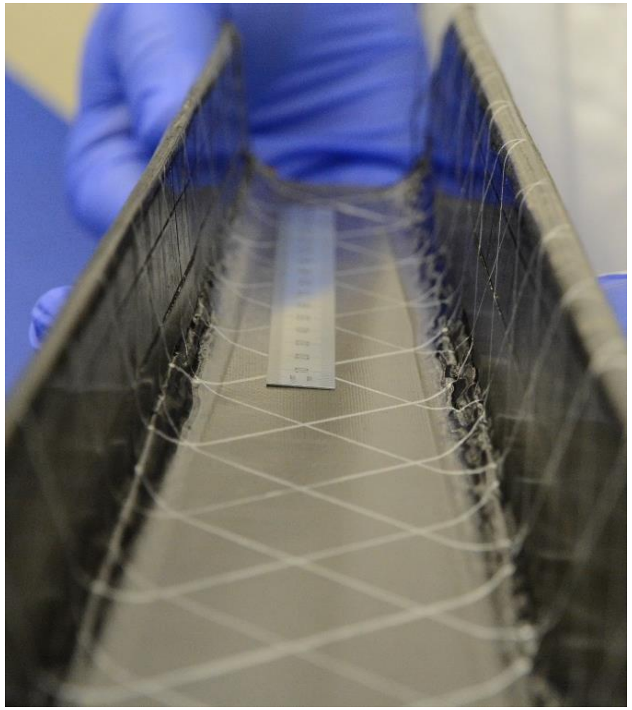
For more information see:
Silva et al (2023), A physics-based approach to composites forming simulation. Proceedings of SAMPE Seattle.

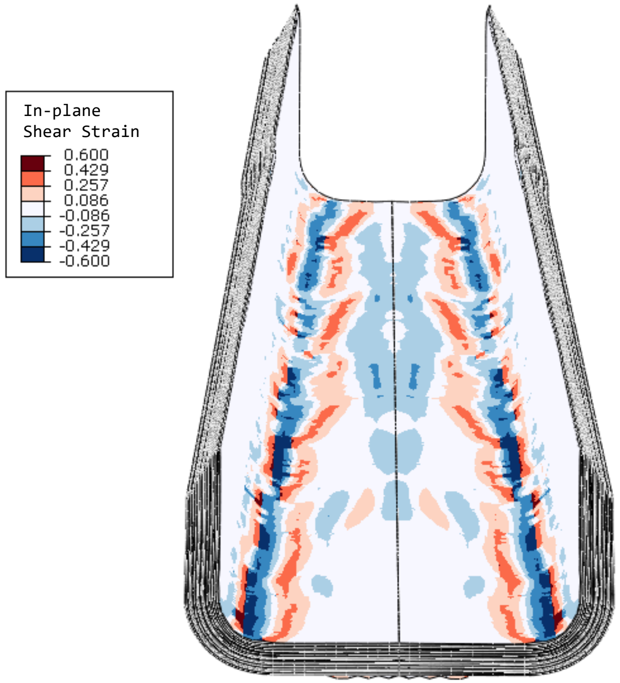
Shell-Based Simulation

C-Channel Example

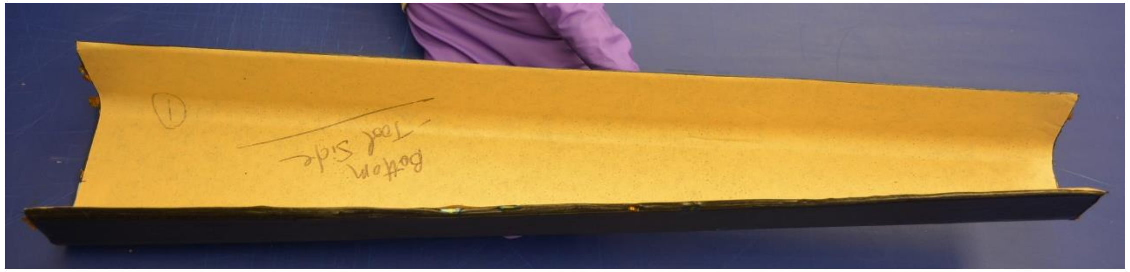
The room temperature forming process showed significant defects at the tool side of the corners

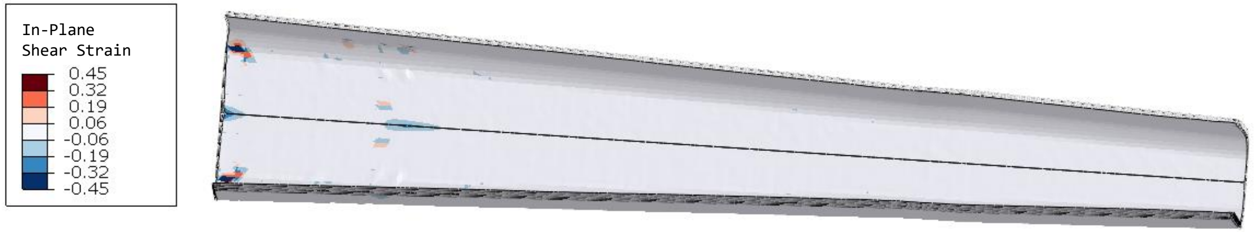
- Large predicted shear strains agree very well with experimental observations





At the optimal forming temperature, wrinkling at the corners is greatly reduced, as predicted by simulation



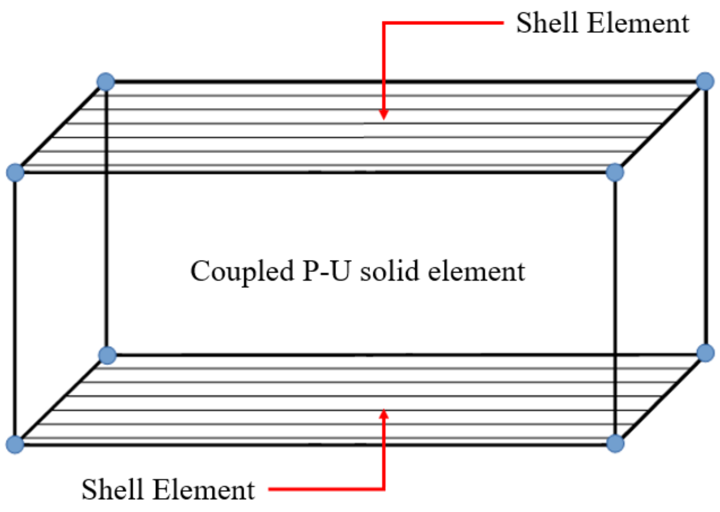


Shell + Solid Representation

Shell + Solid Sandwich

- Plies are discretized individually by a layer of solid elements superimposed with shell elements at the top and bottom surfaces
  - Solid element enables through-thickness deformation and Percolation Flow mechanisms
  - Shell elements are key to simulate ply buckling

- Contact interactions are defined between plies (optional)
- This approach can be used to predict forming and consolidation-driven ply movement and defects.
- Heat transfer analysis can be coupled as well.



Shell + Solid Representation

Solid Elements: Coupled Pore Fluid + Stress

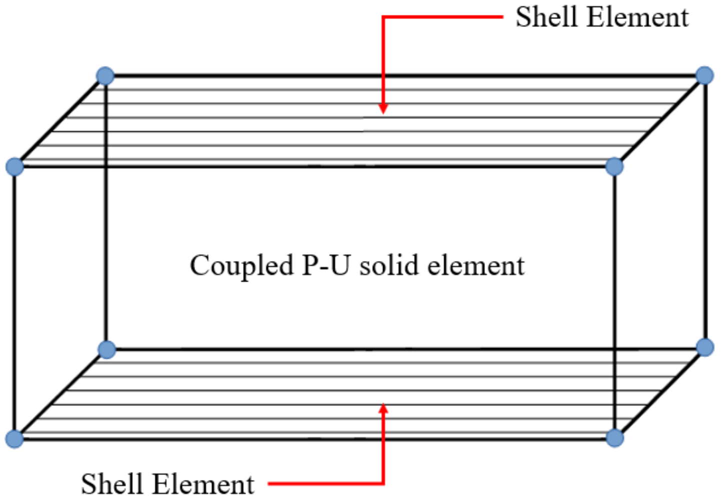
- Ply bulk and shear behaviours and resin flow
- Two-phase (skeleton, resin) element formulation with stress tensor given by:

$$\bar{\boldsymbol{\sigma}} = \boldsymbol{\sigma}_{SK} - p\boldsymbol{I}$$

- Added DOF: hydrostatic pressure of the resin phase (p)

- Resin flow governed Darcy's law:

$$q = \frac{K}{\eta} \nabla p$$



- Material Attributes:
  - Shear (G_{12}, G_{13}, G_{23})
  - Fiber bed compaction ($\sigma_{33} = f(\epsilon_{33})$)
  - Viscosity (η)
  - Permeability (K)

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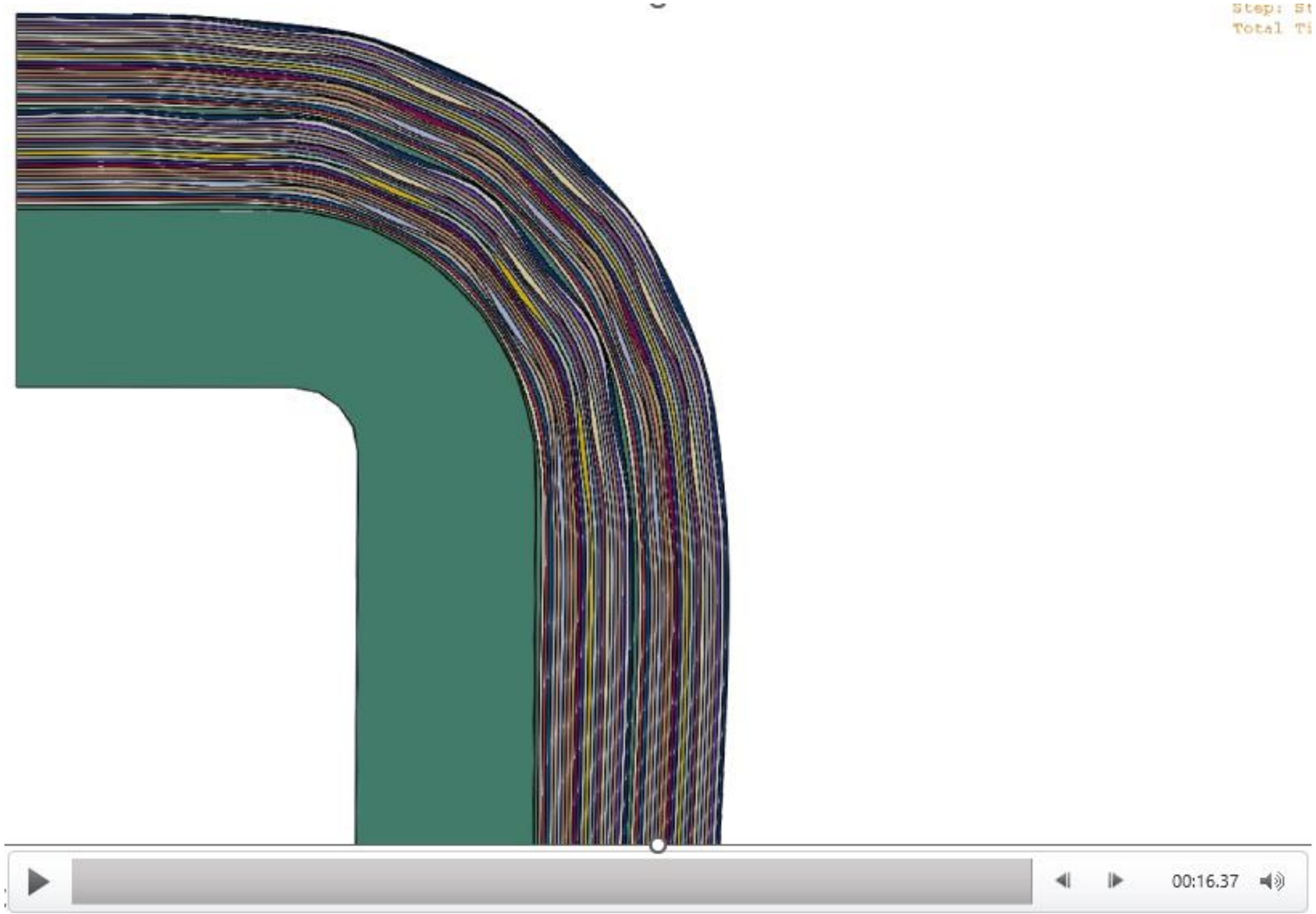
Shell + Solid Representation

Forming Simulation



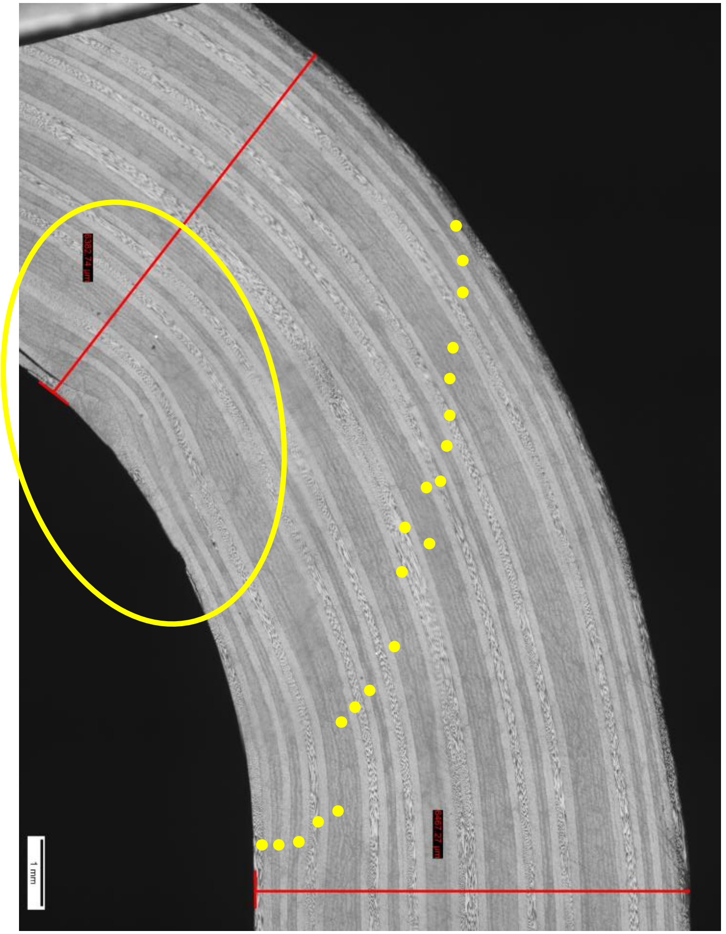
Shell + Solid Represeantation

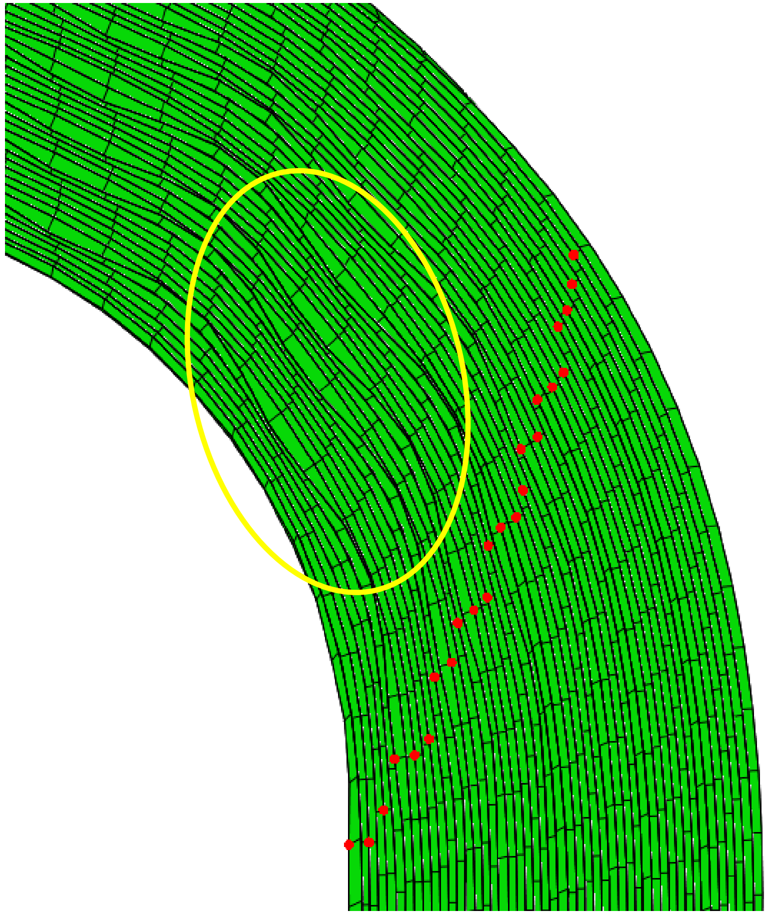
Ply Movement and Wrinkle Prediction

48-ply laminate formed using double diaphragm forming at room temperature

- Comparing shear pattern and wrinkle formation

Micrograph images provided by NRC

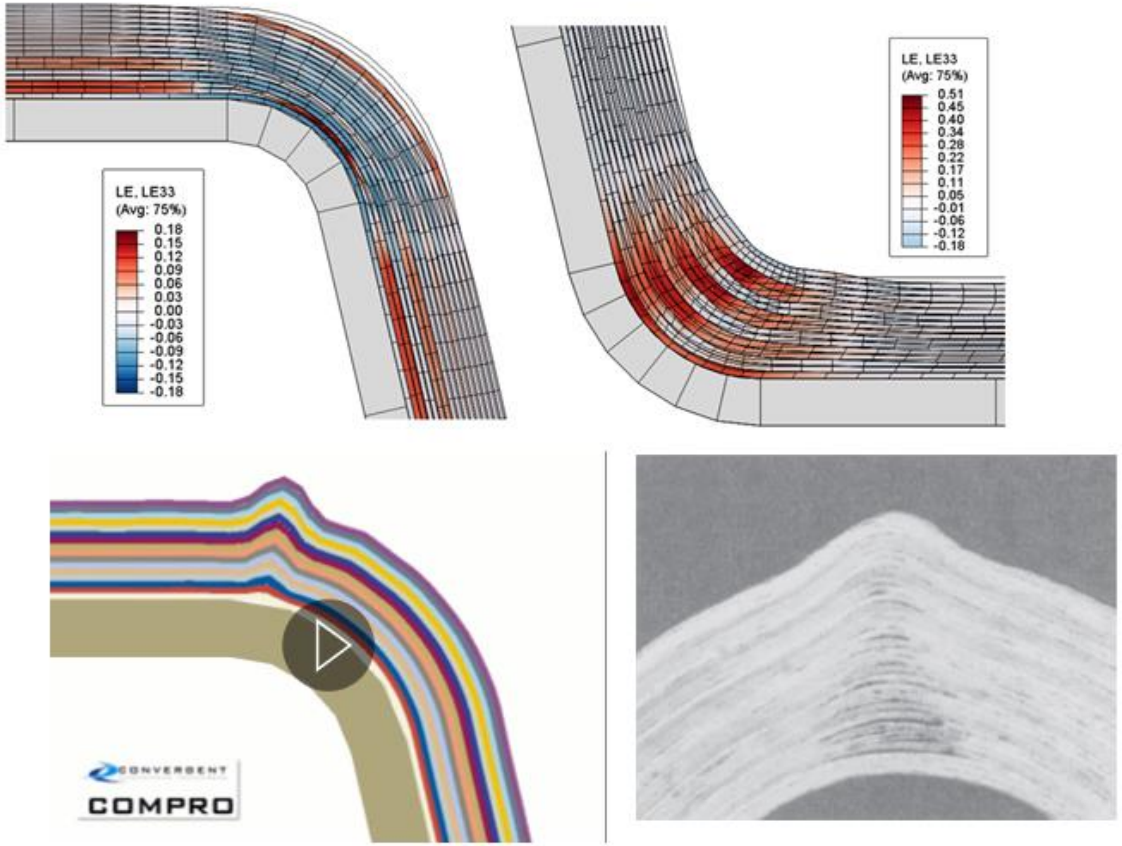




Shell + Solid Representation

Consolidation-Driven Wrinkles

- Curved sections generate pressure differentials between tool-side and bag-side surfaces of the laminate:
  - Convex corners lead to higher pressure and corner thinning (resin outflow)
  - Concave lead to lower pressure and corner thickening (resin inflow)
- As the laminate consolidates over a convex corner, the radius of the outer plies is reduced leading to excess fibre length.
- This excess length must be sheared out through either inter-ply or inter-ply shear mechanisms to avoid defects:
  - Consolidation simulation with constrained edges prevents shearing, thus leading to ply buckling.



Concluding Remarks

- A comprehensive framework for forming characterization and simulation was presented:
  - Key deformation mechanisms were identified.
  - Characterization tests were developed for uncured prepreg (Bending, Shear, Tack, …).
  - Physics-based material constitutive models were developed to fit the observed data.
  - Finite Element Simulation framework developed at various levels:
    - Shell-based representation suitable for forming simulation
    - Shell + Solid representation suitable for modelling forming and consolidation
  - Accurate representation of the tool, forming apparatus and boundary conditions are essential for a high-fidelity forming simulation
  - It was shown that ply deformations and defects generated in FE simulations are consistent with observations of the experimental trials.