MODELING THE STRAIN SOFTENING BEHAVIOR OF ALIGNED DISCONTINUOUS FIBER PREPREG DURING THERMOFORMING

UNIVERSITY OF DELAWARE | CENTER FOR COMPOSITE MATERIALS

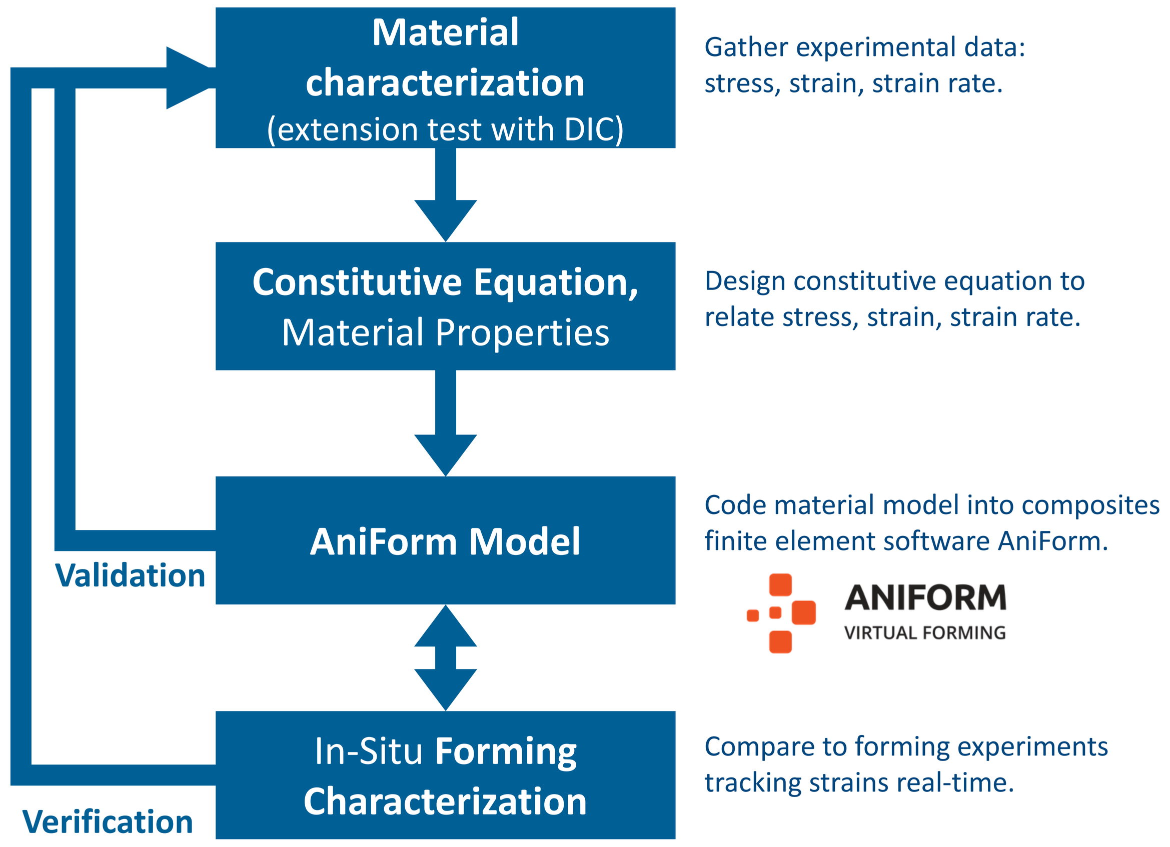
Andrew Stack, (MME)[1,2], Dr. Pavel Simacek[1,2], Kyle Morris, MMS[1,3], Dr. Tom Cender[1,2], Prof. Suresh Advani[1,2]

University of Delaware | Center for Composite Materials[1] | Department of Mechanical Engineering[2] | Department of Materials Science and Engineering[3]

Introduction

- **TuFF** is a highly-aligned chopped fiber prepreg. [1]
- Fibers can slide past one another, allowing for stretch when matrix is fluid.
- **Stretching unlocks complex geometries** in high-rate thermoforming while keeping high, aerospace-grade properties.
- Modeling the thermoforming behavior finds process conditions without using many resources.

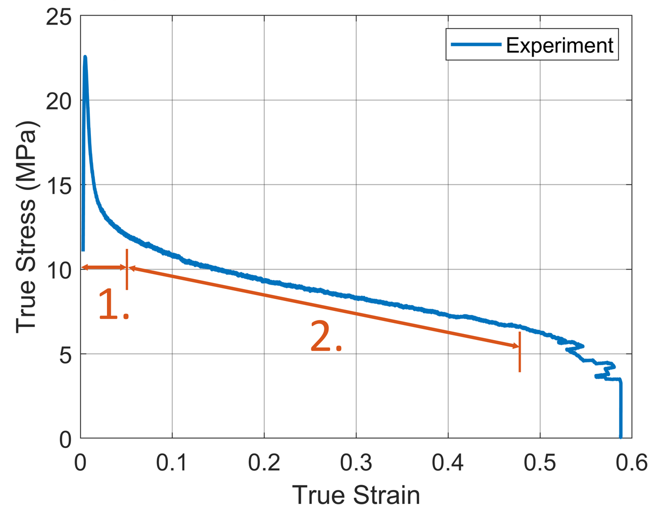
Problem: Develop a finite-element material model for TuFF.



Material Characterization

- **Extension experiments** were performed at varying temperatures, strain rates. [2]
- Stress-strain data shows **two distinct phases**: a peak (1.) and long-term softening as strain increases (2.).

Example shown: 40°C, $\dot{\varepsilon} = 0.001$ s^{-1}



Constitutive Equation

- **Viscous equation** with aligned fiber array magnification [3] was modified with **strain softening component:**

$$[\sigma]_{3x1} = \eta_{resin} * \left(1 - \frac{\varepsilon_{11}}{\varepsilon_{max}}\right)^{A} * [C]_{3x3} * [\dot{\varepsilon}]_{3x1}$$

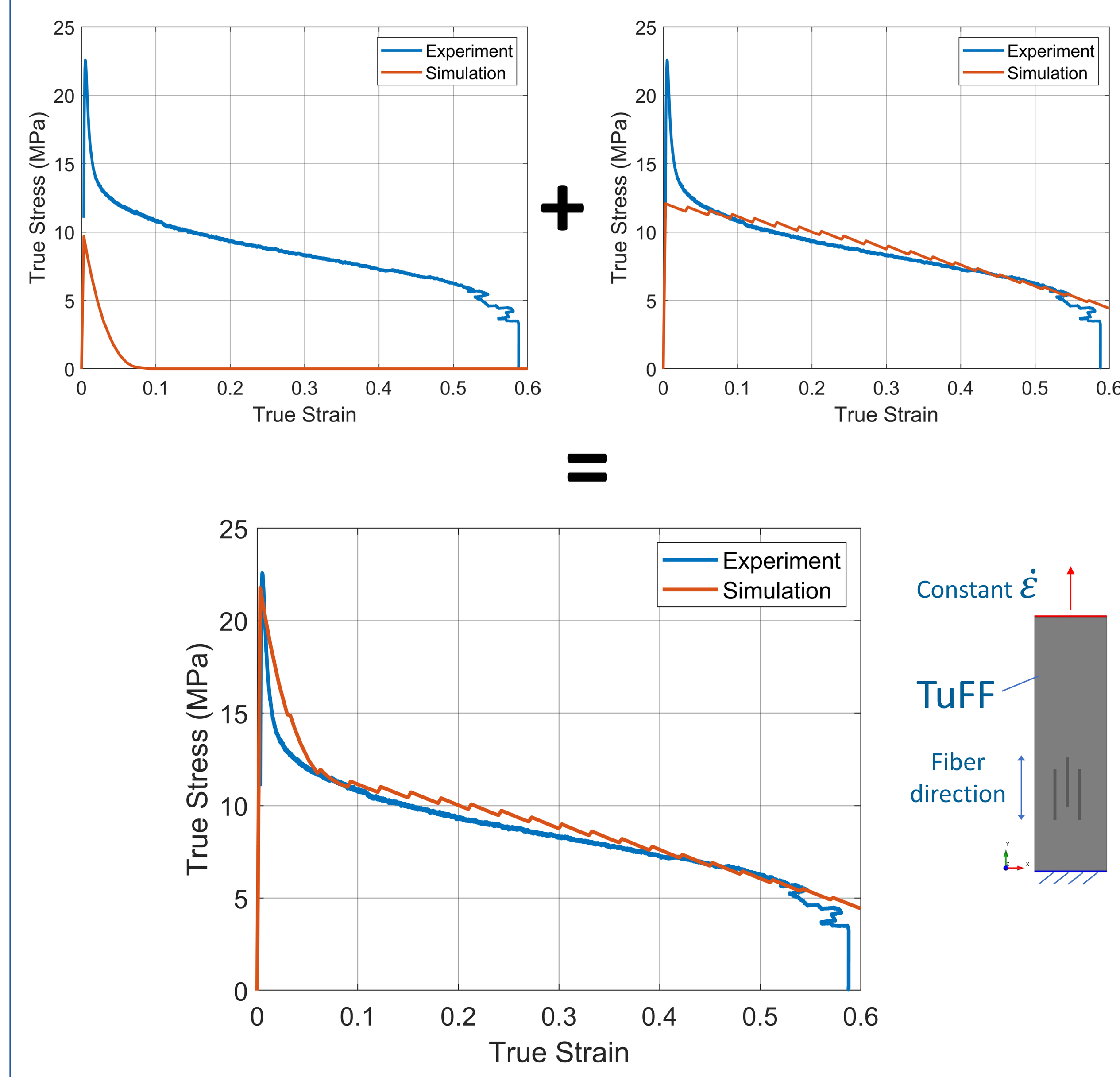
Stresses | Resin viscosity | Strain softening component | Directional magnification factors | Strain rates

- Single use of equation and input set describes one phase.

AniForm Model

- **Constitutive equation was coded into AniForm** user-defined material model.
- Extension tests were modeled, and results were compared to original data.

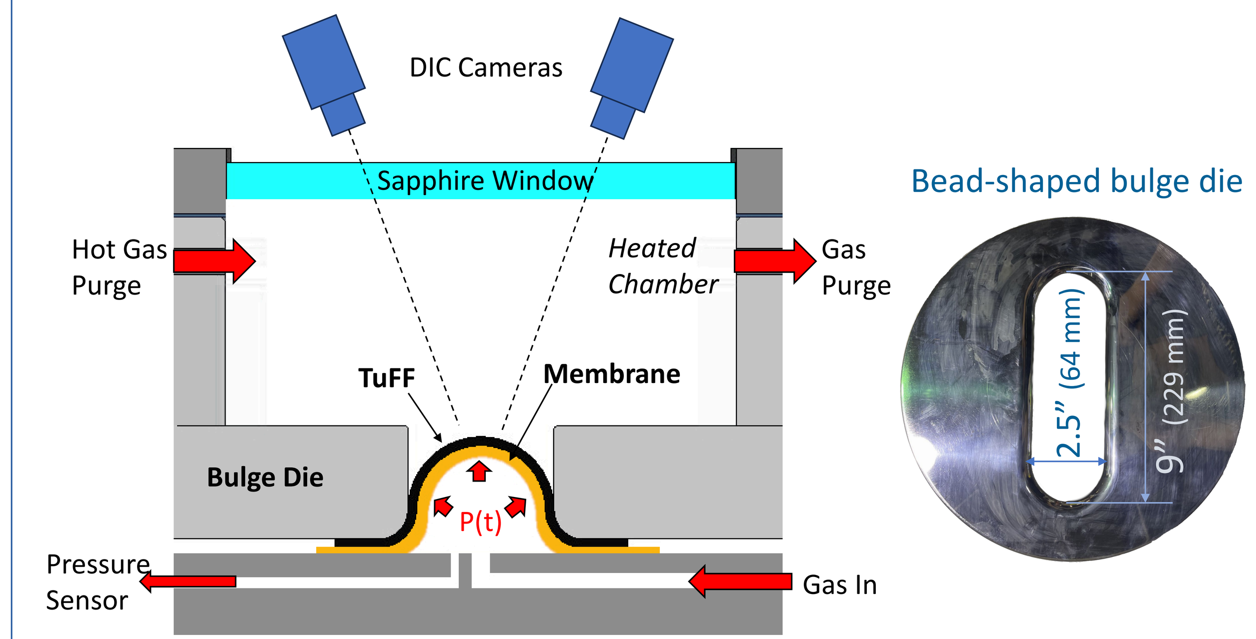
Example shown: 40°C, $\dot{\varepsilon} = 0.001$ s^{-1}



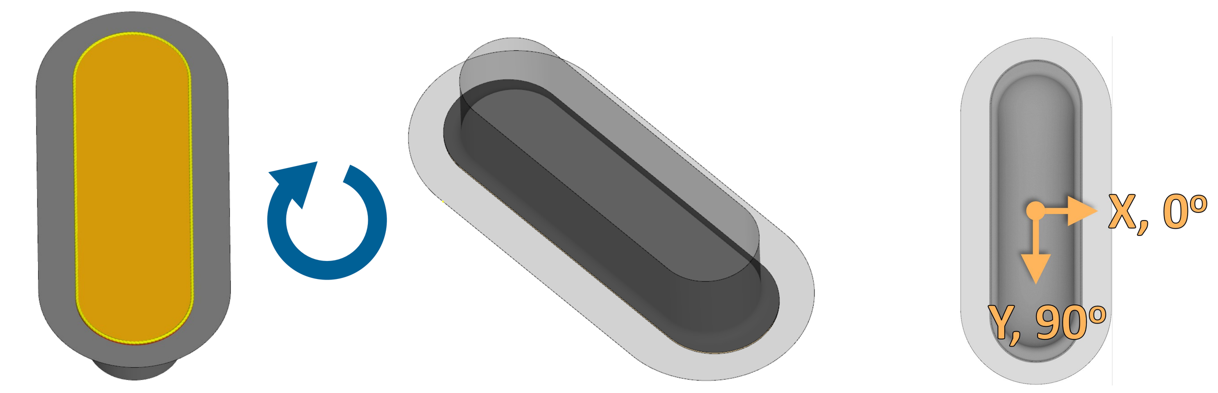
- Models of the peak and long-term softening were **added in superposition** to capture full curve.
- Comparison shows close match, **verifying the model.**

In-Situ Forming Comparison

- **Gas-pressure forming** in laboratory setup allows for digital image correlation (DIC) tracking of strains over time on outermost ply.
- **Laminates** of [0/90]$_S$ and [90/0]$_S$ **were formed** with T = 40°C, P = 16 psi.



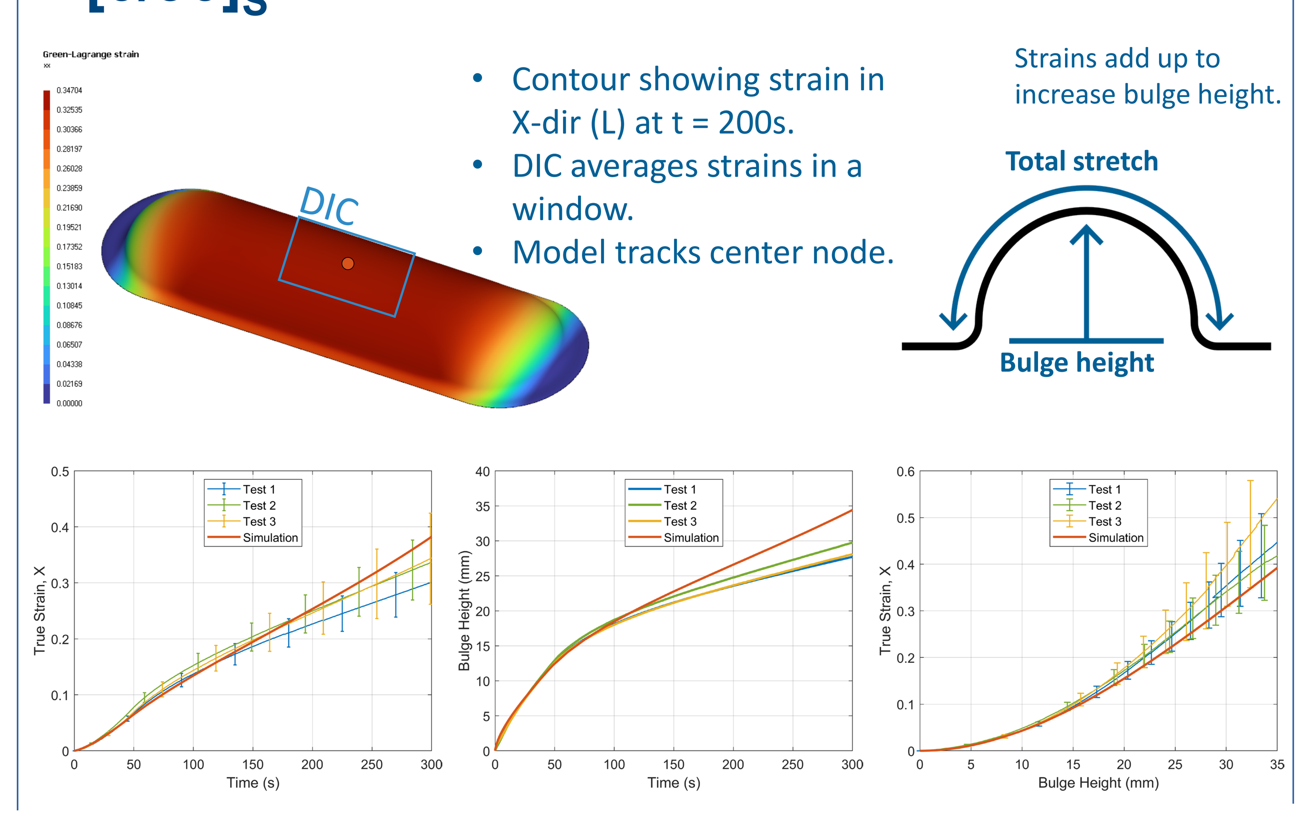
- Forming setup was **modeled in AniForm:**



Computationally-efficient model was constructed | Setup is oriented the same as experiments. Data tracked in the center node. | Coordinate system

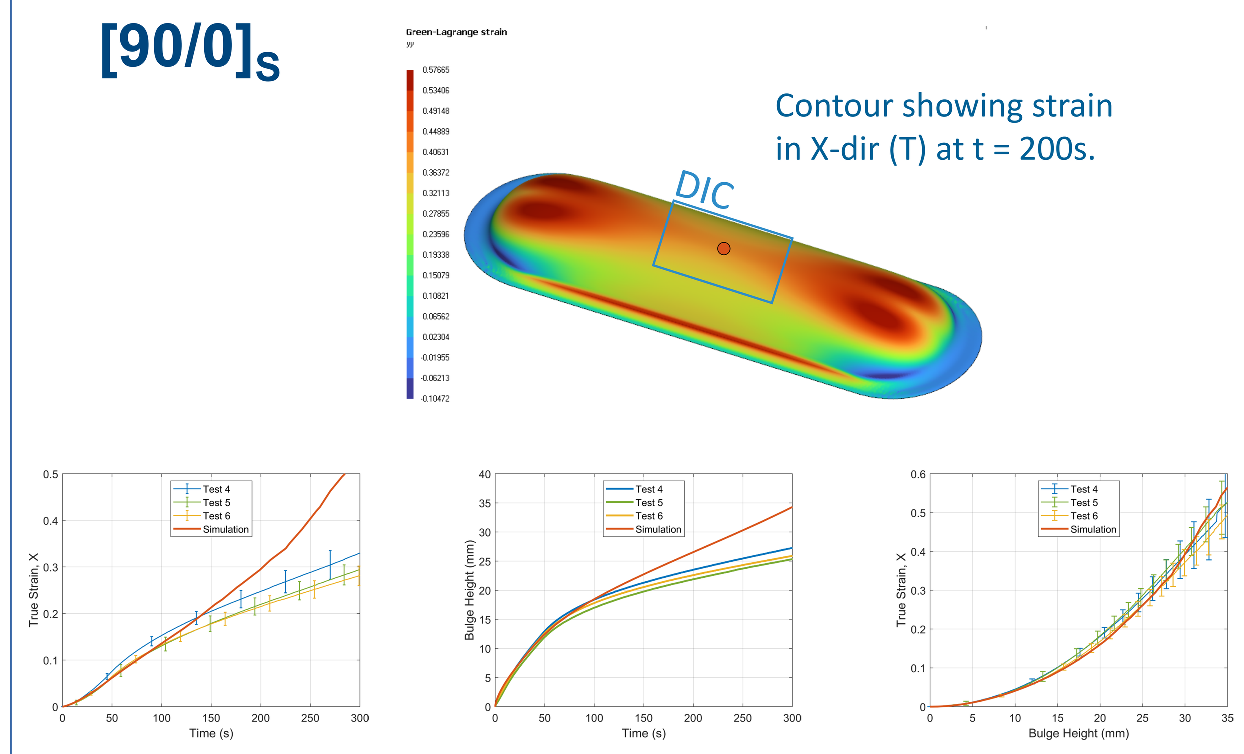
- Local **strain** and overall **bulge height** vs. **time** were compared between experiments and simulation:

[0/90]$_S$



- Longitudinal **strains and bulge height over time showed good correlation** until 250 sec, around 0.3 true strain.

[90/0]$_S$



- Transverse strains, bulge height **showed** good correlation until 200 sec.
- Well-matching ratio of local strain to bulge height (right figure) suggested experiment was stiffer than expected
  - Consistency in material batches being investigated.
- Strain nonuniformity can develop due to very low transverse viscosity and weak ply-ply interface.
  - Shearing and bending caused local strains where 0° ply's higher viscosity resisted.
  - Same nonuniform pattern developed in experiments.

Conclusion: Model of TuFF's thermoforming behavior shows positive development.

References

1. Tierney J, Vanarelli A, Heider D, Yarlagadda S, Gillespie Jr., JW. Aligned discontinuous fiber preforms, composites and systems and processes of manufacture. US. Patent 10,669,659 B2; June 2, 2020.
2. Tomlin, L. J., Cender, T. A., Sauerbrunn, S., & Advani, S. G. (2024). Methodology to establish a forming process window for thermoset aligned discontinuous fiber composites. *Composites Part A: Applied Science and Manufacturing*, *180*. https://doi.org/10.1016/j.compositesa.2024.108064
3. Beaussart, A. J., Hearle, J. W. S., & Pipes, R. B. (1993). Constitutive relationships for anisotropic viscous materials. Composites Science and Technology, 49, 335–339.

Acknowledgements

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