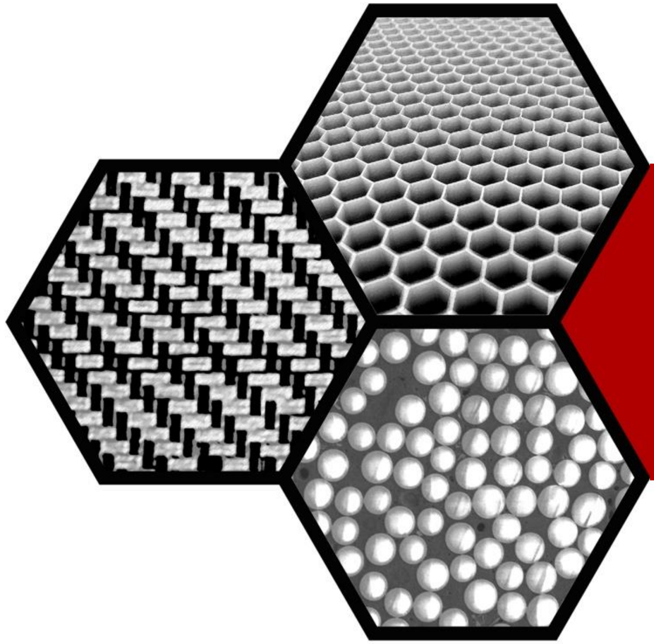

PROCESS MODELING OF THE CO-CURE OF HONEYCOMB CORE SANDWICH STRUCTURES

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Monthly Formal Teleconference
30 March 2018

Project Overview

Physics-Based Modeling of the Co-Cure of Honeycomb Core Sandwich Structures

Long-Term Goal
Develop a physics-based model that allows assessment and optimization of co-cure for aerospace structures

Additional Goals
- Clarify and expand the community's understanding of co-cure processes
- Develop diagnostic tools that enable process analysis and optimization
- Produce guidelines for successful co-cure of honeycomb sandwich structures


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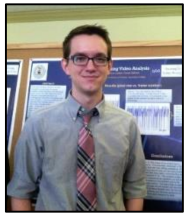
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Project Term: Phase 1 11/01, 2015 – 10/31, 2017
Phase 2 11/01, 2017 – 10/31, 2019

Timeline

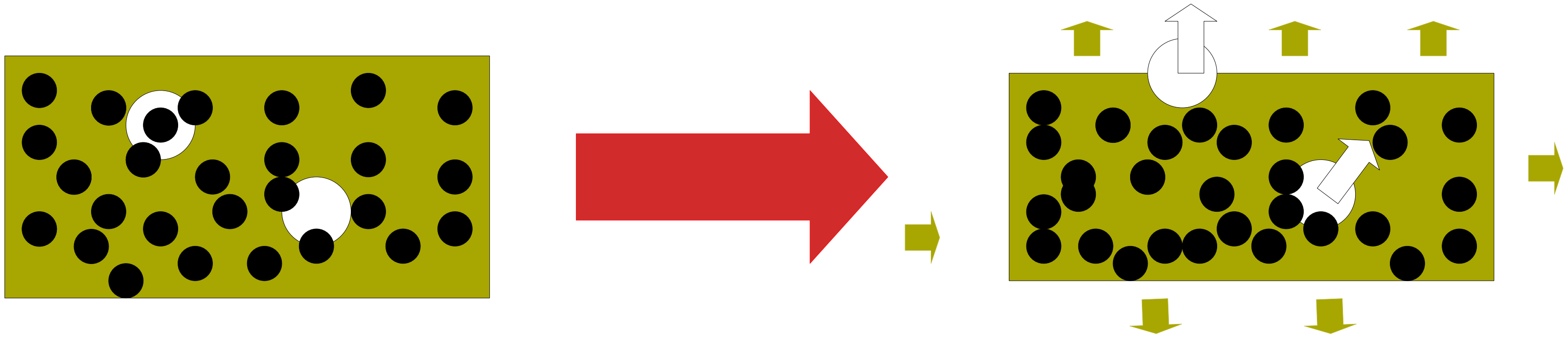
Phase	WORK PACKAGE	YEAR 1				YEAR 2				YEAR 3				YEAR 4			
Phase I	**WP1**																
	1.1 Prepreg	✓	✓	✓	✓	▲ M1.1 ✓											
	1.2 Film Adhesive	✓	✓	✓	✓	▲ M1.2 ✓											
	1.3 Honeycomb Core (E+M)	✓	✓	▲ M1.3 ✓													
	WP2																
	2.1 Governing Equations	✓	✓	✓	✓	✓	✓	✓	✓	▲ M2.1							
	2.2 Lab-Scale Studies	✓	✓	✓	✓	✓	✓	✓	✓	▲ M2.2							
Phase II	**WP3**																
	3.1 Numerical Implementation			✓	✓	✓	✓	✓	✓	✓	✓			▲ M3.1			
	3.2 Lab-Scale Studies									✓	✓						
	3.3 Demonstrator Studies													▲ M3.2			
	WP4																
	4.1 Model Refinement																M4.1 ▲
	4.2 Demonstrator Studies																

M3.1 Implement governing equations within numerical process simulation
M3.2 Validate numerical process simulation using demonstrator case studies

Today's Update

- **Model Development – Facesheet Consolidation**
  - Modeling update
  - Validation details
- **Model Development – Permeability**
  - Modeling update
- **Next Steps – Thoughts**
  - Porosity modeling
  - Model integration
  - Material implementation
  - Validation

Consolidation Problem



- **Fiber Bed with Resin and Porosity f**
- **Fiber Volume Fraction v_f**
- **Reference Frame Fixed to Fiber Bed**
- **Dissolved Volatiles Concentration *c***

Fiber Bed Deforms with Strain e

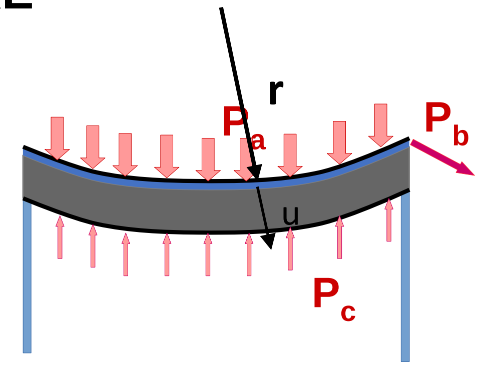
(Linear Strain May Suffice)

- **Resin Flows Relative to Fiber Bed**
- **Volatiles Move Relative to Fiber Bed**
- **Volatiles Move Relative to Resin (Mobility Tensor U)**
- **Volatiles Dissolve in Resin**
- **Volatiles Diffuse, Too**

1D Consolidation Problem – Governing Eqs.

ASSUMING INSTANT DISSOLUTION : $c = K_h p$

THE EQUATIONS FOR DISPLACEMENT, RESIN PRESSURE AND POROSITY ARE



Momentum

$$E_r.u' - E_t\frac{u}{r} + r(E_r.u' - p)' = 0$$

Resin Conservation

$$\frac{\partial u/\partial t}{r} + \frac{\partial u'}{\partial t} - \frac{\partial \phi}{\partial t} = \frac{1}{r}\left(r\left(\frac{K}{\eta}p'\right)\left(1 - \frac{\phi}{1 - v_f}\right)\right)'$$

Volatile Conservation

$$m_m\frac{\partial\left(\frac{p\phi}{RT}\right)}{\partial t} + \frac{\partial\left(K_h\rho p\left(1 - v_f - \phi\right)\right)}{\partial t} = \frac{1}{r}\left(rU\frac{K}{\eta}p'm_m\frac{p\phi}{RT}\right)' + \frac{1}{r}(rJK_hp')'$$

Approach to Solution

- SOLVE FOR CONVENTIONAL COMPACTION WITHOUT POROSITY FOR CONSTANT MATERIAL PROPERTIES (FULLY IMPLICIT)
  - FIRST TWO EQUATIONS ONLY
- ADD VARIABLE MODULI AND PERMEABILITY USING EXPLICIT CONSTANTS WITHOUT POROSITY TRANSPORT
  - FIRST TWO EQUATIONS ONLY
- ADD POROSITY TRANSPORT BY STAGGERED SOLUTION AND EXPLICIT CORRECTION FACTOR IN PREVIOUS SOLUTION
  - IN PROGRESS

Transient Solution for Non-Lin. Material (Time Step)

Linear Case

$$\begin{bmatrix} u \\ p \end{bmatrix}^{n+1} = \boldsymbol{K}^{-1} . \boldsymbol{F}\left(\begin{bmatrix} u \\ p \end{bmatrix}^{n}\right)$$

F is Linear

Non-Linear Case

$$\begin{bmatrix} u \\ p \end{bmatrix}^{n+1} = \boldsymbol{K}^{-1}\left(\begin{bmatrix} u \\ p \end{bmatrix}^{n}\right) . \boldsymbol{F}\left(\begin{bmatrix} u \\ p \end{bmatrix}^{n}\right)$$

u: Radial Displacement
p: Resin Pressure

Without Porosity Transport

Linear Material Allows Implicit Formulation.

Non-Linear Material and 1st Order Euler Time Stepping Suitability (No Real Time Step Limits):

1. Kožený Karmán Permeability
2. Linear Modulus of Elasticity
3. Non-Linear Modulus of Elasticity by Gutowski (Sandwich)

The Same with TVD-RK3 Time Stepping

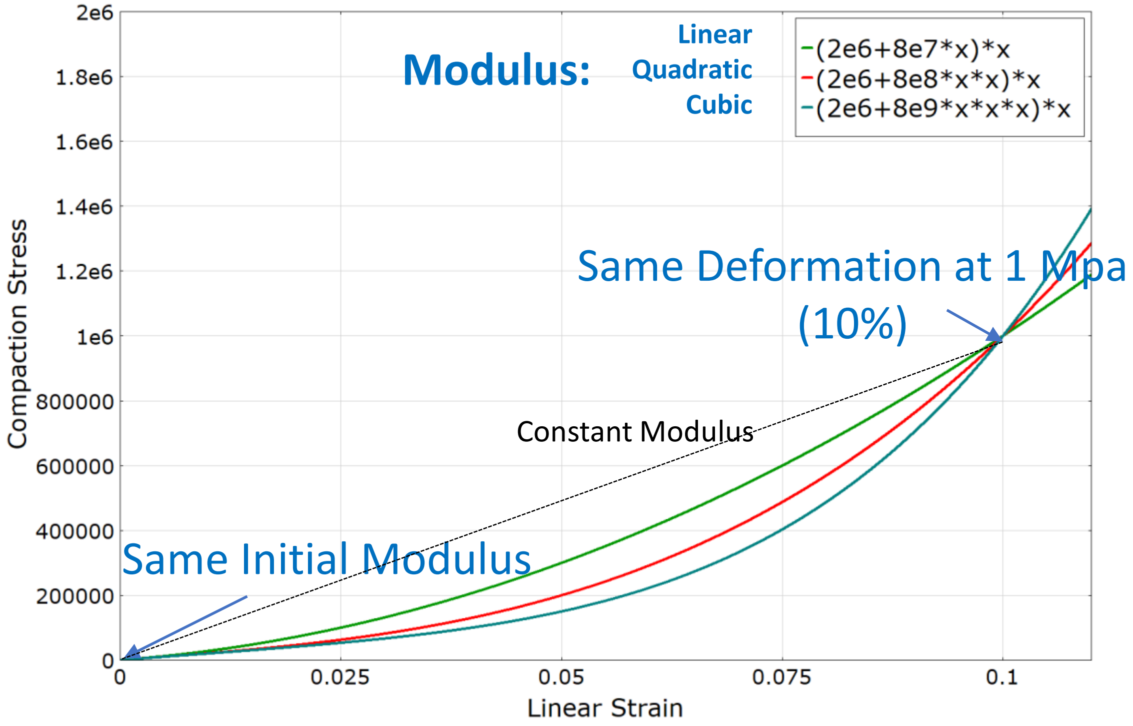
1. Quadratic Modulus of Elasticity Works Without Time Limits

Non-Linear Approach Does Not Work (Or with Unbearable Time Limits):

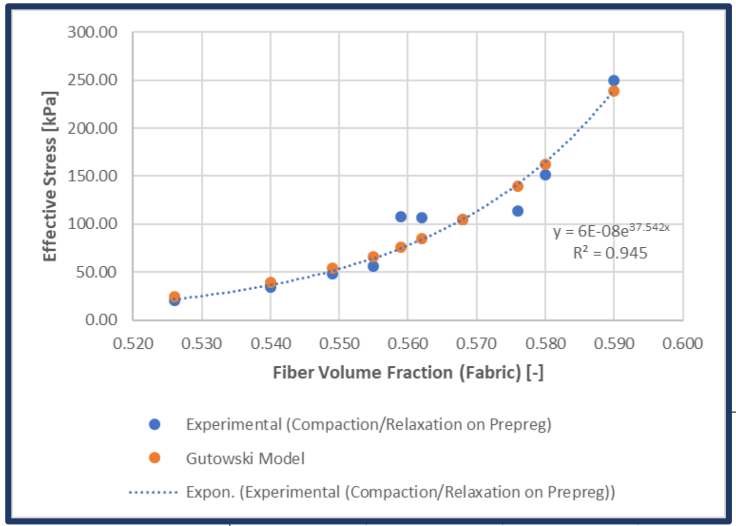
1. Cubic Modulus of Elasticity

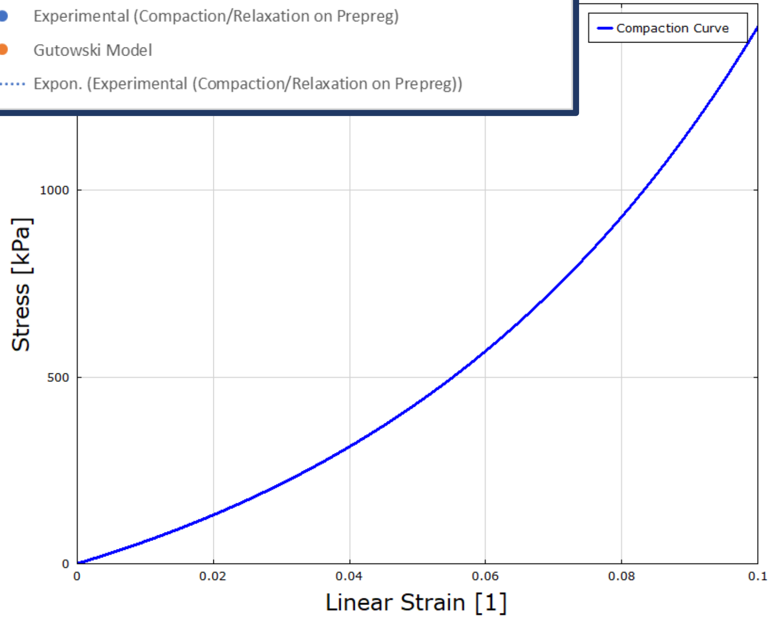
Material Non-Linearity: Transverse Modulus

Theoretical Stress-Strain Curve(s)



Measured Stress-Strain Curve



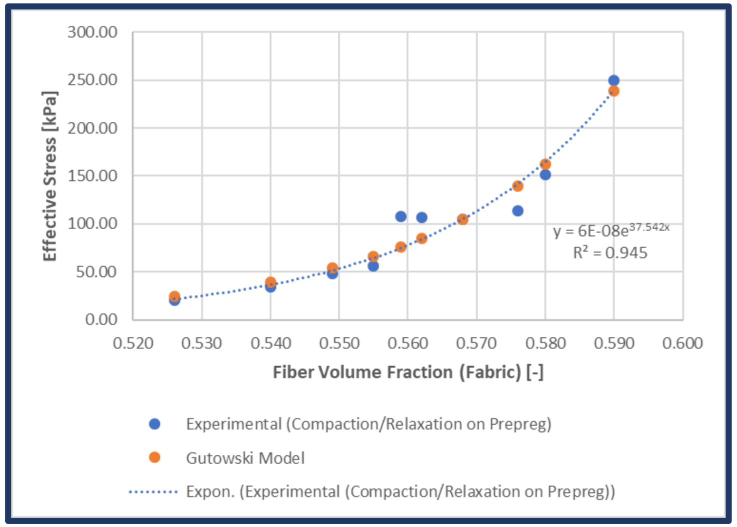


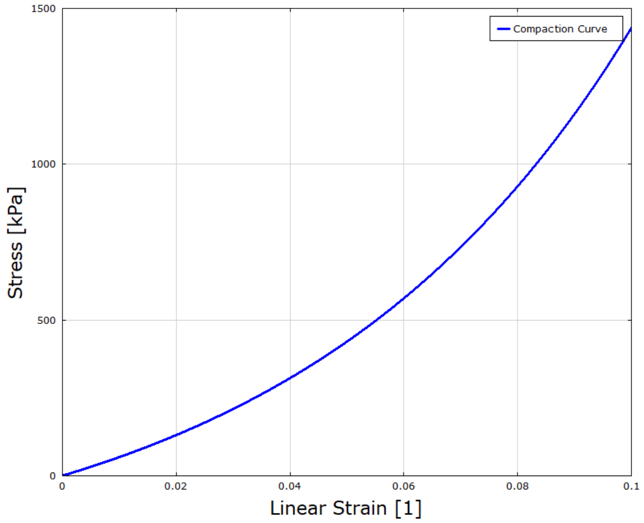
Notes:

1. **Compaction Work at UD Involved Glass Preforms**
2. **Higher Non-Linearity Complicates Numerics**

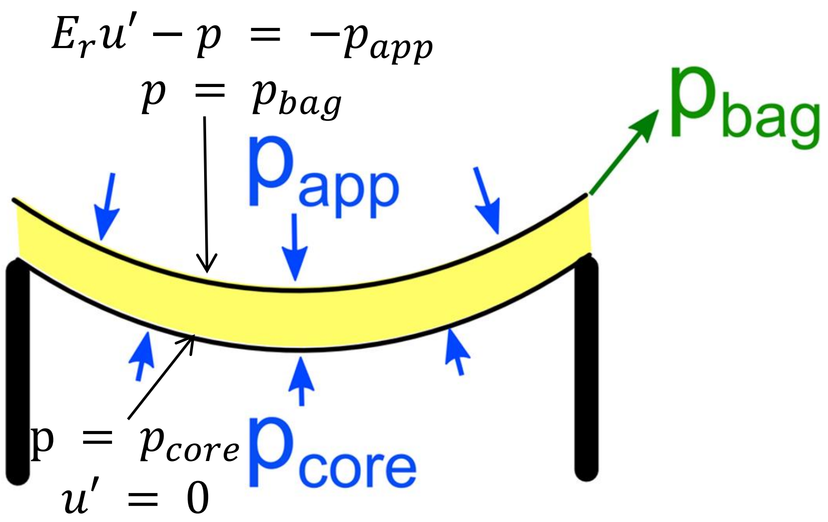
Sample Panel Comparison Details: Material Model

- Prepreg Data Came from Different Material
  - Low Pressure (We went to 377 kPa in Comparison Panels)
  - More Modest Fiber Content (53-59%)
- Fit Modified to Stress-Strain Form
  - Works OK in the Code as Is
  - Non-Linearity not Very Strong
  - Similar to Linear Modulus Dependency
  - May be OK for Co-Cure as the Pressure is Limited





Other Material Data Used in “Comparison”



Thickness=2 mm
Outer Radius = 15 mm
Tangential Modulus = 1 Gpa
Transverse Modulus Nonlinear
Fiber Volume Fraction ~ 0.53
Permeability 1x10^{-14} m^2, Kozeny-Karman
Viscosity = 10 Pa.s

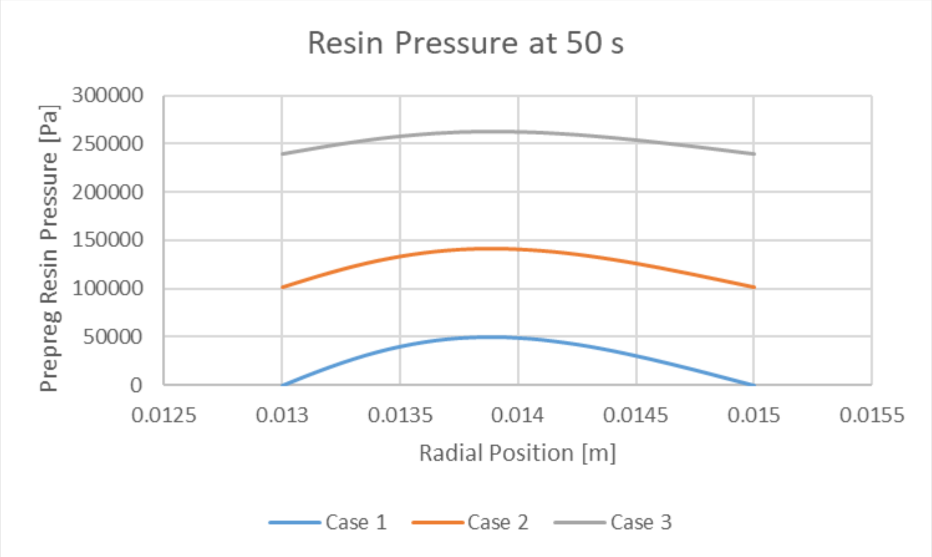
Applied Pressures

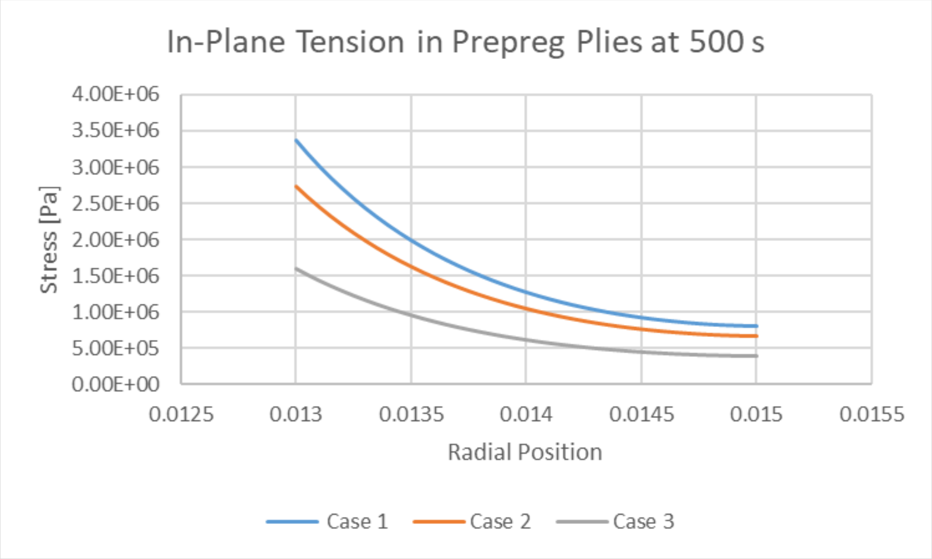
	Case 1	Case 2	Case 3
P_{bag}	O kPa	101 kPa	239 kPa
P_{app}	377 kPa	377 kPa	377 kPa
P_{core}	0 kPa	101 kPa	239 kPa

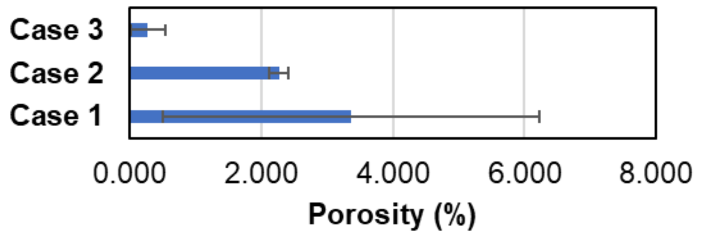
Notes

- **Viscosity Could Be Used Transient, But this is Good “Representative” Value**
- **Tangential Modulus (Prepreg In-Plane Stretching) is Speculative**
- **Permeability is “In Ball Park”**
- **Kozeny-Karman is Commonly Used as It Needs Only One Data Point**
- **Radius Obtained From Expected Dimpling**

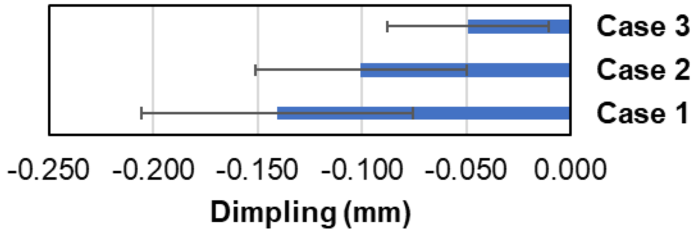
Comparison Details: Good Qualitative Agreement



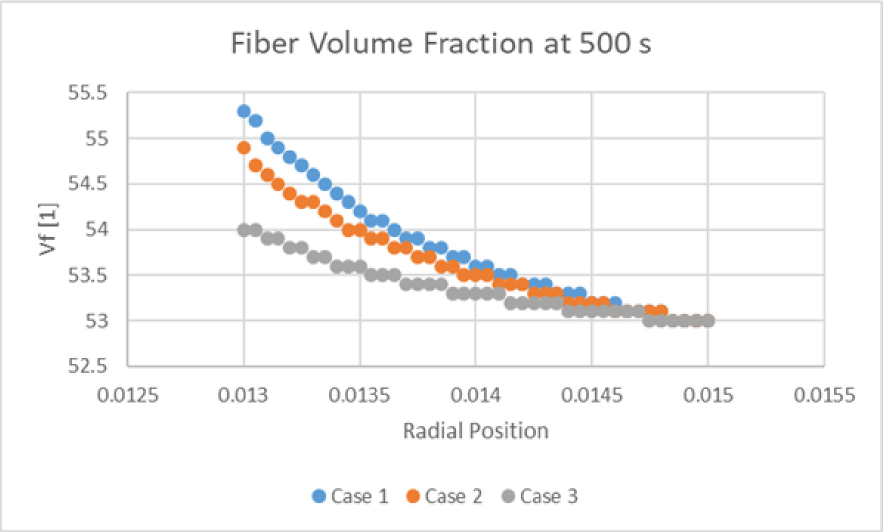


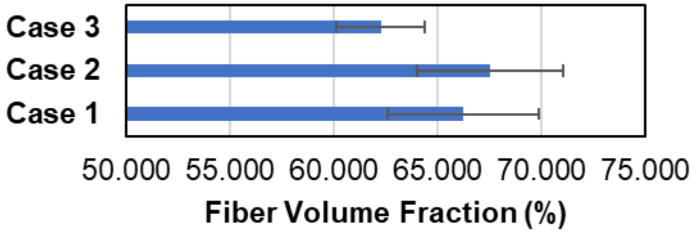


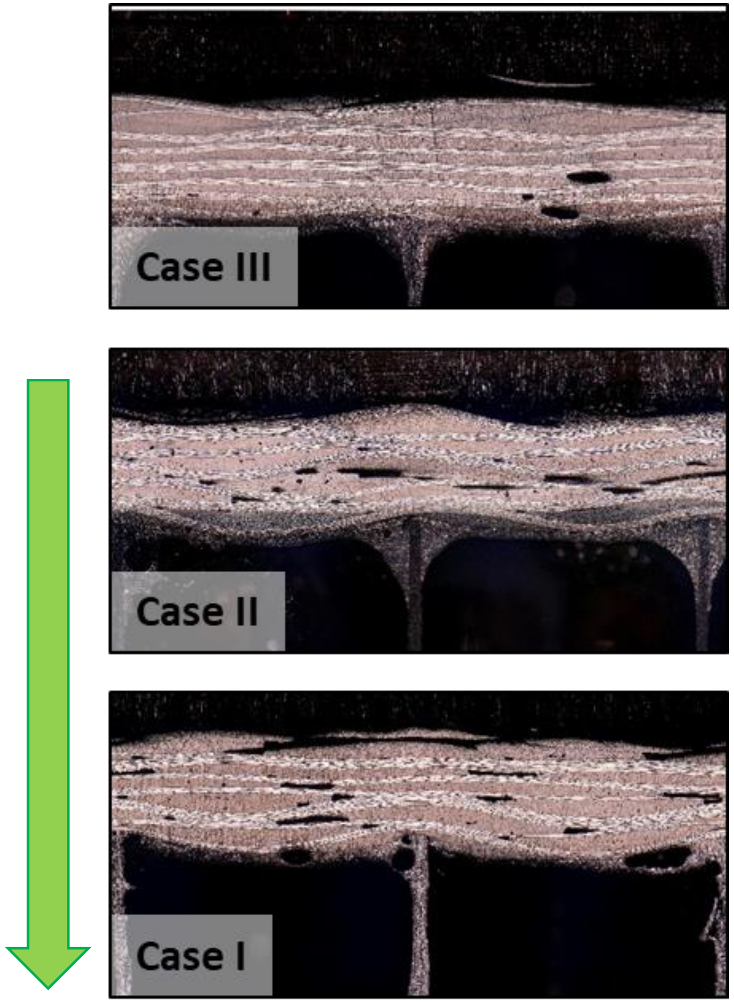
Is the Solubility the *ONLY* Key?



Comparison Details: Reasonable Qualit. Agreement







No Clear Trend in the Experiment

Are Voids "Toward" Core?!

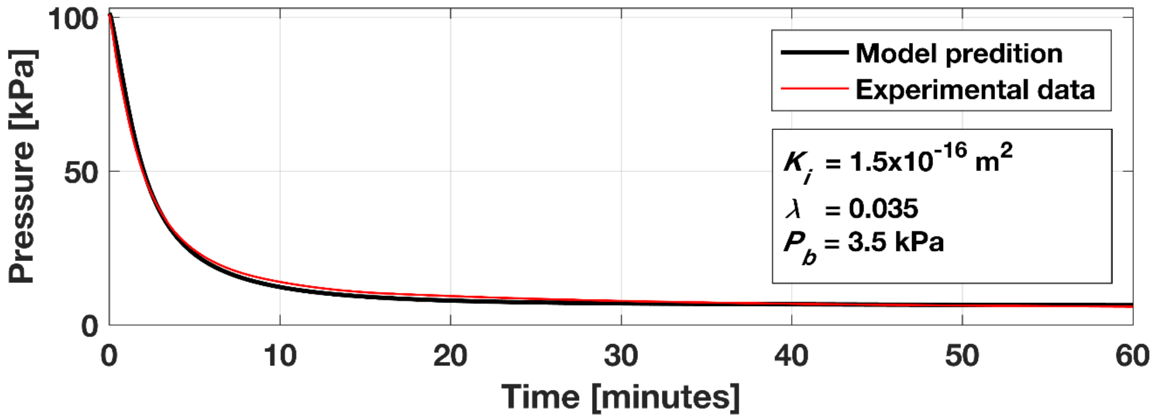
Low Resin Pressure

Permeability Model: Planned Work

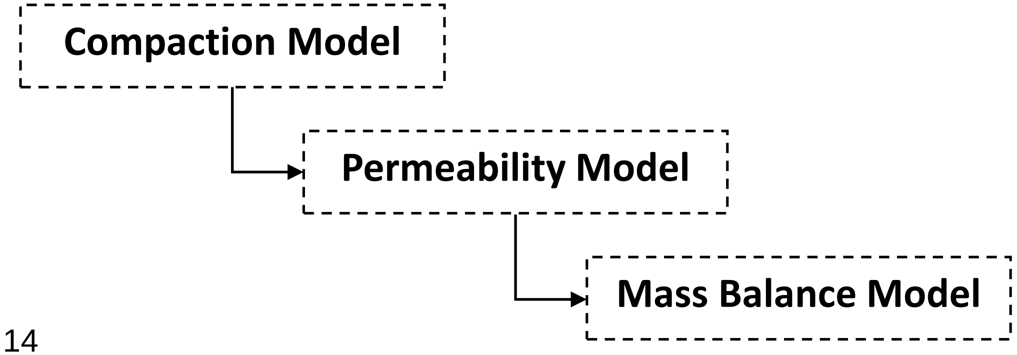
Gas Transport Experiments (Controlled Conditions)

- Variables
  - Ply count
  - Compaction pressure
  - Resin viscosity
- Measured values
  - Gas flow rate
  - Facesheet thickness?
- Other considerations
  - Boundaries: release film, adhesive layer
  - K_x, K_y
  - Material: 8552, 5320-1?

Fitting to Standalone Model



Integrating With Other Submodels



Technical Questions

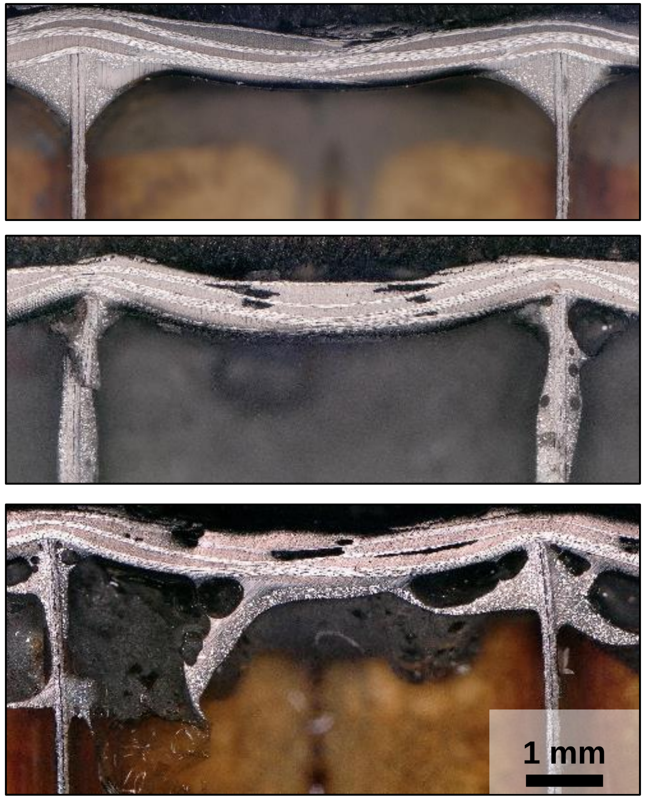
Equilibrated Core

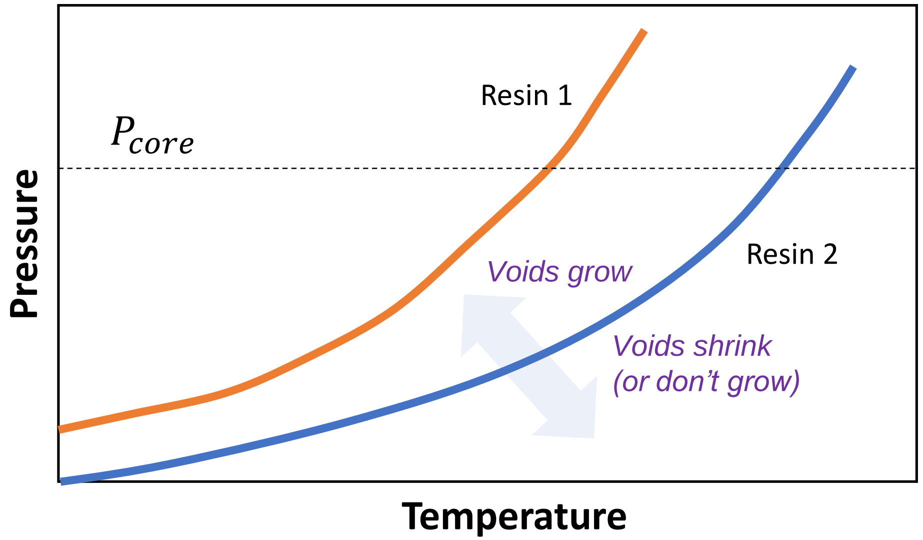
- How can we improve the accuracy of porosity modeling?
  - Void nucleation (currently not considered)
  - Void growth (reasonable first-pass agreement)
  - Void rupture and/or migration (highly stochastic)
- Is the coupling between facesheet consolidation and bond-line formation essential for predictive modeling?
  - Resin bleed can lead to thicker bond-line, larger fillets, and more porosity
- Is the model accurate for OoA/VBO prepregs with low degrees of impregnation?
- What are the next steps for validation?

Sealed Core

- How do we develop an accurate but useable model for prepreg permeability during cure?
- How do we reconcile prepreg permeability and facesheet consolidation?

Porosity Formation





Experimental Data
- *In situ* visuals
- TGA
- Vacuum oven (mass loss)

Model
- Void growth/shrinkage
- Void nucleation (if needed)

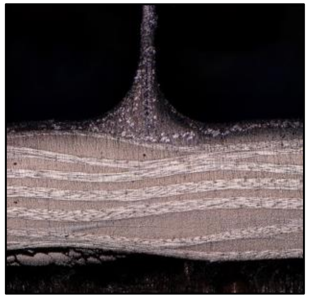
Current State

Model predicts transition at approximately 100 kPa (for adhesive). Tests show that voids in bond-line require > 200 kPa to suppress.

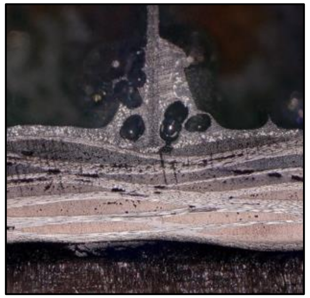
Next Step: Growth/Shrinkage Transition
- Models can be developed for adhesive and prepreg resins.
- Prediction of growth/shrinkage transition can be validated and used to estimate bond-line quality.

Facesheet/Bond-Line Coupling

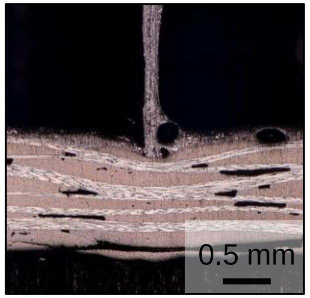
CASE III



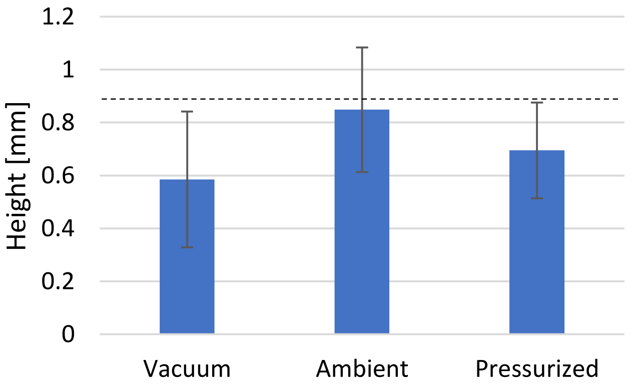
CASE II



CASE I



Visual Observations	Fillet Formation
In Situ: Fillet formation, little void growth Polished Section: Fillets are well-formed, few/no voids	Measured: Fillet height measured for approx. 40 fillets, with large STDEV noted Model: Analytical model solved using known/assumed parameters Model Results: ➢ Model deviation from 2% – 32% ➢ Sources of error: void formation, carrier, resin bleed from prepreg
In Situ: Fillet formation, void growth and entrapment Polished Section: Large fillets, many entrapped voids	
In Situ: Fillet formation, void growth/rupture Polished Section: Small, irregular fillets with some entrapped voids	



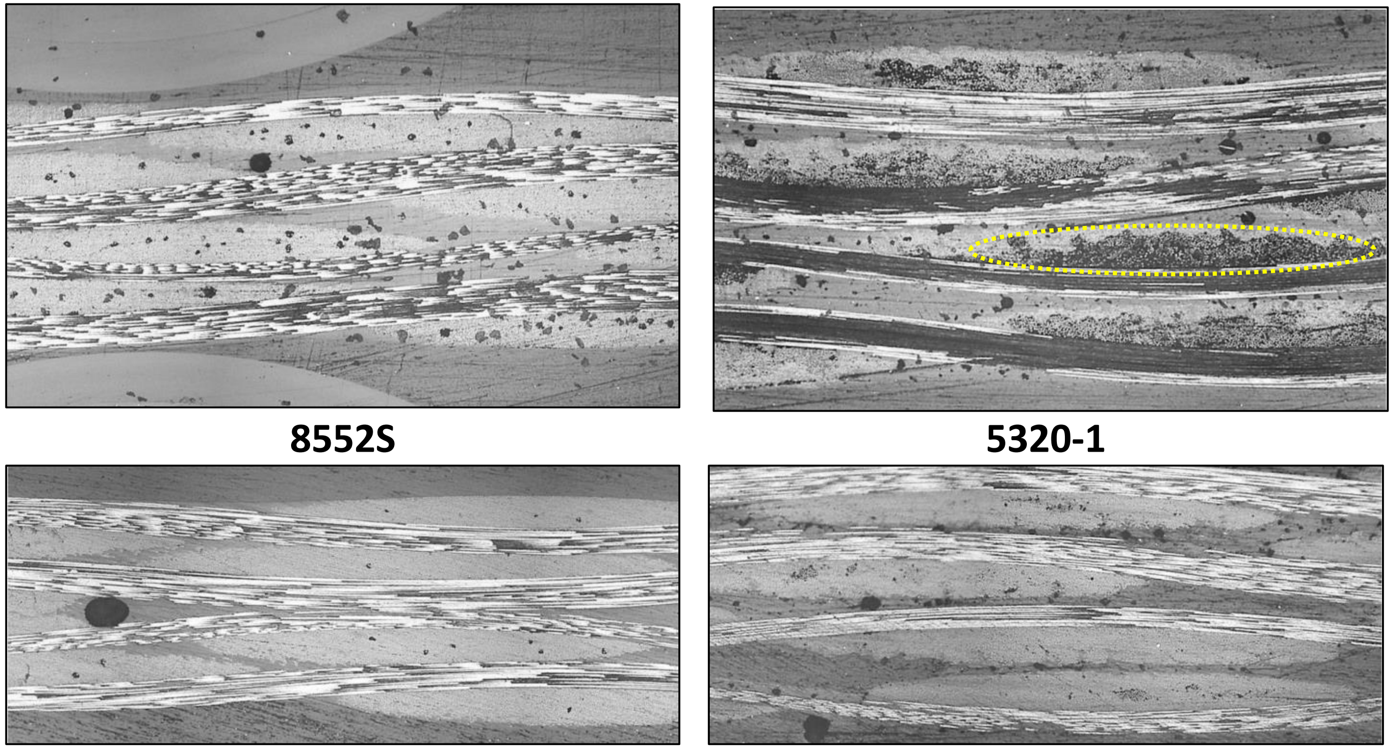
Notes

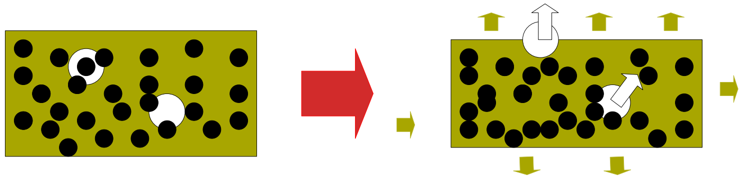
- ➢ Simple analytical model over-predicts fillet height, but remains accurate to within about 15% (average).
- ➢ To account for resin bleed, the model needs to be revised:
  - *Resin mass as input*
  - *Multiple material properties*
  - *Time history dependence*
- ➢ How accurate does the prediction of fillet size need to be, given practical factors and variability?

OoA/VBO Prepreg

Autoclave
- Fiber bed is fully saturated with resin on delivery.
- Consolidation modeling is easier due to uniformity.
- Material: Hexcel 8552S

Out-of-Autoclave
- Fiber bed is not fully saturated with resin due to dry tows
- Consolidation modeling is more challenging due to partial saturation, non-uniformity
- Material: Cytec 5320-1





Questions
- How accurate (or not) is the model for 5320-1?
- Can we decouple tow impregnation from the current consolidation model?
- How do we account for permeability evolution?

Validation

- **Case I:** Equilibrated Core ($P_{core} = 0$ kPa)
  - Sub-Models: Fillet formation, porosity formation
  - Focus: Current
- **Case II:** Equilibrated Core ($P_{core} = 101.3$ kPa)
  - Sub-Models: Fillet formation, porosity formation
  - Focus: Current
- **Case III:** Equilibrated Core ($P_{core} = 240$ kPa)
  - Sub-Models: Fillet formation, porosity formation
  - Focus: Current
- **Case IV:** Sealed Core (Realistic Pressure Evolution)
  - Sub-Models: *Cases I – III* + <u>core pressure</u>
  - Focus: Upcoming (requires facesheet permeability)
- **Cases V+:** Parts with Defined Geometry
  - Sub-Models: *Case IV* + <u>2D geometry</u>
  - Focus: After Cases I – IV are validated

Current Validation Tasks

- <u>Improve methods</u> for collecting test data (esp. for facesheet properties)
- <u>Refine models</u> (equations, inputs) to improve accuracy of fillet formation, porosity evolution, and facesheet consolidation sub-models.

Next Steps

- Prepare additional samples to assess variability.
- Perform validation on external samples (e.g., UTRC test data).

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