Harnessing Manufacturing Science to Increase Composites Use in Aerospace

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Acknowledgements

- Past and current members of the UBC Composites Group, Composites Research Network

- Industrial members of CRN, including The Boeing Company, Toray Americas Inc., Avcorp Industries, and many other collaborators

- The Government of Canada

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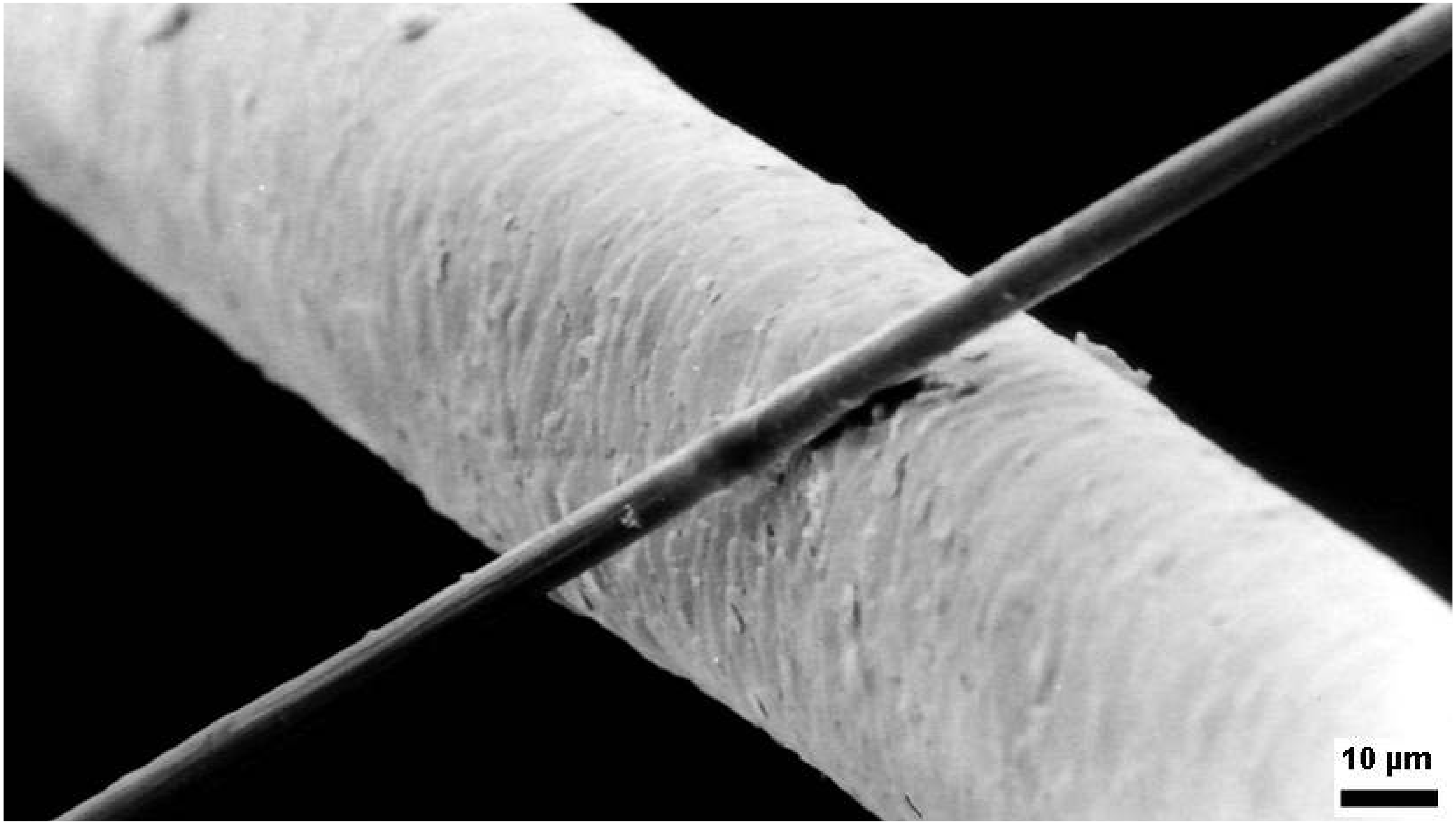
Introduction

- Composite materials are an excellent example of a promising technology that has not became as pervasive as expected, certainly not as quickly as was wanted
- The primary reason is complexity: complexity of design and complexity of manufacturing
- Over the last thirty years, there have been significant advances in manufacturing science, and this science has been captured in process simulation
- Process simulation is a topic of great industrial interest, and where applied effectively, significant benefits have been achieved
- However, there are many interesting scientific problems yet to be solved
- This presentation provides an overview of the current state of the art from our perspective

Carbon Fibres



A 6 μm diameter carbon filament (running from bottom left to top right) compared to a human hair.

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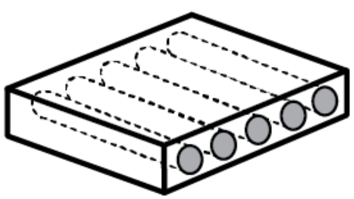
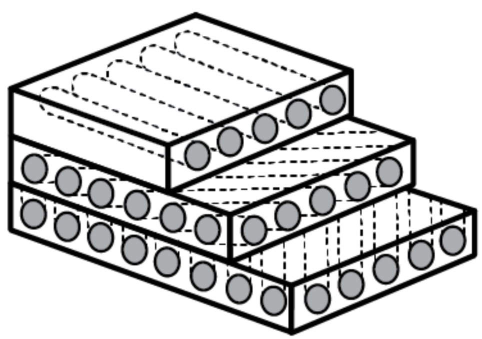
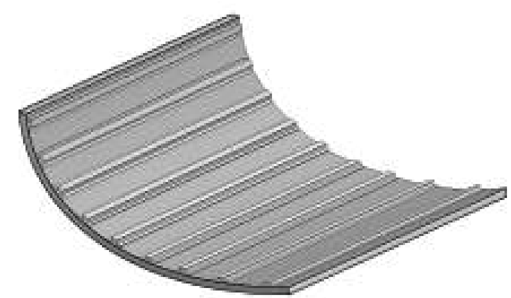
Layered Materials

Lamina	Laminate	Component



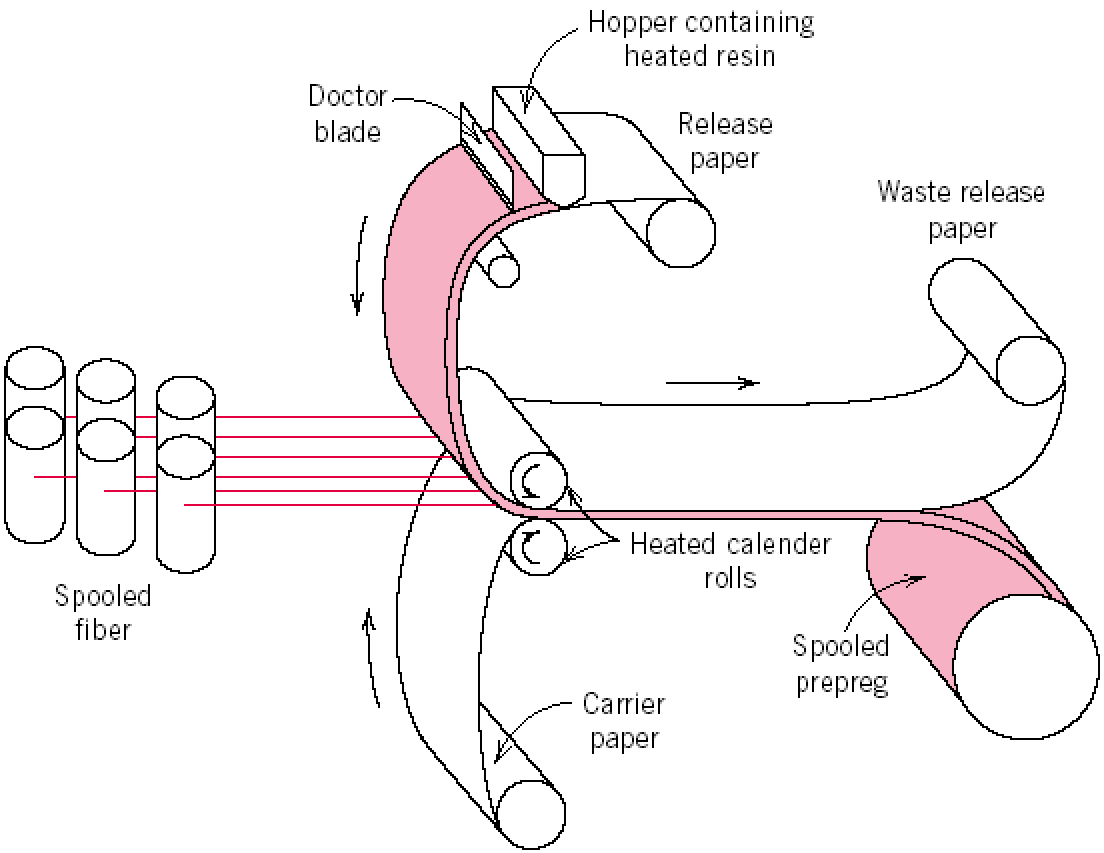




1 layer:
Fiber + Matrix (resin)

Multi-layers

Production of Prepreg



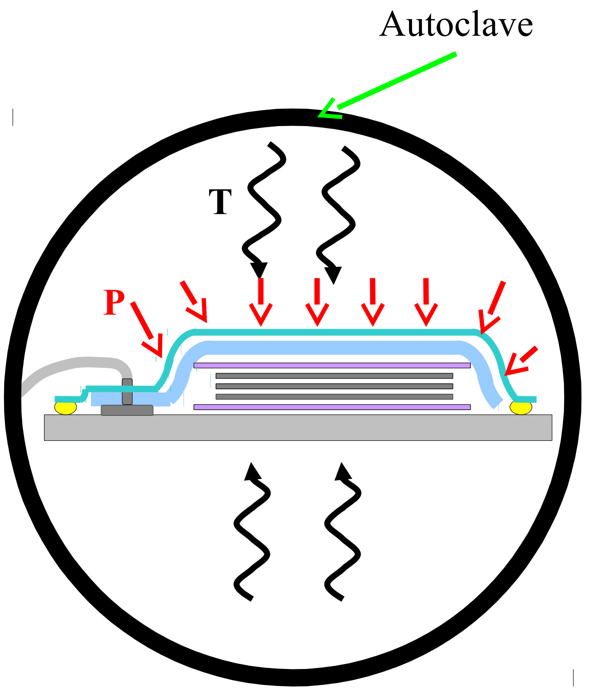
Thermoset Matrix Composite Structures

Prepreg roll

or

Composites Manufacturing

- All composites manufacturing processes can be thought of having a number of steps
  - **Materials deposition management**
    - Infusion, hand layup, AFP, …
  - **Thermal management**
    - Heat and cool part and tool in autoclave, oven, mould, …
  - **Quality management**
    - Thermal, pressure, vacuum history interacts with material deposition history and part/tool geometry to give quality outcomes: thickness change, wrinkling, porosity, …
  - **Residual stress and dimensional control management**
    - Leading to either immediate micro-cracking or reduction in mechanical performance, as well as dimensional spring-in and warpage on detooling



Benefits of Composites: Consolidated Parts

Boeing 747-400	Boeing 787
	
Year: 2002	Year: 2009
Material: Aluminum	Material: Composite
Assembly time: 3 months	Assembly time: 3 days

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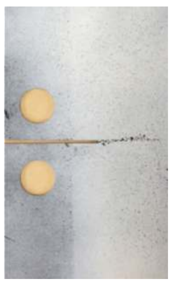
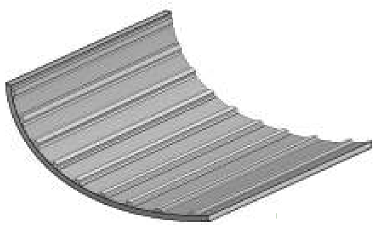
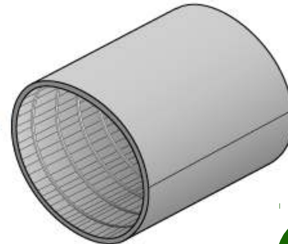
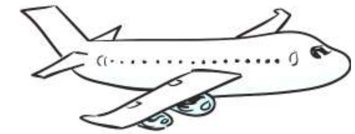
Building Block Approach

A Typical Manufacturing Building Block Approach:









Coupons
- Material Strength
- Material Modulus
- Material Toughness

Thousands

Small Panels, Joints, Features, Elements
- Local Temperatures
- Local Degree of Cure
- Local Material Properties
- Local Void Fraction

Hundreds

Large Panels, Interacting Features, etc.
- Temperature Distribution
- Volume Fraction Distribution
- Residual Stress Distribution
- Void Fraction Distribution

Tens

Full Structure

QUESTION:

Are we testing the same at all levels:
- Material quality
- residual stresses
- dimensions

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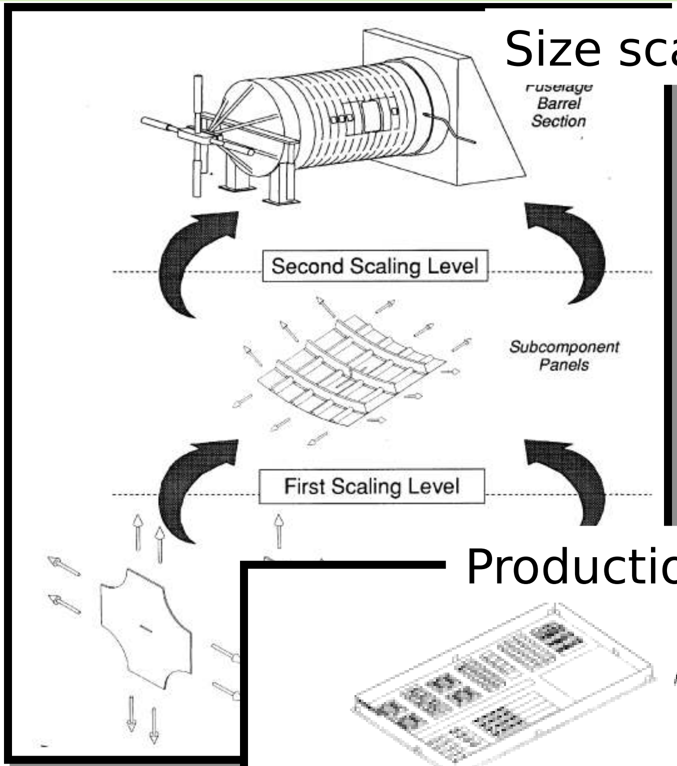
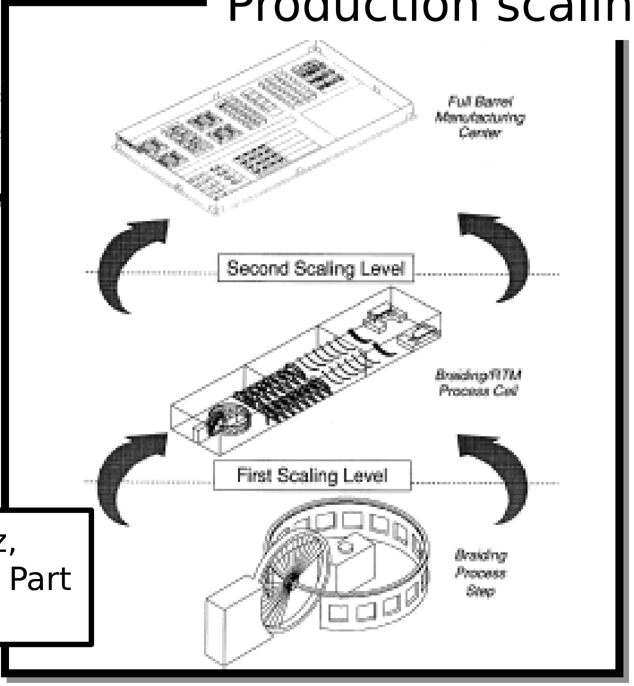
Manufacturing Risk and Cost: A Major Opportunity

- Manufacturing is a major cost and risk, both development and in production
- Scaling up in size and rate entails enormous cost
- Consequently, there is significant conservatism and reluctance in then trying to optimize
- Major risks are front-end loaded, at the conceptual design decision stage, but ongoing recurring cost also accumulates during decades of production, given the long amortization times
- The obvious 21st century risk and cost reduction technologies are automation, simulation, and sensor-based big data

Size scaling



Production scalin



L.B. Ilcewicz, Composites Part A, 1999

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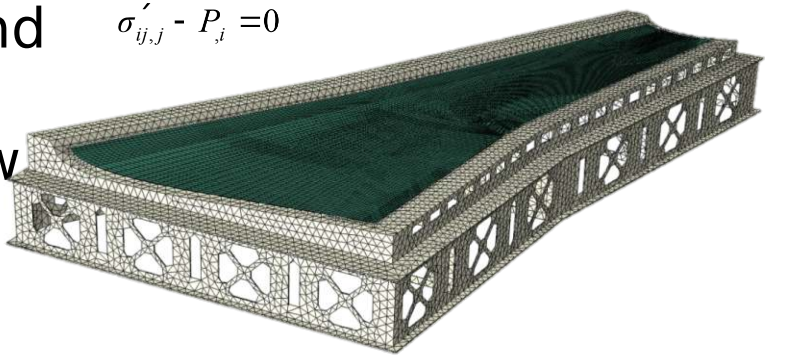
Modelling and Simulation

- In modelling and simulation, we represent the issue as a mathematical problem and solve it
- Capture and represent the science: the chemistry, the physics, and the mechanics of the problem
  - Ties into the digital world around us where geometric and kinematic representation is now the norm
- This has been talked about for a long time, and to many it is still an unrealized promise
- But the last ten years have shown it is real and coming fast

$$\frac{\partial}{\partial t}(\rho C_P T) = \frac{\partial}{\partial x}\left(k_{xx}\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_{yy}\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_{zz}\frac{\partial T}{\partial z}\right) + \dot{Q}$$

$$\dot{u}_{i,i} - \left(S_{ij}P_{,j}/\mu\right) = 0$$

$$\sigma'_{ij,j} - P_{,i} = 0$$

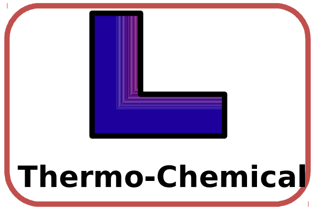


$$\Pi_P = U + \Omega$$

$$\Pi_P = \int_V \frac{1}{2}\varepsilon^T D\varepsilon \, dV - \int_V \varepsilon^T D\varepsilon_0 \, dV - \int_V \varepsilon^T \sigma_0 \, dV - \int_S u_S^T q_S \, dS$$

Process Simulation Outcomes

Process models can be used to design and troubleshoot manufacturing processes and predict defects; some directly, some indirectly

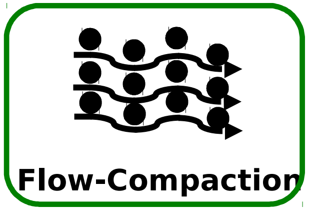


Direct Outcomes

- Temperature History
- DoC Development History
- Lead, Lag and Exotherm

Associated Defects

- Under cure
- Weak bonds
- Heat damage



Direct Outcomes

- Resin and Gas Flow
- Thickness Change
- Resin Pressure

Associated Defects

- Porosity
- Resin rich/starved areas
- Thickness variations
- Fiber waviness, wrinkling

Direct Outcomes

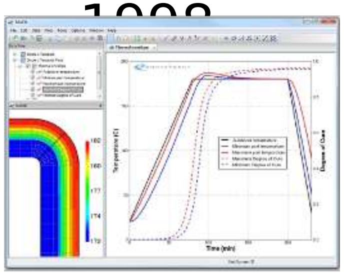
- Residual Stresses
- Cure-induced Deformation

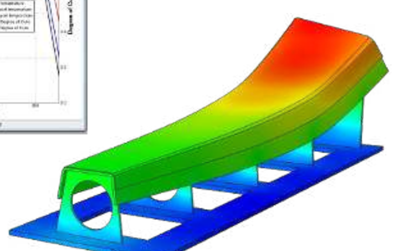
Associated Defects

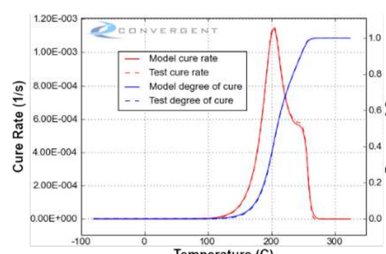
- Matrix cracking
- Delamination, disbonding
- Dimensional conformance

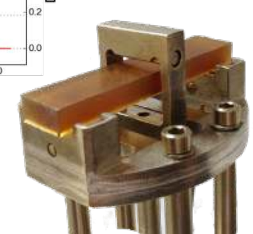
Models as Useful Knowledge Delivery

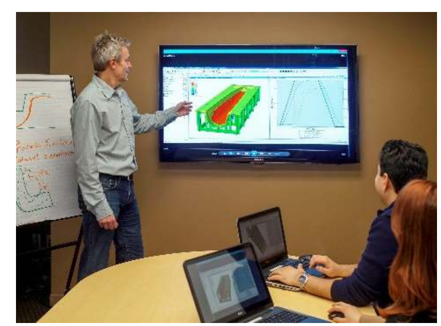
- Composites manufacturing modelling has been a scientific endeavor since the 1970s
- The CRN predecessor, the UBC Composites Group, started working in this area in 1986
- Collaboration with Boeing started in early 1990s
- Increasing successes over the years
- Multiple parallel threads:
  - Development of science base, materials and process characterization, big data (instrumentation), application case studies
- Founding of Convergent Manufacturing Technologies in 1998











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Many Modelling Successes in Last Decades

- Example: Boeing 787 fuselage cure cycle was designed using UBC software (COMPRO), commercially supported by UBC spin-off company (CONVERGENT)

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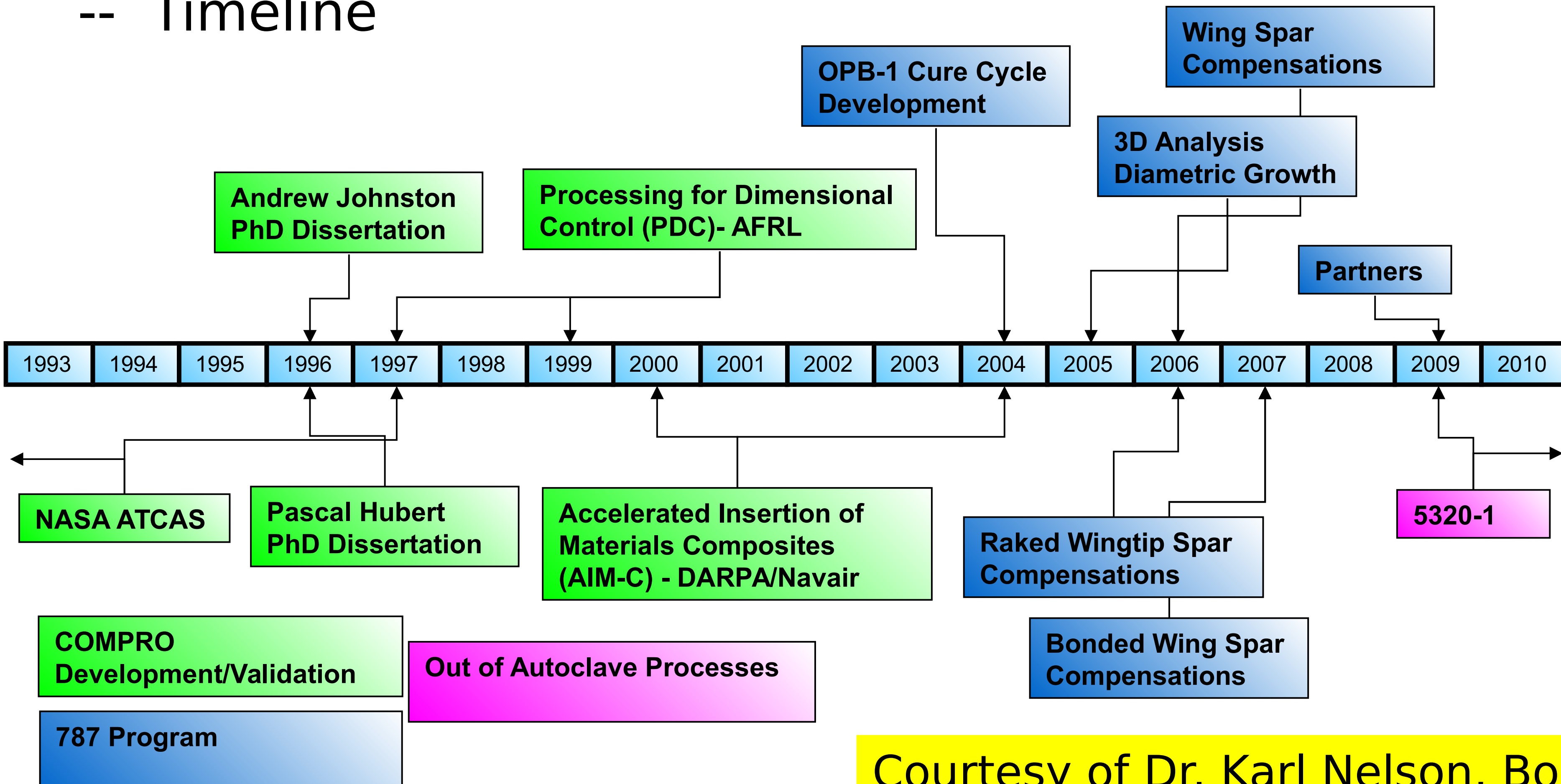
Evolution of Composites Process Modeling

Thermal/Dimensional Analysis

-- Timeline



Courtesy of Dr. Karl Nelson, Boei

Boeing 787 Production

ONE-PIECE

COMPOSITE

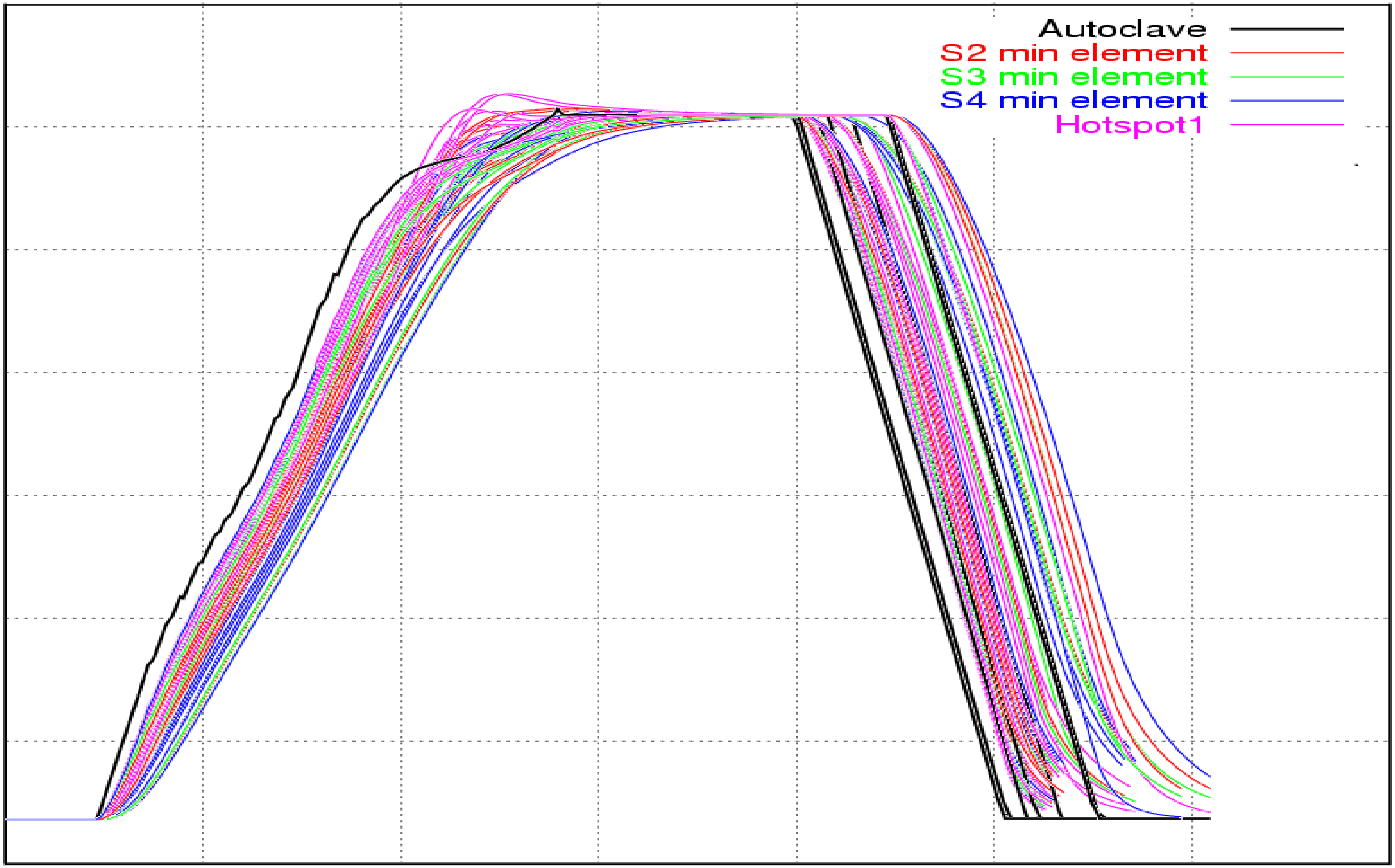
FUSELAGE

787 One Piece Barrel – Cure Cycle 297

- All 787 barrels are cured with one of two cure recipes
  - 297 for Composite Mandrels
  - 297 Mod for Invar Mandrels

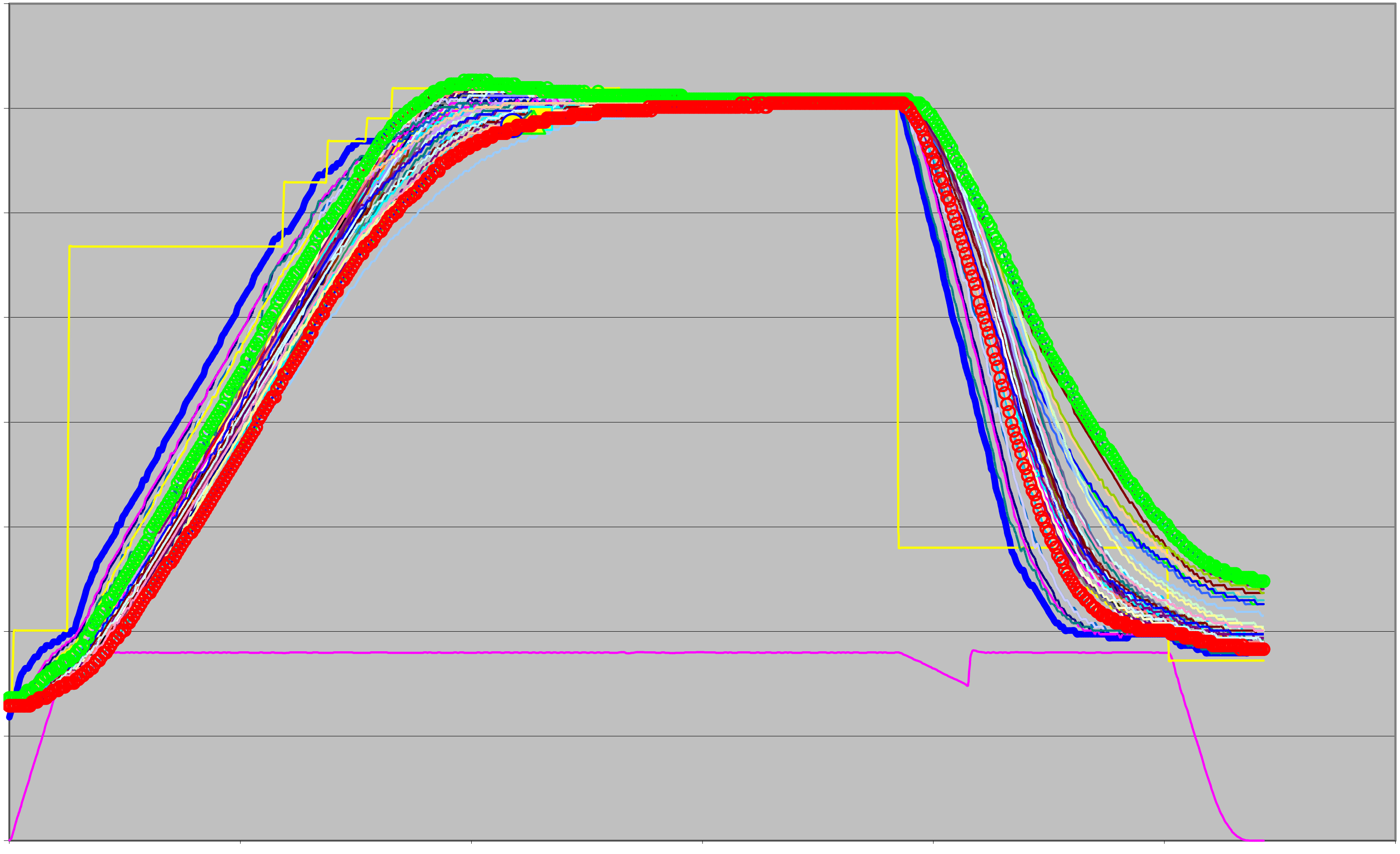
Courtesy of Dr. Karl Nelson, Boeing

Simulation Results



Courtesy of Dr. Karl Nelson, Boein

Data From Production Barrel: Cycle 297



Courtesy of Dr. Karl Nelson, Boein

Preparing for the Future: CRN

- The Composites Research Network is a collaborative research centre hosted by The University of British Columbia:
  - International and Canadian industrial members
  - Research nodes across Canada
- Founded in 2012, building on the original activities of the UBC Composites Group

- **Vision:** A vibrant composites industry where the transition of knowledge into practice is fast, effective, and efficient.
- **Mission:** To create a framework for, and generate a family of, knowledge in practice documents that enable effective and low-risk knowledge-based composites manufacturing and design.

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CRN Focus

- How do we create relevant composites manufacturing science, in an integrated science base?
  - Use manufacturing simulation as a tool to capture this science
  - Use science to select and optimize sensors to measure manufacturing parameters and outcomes
- How can we make better science based manufacturing design decisions?
  - Right-sized for different industries and receptor capacity, from aerospace OEMs to industrial SMEs
  - Protect, advance, and disrupt manufacturing practice
- Demonstrate the value of this “Knowledge in Practice” approach in education, research, and industrial practice
  - Accelerate transition of knowledge into practice via technology

Manufacturing Science to Manufacturing Practice

Manufacturing Science:

Governing Laws Leading to Outcomes:

Models
Measurements
Analysis Methods

Current and Future Science Base
Integration
Validation
Expansion

Manufacturing Quality:

Outcomes cannot become 'Defects'
Chemical
Physical
Mechanical

Classified as:
Materials Deposition Management
Thermal Management
Quality Management
Residual Stress and Dimensional Management

Manufacturing Practice:

Making Manufacturing Decisions:
Factory Equipment
Tooling
Parts
Materials

Part Producibility

Feasibility
Conceptual Phase
Trade Study Phase
Detail Design Phase
Production Phase
Improvement/Development Phases

In the future, the data associated with the factory and product will be as valuable as the factory and product

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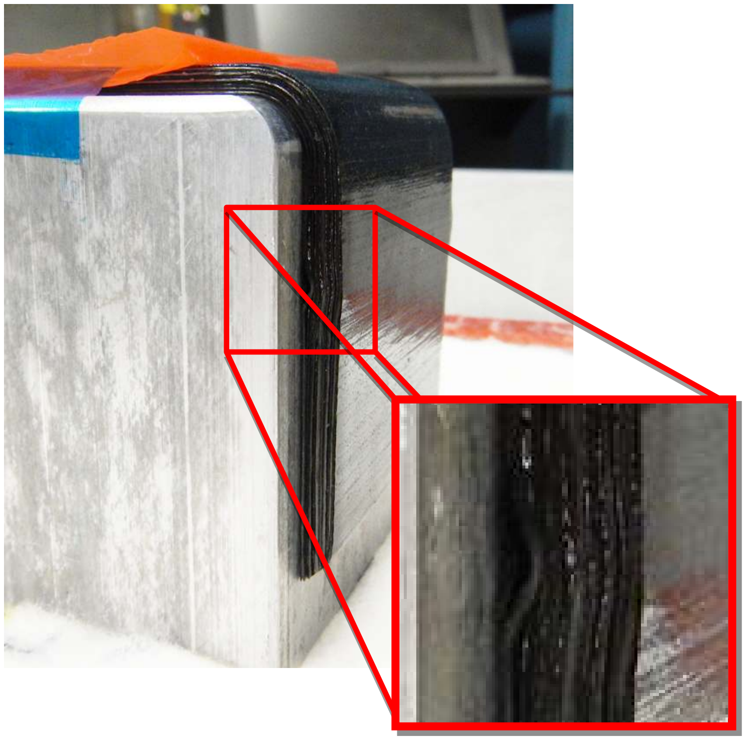
Example of Current Research: Predicting Wrinkles

- Many modern processes are focused on reducing touch labor for reasons of cost and accuracy
- Automation in the form of automated material placement is of great interest:
  - robots laying down material in small width tapes (AFP)
  - or robots laying down flat broad goods, followed by a forming process
- In either case, wrinkling is a problem, as the material will not conform to multiple-contoured surfaces easily
- Much research going on in this area, with our goal being to understand the fundamental physics, and capture in simulation so as to design better processes

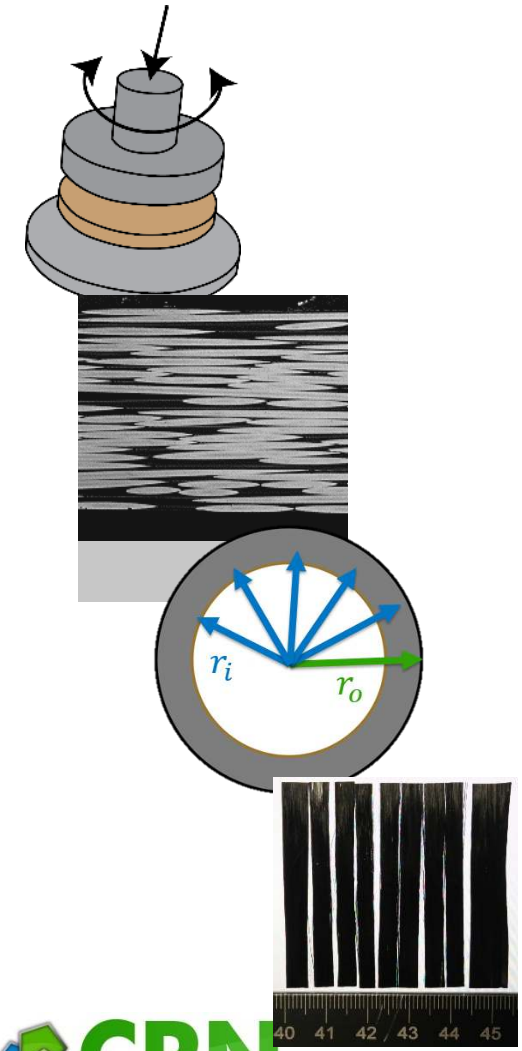
Source of Wrinkles: Excess Fibre Length

- Fibers (and tows) in an uncured prepreg have very high axial stiffness and an extremely low bending stiffness (due to their aspect ratio)
- Any excess length in fibers induced by geometric constraints during deformation has to be accommodated by deviation of fibers from their desired path
- This can be manifested as out-of-plane deformation (puckers, wrinkles, twist and fold) or in-plane deformation (waviness)
- Out-of-plane deformation modes are preferred due to very low out-of-plane bending stiffness of the material

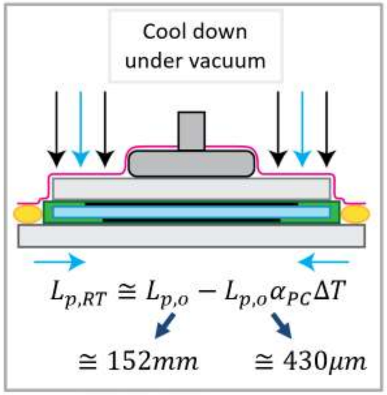


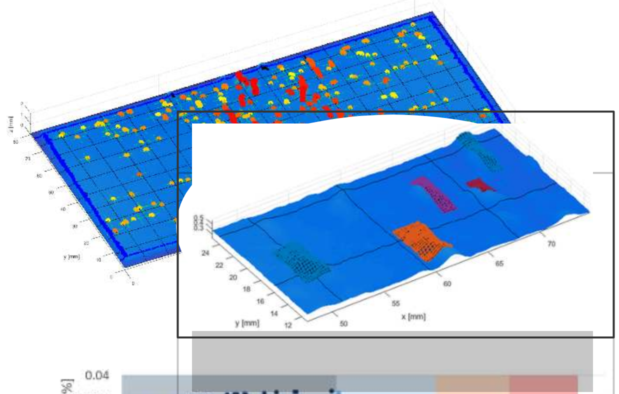
Understanding Fundamental Wrinkling Physics

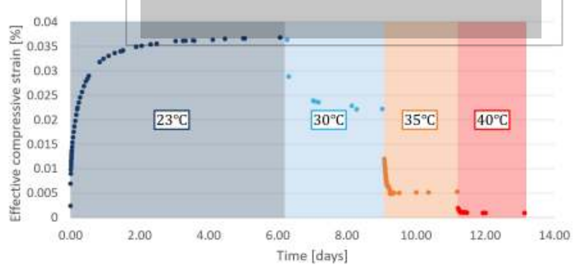
Prepreg characterization



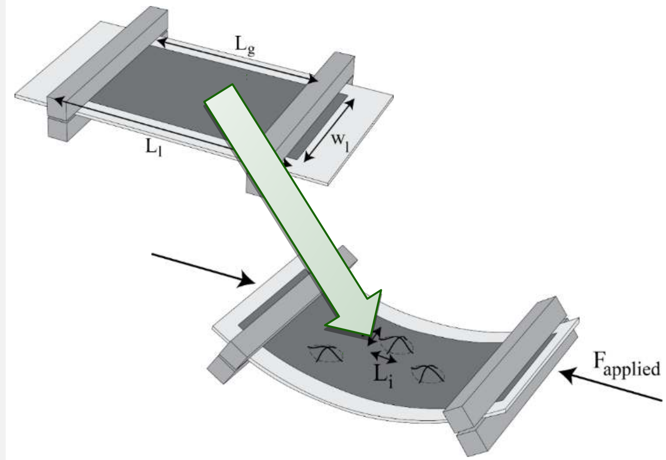
Transient wrinkle growth

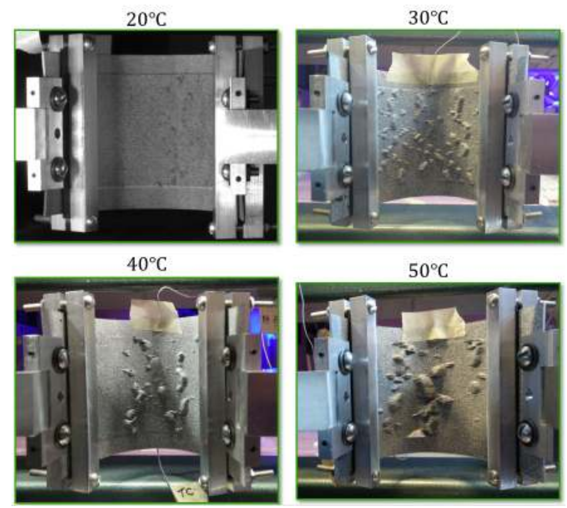






Quasi-static wrinkle growth

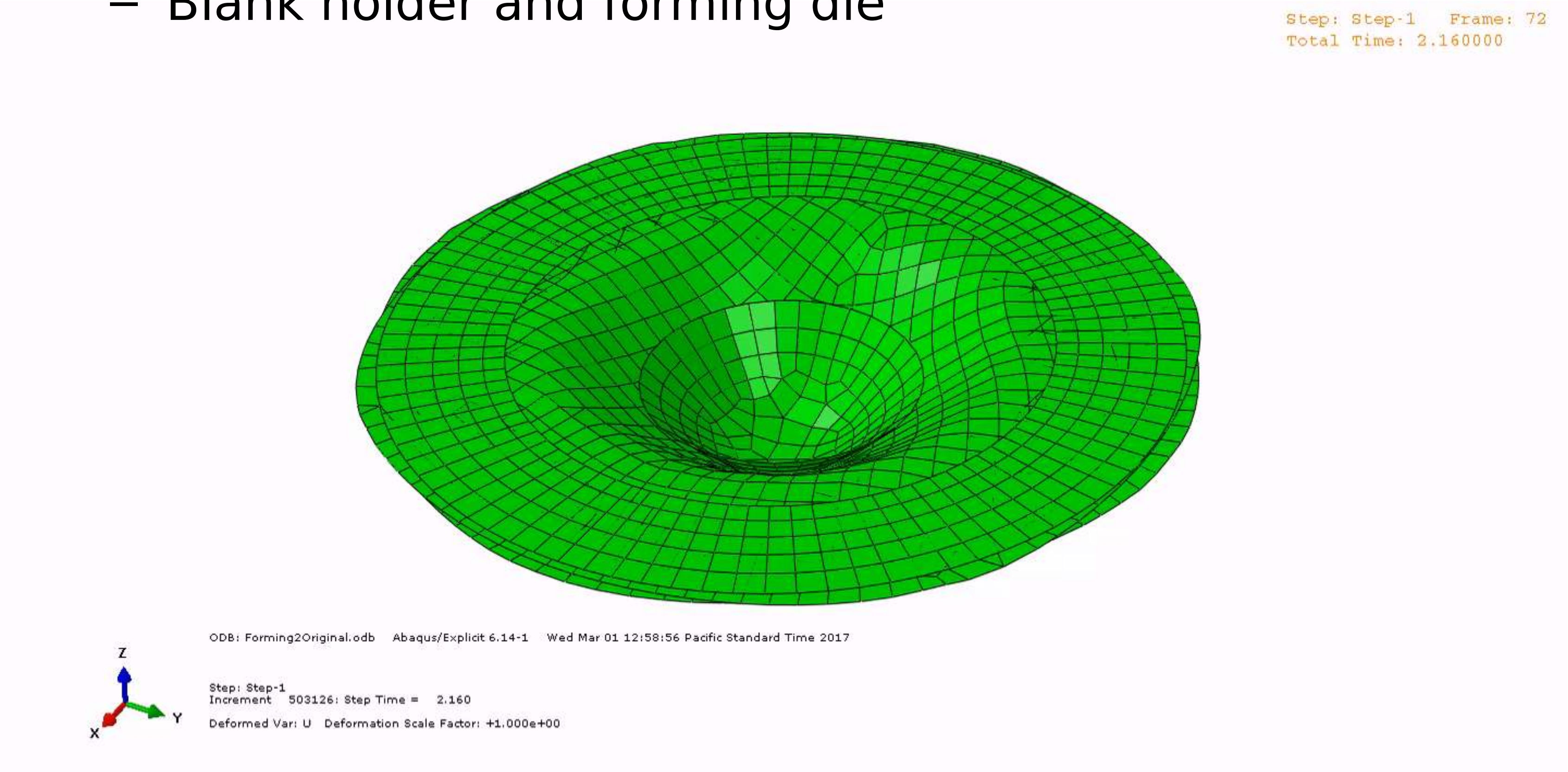




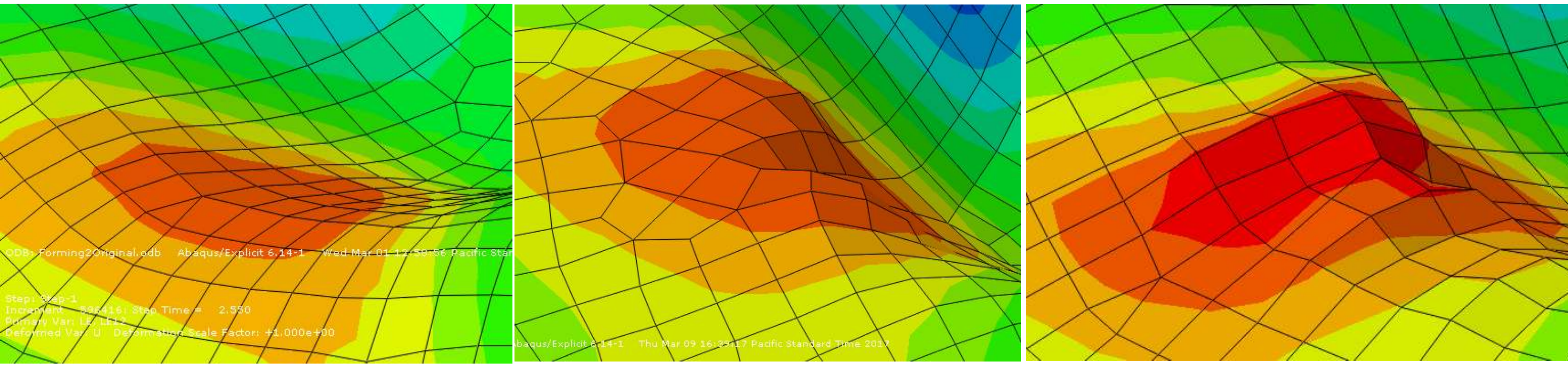
Andrew Stewart PhD thesis

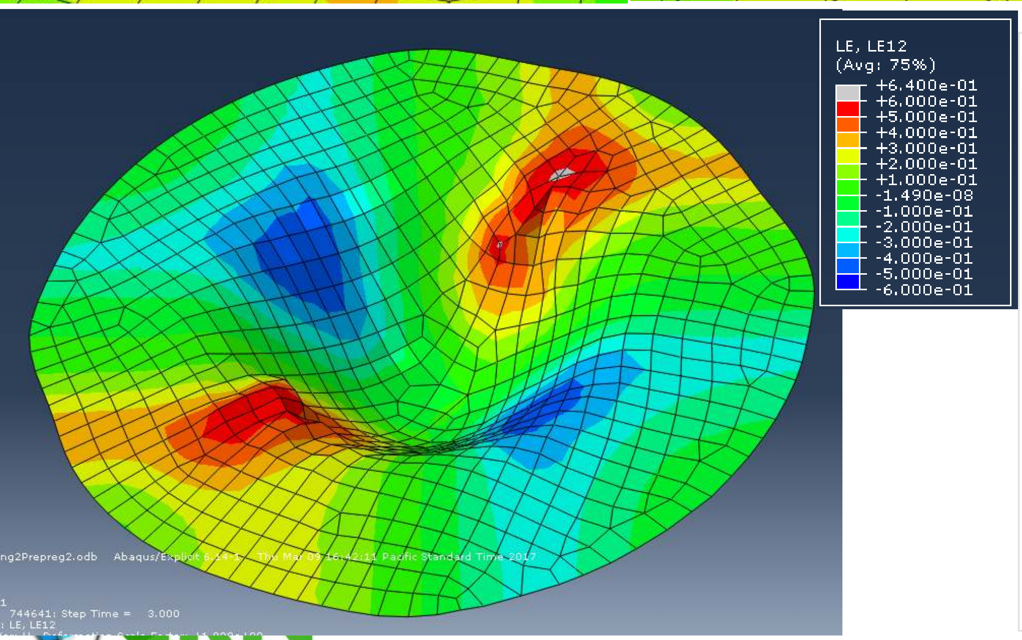
Forming Simulation Example

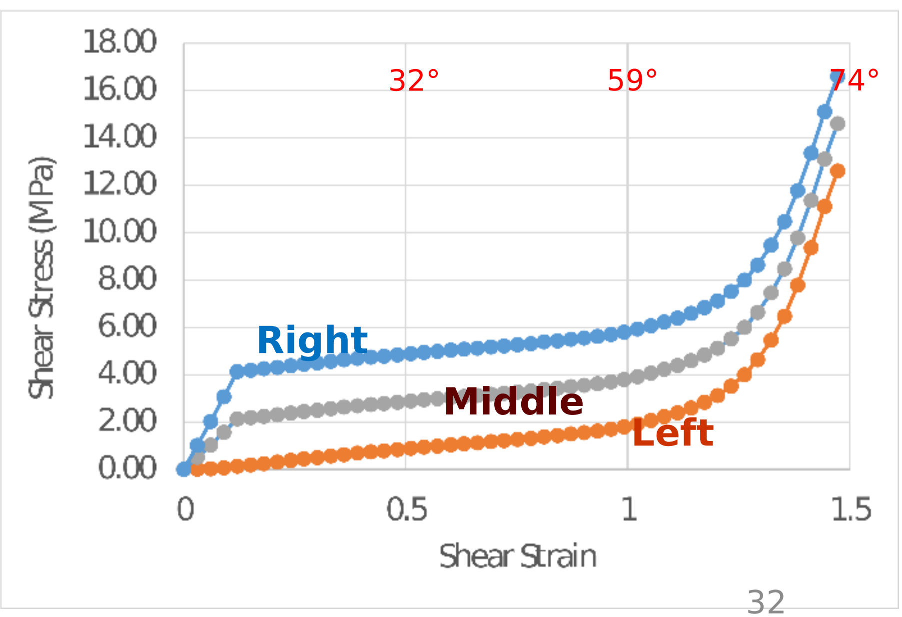
- Simulation of semi-circle forming
  - 3 Layers of fabric (with varying properties to represent dry fabric to viscous prepreg)
  - Blank holder and forming die



Example: Effect of In-Plane Shear Stiffness







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Summary and Conclusions

- Composite materials have not been as successful as expected because of difficulties in design and manufacturing associated with their complexity
- Manufacturing science, as captured and exercised in process simulation has been of great value to date, and is still full of interesting and challenging academic research opportunities
- Equally important to the creation of the manufacturing science is the harnessing of that manufacturing science to create industrial and societal value
- The goal of the Composites Research Network is to work on both the creation and application of manufacturing science, using process simulation as a valuable tool for transitioning the science to application

Tier I and II Members, Nodes, Funding Agencies

BOEING

CONVERGENT

TORAY
Toray Composites (America), Inc.

AVCORP
BETTER SOLUTIONS

University of Victoria

UBC a place of mind

UNIVERSITY OF ALBERTA

McGill

Canadian Light Source
Centre canadien de rayonnement synchrotron

Composites Innovation Centre

CAMOSUN COLLEGE

NRC·CNRC Canada

NSERC CRSNG

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