Simulation Across the Automotive Supply Chain

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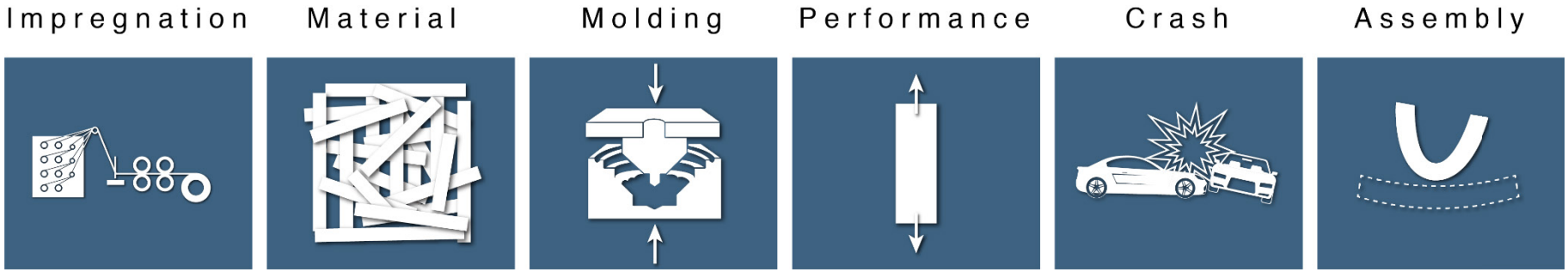
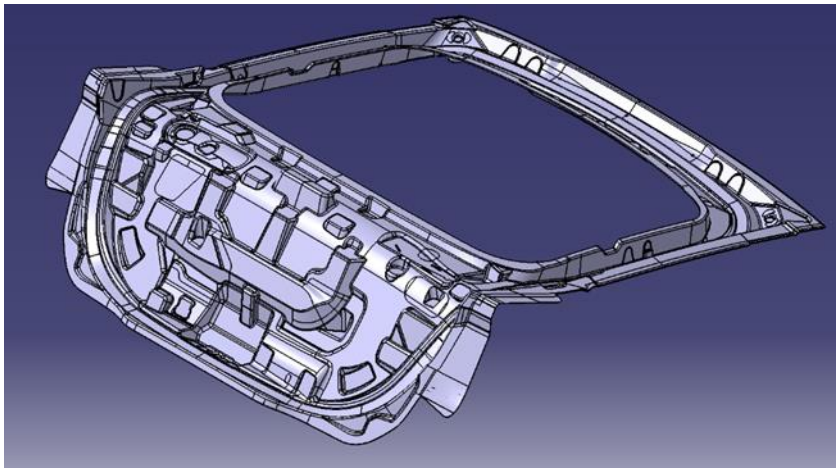
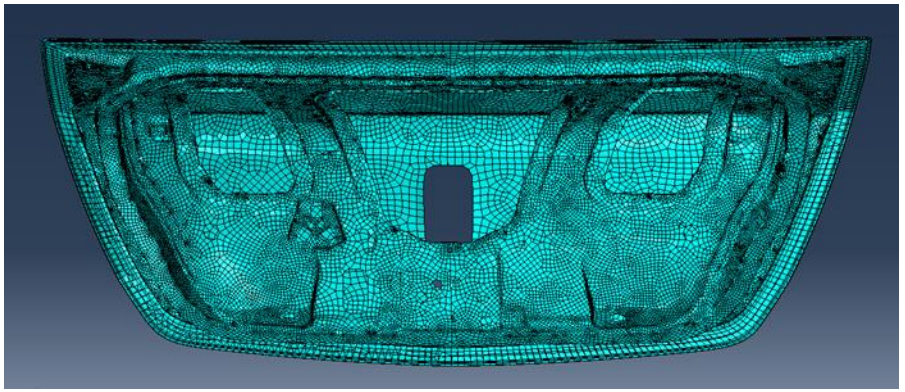
Capture the Physics: Harness the Possibilities



Geometries



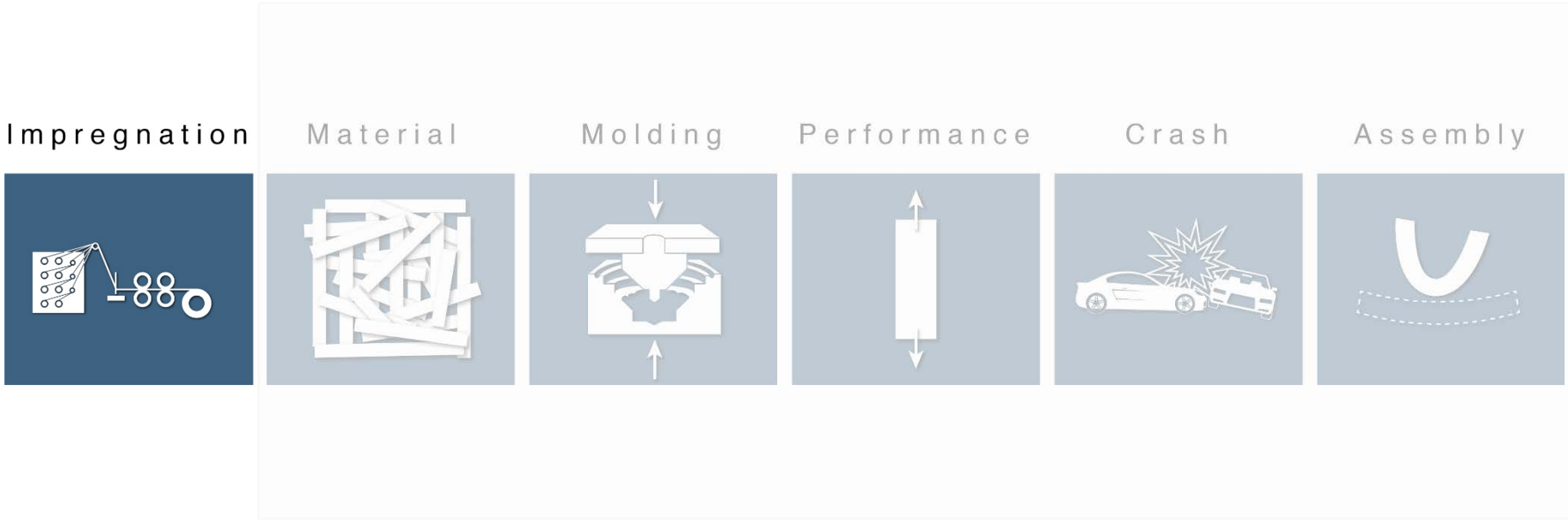
Lift Gate



Deck Lid

Double Dome

Impregnation Simulation

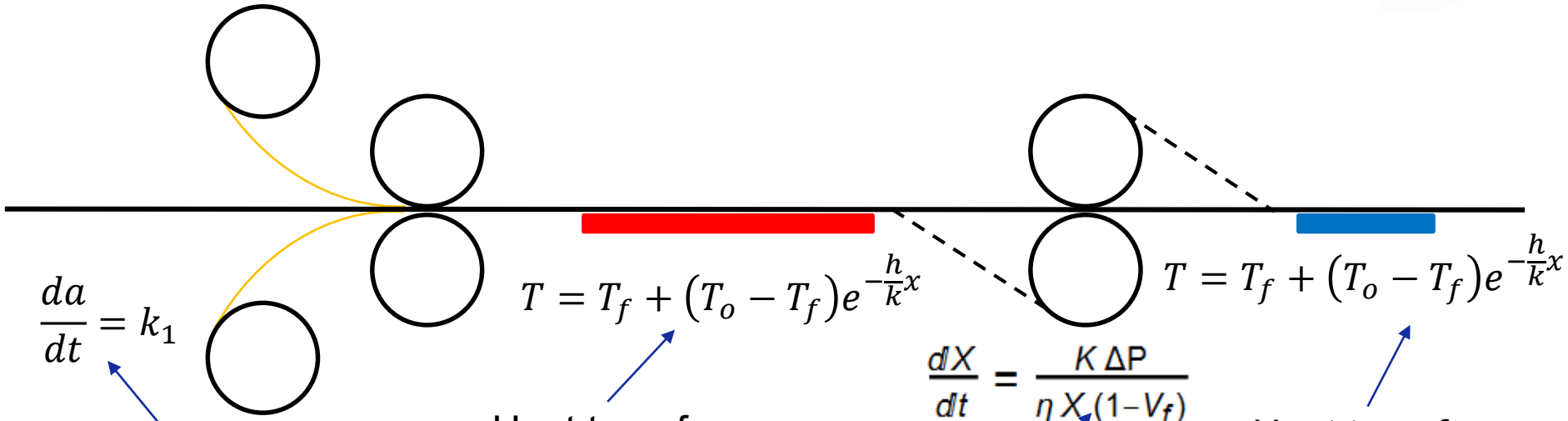


Impregnation Line at Corktown

Filming → Pre-Heating → Impregnation → Quenching

Impregnation Model for Corktown Line

1. Filming
2. Preheat
3. Impregnation
4. Quenching



$$\frac{da}{dt} = k_1$$

Simplified cure kinetics

$$T = T_f + (T_o - T_f)e^{-\frac{h}{k}x}$$

Heat transfer

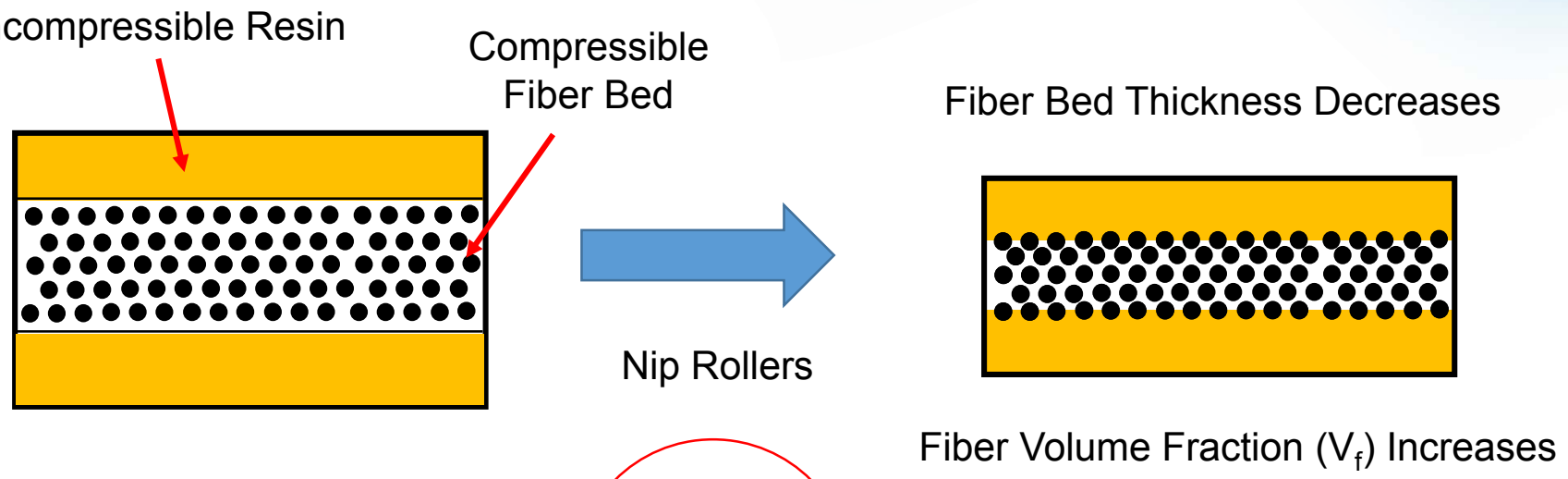
$$\frac{dX}{dt} = \frac{K\,\Delta P}{\eta\, X (1 - V_f)}$$

Resin flow

$$T = T_f + (T_o - T_f)e^{-\frac{h}{k}x}$$

Heat transfer

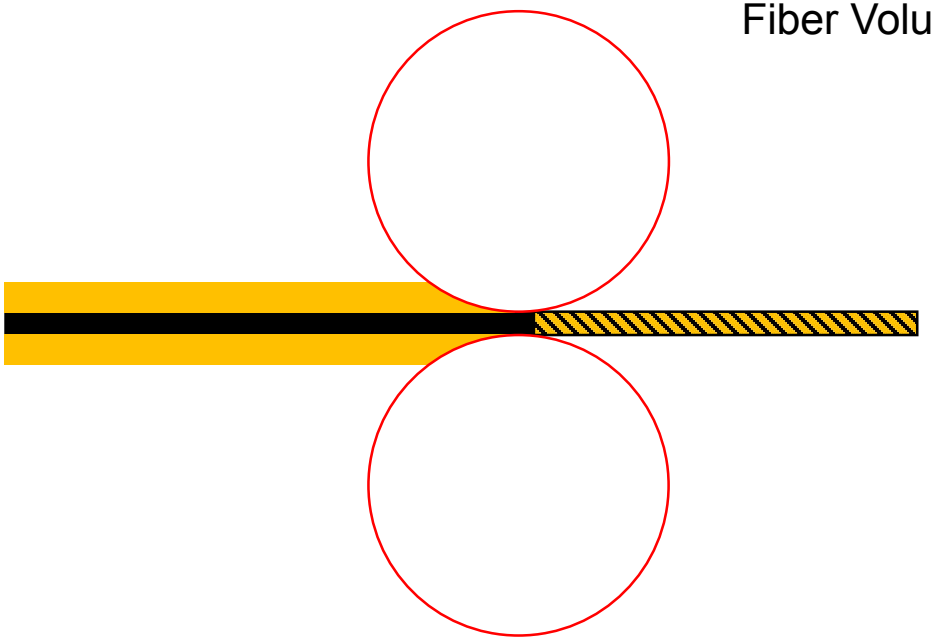
Impregnation Model Physics



Darcy's Law:

$$\frac{dX}{dt} = \frac{K\,\Delta P}{\eta\, X\,(1-V_f)}$$

[Darcy (1856)]

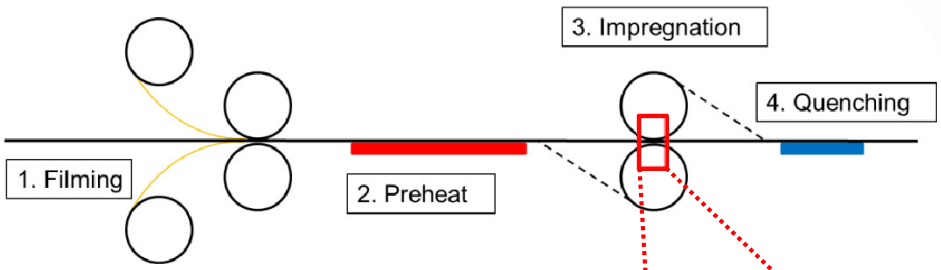


$$\Delta P = A\,\frac{\left(\frac{V_f}{V_o}\right)^{.5}-1}{\left(\left(\frac{V_a}{V_f}\right)^{.5}-1\right)^4}$$

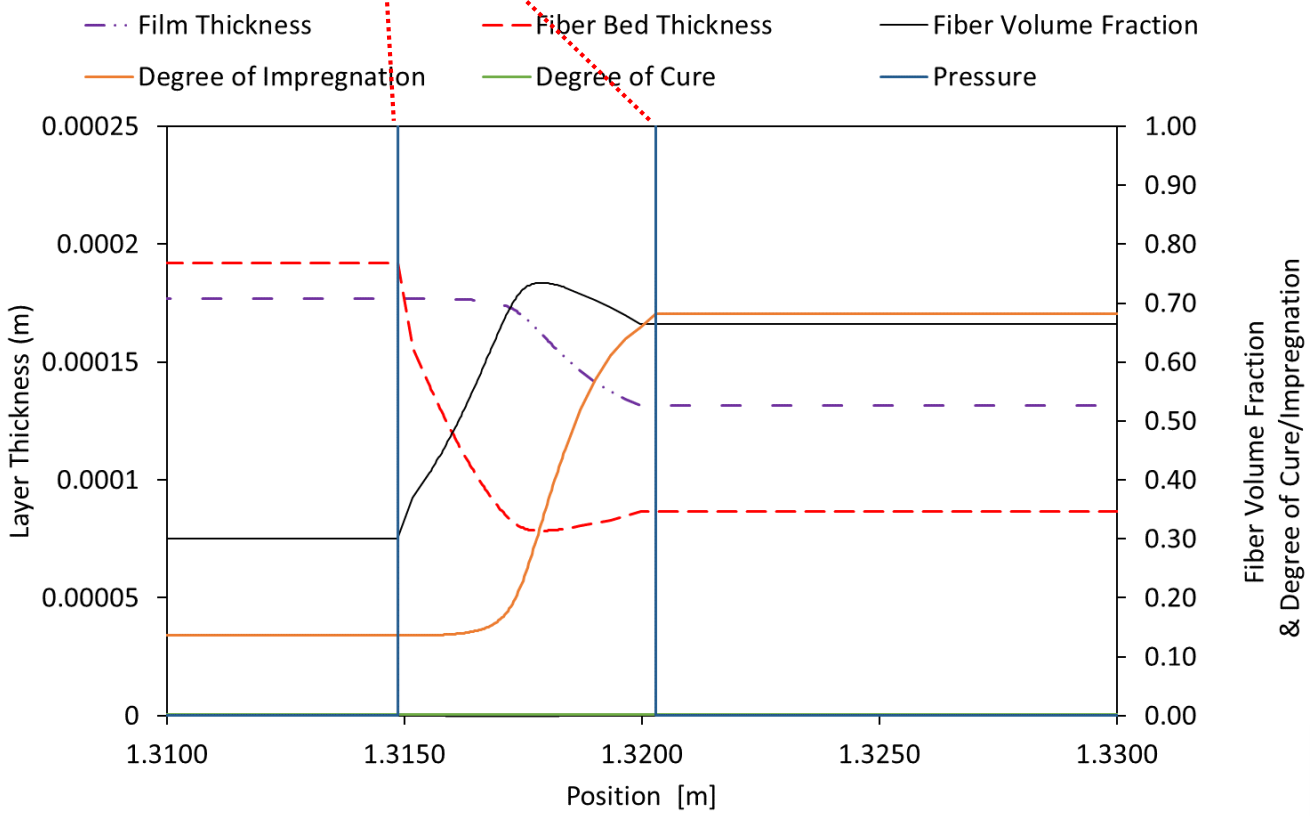
[Gutowski (1983)]

$$K = \frac{\left(1-V_f\right)^3 R_f^2}{4V_f^2\, k}$$

Simulation-Guided Process Control



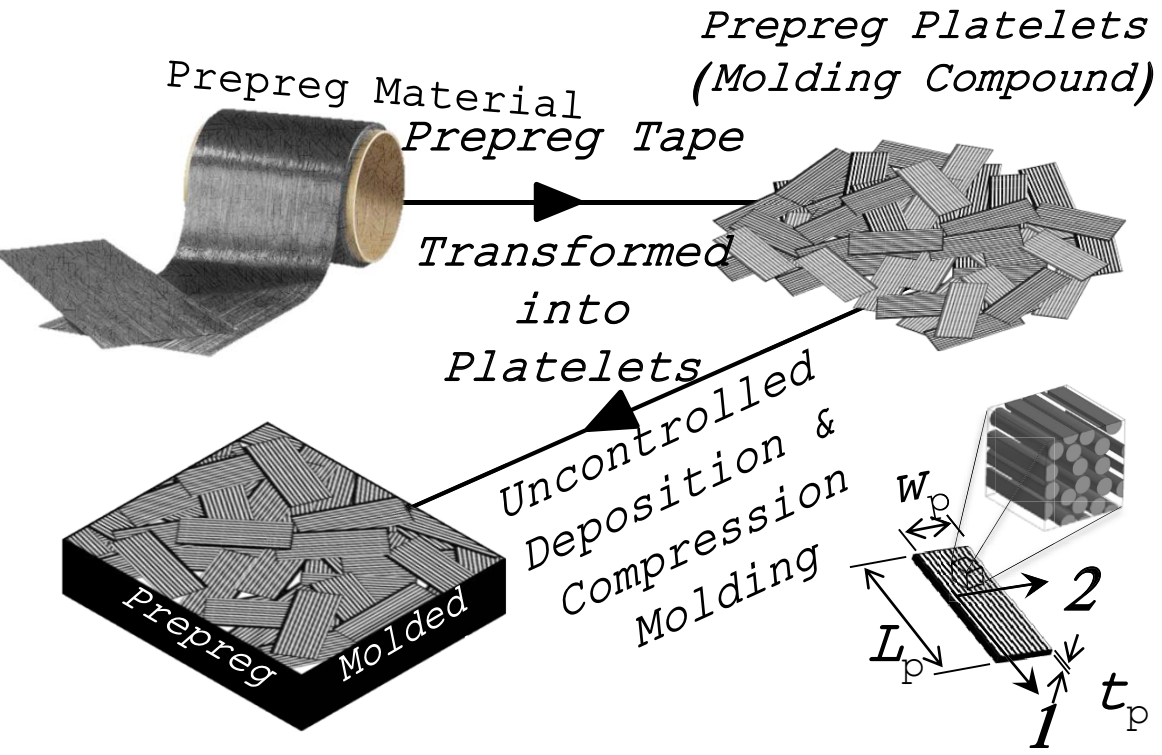
Degree of Impregnation	0.68	
Degree of Cure	0.002	
Processing Time	252	sec
Minimum Flow Channel (Hex Packing)	2.20	µm
Minimum Flow Channel ("Wavy Fibers")	1.06	µm

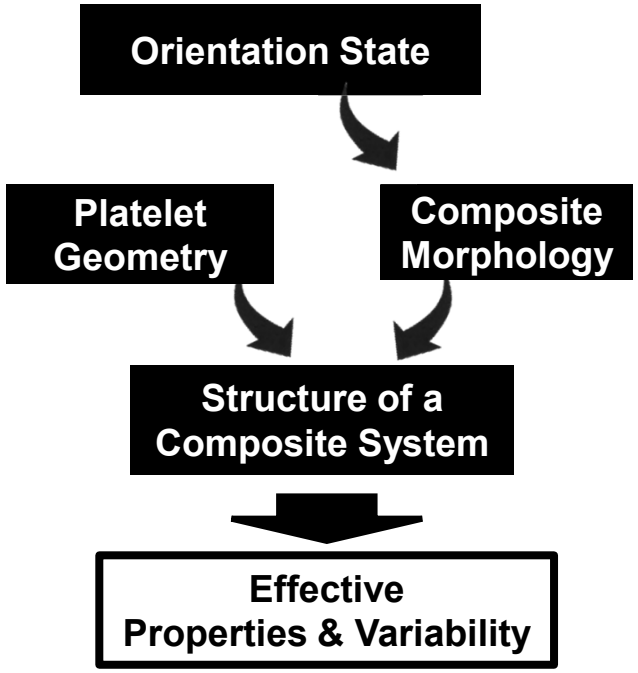


Impregnation Model, Purdue CMSC

Material Form Simulation

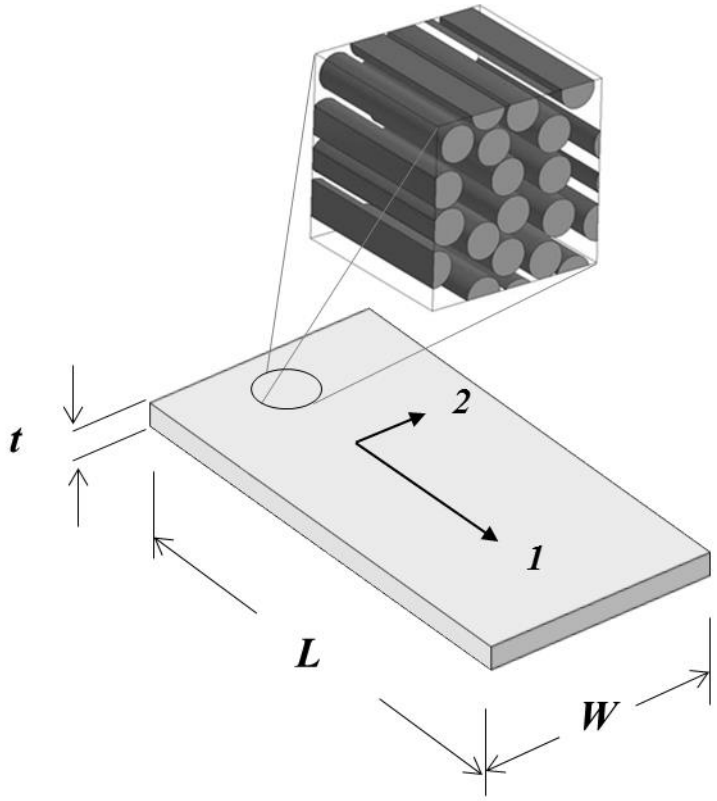
The Effect of Material Form (PPMC) on Performance Variability



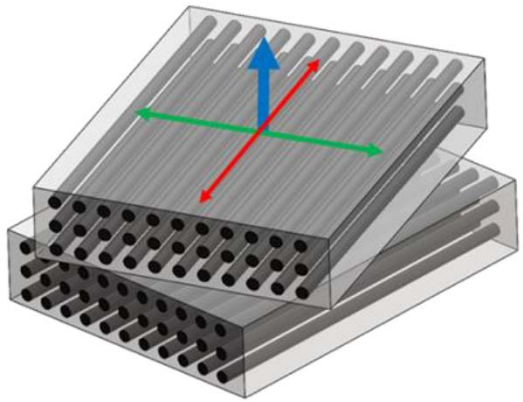


Key Descriptors for Performance

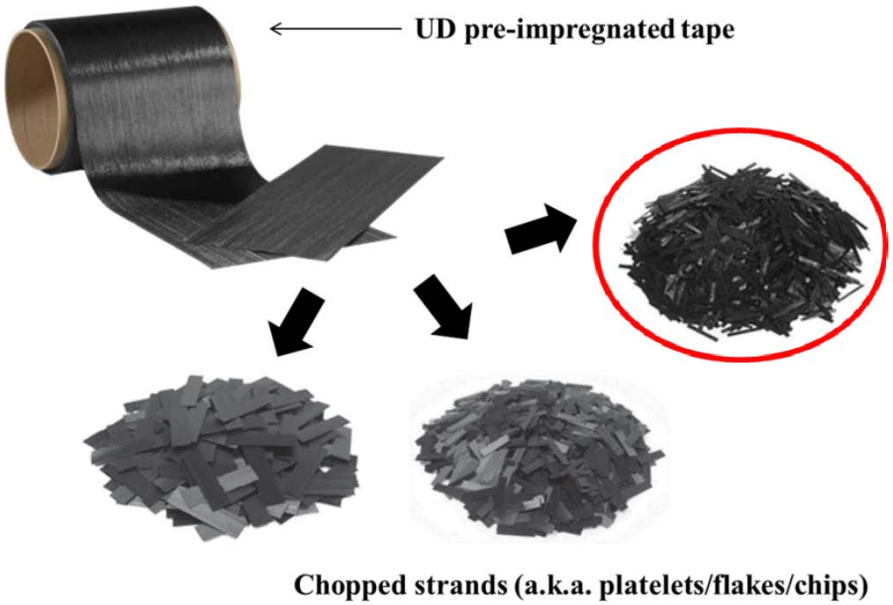
Platelet Aspect Ratio

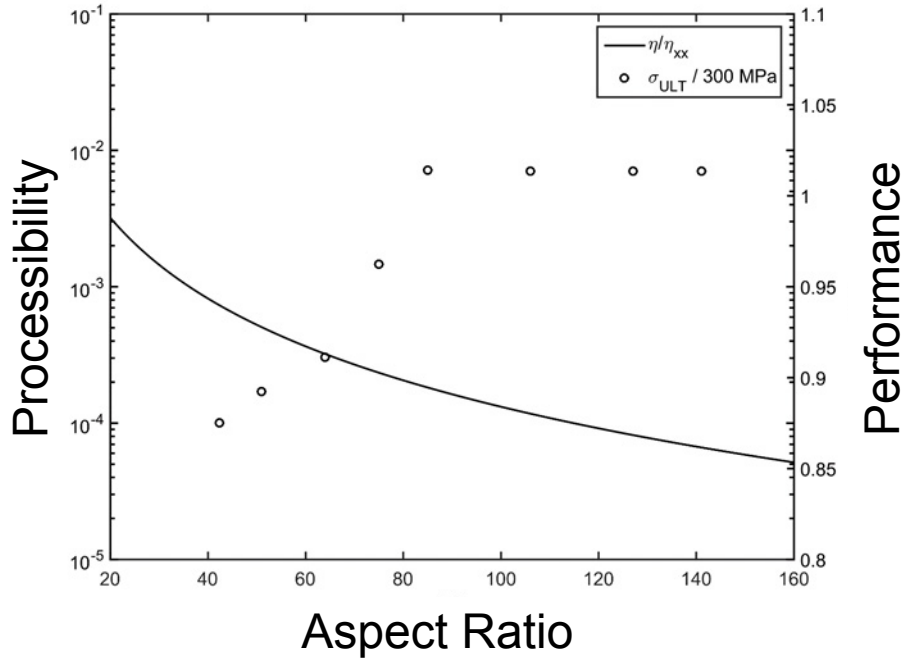


Platelet Orientation



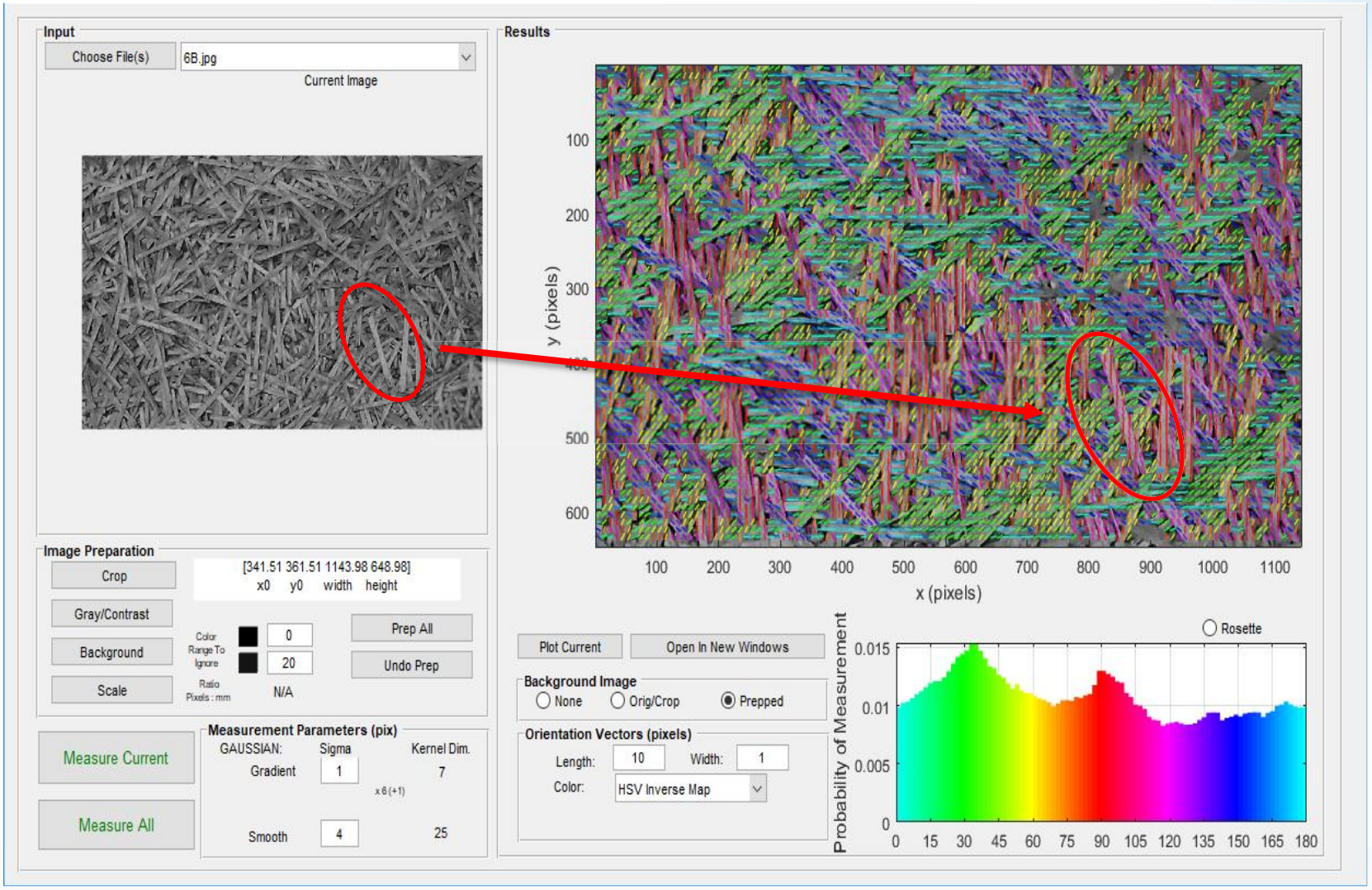
Material Form by Design





Influence of Aspect Ratio, Purdue CMSC

Characterizing Initial Orientation



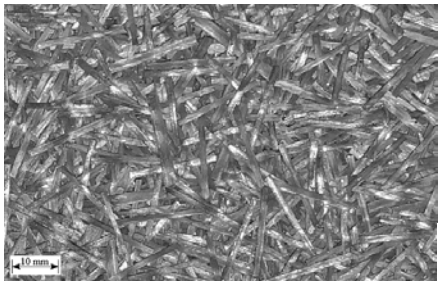
Orientation Measurement, Purdue CMSC

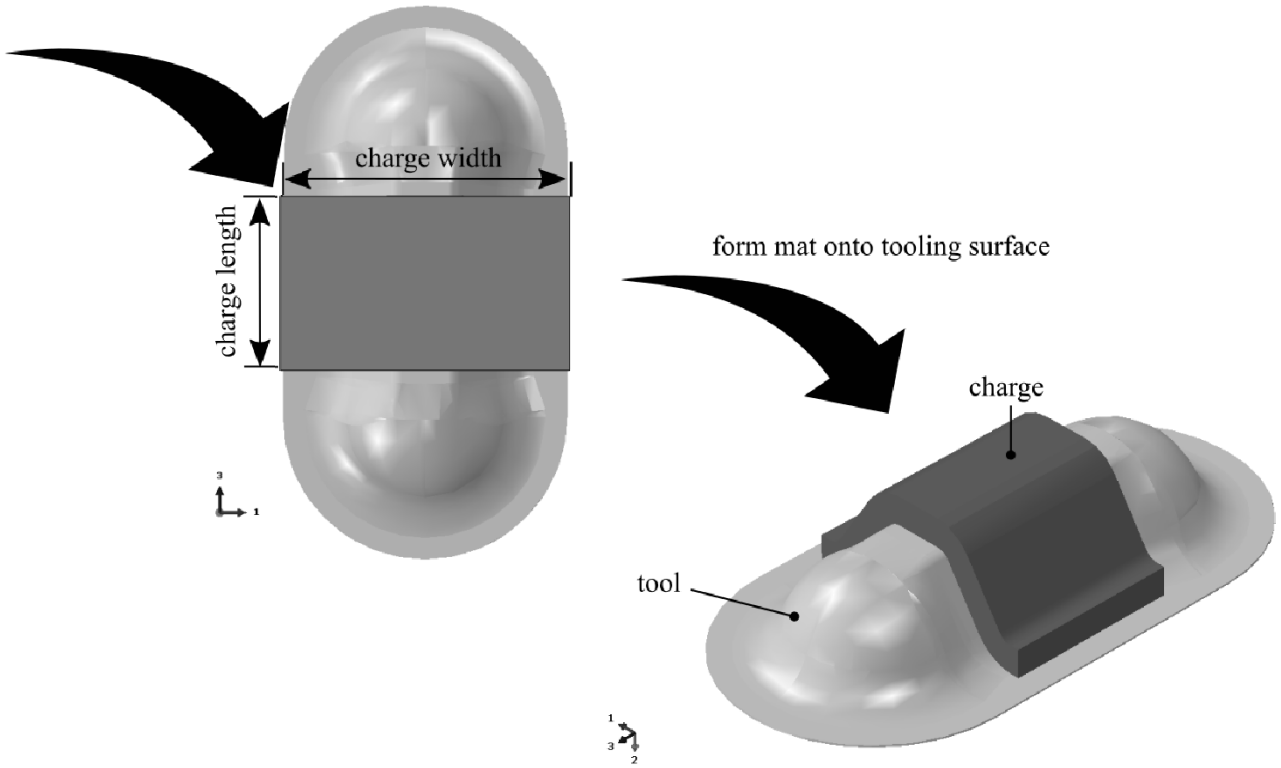
Molding Flow Simulation

Double Dome: Validation Geometry

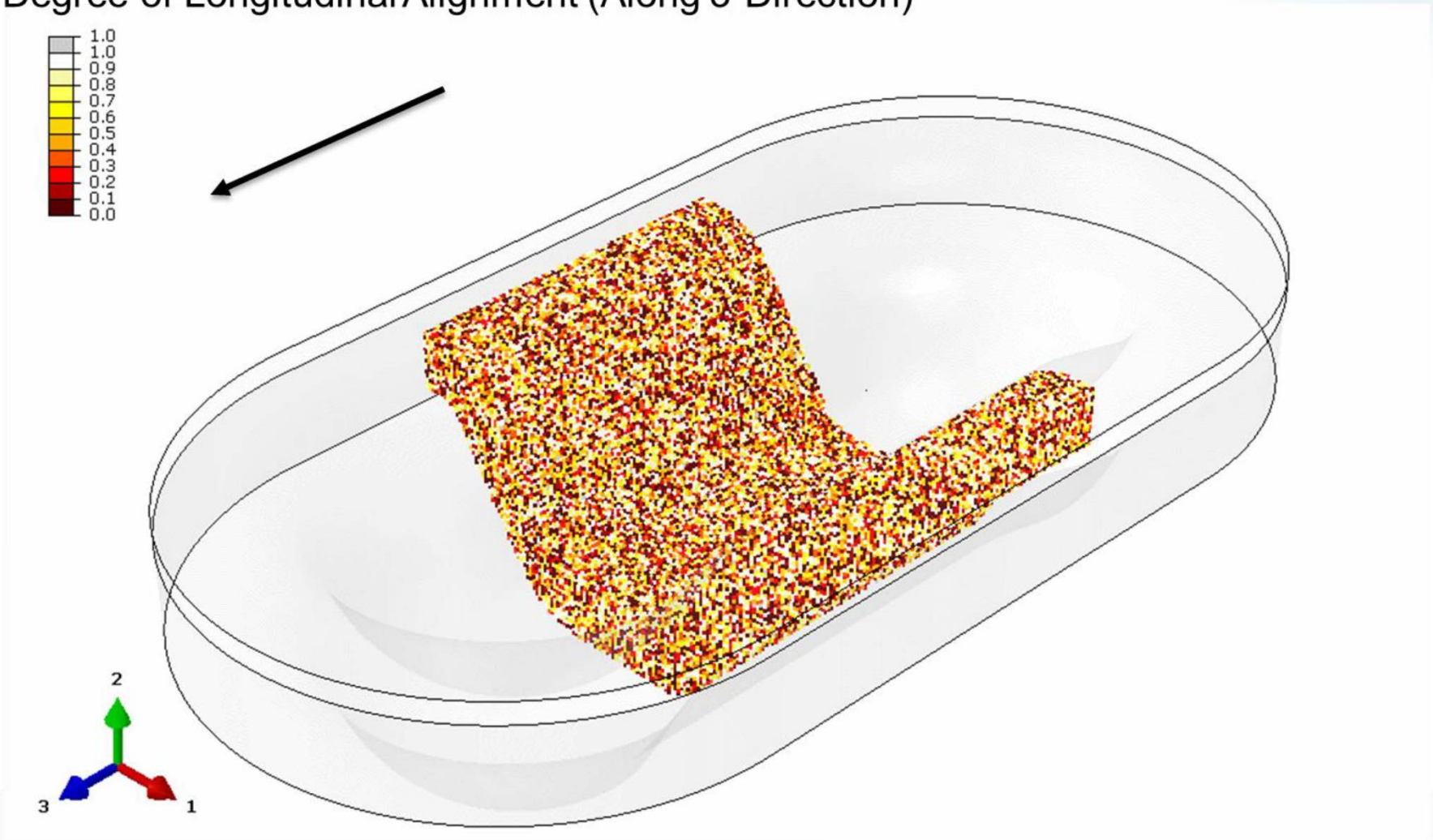
Double Dome Molding Simulation

Mat material form





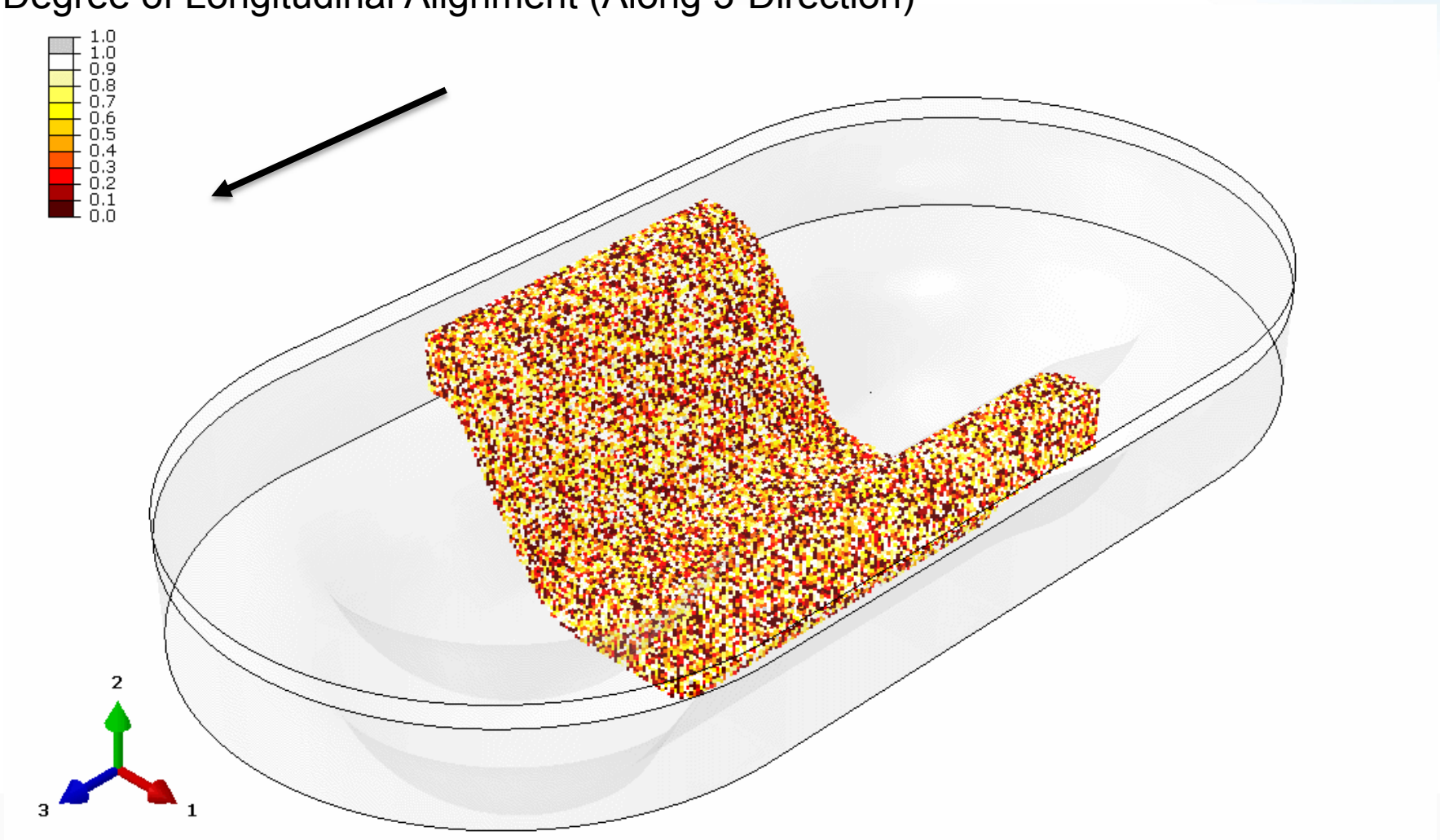
Double Dome Flow Simulation



Molding Simulation in Abaqus, Purdue CMSC

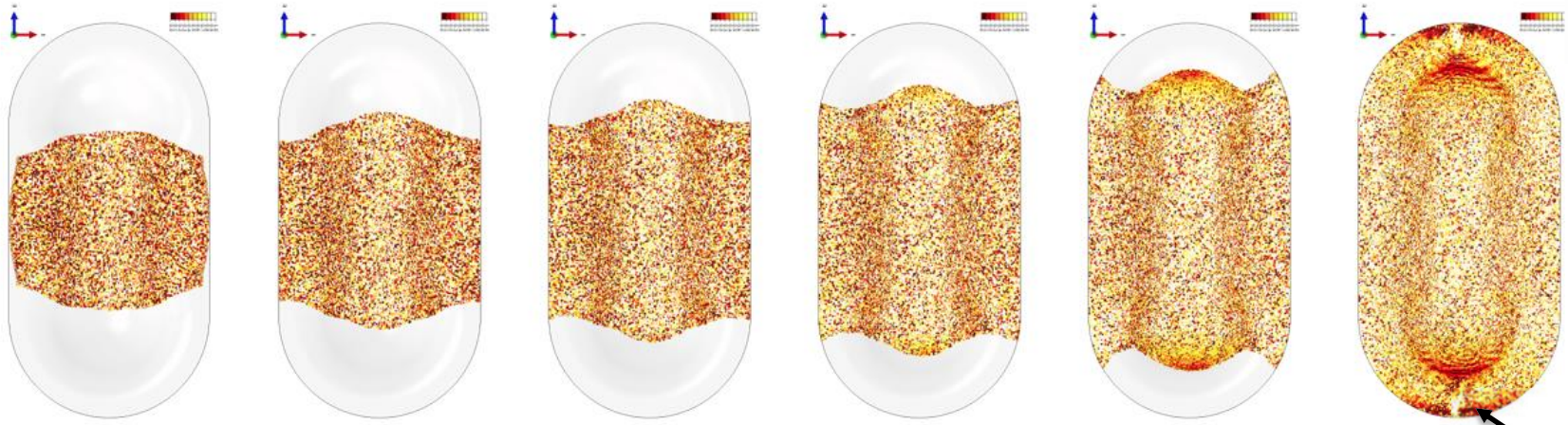
Double Dome Flow Simulation

Degree of Longitudinal Alignment (Along 3-Direction)



Molding Simulation in Abaqus, Purdue CMSC

Flow Validation Against “Short Shots”

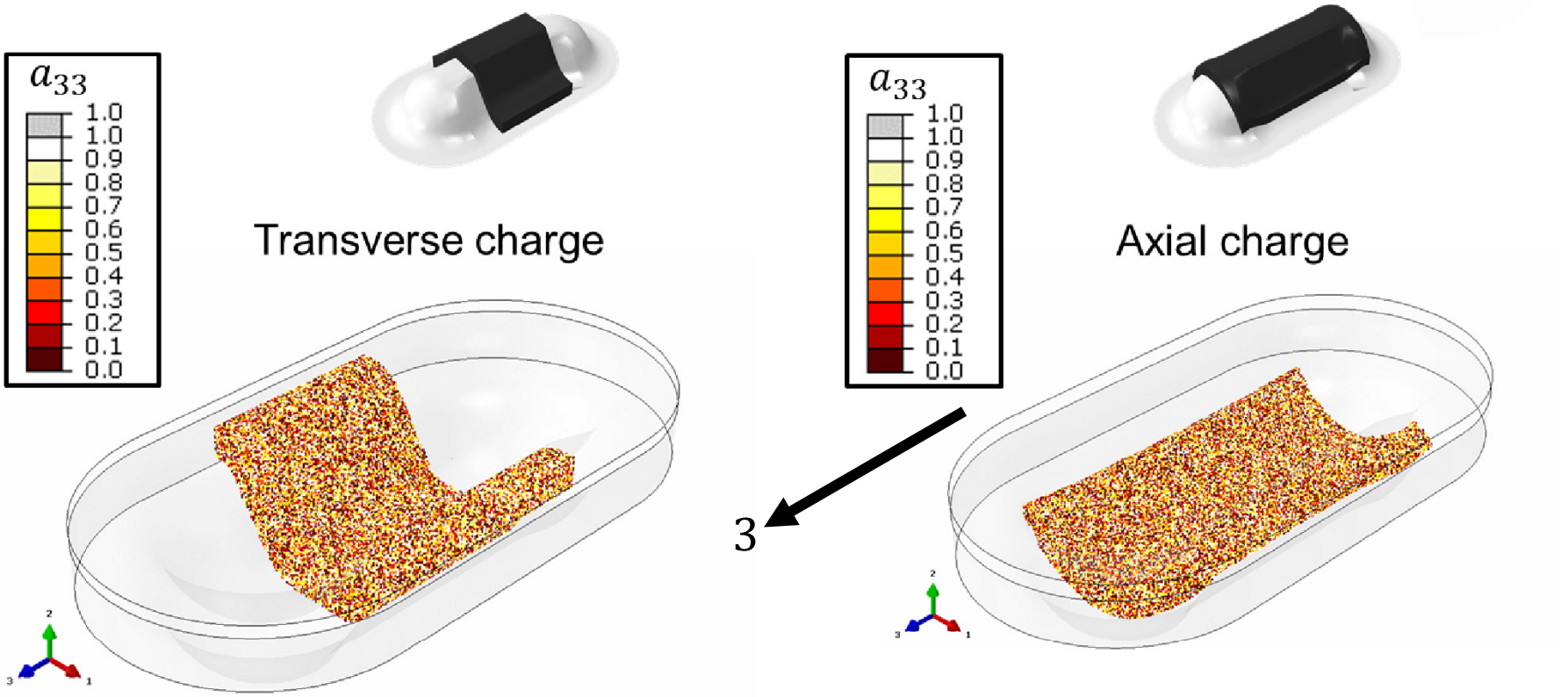


Purdue Molding Simulation “Snapshots”

Knit line prediction confirmed

Dow Molding Experiment “Short Shots”

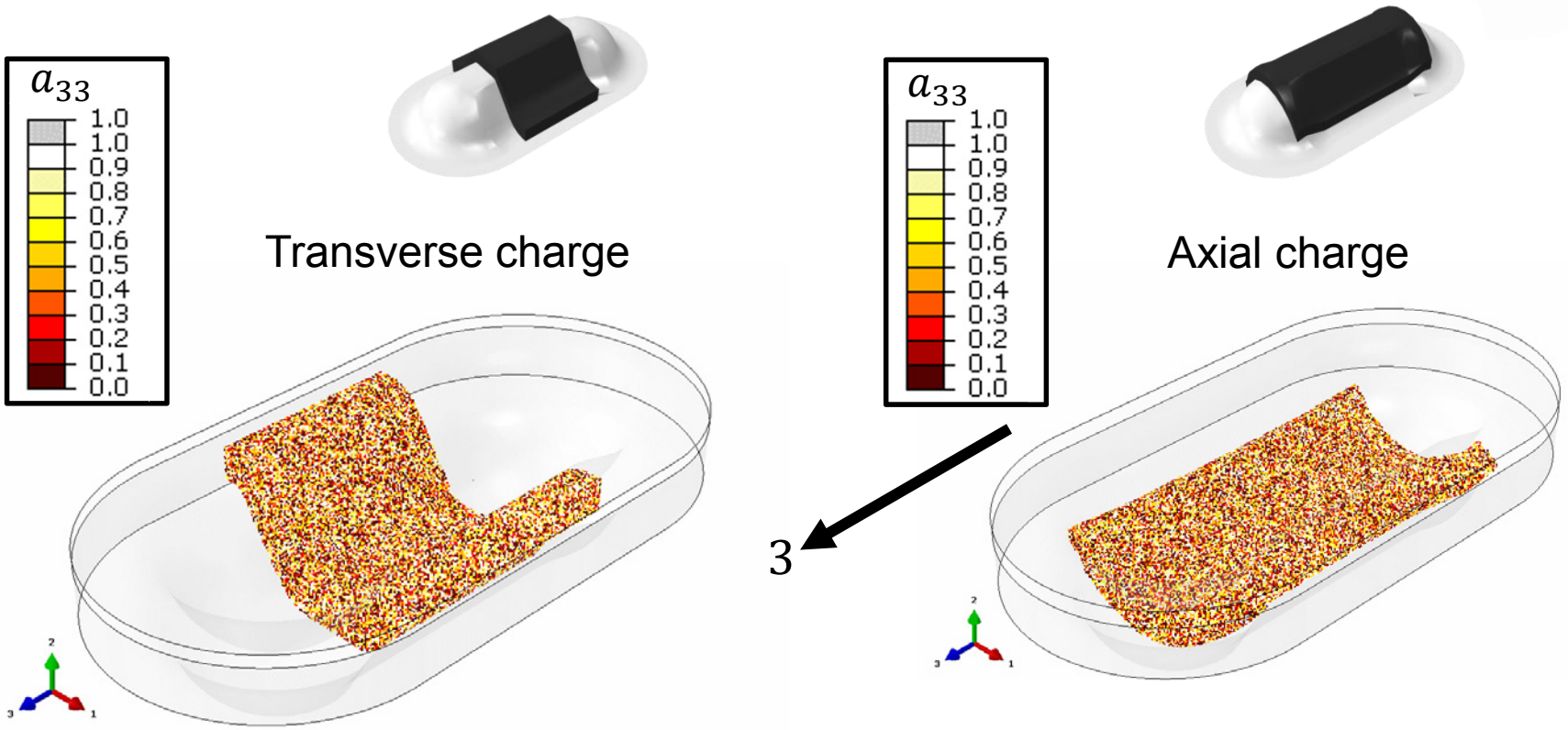
Orientation Engineering through Charge Placement



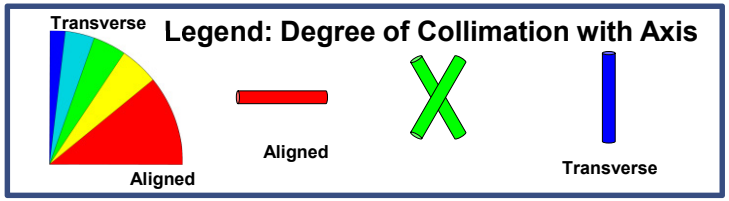
x_3-direction extension gives high a_{33}

Orientation state remains primarily random

Orientation Engineering through Charge Placement

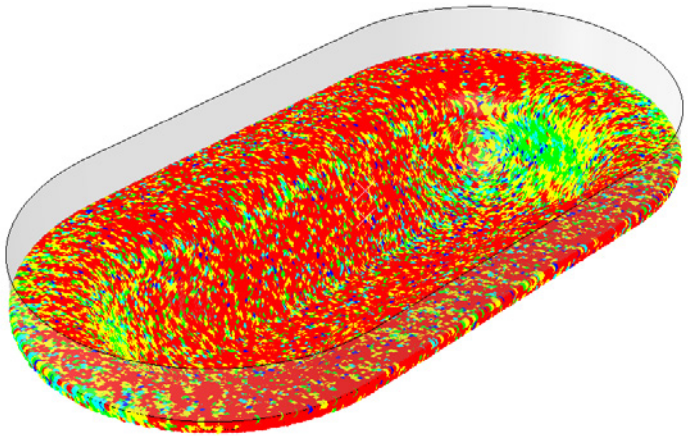


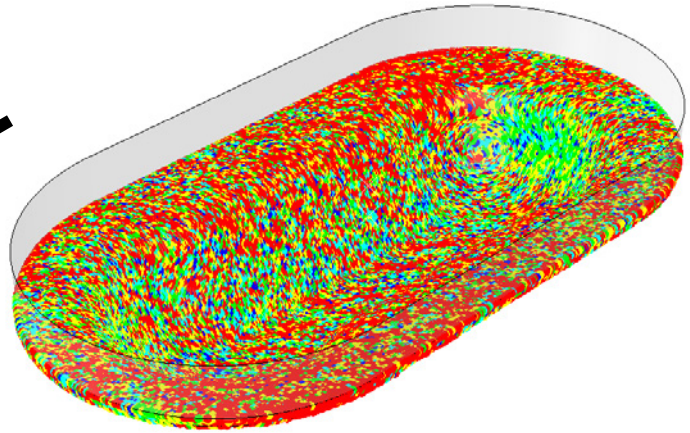
Toward Engineering Platelet Orientations



Transverse charge

Axial charge





3

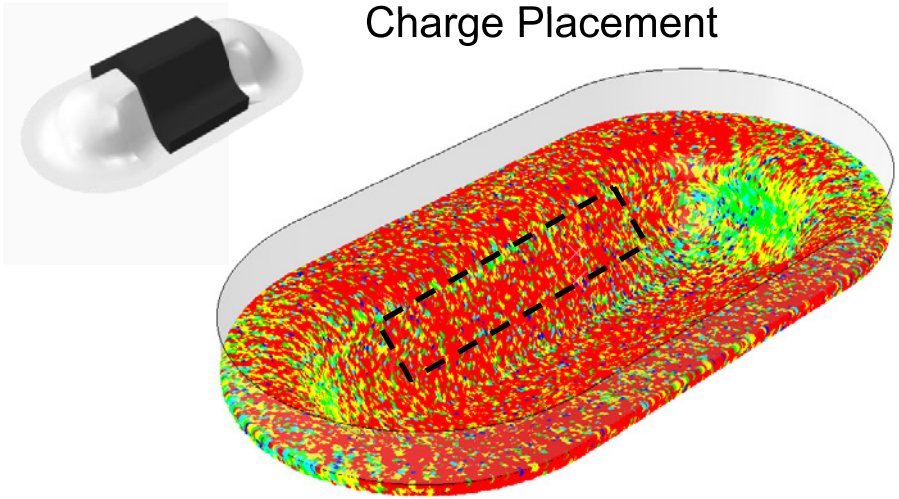
x_3-direction extension gives high a_{33}

Orientation state remains primarily random

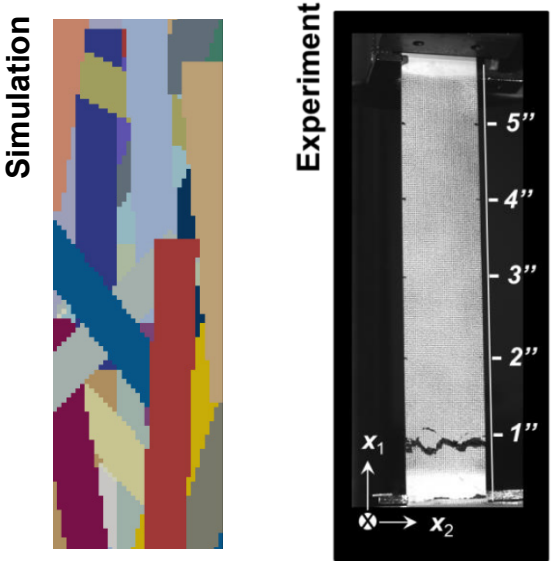
Performance Simulation

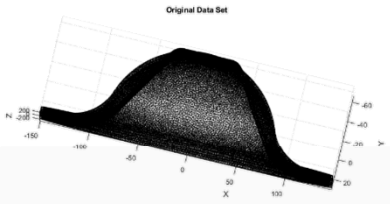
Capturing Orientations in a Performance "Virtual Twin"

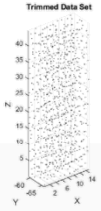
Simulate Flow:
Initial Orientation State
Charge Placement



Use Generated FE Model to **Predict Regional Mechanical Response**

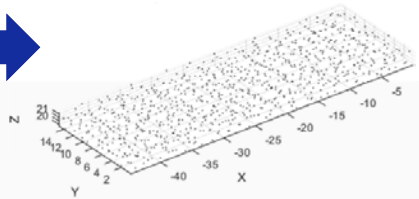


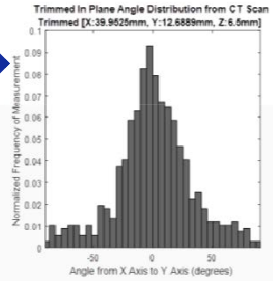




Excise Flow Simulation Data

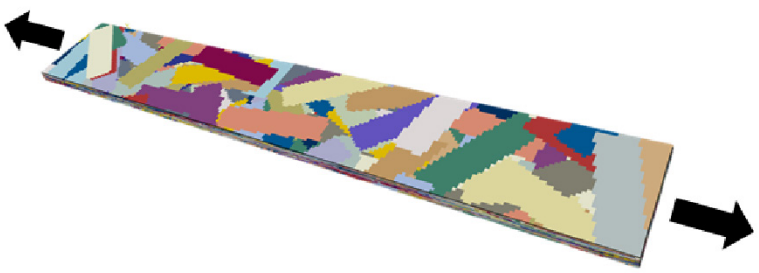
Trim and Transform
to Fit FE Geometry



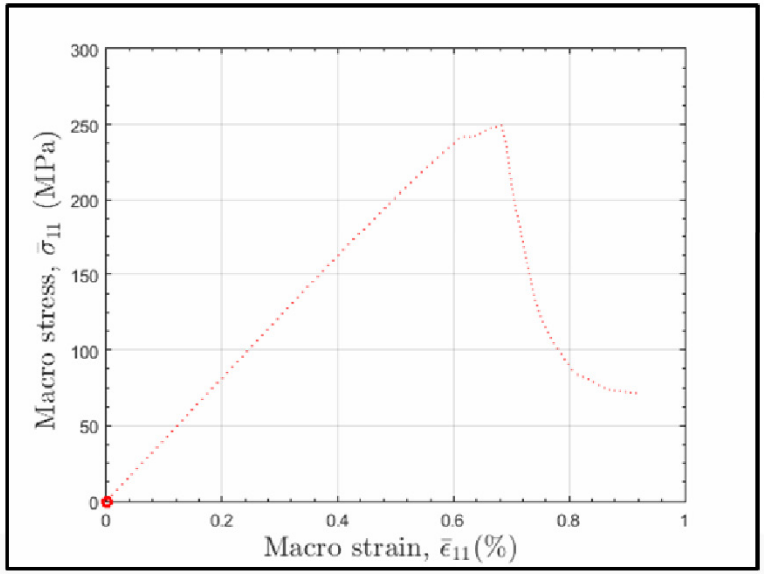


Use **Local Orientation Distribution** to Generate New Virtual Bar

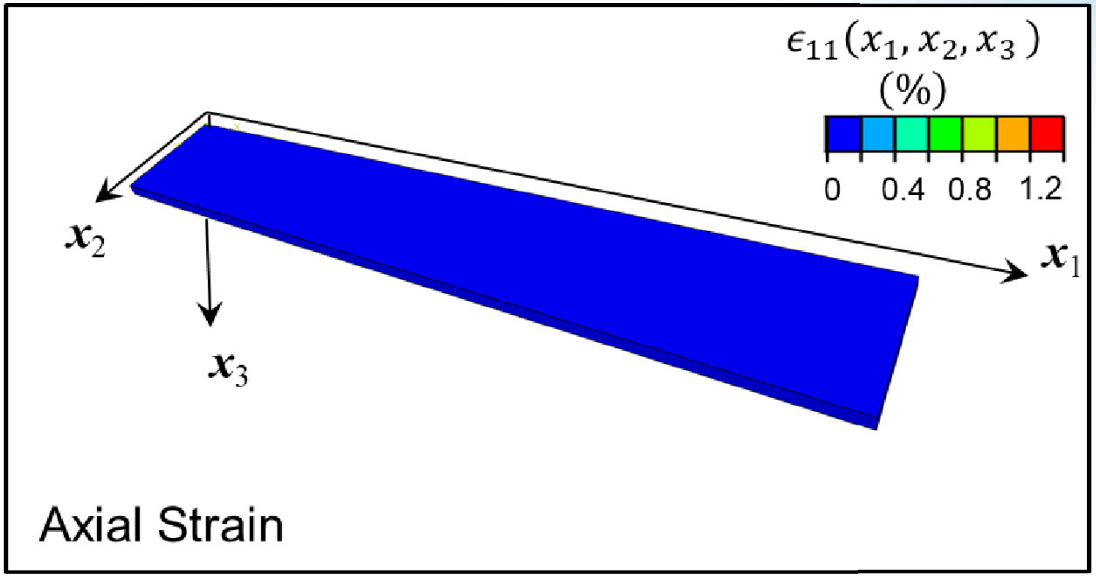
Local Orientations Matter!



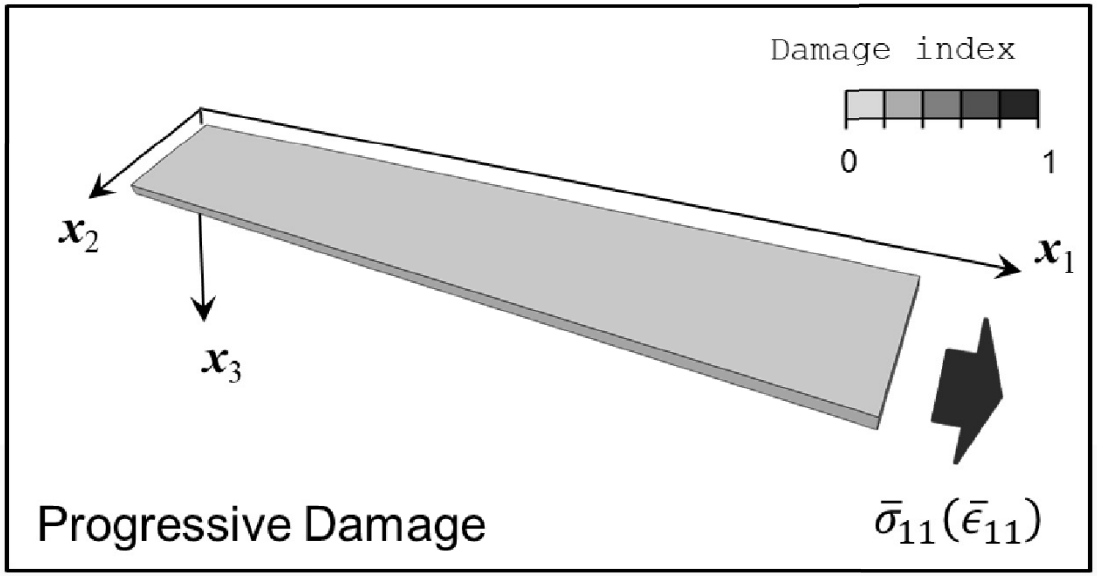
Manufacturing-Informed Tensile Specimen



Stress – Strain



Axial Strain

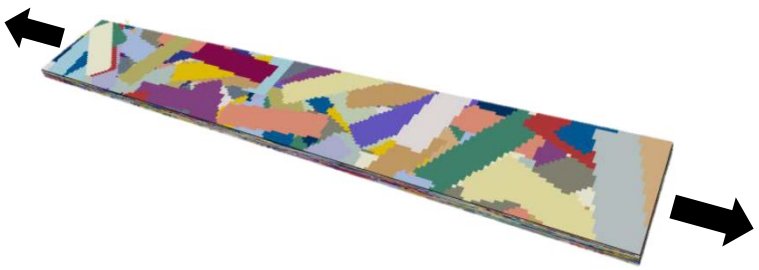


Progressive Damage

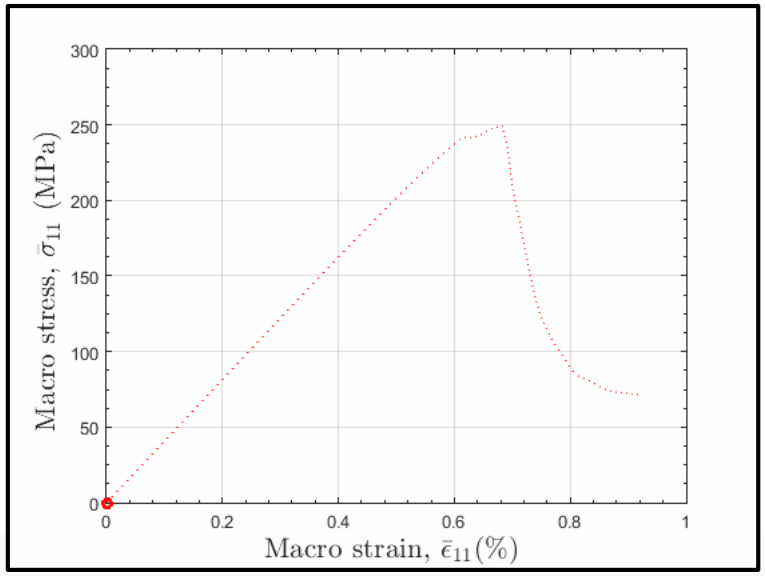
$\bar{\sigma}_{11}(\bar{\epsilon}_{11})$

Progressive Failure Analysis in Abaqus, Purdue CMSC

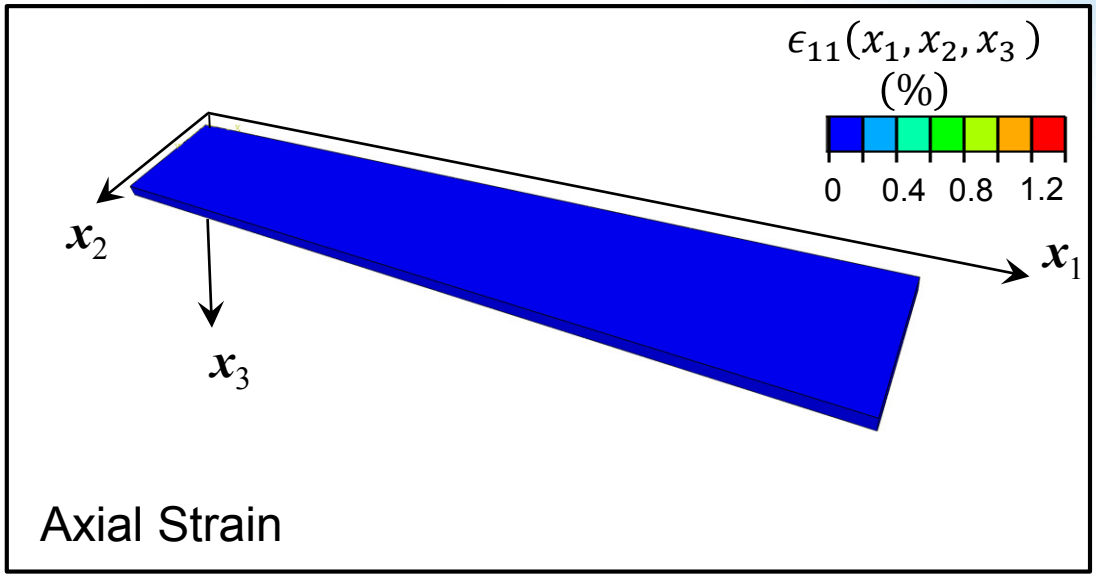
Local Orientations Matter!



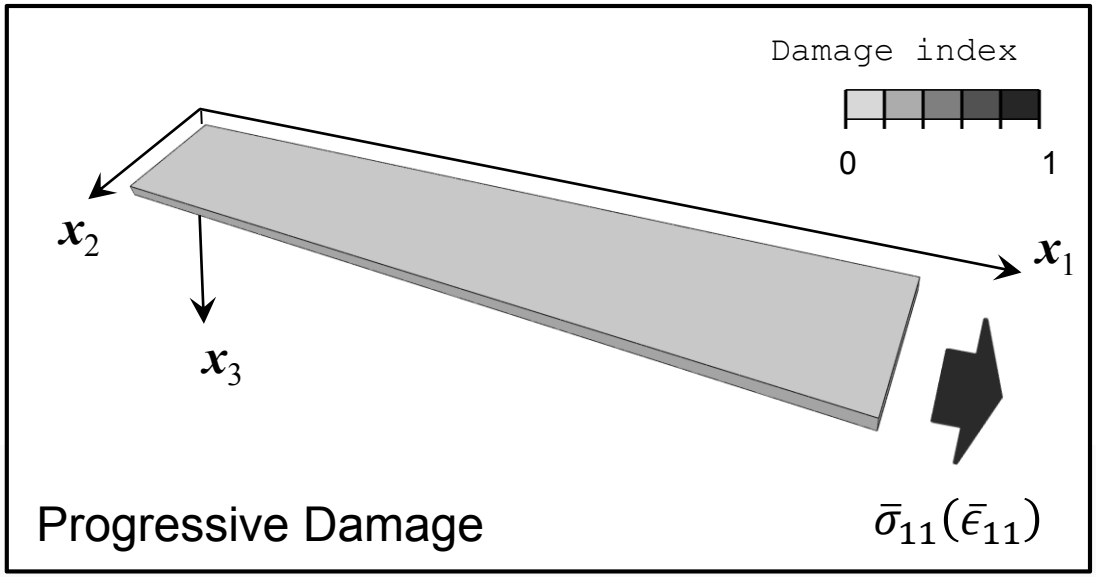
Manufacturing-Informed
Tensile Specimen



Stress – Strain



Axial Strain

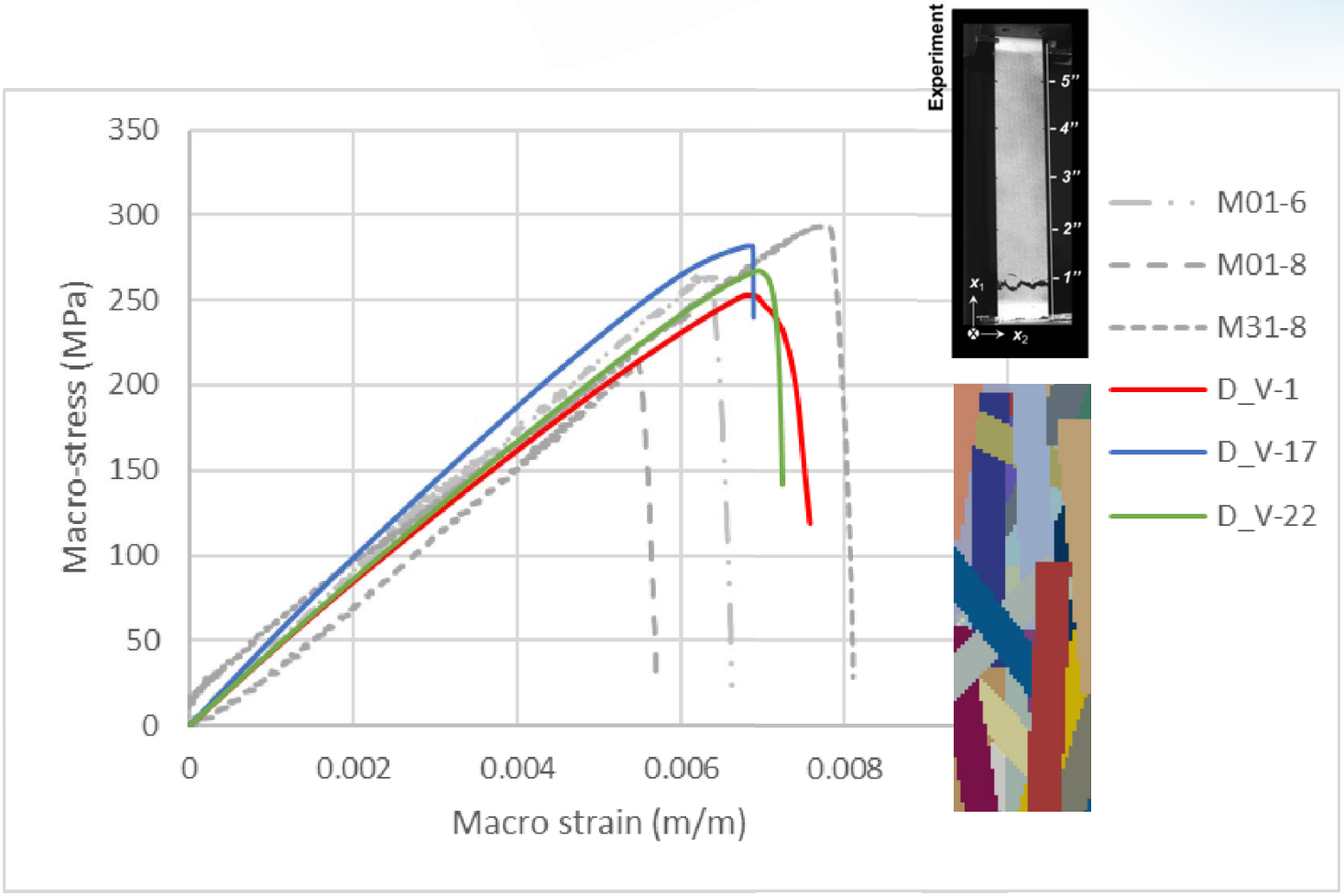


Progressive Damage

$\bar{\sigma}_{11}(\bar{\epsilon}_{11})$

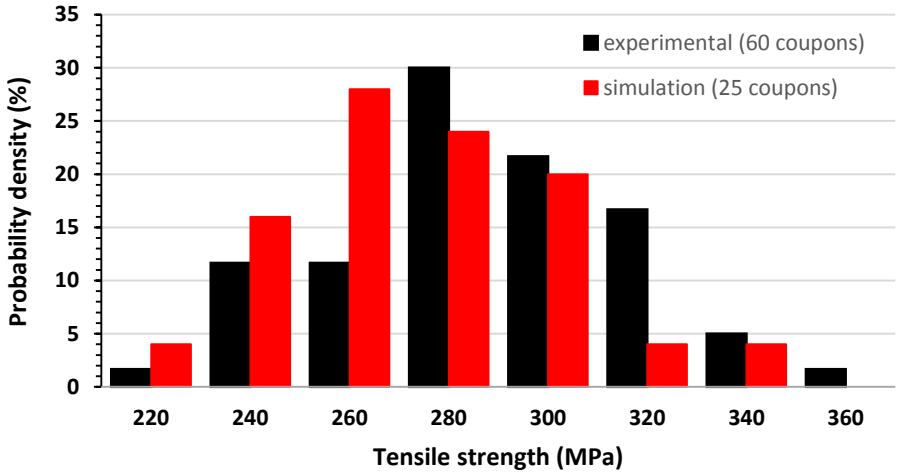
Progressive Failure Analysis in Abaqus, Purdue CMSC

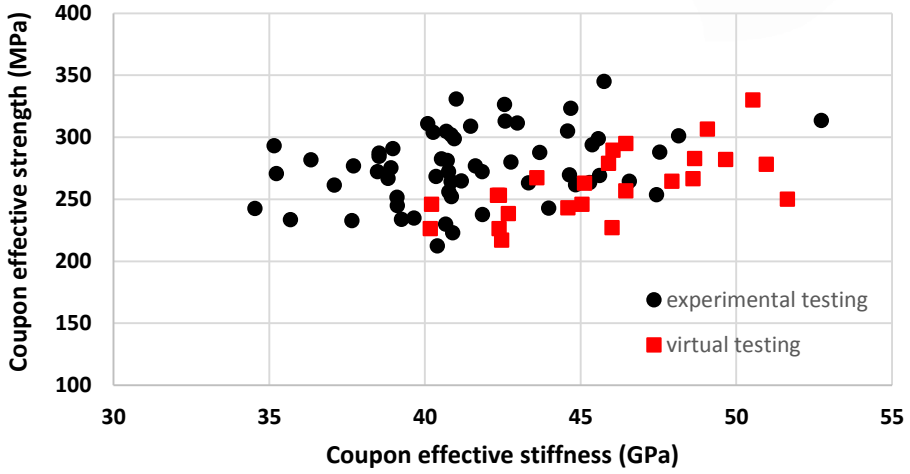
Initial Validation of Performance Prediction

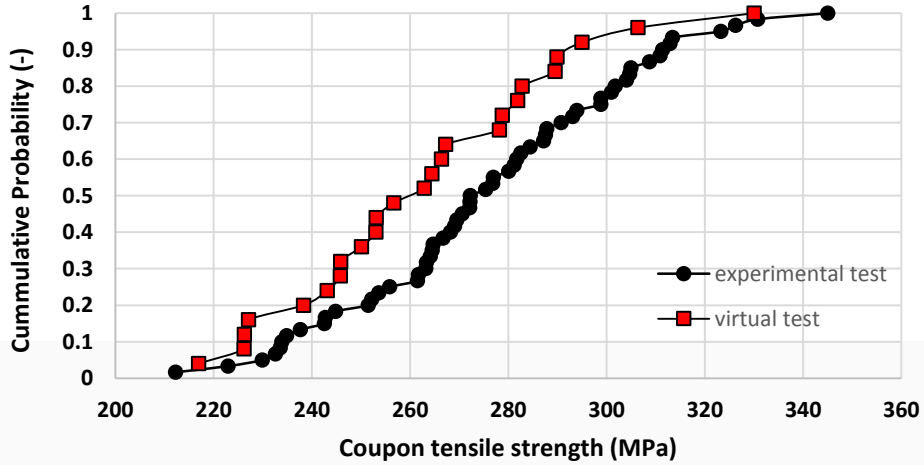


Simulation (color) Predicts Experimental (grey) Performance

Toward Virtual Material Design Allowables



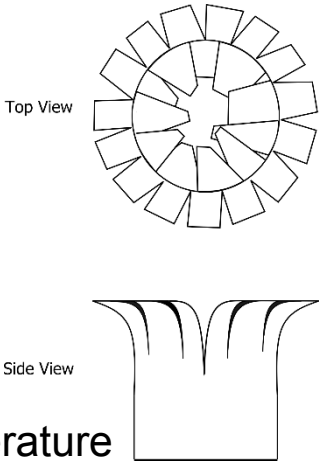
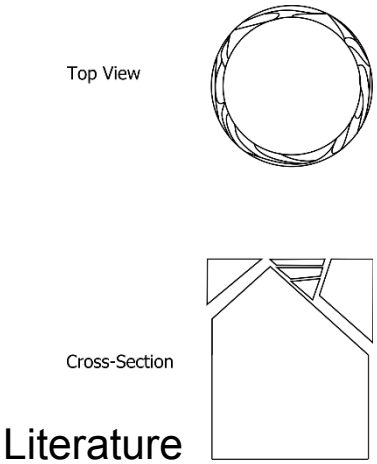
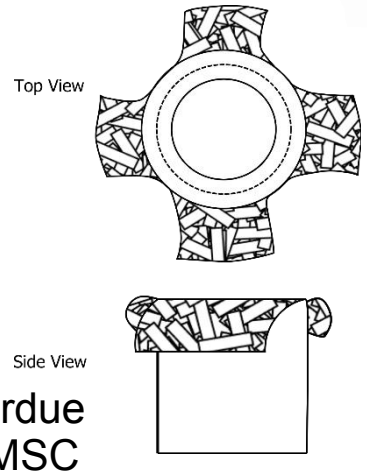




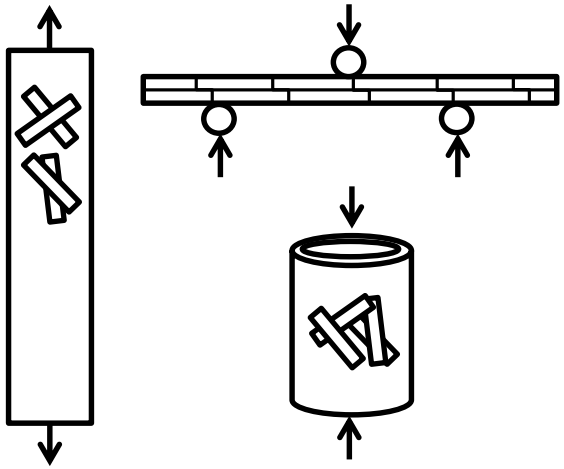
- Experimental data – generated @ DOW
- Virtual testing: from platelet thickness 0.08-0.1mm and global a11=0.5-0.6

Crash Simulation

Failure Morphology of Crush Tubes

	Layup: $[0_{14}]$	Layup: $[0_2/90_{14}]$	PPMC
Morphology			
Purdue Experiment			

Characterizing Novel PPMC for Crash



Tests for material system characterization

- Tensile test, ASTM D3039
- Compression test, modified ASTM D695
- Flexure test, ASTM D7264

```
*MAT_ENHANCED_COMPOSITE_DAMAGE_TITLE
MAT054_FordDowMat
$#     mid        ro          ea          eb          (ec)        prba        (prca)      (prcb)
         2   1800.01.40000E117.440000E97.440000E9       0.017       0.017       0.017
$#     gab         gbc         gca        (kf)        aopt        2way
5.730000E95.730000E95.730000E9         0.0         2.0         0.0
$#      xp          yp          zp          al          a2          a3      mangle
       0.0         0.0         0.0         0.0         0.0         1.0         0.0
$#      vl          v2          v3          dl          d2          d3      dfailm      dfails
       0.0         0.0         0.0         0.0         1.0         0.0        0.05        0.05
$#   tfail        alph        soft        fbrt       ycfac      dfailt      dfailc         efs
1.00000E-9         0.0         0.5         0.0         2.0        0.05       -0.05         0.0
$#      xc          xt          yc          yt          sc        crit        beta
1.110000E91.654000E92.350000E85.860000E79.170000E7        54.0         1.0
$#     pel        epsf        epsr        tsmd       soft2
      80.0         0.0         0.0         0.0         0.5
$#  slimt1      slimc1      slimt2      slimc2      slims      ncyred      softg
       0.2         0.8         0.2         0.8         1.0         0.0         1.0
```

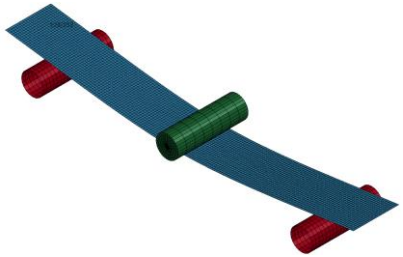
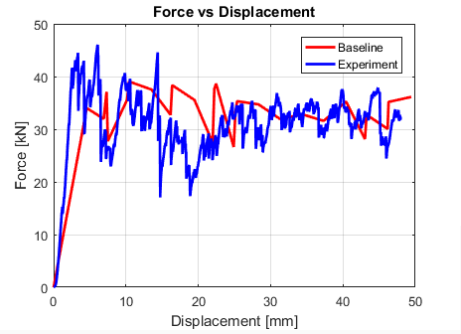
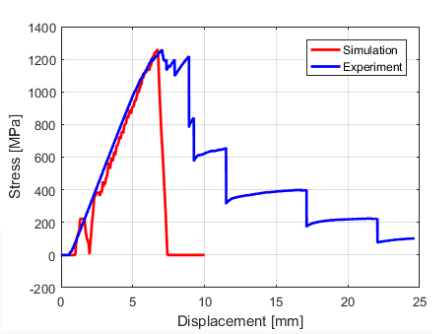
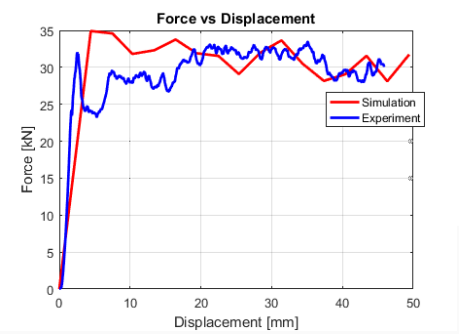
ASTM D 3039 – Tensile test

ASTM D 3518 – ± 45 test

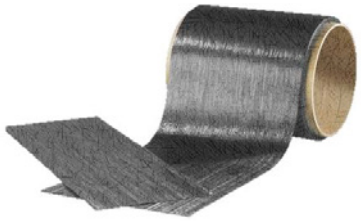
Modified ASTM D 695 – compression test

Tuning parameters

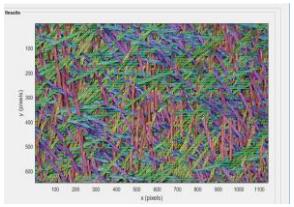
Experimental Characterization

	Layup: $[0_2/90_{14}]$	UD Flexure	PPMC
Simulation			
Experiment			
Comparison			

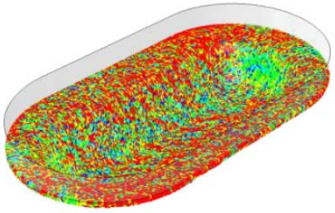
Future Process to Capture Material System



UD Tape Mechanical Characterization



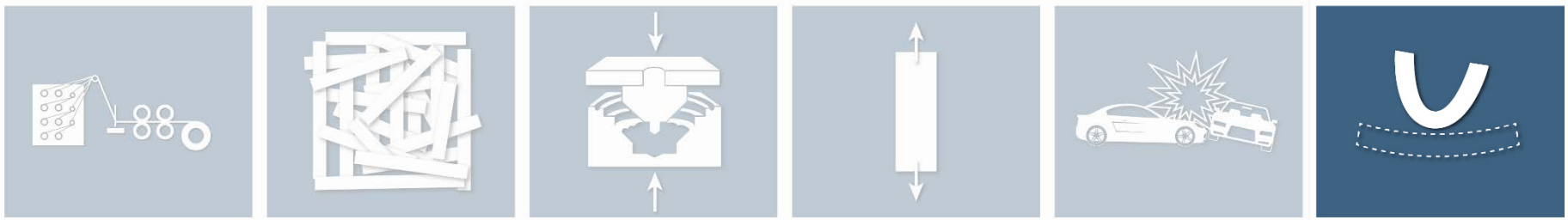
Orientation Characterization



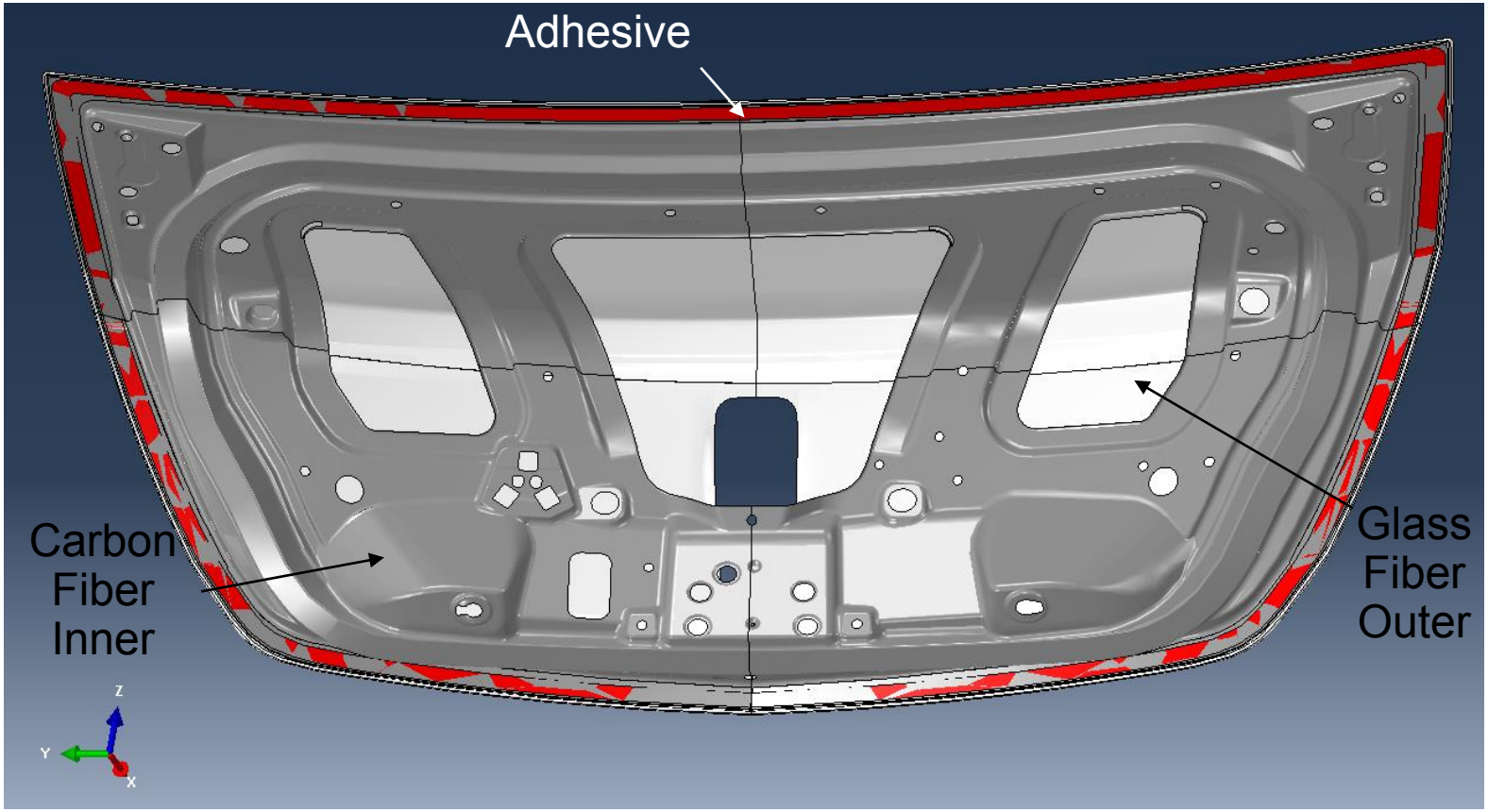
Molding Simulation

Crash Simulation

Part and Assembly Simulation

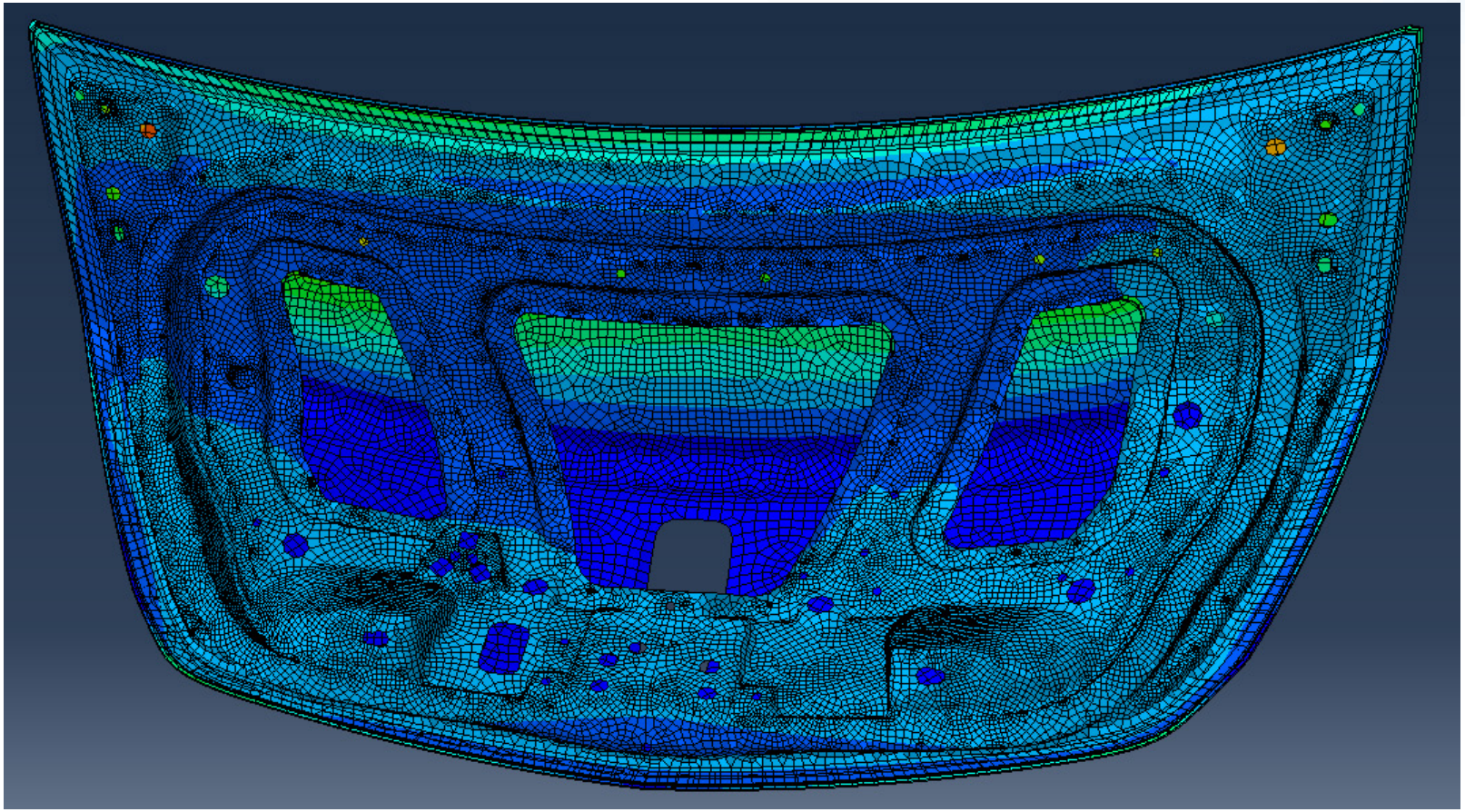


Engineering the Deck Lid



$$CTE_{CarbonInner} \neq CTE_{GlassOuter} \Rightarrow \text{Deformation \& Warpage}$$

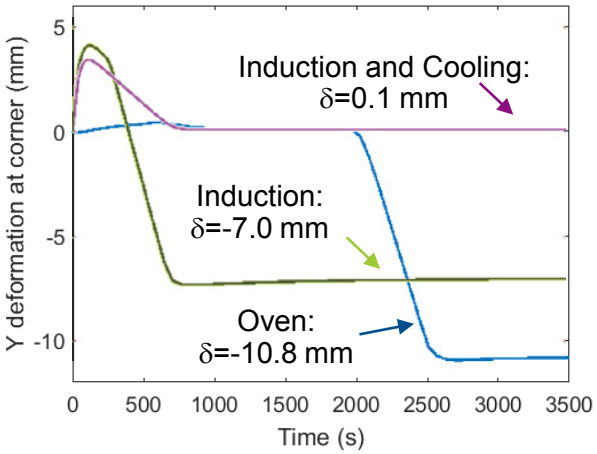
Assembly Challenges and Opportunities



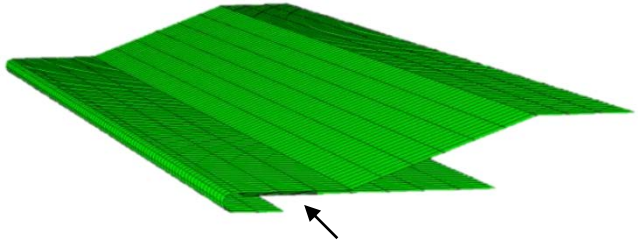
Promising Strategies

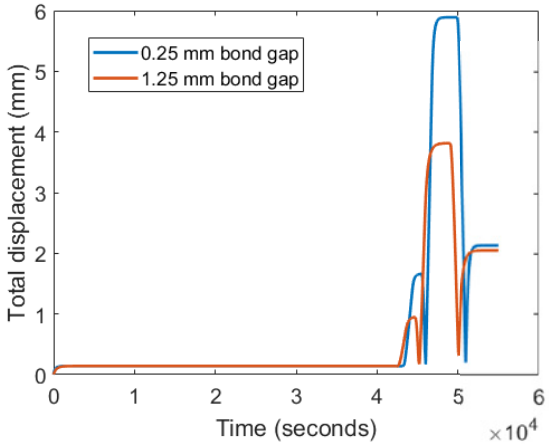
Processing Optimization:
Induction Heating and Cooling

Aluminum (0.9 mm)
Adhesive (1.0 mm)
CF SMC (3.0 mm)



Material Development:
Modifying Adhesive and Bond-line Thickness





Preform Engineering:

Simulation: the Language of Innovation Across the Automotive Supply Chain

Composites Manufacturing & Simulation Center

Impregnation | Material | Molding | Performance | Crash | Assembly

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