

# Simulation of High Pressure Resin Transfer Molding

Design, Modeling and Simulation  
Technology Area

Nathan Sharp, Ph.D.  
Validation Engineer, CMSC

# About the Presenter



Originally from Mesa, AZ.

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BSME from BYU in 2010.

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MSME from Purdue in 2012  
under Professor Doug Adams  
(now at Vanderbilt).

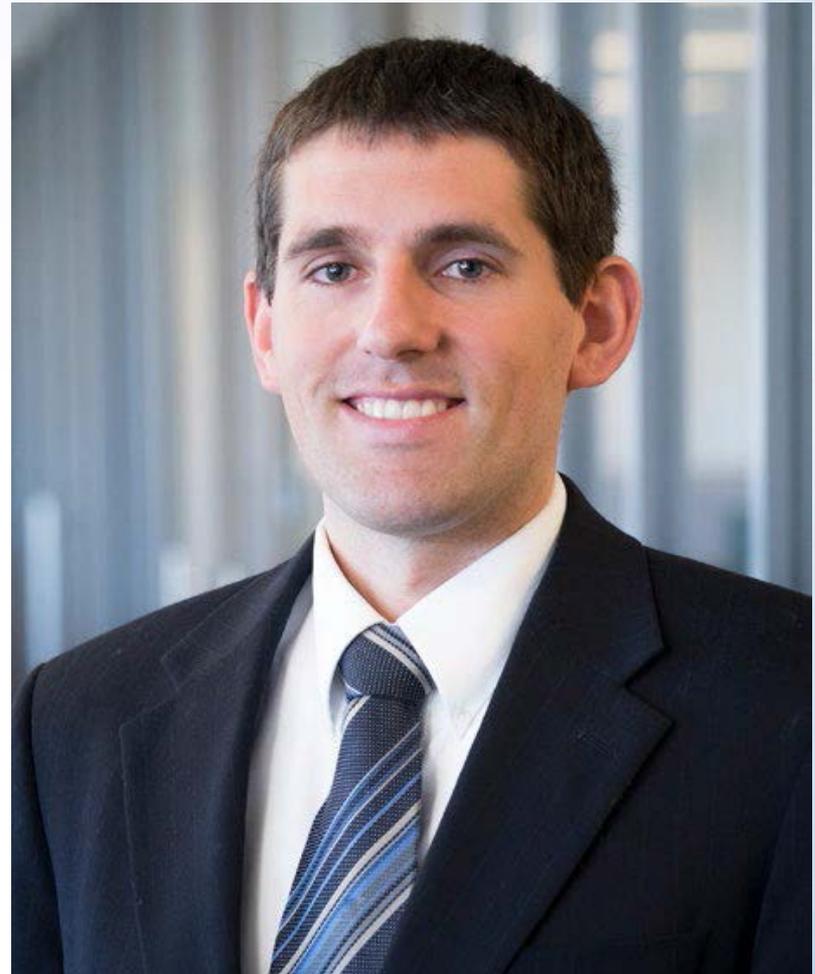
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Ph.D. from Purdue in 2015 under  
Professor R. Byron Pipes.

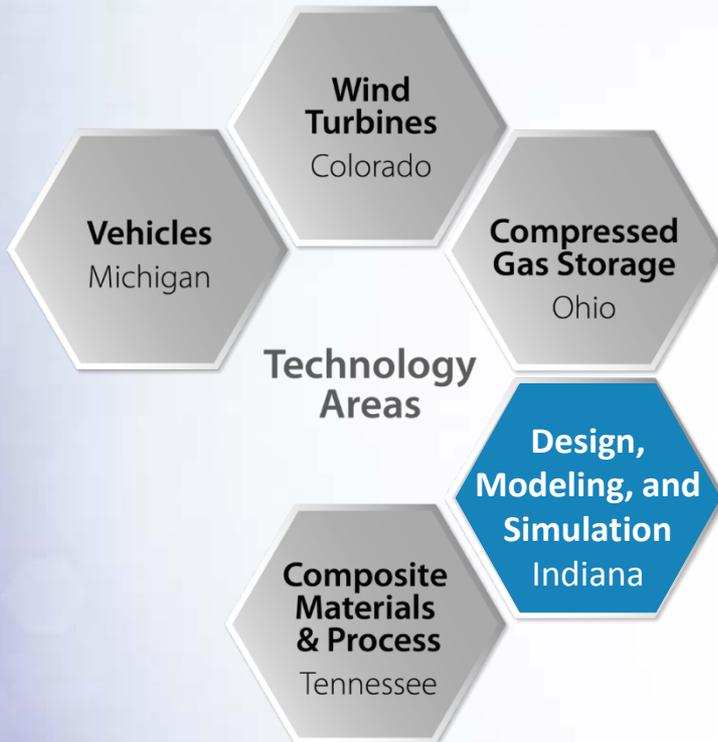
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Validation Engineer at CMSC  
since August 2015.

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# Design, Modeling, and Simulation TA



# Software and Industry Partners



## Integration of many major commercial simulation tools



PAM-FORM  
PAM-RTM  
PAM-DISTORT  
PAM-CRASH



CATIA  
SIMULIA  
BIOVIA  
ENOVIA  
DELMIA



HYPERWORKS  
MDS



SwiftComp  
VABS



COMPRO  
RAVEN



We are developing techniques to integrate commercial simulation tools so that we can create end-to-end process models that allows for manufacturing induced performance simulations.

We are involved in several projects and are eager to assist in others.

## 26 Project Team Participants with others in queue

The collage features logos for the following organizations:

- Ford
- Volkswagen
- GE
- FCA (FIAT CHRYSLER AUTOMOBILES)
- Honda
- LOCKHEED MARTIN
- Local Motors
- DowAKSA
- American Chemistry Council
- DUPONT
- ZOLTEK (Toray Group)
- PPG
- BASF (The Chemical Company)
- CYTEC SOLVAY GROUP
- Dow
- HUNTSMAN (Enriching lives through innovation)
- TORAY (Innovation by Chemistry)
- ARKEMA
- REICHHOLD
- Johns Manville
- FIBRTEC (ADVANCED POLYMER RESEARCH FOR SPECIAL APPLICATIONS)
- DASSAULT SYSTEMES
- UAM (Universal Asset Management)
- GLOBE
- Materials Innovation TECHNOLOGIES
- MVP (Magnum Venus Products)

A map of the United States is shown in the bottom right corner of the collage, with several states highlighted in blue.

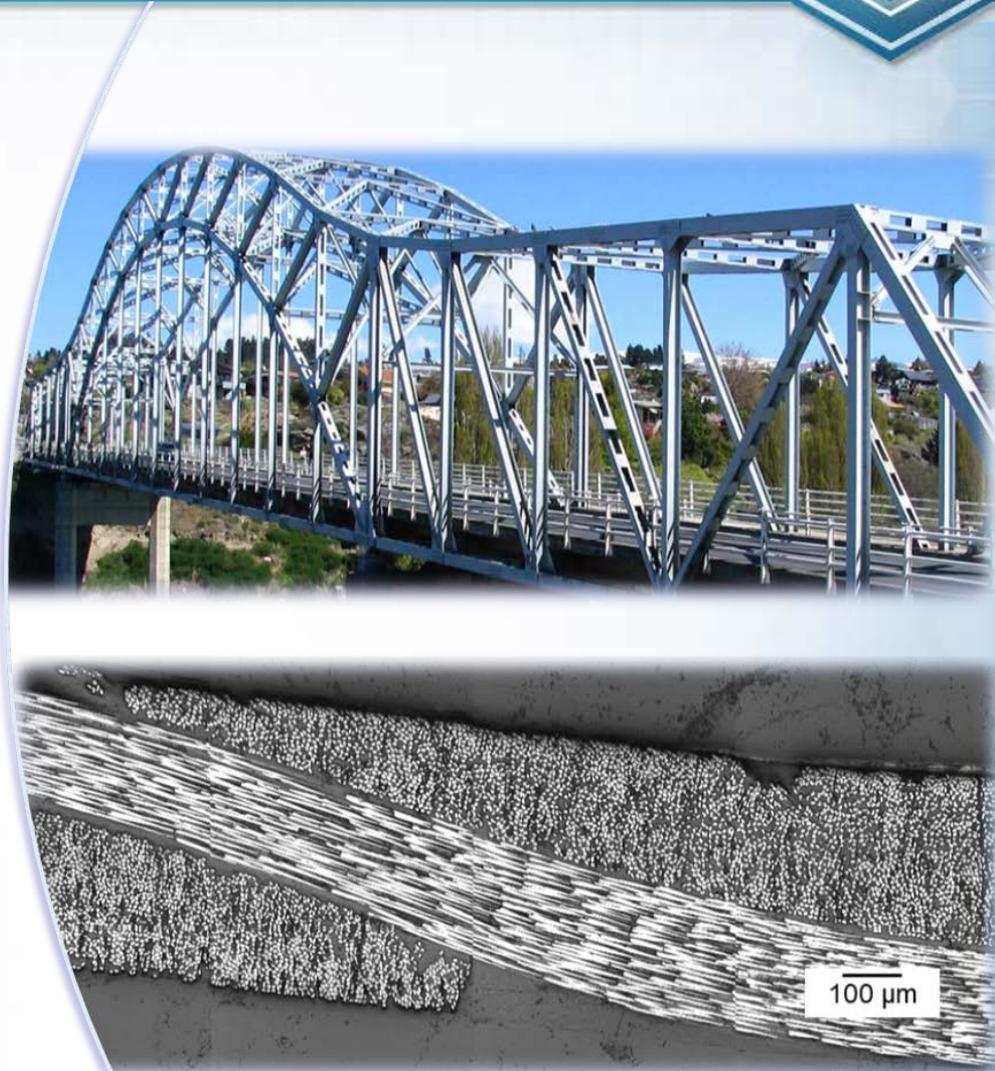
# Why Process Simulation?

Composite materials are actually **structures**.

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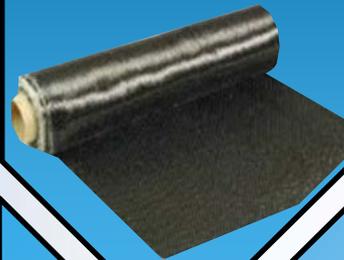
Most composite parts cannot actually be produced with the designed properties because the **manufacturing process** will **change** the **microstructure**.

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# High Pressure RTM Process Flow Diagram

Dry Fabric



Cutting & Assembly



Resin Infusion



Preforming & Draping



Heated Cure

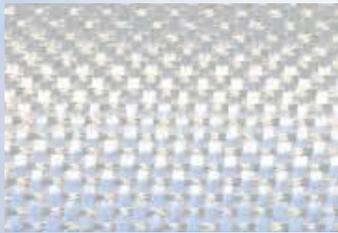


Demolding

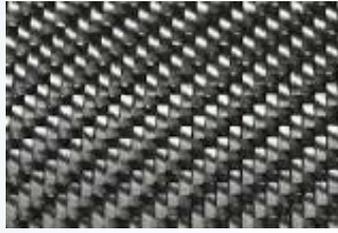


# Fabric

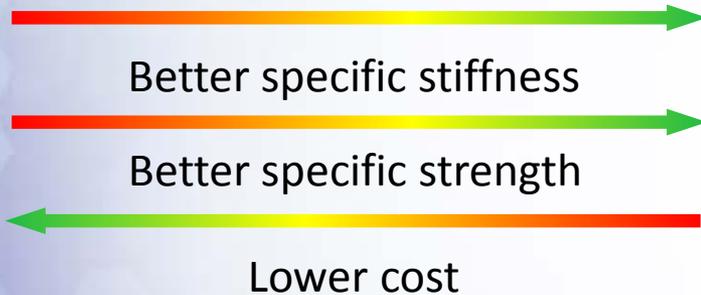
## Material Types



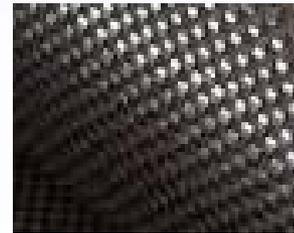
Glass



Carbon



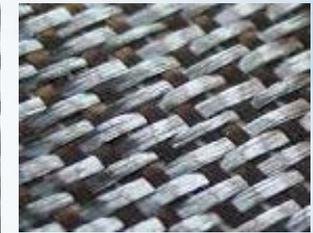
## Woven Fabric Types



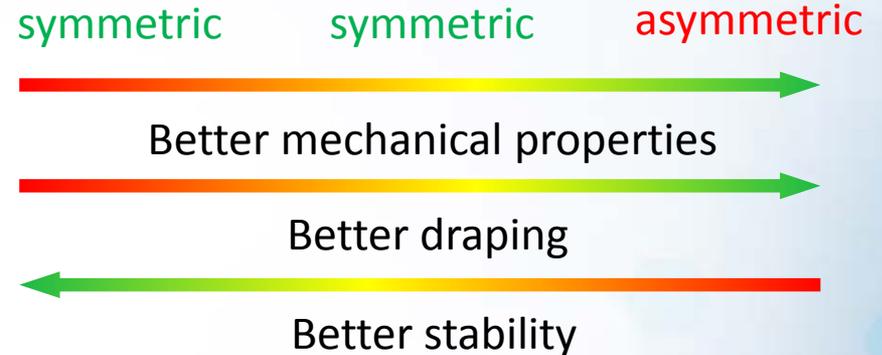
Plain Weave



Twill



Satin

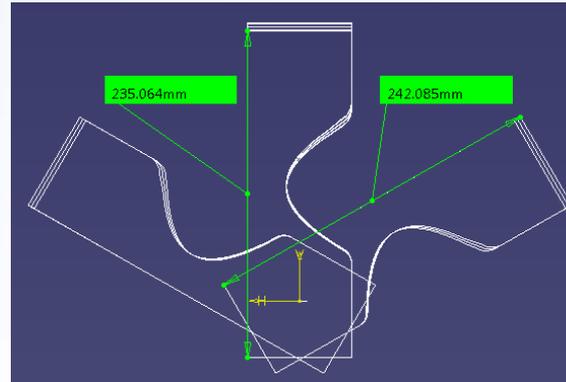
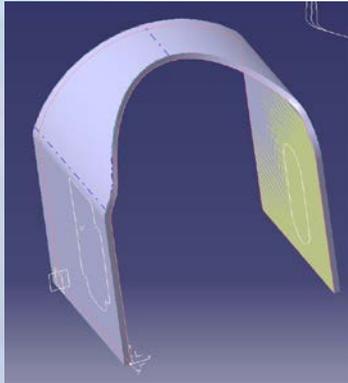


Non-Crimp Fabric



Non-crimp fabric uses stitching to create multiaxial fabrics. The lack of crimp provides better mechanical properties.

# Cutting & Assembly



Part shape definition

Flat shape definition

Flat shape creation

Once a fabric has been chosen and a part shape is generated, the flat shape needed to create the final shape can be calculated and the information is then sent to an automatic cutter to generate the flat shapes. The flat plies are then stacked into the designed configuration at which point they are ready to be placed in the mold.

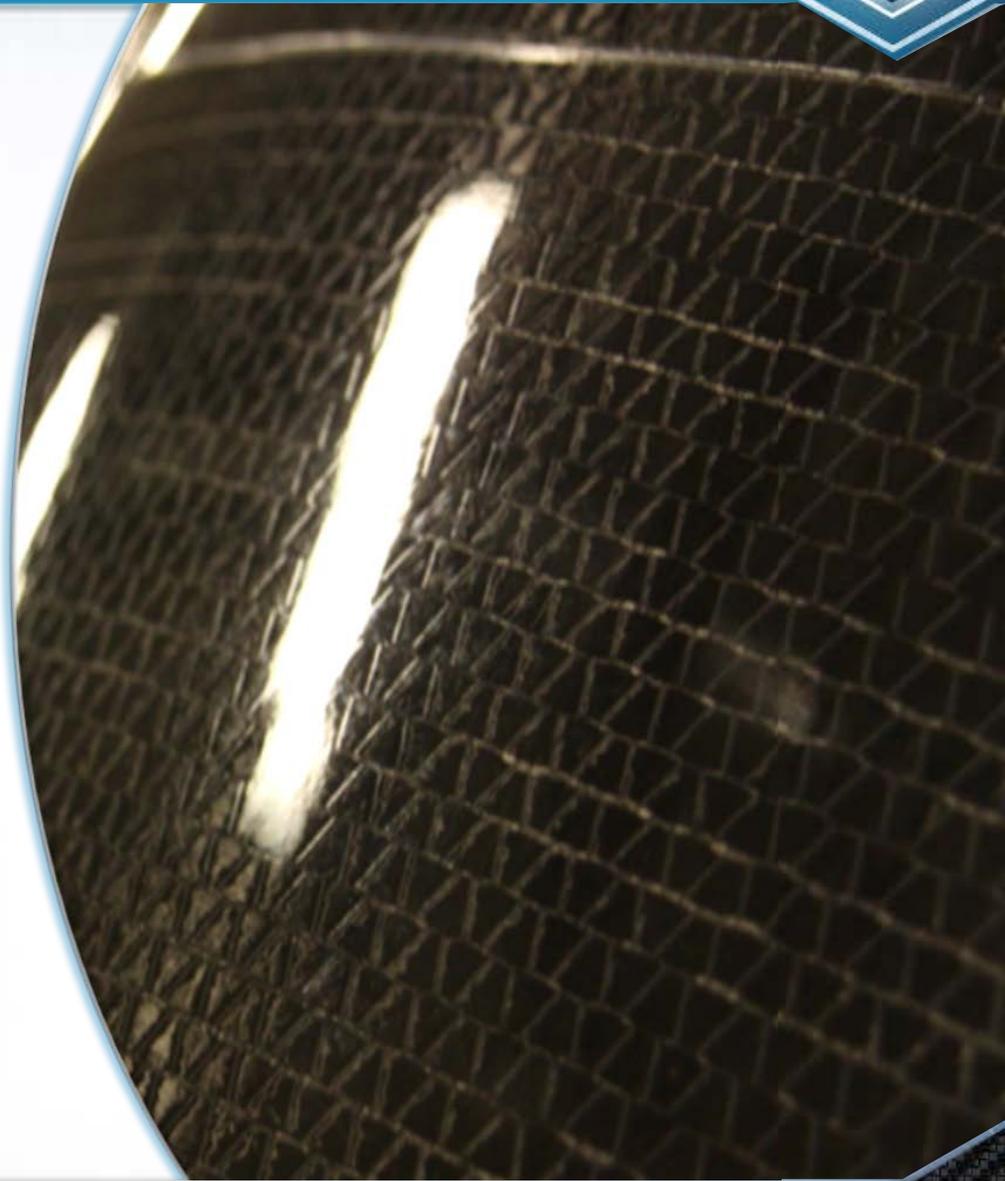
# Preforming / Draping

Fiber directions **diverge significantly** from the nominal when a fabric is formed over a **complex shape**.

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Fiber direction plays the **principal role** in determining **warping and strength**, while shear angles affect fabric permeability.

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# Infusion & Cure

Resin velocity is a function of pressure, viscosity, and fabric permeability.

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Viscosity is a function of temperature and degree of cure.

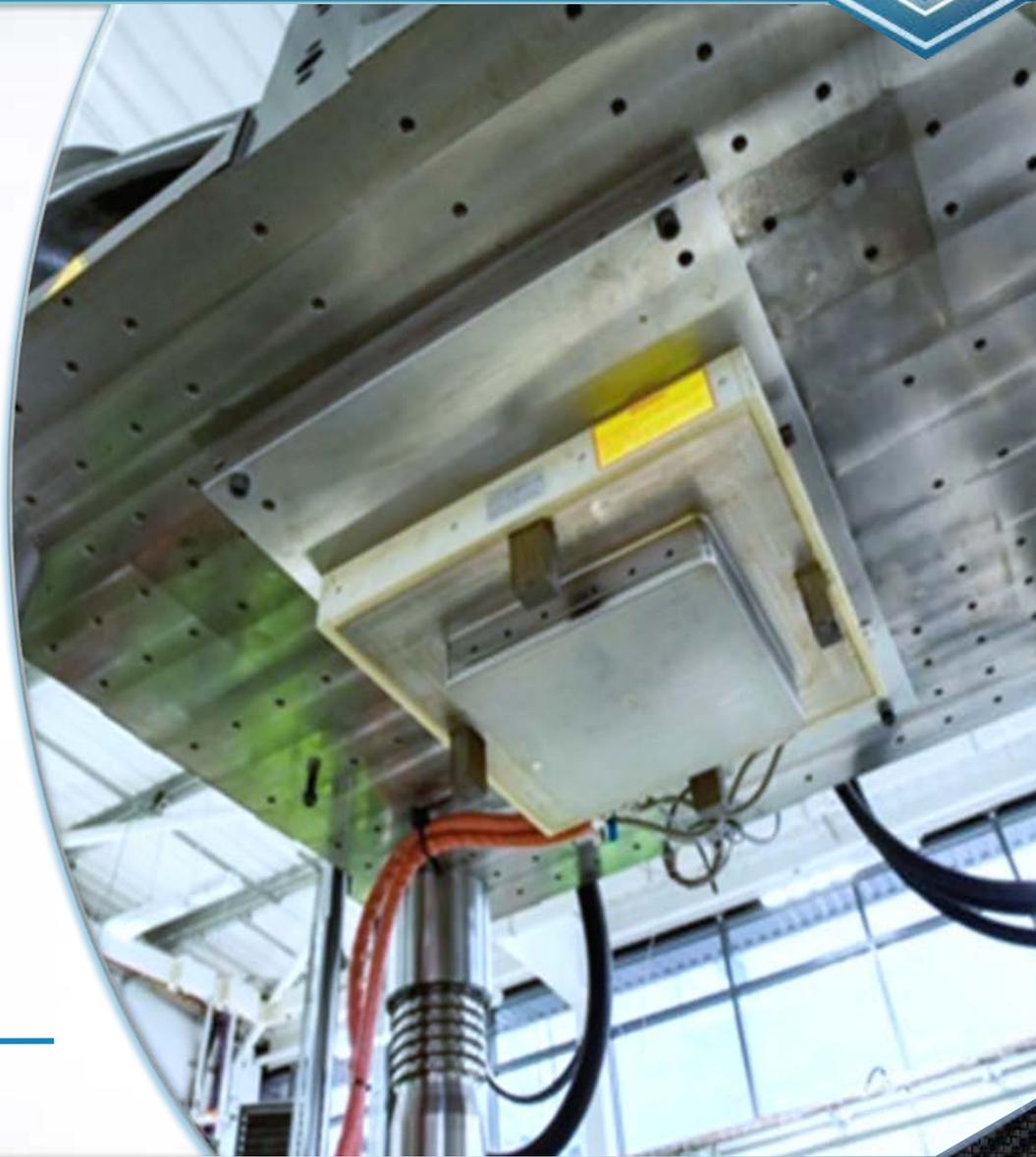
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Resin cure kinetics is a function of temperature.

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Fabric permeability is a function of shearing angle and fiber volume fraction (compaction).

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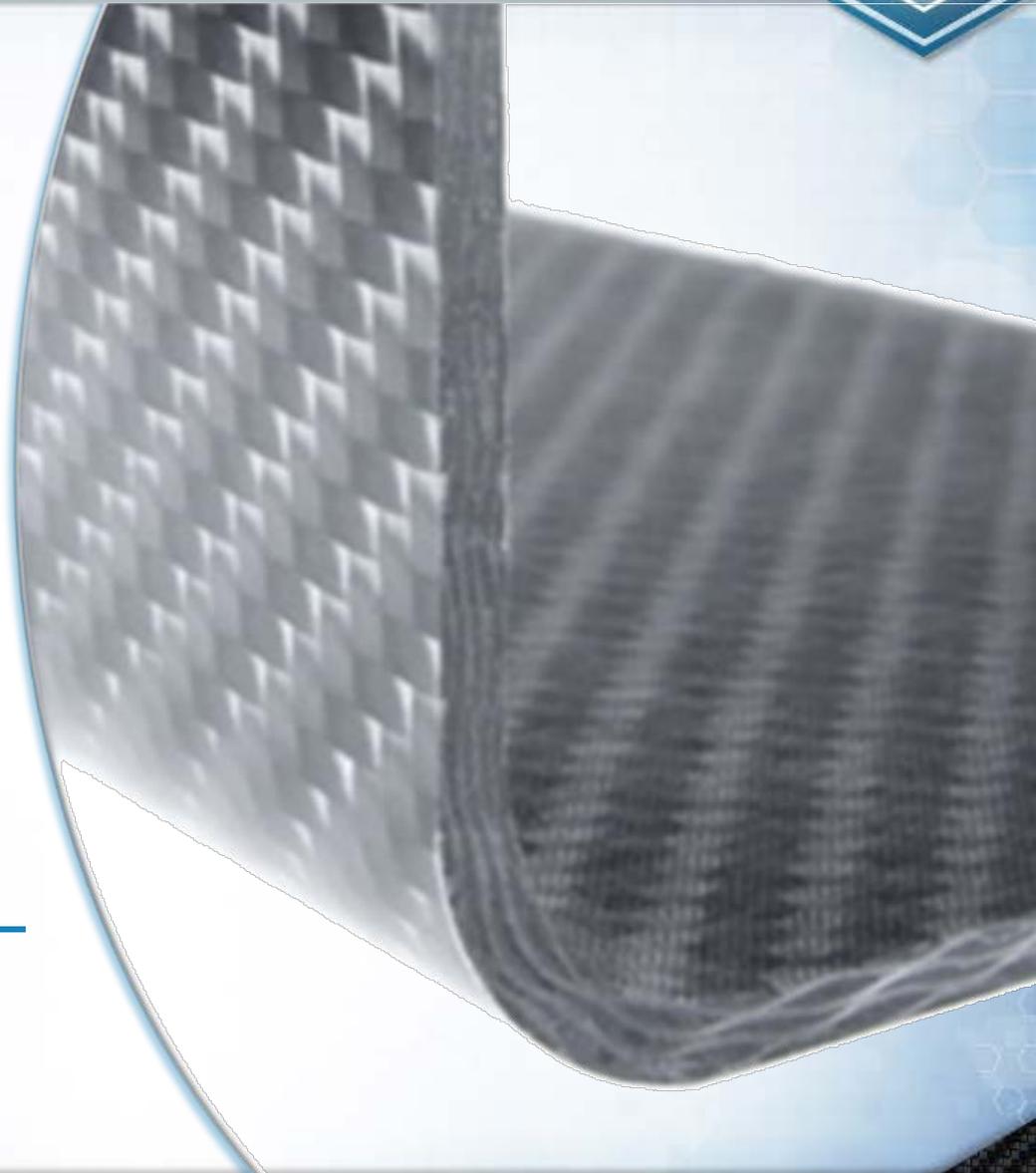
# Demolding

There is **no way** to prevent composite parts from warping after demolding.

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**CTE mismatch** between in-plane and through-thickness directions is the **dominant driver of part deformation**. Others causes include **cure shrinkage**, **cure gradients**, and **mold-part interaction**.

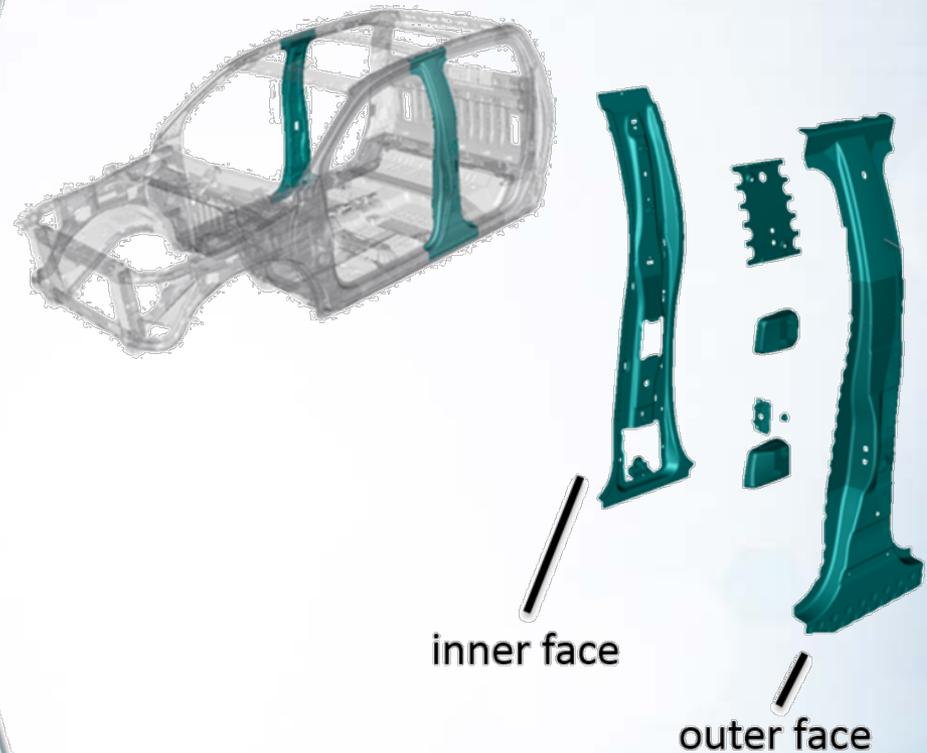
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# Demonstration Part

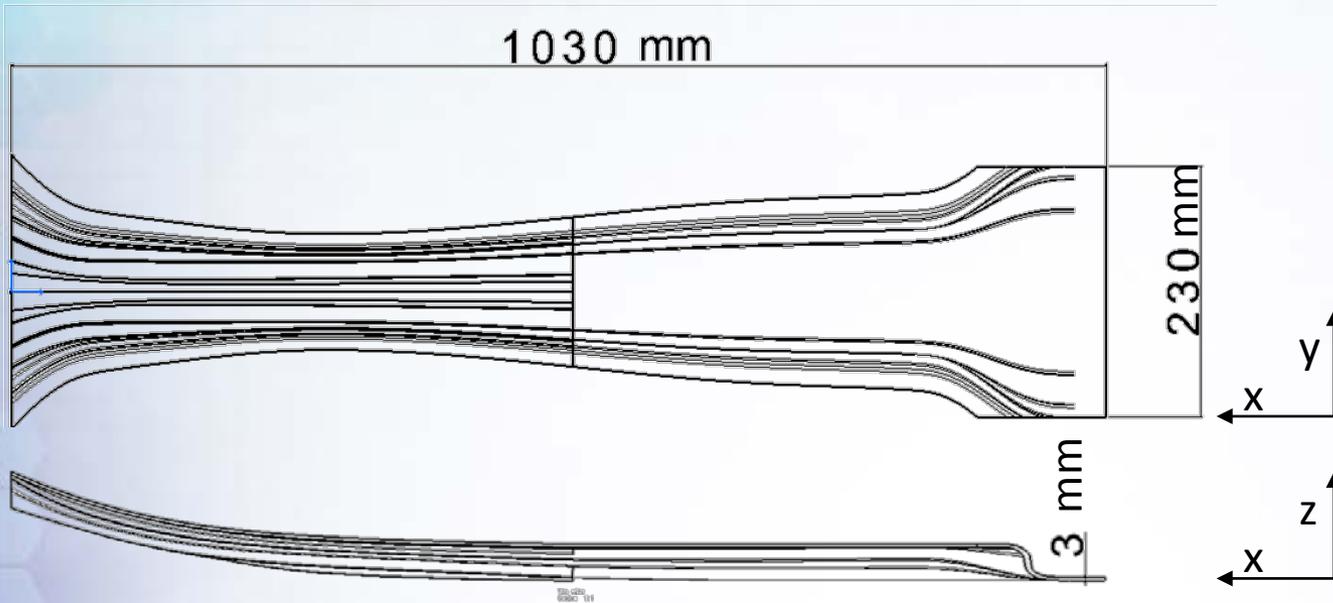
## B Pillar outer face

A “B Pillar” was selected as the demonstration part for the HP-RTM process. HP-RTM works well for structural automotive parts because HP-RTM can create parts with **continuous fiber (high strength)** and **fast cycle times**. Also, the process uses the **same presses** as are used in metal stamping, which prevents the necessity of costly capital purchases.



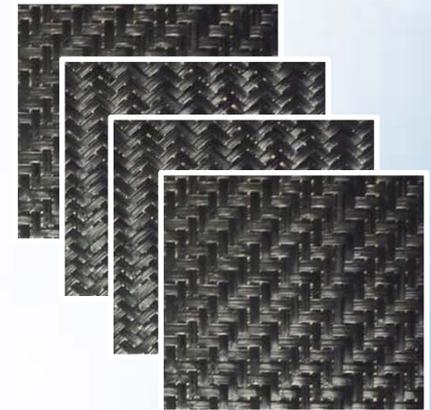
\*only the outer face will be modeled in this presentation

# Part Dimensions and Layup



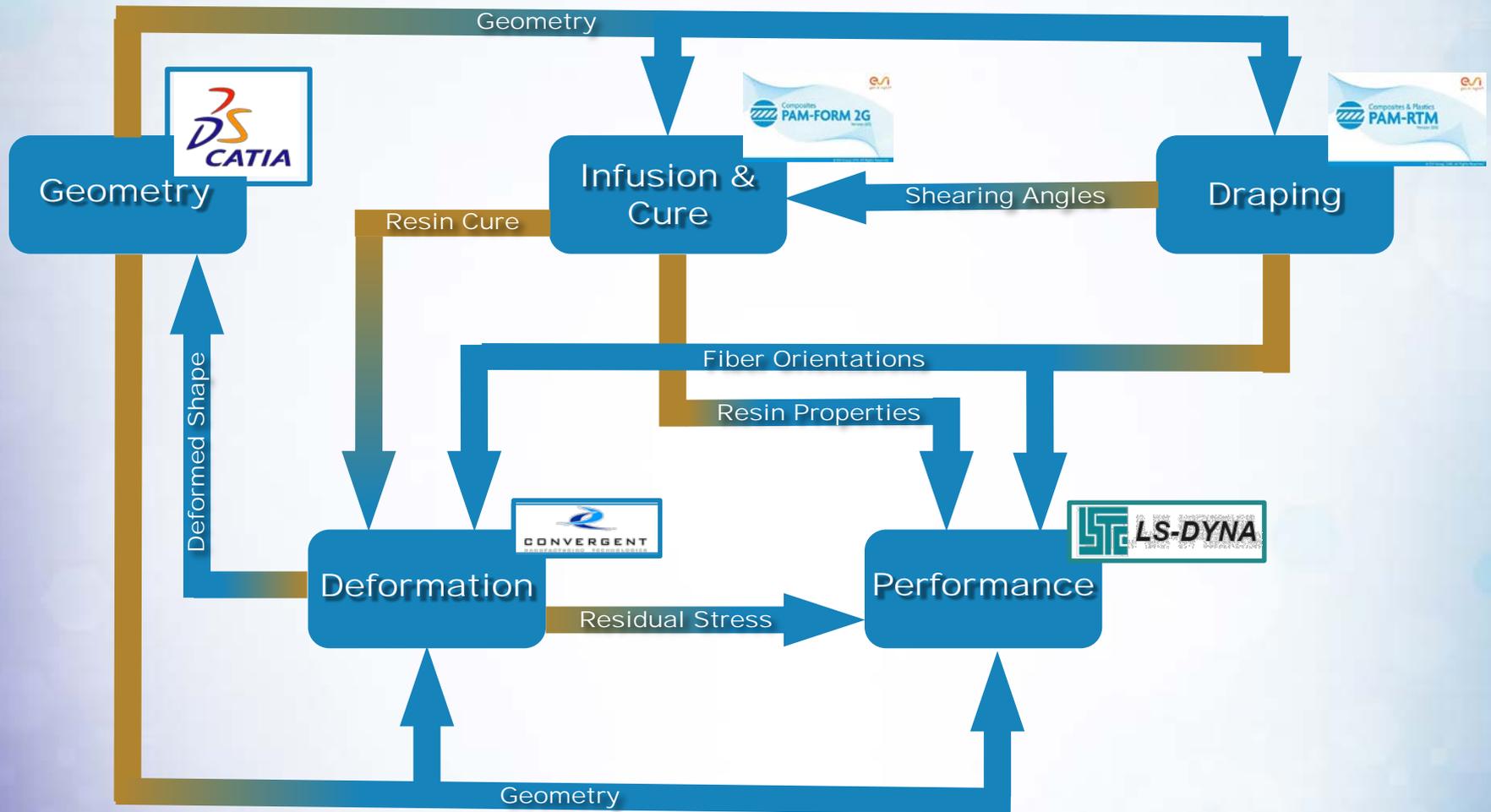
Material: Carbon  
Twill Fabric

Stacking sequence:  
[0,45,45,0]



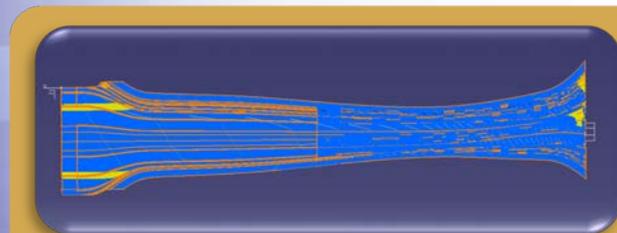
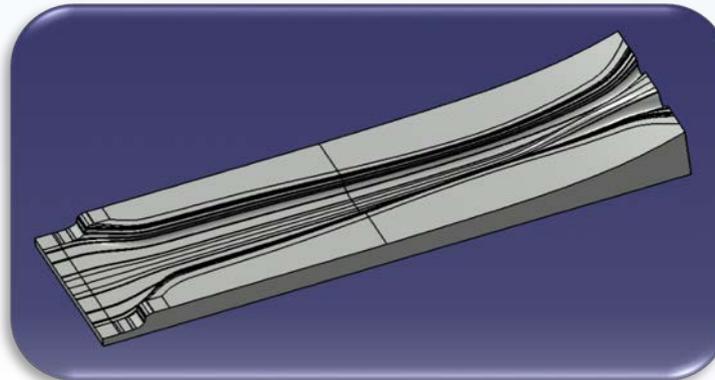
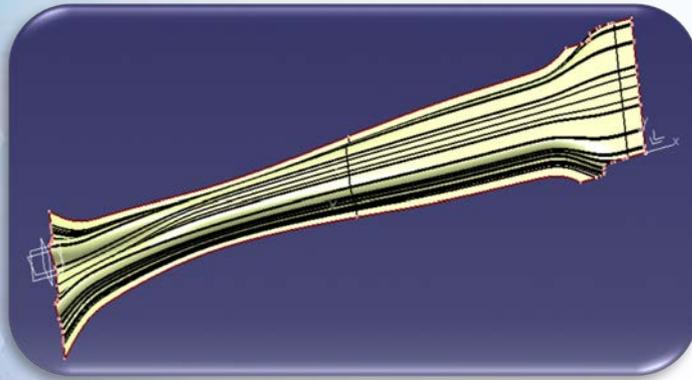
As the focus of the present study is to **demonstrate the physical phenomena** central to the HP-RTM process as well as the **integration of commercial simulation tools** for this simulation, we have chosen a generic B-Pillar geometry shown above.

# HP-RTM Simulation Flow Diagram

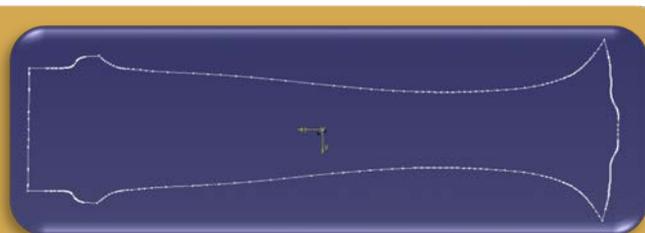


# Geometry Definition

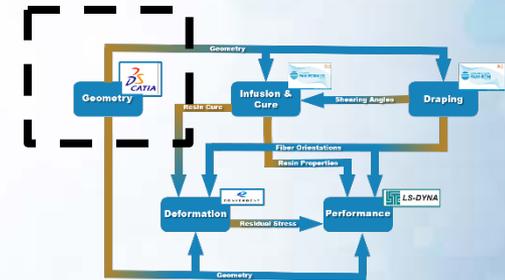
CATIA



Producibility

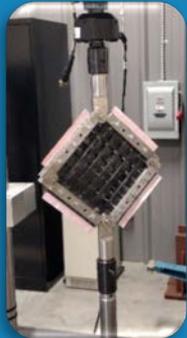


Flat ply shapes

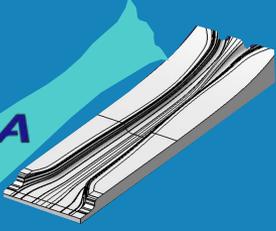


# Draping Overview

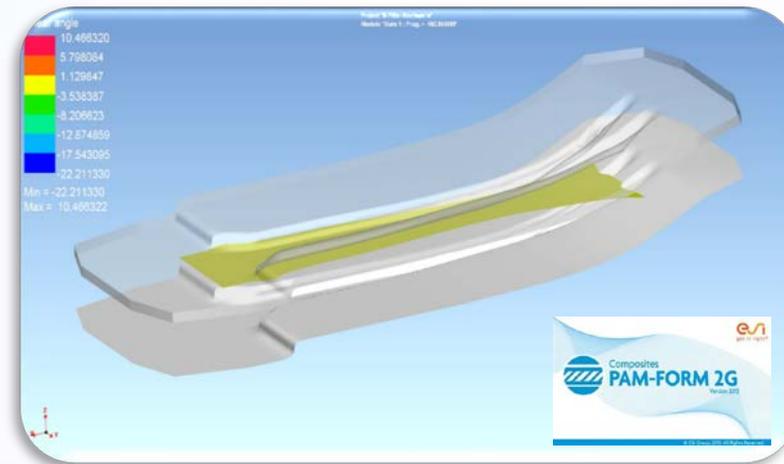
## PAM-FORM



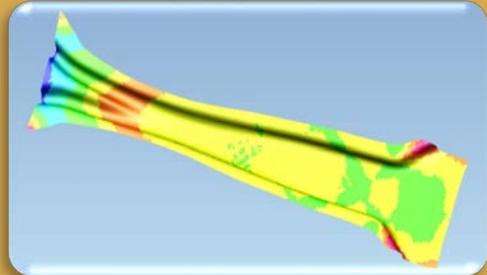
Fiber modulus,  
fabric bending  
stiffness,  
picture frame  
test



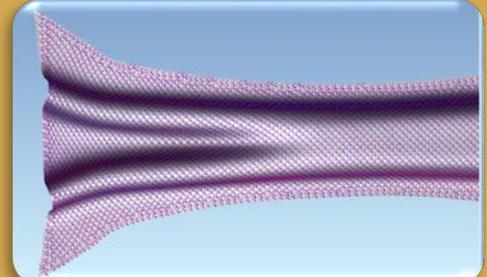
Mold and blank  
geometry



Shear Angles



Fiber Directions



# Draping Inputs

## PAM-FORM

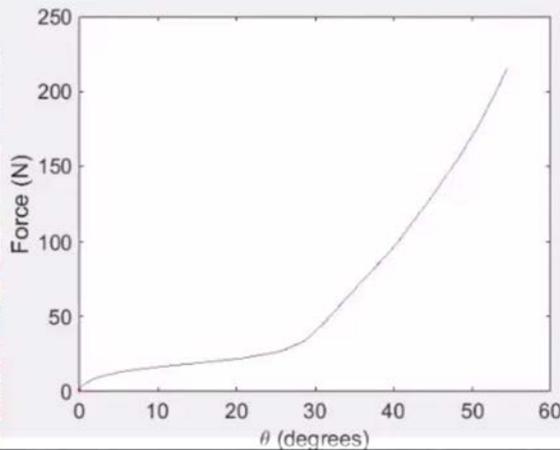
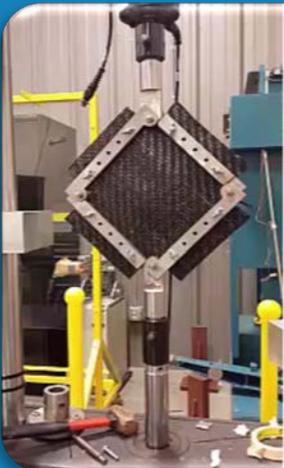
### Tow modulus



### Bending Stiffness



### Picture Frame Test



**Name:** CarbonPlainWeave  
**Type:** Composite

**Mechanics:**  Thermal

**Parameters:**  
 Advanced thickness... Dic...  $\beta$  1.E-6  
 Squeeze flow Fiber content 0.47

**Material law:** Fabric

**Bending:** Warp direction  $\alpha_1$  0.  $E_1$  20  $B_1$  0.5  
 Factor  $B_2$  0.5  
 Stiffness Weft direction

**In-plane shear:** G 1e-005  $G_{lock}$  45.  $G_{lock}$  0.1

**Viscosity:** SRFIL 0.

**G table/curve wizard:**  
 Compressible  
 Experimental data:  
 Arm length: 270  
 Fabric length: 190  
 Initial thickness: 2.

Displacement	Force
0	32.1
0.03	33.033
0.07	33.5
0.11	33.7
0.16	34.0
0.20	34.1
0.24	34.3
0.28	34.6
0.33	34.5
0.37	34.8

Buttons: OK, Add in material, Create table, Create curve, Cancel

# Draping Simulation

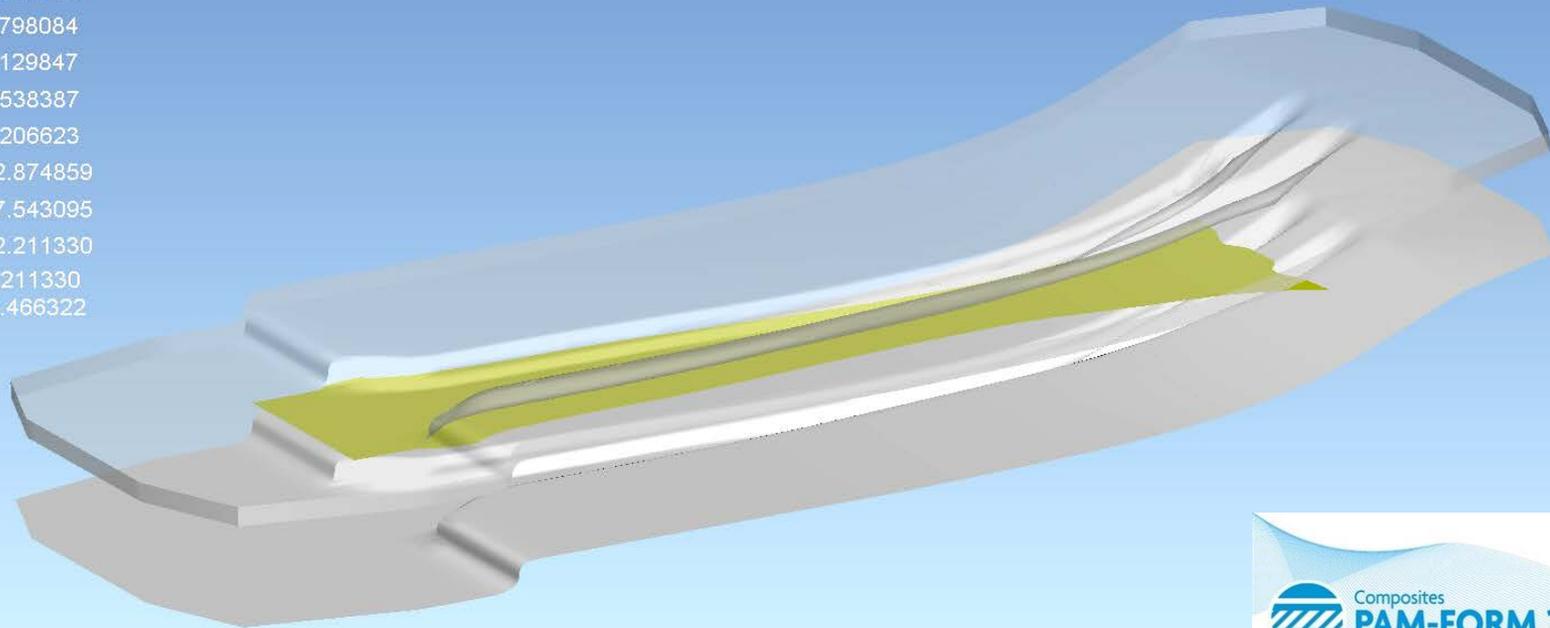
## PAM-FORM

Shear angle



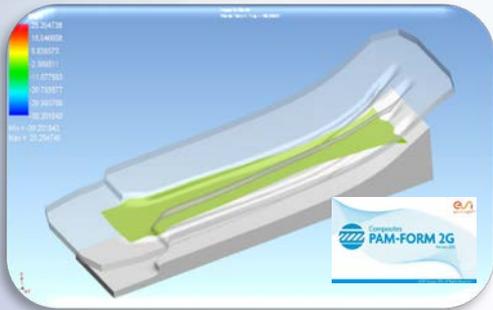
Min = -22.211330  
Max = 10.466322

Project 'B-Pillar-Fourlayers'  
Module 'State 1: Prog. = -102,969009'

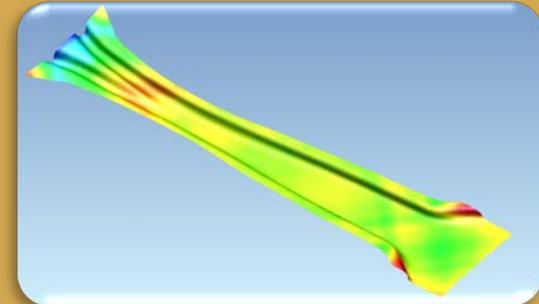
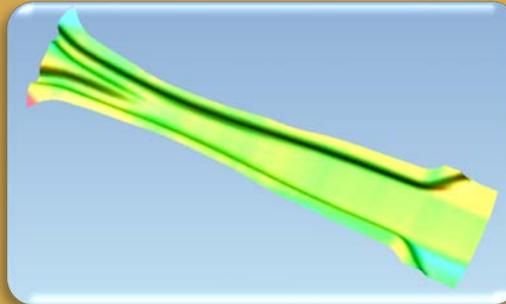


# Draping Outputs

## PAM-FORM



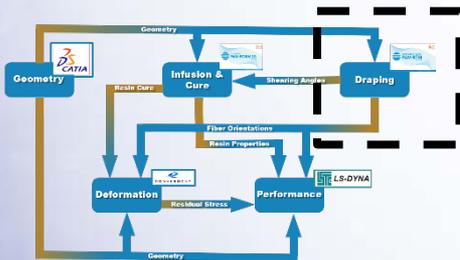
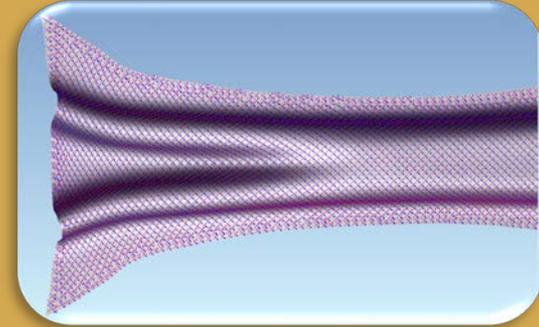
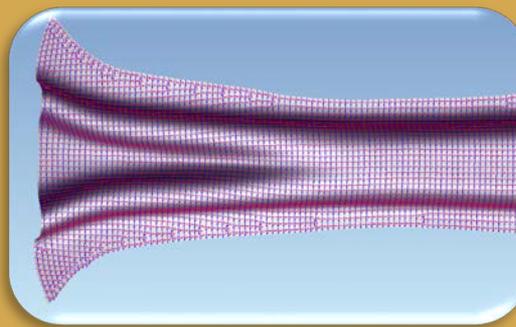
### Shear Angles



0/90 ply

45/-45 ply

### Fiber Directions

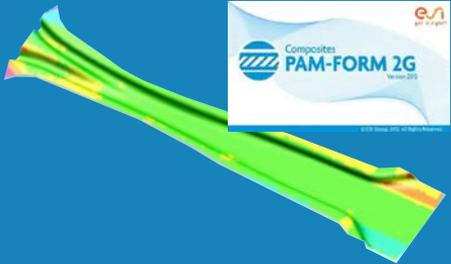


# Infusion and Cure Overview

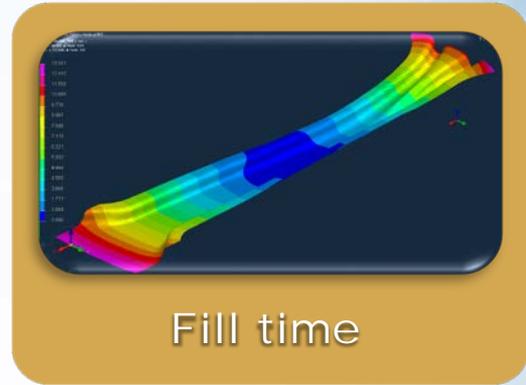
## PAM-RTM



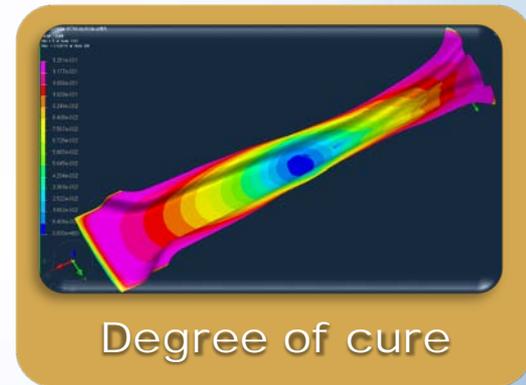
Permeability, cure kinetics, viscosity



Shear angles



Fill time



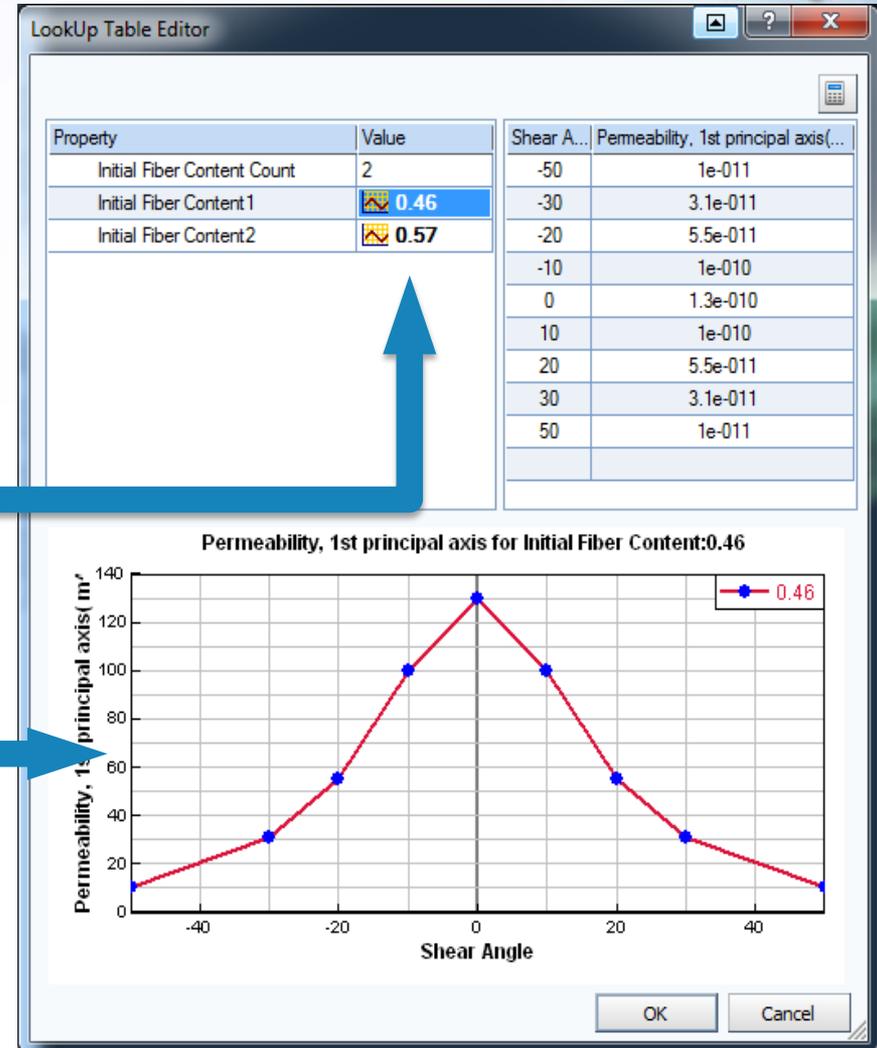
Degree of cure

# Filling Inputs: Permeability

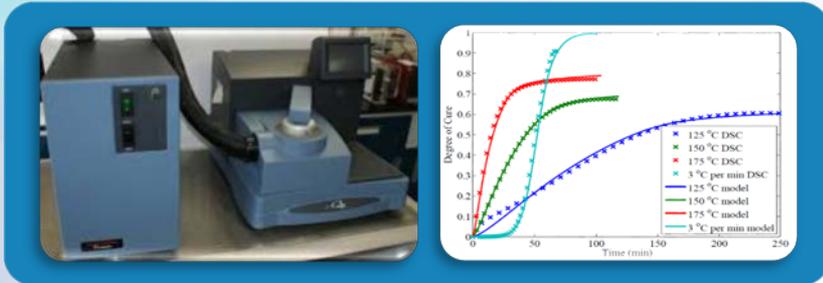


Permeability defined at multiple fiber volume fractions

Permeability as a function of shear angle for a specific fiber volume fraction

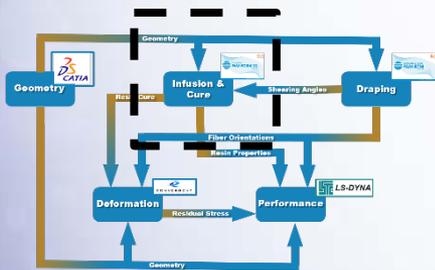


# Filling Inputs: Cure Kinetics



Heat of Reaction

Cure kinetics data from DSC

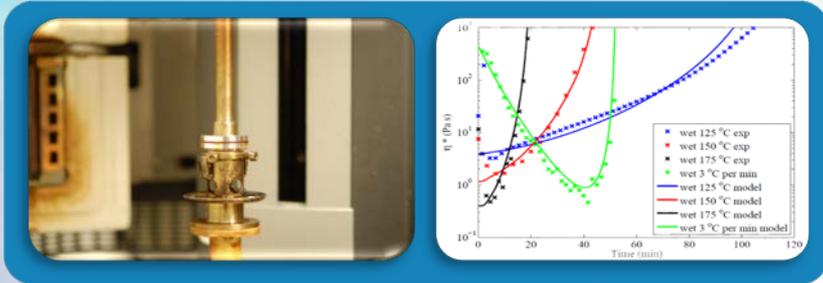


Property	Type	Value	Value Unit	F(°) Unit
Enthalpy	Const.	500	J/kg	
Kinetic	Function			C

X	Y
36.027	0
36.041	-8.5391e-008
36.056	-2.5439e-007
36.065	-3.9296e-007
36.076	-5.0208e-007
36.084	-6.0962e-007
36.094	-7.156e-007
36.103	-8.2e-007
36.112	-9.2283e-007

# Filling Inputs: Viscosity



Viscosity defined at multiple temperatures



Viscosity as a function of degree of cure for each temperature



LookUp Table Editor

Property	Value	Degree of Cure	Newtonian Viscosity(N-s/m <sup>2</sup> )
Temperature1(K)	100	0	1
Temperature2(K)	110	.2	1.5
Temperature3(K)	120	.25	2
Temperature4(K)	130	0.3	5
Temperature5(K)	140	0.4	20
Temperature6(K)	150	.42	50
Temperature7(K)	160	0.44	100
Temperature8(K)	170	.46	250
Temperature9(K)	180	.5	800
Temperature10(K)	190	.52	1000
Temperature11(K)	200		

Newtonian Viscosity for Temperature:150

OK Cancel

# Filling Inputs: Shear Angle

**Composite Display**

Entity:

Component

Type:

Sub type:

Display Options

Thickness amplification:

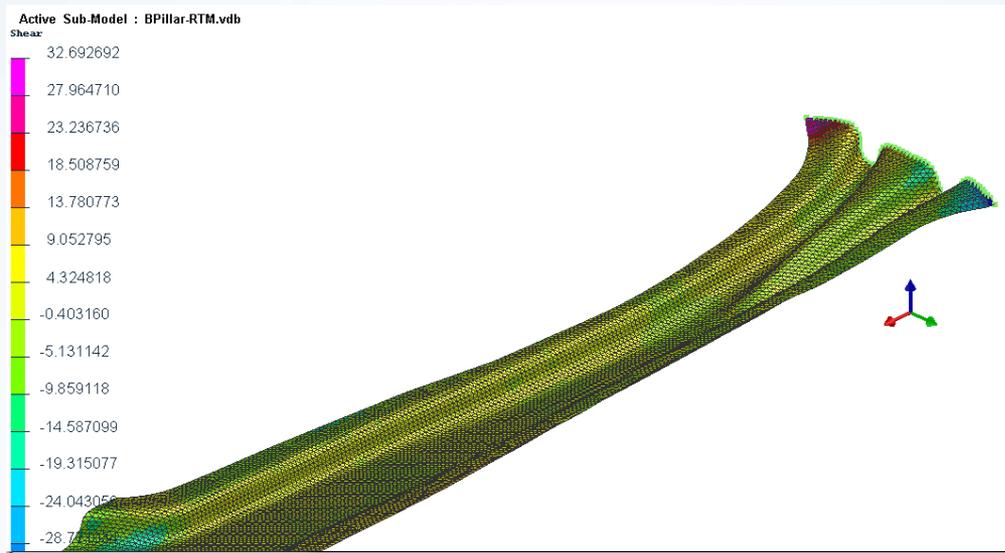
Displayed / Real layer thickness:

3D View

QUIK Options (L)

Ply Mesh  Flat Curve  Edge

ID	Entity Name	L	Color
1	ply 1 B-Pillar90_0_0		
2	ply 2 B-Pillar45_0		



**Layer Design Manager**

LAYER LIST (Part/Ply Association)							
Layer	Parts ID	Reinforcement	Ply	Thickness (mm)	Fiber Content	Angle	Local
ply_1_B-Pillar...	2 5	_B-Pillar90_0_0	Mixture-Rule	1	0.5	0	X
ply_2_B-Pillar...	2 5	_B_Pillar45_0	Mixture-Rule	1	0.5	0	X
ply_3_B-Pillar...	2 5	_B_Pillar90_0_0	Mixture-Rule	1	0.5	0	X

Material

Database  Category  Name  Thickness Unit   Scale Thickness

Part List  2D Parts  3D Parts Mode  Layer  Part Display  List Hidden Layers  3D View

LAMINATE LIST			
Laminate	Part ID	Thickness (mm)	Offset
LAMINATE 4	2 5	3	Middle

Part Selection

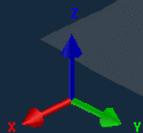
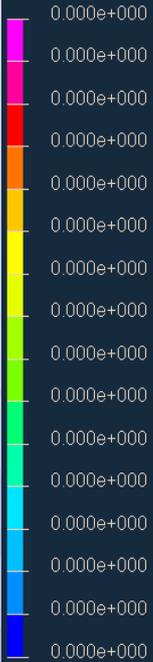
# Filling Simulation

## PAM-RTM

ESI\B\Pillar-RTM-no-hole.erth5

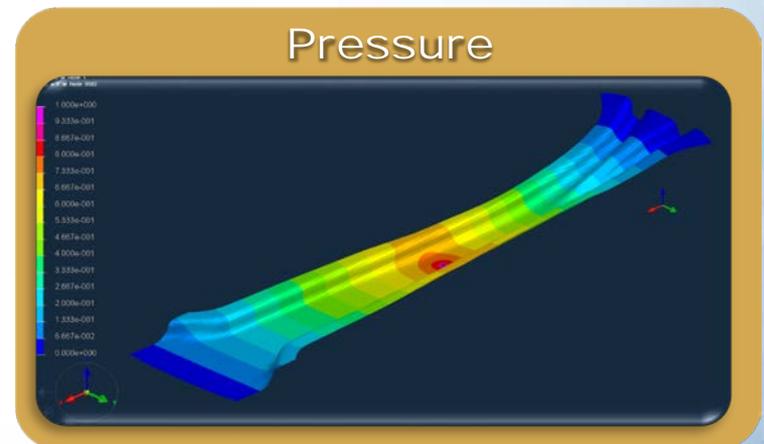
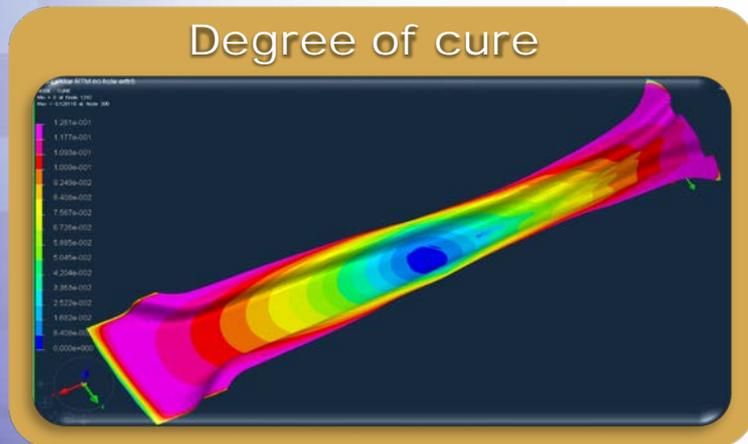
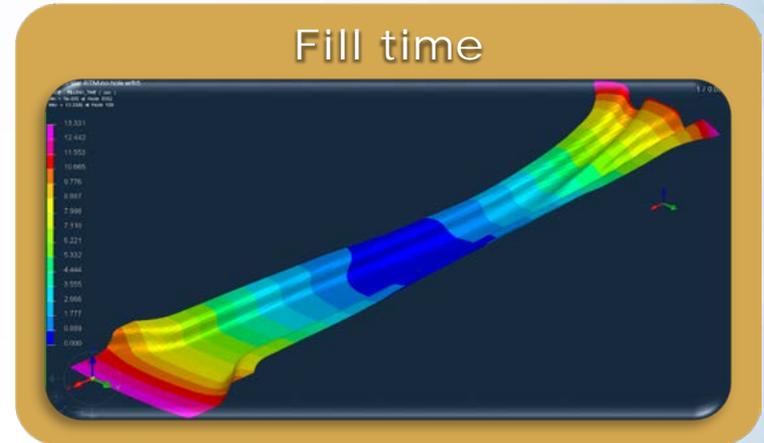
NODE : FILLING\_FACTOR  
Min = 0 at Node 1  
Max = 0 at Node 1

1 / 0.000000



# Filling Outputs

## PAM-RTM



# Deformation Overview

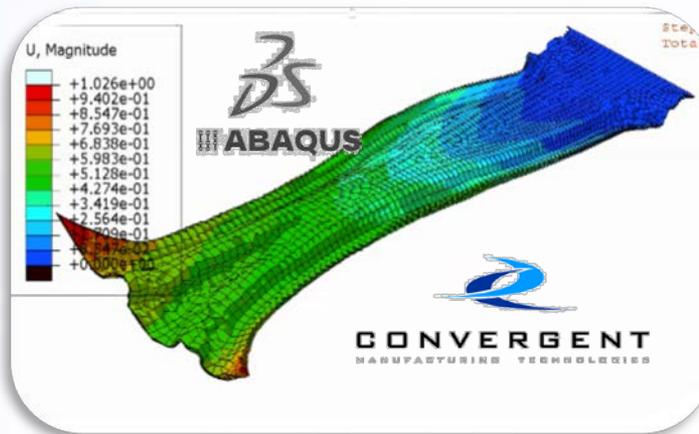
## COMPRO



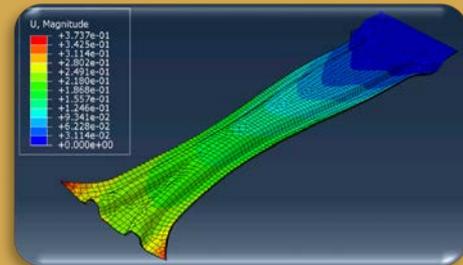
Elastic constants,  
thermal properties,  
cure kinetics



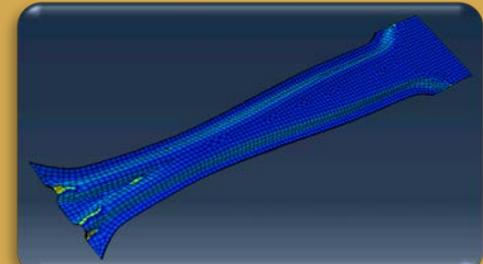
Fiber directions



### Deformation



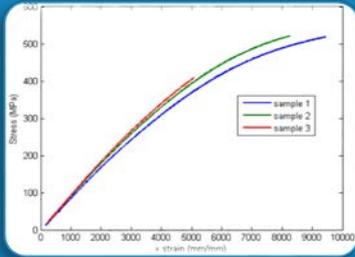
### Residual Stress



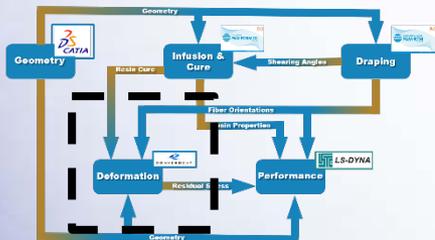
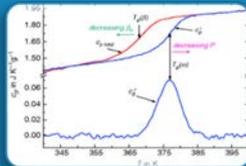
# Deformation Inputs

## COMPRO

### Elastic Constants



### Thermal and Cure Properties



```

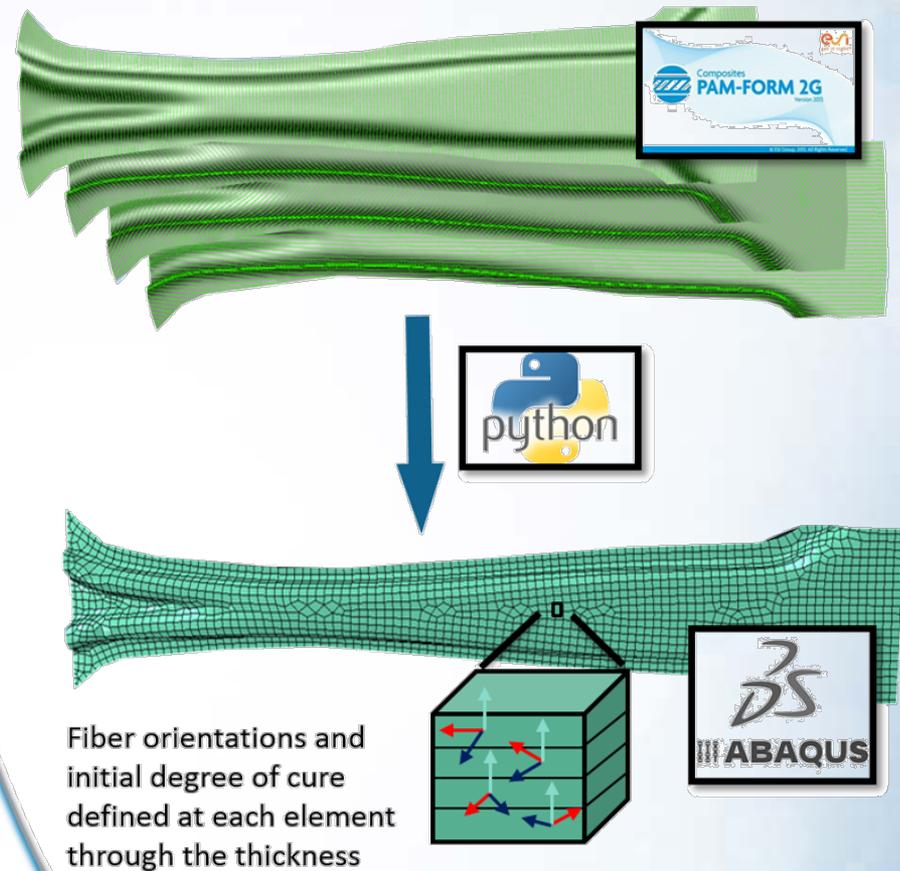
<!-- Release: Open -->
<!-- Internal: Open -->
<!-- Customer: N/A -->
<!-- -->
<!-- ----->
- <material type="fibre" display_name="IM7-12K Fibre" general_name="FIBRE" unique_name="FIBRE-IM7-12K-v1">
  - <revision comment="Initial model in revisioning system" date="2010-02-04" value="1">
    - <density number_of_parameters="3" model="default">
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    - <elastic_properties number_of_parameters="15" model="default">
      <parameter value="2.76E+11" units="Pa" parameter_number="1" name="E11"/>
      <parameter value="0" units="C" parameter_number="2" name="E11_refT"/>
      <parameter value="0" units="Pa/C" parameter_number="3" name="E11_Tf"/>
      <parameter value="1.95E+10" units="Pa" parameter_number="4" name="E33"/>
      <parameter value="0" units="C" parameter_number="5" name="E33_refT"/>
      <parameter value="0" units="Pa/C" parameter_number="6" name="E33_Tf"/>
      <parameter value="7.0E+10" units="Pa" parameter_number="7" name="G13"/>
      <parameter value="0" units="C" parameter_number="8" name="G13_refT"/>
      <parameter value="0" units="Pa/C" parameter_number="9" name="G13_Tf"/>
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      <parameter value="0" units="Pa/C" parameter_number="12" name="nu13_Tf"/>
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      <parameter value="0" units="Pa/C" parameter_number="15" name="nu23_Tf"/>
    </elastic_properties>
    - <cte number_of_parameters="5" model="cte1">
      <constraint value="0" severity_parameters="60.;1.;" initial_severity="60" severity_model="1" isMinimum="false" variable="temp"/>
      <parameter value="-4.00E-07" units="unknown" parameter_number="1" name="NominalCTE1"/>
      <parameter value="5.60E-06" units="unknown" parameter_number="2" name="NominalCTE2"/>
      <parameter value="20." units="C" parameter_number="3" name="T0"/>
      <parameter value="0." units="unknown" parameter_number="4" name="Tf"/>
      <parameter value="0." units="unknown" parameter_number="5" name="Tf1"/>
    </cte>
    - <specific_heat number_of_parameters="3" model="default">
      <constraint value="0" severity_parameters="30.;1.;" initial_severity="30" severity_model="1" isMinimum="false" variable="temp"/>
      <parameter value="711.76" units="J/(kg K)" parameter_number="1" name="NominalCp"/>
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    </specific_heat>
    - <conductivity number_of_parameters="5" model="default">
      <constraint value="0" severity_parameters="60.;1.;" initial_severity="60" severity_model="1" isMinimum="false" variable="temp"/>
      <parameter value="2.4" units="W/(m K)" parameter_number="1" name="NominalKt"/>
      <parameter value="11.8025" units="W/(m K)" parameter_number="2" name="NominalKl"/>
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    </conductivity>
  </revision>
</material>
  
```

# Property Mapping

Fiber directions from **PAM-FORM surface mesh** need to be mapped to the **ABAQUS solid mesh**. ABAQUS does not have a built in way to import fiber directions.

A Python script was written which maps each solid mesh node to its nearest surface mesh counterpart and **defines the properties through the thickness**.

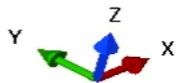
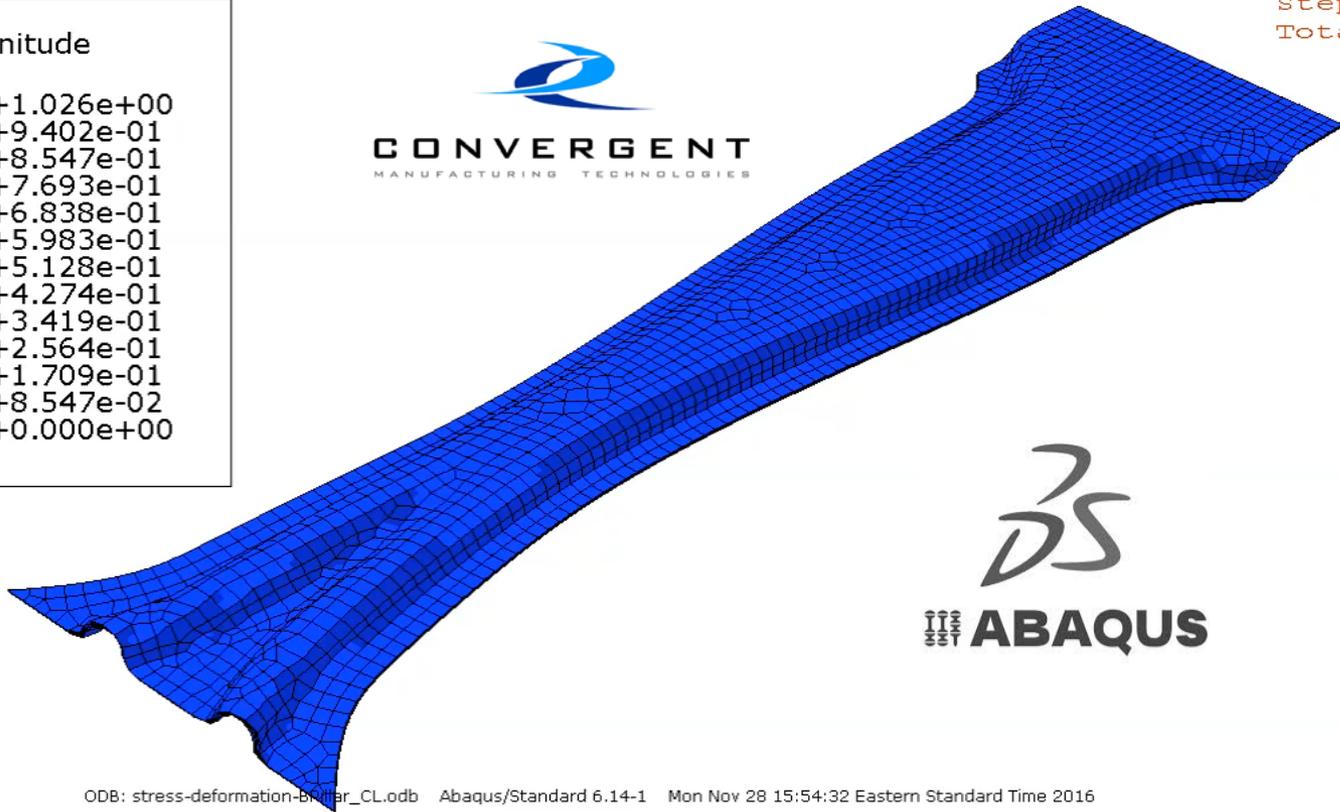
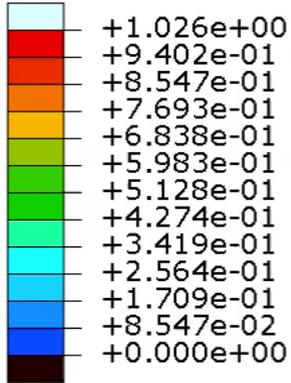
**Degree of cure data** is also mapped from PAM-RTM into ABAQUS using the same method.



# Deformation Simulation

COMPRO

U, Magnitude



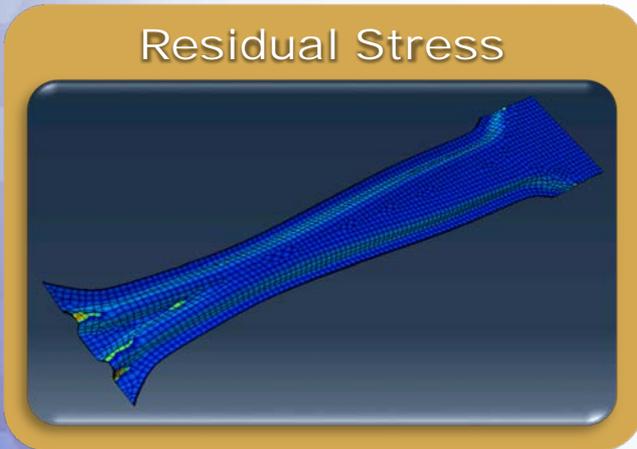
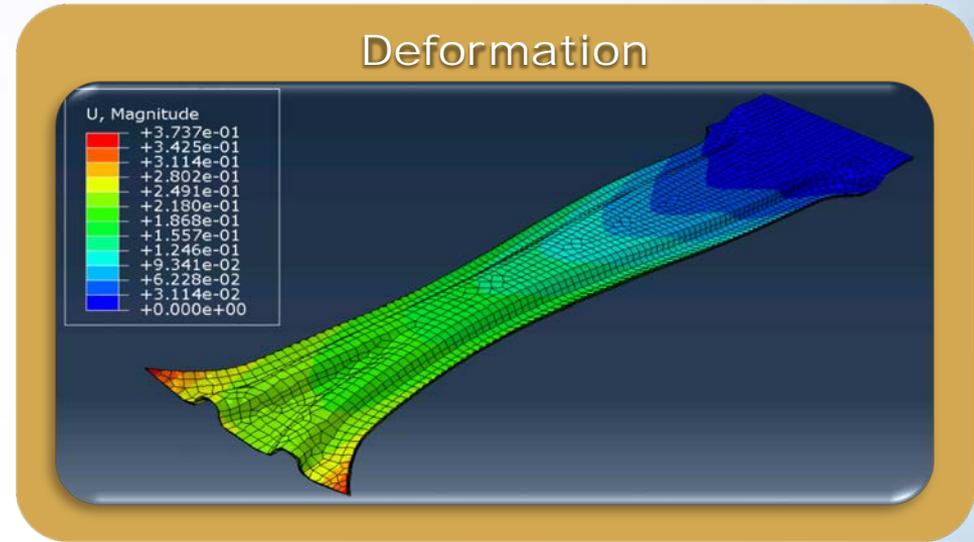
ODB: stress-deformation-Bottle\_CL.odb Abaqus/Standard 6.14-1 Mon Nov 28 15:54:32 Eastern Standard Time 2016

Step: Step-Stress-Deformation  
Increment: 0; Step Time = 0.000  
Primary Var: U, Magnitude  
Deformed Var: U Deformation Scale Factor: +2.793e+02

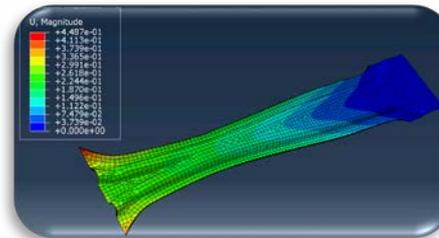
Deformed Var: U Deformation Scale Factor: +2.793e+02

# Deformation Outputs

## COMPRO



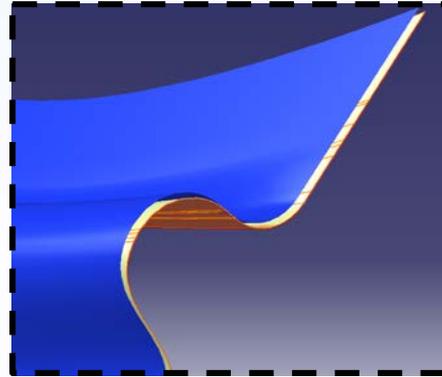
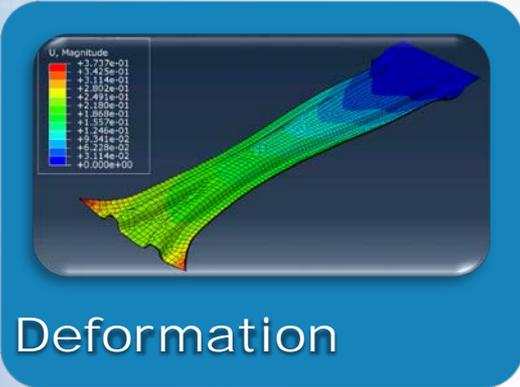
Deformation without Draping:



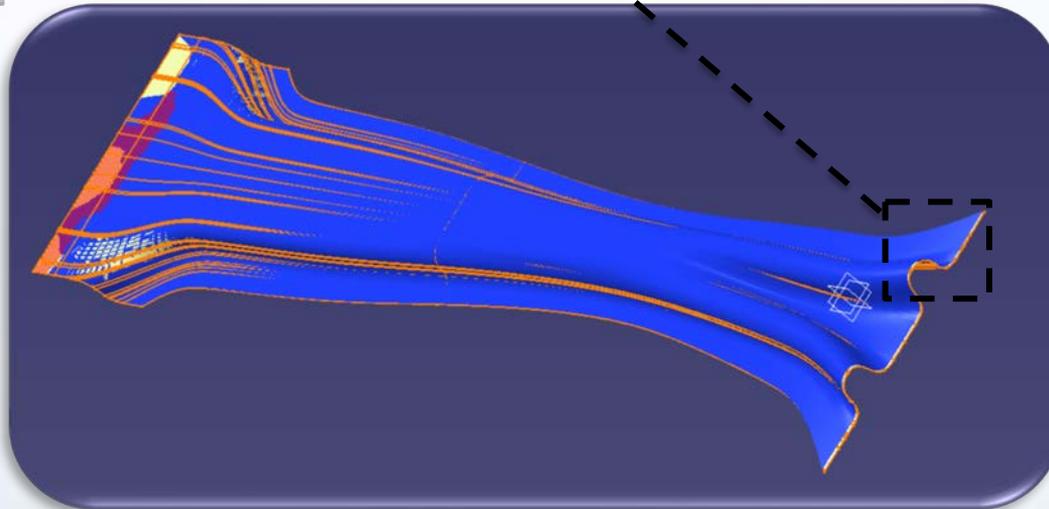
Compared to the B Pillar model without draping, there is a 17% difference in maximum deformation

# Mold Geometry Compensation

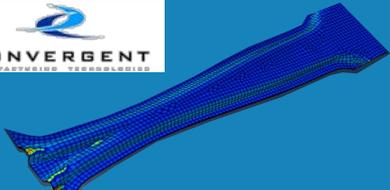
CATIA



The process is iterated with the new geometry and the deformation is checked again to make sure the deformed part matches the desired geometry.



# Manufacturing Informed Performance



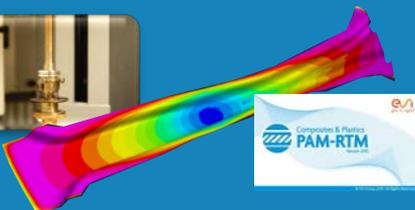
Residual Stress



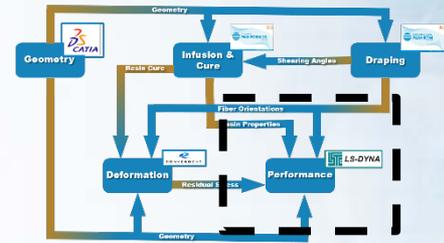
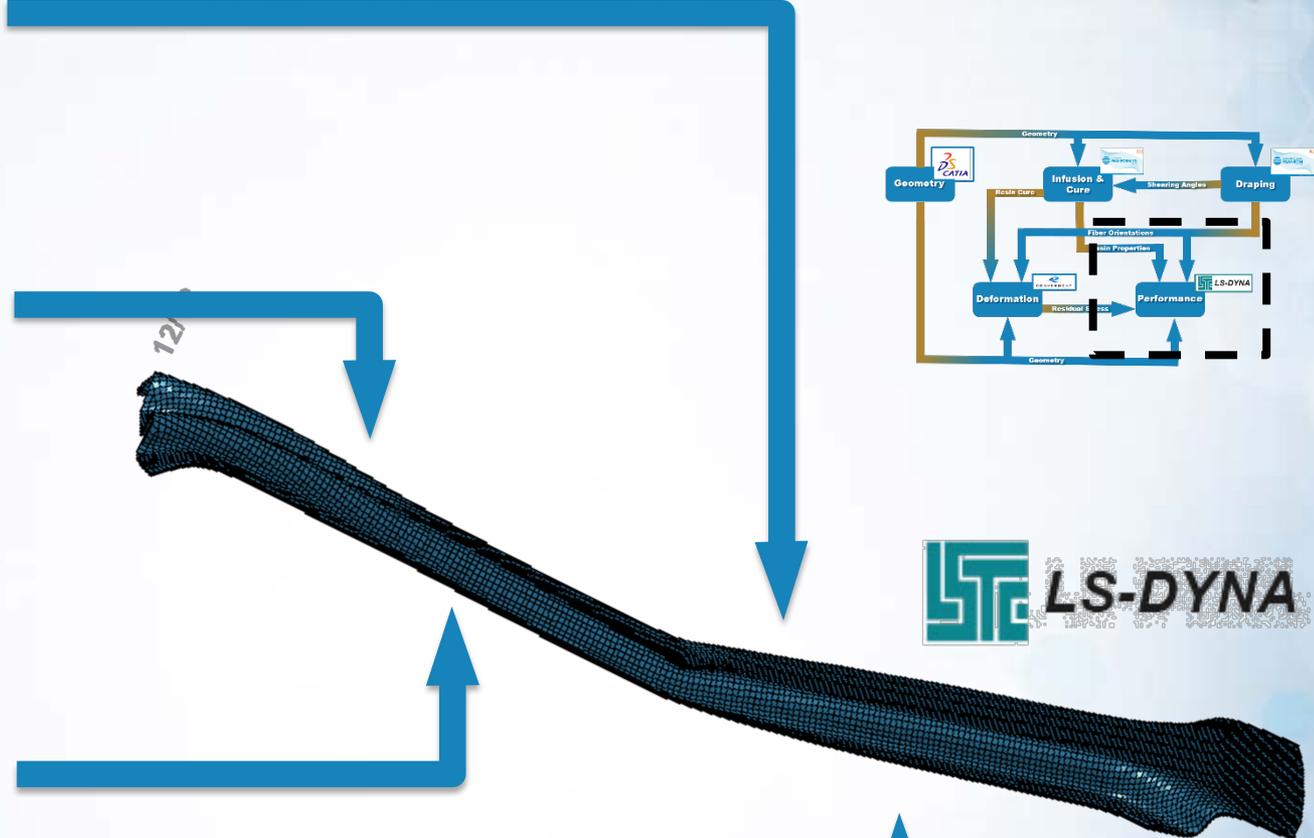
Fiber directions



Compensated mold geometry



Resin properties



# Validation



Draping simulations will be validated optically.

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HP-RTM system will be used to validate injection.

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CMM machine will be used to validate deformation.

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High energy impact tester will be used to validate performance.



# Summary

Any amount of geometrical complexity will **change the fiber directions** and therefore properties of the finished part.

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Deformation from residual stresses built up during molding and cooldown is **unavoidable**: it can only be **compensated for, not eliminated**.

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The **performance** of the finished part **can ONLY be accurately modeled** by considering changes introduced during **MANUFACTURING**.

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