USAMP

Validation of Material Models: Development of Carbon Fiber Reinforced Thermoplastic Composites

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FCA
FIAT CHRYSLER AUTOMOBILES

GM

BASF
The Chemical Company

shape CORP

TENCATE

CHOMARAT

Abstract

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Thermoplastics composites are increasingly competing with thermosets because of the advantages these materials offer in terms of short cycle time, good toughness, and recyclability. However, thermoplastic composites, especially those that are reinforced with continuous carbon fibers, still have significant barriers to overcome before they are widely used in large and complex automotive structural components. These include cost, mass production methods, and predicative technique for performance as well as processing. Research has been ongoing under United States Advanced Materials Partnership (USAMP), various consortia and universities to assess and develop this technology. This paper will outline the primary development of carbon fiber weave reinforced Nylon for crush cans in a vehicle front end structure. This is a collaboration effort between FCA, Ford, General Motors and suppliers through the USAMP VMM project and funded by the department of energy (DOE). Low cost carbon fiber developed by ORNL has also been investigated and will be discussed.

Agenda:

- Background/ introduction of whole project
  - Thermoplastic objective: Material and process development
- Current design of parts
- Material selection
  - Why thermoplastics; advantages (disadvantages); material sources and selection criteria (part needs, design); low cost carbon fiber(film production..), c-ply; comparison data for material selection
- Process development
  - Design requirements, tooling constraints, oven,
- Tooling design, molding equipment
- Assembly
- Material testing
- Physical testing
- Correlation
- Next steps
- Acknowledgments

Background

- Cooperative project with U.S. DOE and USAMP
- Validate material models to predict crash performance in carbon fiber composite automotive structures.
- Models developed in LS-DYNA, RADIOSS, PAM-CRASH, Abaqus, as well as ACC/USAMP developed models from University of Michigan and Northwestern.
- Predictions compared to experimental results from dynamic crash testing of front bumper and crush can systems.
- Successful validation of crash models will facilitate improved design of lightweight carbon fiber composites in automotive structures for significant mass savings.

Thermoplastic Objective

1. Create carbon composite layup for material testing and CAE card generation.
   - ❑ Identify materials for part construction
   - ❑ Test manufactured part layup construction
     - ❑ Generate material card: MAT_058 for LS-DYNA for each material

2. Manufacture crush cans with thermoplastic carbon composites
   - ❑ Use existing tooling when thermoset run is complete
   - ❑ Manufacture parts with similar layup construction
   - ❑ Trim parts
   - ❑ Adhere can halves
   - ❑ Provide complete assemblies for testing

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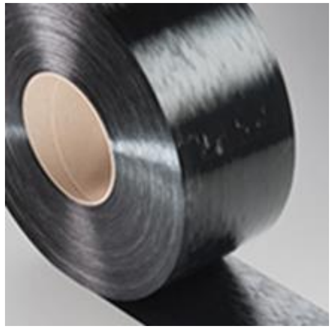
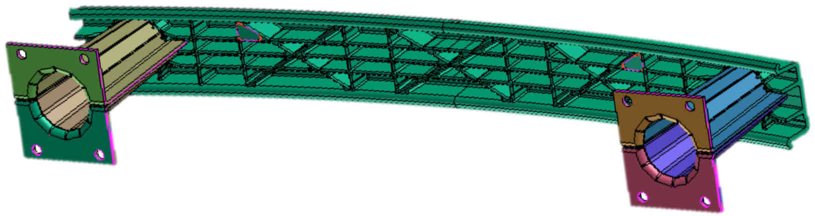


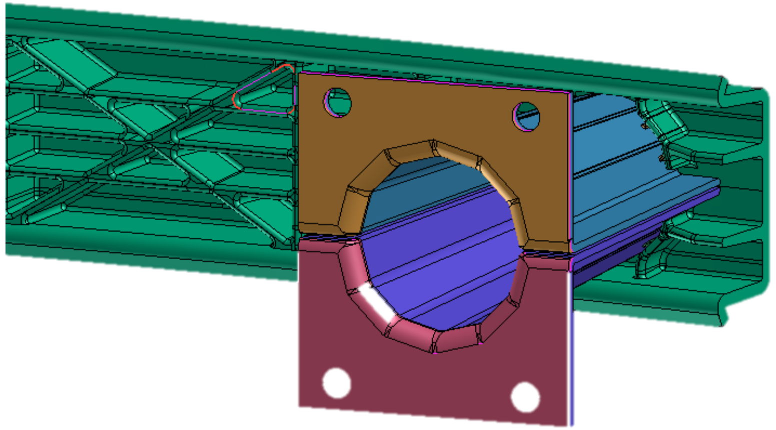
TENCATE
Performance Composites

Current Design of Composite FBCC

- **Design of *__Thermoset__* Composite FBCC**
  - Crush cans are 12 QI layers of woven carbon fabric
  - Bumper beam C-Channel is 24 layers of QI woven carbon fabric
  - Ribs & crush can back flange are carbon fiber SMC



- **Design direction set for molding of thermoset carbon crush can and front bumper system**
  - Tooling designed for compression molding of epoxy/CF and SMC
  - Material layup determined by material testing and simulation
- **Thermoplastic phase was completed with original compression tooling and similar material makeup**

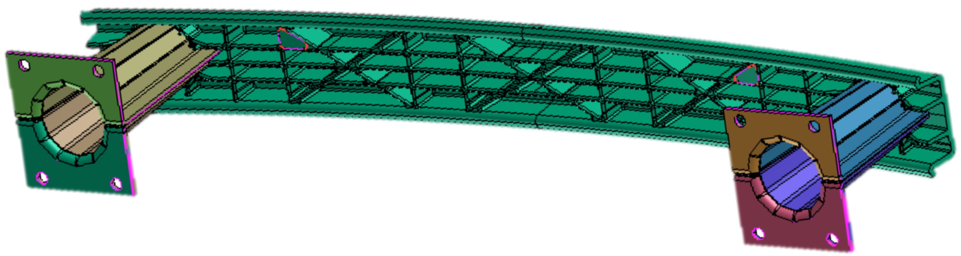


***See other USAMP presentations for results of study with thermoset materials**

Thermoplastic Composites

Why use thermoplastic composites?

Advantages:	Disadvantage:
• Rapid forming- Low cycle time • Reheat/reform in additional processes • Joining: Hot plate welding… • Toughness • Easier to recycle	• Reduced performance with heat when compared to thermosets • Availability of composite prepregs • Lower fiber volume content



How will thermoplastic/carbon fiber compare to similar thermoset crush can on the basis of predictability and performance?

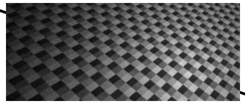
Material Selection
Criteria

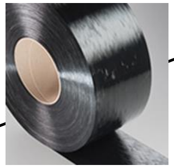
- Use of carbon fiber as reinforcement
  - Specifically continuous fiber for can body: Twill woven (2x2) fiber to mimic thermoset can design
  - Discontinuous carbon fiber for flanges of crush can
- Custom layup and design thickness
  - QI layup similar to established design
  - 2.81 mm woven laminate thickness target to match produced tooling
  - 5.81mm discontinuous composite thickness for crush can back flange
  - Supplier consolidation
- Commercially available
  - Reinforcement and resin available for panel production

Material Selection
Chosen Materials/Process Design

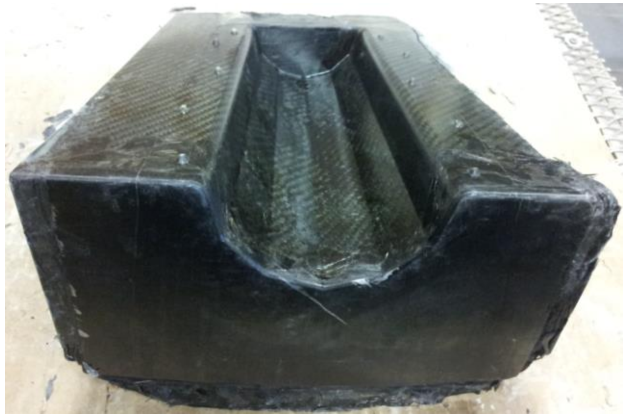
- ❑ Woven laminate panels consolidated by Tencate
- ❑ Material Testing competed by Datapoint Labs
- ❑ Patterns cut by Shape Corp

- ❑ UD Panels consolidated by BASF
- ❑ Material combined with chopped CF tape by Shape Corp
- ❑ Material testing completed by Datapoint Labs





- ❑ Materials heated and molded by Shape and USCAR team at Century Tool and Gage
- ❑ Parts trimmed by Future Tool and Machine
- ❑ Cans adhered/assembled by Dow Automotive
- ❑ Coupon testing to be completed Ford
- ❑ Axial crush/crash testing at GM
- ❑ Simulation/Correlation done by Shape Corp



Material Selection
Design

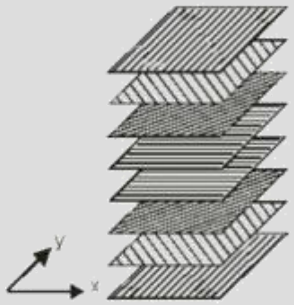
TENCATE
Performance Composites

- Carbon fiber/PA6 panels produced at Tencate Performance composite in Camarillo, CA
- *Based* on Tencate Cetex TC912 product

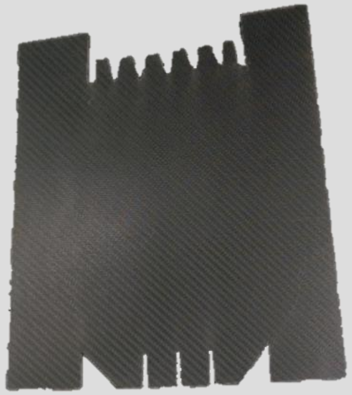
PHYSICAL PROPERTIES
TENCATE CETEX TC912 C-PA6 50/50

Property	Value
Mass of fabric	415 g/m² (12.24 oz/yd²)
Mass of fabric + resin	715 g/m²
Resin content by volume	50%
Resin content by weight	42%
Moisture pick up by weight	1.5-1.8%
Ply thickness	0.47 mm (0.019 in)
Specific gravity (density)	1.52 g/cm³
Tg (DSC)	60°C (140°F)
Tm	220°C (428°F)

3k Twill weave
2.85 mm thick panels
7-layer QI
0/±45/90/±45/90/±45/0



Patterns laser cut from panels

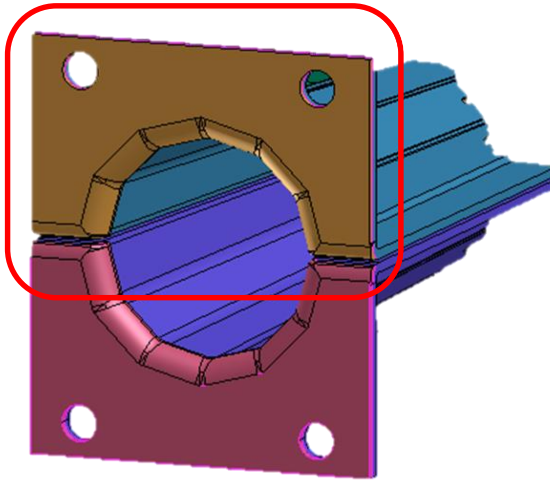


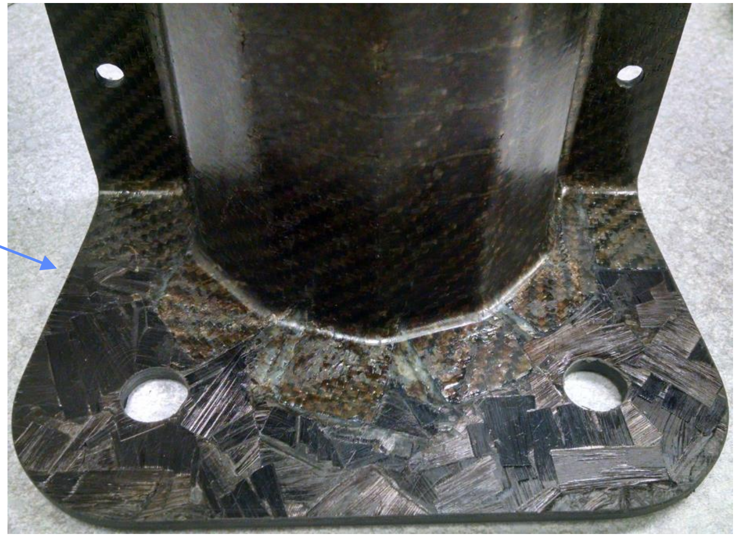
Compression Molding

Material Selection

Crush Can Flange

- ❑ Ultramid B3WC12 UD01 0160 BK0564 Ultratape used to create inserts for flange area.
- ❑ BASF supplied consolidated continuous carbon fiber Ultratape layups using a 0/90 pattern in 5.8mm thick final product. Continuous layup used as carrier to transfer material from oven to compression mold.
- ❑ Chopped tape added fill dart areas of can body
- ❑ Ultratape allows for additional formability in the transition from the crush can to the flange.
- ❑ The performance can be further optimized in the future through altering the tape orientation.

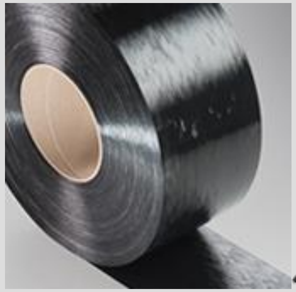




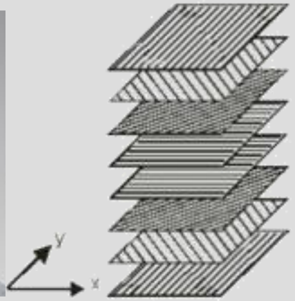
Material Selection

Flange Insert Process

Ultratape

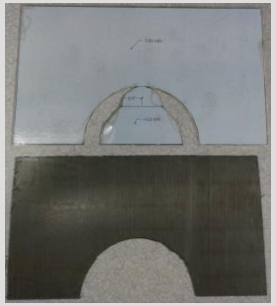


0/90 Layup



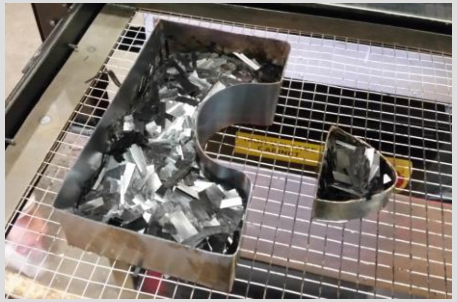
1.2 mm

Cut Pattern



Chopped Tape

Heat



Ultratape B3EC12 UD02 0160 UN Exp.

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Preliminary Datasheet [3)]

Typical values for uncoloured product at 23 °C[1)]	Test method	Unit	Values[2)]
Properties			
Polymer abbreviation	-	-	**PA6**
Density	ISO 1183	g/cm³	**1.46**
Fiber content, wt	ISO 1172	%	**60**
Thickness		mm	**0.16 / ***
Mechanical properties			**dry / cond.**
Tensile modulus	ISO 527-4	GPa	**102 / -**
Stress at break	ISO 527-4	MPa	**1800 / -**
Strain at break	ISO 527-4	%	**1.7 / -**
Flexural modulus	ISO 14125	GPa	**93 / -**
Flexural strength	ISO 14125	MPa	**1090 / -**

Flange Inserts "Tacked" for rapid molding

USAMP

Material Selection
Additional Material Exploration

Low Cost Carbon Fiber

- Carbon Fiber Produced by ORNL
- Conversion to fabric by Chomorat
- PA6 Film Produced by BASF
- Consolidation of Panels by Tencate
- Patterns cut at Shape Corp.
- Crush can molded by Shape and USCAR team at Century
- Crush Can Trimming by Future Tool
- Adhesion and assembly by Dow
- Coupon testing to be completed Ford
- Axial Crush testing to be done at GM

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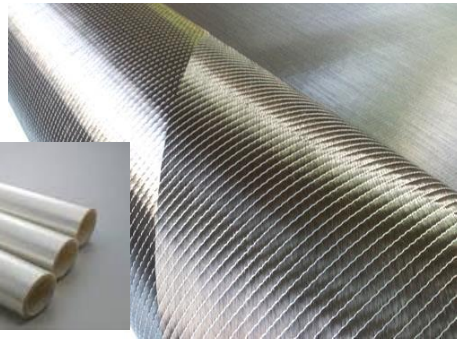
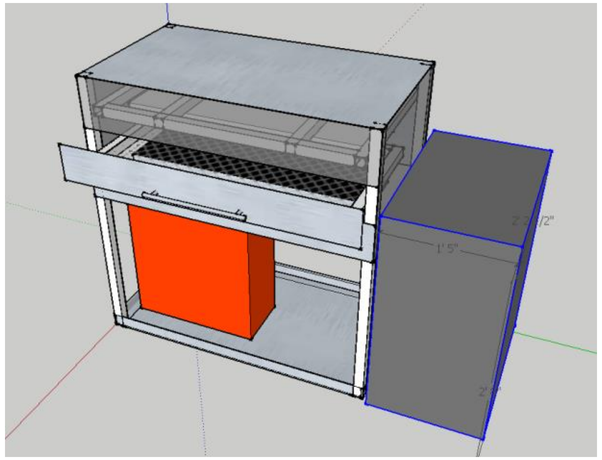


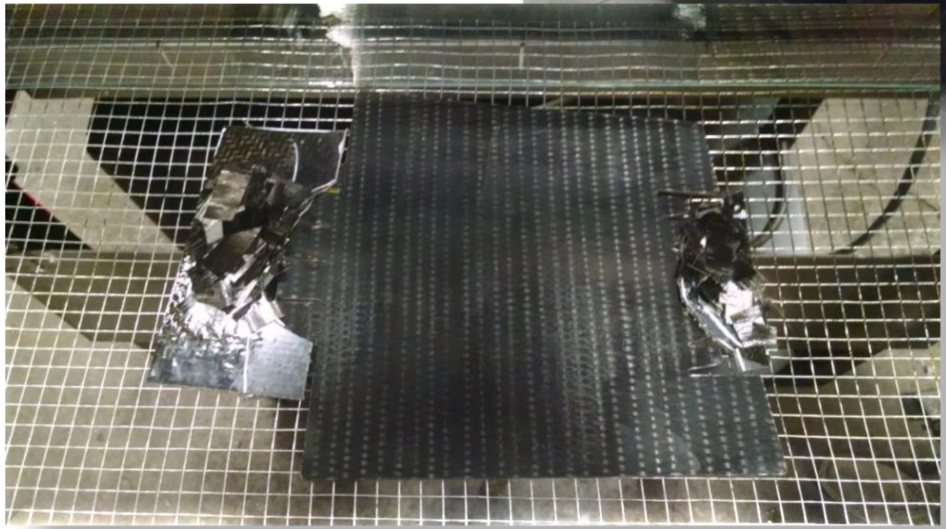
Process Development
Equipment

Oven Design:

- Shape Corp. built radiant oven for sampling
- Adjustable frame for radiant panel spacing
- Heating tray for fast composite removal
- Cycle control timers to allow fine control of power cycle
    - On timer and off timer to produce square wave power input to radiant panels
- Oven trialed at Shape
    - Tuned heat cycle timing
    - Adjusted radiant panel distances
- Final Heat cycle 5s on 10s off

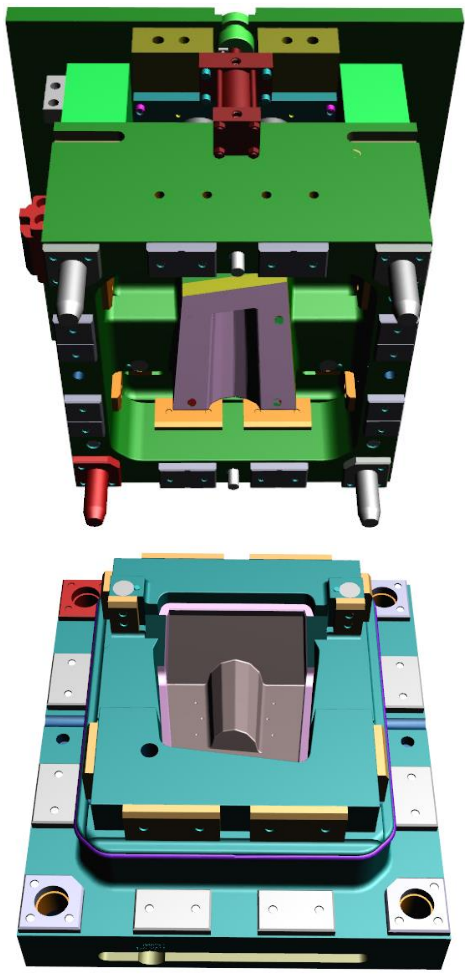
~ 570 °F (300 °C) radiant panel surface temperature





Process Development

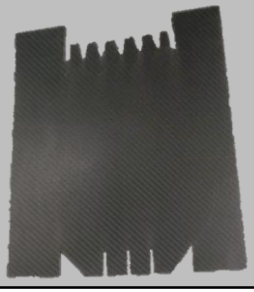
Tooling

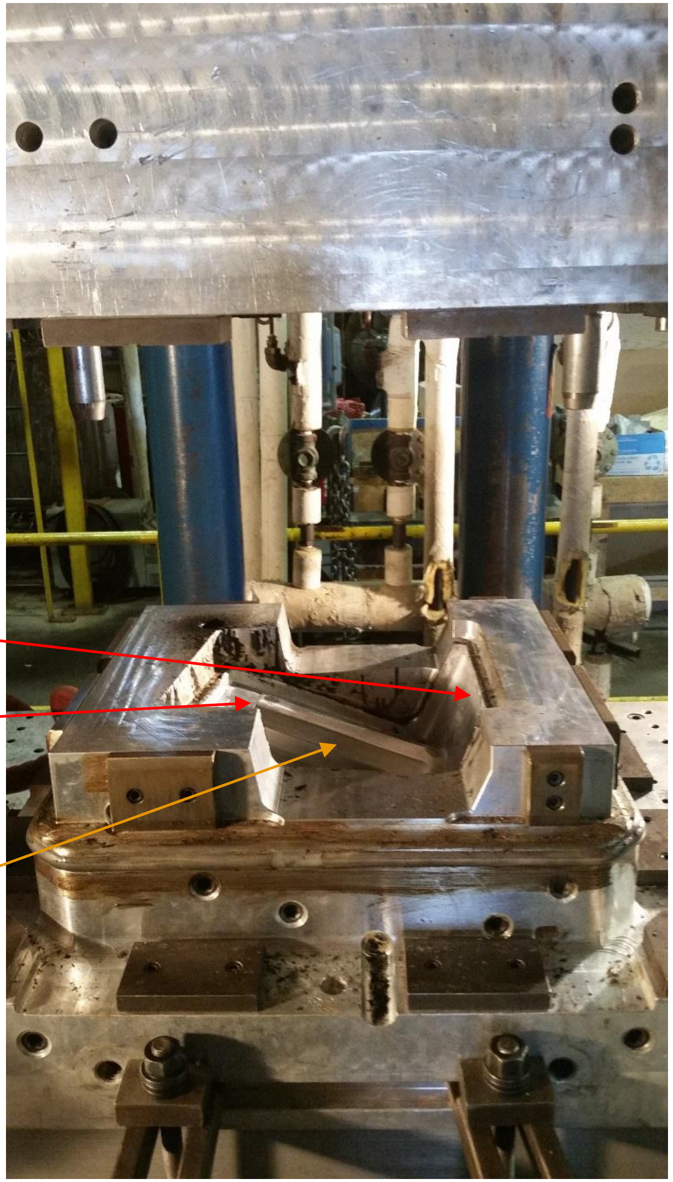


- ❑ Compression tooling designed by USCAR team for molding *thermoset* crush cans
- ❑ Tooling used to mold full quantity of *thermoset* cans before thermoplastic molding phase

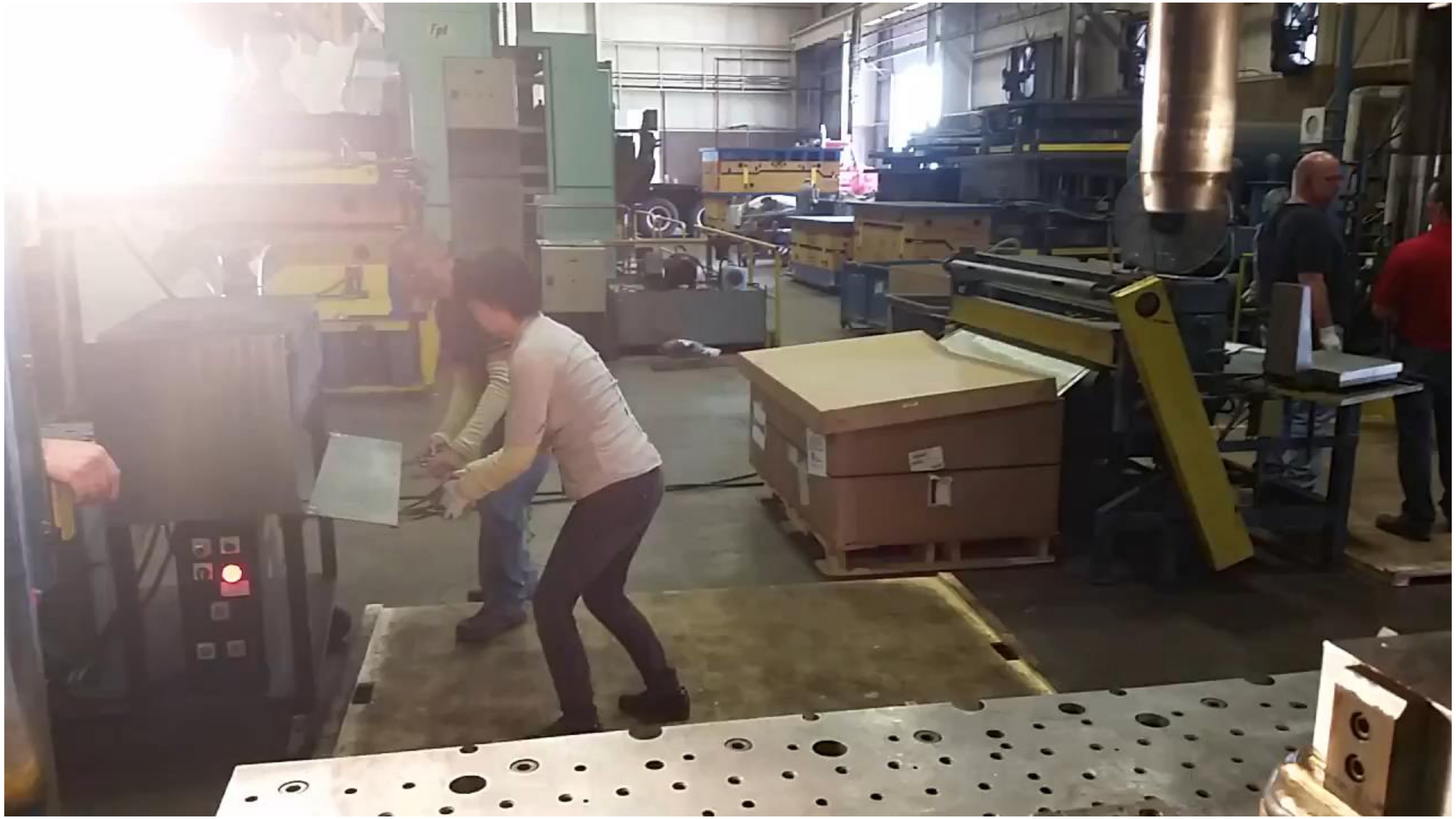
Flange Material Inserted First

Woven Material Placed second



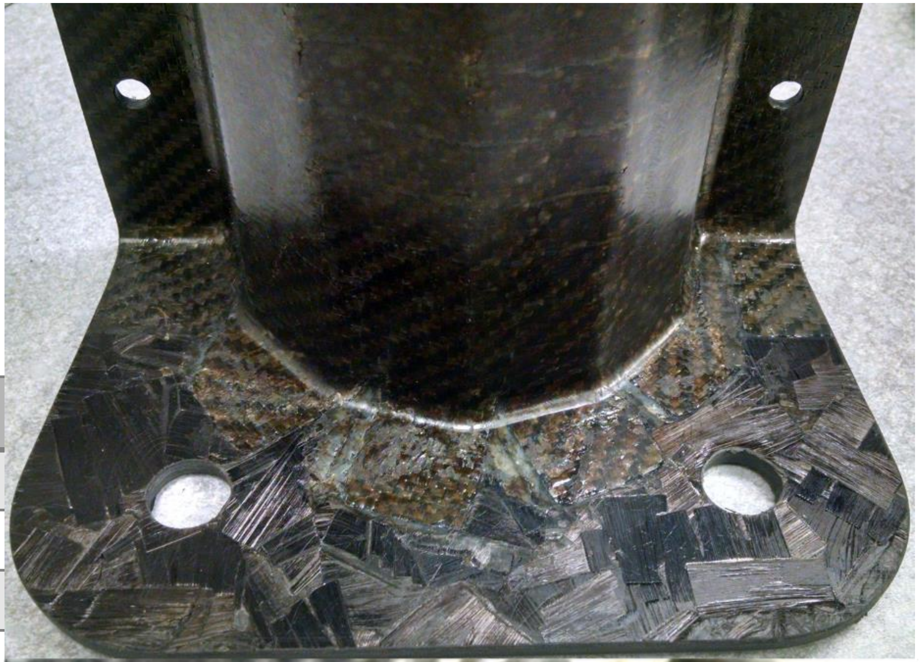


Process Development



Process Development
Molding

Molding Parameters	Setting	Measurement
• Oven Settings		
Power cycle- on setting	5 sec	
Measured radiant panel surface temp		570 F
Power cycle- off setting	10 sec	
Measured radiant panel surface temp		540 F
• Press settings		
Tonnage	400	
Platen position	Partial close	
Hold time		60 sec
Mold Close rate	Fixed	
• Tool Settings		
Tool temperature	290 F	
Mold Release	None added	



Process Development
Molding

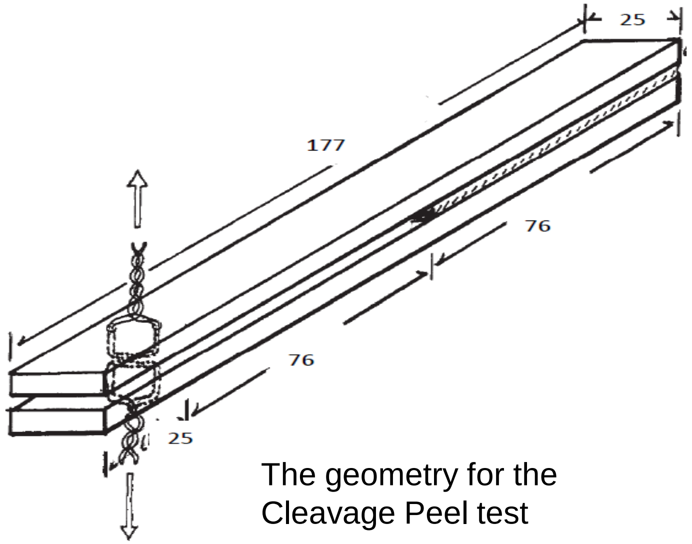
Initial Molding Results

- Part trim: Good; only minor fraying at flange holds on parts 1,2,&4
- Back flange radius not completely filled in on parts 1&3: Due to lower flange insert material shifting during mold close
- Parts 1,2,5: Can body material oxidation on parts causing slight blistering
- All darts filled in well with chopped tape
- Part3: Chopped material shifted into can body
- Part Measurements: Tooling hitting hard stops
    - **Target Dimensions: Points 1-7: 2.81mm; Points 8-10: 5.81mm**

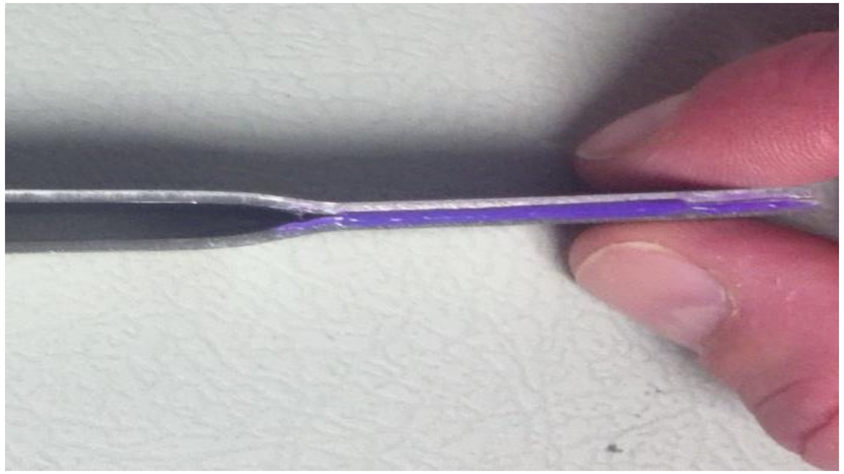
		Measurements (mm)									
Date	Part #	Pt 1	Pt 2	Pt 3	Pt 4	Pt 5	Pt 6	Pt 7	Pt 8	Pt 9	Pt 10
4/13/16	1	2.76	2.80	2.83	2.76	2.81	2.79	2.45	5.25	5.35	5.42
	2	2.75	2.80	3.14	2.75	2.79	2.94	2.32	5.37	5.34	5.19
	3	2.89	2.95	2.94	2.99	3.03	2.95	2.42	5.14	5.27	5.15
	4	2.72	2.80	2.86	2.74	2.80	2.88	2.35	5.24	5.28	5.14
	5	2.77	2.84	2.91	2.81	2.86	2.94	2.34	5.19	5.21	5.14

Mechanical Testing Selection:

- Lap shear (ASTM D1002)
- Cleavage Peel (ASTM 3807)
- Impact Peel (ISO 11343)



The geometry for the Cleavage Peel test



Adhesive Evaluation @ Room Temperature

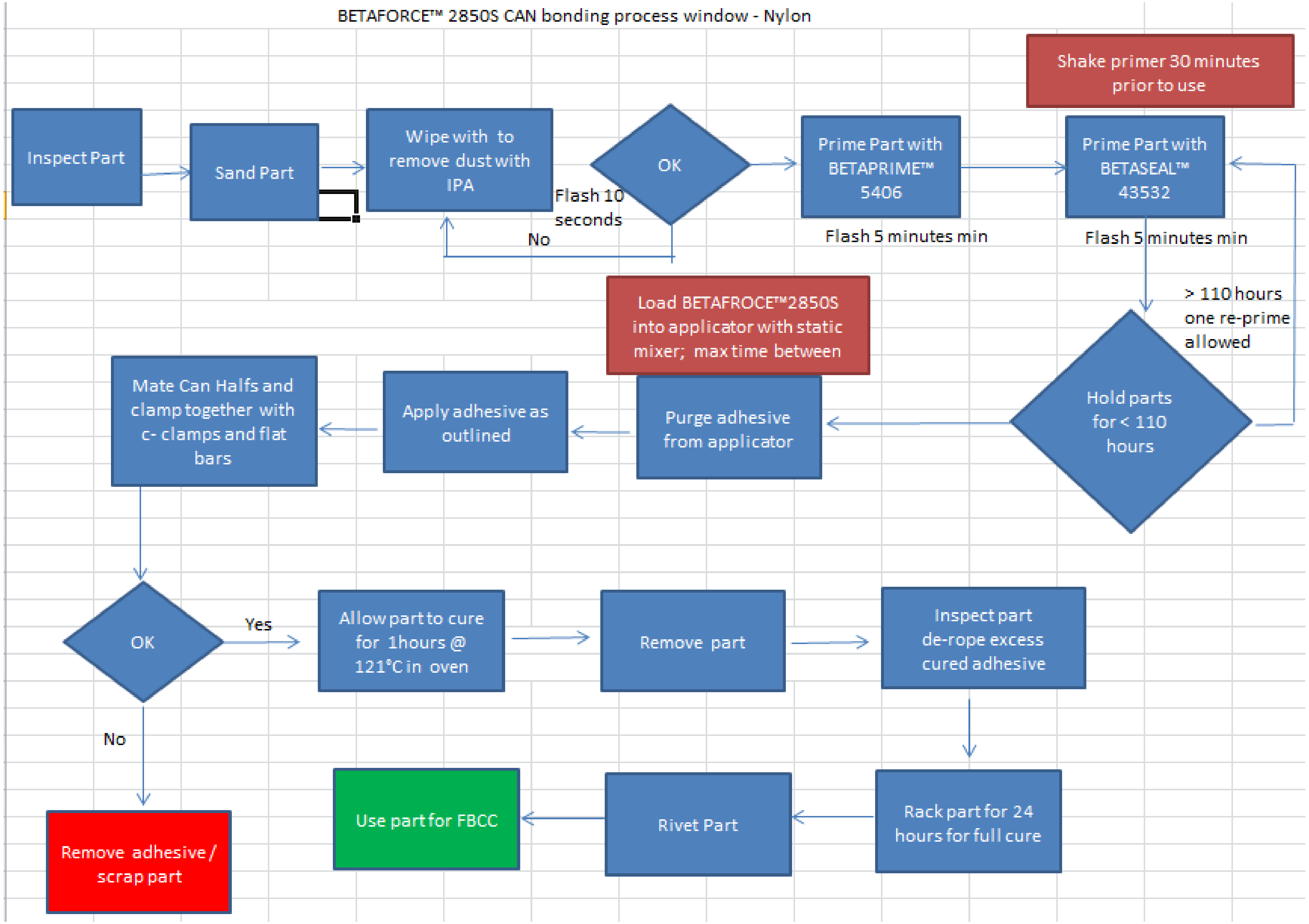
PA6/Carbon Composite

	BETAMATE™ 73326M/27M	BETAFORCE™ 2850L
Chemistry	Epoxy	Polyurethane
Lap Shear (psi)	1331 ± 224 100% CF	1300± 102 100% CF
Cleavage Peel Max Load (lbs) Peel (Lbs·In)	23.7 ±21.2 12.6 ± 4.4 100% CF	53.6 ± 3.0 44.3 ± 5.0 100% CF

CF = Cohesive Failure of the Adhesive

Assembly

Crush Can Assembly Procedure-Nylon



Material Testing

DatapointLabs

Datapoint Labs Test ID: G-794

Test	Data	Replicates
ASTM D792	Solid Density	2
ASTM D3039	Tensile Modulus, Poisson's ration, tensile strength at yield or break, stress-strain curves	5
ASTM D3410	Compressive Modulus, compressive stress/strain data, compressive yield strength or fail strength	5
ASTM D5379	Shear stress-strain data	3
* Strain rates	3 strain rates added for testing	

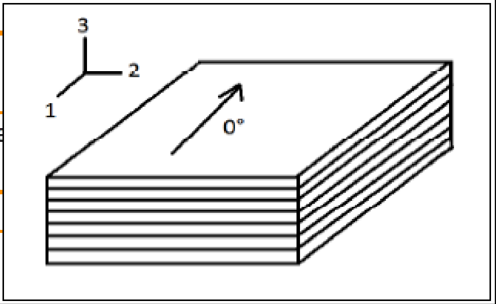
Testing to Generate Mat_058 for LS-DYNA

Tensile Properties: 0.01 /s, 0° direction
Tensile Properties: 1 /s, 0° direction
Tensile Properties: 100 /s, 0° direction
Tensile Properties: 0.01 /s, 90° direction
Tensile Properties: 1 /s, 90° direction
Tensile Properties: 100 /s, 90° direction
Compressive Properties: 0° direction 0.01 /s
Compressive Properties: 0° direction 1.0 /s
Compressive Properties: 90° direction 0.01 /s
Compressive Properties: 90° direction 1.0 /s
Shear Properties: 3-2 direction, 0.01 /s
Shear Properties: 3-2 direction, 1.0 /s
Shear Properties: 1-2 direction, 0.01 /s
Shear Properties: 1-2 direction, 1.0 /s
Shear Properties: 2-1 direction, 0.01 /s
Shear Properties: 2-1 direction, 1.0 /s

Material Testing

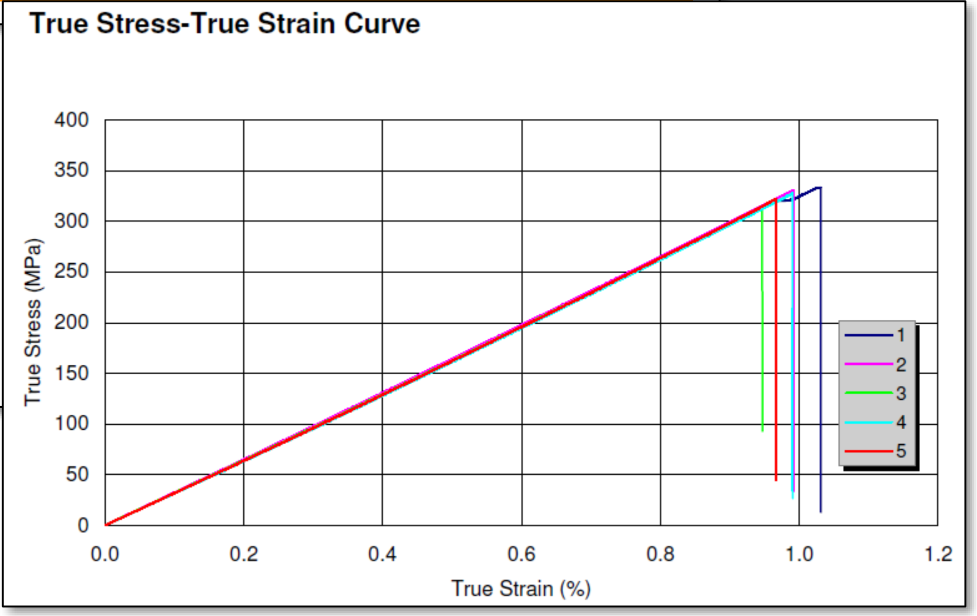
Tensile Properties: 0.01 /s, 0° direction

Method	ASTM D3039 Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials (modified for rate dependency)		
Instrument	Instron 8872 Servohydraulic UTM2		
Specimen	type	straight sided	
	conditioning	40 hours, 23 ℃, 50%RH	
	other preparation	cut from sheet	
	specimen width	9.97	mm
	specimen thickness	2.87	mm
	specimen gage length	10	mm
Parameters	test temperature	23	℃
	lab humidity	45	%RH
	crosshead speed	6	mm/min
	# of replicates	5	
Calculations	strain range for E	0.05 - 0.25	%
	offset condition	0.2	%
Extensometry	axial	contact, 8mm gage	
	extensometer class	B-1	
Uncertainty	per standard		



Properties

Replicate	Modulus E MPa	Offset Yield Stress MPa	Strain at Offset Yield %	Tensile Strength MPa	Strain at Yield %
1	31671	330.0	1.04	330.0	1.03
2	32417	327.7	1.00	327.7	1.00
3	31924	310.2	0.95	310.2	0.95
4	31540	324.1	0.99	324.1	0.99
5	31749	319.2	0.97	319.2	0.97
Mean	31860	322.2	0.99	322.2	0.99
Std Dev	341	7.9	0.03	7.9	0.03

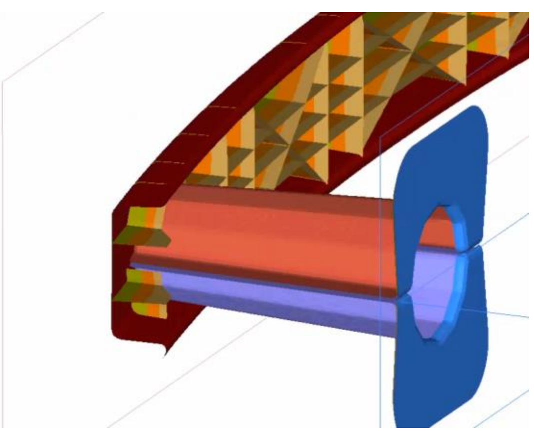


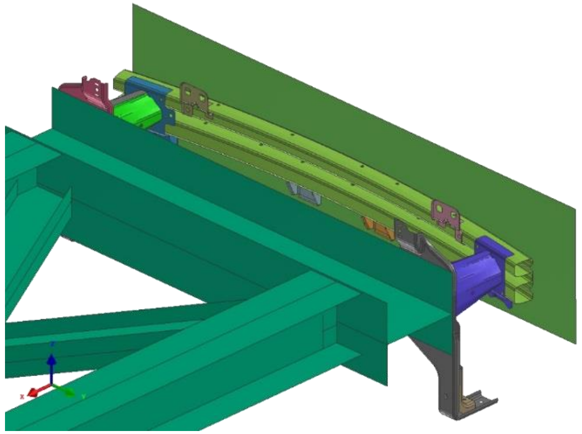
Accomplishments
Summary

- Sourcing commercially available material to achieve design thickness of crush can tooling.
- Design and build of radiant oven for sampling at compression molding site
- Development of carbon fiber inserts using tape from BASF
- Molding of CF/PA6 cans with compression tooling designed for prepreg/SMC process.
- Characterization of custom material system used for producing crush cans
- Identified best case construction and processing for thermoplastic FBCC systems for possible further exploration

Next Steps
Correlation

- ❑ Simulation of crush in LS-DYNA
- ❑ 35 mph sled testing at GM
- ❑ Correlation study to determine accuracy of model with Mat_058
- ❑ Recommendations for tuning and improvement





Loads, Boundary Conditions and Analysis Parameters	Value/Function
Sled Mass (Ignoring Bumper-Crush Can assembly components)	300 kg
Initial Velocity	15.65 mm/ms (35 mph)
DoF @ Rigid Wall	Fixed
DoF @ Sled CG Node	011111 (Only X-Translation Allowed)
Contact within Parts	Self Contact Type 36
Contact Between Parts and Rigid Barrier	Node-to-Segment Contact Type 33

Next Steps
Future Work

- ❑ Mechanical Testing of Low Cost Carbon fiber NCF made from ORNL fiber and PA6 film
- ❑ Axial crush of low cost carbon crush cans with comparison to previous materials
- ❑ Optimization of design of thermoplastic crush can with axial crush results
  - Recommend laminate changes
  - Recommend structural changes
- ❑ Explore options for improving correlation to prediction of thermoplastic carbon fiber composites
- ❑ Simulate complete FBCC system with carbon fiber thermoplastic properties
- ❑ Identify best case construction and processing for thermoplastic FBCC systems for possible future exploration

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