Development of Thermoplastic Pultrusion with Modeling and Experiments

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GATE Scholar

<u>Project ID: LM085</u>

<u>Project No: DE-EE-0005580</u>

<u>Program Manager: Adrienne Riggi</u>

Project Summary*
(The budget below represents the entire GATE Center. This presentation is only a sub-set of the DOE GATE effort.)

Timeline
Project Start - Oct 2011
Project End – Sep 2016
72.6 % complete

Budget (Overall GATE Center)
Total project: $750,000*
DOE portion: $600,000
University Cost Share: $150,000
$447,420 DOE
$325,000 Expended
72.6% complete

Barriers
- Limited information on advanced materials database
- Lack of high temperature properties

Partners
- ORNL
- MIT- RCF
- Owens Corning
- Polystrand, PPG
- CIC, Canada

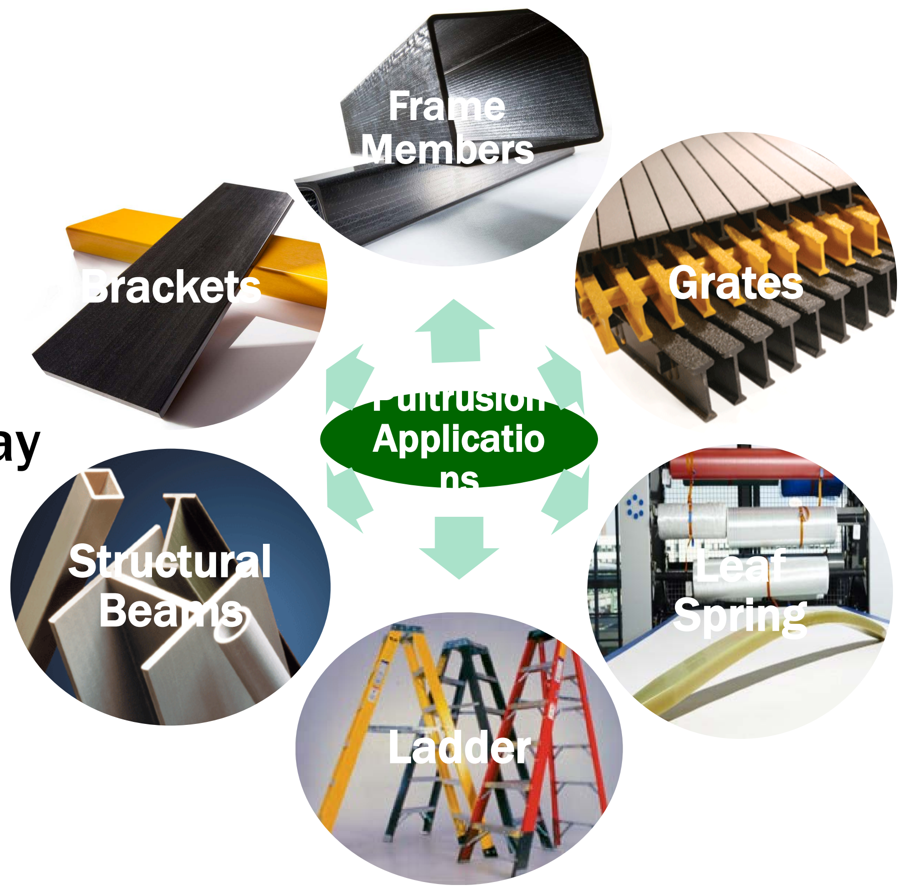
Khongor Jamiyanaa (GATE Scholar) - Background

- Graduated from Colorado State Univ. in 2010
  - BS in Mechanical Engineering, Minor in Mathematics
- Graduated from Univ. of Alabama at Birmingham in 2014
  - MS in Materials Science and Engineering
  - Research Thesis: Design and modeling of Thermoplastic Pultrusion Process
- 1yr Co-op internship at Owens Corning Science & Technology center in 2013.
  - Application Development Engineer

RELEVANCE
Pultrusion Applications in Automotive, Truck and Mass Transit

<u>Wide Ranges of cosmetic and structural applications</u>:

- Transportation
- Truck frame members
- Vehicle underlay tray
- Truck bed liner
- Leaf Springs
- Utility applications
- Brackets



<u>Pultrusion Offers:</u>

- High strength-to-weight ratio
- Corrosion resistance
- Thermal insulation
- Electric insulation
- Cost effective
- Rapid and efficient

http://www.strongwell.com/markets/custom-pultrusions/
http://www.fibergrate.com/products
http://www.creativepultrusions.com/pultruded-systems/composite-utility-poles/

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http://www.compositesworld.com/articles/composite-leaf-springs-saving-weight-in-production-suspension-systems

RELEVANCE
GATE Project

- Technique to produce fiber reinforced polymer (FRP) composites of a profiled shape.
- FRP material pulled through a temperature controlled die to shape the material.
- Highly aligned, constant cross-section, linear length, continuously pulled.
- Both thermosets and thermoplastics can be pultruded, the process slightly differ.

Thermoset Pultrusion

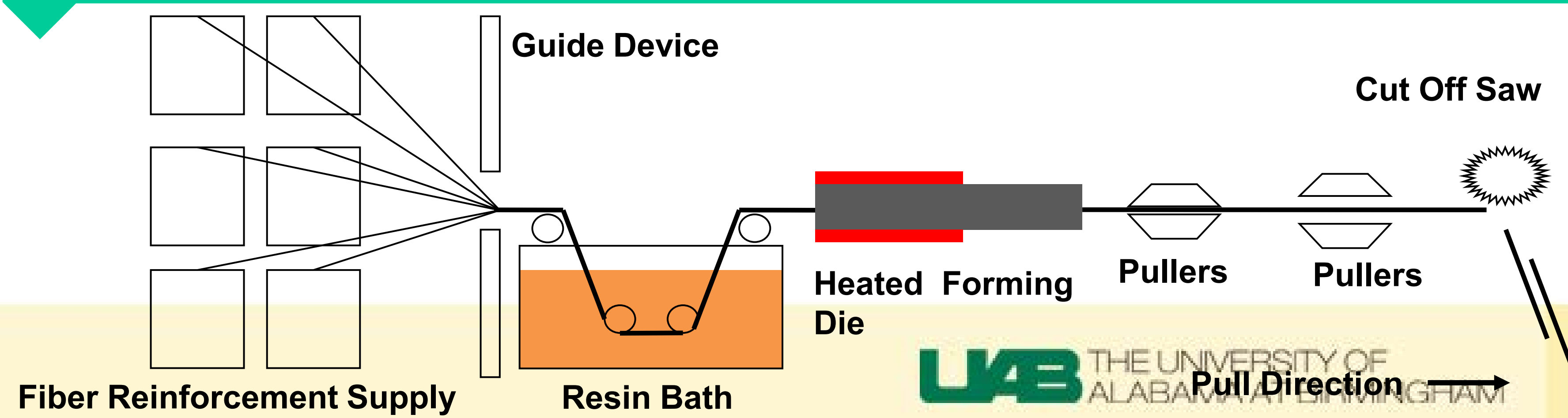
- Thermoset pultrusion is a mature process
- Available commercially
- Much easier to process with thermoset matrix than thermoplastic matrix
- Lower viscosity, easy to wet out, does not require excess pulling force
- Offer higher thermal and chemical stability

1 • Virgin continuous fibers are pulled through a guidance system

2 • Fibers enter a resin bath and get saturated with the matrix

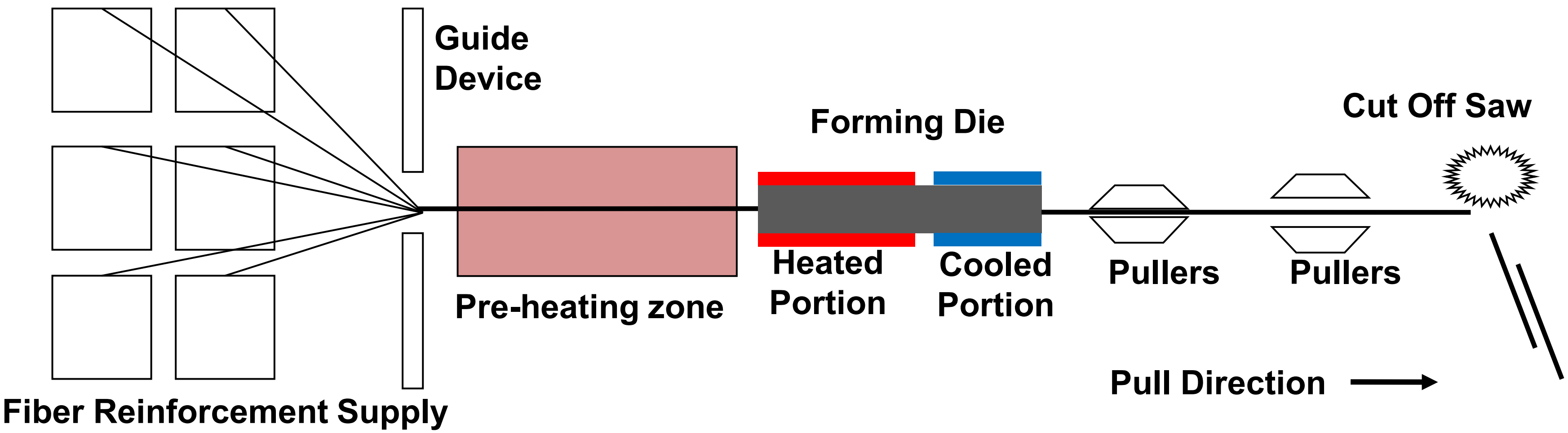
3 • Fibers then enter a die to be shaped and heat is applied to initiate the curing process

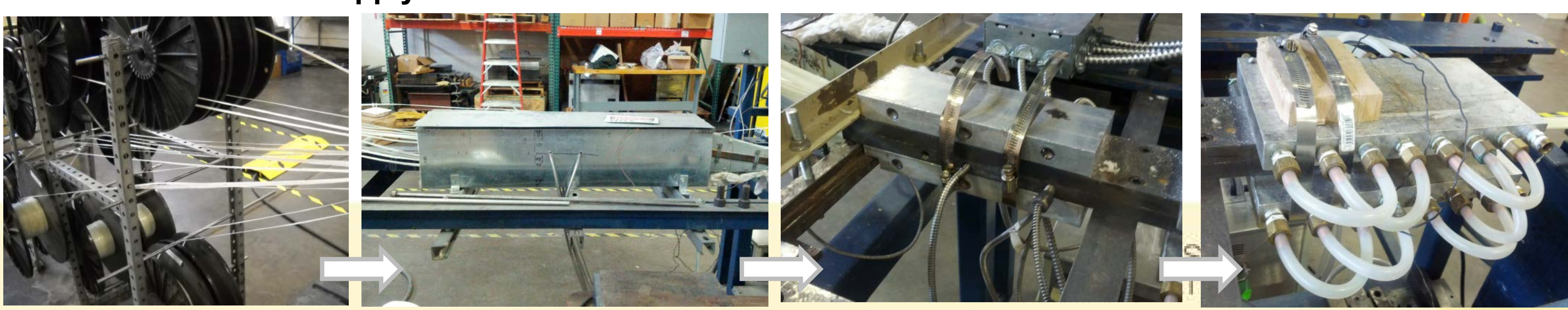
4 • The formed composite is continuously pulled and cut at the preferred length



Thermoplastic Pultrusion

- Thermoplastic pultrusion is a relatively new process.
- Limited research has been done.
- Process is complicated by the high resin viscosity of thermoplastics
    - Two to three orders of magnitude higher than thermoset resin





Project Overview and Objectives

Difficulties of thermoplastic pultrusion process:

- The high resin viscosity
- The non-Newtonian resin flow
- Resin solidification and melting
- Possibility of more than one die

Advantages of Thermoplastics

- Higher facture toughness, damage tolerance
- Recyclable
- Can be welded
- Easy to maintain, safer (no styrene emission)

There is a general lack of well established standard or methods of designing pultrusion line for thermoplastic matrices.

This study attempts to develop models and methods to determine an optimal design for a thermoplastic pultrusion die by:

1) Creating analytical and computer generated models to design.
2) Using CFD model to capture the flow inside the die.
3) Validate the model with experimental methods.
4) Develop a method to measure residual stress in pultruded composites.

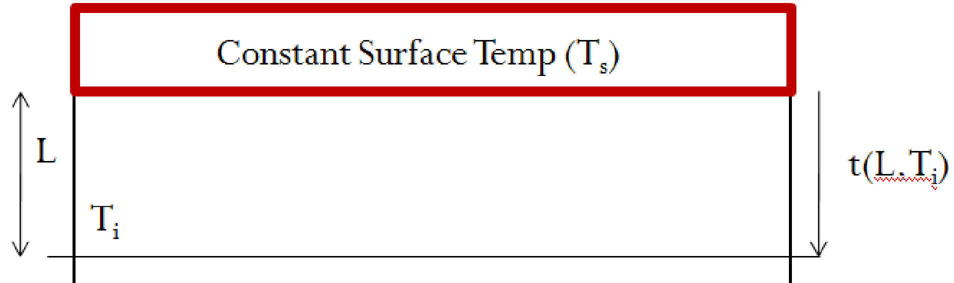
Project Milestones

Milestones	Status
Design Thermoplastic Pultrusion Die	Analytical model, software models were created (2010-2011)
Manufacture the die	Die made in house at UAB (2011)
Experimental Work	Models were validated with experiments (2012)
Owens Corning (OC) Internship	Completed year long internship at OC (2013)
Report Finding/Thesis	Masters work defended (2014) Publishing work

Project Approach and Accomplishments

Pultrusion Die Design and Modeling

- Thermoplastic pultrusion was viewed as a form of energy transfer as opposed to chemical reaction (cross-linking) found in thermosets.
    - Heat is introduced to melt and consolidate
    - Heat is taken out to freeze and solidify
- Die was designed based on the amount of temp. and time required to melt and solidify the material all the way through its thickness depending upon the pulling speeds.



- To design the die, The process was considered as 1D transient heat conduction problem.
- The pultruding material was lumped as plain wall with finite thickness *L* of uniform temp T_i.
- The length *d* of the die was determined by first calculating the time it took the surface temp. T_s to transfer through the thickness and melt the center.

Pultrusion Die: Analytical Modeling

Time-dependent conduction, plane finite wall, heat transfer:

$$\frac{T_m - T_s}{T_i - T_s} = \sum_{n=1}^{4} \left(C_n \cdot \exp\left(-\zeta_n^{\,2} \cdot Fo\right) \cdot \cos\left(\zeta_n \cdot L\right)\right)$$

Where C_n coefficient: $C_n = \dfrac{4\sin(\zeta_n)}{2 \cdot \zeta_n + \sin(2\zeta_n)}$

The eigenvalues are the positive roots of the time dependent equation (values gathered from heat transfer book): $\zeta_n \cdot \tan(\zeta_n) = Bi$

The Biot number, the Fourier number, and relates the material's thermal properties: $Bi = \dfrac{h \cdot L}{k}$ $\quad Fo = \dfrac{\alpha \cdot t}{L^2}$ $\quad \alpha := \dfrac{k}{\rho \cdot c_p}$

- **Material: Polypropylene with E-Glass (PP-GF)**
  - **Hot melt impregnated tapes. 60% FWF.**
- **Thermal properties of the composite calculated with rule of mixtures**

Material	Thermal Conductivity k	Density ρ	Heat Capacity c_p	Melt Temperature T_m	Weight Fraction W_f
Polypropylene	$0.2 \frac{w}{m\ K}$	$900 \frac{kg}{m^3}$	$1950 \frac{J}{kg\ K}$	167^oC	0.407
E-Glass	$1.0 \frac{w}{m\ K}$	$2540 \frac{kg}{m^3}$	$840 \frac{J}{kg\ K}$	$>800^oC$	0.593
G/PP	$0.381 \frac{w}{m\ K}$	$1458 \frac{kg}{m^3}$	$1572 \frac{J}{kg\ K}$	167^oC	1

$$c_p := c_{p\_g} \cdot V_f + c_{p\_pp} \cdot (1 - V_f) \qquad \rho := \rho_f \cdot V_f + \rho_r \cdot (1 - V_f) \qquad k := \left(\frac{W_f}{k_g} + \frac{1 - W_f}{k_{pp}}\right)^{-1}$$

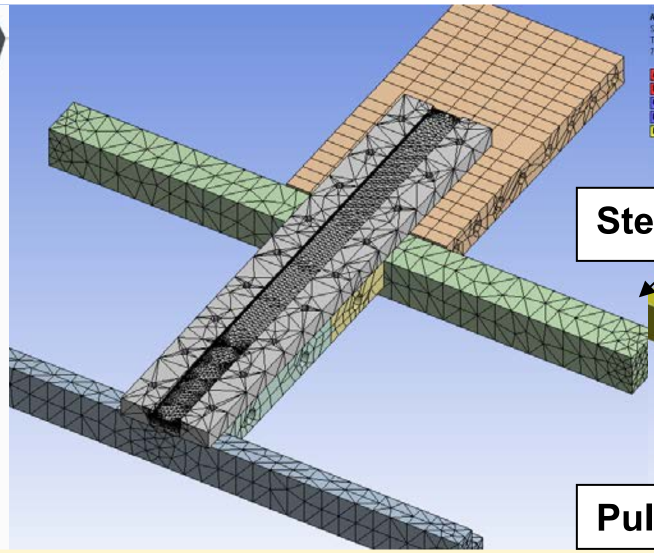
F. P. Incropera, D. P. Dewitt, T. L. Bergman, A. S. Lavine. *Fundamentals of Heat and Mass Transfer.* Hoboken : John Wiley & Sons, 2007. pp. 487, A-36.

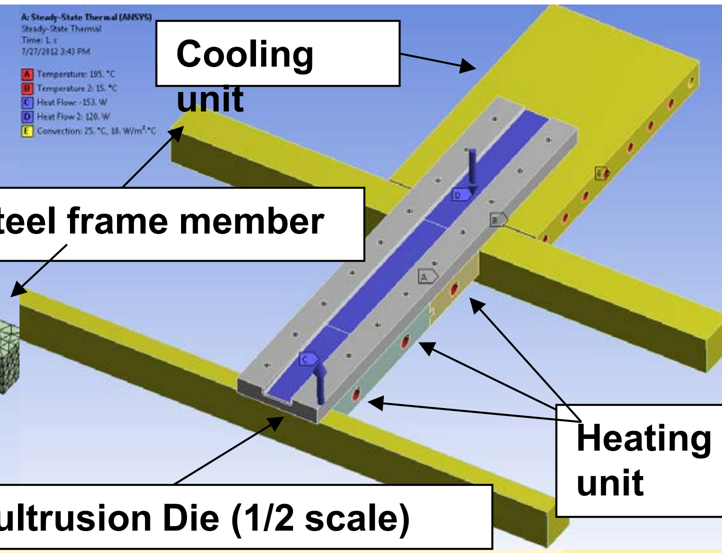
Results - Design and Modeling

- Solving for the time and the required minimum temperature:
  - It takes about 10 seconds to melt all the way through 4.3mm
  - If the surface temperature is 185°C.
- The length of the die:
  - 14.4cm was need for the material to stay in the die for 10 seconds
  - The length was considering the highest pull speed of 14.4mm/sec
    - By considering the highest pull speed, gives a safety cushion
    - If the operating speed is slower, the material will be in die longer, giving more time to melt thoroughly.
- Once the material has fully melted and consolidated, it is cooled inside to the maintain the shape.
  - A reverse calculation was made to determine the length for the center to cool to its crystallization temp T_c of 100°C
  - Using the same max speed, the length required to cool was 11.5 cm.

Pultrusion Die: CAD and FEA Model

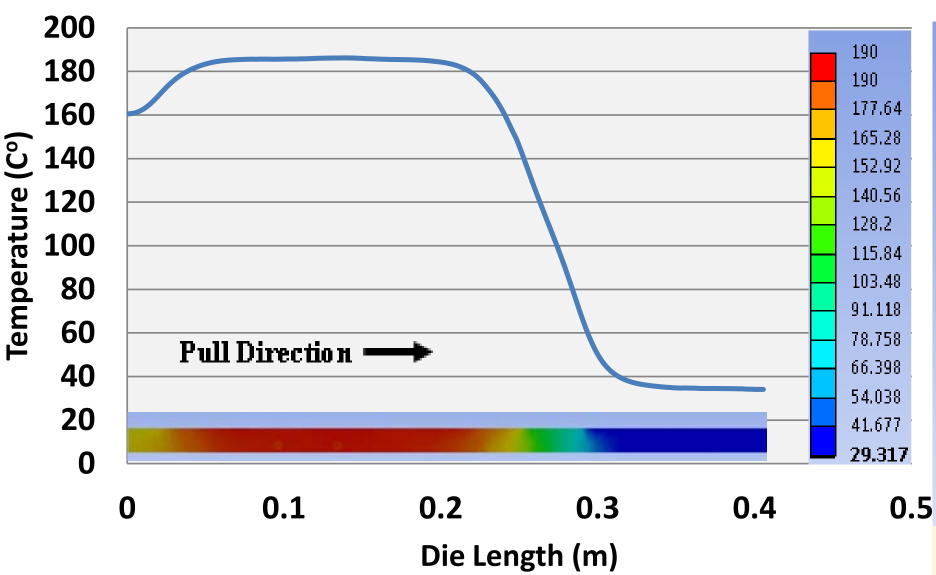
- Following the analytical heat transfer model, CAD software was used to design the die.
  - Die had rectangular cross-section. 25.4mm by 4.3mm.
  - Made of two symmetrical halves.
- FEA was performed to understand the die temperature profile
- The model simulates the conductive heat transfer from the heating/cooling units.
  - Cartridge heaters/chiller was assigned constant surface temp.
  - Thermal contact resistance was applied between surfaces
  - Natural convection was applied to exposed surfaces

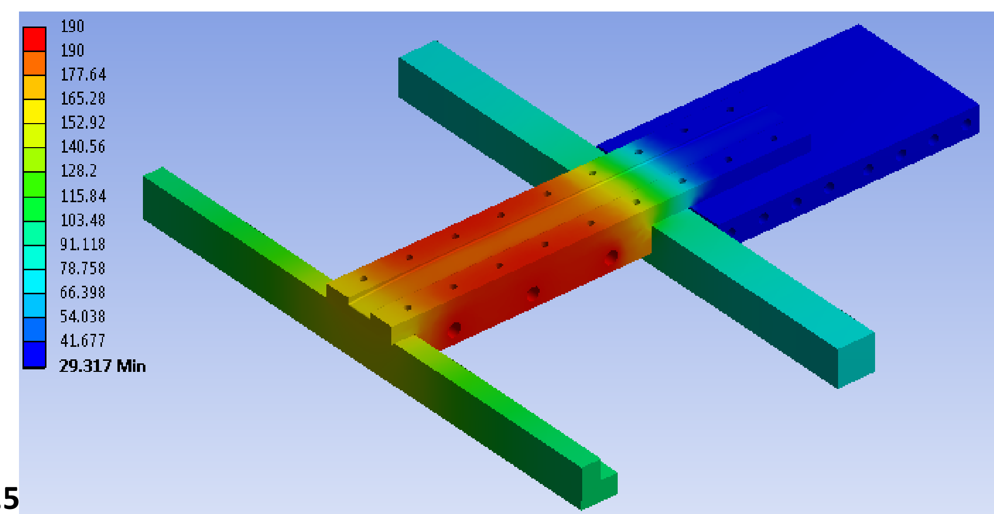




Results - CAD and FEA Model

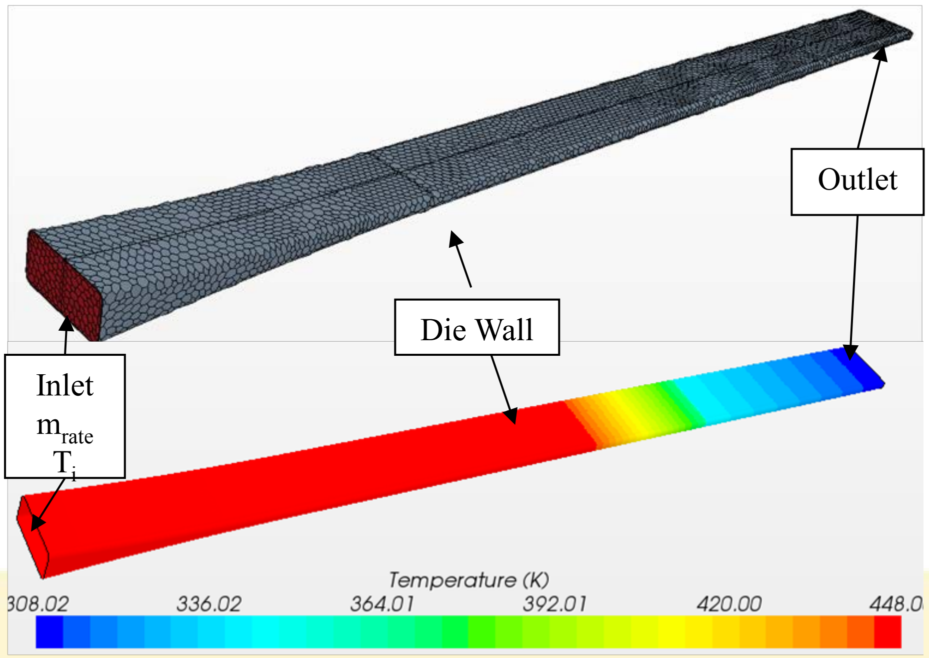
- As discussed in the Die Design section, the die surface temp needs to be:
    - 185 °C for 14.4 cm when pultruding at 14 mm/sec
- Iterative design process was conducted to determine the:
  - The heating power, number of heaters, the distance between each heating unit.
- The heating and cooling units were optimized to achieve the required temperatures for 14.4cm to melt and 11.5cm to cool the material.
    - Three 0.5”diameter, 300W cartridge heaters, 3” apart, and heated to 190°C were needed to reach proper temperature profile

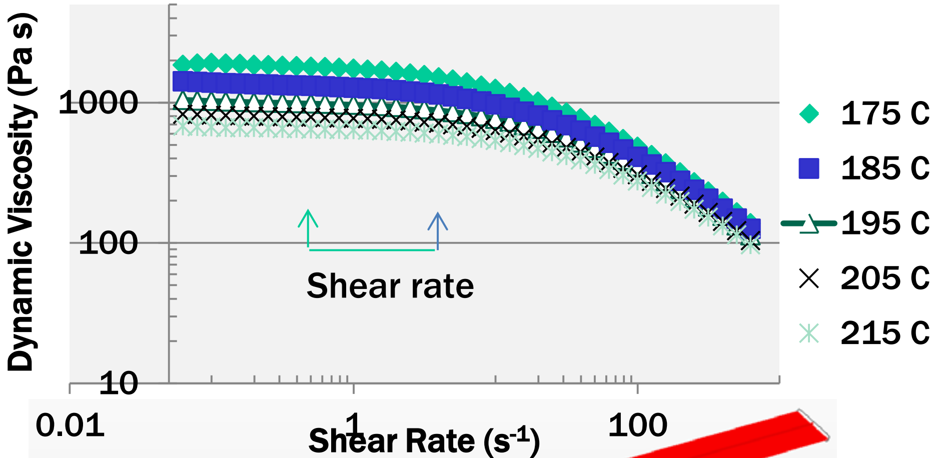


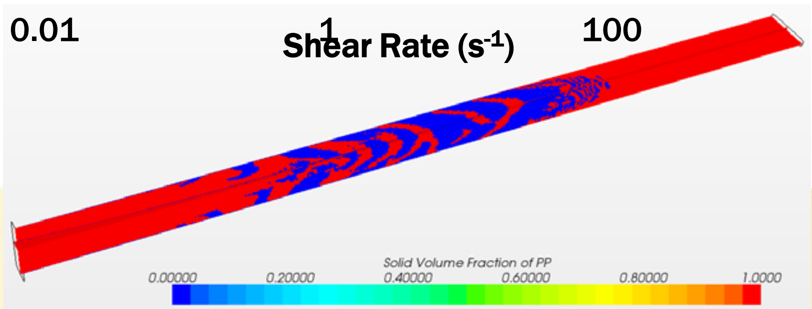


Pultrusion: CFD Model

- CFD software was used to model the molten flow inside the die. The model used to predict the pulling force and where the resin melts and solidifies.
- In thermoplastic pultrusion, the matrix heated till it melts and the pulling force creates fluid dynamic motion inside the die.
- CFD was used to predict where the resin melts and solidifies, the maximum force required to pultrude and determine the effect processing parameters.

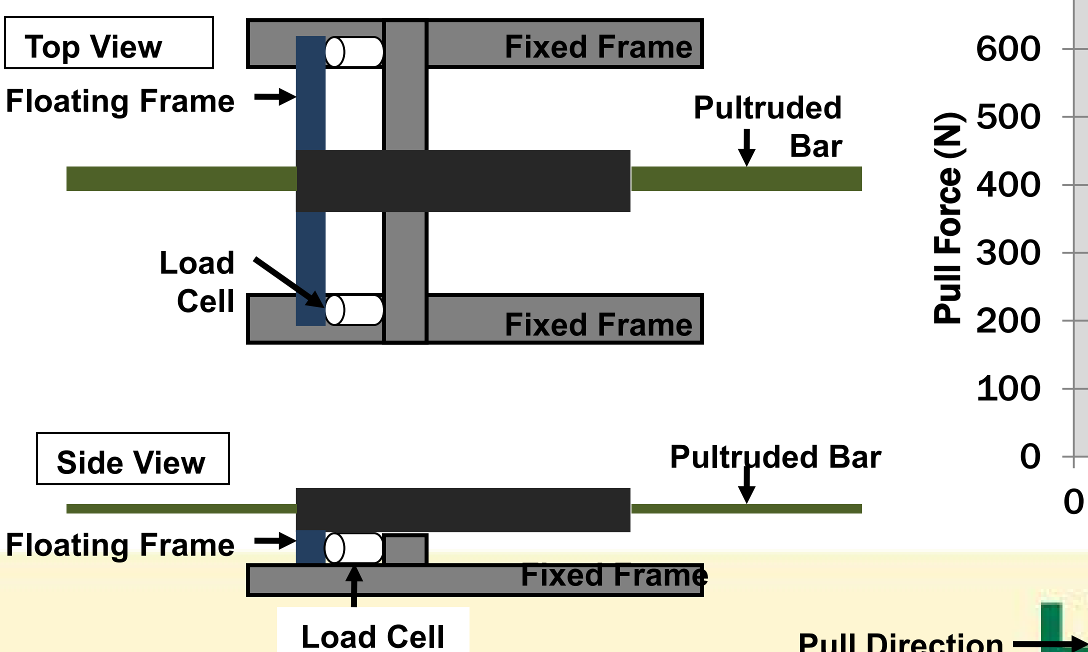


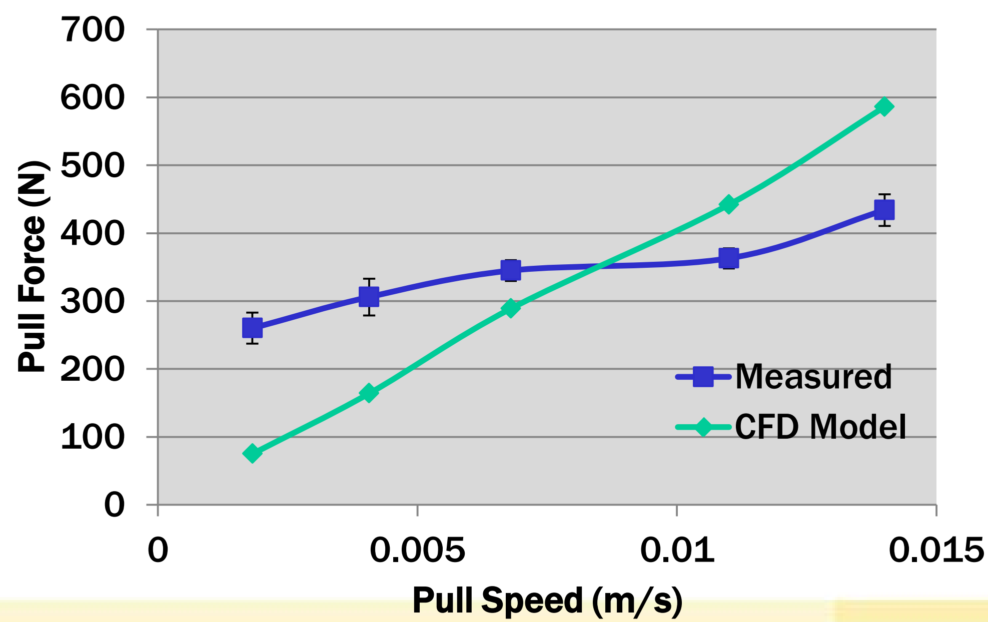




Results - CFD Model

- Pull force measured experimentally to validate the CFD model.
- The pultrusion was converted to a “floating system” to measure the pull force in-situ.
- The experimental results correlated well with the predicted CFD models
- Both show a trend that increases in pulling force as the pull speed increases.

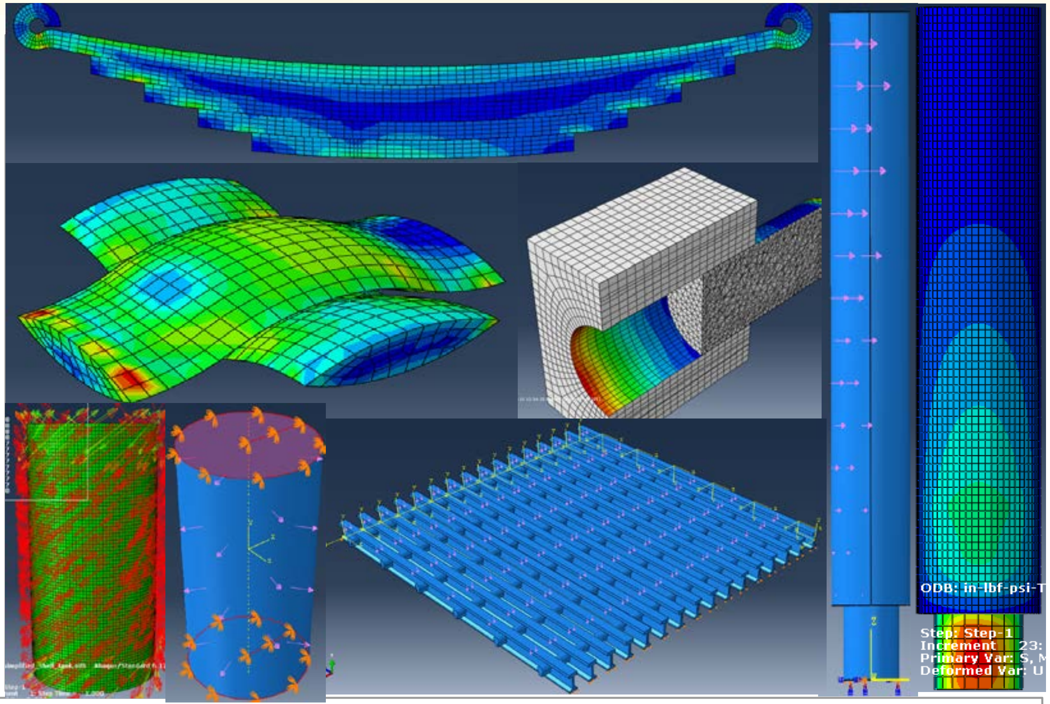




Collaborative Work with Partners

UAB – Owens Corning Co-operative Internship GATE Industry Leverage

- Completed the 1st UAB-OC internship.
- Worked as an Application Development Engineering in the Composite Design Modeling Solutions Team.
- Developed innovative design solution and leveraged FEA models to meet business demands in the composite market.
- Rational Program, more students are assigned to go.



•Formulated an analytical model to predict various stainless steels performance in different corrosive environments such as sea water, HCl, and H_2SO_4.
•Model used to predict lifespan of stainless in corrosive environment and convert stainless steel to FRP.
•Work was presented at NACE conference and included in the OC Corrosion Guide handbook

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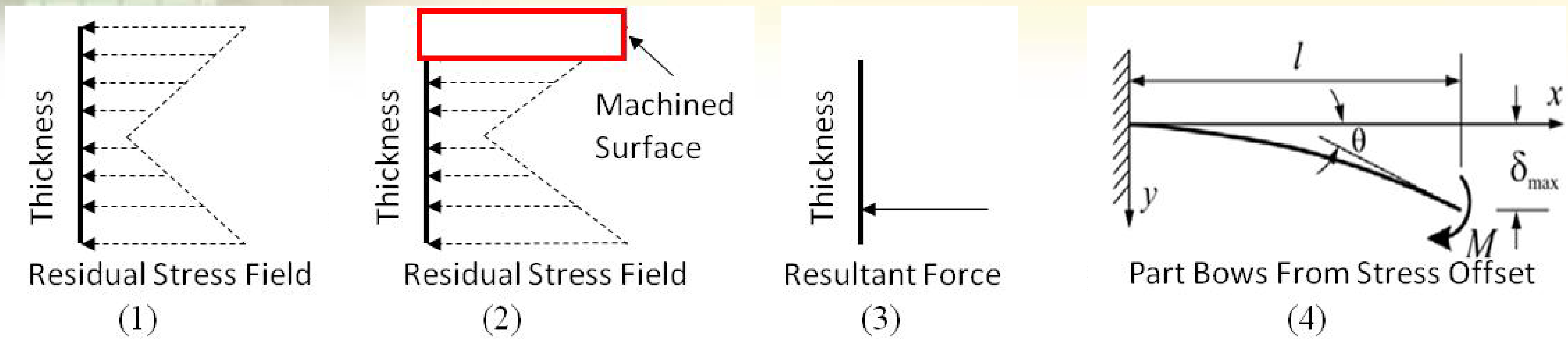
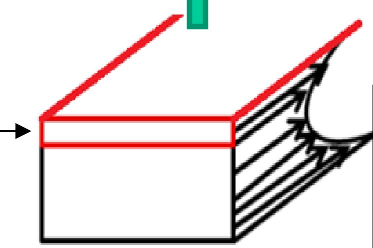
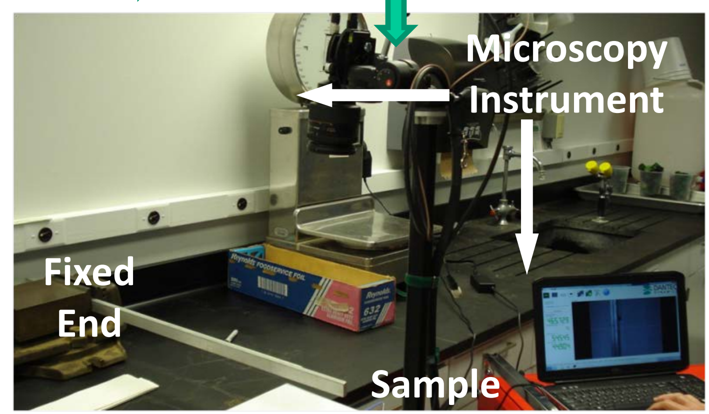
Thermoset Pultrusion-
Residual Stress Through the Thickness



Machined surface: 0.01” off top surface, then 0.03”, and finally 0.06”



Pultruded Part Total Thickness: 0.125



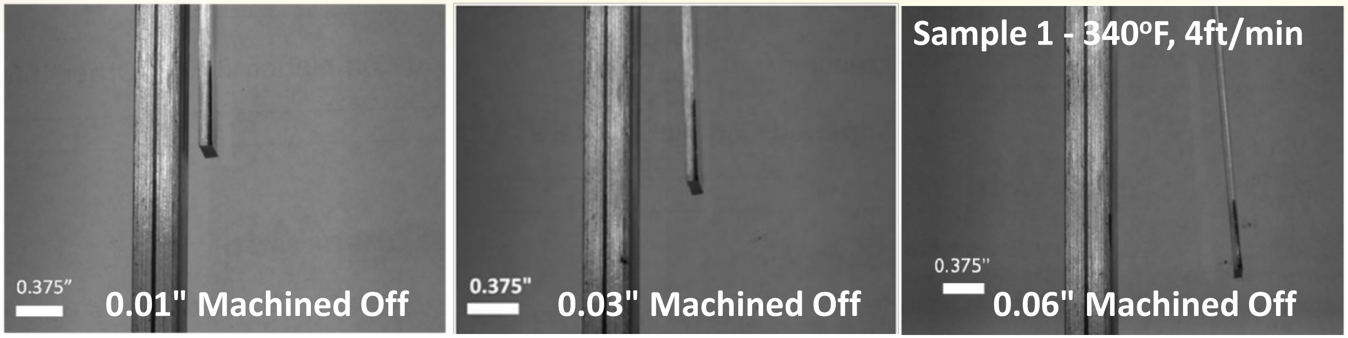
- Residual stress calculated by relieving the stress
- Stress is relieved by machining the top surface
- The equitant force is offset
- The part deflects to balance itself
- Cantilever beam theory is used to calculate the internal stress
- Process is repeated at different levels through the thickness

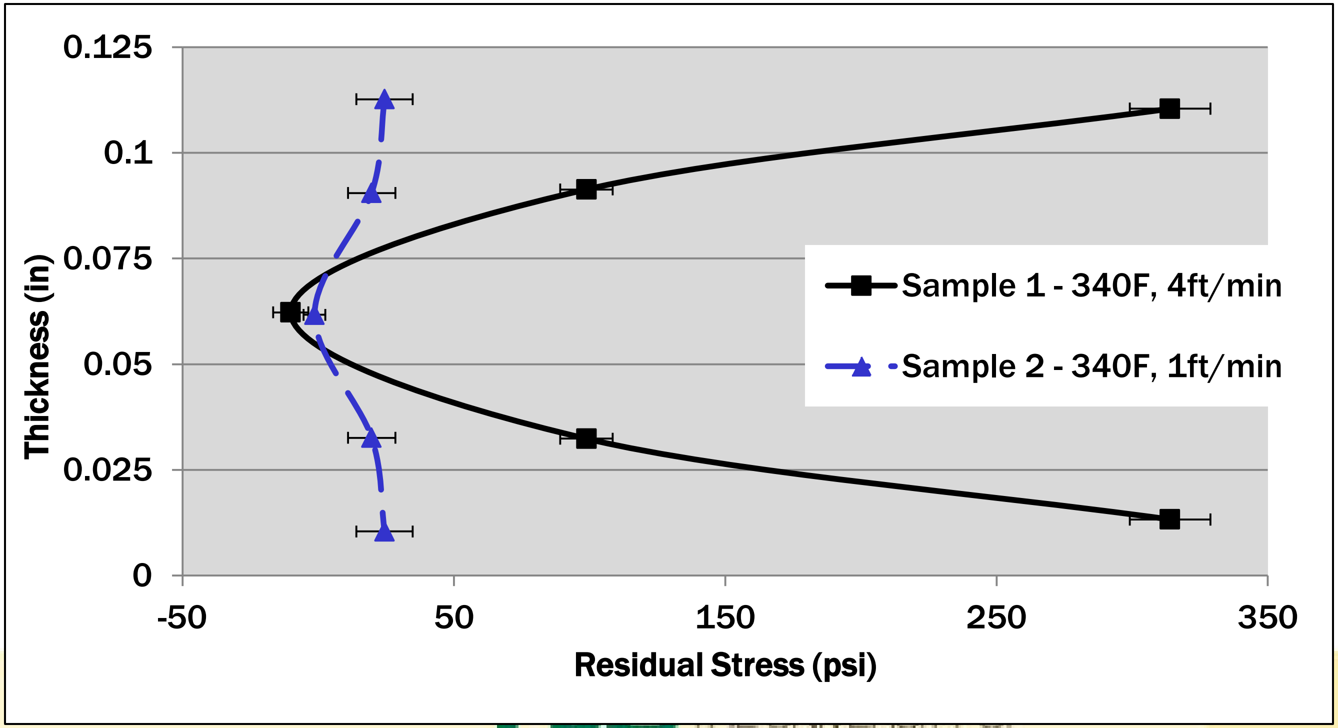
$$M = \frac{2 * \delta * E * I}{L^2} \qquad F = \frac{M}{t}$$

$$P_{Residual\ Stress} = \frac{F}{A_{Machined\ Area}}$$

Results - Residual Stress Through the Thickness

- Residual Stress was greatest on outer edges
- Stress increases non-linearly from center to the edge
- Almost no stress in the center
- Confirms that the residual stress has a gradient
    - If stress field was even, the part would not bow.
- Pull Speed:
    - 4ft/min to 1ft/min
    - All other parameters kept constant
- Residual stress was greatly influenced by the pull speed
    - Residual stress lowered from 314psi to 24psi
    - Deflection also lowered from 0.8” to 0.11”





Summary

Through the GATE funding:

- Developed multiple models pultrusion die for thermoplastics
- Established a baseline for thermoplastic pultrusion design criteria
  - Could be used for any fiber/matrix combination including carbon fiber.
- Developed a method to measure residual stress in pultruded composites
- Completed 1 year industry experience with UAB-OC Co-op internship
- Received sound understanding and hands on experience in many composite process techniques and ASTM testing methods
  - Pultrusion, VARTM, extrusion, compression molding, and injection molding.
- Trained on multiple CAD/FEA modeling softwares
  - Pro/E, Abaqus, Ansys WB, Star-CCM+, HyperMesh, MoldFlow® and MathCAD.

Publications

- *Thermoplastic Pultrusion Modeling and Experimental Studies*, **Khongor Jamiyanaa**, University of Alabama at Birmingham. 2012 SPE ACCE Student Poster
- *Modeling and Experimental Studies on Thermoplastic Composite Pultrusion,* **Jamiyanaa, Khongor. Vaidya, Uday.** University of Alabama at Birmingham. ACMA 2013 Technical paper, pultrusion track.
- *Performance Comparison of Stainless-Steel and E-CR Based FRP Composite in Corrosive Environment.* **Vaiyda, Amol., Spoo, Kevin., Jamiyanaa, Khongor.** Owens Corning, University of Alabama at Birmingham. NACE International Conference.
- *What Causes Bow in Pultrusion*. **Jamiyanaa, Khongor.** University of Alabama at Birmingham. Alabama Composites Conference, 2013. Student Poster.
- *Development of Residual Stress in Pultruded Composites.* **Jamiyanaa, Khongor., Spoo, Kevin.** University of Alabama at Birmingham, Owens Corning. 2014 ACMA CAMX Conference. Pultrusion Track. *(Up-coming)*

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