Advances in Fiber Alignment for TuFF Preforms: Investigating Fiber Orientation Dynamics and Process Optimization

Presenter: Navid Niknafs

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Objectives

- Investigate dynamics of fiber alignment within a water film.
  - Propose a physics-based model fiber reorientation.
  - Optimize the throughput of TuFF.

- Improve quality of TuFF preforms for thin ply (8 gsm blocks)
  - Reduce window gap size distribution
  - Retain areal weight uniformity

- Approach
  - Benchmark current alignment process
  - Propose a physics-based model for fibers reorientation
  - Identify origin of window gap formation
  - Design, fabricate new scalable spillway
  - Conduct experiments and characterize microstructure
Project Overview - TuFF Thin Ply (8gsm building block using baseline alignment process)

- Highly aligned short fiber (IM7 3mm) in form of sheets:
  - IM7 3mm LM-PAEK
  - Fiber aspect ratio: 600:1
  - 95% fibers aligned ± 5°
  - 300psi consolidation pressure, 380C process temperature 50% nominal FVF.
  - Cross-ply laminates (areal weight of 90° layer included 60 gsm, 120 gsm and 240 gsm)

- Variability increases in thin ply 90-degree layers as areal weight decreases
  - Resin content
  - Fiber dispersion
  - Local FVF
  - Ply thickness

<table>
<thead>
<tr>
<th>Fiber Volume Fraction</th>
<th>60 gsm</th>
<th>120 gsm</th>
<th>240 gsm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (%)</td>
<td>35.9</td>
<td>42.1</td>
<td>47.4</td>
</tr>
<tr>
<td>SD</td>
<td>5.5</td>
<td>2.8</td>
<td>1.2</td>
</tr>
<tr>
<td>CV (%)</td>
<td>15.5</td>
<td>6.6</td>
<td>2.6</td>
</tr>
</tbody>
</table>

60 gsm

FVF ≈ 35%

120 gsm

FVF ≈ 28%

FVF ≈ 49%

FVF ≈ 47%
Project Overview – Variation in TuFF Thin Ply

• Hypothesis: Reducing window gap size in preform will lead to
  1) increase in Fiber Alignment
  2) reduction in the variability.

• To achieve higher FVF (57%):
  ✓ 8 gsm preforms are stacked
  ✓ Nesting occurs to fill window gaps
  ✓ 120 gsm stack is current limit

• Approach
  I. Characterize the fiber alignment process.
  II. Develop a physics-based model for fiber orientation dynamics on the spillway.
  III. Identify source of window gaps during fiber alignment.
  IV. Develop technique to measure distribution of window gap in preform.
  V. Develop new spillway for window gap reduction.
  VI. Conduct key experiments to demonstrate feasibility.
Process Characterization

• Experimental Setup for Process Characterization

I. Water Film Thickness (confocal Displacement sensor)
II. Fiber Alignment Dynamics (Highspeed Camera)
Process Characterization - Water Film Thickness

- Water Film Thickness Measurement

Experimental Measurements Constructed in 3D Model

Water/Fiber jet on the spillway

12”

Water Film Thickness (ConfocalDT)

*Normalized Experimental Data
Process Characterization: Experimental Investigation of Fiber Alignment

- Highspeed imaging

Highspeed imaging (8k fps) of fibers within flow

Orientation Distribution

**Image Analysis for Fiber Orientation Dynamics**

- Raw Image
- Filter
- Fiber Detection
Physics Based Model: Problem Formulation

- Fiber position and orientation is described by its centroid position \( x_c \) and its orientation \( p \).
- Fibers are subjected to a velocity field along their length.
- The transferred momentum to fibers from water rotates fibers with respect to the fiber relative velocity.

\[ \begin{align*}
\text{Conservation of Linear momentum:} &
\int_{-L/2}^{L/2} \mathbf{v}(x_c + sp) - \dot{x}_c - s\dot{p} \, ds = 0 \\
\dot{p} = &\left( \frac{V_p \cdot V_p}{V_p \cdot V_p - (p \cdot V_p)^2} \right) (p \times V_p)
\end{align*} \]

\[ \begin{align*}
\text{Conservation of Angular momentum:} &
\int_{-L/2}^{L/2} \mathbf{v}(x_c + sp) - \dot{x}_c - s\dot{p} \times (x_c + sp) \, ds = 0
\end{align*} \]
Process Characterization – Physics Based Model

- Fiber orientation dynamics within a thin water film
  - Benchmark: obstacle on the spillway

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**Experimental Measurements**
- Water film Thickness
- Fibers Velocity

**Digital Twin Model**
- COMSOL
- Velocity Field
- Fiber Orientation

**Model Validation**
- Physics-based model

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**Experimental Setup**
- Polycarbonate
- Flow
- Inlet (1.5 m/s)
- Inlet Thickness (0.5 mm)
- Obstacle Size (0.3 mm)
- Obstacle

**Simulation Parameters**
- Solution: Water Domain
- Boundary Conditions:
  - Inlet
  - Wall
  - Outlet

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**Model Validation**
- Validation against experimental measurements
Physics Based Model Validation

- Fiber Orientation Dynamics
- Experimental data limitation: Distance of Fibers from Spillway Surface

Digitized Experimental data

![Diagram showing fiber orientation dynamics and experimental data](image-url)

- Top View
- Front View

- Flow Direction
- Obstacle
- Wire
- Distance From Obstacle
- Polycarbonate
- Orientation Angle [Degree]
- Distance from Obstacle [mm]
Physics Based Model Validation - Fiber Orientation Distribution

- Effect of obstacle on fiber orientation distribution.

- Fiber Orientation Distribution Tensor:

\[ A_2 = \begin{bmatrix} A_{xx} & A_{xy} & A_{xz} \\ A_{xy} & A_{yy} & A_{yz} \\ A_{xz} & A_{yz} & A_{zz} \end{bmatrix} \]

\[ A_2 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \]

\[ A_2 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \]

\[ A_2 = \begin{bmatrix} 0.5 & 0 & 0 \\ 0 & 0.5 & 0 \\ 0 & 0 & 0 \end{bmatrix} \]
Process Characterization – Water Film Thickness

- Frequent waves in measured data.
- Consistent waves within the flow.
- Waves visualization
- Analysis of wave’s frequency

Waves Frequency 45Hz

Pump-induced waves within the flow.

8" distance from nozzle
Hypothesized Source of Windows - Waves on the Spillway

- Hypothetical Characteristic Length of Windows ($\lambda^*$)

\[ f_s : \text{Frequency of waves} \]
\[ v_B : \text{Belt Speed} \]
\[ \lambda^* : \text{Characteristic Length of Windows} \]

\[ \lambda^* = \frac{v_B}{f_s} \]

$\lambda^* \approx 0.03 - 0.06 \text{ mm}$

\[ f_s = 45 \text{ Hz} \]
\[ v_B = 2.75 \text{ mm/s} \]
TuFF Microstructure Quantification by ML Image Processing

- TuFF Sheet Microstructure
- Machine Learning application in Image Processing
- Segmented Image: Fibers vs. Windows

- Process segmented images on MATLAB
- Object Detection (Windows)
- Information of individual Windows (location, size, width, etc.)
TuFF Microstructure Quantification by ML Image Processing

- Processed data
- Focus on Large Windows
- Window Width Distribution

Window Area Threshold 0.001 mm²
Window Area Threshold 0.005 mm²
Window Area Threshold 0.010 mm²

Threshold 0.010 mm²

Fiber Window
Selected Window

Number of Gaps

Gap Width (mm)
Process Improvement – New Manufacturing Design

- Modify the manufacturing design to eliminate waves on spillway.

- Ogee Spillway:
  - Provide a control over water depth for Dam’s spillway.
  - Formulated by US Army Corps.

- Downstream Curve Formulation (Ogee Spillway)

\[ x^n = kH_d^{n-1}y \]

\[ Q = CLH_d^{1.5} \]

<table>
<thead>
<tr>
<th>Approach Angle (Degree)</th>
<th>n</th>
<th>k</th>
</tr>
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<tbody>
<tr>
<td>90</td>
<td>1.85</td>
<td>2</td>
</tr>
<tr>
<td>71</td>
<td>1.836</td>
<td>1.936</td>
</tr>
<tr>
<td>56</td>
<td>1.81</td>
<td>1.939</td>
</tr>
<tr>
<td>45</td>
<td>1.776</td>
<td>1.873</td>
</tr>
</tbody>
</table>

\( k, n \): Design parameters based on the approach angle.
\( H_d \): Head.
\( Q \): Flow rate.
\( L \): Width of spillway.
Process Improvement – New Manufacturing Design

- Automated Design (in MATLAB) based on the Flow Thickness and Flow Rate.
- 3D Printed by PLA.

Curve Formulation in MATLAB

Spillway

Baffle

3D Model for Prototyping

Fabricated setup mounted on the TuFF manufacturing line
**Results – Wave Reduction**

- Significant wave reduction by the new design.
- Wave amplitude reduced by 2-4 fold.

<table>
<thead>
<tr>
<th>Design</th>
<th>Normalized Flow Rate</th>
<th>Water Thickness (mm)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Average</td>
<td>Standard Deviation</td>
</tr>
<tr>
<td>Nozzle</td>
<td>1.0</td>
<td>0.523</td>
<td>0.0418</td>
</tr>
<tr>
<td>Overflow Spillway</td>
<td>1.3</td>
<td>0.958</td>
<td>0.023</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>0.782</td>
<td>0.019</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>0.552</td>
<td>0.011</td>
</tr>
</tbody>
</table>

*Graphs showing wave amplitude reduction at 4" distance from spillway crest and 8" distance from nozzle.*
Results – TuFF Microstructure Comparison

• Visual Comparison

Nozzle Configuration
Areal Weight = 7.5 gsm

1000μm

Spillway Configuration
Areal Weight = 6.1 gsm
Results – TuFF Microstructure Comparison

- Quantitative Comparison
- Gap Threshold 0.010mm²

Eliminated waves by new spillway reduces gap windows width

“Gamma Distribution Function”
Results – TuFF Microstructure Comparison (Fiber Alignment)

- Current alignment limitation: 95% fibers aligned ± 5°
- Describe each window by a triangle.

\[ \alpha = \tan^{-1}\left(\frac{G}{L_f}\right) \]

- \( \alpha \): Fibers Misalignment Threshold

\[ G : \text{Window Gap Width} \]
\[ L_f : \text{Fiber Length} \]
Conclusions

- Benchmarked the current alignment process.
  - Process characterization
  - Quantitative analysis of TuFF microstructure.

- Proposed a physics-based model to predict fiber orientation within thin film of water.

- Hypothesis the origin of large window gaps.

- Designed, fabricated a new scalable spillway.

- The Ogee overflow design minimizes spillway wave amplitudes.

- Wave reduction on the spillway effectively closes large windows.

- Aligning fibers with reduced window width leads to
  1) TuFF preforms with higher fiber alignment.
  2) Thin ply composites with fewer layers and lower areal weight.
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