Computational Investigation into the Effects of Platelet Size, Thickness, and Flow on the Tensile Properties of Discontinuous Fiber Composites

4/19/2023

Marco Salviato (UW)

JAMS meeting 2023
Research Team

University of Washington

PIs: Marco Salviato (AA), Jinkyu Yang (AA)

Graduate students: Seunghyun Ko, Troy Nakagawa, Zhisong Chen, Collins Davis, James Davey
(Total of 12: 2 PhD and 10 master)

Undergraduate students: Yusuf Rasyid, Alexander Javor, Luke Kuklenski...
(50+ students)

FAA:

Dave Stanley (Technical monitor)
Larry Ilcewicz (Sponsor)
Amhet Oztekin (Other)
Cindy Ashforth (Sponsor)

Industry Mentors:

William Avery (UW)
Michael Larson (Boeing)
Ebonni Adams (Boeing)
Matthew Soja (Boeing)
Scott James (Sekisui Aerospace)
Introduction
Carbon Fiber Reinforced Composites Market

Primary Structures

Secondary Structures
Discontinuous Fiber Composites (DFCs)

- Achieve complex contours
- Minimum material waste
- Short curing period (within 2 minutes – Hexcel’s HexMC)
- Suitable for automation
- Cost saving

Platelet (Chip) based, discontinuous fiber form

Compression molding

Injection molding

Mitsubishi and Toyota

Boeing
Project Overview
Challenges for DFCs – Design Guidance

Building Block Approach

Design Guidance

Analysis Tools

Proof Testing

Laminate Stacking Sequence

Fiber properties
Matrix properties
Interface properties

Part Level

Coupon Level

Laminate Level

Random platelets orientations

Platelet geometry
Size Effects
Void content
Project Plan

Year 1
- Utilize existing data from Boeing / Purdue U. (flat tensile coupons)
- Develop computational tools
- Design 2021 experiment plan

Year 2
- Execute experiment plan (flat tensile coupons)
- Analyze the results using the computational tools
- Expand CT-measured platelet orientations

Year 3
- Analyze flow effects
- Extend finding of flat coupons to 3D structures

Experiment: Flat tensile coupons
- 2020
- 2021
- 2022
- 2023
2020
- Utilize existing data from Boeing / Purdue U. (flat tensile coupons)
- Develop computational tools
- Design 2021 experiment plan

2021
- Execute experiment plan (flat tensile coupons)
- Analyze the results using the computational tools
- Expand CT-measured platelet orientations

2022
- Analyze flow effects
- Extend finding of flat coupons to 3D structures

2023
- Experiment: Flat tensile coupons
- 3D Structures

Experiment:
- Flat tensile coupons
- 3D Structures

Project Plan
Year 1 (2020-21) Summary
Finite Element Framework

Random Meso-structure Generator

Matrix damage

Fiber damage

Resin rich
Key Conclusions from Year 1 Study

(1) Significant thickness effect

Wide range of thicknesses: 0.065” to 0.25”

data concentrated at thickness 0.15”

(2) Significant platelet width effect

Narrow vs. Square 1/2”

(3) Significant Platelet Orientation Effect

Only at thickness 0.15”

Both platelets + all thicknesses

(4) Significant flow effect

Low flow (flat) High flow (forks)

(5) Number of tests in literature was not statistically significant

Cochran’s formula

At least 22 needed
Year 2 (2021-22) Summary
1. Narrow and square platelets had insignificant modulus thickness effects.
2. Narrow and square platelets had significant strength thickness effects.
3. The narrow platelets outperformed the square platelets.
Simulation result: Tensile modulus

- Simulations capture the thickness effect precisely.
- At the saturated thickness, the modulus difference between the narrow and square is negligible.
- Using the ideal random orientations, the model underpredicts the CoVs (12% vs 2%).
Simulation result: Tensile strength

- Simulations capture the thickness effect precisely.
- At the saturated thickness, the strength difference between the narrow and square is only 7%.
- Using the ideal random orientations, the model underpredicts the CoVs (13% vs 4%).
Project Plan

2020
- Utilize existing data from Boeing / Purdue U. (flat tensile coupons)
- Develop computational tools
- Design 2021 experiment plan

2021
- Execute experiment plan (flat tensile coupons)
- Analyze the results using the computational tools
- Expand CT-measured platelet orientations

2022
- Analyze flow effects
- Extend finding of flat coupons to 3D structures

2023

Experiment: Flat tensile coupons
3D Structures

Experiment: Flat tensile coupons

Experiment: Flat tensile coupons
Year 3 (2022-23) Summary
Objective

1) Investigate the platelet width effect

Narrow 1/2” vs. Square 1/2”

2) Investigate flow effect

Low flow (flat) vs. High flow (forks)

Parameters

Numerical

3) Study of platelet orientations using a μCT scan

In-Plane Angle (Deg)

<table>
<thead>
<tr>
<th>Flow</th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
<th>R5</th>
<th>R6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat</td>
<td>A_{11} = 0.505</td>
<td>A_{11} = 0.502</td>
<td>A_{11} = 0.518</td>
<td>A_{11} = 0.530</td>
<td>A_{11} = 0.527</td>
<td>A_{11} = 0.533</td>
</tr>
</tbody>
</table>

Flow direction
Flow effect in UNT (Experimental)

(a) Modulus @ thickness = 0.15”
(b) Strength @ thickness = 0.15”

High flow condition promotes the modulus due to favorable platelet orientations but hard to make conclusion on the strength. We may need larger number of test coupons.
**Flow effects in the Square platelets**

(a) Low flow (square platelets)

(b) High flow (square platelets)

<table>
<thead>
<tr>
<th></th>
<th>Normalized Modulus</th>
<th>Normalized Strength</th>
<th>$A_{11}$ mean</th>
<th>$A_{11}$ CoV</th>
<th># of Scans</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Flow</td>
<td>$0.82 \pm 7.0%$</td>
<td>$0.37 \pm 8%$</td>
<td>$0.49, (44.5^\circ)$</td>
<td>9.2</td>
<td>5</td>
</tr>
<tr>
<td>High Flow</td>
<td>$1.0 \pm 7.0%$</td>
<td>$0.41 \pm 7%$</td>
<td>$0.62, (51.9^\circ)$</td>
<td>7.7</td>
<td>5</td>
</tr>
<tr>
<td>Perc. Increase [%]</td>
<td>22%</td>
<td>10%</td>
<td>27%</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Flow effects in the Narrow platelets

(a) Low flow (narrow platelets)

(b) High flow (narrow platelets)

<table>
<thead>
<tr>
<th></th>
<th>Modulus</th>
<th>Strength</th>
<th>$A_{11}$ mean</th>
<th>$A_{11}$ CoV</th>
<th># of Scans</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Flow</td>
<td>0.9 ± 13%</td>
<td>0.47 ± 12%</td>
<td><strong>0.49 (44.5°)</strong></td>
<td>4.8</td>
<td>3</td>
</tr>
<tr>
<td>High Flow</td>
<td>1.0 ± 11%</td>
<td>0.45 ± 9%</td>
<td><strong>0.63 (52.5°)</strong></td>
<td>5.8</td>
<td>5</td>
</tr>
<tr>
<td>Perc. Increase [%]</td>
<td>11%</td>
<td>-4%</td>
<td><strong>29%</strong></td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Square Platelet High Flow

Failure location matches with experiments
Square Platelet High Flow

Normalized Modulus $[E/E_0]$ vs. CT Scan

<table>
<thead>
<tr>
<th>CT Scan</th>
<th>CT 1</th>
<th>CT 2</th>
<th>CT 3</th>
<th>CT 4</th>
<th>CT 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus</td>
<td>4.37</td>
<td>-0.28</td>
<td>2.92</td>
<td>-6.31</td>
<td>-4.73</td>
</tr>
<tr>
<td>Strength</td>
<td>-4.06</td>
<td>15.13</td>
<td>5.24</td>
<td>16.96</td>
<td>6.23</td>
</tr>
</tbody>
</table>

Percent difference to experiments

Normalized Strength $[\sigma/\sigma_0]$ vs. CT Scan
Testing 2 configurations of the Sekisui QForge Bracket
1. Square Platelet (14 brackets)
2. Narrow Platelet (14 brackets)
• DIC at the top load pin where we think failure will occur
Sekisui Bracket

- Fiber angle vector
- Base is aligned going in, along Y-axis (red and blue)
- Top is aligned along the X-axis (Yellow)
Sekisui Bracket Dimensions

3/8” bolt cut to the nonthreaded part and used as a pin

1/4” bolt are used to fasten base
Sekisui Bracket NP Fracture

1) Sekisui Bracket NP Fracture Load Frame

2) Load Frame
Sekisui Bracket NP Fracture
Joint Centers of Excellence for Advanced Materials

- Displacement from DIC averaged between the two sides
- Narrow platelet bracket is **stiffer and stronger**
  - Stiffness percent difference: 51.85%
  - Strength percent difference: 20.28%
- This is similar to the UNT specimen
  - 0.15” coupon had an 8% and 27% difference in stiffness and strength respectively
- Some difference could also be due to voids or flow effects
Simulation of Tension test

- Fixture is explicitly modeled
- Boundary conditions are the same as experiment
• Stiffness matches and strength under predicted by 8%
• Calibrate material properties
Tension Simulation Results – Damage Variables

Matrix Damage

Fiber Damage

<table>
<thead>
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<th>SDV30</th>
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<tbody>
<tr>
<td>+1.000e+00</td>
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<tr>
<td>+9.167e-01</td>
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</tr>
<tr>
<td>+8.333e-01</td>
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<tr>
<td>+7.500e-01</td>
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<tr>
<td>+6.667e-01</td>
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<tr>
<td>+5.833e-01</td>
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<tr>
<td>+5.000e-01</td>
<td></td>
</tr>
<tr>
<td>+4.167e-01</td>
<td></td>
</tr>
<tr>
<td>+3.333e-01</td>
<td></td>
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<tr>
<td>+2.500e-01</td>
<td></td>
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<tr>
<td>+1.667e-01</td>
<td></td>
</tr>
<tr>
<td>+8.333e-02</td>
<td></td>
</tr>
<tr>
<td>+0.000e+00</td>
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<table>
<thead>
<tr>
<th>SDV29</th>
<th></th>
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<tbody>
<tr>
<td>+1.000e+00</td>
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<tr>
<td>+9.167e-01</td>
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