Certification of Discontinuous Composite Material Forms for Aircraft Structures

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University of Washington

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Recyclability

Synergistic project

Inside Composites

Composites Forecast and Consulting LLC

Primary Product

“Waste” Pre-preg

Secondary Product

New End-User

Global carbon fiber demand

Estimated Wasted Material

Composites Forecast and Consulting LLC

CECAM

JAMS

AMTAS

Joint Advanced Materials & Structures Center of Excellence

Composites Forecast and Consulting LLC

CECAM

JAMS

AMTAS

Joint Advanced Materials & Structures Center of Excellence
Introduction

Made of composites?

Aviationweek.com
Avstop.com
compositestoday.com
Introduction

Large volume manufacturing

Part complexity

Recyclability

Toray

Inside Composites

Tencate

Composites Forecast and Consulting LLC
Discontinuous Fiber Composites (DFCs)

Platelets-based composite

Compression molding

Large volume manufacturing

Hexcel

Recyclability

Typical Prepreg Scrap Streams
- Ply cuter scrap – Type SL
- Ply cuter scrap – Type LR
- Prepreg Olivier – Out of Spec

Part Complexity

Greene Tweed

Nutt, 2014, CAMX
Current challenges:
Lack of design guidelines for the DFCs with the presence of notches or holes

Conventional application of DFC

Hexmc parts, Hexcel

Qian, 2011

Feraboli, 2009
Current challenges:
Lack of acceptance/rejection criteria for defected DFC components
Quasi-brittle fracture behavior of DFCs

Effect of the characteristics dimension on the nominal strength

*FPZ = Fracture process zone
*PZ = Plastic zone

FPZ is **large** in DFC

Bazant, 1998
Fracture Process Zone in DFCs

Platelet size: 25×4 mm
Thickness: 3.3 mm
$c_f = 6.55$ mm, $R_y = 8.85$ mm

Platelet size: 50×8 mm
Thickness: 3.3 mm
$c_f = 7.43$ mm, $R_y = 10.87$ mm

Platelet size: 75×12 mm
Thickness: 3.3 mm
$c_f = 14.16$ mm, $R_y = 17.95$ mm

Carbon twill 2×2
Thickness: 1.9 mm
$c_f = 1.81$ mm, $R_y = 5.01$ mm

Quasi-brittle behavior of notched DFC structures

Brittle

(a) Brittle

Linear elastic

\[ \sigma_{Nc} \]

\[ A_g = \text{GROSS SECTION AREA} \]

\[ A_n = \text{NET SECTION AREA} \]

\[ \sigma_{Nc} \cdot \frac{A_g}{A_n} \]

Ductile

(b) Ductile

Linear elastic

\[ \sigma_{Nc} \]

plastic deformation

\[ \sigma_{Nc} \cdot \frac{A_g}{A_n} \]
(1) To develop an experimental protocol for the characterization of fracture toughness of DFCs

(2) To investigate the effects of material morphology (e.g. platelet size and distribution) and geometrical features (e.g. structure thickness and notch radius) on the fracture behavior

(3) To develop computational tools to describe the mechanics of DFCs

(4) To formulate certification guidelines for DFC structures

Platelet size:
- 75×12 mm
- 50×8 mm
- 25×4 mm
Specimen preparation

1) Cut into strips

2) Remove backing tape

3) Cross-cut the strips

4) Distribute platelets randomly
Investigated Platelet Sizes

25×4 mm

*50×8 mm

75×12 mm

*platelet size is commonly used in commercial products

Feraboli et al. J. Reinf Plast and Comps, 2009, Boursier et al. SAMPE, 2010
### Summary of Platelets Sizes and Thicknesses Investigated

<table>
<thead>
<tr>
<th>Size</th>
<th>Platelet size effect study</th>
<th>Thickness effect study</th>
<th>Platelet size effect study</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>75×12 mm, T = 3.3 mm</td>
<td>50×8 mm, T = 3.3 mm</td>
<td>50×8 mm, T = 4.4 mm</td>
</tr>
<tr>
<td></td>
<td>50×8 mm, T = 3.3 mm</td>
<td>50×8 mm, T = 4.4 mm</td>
<td>50×8 mm, T = 2.1 mm</td>
</tr>
<tr>
<td></td>
<td>25×4 mm, T = 3.3 mm</td>
<td>50×8 mm, T = 2.1 mm</td>
<td>50×8 mm, T = 1.1 mm</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>9</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>9</td>
<td>7</td>
</tr>
<tr>
<td>Total1</td>
<td>27</td>
<td>27</td>
<td>29</td>
</tr>
<tr>
<td>Total2</td>
<td>239</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Coupon is well within the LEFM region, no need to test it.
specimen geometry

- Coupon sizes are proportionally scaled in width, gauge length, and crack length
- Thickness is constant = 3.3 mm
Typical Force and Displacement curves

- **Load (kN)**
- **Displacement (mm)**

Legend:
- **Size 2**
- **Size 3**
- **Size 4**
- **Size 5**

- Width: 6.3 mm
- Width: 20 mm
- Width: 40 mm
- Width: 80 mm

FPZ size:
- 20 mm
- 10 mm

80 mm
<table>
<thead>
<tr>
<th>120 mm</th>
<th>80 mm</th>
<th>40 mm</th>
<th>20 mm</th>
<th>6.3 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.jpg" alt="Image" /></td>
<td><img src="image2.jpg" alt="Image" /></td>
<td><img src="image3.jpg" alt="Image" /></td>
<td><img src="image4.jpg" alt="Image" /></td>
<td><img src="image5.jpg" alt="Image" /></td>
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<tr>
<td><img src="image6.jpg" alt="Image" /></td>
<td><img src="image7.jpg" alt="Image" /></td>
<td><img src="image8.jpg" alt="Image" /></td>
<td><img src="image9.jpg" alt="Image" /></td>
<td><img src="image10.jpg" alt="Image" /></td>
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<td><img src="image11.jpg" alt="Image" /></td>
<td><img src="image12.jpg" alt="Image" /></td>
<td><img src="image13.jpg" alt="Image" /></td>
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<td><img src="image15.jpg" alt="Image" /></td>
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<td><img src="image16.jpg" alt="Image" /></td>
<td><img src="image17.jpg" alt="Image" /></td>
<td><img src="image18.jpg" alt="Image" /></td>
<td><img src="image19.jpg" alt="Image" /></td>
<td><img src="image20.jpg" alt="Image" /></td>
</tr>
</tbody>
</table>

**Typical Fracture Surfaces (50 x 8 mm platelets)**
Fracture Surfaces (50 x 8 mm platelets) – thickness effect

<table>
<thead>
<tr>
<th>Thickness</th>
<th>D = 20 mm</th>
<th>D = 40 mm</th>
<th>D = 120 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 mm</td>
<td><img src="image1" alt="Notch" /></td>
<td><img src="image2" alt="Notch" /></td>
<td><img src="image3" alt="Notch" /></td>
</tr>
<tr>
<td>2.2 mm</td>
<td><img src="image4" alt="Notch" /></td>
<td><img src="image5" alt="Notch" /></td>
<td><img src="image6" alt="Notch" /></td>
</tr>
<tr>
<td>4.1 mm</td>
<td><img src="image7" alt="Notch" /></td>
<td><img src="image8" alt="Notch" /></td>
<td><img src="image9" alt="Notch" /></td>
</tr>
</tbody>
</table>
Result 2: Fracture surfaces and DIC

Platelet size of 75×12 mm

Width = 120 mm

Width = 20 mm
Bažant’s Size Effect Law

Define the nominal stress in the specimen as:

\[ \sigma_N = P/(tD) \quad P = \textit{applied load}, \ t = \textit{thickness}, \ D = \textit{width} \quad (1) \]

The following expression holds for the fracture energy:

\[ G_f(\alpha) = \frac{\sigma_N^2 D}{E^*} g(\alpha, D) = \frac{\sigma_N^2 D}{E^*} g\left(\alpha_0 + \frac{c_f}{D}, D\right) \quad \alpha = a/D \]

\[ g = \text{dimensionless energy release rate} \quad E^* = \text{effective modulus} \quad c_f = \text{FPZ length} \quad (2) \]

By expanding \( g \) in Taylor Series for a const \( D \), retaining only 1\(^{\text{st}}\) order terms and re-arranging:

\[ \sigma_N = \sqrt{\frac{E^* G_f}{Dg(\alpha_0, D) + c_f g, \alpha(\alpha_0, D)}} \quad \text{Bažant’s Size Effect Law} \quad (SEL) \text{ for quasi-brittle materials} \quad (3) \]
1. DFC shows a strong size effect.
   a) we can clearly observe the transition from the strength to energy driven fracture.
   b) Neither strength nor LEFM can predict the behavior of the DFC.
   c) The notch insensitivity is observed when the specimen size is moving away from LEFM region (or when the width is below the transition width, $D_0$).

2. The platelet size has a strong effect in fracturing behavior of DFC
   a) Smaller the platelet size, the DFC behaves more brittle manner
Result: Size effect curves – (varying thickness)

- Thickness: 4.1 mm
  - $\sigma_0 = 0.355$ [GPa]
  - $D_0 = 22.42$ [mm]

- Thickness: 2.2 mm
  - $\sigma_0 = 0.306$ [GPa]
  - $D_0 = 22.87$ [mm]

- Thickness: 1.1 mm
  - $\sigma_0 = 0.423$ [GPa]
  - $D_0 = 7.35$ [mm]
Result: Size effect curves – (thermoplastics)

Platelet size: 12.7×12.7 mm

\[
\log(\sigma_N/\sigma_0) = 0.308 [\text{GPa}]
\]
\[
D_0 = 26.0 [\text{mm}]
\]

Platelet size: 12.7×1.58 mm

\[
\log(\sigma_N/\sigma_0) = 0.362 [\text{GPa}]
\]
\[
D_0 = 14.49 [\text{mm}]
\]

*Thickness = 3.8 mm
Microstructure generation

- Finite element model is based on stochastic laminate analogy [Tuttle, 2010, Selezneva, 2015]
- Platelet center point and its orientation is randomly chosen

Partition to save layup information
Partition layup info: [45/-5]

Random platelet generation

Example of platelet generation
Experimentally-verified morphology

We observed a total of 90 cross-sections to measure the distributions.
Let’s relate the nominal stress to the energy release rate through a dimensionless function $g$:

$$G = \frac{\sigma_N^2 D}{E^*} g(\alpha), \quad \sigma_N = \frac{P(u)}{t D},$$

where $P = \text{load}$, $u = \text{applied displacement}$

For a given $u$, $G$ can be calculated by leveraging on its definition:

$$G(u, a) = -\frac{1}{t} \left( \frac{\partial \Pi(u, a)}{\partial a} \right)_u \approx -\frac{1}{t} \frac{\Pi(u, a+\delta a/2) - \Pi(u, a-\delta a/2)}{\delta a}$$

Where $\Pi = \text{total strain energy in structure } (= \text{ALLIE in Abaqus})$

Then, $g(\alpha) = \frac{GE^*}{\sigma_N^2 D}$, and $g'(\alpha) = \frac{dg(\alpha)}{da}$

“$g$ accounts both for the geometry and microstructural effects, therefore it is important to explicitly model the DFC’s microstructure”

Finally,

$$G_f = \frac{\sigma_N^2 D}{E^*} g(\alpha_0), \quad c_f = \frac{D_0 g'(\alpha_0)}{g(\alpha_0)}$$
Dimensionless Energy Release Rates in DFCs

a) 75×12 mm

- FEA mean: 0.892
- Average STD: 0.058

b) 50×8 mm

- FEA mean: 0.952
- Average STD: 0.096

c) 25×4 mm

- FEA mean: 0.935
- Average STD: 0.079

\[ g(\alpha) \]

Specimen Width, \( D \) [mm]
Intra-laminar mode I fracture energy of DFC (platelet effect)

Size effect law: \( \sigma_N = \frac{E^*G_f}{\sqrt{Dg(\alpha_0) + c_f g'(\alpha_0)}} \)

<table>
<thead>
<tr>
<th>Effective FPZ length, ( c_f ) (mm)</th>
<th>Fracture energy, ( G_f ) (N/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 × 4 (mm)</td>
<td>6.55 ± 1.07</td>
</tr>
<tr>
<td></td>
<td>33.59 ± 2.86</td>
</tr>
<tr>
<td></td>
<td>( \Delta 0.0% )</td>
</tr>
<tr>
<td>50 × 8 (mm)</td>
<td>7.43 ± 0.83</td>
</tr>
<tr>
<td></td>
<td>53.72 ± 6.14</td>
</tr>
<tr>
<td></td>
<td>( \Delta 59.9% )</td>
</tr>
<tr>
<td>75 × 12 (mm)</td>
<td>14.2 ± 1.85</td>
</tr>
<tr>
<td></td>
<td>64.98 ± 2.79</td>
</tr>
<tr>
<td></td>
<td>( \Delta 93.5% )</td>
</tr>
</tbody>
</table>

![Graph showing fracture energy vs. platelet length]
Intra-laminar mode I fracture energy of DFC (thickness effect)

Size effect law: \( \sigma_N = \sqrt{\frac{E^* G_f}{Dg(\alpha_0) + cf g'(\alpha_0)}} \)

<table>
<thead>
<tr>
<th>Effective FPZ length, ( c_f ) (mm)</th>
<th>Fracture energy, ( G_f ) (N/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 (mm) 1.33 ± 0.63</td>
<td>31.02 ± 6.50 Δ0.0%</td>
</tr>
<tr>
<td>2.2 (mm) 3.84 ± 0.65</td>
<td>39.69 ± 4.56 Δ28.0%</td>
</tr>
<tr>
<td>3.3 (mm) 7.43 ± 0.83</td>
<td>53.72 ± 6.14 Δ73.3%</td>
</tr>
<tr>
<td>4.1 (mm) 3.70 ± 0.46</td>
<td>46.85 ± 3.99 Δ51.1%</td>
</tr>
</tbody>
</table>

Thickness effect:

![Graph showing thickness effect](image)

- Experiment
- Simulation
Ongoing work: mesoscale model

- Spectral Stiffness Microplate model
- Linear softening damage evolution
- Quadratic stress Criteria

\[
\left( \frac{t_n}{t_n^0} \right)^2 + \left( \frac{t_s}{t_s^0} \right)^2 + \left( \frac{t_t}{t_t^0} \right)^2 = 1
\]

Platelet Damage/Failure

Cohesive Damage/Failure

Salviato et al., Compos Struct, 2016
Most of fracture happens at the notch.
Matrix damage distributions in different layers

Layer 5

Layer 10

Layer 15

Localized damage at the notch
Abaqus Result Size Small Coupon

Fracture surfaces of Small Coupons

Coupon 1

Fracture happens away from the notch
Simulated fracture morphology

Layer 1

Layer 4

Layer 16

Final Failure

Damage

Damage

Damage
Simulated fracture morphology

Layer 5

Layer 8

Layer 19

Final Failure
Summary

1. DFC structures feature a significant energetic (type II) size effect;
2. Depending on the platelet size and thickness relative to the structure size, the size effect may transition from energetic to energetic-statistical;
3. Combining stochastic FEA and equivalent fracture mechanics, Bažant’s size effect law was extended to DFCs and shown to be in excellent agreement with the experiments;
4. Increasing the platelet size leads to higher fracture energies and improved damage tolerance;
5. A similar effect is obtained by increasing the number of platelets through the thickness;
6. Ongoing analyses suggest that stochastic mesoscale modeling can effectively capture both the energetic and energetic-statistical size effects in DFCs.
Looking forward

**Benefit to aviation:**

1. Novel experimental framework for characterization of the fracture toughness of DFCs;
2. Investigation of platelet size effect and thickness effect on fracturing behavior
3. Development of certification guidelines for defected DFC structures and its validation (in progress)
4. Construction of a database of fracture energy for both thermosets and thermoplastic DFCs

**Future needs:**

1. Better understanding on inter-laminar fracturing behavior;
2. Investigation on the use of failure probability theory to capture the significant randomness of material behavior
3. Investigation of the correlation between local platelet morphology in real components and fracturing behavior
Acknowledgements

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