Analysis and Design of Textile–Reinforced FRPs

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Background

Structural FRP composites are being considered for usage in civil infrastructure applications.

Perceived Advantages:
- lightness
- durability
- damping characteristics

Perceived Disadvantages

mechanical performance characteristics
Research Objectives

Find better arrangements of fibers in composites to improve overall mechanical performance.

Explore possibilities systematically using analytical/computational methods.

Improve methods for analysis of composite materials.

Prototype and test the best material designs to verify.
Stiffnesses & Strengths of Aligned Fiber Composites are Highly Anisotropic

<table>
<thead>
<tr>
<th>Elastic Moduli (GPa)</th>
<th>Glass (50/50)</th>
<th>Graphite (50/50)</th>
<th>Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{1111}$</td>
<td>38.29</td>
<td>129.0</td>
<td>268.8</td>
</tr>
<tr>
<td>$C_{2222}, C_{3333}$</td>
<td>8.81</td>
<td>10.4</td>
<td>268.8</td>
</tr>
<tr>
<td>$C_{1212}, C_{1313}$</td>
<td>3.32</td>
<td>3.57</td>
<td>76.9</td>
</tr>
<tr>
<td>$C_{2323}$</td>
<td>2.60</td>
<td>2.67</td>
<td>76.9</td>
</tr>
</tbody>
</table>
Analytical/Computational Tools Used

A. Homogenization: For a given composite, solve unit cell problem(s) to calculate effective strengths & stiffnesses.

Unit Cell for Homogenization & Reinforcing Design

\[ E = \langle \varepsilon(X) \rangle : \text{Macro Strain} \]
\[ S = \langle \sigma(X) \rangle : \text{Macro Stress} \]
B. Material Topology Optimization

Optimize material arrangements to enhance mechanical performance.

Properties associated with each material arrangement are calculated using homogenization.

Generate Initial Design

Calculate Properties (Homogenization)

Are Properties Optimal?

Modify the Design

No

Stop

Yes
Example: Compliance Minimization of a Boron–Epoxy Composite
Results of Material Topology Optimization

40% graphite  
60% epoxy

\[ C_{2323} = 2.09 \text{GPa} \]
\[ C_{2222}, C_{3333} = 7.96 \text{GPa} \]
\[ C_{1111} = 104 \text{GPa} \]

50% graphite  
50% epoxy

\[ C_{2323} = 2.67 \text{GPa} \]
\[ C_{2222}, C_{3333} = 10.4 \text{GPa} \]
\[ C_{1111} = 129 \text{GPa} \]

60% graphite  
40% epoxy

\[ C_{2323} = 3.60 \text{GPa} \]
\[ C_{2222}, C_{3333} = 15.1 \text{GPa} \]
\[ C_{1111} = 155 \text{GPa} \]
Significance of Results

Demonstrate necessity of getting fiber material to behave multi-axially.

Demonstrate advantages of integration & continuity of fiber material in three orthogonal directions.

Some material arrangements are fairly complex, and others are much simpler (more manufacturable).

Complex Arrangement

Simpler Arrangement
Manufacturability Concerns

- Re-designed composites contain continuous, monolithic, glass or graphite phases.
  - LCVD for small scale parts/structures
  - Infeasible for large scale structural composites

- Current trend is toward textile reinforcing
  - Gives 3-D reinforcing (weaker anisotropy)
  - Capabilities for producing 3-d weaves & meshes are developing rapidly

- Designed material arrangements are therefore approximated as textiles and re-analyzed.
Desired Material Arrangement
(unit cell)

Textile Composite Approximation

a) Graphite plane weave with longitudinal infills.  
b) Graphite–epoxy unit cell.
Comparative Axial Stiffnesses ($C_{1111}$)

Graphite Volume Fractions

Constrained Axial Moduli (GPa)

- Voigt Bound
- Reuss Bound
- Lattice composite
- Aligned fiber composite
- Textiled composite

Graphite Volume Fractions

0 0.5 1.0
Comparative Transverse Stiffnesses ($C_{2222}$, $C_{3333}$)

Graphite Volume Fractions

Constrained Transverse Moduli (GPa)

- Voigt Bound
- Reuss Bound
- Lattice composite
- Textiled composite
- Aligned fiber composite
Comparative Shear Stiffnesses ($C_{2323}$)

Graphite Volume Fractions

Constrained Transverse Moduli (GPa)

- Voigt Bound
- Reuss Bound
- Lattice composite
- Aligned fiber composite
- Textiled composite
Summary of Findings (to date)

Non-axial properties are improved significantly with usage of textile reinforcing.

There are tradeoffs, however.

Reductions in axial stiffnesses are ~45%.

Textiles considered thus far do not achieve desired level of "integration". Shear properties need further improvement.

Additional textile schemes that approximate continuous reinforcement must be considered.

Achieving high density of reinforcing phase can be difficult in textiles.

Creation of FEM textile models is a challenge, but significant progress has and is being made.