Tutorial
Use of Composites in Optical Systems

Anoopoma P. Bhowmik
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College of Optical Sciences - University of Arizona
Overview

- Introduction
- Composite basics
- Some case studies
- Failure modes
- Conclusion
Introduction

- Purpose: Provide general familiarity and resources for consideration of composites in optical systems
- Complements: A more detailed and thorough paper on the class website

http://www.optics.arizona.edu//optomech/Fall09/...
Basics

- Main components
  - Reinforcement material: typically fibers/particles
  - Matrix material: typically resin or epoxy
- Common forms: pultrusion, laminate, and foam-core
Calculations

- Simple geometry allows for approximation of composite density and Young’s modulus

\[
\rho_m = \frac{1}{\left[ \frac{W_f}{\rho_f} + \frac{1-W_f}{\rho_r} \right] (1 + H_m)}
\]

\[
E_m = n \frac{E_f A_f}{A_m} + E_r \left[ 1 - n \frac{A_f}{A_m} \right]
\]

- Fiberglass-resin example (pultrusion):
  Fiber specific stiffness = 16 GPa g/cm³
  Composite specific stiffness = 68 GPa g/cm³
  This is the primary reason we use composites!
Tailoring mechanical properties

- Also, additional design degrees of freedom in manufacturing process
Case Study: SXA Mirror

- SXA = 2024 aluminum alloy/ 30% silicon carbide particulate metal matrix composite
- Chosen over glass and Beryllium
  - High specific strength, stiffness, stability, moderate machining cost
- Beam footprint = 25 cm
- Final weight = 806 grams

Fabrication process
- Machining, thermal stabilization, electroless nickel plating, polishing, and coating

Final performance
- Surface figure was flat to within $\sim \lambda/8$ power
- $\sim \lambda/6$ irregularity over any 120mm diameter area

Thermal performance
- “no change” for exposure to temperatures $\sim 160^\circ C$
Case Study: Carbon Fiber Mirror

- Conical mirror 1.3m diameter, 0.5m height, polished surface area 2m², total weight 8 kg
- M46J/EX-1515= ~ 70% high modulus carbon fiber, ~30% cyanate ester resin matrix
- For use in ISS experiment: space-qualified materials
- The specific stiffness of CFRP ~ 5 times greater than steel.
- The coefficient of thermal expansion for CFRP is very low at 1-2 ppm. This is ~ 20 times lower than for aluminum.
Case Study: Cesic Mount

- Cesic = carbon-fiber-reinforced silicon carbide composite
- Very close CTE to that of silicon foam-core element
- Very useful material properties
- Good material for mounting a silicon foam-core element
Failure Modes

- Three types: laminar/plate uniform stress, stress concentration, and sharp cracks

Comparison of laminar failure to isotropic plate failure

Resulting incremental failure

Figure 4-33  Load-Deflection Behavior of Metal Plates

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Failure Modes (2)

- Failure due to sharp cracks: Use fracture mechanics in same way as for isotropic glass
  - Failure = $K_I > k_{IC}$

**Stress Intensity Factor**

\[ K_I = Y\sigma \sqrt{\pi a} \]

**Fracture toughness geometry**

- Average stress failure criterion
  \[ k_{IC,1} = F_0 \sqrt{\frac{\pi a a_0}{a_0 + 2a}} \]

- Stress concentration failure criterion
  \[ k_{IC,2} = F_0 \sqrt{\pi a} \sqrt{1 - \left(\frac{a}{a + d_0}\right)^2} \]

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Ways to fight failure

- Thermal stability
  - Proper volumetric balance of high-modulus, reinforcing fiber with negative CTE, and matrix resin with positive CTE

- Moisture-induced stability
  - For <1ppm strain change: Use high modulus fiber, low moisture absorbing resin partially pre-saturated with moisture, and have a metal seal with low flaw density (0.1-0.01%), and seal thickness such that the net CTE is $0.00 \pm 0.05$ppm/°C.
# Comparison of Composite Materials

<table>
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<tr>
<th>Material</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Typical Applications</th>
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<tbody>
<tr>
<td><strong>Metal Matrix Composites</strong></td>
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<td>SiC/AL (Discontinuous SiC particles)</td>
<td>• Isotropic&lt;br&gt;• Large database&lt;br&gt;• 1.5 x modulus and strength of aluminum alloys with the same density</td>
<td>• Most not weldable&lt;br&gt;• Machinable, but results in high tool wear&lt;br&gt;• Lower ductility than aluminum alloys&lt;br&gt;• Limited flight heritage</td>
<td>• Truss fittings&lt;br&gt;• Brackets&lt;br&gt;• Mirrors and optical benches</td>
</tr>
<tr>
<td>B/Al (Continuous boron fiber)</td>
<td>• High strength vs. weight&lt;br&gt;• Low CTE</td>
<td>• Anisotropic&lt;br&gt;• Expensive</td>
<td>• Truss members&lt;br&gt;• Shuttle payload doors</td>
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<td><strong>Polymer Matrix</strong></td>
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<td>Aramid/Epox (e.g. Kevlar or Spectra fibers with epoxy matrix)</td>
<td>• Impact resistant&lt;br&gt;• Lower density than graphite/epoxy&lt;br&gt;• High strength vs. weight</td>
<td>• Absorbs water&lt;br&gt;• Outgases&lt;br&gt;• Low compressive strength&lt;br&gt;• Negative CTE</td>
<td>• Solar array structures&lt;br&gt;• Radio frequency (RF) antenna covers</td>
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<tr>
<td>Carbon/Epox (High-strength fiber)</td>
<td>• Very high strength vs. weight&lt;br&gt;• High modulus vs. weight&lt;br&gt;• Low CTE&lt;br&gt;• Flight heritage</td>
<td>• Outgasses (matrix-dependent)&lt;br&gt;• Absorbs water (matrix-dependent)</td>
<td>• Truss members&lt;br&gt;• Face sheets for sandwich panels&lt;br&gt;• Optical benches&lt;br&gt;• Monocoque cylinders</td>
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<tr>
<td>Graphite/Epox (high-modulus fiber)</td>
<td>• Very high modulus vs. weight&lt;br&gt;• High strength vs. weight&lt;br&gt;• Low CTE&lt;br&gt;• High thermal conductivity</td>
<td>• Low compressive strength&lt;br&gt;• Ruptures at low strain&lt;br&gt;• Absorbs water and outgasses (matrix-dependent)</td>
<td>• Truss members&lt;br&gt;• Antenna booms&lt;br&gt;• Face sheets for sandwich panels&lt;br&gt;• Optical benches&lt;br&gt;• Monocoque cylinders</td>
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<tr>
<td>Glass/Epox (Continuous glass fiber)</td>
<td>• Low electrical conductivity&lt;br&gt;• Well-established manufacturing processes</td>
<td>• Higher density than graphite/epoxy&lt;br&gt;• Lower strength and modulus than graphite/epoxy</td>
<td>• Printed circuit boards&lt;br&gt;• Radomes</td>
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Conclusion

- There are many design degrees of freedom made available with composites
- Over 60 years of US participation in the composite industry: many lessons learned
- Further research
  - Will drive product cost down
  - Will create new developments
Some Interesting References

- “CFRP Mirror” [http://www.compositemirrors.com](http://www.compositemirrors.com)
- “Athermal telescope” [http://www.cesic.de/...html](http://www.cesic.de/...html)
- “Cesic Mirror” [http://spiedl.aip.org/...](http://spiedl.aip.org/...)
- “Failure” [http://www.emba.uvm.edu/.../me257/](http://www.emba.uvm.edu/.../me257/)
Questions?

Please contact the author at:
abhowmik@optics.arizona.edu