Tutorial
Use of Composites in Optical Systems

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Introduction to Opto-Mechanical Engineering

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Overview

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

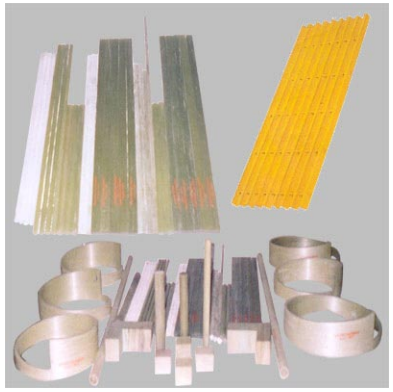
Introduction

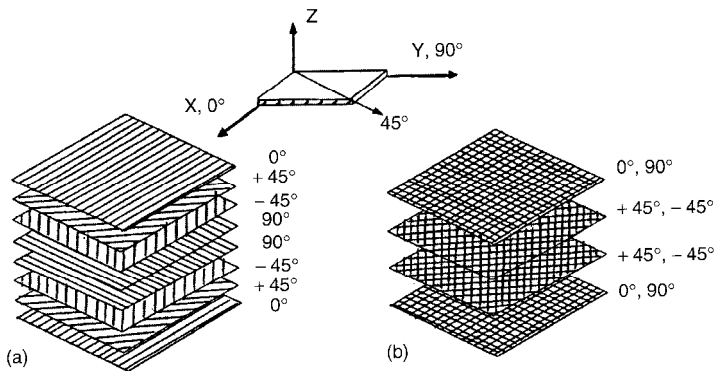
- Purpose: Provide general familiarity and resources for consideration of composites in optical systems
- Complements: A more detailed and thorough paper on the class website

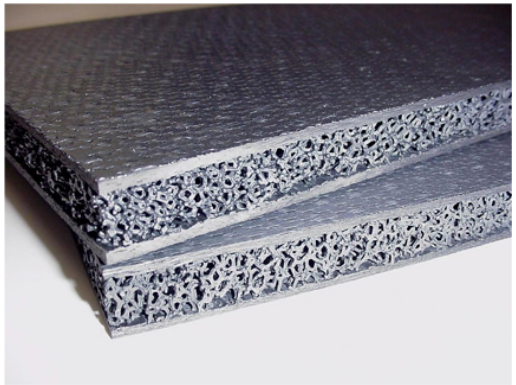
http://www.optics.arizona.edu//optomech/Fall09/...

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

$$\rho_m = \frac{1}{\left[\frac{W_f}{\rho_f} + \frac{1-W_f}{\rho_r}\right](1+H_m)} \qquad E_m = n\frac{E_f A_f}{A_m} + E_r\left[1 - n\frac{A_f}{A_m}\right]$$

- Fiberglass-resin example (pultrusion):

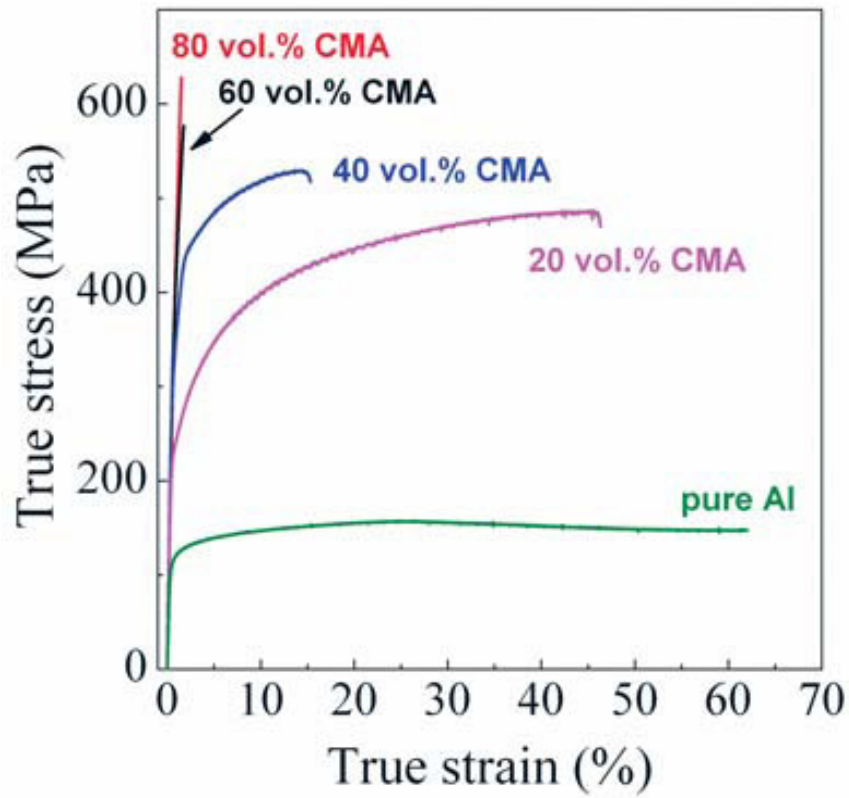
Fiber specific stiffness = 16 GPa g/cm^3

Composite specific stiffness = 68 GPa g/cm^3

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 ~$\lambda/8$ power
  - ~$\lambda/6$ irregularity over any 120mm diameter area
- Thermal performance
  - "no change" for exposure to temperatures ~160°C

Case Study: Carbon Fiber Mirror

Mandrel mold on rotational mount

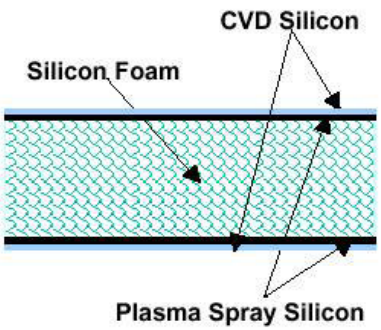
Final mirror

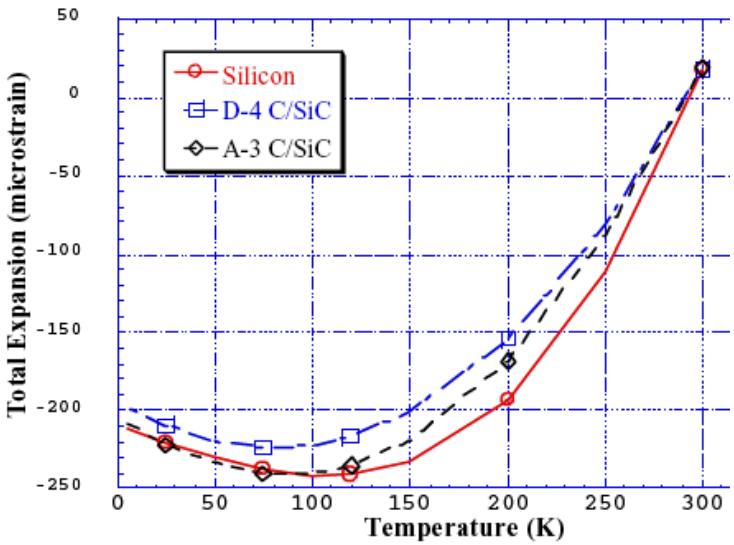
- Conical mirror 1.3m diameter, 0.5m height, polished surface area 2m^2, total weight 8 kg
- M46J/EX-1515= ~ 70% high modulus carbon fiber, ~30% cyanate ester resin matrix
- For use in ISS experiment: space-qualified materials
- The specific stiffness of CFRP ~ 5 times greater than steel.
- The coefficient 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

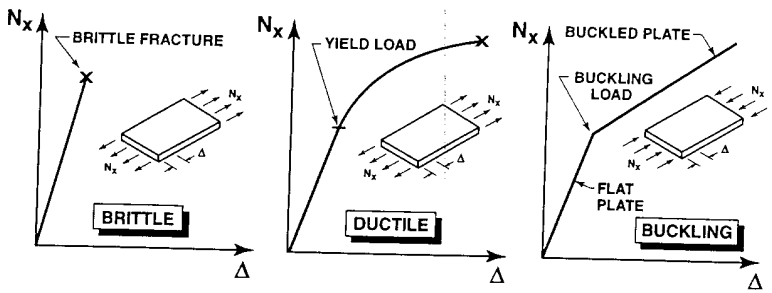
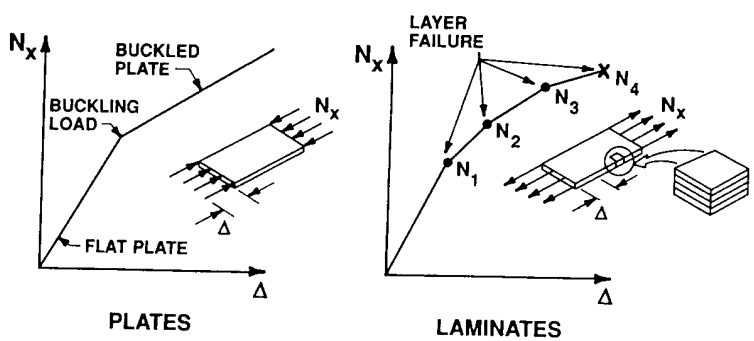
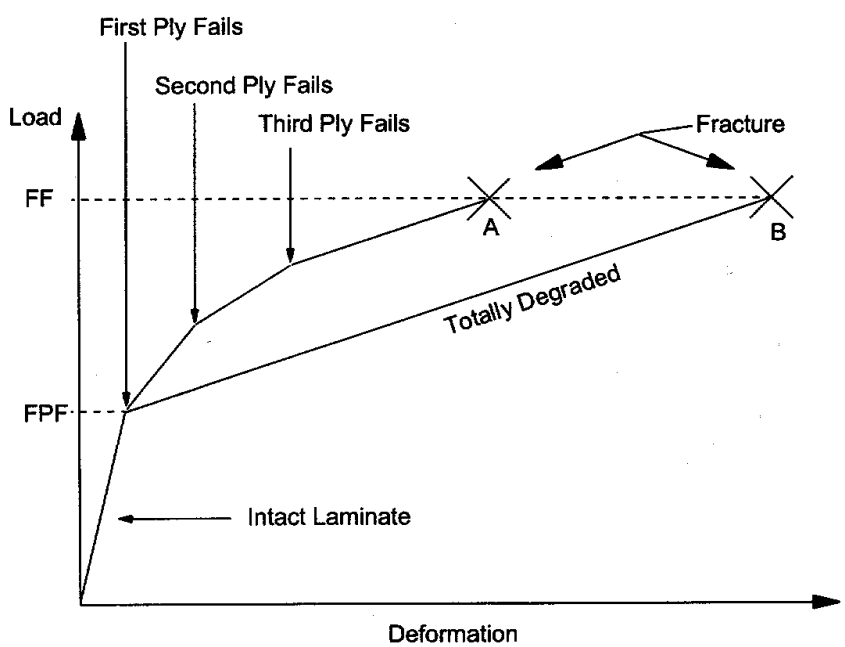


Figure 4-33 Load-Deflection Behavior of Metal Plates



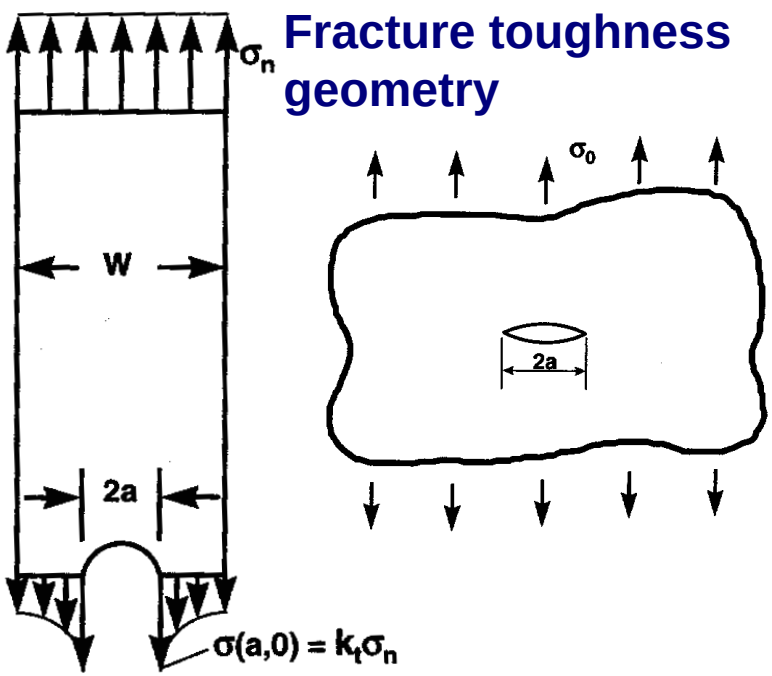
Resulting incremental failure



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 $k_{IC,1} = F_0\sqrt{\dfrac{\pi a a_0}{a_0 + 2a}},$

Stress concentration failure criterion

$$k_{IC,2} = F_0\sqrt{\pi a}\sqrt{1-\left(\frac{a}{a+d_0}\right)^2}$$

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±0.05ppm/°C.

Comparison of Composite Materials

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

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

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- “Athermal telescope” http://www.cesic.de/...html
- “Cesic Mirror” http://spiedl.aip.org/...
- “Failure” http://www.emba.uvm.edu/.../me257/
- M. H. Krim, “Design of highly stable optical support structure” Opt. Eng., 14, 552, 1975 www.optics.arizona.edu/.../Krim%201975.pdf
- Regarding cost-effectiveness of composites: “Advances in the manufacture of advanced structural composites in aerospace– a mission to the USA” http://www.netcomposites.com/...pdf

Questions?

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