Tutorial: Applied Use of Composites in Optical Systems

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Abstract

The purpose of this paper is to provide a brief discussion of the applied use of composites in optical systems. This paper is meant for the interested reader in design of optical elements and support structures, and how composites may be used in both scenarios. First, an overview regarding composite theory is summarized. Secondly, use of composites as optical elements and as support structures of optical systems is discussed. Throughout, numerous examples are used as case studies to illustrate application.

Introduction

Composite materials (or composites) for short are defined as materials comprised of two essentially different engineered elements. Their combination can be varied during fabrication and thus allows for unique macroscopic properties such as the following:

- The mechanical properties tend to be orthotropic, or defined by the direction of applied load, rather than isotropic, or defined equally in all directions
- They can exhibit high strength to weight ratio, are lightweight, can maintain a low coefficient of thermal expansion (CTE), can be corrosion and weather resistant, etc.
- Some can be heated and shaped multiple times with little change in material properties

According to Yoder[1], the most important types of composites for optical instrument applications are polymer (resin) matrix composites (PMCs) and metal matrix composites (MMCs) and will be focused on in this paper.

The purpose of this paper is to investigate the use of composites in optical systems through discussion of design examples and case studies. Section 1 will provide a brief review of the theory used to model composite behavior. Section 2 will describe two case studies that illustrate the use of composites in optical elements and support structures. Finally, Section 3 will describe some ways composites can fail and potential solutions to improve their performance.

Section 1: The theory of composite materials

Composites are generally composed of two materials: the reinforcement material (typically aligned fibers, chopped fibers, whiskers, or particles) and the matrix (resin or binder). The reinforcement material provides overall strength of the material in a specific direction. The resin holds the fibers together, protects them from mechanical and environmental damage, and transfers stress between them. Fabrication typically consists of placing the reinforcing material into a mould of the desired shape. Then semi-liquid matrix material is either sprayed or pumped into the mold to form the object. Pressure is applied to force out air bubbles. Finally, heat is applied to set the composite.

1.1 Pultrusion

A method of fabrication called pultrusion (from "pull" and "extrusion") stretches the reinforcement material in one particular direction as the matrix is set. This process is ideal for manufacturing products that are straight and have a constant cross section, such as support beams. Figure 1 below illustrates this manufacturing process.

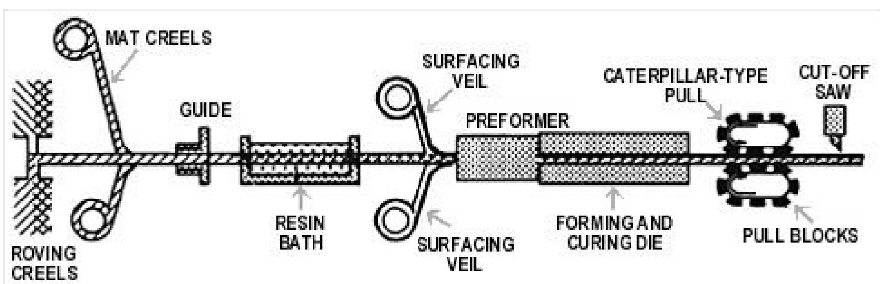


Figure 1: Schematic for Pultrusion Process[3]

For a composite fabricated in pultrusion, the total density[3] can be calculated using the conversion equation for resin (matrix material) and filler (reinforcement material) shown in Equation 1:

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

where
- ρ_m = density of resin-filler mixture [lb./in^3]
- W_f = weight fraction of filler (weight of filler/weight of resin-filler mixture)
- ρ_f = density of filler [lb./in^3]
- $1 - W_f$ = weight fraction of resin
- ρ_r = density of resin [lb./in^3]
- H_m = void fraction of resin-filler mixture to the entire matrix

For example, a fiberglass composite, with $W_f = 30\%$, $\rho_f = 0.094$ lb./in^3, $\rho_r = 0.047$ lb./in^3, and $H_m = 10\%$, the resulting composite density ρ_m is 0.05 lb./in^3.

The strength[4] of a composite fabricated in pultrusion can be approximated using Equation 2:

$$E_m = n\frac{E_f A_f}{A_m} + E_r\left[1 - n\frac{A_f}{A_m}\right] \tag{2}$$

where
- E_m = Young's modulus of the composite [kPa]
- n = number of bars of filler included
- E_f = Young's modulus of the filler material [kPa]
- A_f = surface area of the filler material [m^2]
- A_m = surface area of the composite [m^2]
- E_r = Young's modulus of the resin material [kPa]

For example, a fiberglass composite, with n= 4, E_f = 1.6 E 7 kPa, A_f = 1.96 E-5 m^2, A_m = 3.14 E-4 m^2, and E_r = 2 E 7 kPa, the resulting composite Young's modulus is 1.9 E 7 kPa. Now compare the specific stiffness (density/ Young's modulus ratio) for the filler material and matrix material. For the fiberglass, the specific stiffness of the fiberglass is 0.16 g kPa/cm^{3}and for the composite it is 0.68 g kPa/cm^3. This illustrates an advantage of the composite over an isotropic solid. However, Equation 2 does not account for voids in the mixture and is an approximation.

1.2 Laminated composite sheets

Another useful fabrication process is to build sheets of composite material to produce thin structures with complex shapes, such as curved panels. In this process, individual sheets of woven fiber reinforcement material are saturated with the matrix over a molded shape. Once the desired thickness has been established, the entire structure is cured. Figure 2 below illustrates the use of varying angles to build a quasi-isotropic structure.

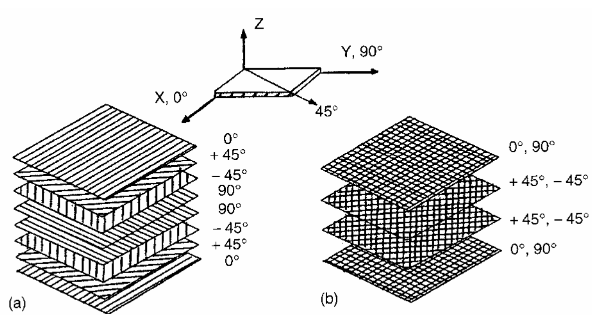


Figure 2. Two examples of quasi-isotropic laminated composite sheets

(a) Eight unidirectional layers

(b) Four bidirectional layers arranged at the indicated angles

Typically, each unidirectional layer has a thickness between 32-254 microns, with 127 microns being the most commonly used thickness. The multidirectional layers are usually between 64-254 microns thick, with 127 microns also the most common thickness.

Figure 3 illustrates the geometry used to calculate the laminate sheet's Young's modulus.

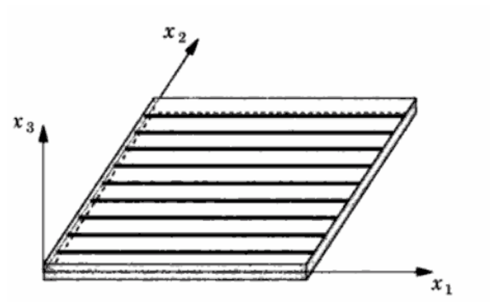


Figure 3: Unidirectional composite layer with coordinate system (x_1, x_2, x_3) where x_1 is oriented along the reinforcement fiber direction[5]

Equation 4 illustrates a theoretical calculation of the material properties[5] of the laminate.

$$E_1 = E_f V_f + E_r V_r, \qquad \nu_{12} = V_f \nu_f + V_r \nu_r,$$
$$E_2 = \frac{E_f E_r}{E_f V_r + E_r V_f}, \qquad G_{12} = \frac{G_f G_r}{G_f V_r + G_r V_f}, \tag{4}$$

where
- E_1 = Young's modulus of the composite along x_1
- E_2 = Young's modulus of the composite along x_2
- ν_{12} = Poisson's ratio of the composite in the x_1-x_2 plane
- G_{12} = Shear modulus of the composite in the x_1-x_2 plane
- E_f = Young's modulus of the filler material [kPa]
- E_r = Young's modulus of the resin material [kPa]
- V_f = volume ratio of the filler material (volume of filler to total volume ratio)
- V_r = volume ratio of the resin material (volume of resin to total volume ratio)
- ν_f = Poisson's ratio of the filler material
- ν_m = Poisson's ratio of the resin material

Notice this calculation does not consider the thickness or dimensions of the material. It assumes a single, bi-directional laminar ply, therefore, it is a simple approximation.

1.3 Metal Matrix Composites

Some composites can be formed via powder metallurgy or in a foam structure between two sheets and can thus be machined with the same flexibility as metals to be lightweighted without sacrificing stiffness, in contrast to the unreinforced base material. Figure 4 shows a comparison of stress-strain curves for MCC's as the amount of aluminum alloy is reduced.

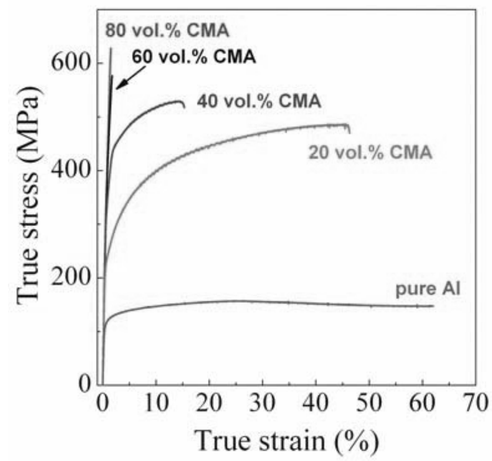
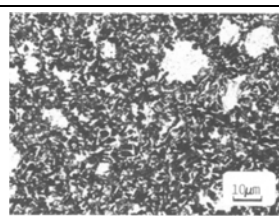
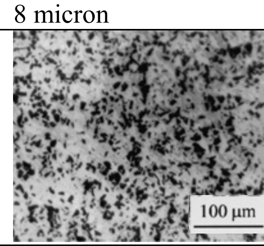
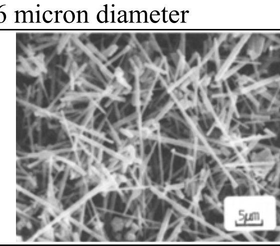


Figure 4: Comparison of stress-strain curves for increasing amounts of complex metal alloy (CMA) in a composite with aluminum[6]

Table 1 summarizes some characteristics of aluminum matrix composites. The information is compiled from P. R.Yoder Jr., W.R. Mohn, D. Vukobratovich, 10. H. J. Yru, K. H. Chung, S. I. Cha, and S. H. Hong

Table 1: Comparison of Aluminum and Silicon Carbide Matrix Composite Materials[2, 9, 10]

Property	**Instrument Grade**	**Optical Grade**	**Structural Grade**
Matrix alloy	6061-T6	2124-T6	2021-T6
Volume % SiC	40	30	20
SiC form	Particulate	Particulate	Whisker
CTE (x 10^6 K^{-1})	107	12.4	14.8
Thermal conductivity (W/mK)	127	123	Unknown
Young's Modulus (MPa)	145	117	127
Density (g/cm^3)	2.91	2.91	2.86
Image Type/ Mean Particle Size	Optical-light micrograph/ 3.5 micron	Unknown/ 8 micron	Scanning electron micrograph/ 0.6 micron diameter
Sample Image			

1.4 Comparison of Composite Material Properties and Applications

Table 2 on the next page summarizes some common composite materials used in optical systems, along with design advantages, disadvantages, and specific applications.

Table 2: Comparison of Metal Matrix and Polymer Matrix Composite Materials[2]

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

Section 2: Use of composites in optical design

Due to their unique material properties, composites can be used instead of metal or glass for mirror substrates, as well as for supporting structural components. The following are some case study examples of using composites in optical design. The reader is encouraged to explore other developments by starting with the references listed in this paper.

2.1 SXA Mirror Example [7, 8]

One mirror, described by Yoder in Chapter 13.6, was made from SXA[A], an aluminum/silicon carbide metal matrix composite (MMC). SXA comprises of 2024 aluminum alloy and 30%

[A] SXA is made by Advanced Composite Materials Corporation, LLC., Greer, South Carolina silicon carbide particulate, by volume. The mirror was large enough to fit a beam footprint 25 cm in diameter and had a finished weight of only 806 grams. SXA was chosen over glass and beryllium due to its high specific strength and stiffness, good stability, and moderate machining cost. The mirror was fabricated by a process sequence of machining, thermal stabilization, electroless nickel plating, polishing, and a high efficiency, laser damage-resistant optical coating. After fabrication, the surface figure was flat to within ~λ/8 power and ~λ/6 irregularity over any 120mm diameter area. The mirror withstood exposure to temperatures of 160°C without change.

2.2 Silicon Mirror and Cesic Structure Example

IR detectors have driven the research to develop mirror substrates that can be used at cryogenic temperatures. Silicon glass has both a very low CTE and high thermal conductivity which is favorable for mirror applications. A single-crystal reflecting surface of a silicon mirror can be polished to <λ/10 PV at 0.633 nm wavelength and with microroughness <5Å rms. However, even when combined with a silicon foam-core structure, this part is still very fragile cannot be machined for mounting. Therefore, combination with a composite material known as Cesic[B] has been considered and developed. Cesic is a carbon-fiber-reinforced silicon carbide that has a very close CTE to that of silicon, as well as low density, high stiffness, high bending strength, no porosity, no outgassing, isotropy in CTE, thermal conductivity, low machining cost, and high chemical, corrosion, and abrasion resistance. As a final advantage, Cesic can be machined into fasteners that can withstand a high tensile force approaching 50,000 N. Therefore, Cesic is a material to be considered for optical structures holding silicon elements due to its similar CTE and other mechanical properties.

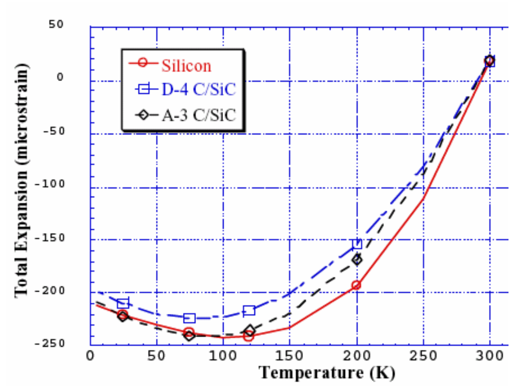
(a)  (b) 

Figure 5: (a) Cesic mount with silicon mirror. (b) Comparison of thermal performance for Cesic and Silicon

[B] Cesic is a proprietary formulation produced by ECM Ingenieur-Unternehmen für Energie- und Umwelttechnik GmbH, of Munich, Germany.

Section 3: Composite failure

3.1 Design of Composite Structures in terms of Stability[11]

R.A. Brand describes numerous failure methods for composites as a way to systematically design stable composite structures for laminar composites with protective metal coatings. The key concepts are summarized here:

- Thermal stability: achieved by the proper volumetric balance of high-modulus, reinforcing fiber having a negative CTE, and a matrix resin with positive CTE
- Moisture-induced stability: Expansion can occur when water diffuses into the matrix resin causing a volumetric matrix change, defined by the coefficient of moisture expansion (CME). The CME is affected by many factors: fiber modulus, fiber volume, temperature, relative humidity, diffusion constant, equilibrium moisture content of the resin, time of exposure, laminate thickness, and flaw areas in the protective covering if there is one. One approach is to use a high-modulus fiber and a low moisture-absorbing-resin system, such as cyanate ester. If a metal coating is added, then the CTE becomes more positive with increasing coating thickness, modulus, and CTE of the metal, and the rate of moisture absorption decreases.
- Design options for dimensional stability in order of ppm strain change
    - Maximum (<1 ppm strain change): The laminate has a high modulus fiber, low moisture absorbing resin partially saturated with moisture already, and metal seal with low flaw density (0.1-0.01%), thickness such that net CTE is 0.00±0.05ppm/°C.
    - Excellent (1-2 ppm strain change): near-zero CTE laminate combined with a melt-applied eutectic whose moisture is vaporized at high temperatures.
    - Moderate (3-5 ppm): High modulus fibers, low moisture absorbing resin, flawed (~1%) barrier/ sealant
    - Minimal (5-10 ppm): May be the most cost effective approach. This design uses only a high-modulus fiber and a low-moisture-absorbing resin without any protective coating. If the relative humidity (<50%) and temperature fluctuations can be controlled, then relatively good dimensional stability can still be achieved.

3.2. Definition of mechanical failure modes of composites

J. C. Iatridis outlines mechanical failure of laminate composites in his lecture notes for the ME 257 course at the University of Vermont[11]. The key concepts and some illustrative figures are included here to promote understanding.

- Define all failure modes in terms of: fiber failure and matrix failure. These are illustrated for a laminate composite in Figure 6 below.

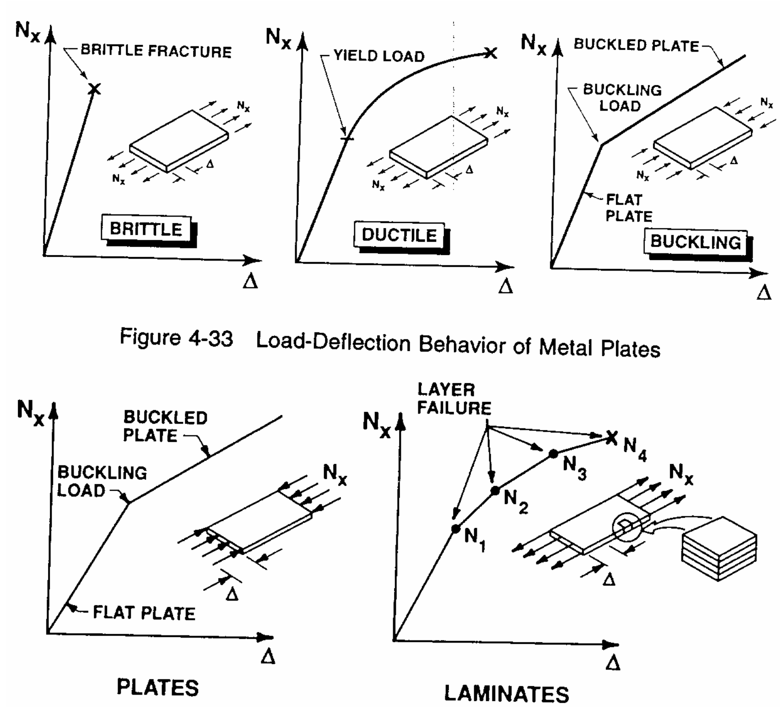


Figure 6: Analogy between Buckled Plate and Laminate Load-Deformation Behavior

- For a laminate composite, the process of failure is as follows:
  - Define the loading criteria with boundary conditions at the top and bottom ply
  - Define failure of the first layer
  - Define resulting degradation of the material properties and iterate

This process is depicted graphically in Figure 7 on the next page

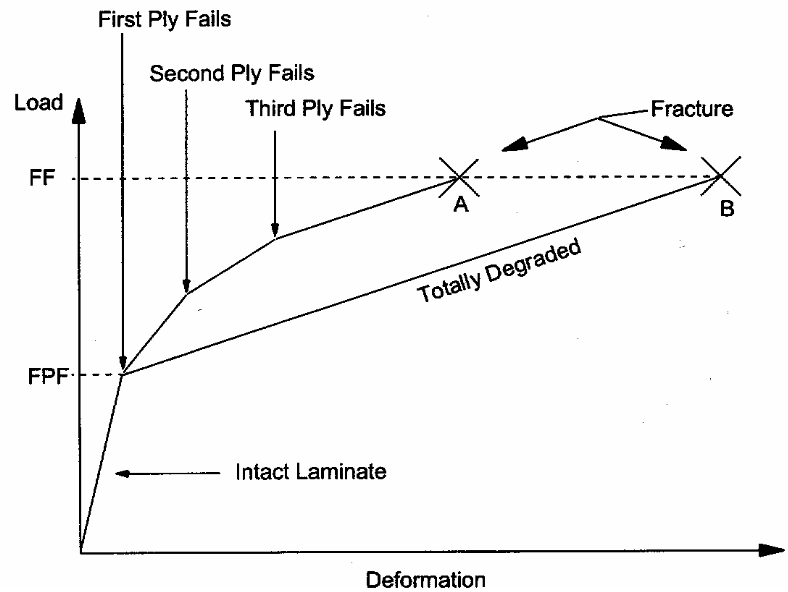


Figure 7: Determination of fiber failure by an incremental approach

- Failure from stress concentrations: localized contact stress can lead to failure and is modeled with geometry shown below in Figure 8.

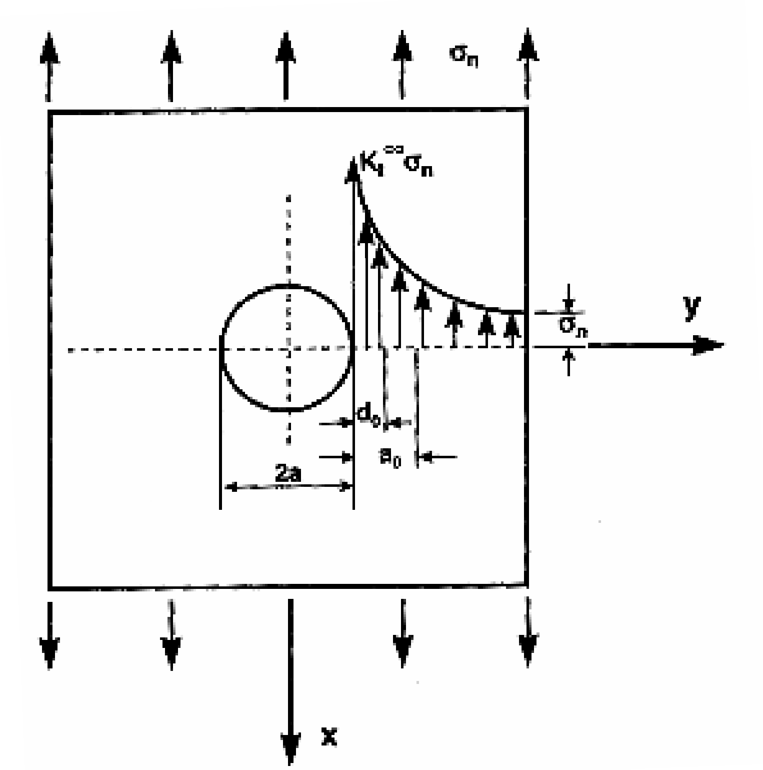


Figure 8: Failure occurs when stress (σ_n) at a distance (d_0) from edge of discontinuity exceeds the un-notched composite tensile strength F_0

- Failure due to sharp cracks: Can use fracture mechanics to model and predict composite failure as outlined in Equation 5 below. Failure occurs at K_I exceeds k_{IC}..

$$K_I = Y\sigma\sqrt{\pi a} \qquad k_{IC,1} = F_0\sqrt{\frac{\pi a a_0}{a_0 + 2a}},\ k_{IC,2} = F_0\sqrt{\pi a}\sqrt{1-\left(\frac{a}{a+d_0}\right)^2} \qquad (5)$$

where
- K_I = Stress intensity factor
- σ = Applied stress
- a = Radius of the sharp crack
- $k_{IC,1}$= Average stress failure criterion
- $k_{IC,2}$= Stress concentration failure criterion
- F_0 = Nominal composite tensile strength without the crack
- a_0 = Average distance from the crack
- d_0 = Average distance from the edge of the crack

  - It should be noted that composites are much more resilient to absorbing the energy of a propagating crack than the isotropic fiber materials are. This is due to the "matrix stress shielding" effect such that there is zero stress at the crack site. So, as the crack propagates, it encounters fiber, and loses energy as it interacts with fiber particles locally. This allows the composite as a whole to absorb a large amount of stress before complete failure occurs. Therefore, cracks are a function of the composite thickness and stress level.
- Failure in composites occurs due to delamination, matrix cracking, and fiber failure
- Fatigue resistance of composites is generally very good. However, fatigue life is complicated by interaction with factors such as matrix cracking, delamination, and impact damage.

Conclusion

Composites provide many additional design degrees of freedom that should be carefully considered when designing both optical elements and systems. Technology is continually improving to drive down the cost on available products as well as provide ever more design flexibility. This tutorial has provided a very brief glimpse of some theory, uses, and concerns associated with using composites. However, much more detailed FEA and experimental analysis is highly recommended prior to use in a developed design.

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