Designing With Composites: Engineering Fundamentals

A Norplex-Micarta White Paper

Executive Summary

Composites have the unique ability to be customized to the requirements of myriad applications, driving use well beyond the aerospace and transportation sectors. Because composites are both heterogeneous and anisotropic, composite design and analysis rely upon a framework that expands on the traditional mechanics of materials approaches. This paper will present an overview of these approaches and apply that understanding to a structured development process which is unique to the design of composite materials.

I. An Introduction to Composites

Designing a composite part is in some ways a designer's dream, with nearly infinite combinations of materials that can be utilized to achieve specific design goals. This flexibility also presents a challenge—specifically, how to choose the inputs and build the composite most suitable for an application. Even if a designer begins with a set of assumptions such as material properties desired for a part or a fixed geometry, the sheer number of options requires a reliable framework for design decisions.

Composites have recently gained much attention due to their weight-adjusted (or specific) stiffness and strength, which allow for lightweighting in fly- or drive-away applications. Thus, aerospace, and now, automotive companies are increasing the composite content in their products. Demand is increasing in other industries based on additional material properties available in composites.

Beyond the benefit of lightweighting, composites have numerous advantages arising from their unique construction.

What accounts for these materials to be sought for specific applications? First, designers have unprecedented access to empirical data at the coupon level. Secondly, improved (and lower-cost) analytical software tools have made complex analysis significantly faster and more cost-effective. Third, the anecdotal success of composites in demanding applications is ever growing. Finally, the structured design process is robust enough to address even complex failure modes such as fatigue. The level of confidence is such that entire fuselages are being constructed from composites.

Key characteristics of composites

Because of how composites are produced, they are both heterogeneous and anisotropic. Let's address these terms in detail.

Heterogeneity
Composite materials are heterogeneous because they are composed of different materials with different physical, mechanical and electrical properties.

Anisotropy
Composites have different mechanical and electrical properties along different axes. Due to these characteristics, composites must be analyzed with more rigor than homogeneous and isotropic materials. Fortunately, an analysis method used for composites extends from the classical mechanics of materials approaches already familiar to designers.

In the balance of this paper, we will address these aspects of composites and present an overall design methodology. To understand how to make these materials work in a specific application, we will first address how composites are built.

II. How Composites Are Built

Composite materials are made up of two or more different materials, referred to as the matrix and the reinforcement.

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Each combination is chosen for its ability to deliver predictable and repeatable performance to match the application's requirements. Since these materials have very different properties, the heterogeneity of composites must be addressed to support the analysis of composite parts and structures.

The matrix functions to bind the reinforcement together and protect it. A composite matrix will be one of three types: polymer, metal or ceramic.

This paper will concern itself with thermoset polymer matrix composites. Thermosets undergo a high-temperature curing process by which the chemical structure of the polymer is irreversibly cross-linked. Therefore, thermosets do not melt after curing, as opposed to thermoplastic materials, which do melt.

The reinforcement, sometimes referred to as the substrate, is considered the primary contributor to the strength and stiffness of the composite. Potential reinforcements that can be effectively utilized are nearly infinite. Common reinforcement materials include paper, cotton fabrics, glass, aramids, nylon and carbon fiber. Other materials such as virgin PTFE or rubber can be incorporated into the composite to achieve specific design objectives.

When designing with composites, it is helpful to structure our approach around their construction. The following outline details the levels upon which composite design and analysis are based, and will facilitate further discussion.

0. Molecular
The chemical composition of the resin matrix or the reinforcement can be adjusted to achieve a different property in the constituent material. It is generally outside the analysis of composites to look at the chemical interactions or makeup of the matrix or the reinforcement at the molecular level.

1. Constituent
The discrete materials in the composite. These will be, at minimum, a resin matrix and a reinforcement. Other additives may also be constituents. The engineering constants and other relevant properties of the constituents are inputs to the next level of analysis and design.

2. Lamina
A single layer of the combined constituents. This is generally the first level of composite analysis, and is concerned with the compatibility and processability of the constituents as well as the first adaptations of traditional mechanics of materials approaches to understanding stress-strain relationships.

3. Laminate
The layering of two or more lamina. This level of analysis begins to address the impact of the varying properties of individual lamina on the overall laminate.

4. Part
This is the final level where the geometry is defined and generally the input to an overall structural design.

The rule of mixtures is an easy starting point to conduct "what-if" analysis of a lamina.

III. A Framework for Analyzing Heterogeneity

A composite material has different properties from one individual point to another. However, once an area is analyzed which is sufficiently large relative to the size of the constituents, the differences observed at a smaller scale are generally not of practical significance.

Effective modulus of a heterogeneous material

The scientific literature uses what is called the effective modulus of an equivalent homogenous material[1] to describe this averaging of constituent properties. Therefore, the composite will exhibit the same elastic response an equivalent homogeneous material would under the same loading conditions. This micromechanical construct is useful as it allows us to build stress-strain relationships and to predict certain properties using the rule of mixtures.

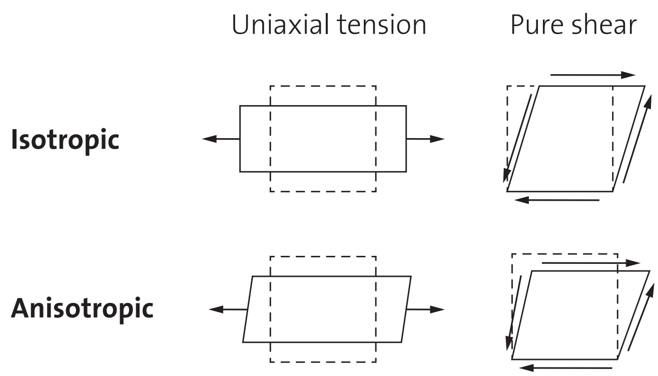
The rule of mixtures is used to quickly evaluate the potential strength and stiffness of a lamina if the constituent properties are known. The rule states that the resulting lamina properties are proportional to the volume fraction-weighted properties of the constituents. This has proven reliable for longitudinal (along the direction of the reinforcement) modulus and can be adapted to become a starting point for other properties, even electrical properties.[2] This rule is helpful to guide our understanding of how composites work. Nevertheless, it is an approximation and all results from this approach must be fully tested as part of the design validation process.

IV. Designing with Anisotropy

We will begin by discussing the approach to analyzing anisotropy in lamina. But first, we will address another way in which composites behave non-intuitively.

In an isotropic material, normal stresses only cause normal strains and shear stresses only cause shear strains. But because composites are neither homogeneous nor isotropic, normal stresses can create both normal and shear strains. Likewise, shear stresses can create shear and normal strains. Thermally induced strains will cause different distortions in different directions, thus creating different stresses. This characteristic of composites is called shear coupling[3]. While this phenomenon complicates analysis, designers take these effects into account during the design process using a well-developed theoretical framework.

Deformations for Various Materials



Source: Agarwal, B. D., Broutman, L. J., & Chandrashekhara, K., Analysis and Performance of Fiber Composites, 2006

Anisotropy at the lamina level
Analyzing and designing composites starts with an understanding of the constituents. Those constituents are first combined into a lamina, considered, for analysis purposes, as a 2-D object.

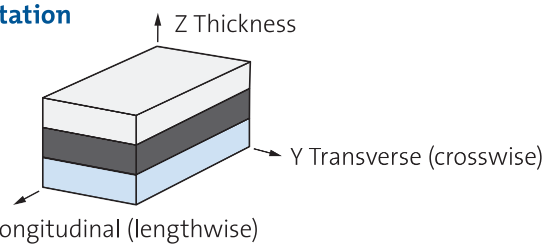
Given that the primary strength and stiffness of a lamina are derived from the reinforcement, any anisotropic behavior of the reinforcement will be a corresponding property of the lamina. Therefore, lamina have five independent stress-strain relationships that must be understood. These are the longitudinal tension and compression, the transverse tension and compression, and finally shear.[4] Each of these are different. Transverse tension is generally the least strong,[5] particularly when the lamina is constructed from a reinforcement with all fibers oriented in the same direction (commonly called unidirectional fiber).

Once individual lamina properties are known, they can be combined to form a laminate. The laminate will derive its properties from the lamina. The analysis at this level begins to focus on the lamina interface.

Anisotropy at the laminate level
By constructing a composite lamina by lamina, the strength, stiffness, hardness, wear resistance and electrical properties can be applied in the location and direction to best achieve the design objective. But once again, the lamina themselves are anisotropic; therefore, the resulting laminate—even when built monolithically from the same lamina—will be anisotropic.

While there are several theoretical approaches that can be used to address anisotropy, we will continue with a mechanics of materials approach since it is the most straightforward and assists us as we work toward building a final part geometry.

Laminate Testing Axis Orientation



The behavior of lamina bonded together to make a laminate can be described by classical lamination theory (CLT). Using CLT, closed-form stress equilibrium and strain-displacement equations guide the initial understanding of laminate behavior, including shear coupling. The CLT approach is helpful, but in order to consider displacements across lamina interfaces as continuous, it must ignore interlaminar shear stresses.[6]

Thickness strength (Z-direction) of a laminate is generally limited by the tension and is affected by stress concentrations between the matrix and the reinforcement, similar to the way transverse tension is affected in a unidirectional lamina. The effect of these stress concentrations causes the strength of the composite to be lower than the tensile strength of resin matrix alone. These effects are complex, difficult to predict, and are generally affected by what is called the reinforcing fiber packing geometry.[7] In-plane shear (also commonly called interlaminar shear) strength is likewise affected by the fiber packing geometry.

It is important to note that the analysis above is limited to single-axis (even off-axis) scenarios. In most practical applications, multiaxial loading conditions are present. For that reason, composites are rarely produced with unidirectional fiber lamina all arranged in the same orientation.

V. A Starting Point for Designing Components from Composites

As in all design problems, understanding external loads and supports is critical, but composite design is different from that of isotropic materials. The orientation of the reinforcement must be deliberately designed to handle external loads. Other effects including the operating environment must be addressed in detail.

Best practices for understanding composites have been compiled in the Composite Materials Handbook,[8] recognized as an essential resource for composite material design.

The handbook's approach follows a building block methodology originally developed for the U.S. Department of Defense:

1. Understand expected loads and conditions, such as strain rate and service temperature
2. Understand the design window for the geometry
3. Understand the potential failure modes, per the accompanying table
4. Determine resultant stresses
5. Review current material data
6. Model the part as necessary
7. Prototype and test

Design Criteria and Associated Failure Modes

Design criteria	Associated failure modes
Strength	Fracture
Stiffness	Excessive deformation
Stability	Buckling
Hygrothermal effects	Property degradation, expansion and contractions, residual stress
Life or durability	Fatigue, creep
Weight	Too heavy
Cost	Not economical
Manufacturability	Impractical, warping

Source: Gibson, Ronald F., Principles of Composite Material Mechanics, Third Edition, 2012

The need for detailed analysis

Technical data bulletins and micromechanical models provide data to quickly screen materials according to the properties relevant to the design. However, for design inputs, specific testing may be required to validate engineering constants for a particular application. There is no substitute for experimental characterization, particularly when temperature or other environmental effects must be considered. Given the complexity of predicting properties of a composite dominated by the reinforcing fiber packing geometry, it has proven useful to use engineering constants derived from laminate-level direct experimentation.

These coupon-level tests are the inputs to detailed part models. As discussed before, understanding the strength and stiffness in the principal material axes and the potential failure modes allows for analysis of stress levels that may be generated using Finite Element Analysis (FEA) tools. Even some of the more basic CAD tools on the market are capable of modeling laminated parts under the assumptions of CLT to take into account shear coupling. While these tools may be sophisticated enough for linear static analysis, high-energy or dynamic conditions require specialized FEA tools and detailed analysis. That level of analysis is generally utilized by industries such as aerospace, where component testing under environmental conditions of use is expensive but the consequence of failure is extreme.

Even if advanced FEA models are used to optimize design or analyze complex conditions such as thermally induced strains, the part will need to be built and tested to failure. While this process is normal for designs on all materials, it becomes even more important in the design of composite parts due to the number of potential failure modes. Some failure modes are difficult or impossible to predict using only theoretical constructs.

VI. How Stock Laminate Shapes Can Accelerate the Design and Development Process

Many designers of composites have become accustomed to working with unidirectional lamina when designing laminates for complex shapes to be produced in a single fabrication step using a molding process. They would go through the various design stages and ultimately fabricate a part (such as an airplane wing) in an autoclave.

It has proven useful to use engineering constants derived from laminate-level direct experimentation.

Before that approach was even available, composite materials have been produced in stock shapes such as sheets, rods and tubes, then fabricated into the desired geometry. While this approach does not start with a net shape, it has several advantages.

Those advantages include no need for specialized tooling or molds, which allows for faster prototyping. Secondly, these composite materials are produced through high-speed, automated processes, which are designed to ensure a very repeatable and consistent product in large volumes.

Finally, many of these materials have already been produced and are readily available for new applications or as a starting point for the design of a new material. This permits use of established performance anecdotes at the very beginning of the design process. The complexities of predicting performance of a new composite can be reduced using coupon data and practical application experience, baseline testing utilizing existing materials, and analytical models such as those presented in this paper.

The information provided herein is based upon published academic work and anecdotal evidence compiled by Norplex-Micarta. This is not a definitive guide to the analysis or design of composites. To assure the material's performance is adequate for a specific application, customers should independently verify performance characteristics of interest.

About Norplex-Micarta
Beginning with Bakelite phenolic resin in the early 20th century, Norplex-Micarta has led the development of new and advanced thermoset composite materials including its namesake material, micarta. Norplex-Micarta reliably and consistently develops and supplies quality materials for some of the most demanding applications around the world.

We work directly and collaboratively with designers to solve complex problems. Decades of experience developing new composites for industrial, aerospace, power generation, medical equipment, military and transportation uses has enabled Norplex-Micarta to develop a suite of standard products that are the basis for our ongoing development work. These standard products allow designers to establish a performance baseline and familiarize themselves with the potential of new materials and applications. These initial building blocks are continuously being augmented with new technologies, allowing designers to be creative in considering new material solutions to difficult design problems.

Each Norplex-Micarta manufacturing facility has a set of unique capabilities. The company headquarters, primary design center and manufacturing complex in Postville, Iowa, USA, processes a variety of resin and substrate combinations in pre-preg, sheet, convolute rolled tube and molded shape form. A state-of-the-art facility in Changzhou, P.R. China, focuses on the design, production and fabrication of glass-epoxy materials. Laboratories in both ISO9000-certified facilities are equipped with sophisticated test equipment to support development and ongoing verification of materials.

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