Introduction to Composite Materials

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Composite materials are an advanced family of materials that have been in development for decades and continue to gain usage in the aerospace, marine, automotive, and sporting goods industries. While composites enjoy benefits such as high strength-to-weight and stiffness-to-weight ratios, they are considerably more complicated than most metals and plastics. This class provides an introduction to composite materials and is intended for users with a little background or no background on composites. Attendees learn what a composite material is and the advantages/disadvantages of composites, as well as an overview of design, analysis, and manufacturing methods for composites. Finally, Autodesk® products with composites functionality are briefly discussed.

Learning Objectives

At the end of this class, you will be able to:

- Explain what a composite material is
- List the benefits of composites
- Identify the challenges of designing and analyzing composites structures
- Identify Autodesk products that have composites functionality

About the Speakers

Rick Dalgarno worked as a Composite Engineer for Firehole Composites for 5 years and now works as a Technical Consultant for Autodesk (Firehole Composites was recently acquired by Autodesk). He earned his BSME and MSME from the University of Wyoming. Rick is an expert in advanced finite element analysis of composites and is particularly experienced in the use of progressive failure methods to determine damage evolution in composite structures. Working with aerospace, marine, sporting goods, and motor sport companies, in addition to government research laboratories, Rick has analyzed an extensive range of composite applications. He has authored or co-authored 6 journal and conference publications specific to composite materials.

Jerad Stack has experience in the management and delivery of simulation software that spans more than a decade. In that time, he has worked with applications ranging from military satellites, to commercial aircraft, to Formula One racecars. This experience in the industry has given him a vast understanding of the business and technology of modeling and simulation software. Previous to the company's acquisition by Autodesk in March 2013, Jerad was the CEO of Firehole Composites. As CEO he formulated and executed the company's strategies towards better design and analysis software for composite materials. Now at Autodesk, Jerad is part of the Simulation Product Management team where he is helping shape the future direction of Autodesk's simulation product portfolio.

Understanding Composite Materials

Definition

The word composite can assume many definitions depending on the context in which it is used. The most general definition of the word composite is: A composite material is a material that is made from two or more different materials.

By this definition, the following are examples of composite materials:

- Steel
- Carpet
- Chocolate chip cookie

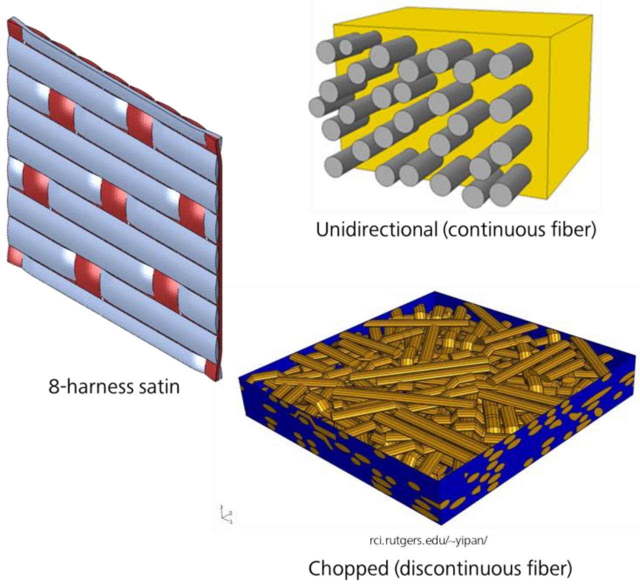
The definition that we use here is more specific: A **composite material** is an *engineered* material that contains two or more clearly distinguishable constituents with significantly different properties.

Of particular note are the words engineered and constituent. By engineered, we are simply stating that the material is man-made and designed for an intended application. The word constituent is used to refer to the parts of the composite, namely, the fiber and matrix. Here, we focus our attention on fiber-reinforced matrix composite materials.

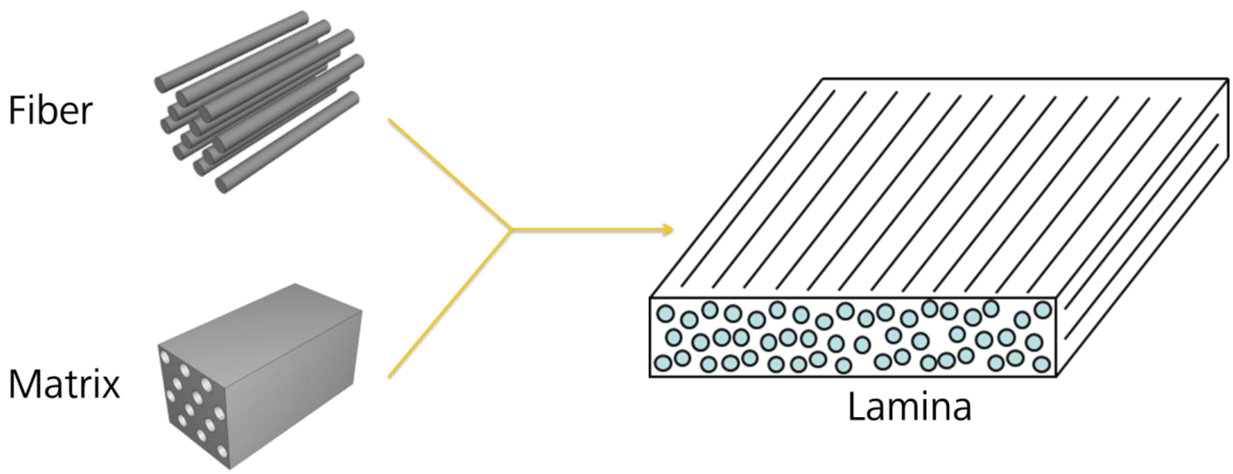
Fiber-Reinforced Composite Materials

This class of composite materials consists of the one or more fiber constituents bound by a matrix (resin) constituent. The fiber is typically made from carbon, glass, or Kevlar and is very stiff and strong in relation to the matrix. On its own, fibers are flexible and therefore require some form of support in order to prevent buckling. Thus, the purpose of the matrix constituent is to support and align the fibers while providing a path for load transfer.

To fully define a composite material, a microstructure must be identified. The microstructure characterizes the geometric configuration of fibers and matrix. Common forms include unidirectional (continuous fibers aligned in the same direction) and woven (tows – bundles of fibers, woven together).



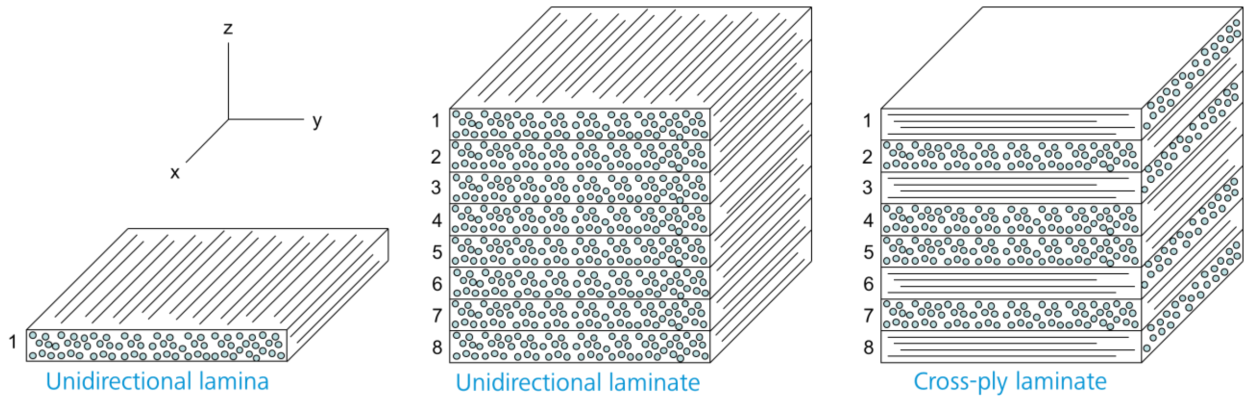
A single layer of a composite is referred to as a **lamina or ply**. A ply is defined by the fiber type, matrix type, and microstructure. Below, we see an example of a unidirectional ply.



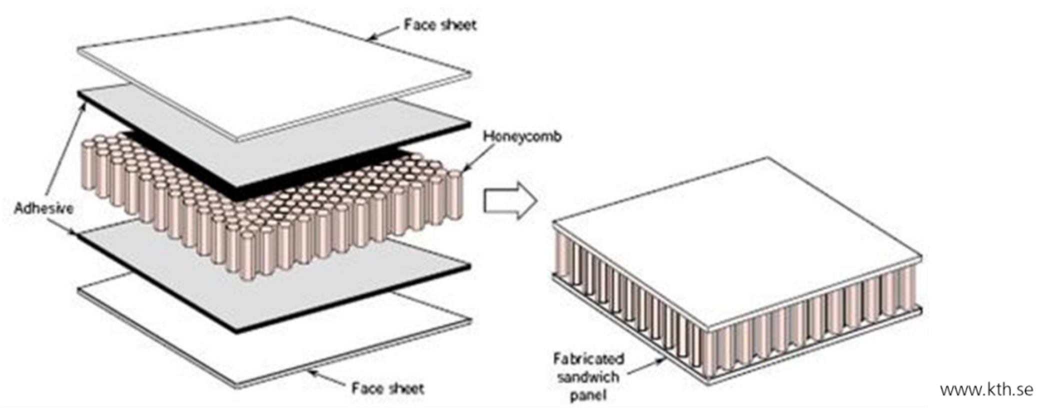
On its own, a ply is not very useful for a few reasons.

1. It is thin – typical unidirectional ply thickness is on the order of 0.01 inches. Thin materials are unable to carry significant load.
2. Composites are weaker in some directions than others.

To overcome these shortcomings, composite structures are made from laminates. A **laminate** is a stack of individual plies. The layup defines the stacking sequence for each ply in the laminate. In the example below, we see a laminate that consists of 8 plies and each ply has the same orientation. This is referred to as a unidirectional laminate. As with the individual ply, the unidirectional laminate suffers from low strength in the y-direction. By alternating the ply orientations we create a cross-ply laminate that has strength and stiffness in both the x- and y-directions.

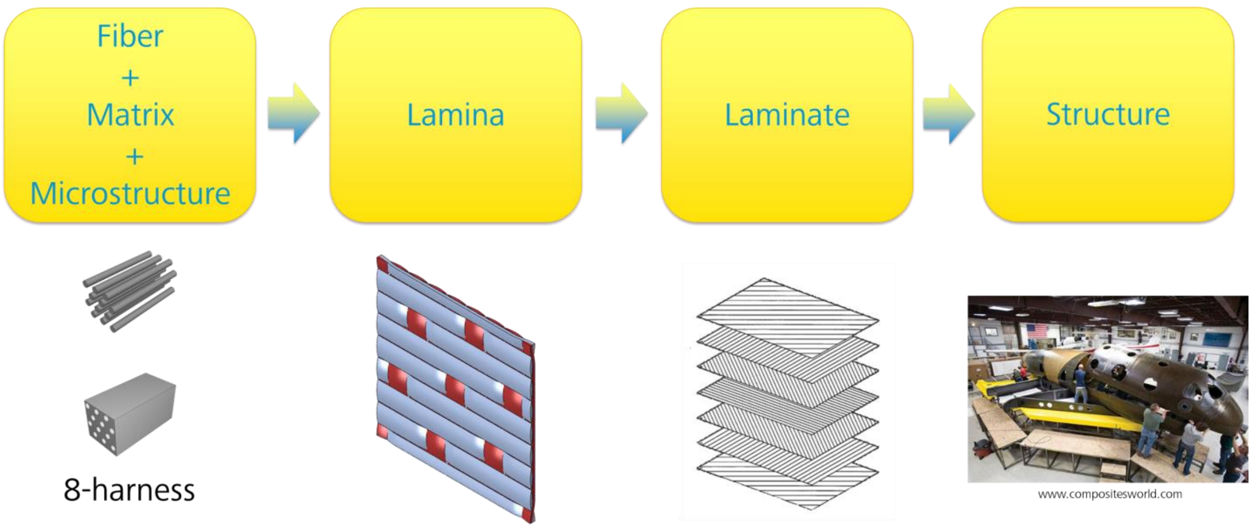


A laminate may contain different composite materials (a uni and woven material, for example) and often, a core made from foam, honeycomb, or wood. The core acts like the web in an I-beam and dramatically increases the bending stiffness of the laminate.



Many different laminate are usually required to build a **structure** that contains composites, such as a wind turbine or the Boeing 787. For instance, the laminate at the base of the wind turbine blade is different than the laminate at the tip of the wind blade. In the case of the Boeing 787, the primary laminate for the fuselage is different than the laminate used in the nacelle.

In summary, fibers, matrices, and microstructures are the building blocks of a lamina. A laminate is made by stacking layers of lamina at various angles. Finally, a composite structure is made from several types of laminates.



Fabrication of Composite Structures

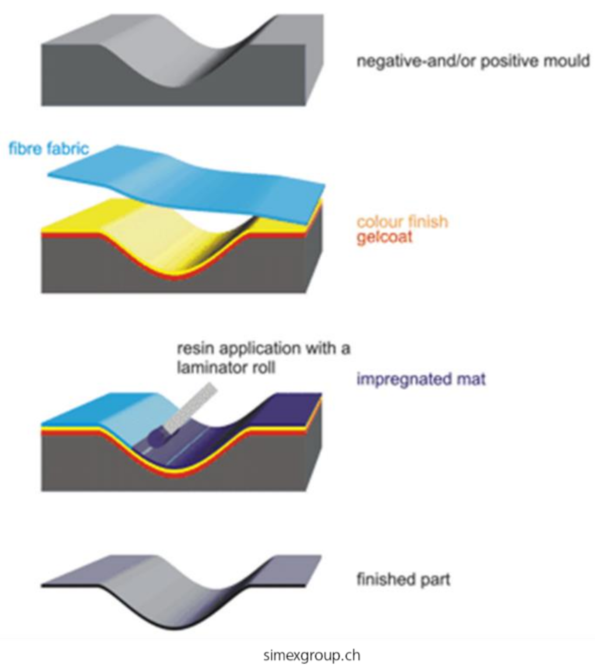
There are many methods for fabricating structures made from composite materials. As with the fabrication of a structure made from any material, the choice of fabrication method for a composite structure depends on the cost, application, complexity of the part, volume, etc.

The most common fabrication methods for composites are:

- Hand lay-up
- Filament winding
- Tape placement
- Injection Molding
- Spray-up
- Forming

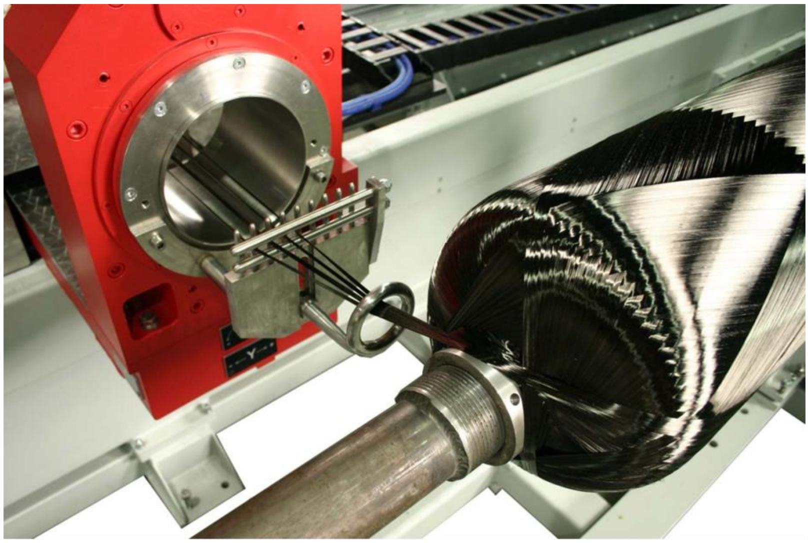
Hand lay-up

In this method, the fibers are manually placed onto a mold and then resin is applied by spraying, pouring, or rolling. A vacuum bag is often applied to compact the material and aid in curing. This method is labor intensive and can produce inconsistent/low-tolerance parts.



Filament winding

This is a machine driven process where a fibers are wound around a spinning mandrel. The fibers are either pre-impregnated with resin or pass through a resin bath before being applied to the mandrel. Because this is an automated process, quality control is good. A common application is the fabrication of pressure vessels, but this is also used to produce driveshafts and pipes.



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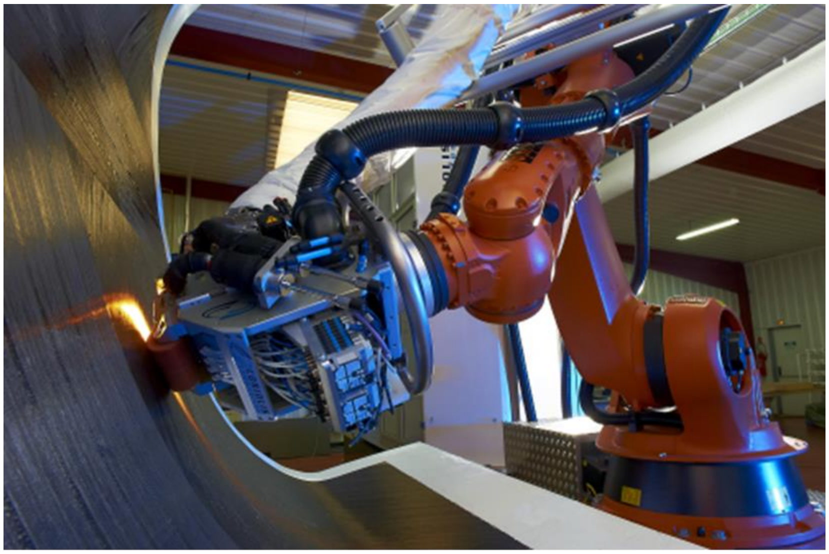
Tape placement

This is a highly automated process that requires expensive machinery and tooling. Strips of composite tape (pre-impregnated fiber) are laid onto a mold by a computed controlled machine. Output rates are surprisingly fast and precise tolerances are achieved. This method is often used in the aerospace industry to produce large components such as fuselage sections and stabilizers. Usually, high-end composites are used so material cost is a consideration.



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Injection Molding

Chopped fibers and resin are injected into a closed mold until the part is cured. The part is then released from the mold. Continuous fibers may be injected, but this is a specialty application and is not the norm. The main benefit for injection molding is high volume.

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Spray-up

This process may be machine driven but is most commonly a manual procedure. A spool of continuous fibers is fed into a spray gun that chops the fibers and mixes them with resin and spays the mixture onto a mold. This process is faster than a hand lay-up but suffers from the same problems: inconsistencies in thickness and fiber volume fraction and low compaction.

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Forming

In this method, fibers are placed onto a mold with resin, the mold is closed, and a combination of pressure and temperature is applied until the part is cured. Variations of the method include:

- Resin-Transfer Molding (RTM) – Resin is injected into the mold under pressure
- Vacuum-Assisted RTM (VARTM) – Resin is drawn into the mold with a vacuum

Benefits include low cycle times, the ability to create Class A finishes, and the option of using lower cost materials.

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Manufacturing Defects

Defects can easily be introduced to the structure during manufacture. For higher end applications, like aerospace, avoiding defects is critical as they can precipitate into premature structural failure. Common defects are:

- Voids – Regions where there is empty space instead of matrix/fiber
- Ply-misalignment – Orientation of a ply is incorrect (46° instead of 45°, for example)
- Fiber waviness – The fibers have slight undulation instead of being straight
- Thickness variations
- Inconsistent fiber volume fraction
- Incorrect cure – Wrong temperature/pressure/duration

Why are Composites Attractive?

Given all of the complexities of composites, why are they used? As we will see, composites have many attractive features that outweigh their negative features.

Composites are used in nearly every industry but are particularly prevalent in the following industries:

Personal & Leisure Goods

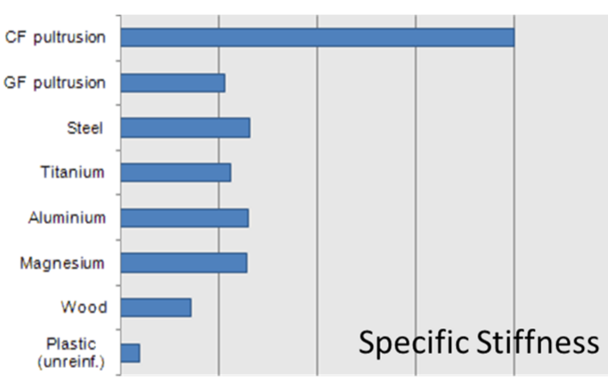
Aerospace & Defense

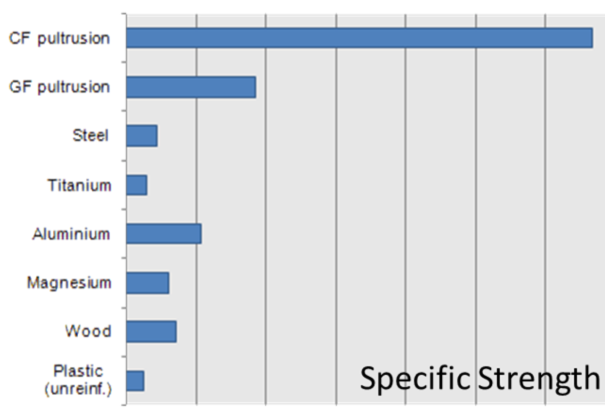
Automotive & Transportation

Infrastructure

Composites are Lightweight

Compared to other materials, composites have relatively high specific-stiffness and specific-strength. Therefore, in applications where weight is an issue (think automotive and aerospace), composite are always at the top of the list for preferred materials.





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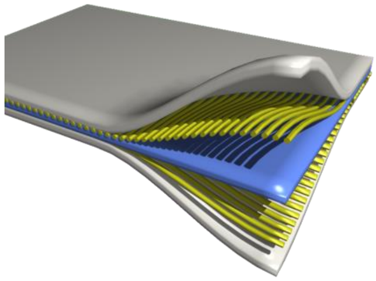
Property Tailoring

The orientation and stacking sequence of plies can be used to tailor the response of a laminate. The stiffness, strength, or nonlinear behavior may be customized. Cores can be added to add bending stiffness.



Manufacturing Advantages

As shown in the table below, the new Boeing 787 fuselage assembly has less than 10,000 holes drilling operations compared to 1 million for the Boeing 747.

	Boeing 787	Boeing 747
Percent Composites (by Weight)	**50%**	**Less than 5%**
First Barrel Part Count	One Integrated Composites Part	1500 Aluminum Sheets 40k-50k Fasteners
Holes Drilled Into Fuselage During Assembly	Less that 10,000	One Million

Complex geometries can be manufactured.

Red Bull Formula 1 Front Wing
(Image: Formula1.com)

Composite Crew Module
(Image: NASA's Langley Research Center)

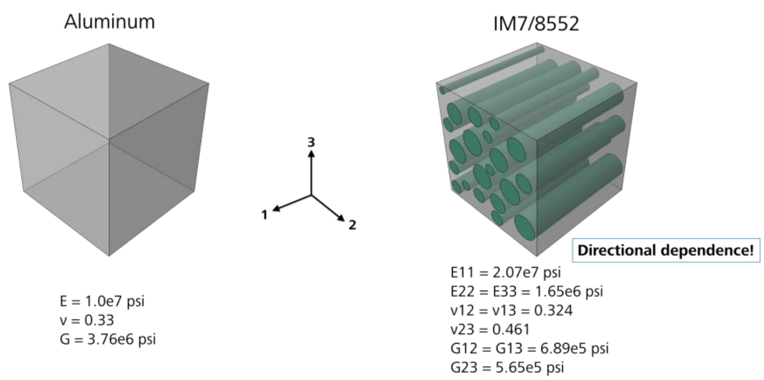
Composites are Corrosion Resistant

Cured-in-place pipe (CIPP) enables repair of deteriorating underground water/wastewater pipelines without expensive excavation. (Image: Craftsman Pipilining)

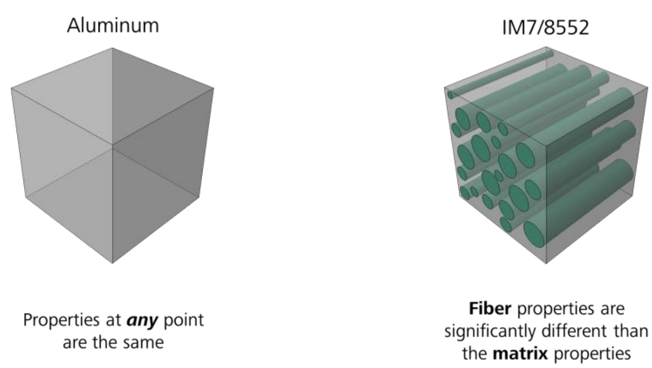
Composite Engineering Challenges

Designing and analyzing composites is challenging because of 2 fundamental reasons:

- Composites are **nonisotropic** - They exhibit directional dependence of material properties



- Composites are **heterogeneous** – The properties at any given point are not the same



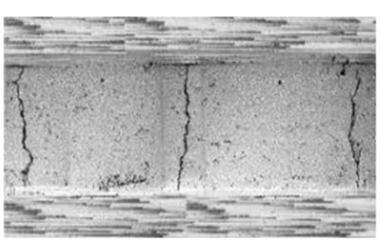
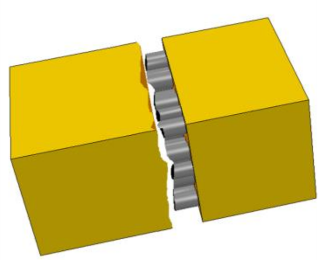
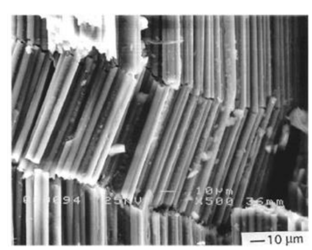
Failure Modes in Composites

As we've learned, there are endless combinations of fibers, matrices, and microstructures and composites are nonisotropic and heterogeneous. Realizing this, it becomes easy to appreciate that there are many failure modes for composites. In addition, failure modes are dependent on:

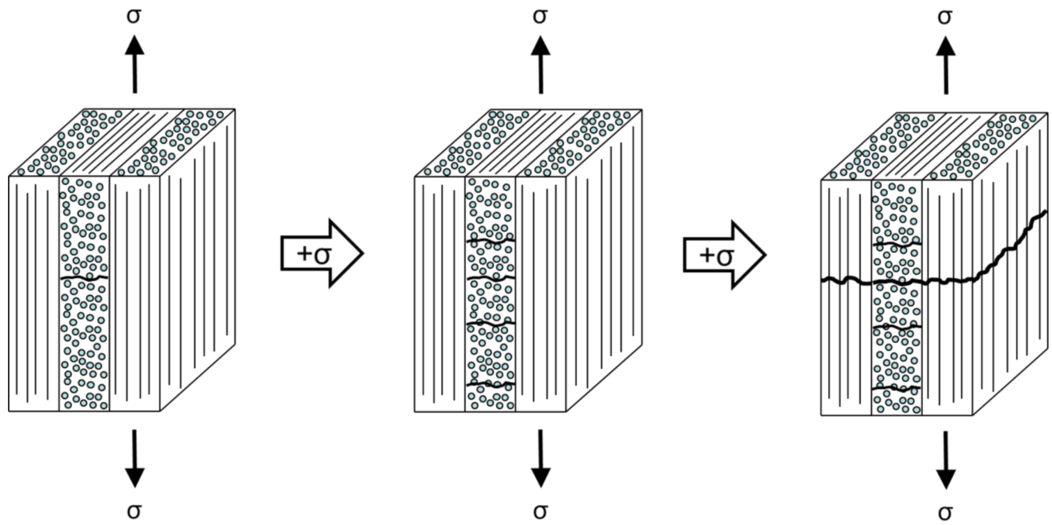
- The layup
  - Quasi Quasi-isotropic – $[0/45/90/-45]_s$
  - Hard – $[0_2/45/0_2/-45/0_2/90/0_2]_s$
  - Soft – $[\pm45/0/\pm45/90/\pm45/0/\pm45/90]_s$
- … and the structure
  - Open-hole coupon
  - Fuselage
  - Tube
- … and the environment
  - Elevated temperature
  - Exposure to cryogens
- … and
  - Fatigue
  - Thermal cycling
  - Impacts

Although the list above may make the problem of analyzing failure in composites seem intractable, we must simplifiy the problem and realize that failure occurs in the fiber or the matrix. In other words, failure occurs in the constituents. Let's consider failure modes for unidirectional composites. The following are possible modes:

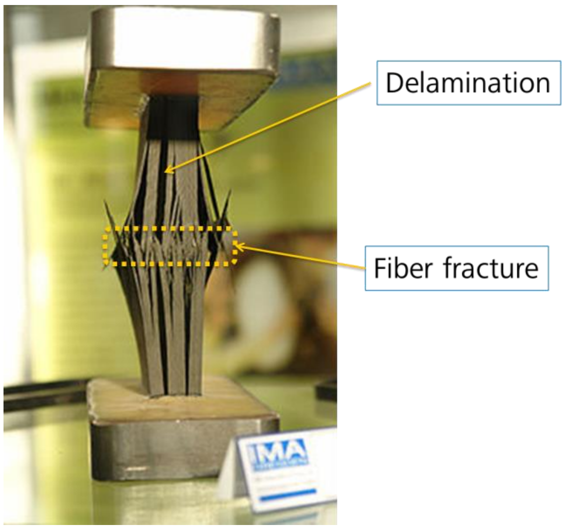
- Fiber pullout – this is when the fiber debonds from the matrix
- Microcracking in the matrix
- Fiber fracture in tension
- Fiber buckling in compression

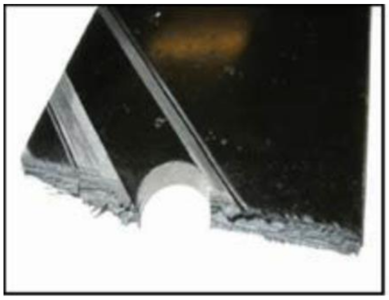
At the laminate level, the progression of failure for an axially loaded cross-ply laminate is illustrated below. Here, microcracks first appear in the matrix due to tension and as the load increases more microcracks form until the matrix is saturated with cracks and the fibers fail in the adjacent plies.

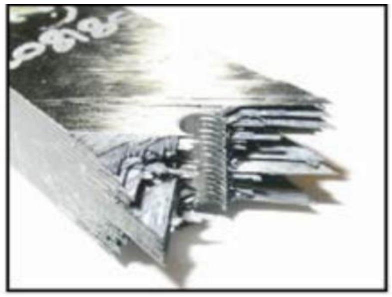


The above are examples of failure that occur within the ply (intra-ply failures). Failure can also occur between plies (known as inter-ply failures). The most common form of inter-ply failure is **delamination**. As a structure undergoes failure, both forms of damage are usually present.



Shown below are examples of failure modes for an open-hole plate.


Fiber tensile

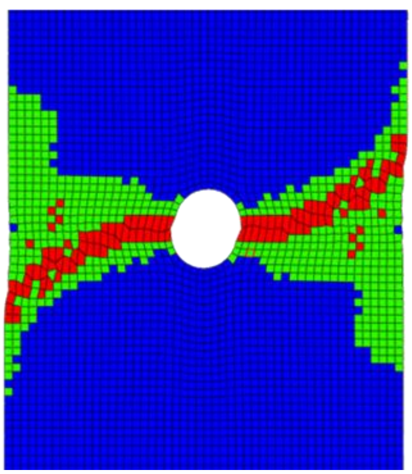

Fiber pull-out

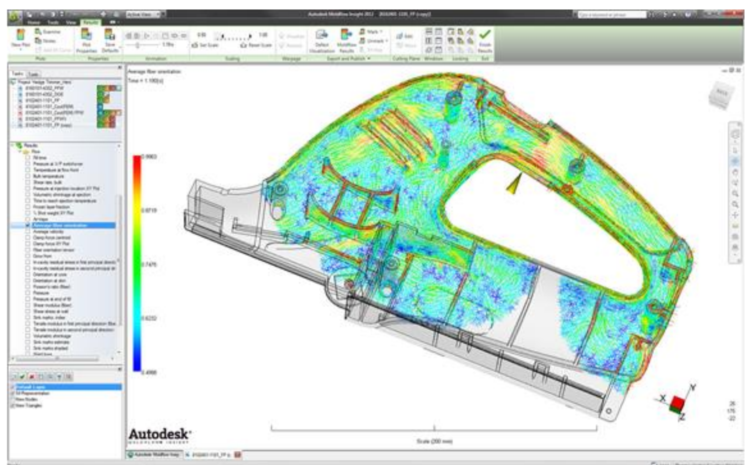

Delamination

Song K., Li Y., and Rose C.A., "Continuum Damage Mechanics Models for the Analysis of Progressive Failure in Open-Hole Tension Laminates", 52nd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, 2011.

Simulation of Composite Structures

How does one analyze a composite structure? It should be clear by now that composite structures are complex, therefore any type of analysis is greatly aided by computational methods. The finite element method (FEM) is widely used in the analysis of composite structures. The FEM can be used to simulate the stiffness, stresses/strains/deformations, and local and global failure of composite structures. Software tools can also be used to simulate manufacturing techniques such as the flow of injected composites.



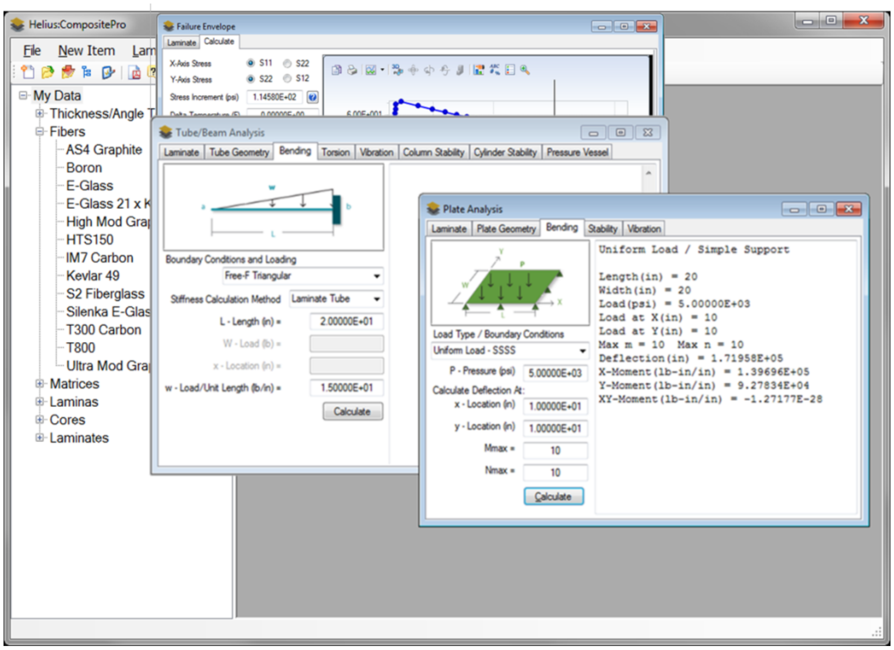


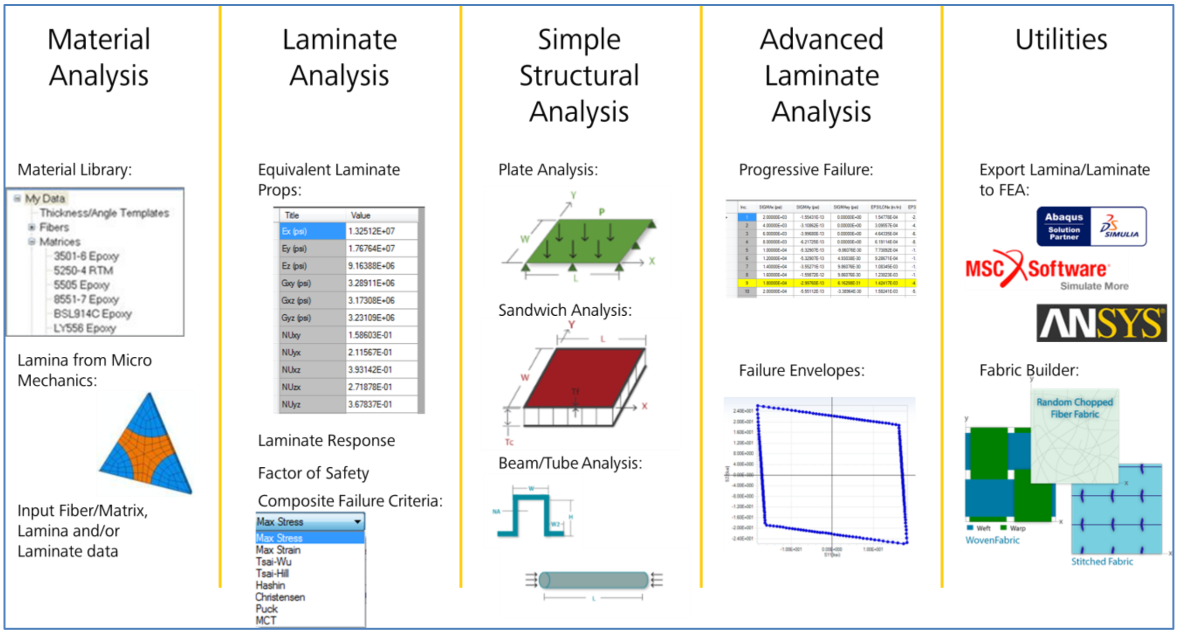
Composites Simulation Software by Autodesk

Autodesk has several software tools that are designed to help with the design, manufacture, and analysis of composites. For design, we offer Autodesk Simulation Composite Design 2014 (ASCD). Manufacture of composites is the focus of Autodesk Simulation Moldflow Advisor 2014 (Moldflow). Finally, analysis is handled by Autodesk Simulation Composite Analysis 2014 (ASCA).

Autodesk Simulation Composite Design 2014

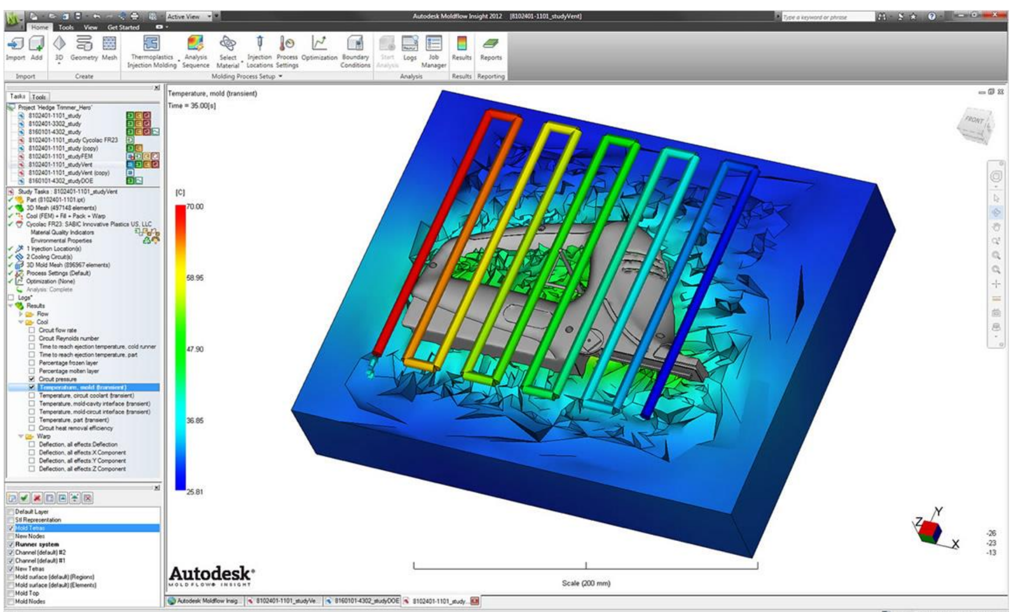
ASCD 2014 is used to perform preliminary design of composite structures. It is a standalone desktop application that includes a composites material library, can perform analysis of laminates and simple structures, and includes several composite design utilities.





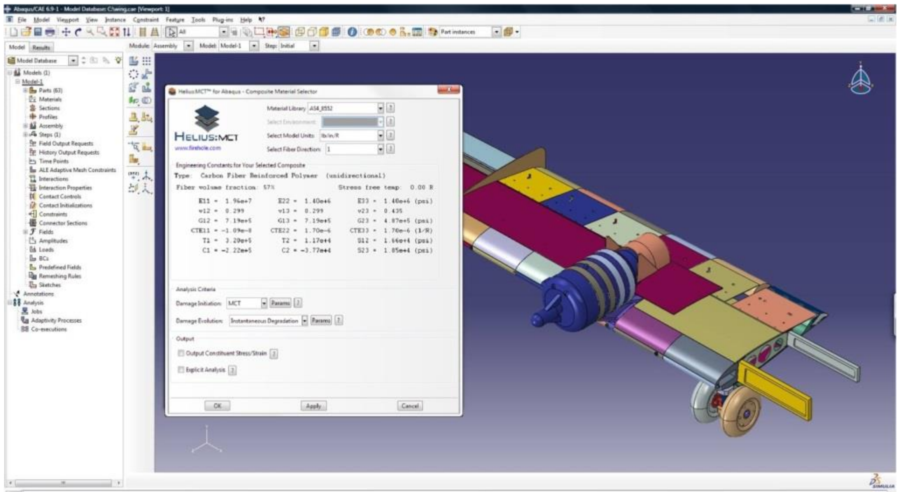
Autodesk Simulation Moldflow Advisor 2014

Moldflow simulates the manufacture of injected molded composite parts. Popular features include the ability to determine temperature variations, simulation of the fiber orientation, shrinkage and warpage predictions, and thermoset flow simulation.



Autodesk Simulation Composite Analysis 2014

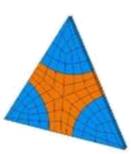
ASCA 2014 is a plug-in for finite element analysis software. The principal feature of ASCA 2014 is the simulation of damage in composite structures. It uses Multi-Continuum Technology (MCT) to extract stresses and strains in the fiber and matrix constituents, which provides a finer resolution than other composites analysis tools. Both inter-ply (delamination) and intra-ply (fiber and matrix) failure mechanisms are captured.

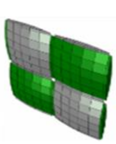


Material Management

Characterized constituent behavior from lamina inputs:

- Uses an iterative micromechanics based solver to calculate "in-situ" properties.
- Calculates constituent nonlinearity from lamina inputs.



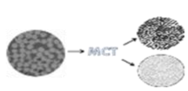


Multiscale Analysis

Multiscale analysis allows constitutive relationship to be applied where they are most accurate, at the constituent level, rather than the homogenized lamina level.

Microstructural support for:

- Unidirectional
- Plain Weave
- 5H Satin Weave
- 8H Satin Weave
- Delamination



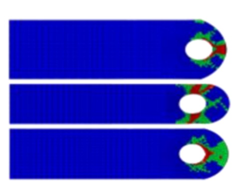
Failure, Damage & Fatigue

Eight failure criteria offered:

- MCT
- Hashin
- Puck
- Christensen
- Tsai-Wu
- Tsai-Hill
- Max Stress
- Max Strain

Models for damage tolerance & delamination.

$$\pm A_1^f \left(I_1^f\right)^2 + A_4^f I_4^f = 1$$



Material Nonlinearity

Material nonlinearity is Helius:MCT's specialty:

- Robust algorithms to greatly improve convergence
- Multiple material models
  - Brittle unload
  - Strain softening
  - Crack accumulation
  - Ductile softening