SM1933 - Introduction to Composite Materials

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Class summary

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.

Key learning objectives

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

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

Understanding Composite Materials

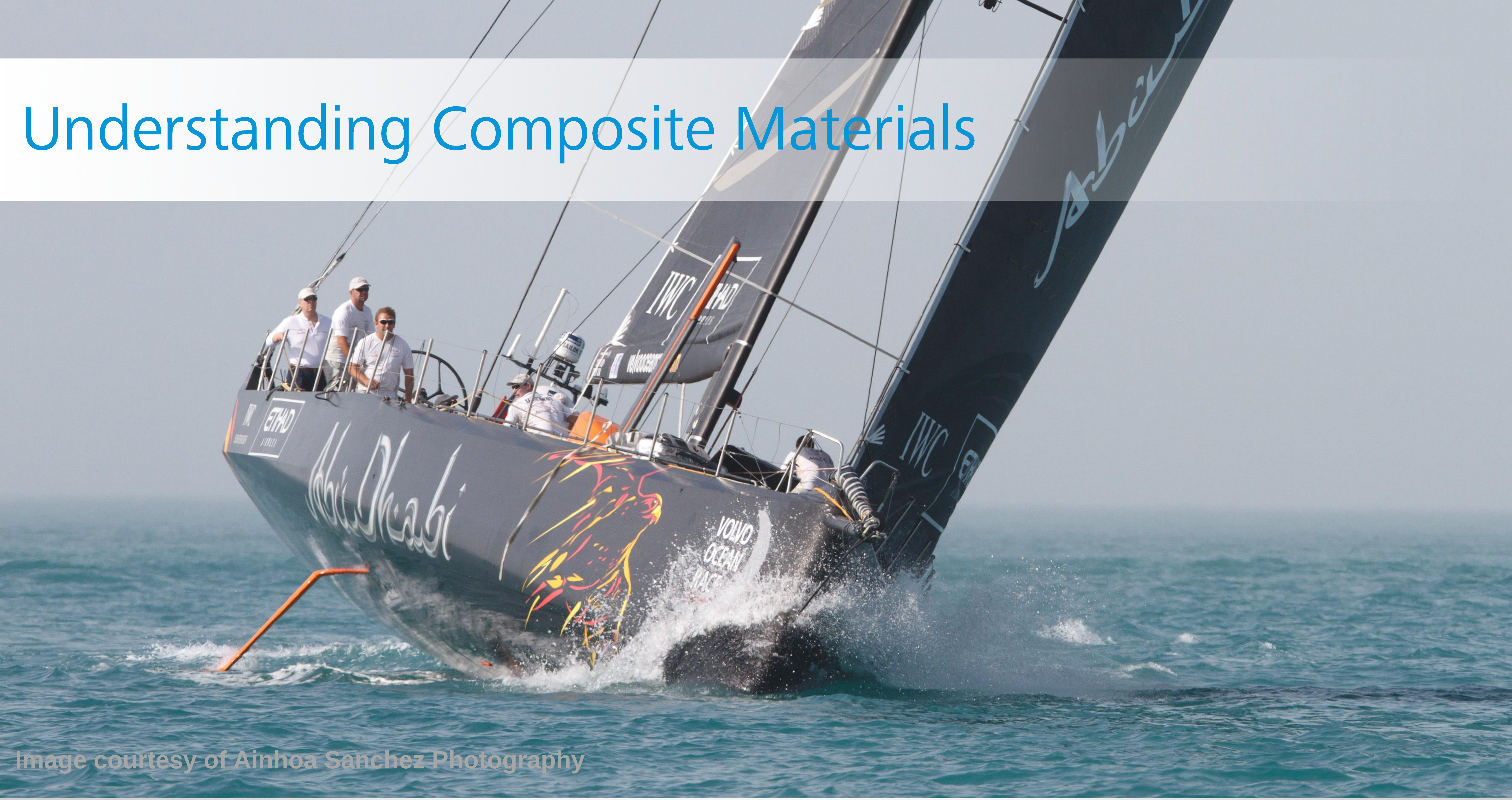
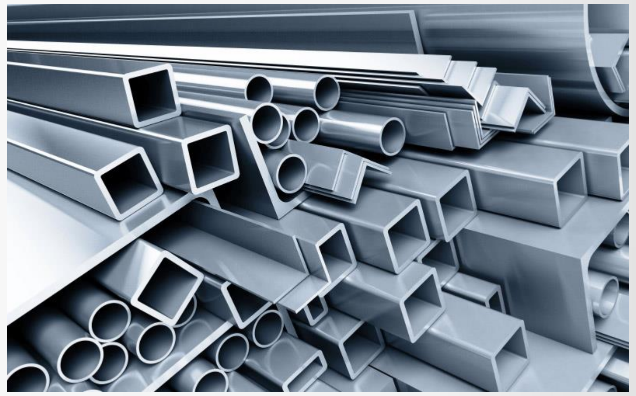


Image courtesy of Ainhoa Sanchez Photography

Definition

- A composite material is most generally defined as a material that is made from two or more different materials
- According to this definition, the following are examples of composite materials:
  - Steel (iron + carbon)
  - Carpet (backing fabric, yarn, glue, …)
  - Duct tape (cloth + tape …)



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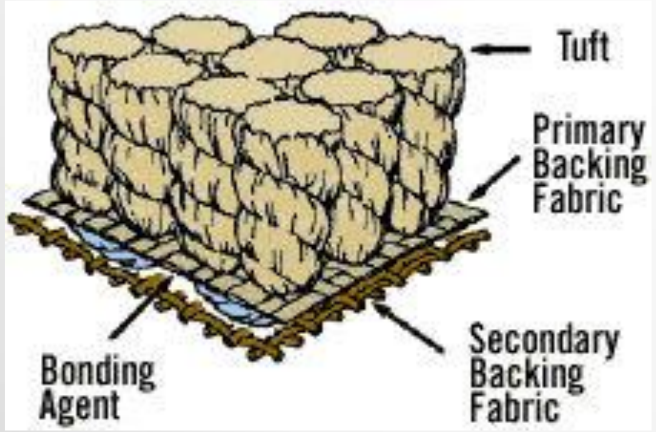

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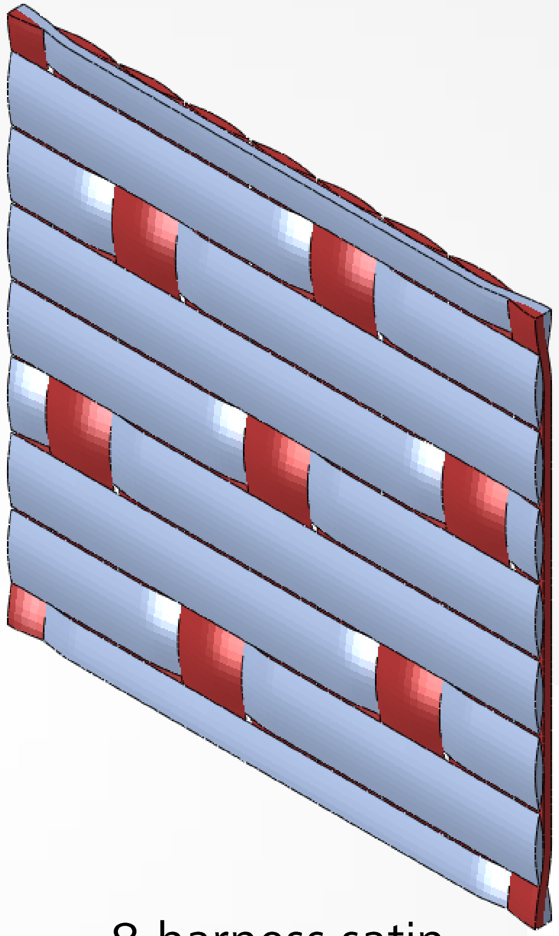
Definition

- Our definition is more specific:
  - A composite material is an *engineered* material that contains two or more clearly distinguishable constituents with significantly different properties

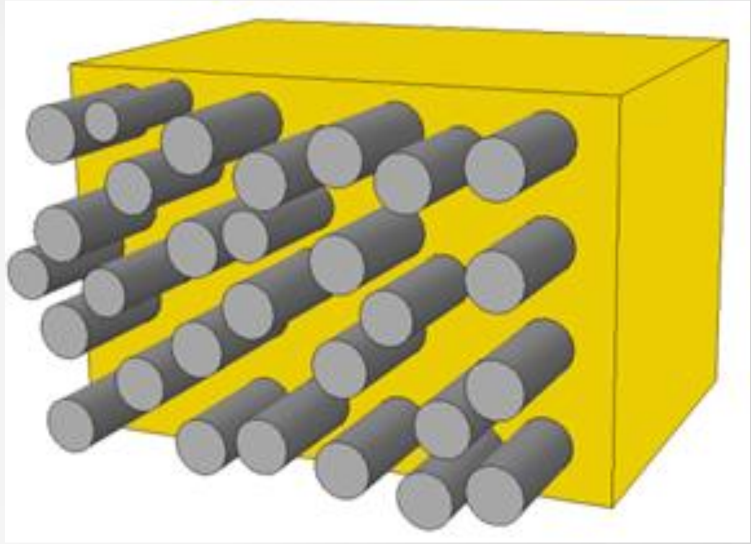
- The focus of this presentation will be on fiber-reinforced matrix composite materials

Fiber-Reinforced Composite Materials

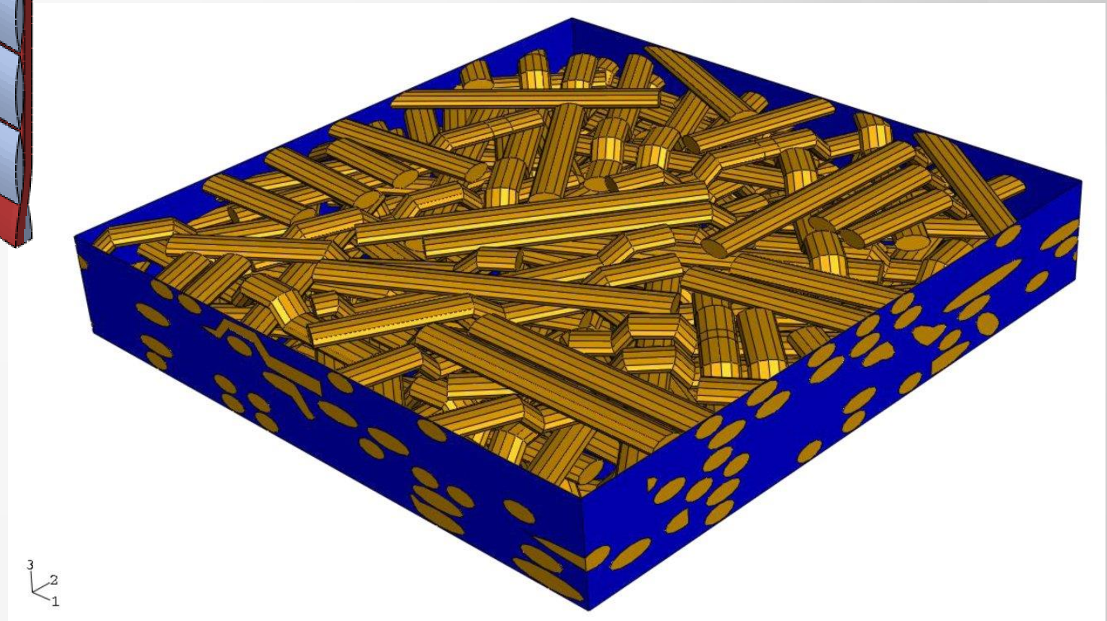
- Consist of:
  - Fiber
    - Carbon, glass, Kevlar, ceramic
    - Provides strength and stiffness
  - Matrix
    - Thermoset, thermoplastic, metal, ceramic
    - Provides support for the fibers (inhibits buckling of the fibers)
  - Microstructure
    - Unidirectional, woven, chopped



8-harness satin



Unidirectional (continuous fiber)

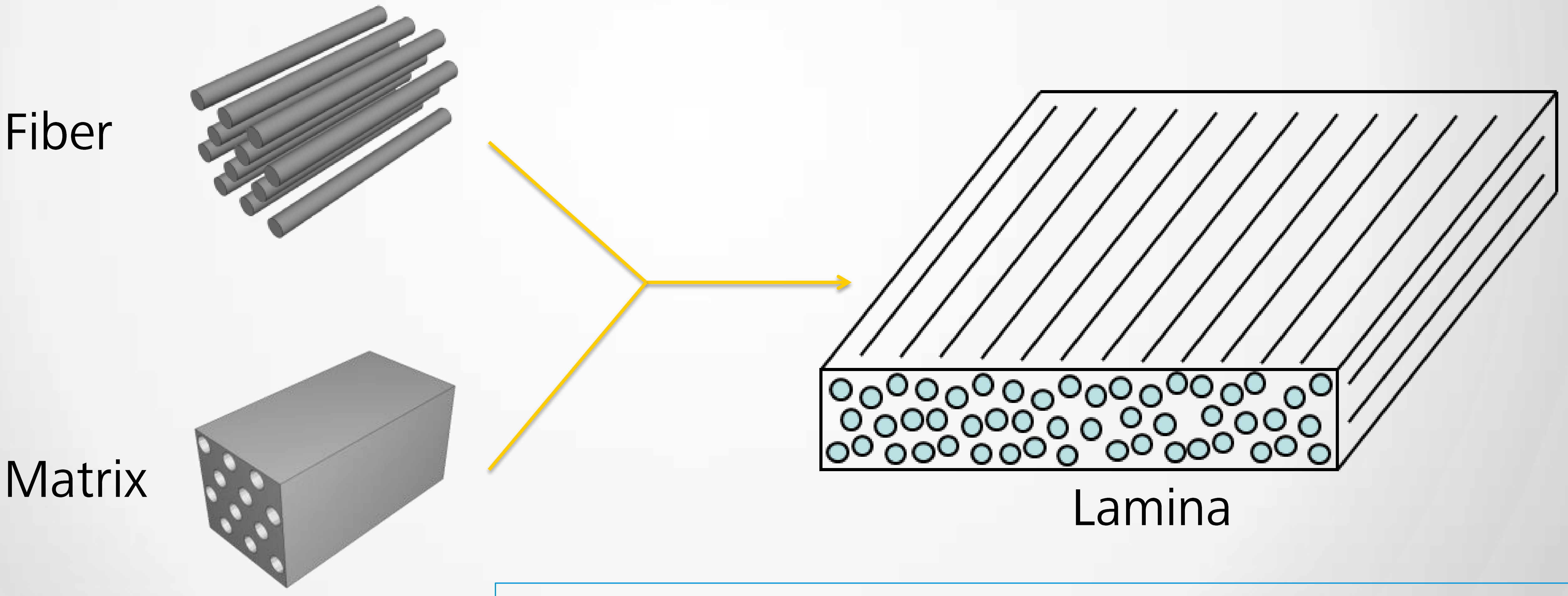


rci.rutgers.edu/~yipan/

Chopped (discontinuous fiber)

Building a Composite Structure - Lamina

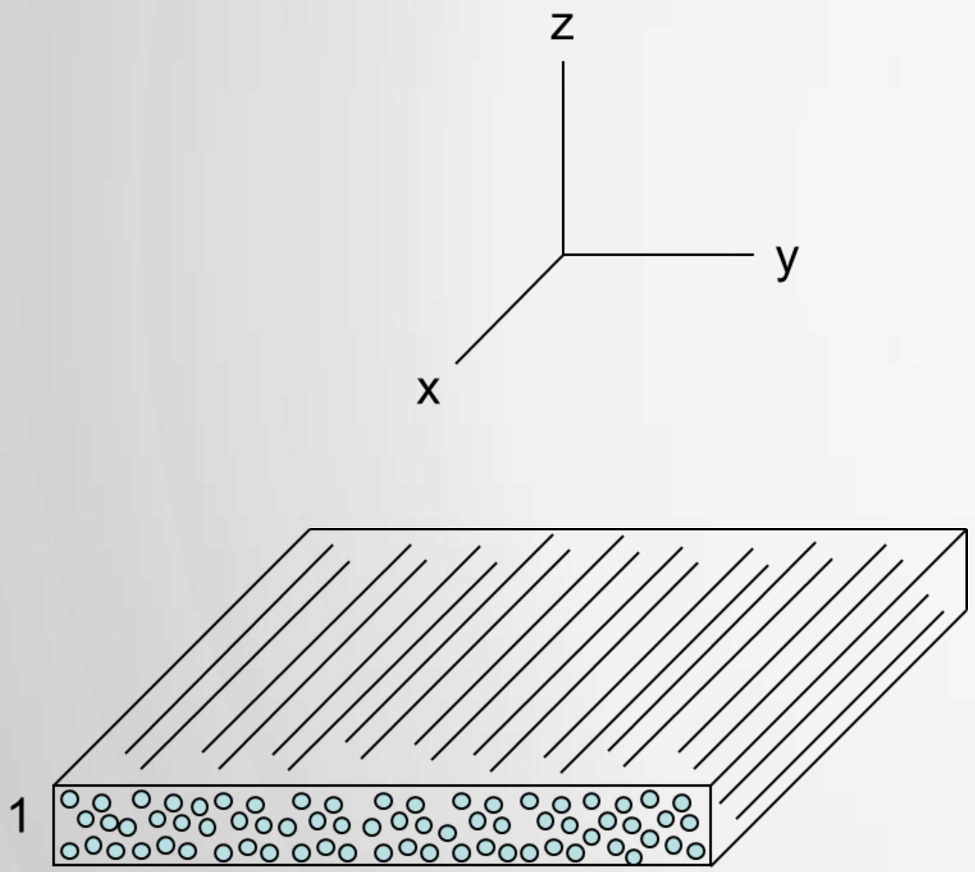
- The fiber and matrix material are the building blocks of an individual **lamina** (ply)



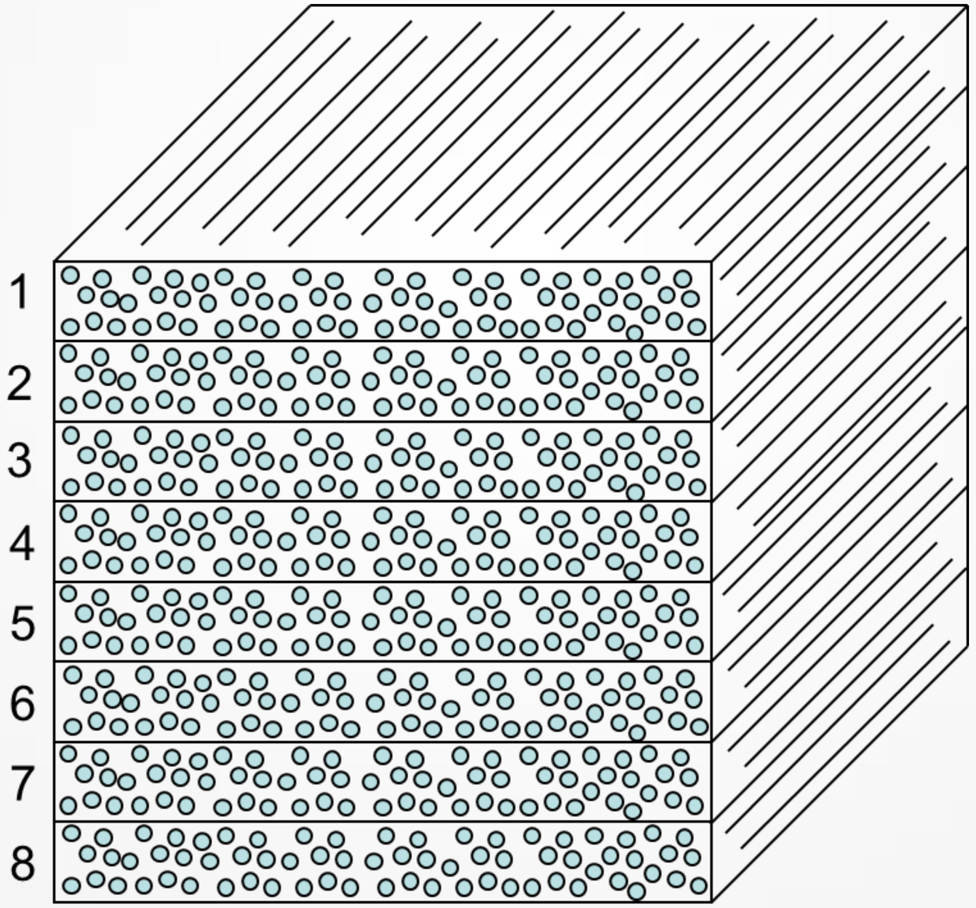
Fiber volume fraction: Volume of fibers relative to volume of lamina

Building a Composite Structure - Laminate

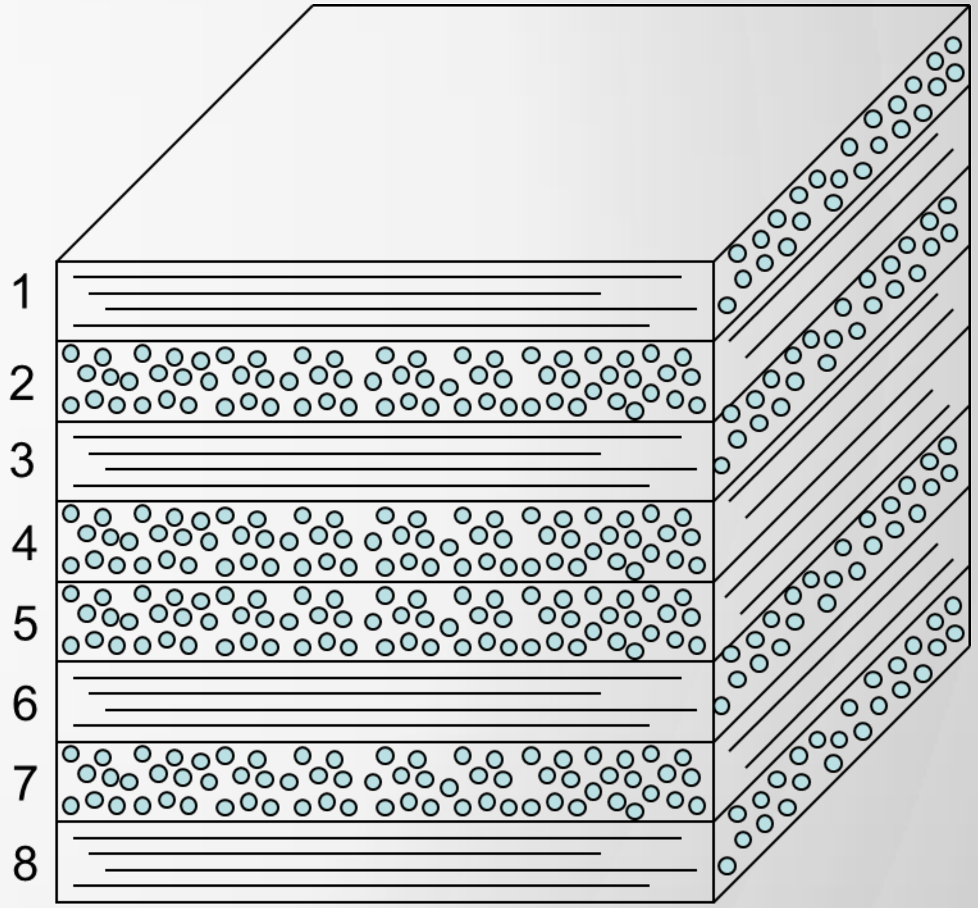
- A **laminate** is a sequence of laminas that are stacked at various orientations



Unidirectional lamina



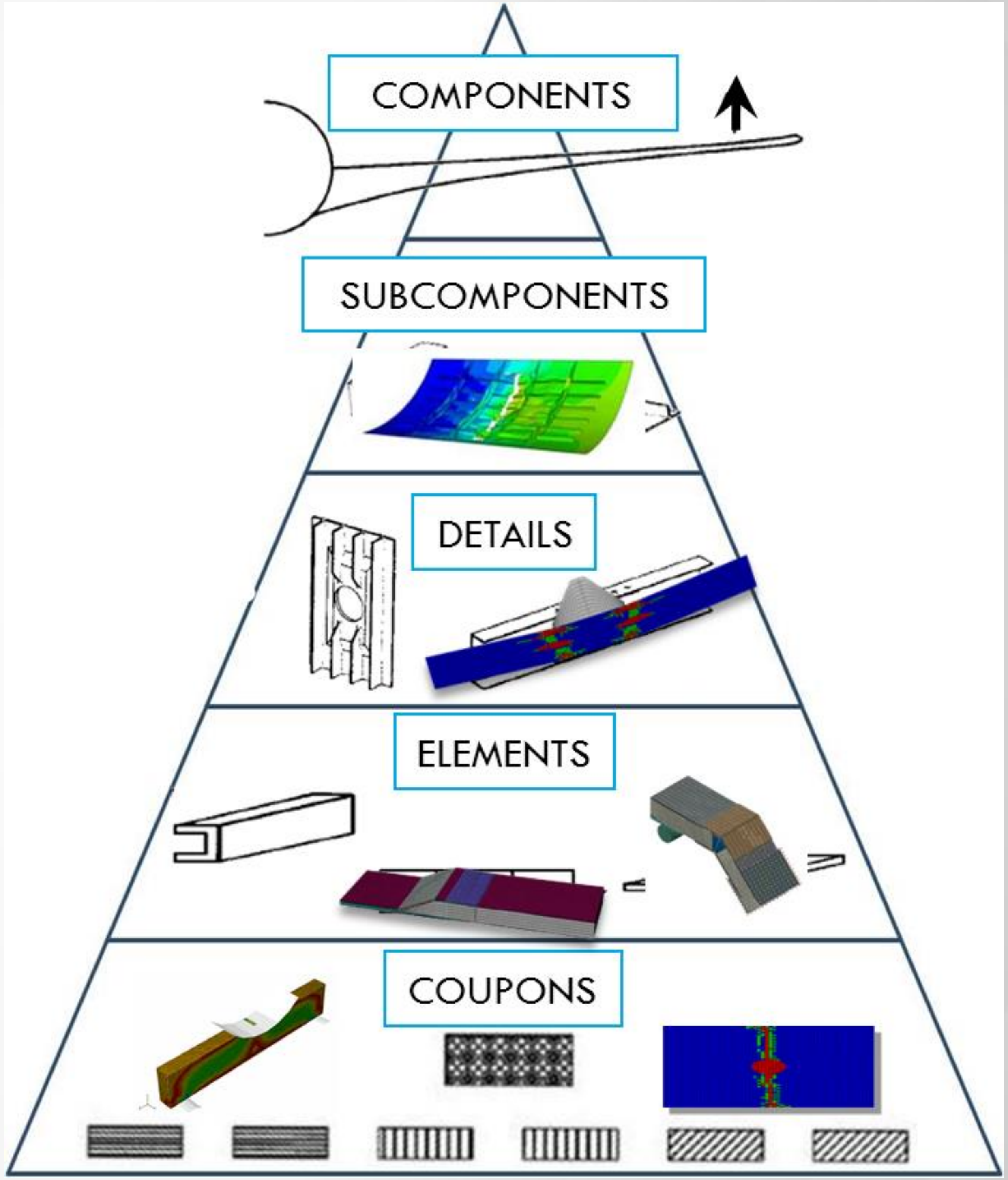
Unidirectional laminate



Cross-ply laminate

Building a Composite Structure – The Structure

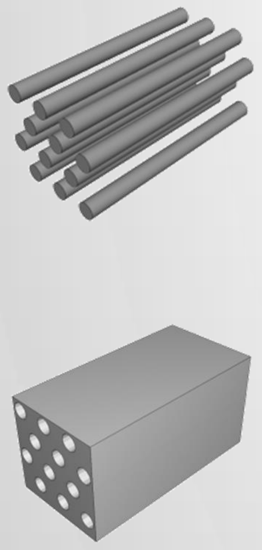
- Finally, a combination of laminates is used to build a composite structure



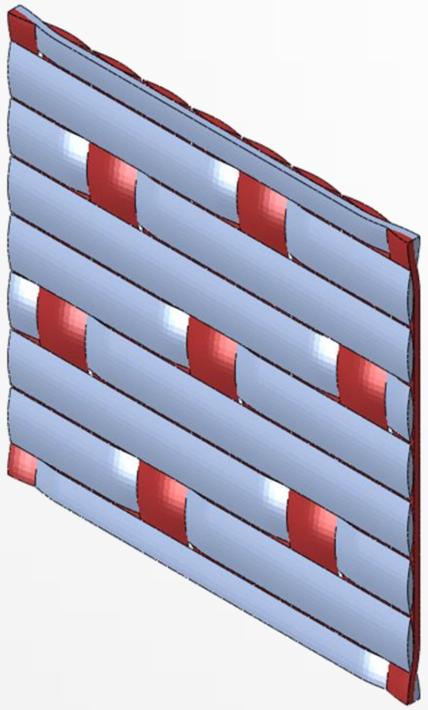
Review

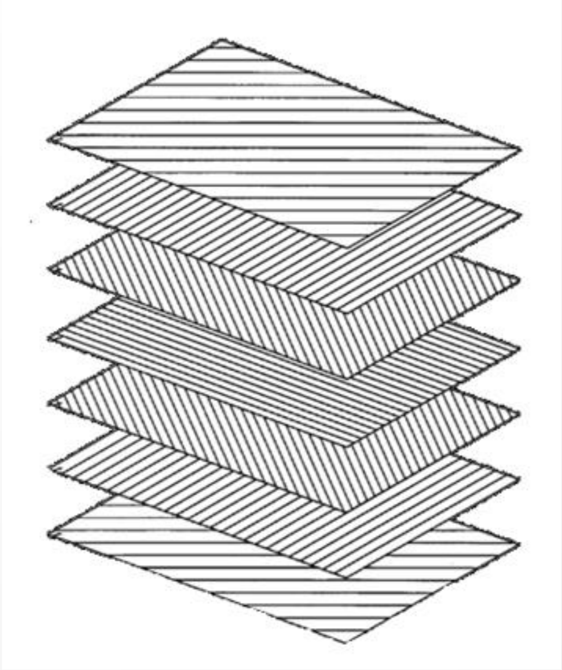
Fiber
+
Matrix
+
Microstructure

→ Lamina → Laminate → Structure



8-harness



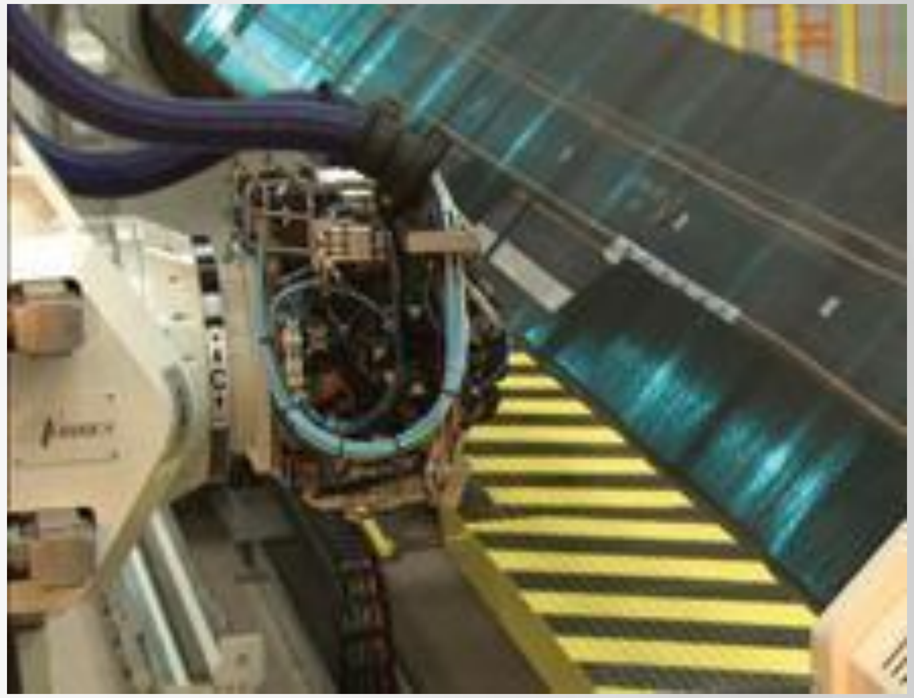


www.compositesworld.com

Manufacturing Methods

- There are many methods for fabrication
  - Choice depends on cost, application, material form
- Common methods
  - Hand lay-up
  - Filament winding
  - Tape placement
  - Injection Molding
  - Spray-up
  - Forming

gdecotech.com



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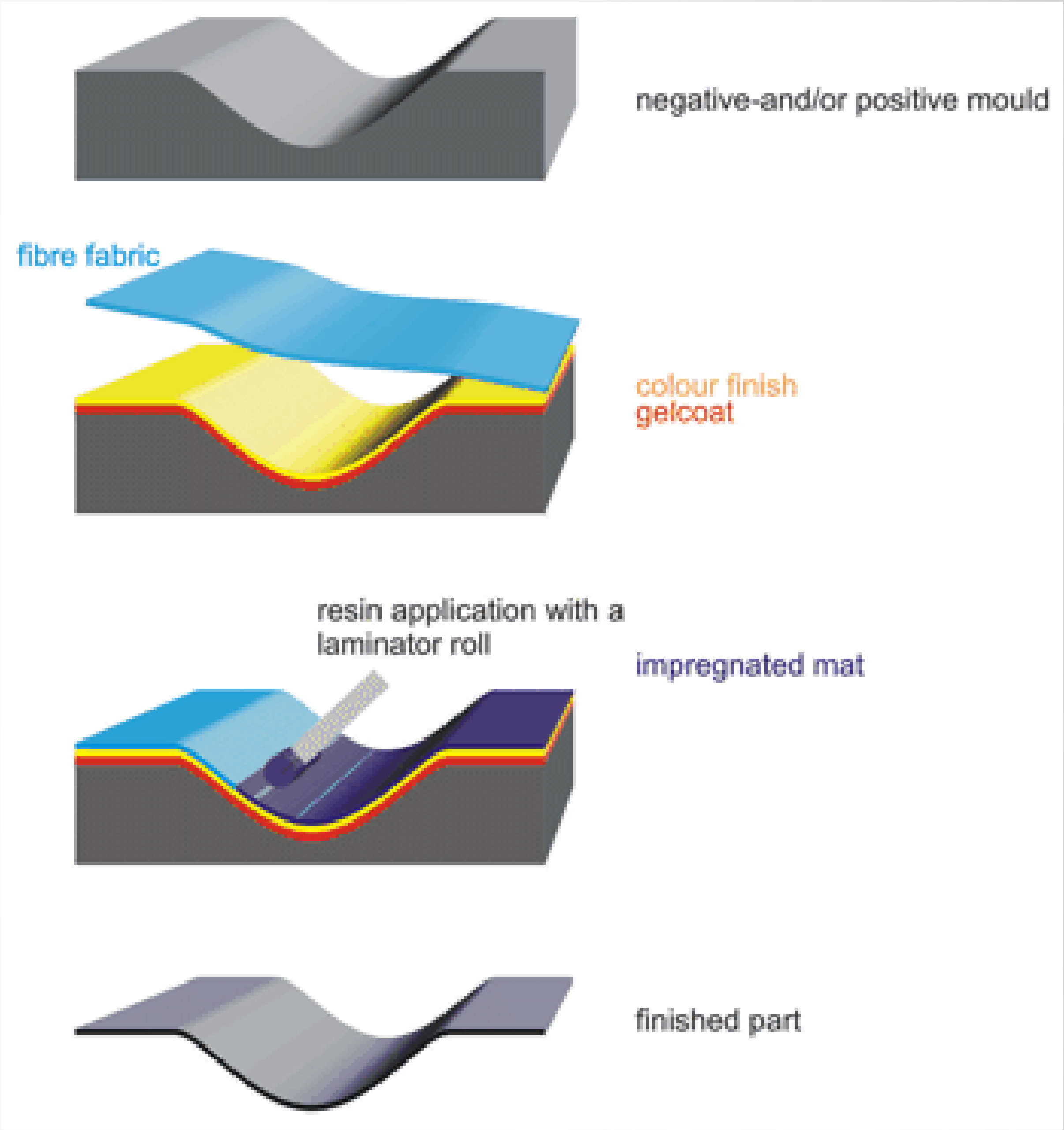
Hand Lay-Up (Wet Lay-Up)

- Fiber layers are manually placed onto mold
- Resin is applied by spraying, pouring, or rolling
- Often vacuum bagged during cure
- Labor intensive
- Inconsistent fiber volume fraction



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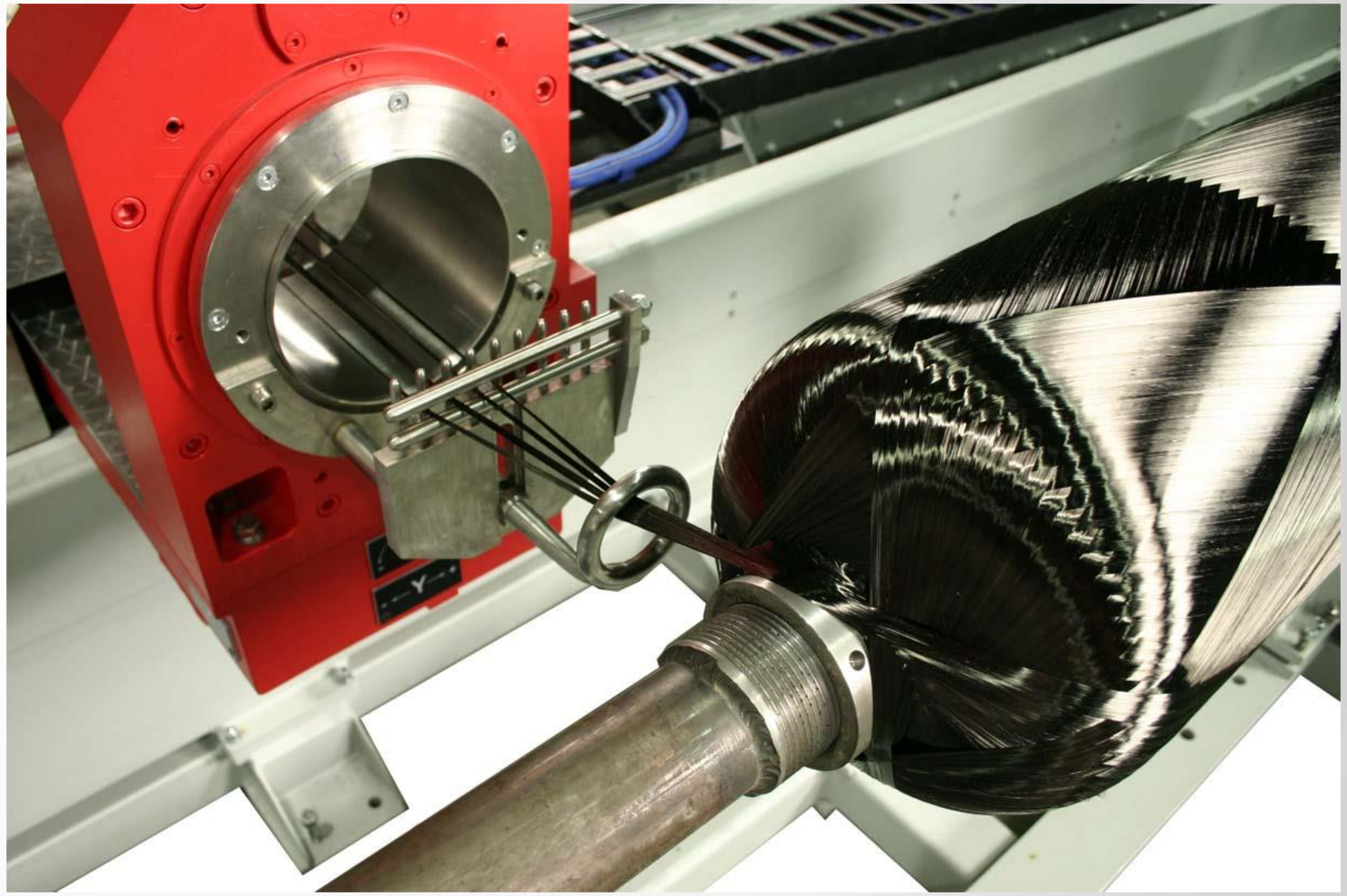
Filament Winding

- Fibers are wound around spinning mandrel
- Fibers pre-impregnated with resin or pass through resin bath prior to winding
- Automated process with good orientation control
- Commonly used for pressure vessels



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Tape Placement

- Strips of composite “tape” are laid onto a mold by a computer controlled machine
- High output rates
- Precision applications
- Used heavily in aerospace

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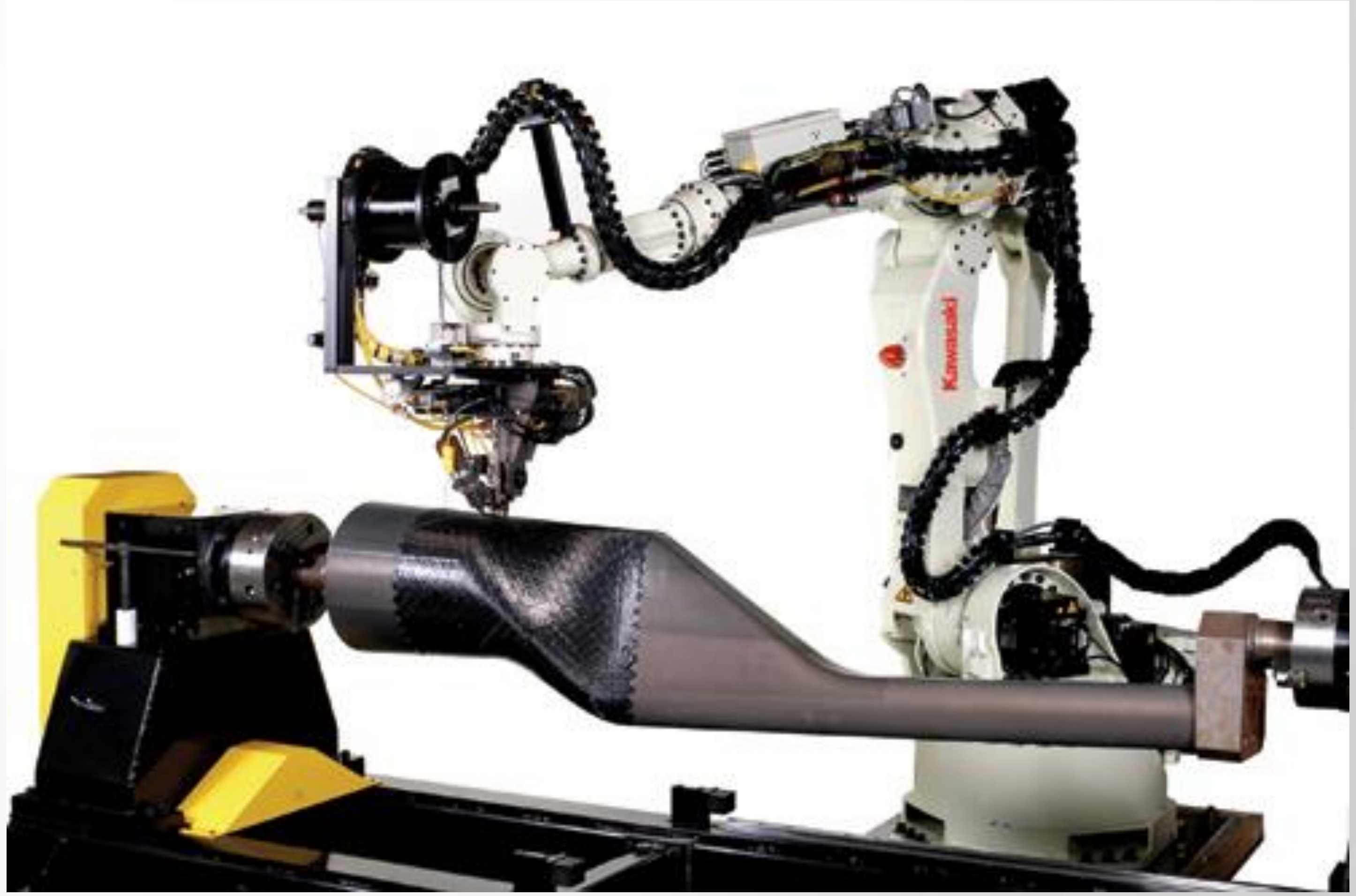

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Injection Molding

- Chopped fibers and resin are injected into a closed mold
- High volume
- Mainly used for smaller components

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Spray-Up

- Chopped fibers and wet resin are applied to a mold using a spray gun
- Faster and cheaper than hand lay-up
- Wide variation in mechanical properties


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Forming/Molding

- Continuous fiber, fiber weave or fabric is placed into a mold with resin, then mold is closed and held under pressure until cured
  - RTM – Resin is injected into the mold under pressure
  - VARTM – Resin is drawn into mold with vacuum
- Can create Class A finish
- Low cycle times
- Lower cost materials

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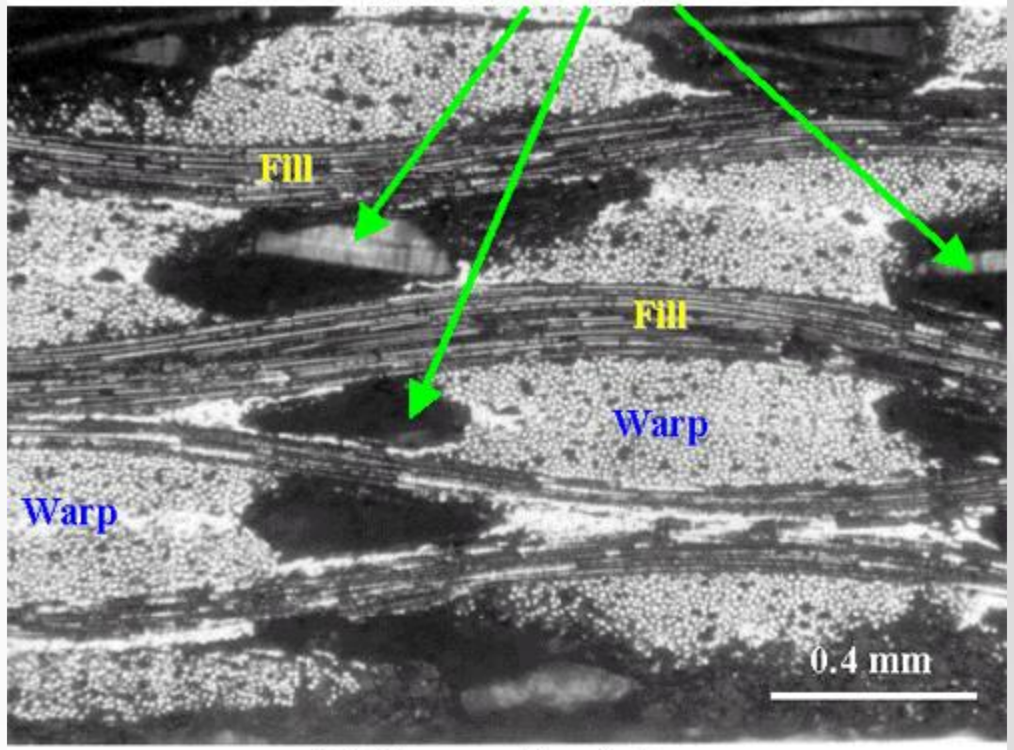
Quality of Manufacture

- There are many defects that can be introduced during fabrication
  - Voids
  - Ply-misalignement
  - Fiber waviness
  - Thickness variations
  - Inconsistent FVF
  - Incorrect cure (wrong temperature/pressure/duration)



(b) Cross-sectional view

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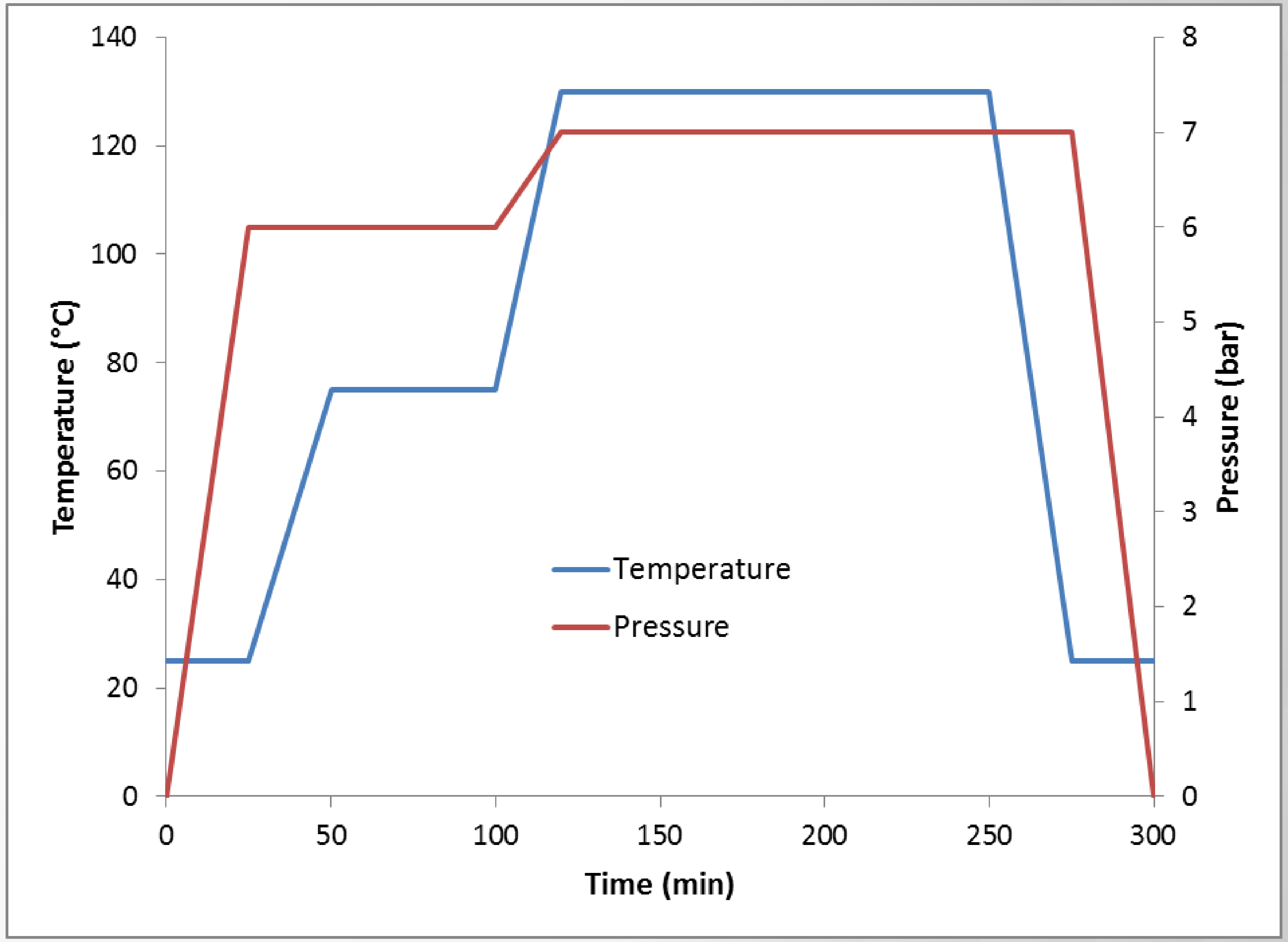
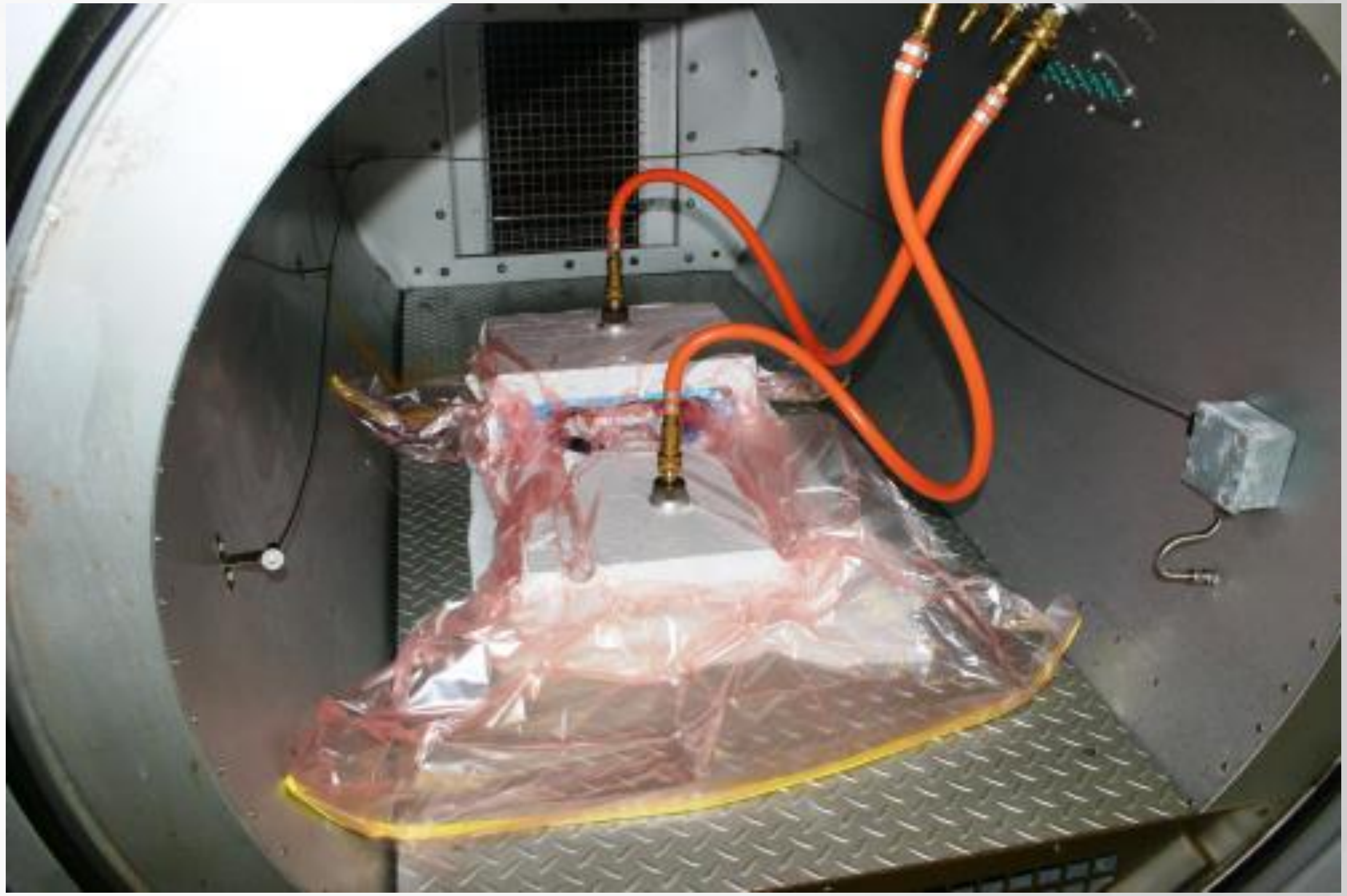
Cure Cycle

- Curing of a composite involves mechanical and chemical processes
  - Mechanical: Apply pressure to remove trapped air/voids and to compact the individual plies
  - Chemical: Apply temperature to initiate polymer crosslinking reaction



Cure Cycle – Autoclave vs OOA

- Autoclave
  - Part is vacuum bagged and placed into an autoclave
  - Pressure and temperature inside autoclave is regulated by cure cycle
  - High pressure => Low void content
- Out-Of-Autoclave (OOA)
  - Vacuum is applied to part (via bagging, closed mold) and heat/pressure are applied by means other than autoclave (oven, for example)
    - Example: RTM



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Why Composites?

Image: BMW i3 Electric Vehicle

Where are composites used?

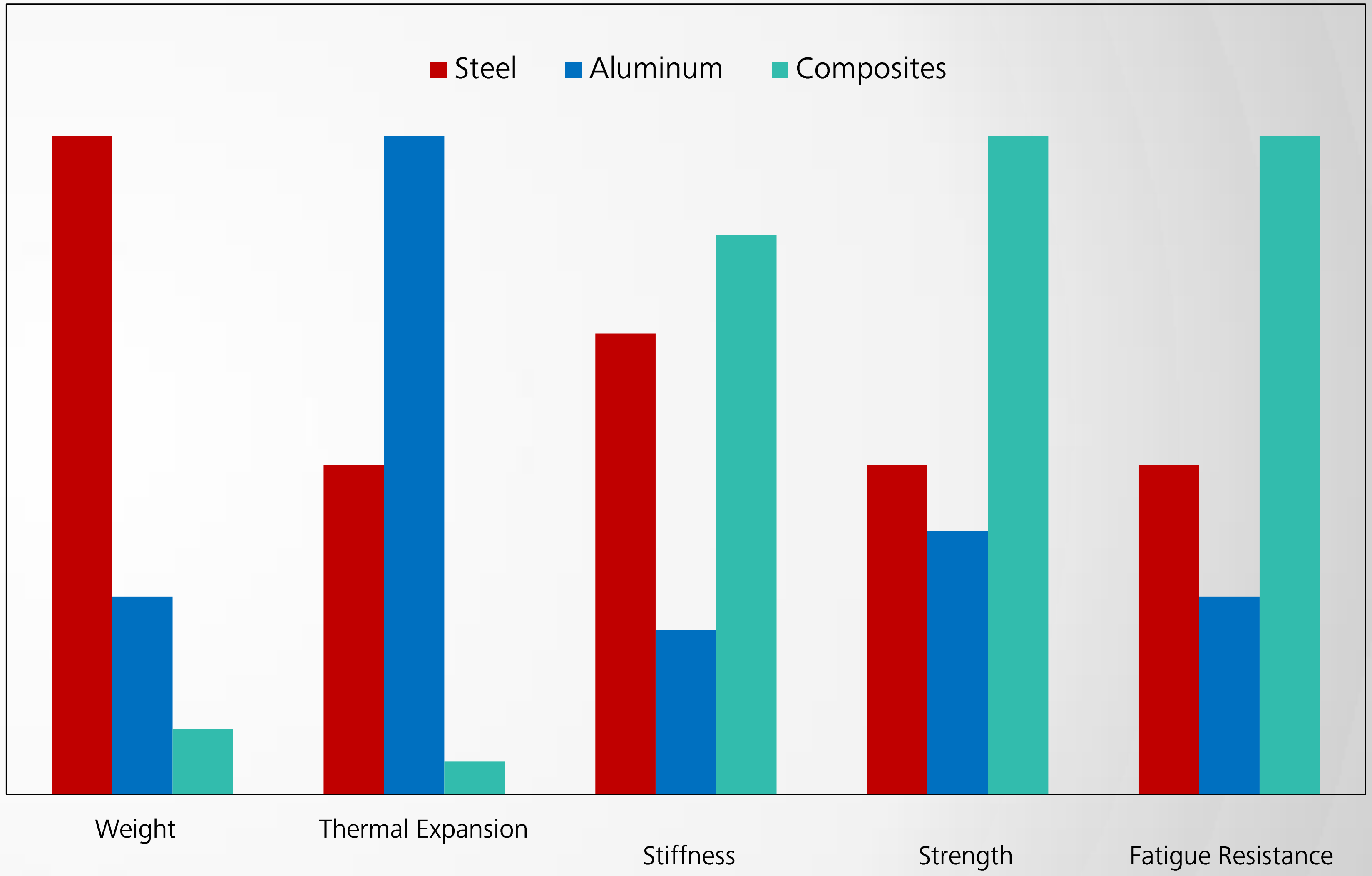
Personal & Leisure Goods

Aerospace & Defense

Automotive & Transportation

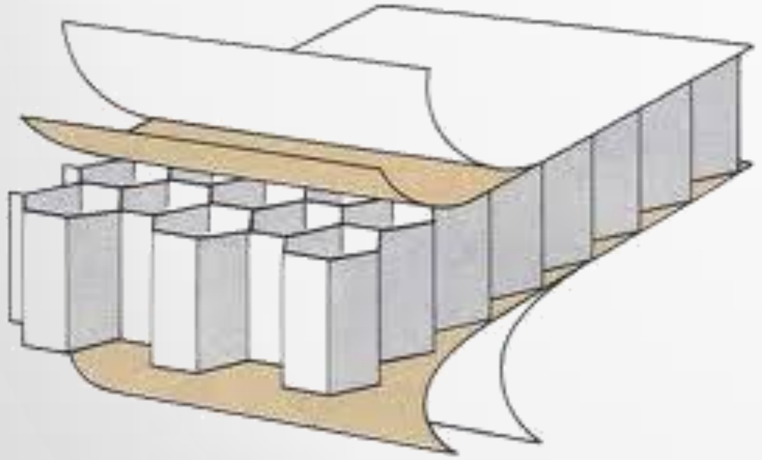
Infrastructure

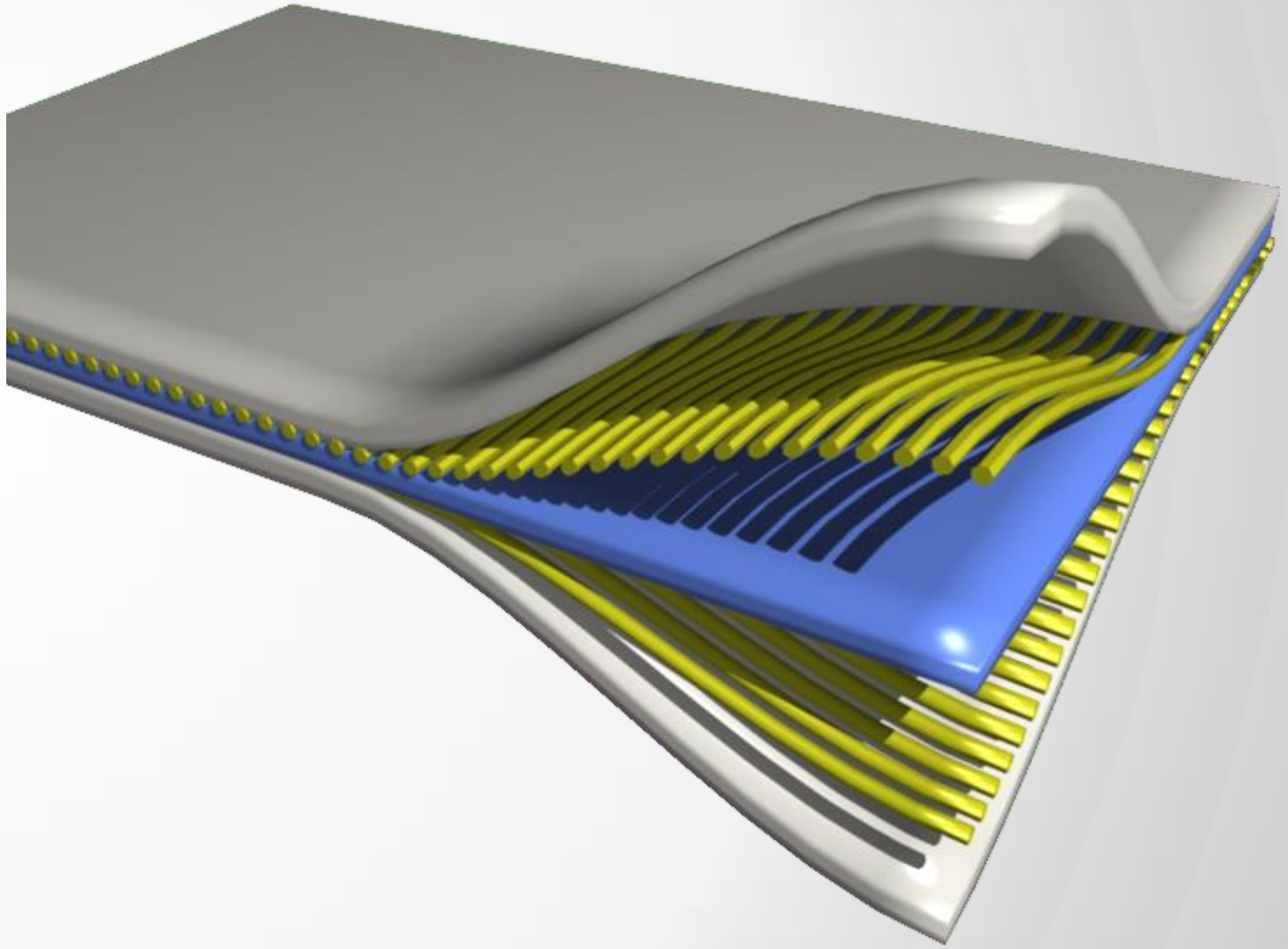
Why Composites? | Lightweighting



Why Composites? | Property Tailoring

- The orientation and stacking sequence of plies can be used to tailor the response of a laminate
  - Elastic properties
  - Failure modes
  - Nonlinear properties
- Can be used with other materials
  - Metal plies
  - Honeycomb plies (i.e. cores)





Why Composites | Manufacturing Advantages

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

Why Composites | Complex Geometries

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

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

Why Composites | Corrosion Resistant

Annual cost of metallic corrosion worldwide in 2012 was est. $2.2 trillion (USD)

- World Corrosion Organization (New York, N.Y.).

Scrubbers and chimneys that remove sulfur dioxide (SO2) from flue gas emissions in coal-burning plants
(Image: Plasticos Industriales de Tampico)

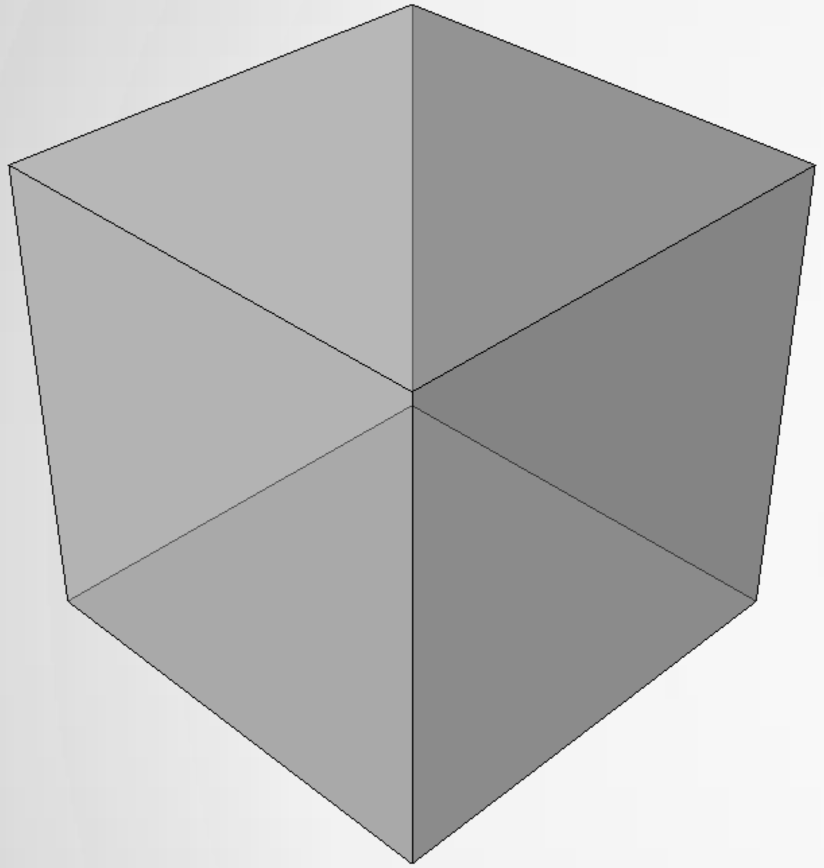
Cured-in-place pipe (CIPP) enables repair of deteriorating underground water/wastewater pipelines without expensive excavation.
(Image: Craftsman Pipilining)

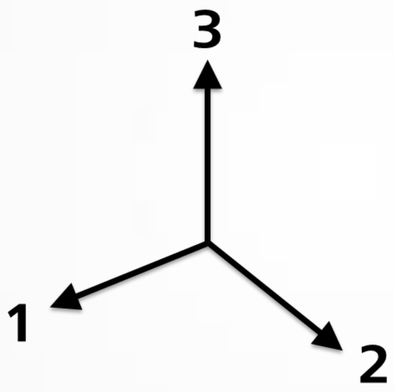
Composite Engineering Challenges

Image courtesy of Magna Steyr Design

Composites are Nonisotropic

Aluminum





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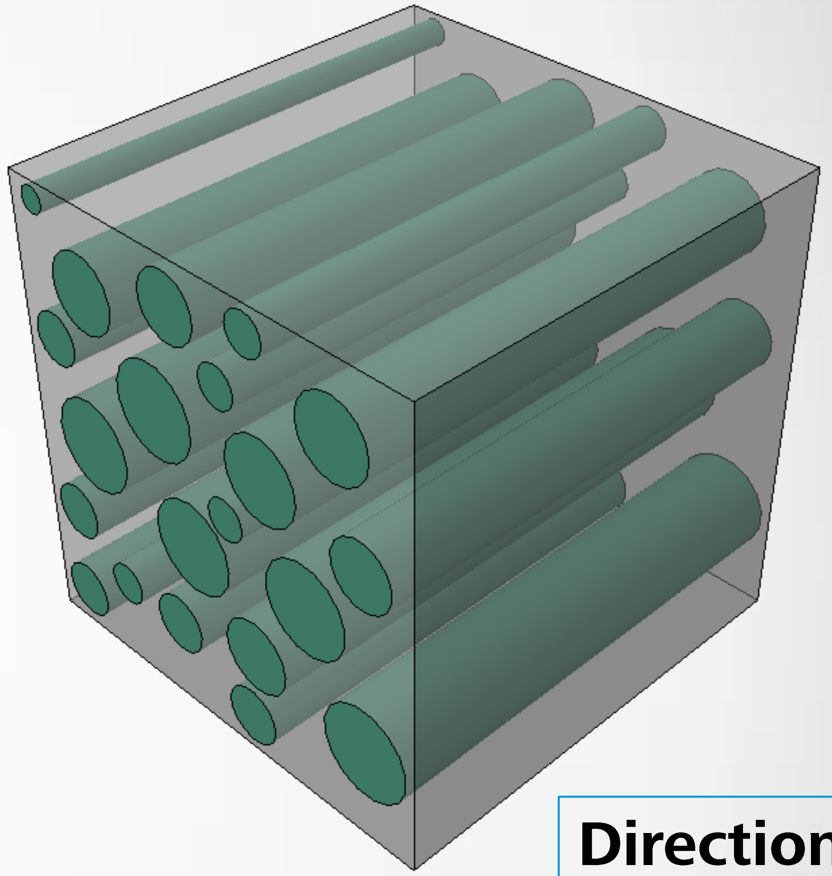


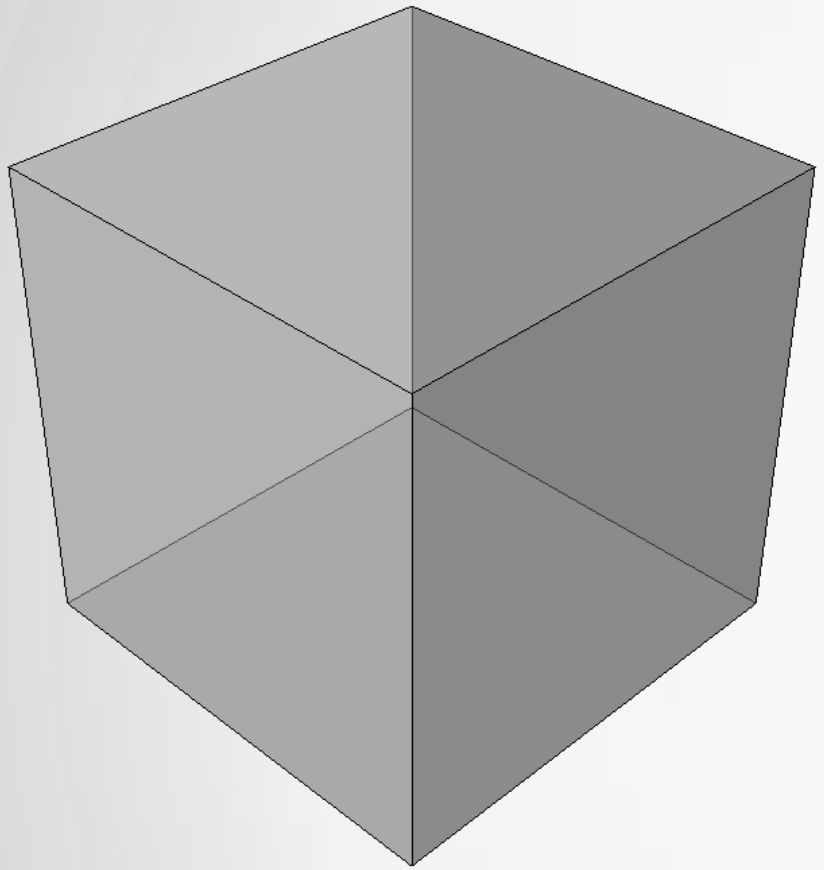
Directional dependence!

E = 1.0e7 psi
v = 0.33
G = 3.76e6 psi

E11 = 2.07e7 psi
E22 = E33 = 1.65e6 psi
v12 = v13 = 0.324
v23 = 0.461
G12 = G13 = 6.89e5 psi
G23 = 5.65e5 psi

Composites are Heterogeneous

Aluminum



Properties at ***any*** point are the same

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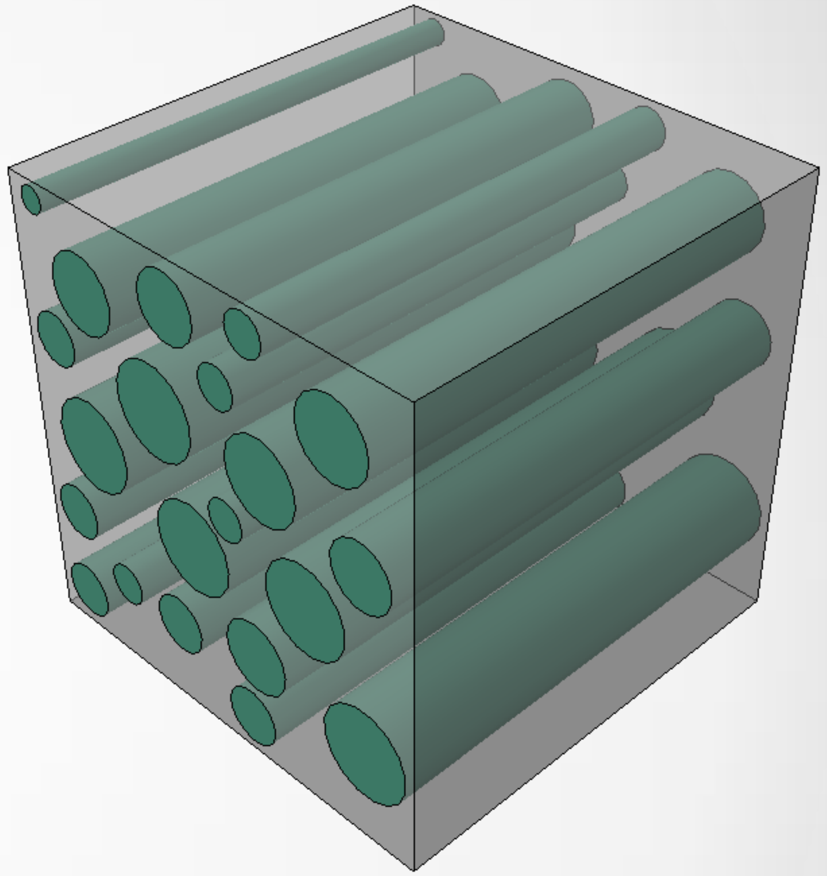


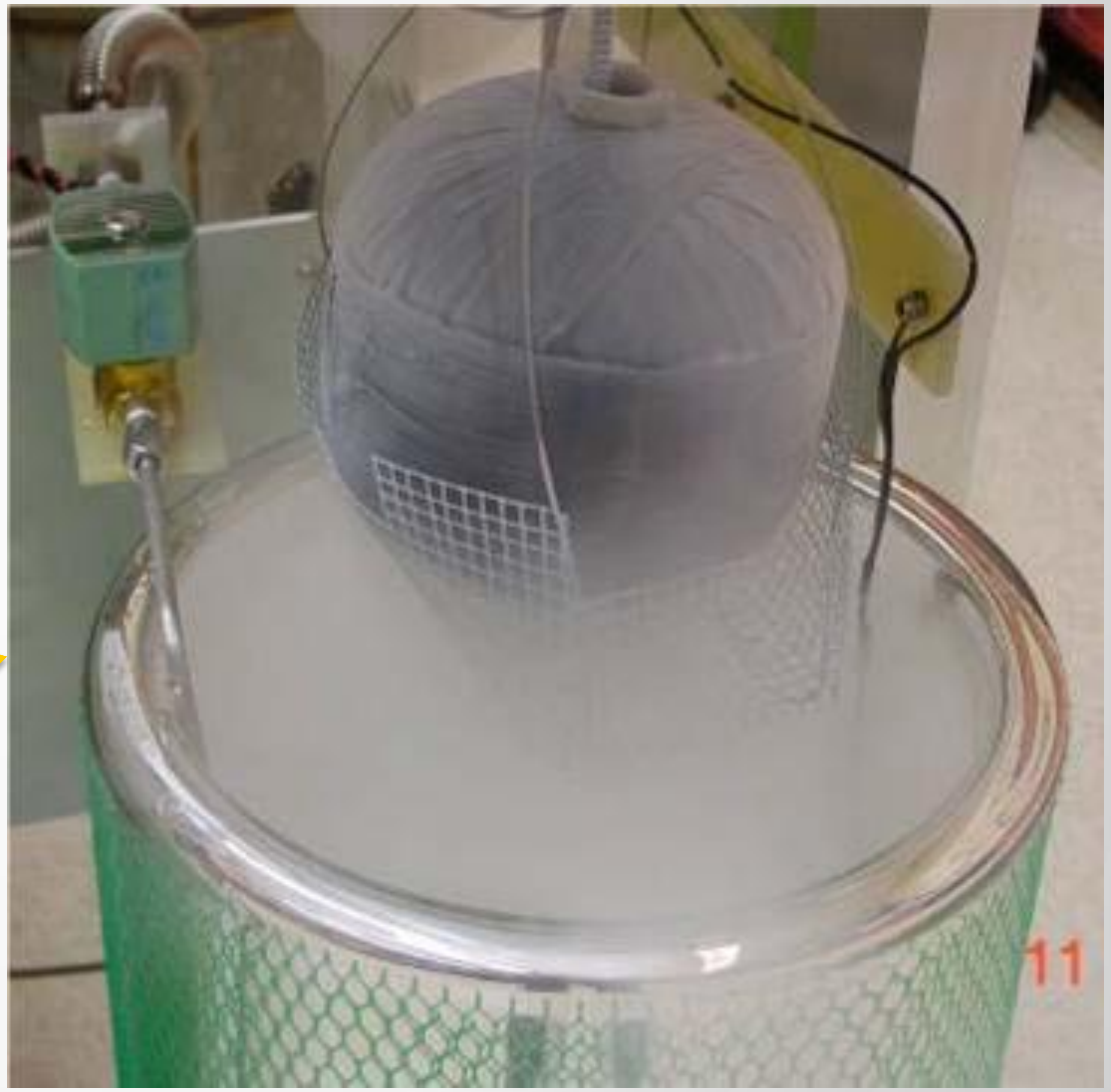
Fiber properties are significantly different than the **matrix** properties

Failure Modes

- Recall what we've discussed:
  - Endless combinations of fiber, matrices, and microstructures
  - Composites are nonisotropic and heterogeneous
- With this in mind, it is easy to understand that there are many failure modes for composites
- For example:
  - Unidirectional materials have different failure modes than woven materials
  - Toughened resins are much less brittle than non-toughened resins

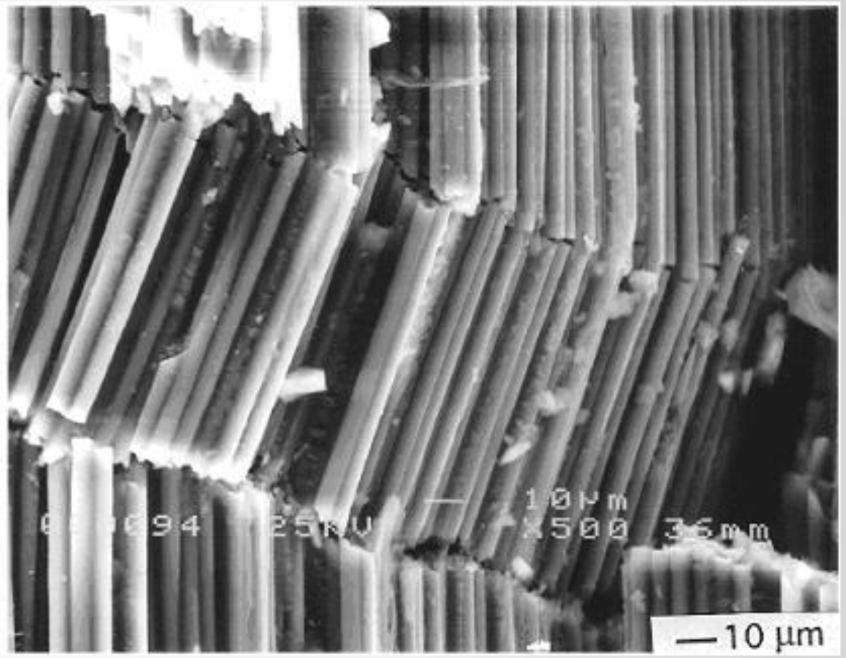
Failure Modes

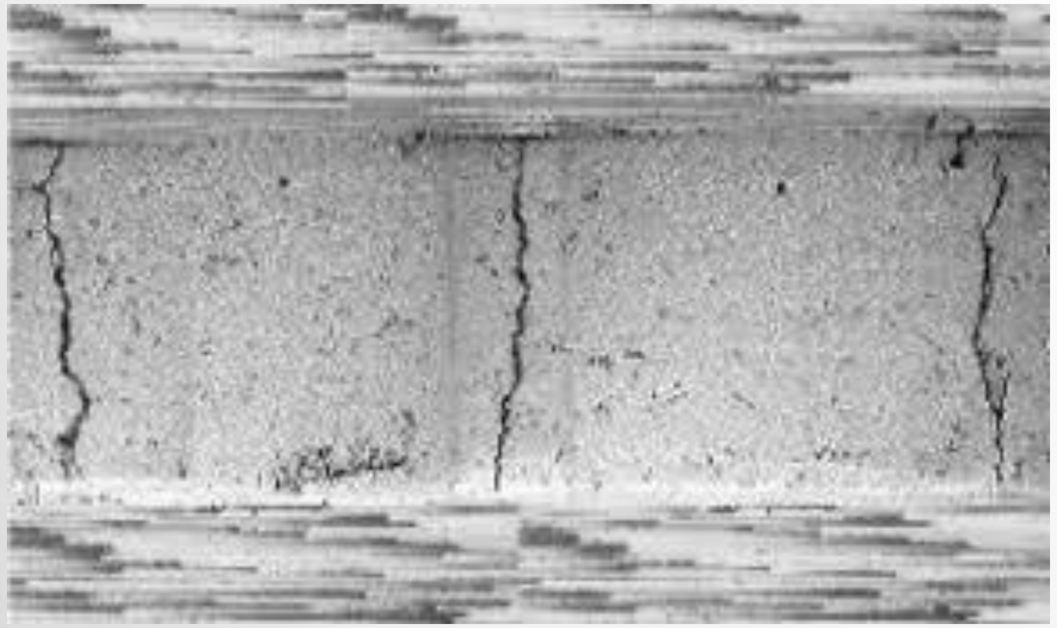
- The failure mode is further dependent on the layup
  - Quasi-isotropic – $[0/45/90/-45]_s$
  - Hard – $[0_2/45/0_2/-45/0_2/90/0_2]_s$
  - Soft – $[\pm45/0/\pm45/90/\pm45/0/\pm45/90]_s$
- … and the structure
  - Open-hole coupon
  - Fuselage
  - Tube
- … and the environment
  - Elevated temperature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

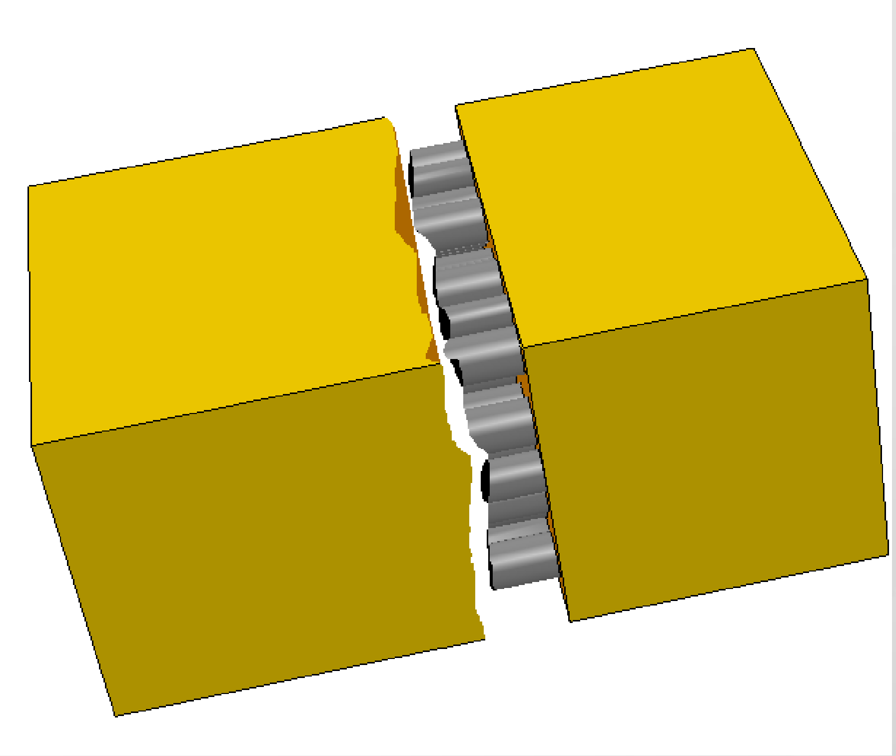


Lamina Failure Modes - Unidirectional

- Failure occurs within the constituents!
  - Fiber pullout (debonding of fiber/matrix)
  - Microcracking in the matrix
  - Fiber fracture in tension
  - Fiber buckling in compression

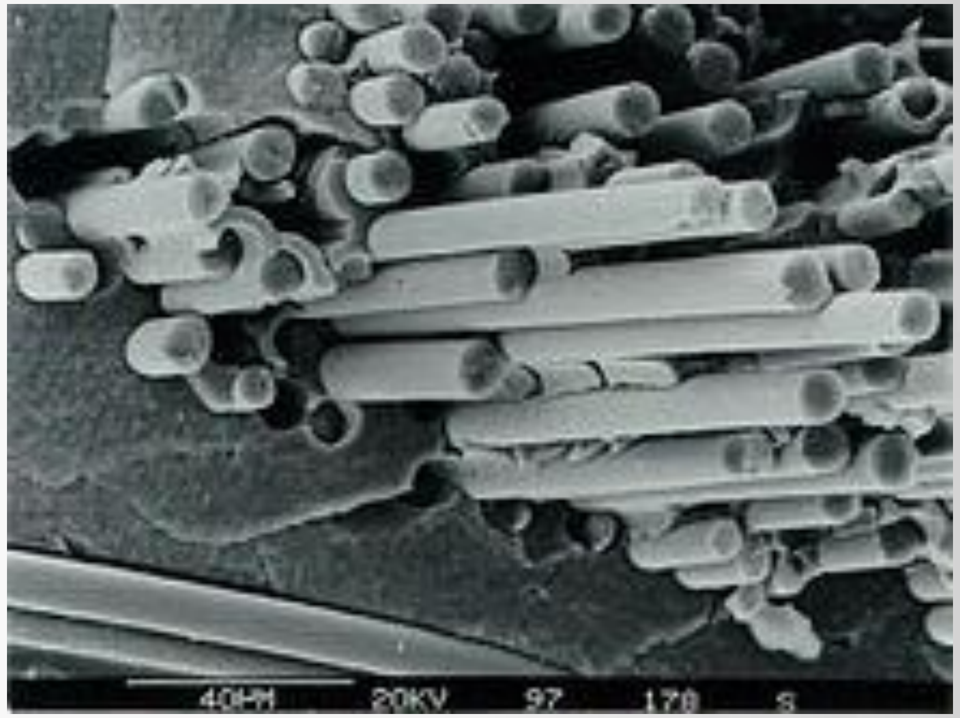


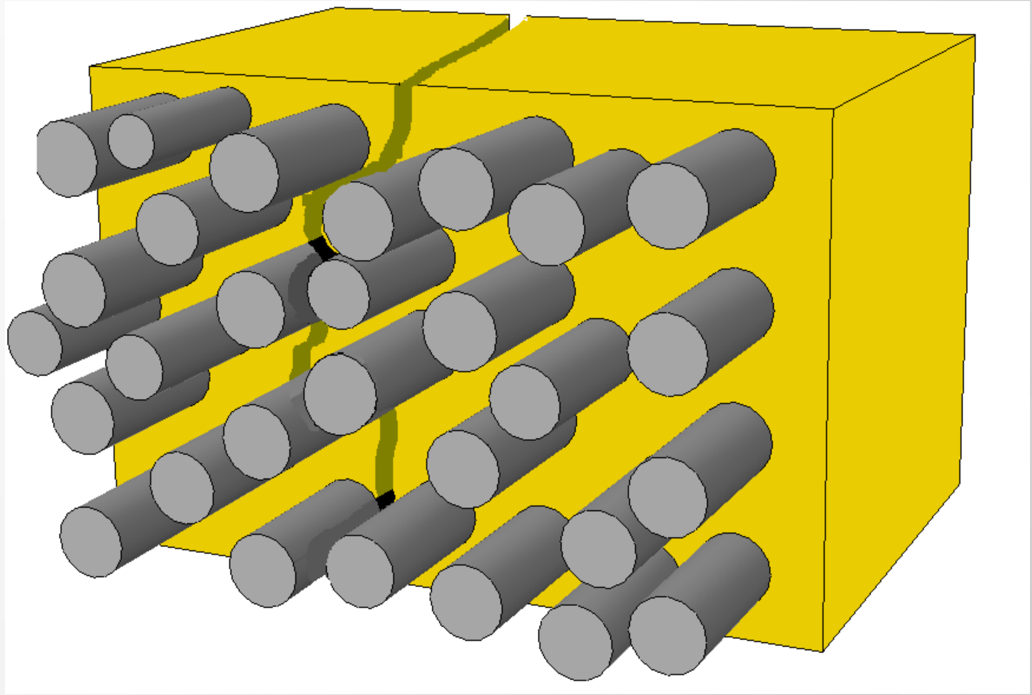




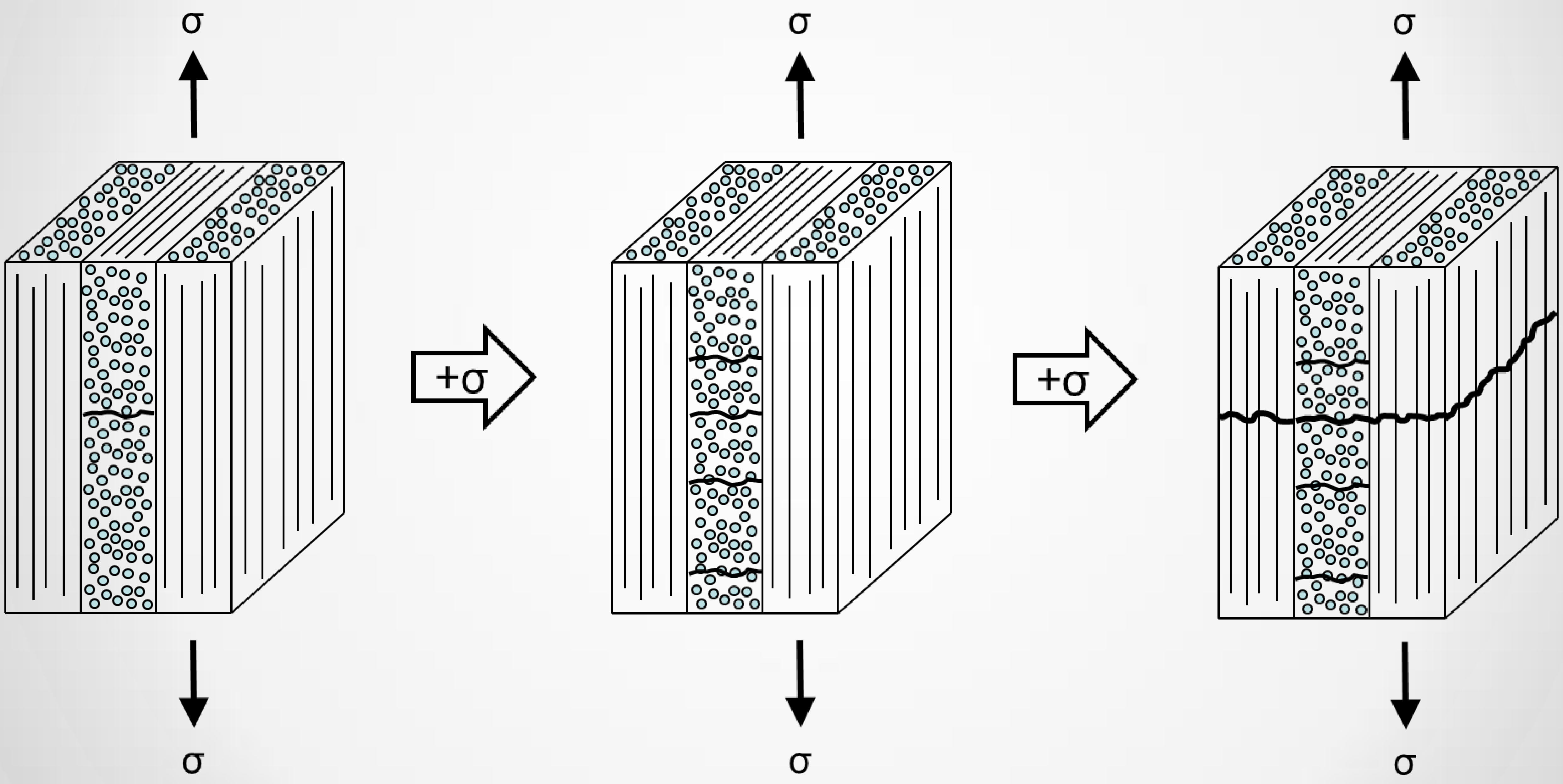
Lamina Failure Modes - Unidirectional

- Consequences of failure
  - Fiber pullout (debonding of fiber/matrix)
    - Stiffness loss in fiber direction
  - Microcracking in the matrix
    - Stiffness loss perpendicular to crack plane
  - Fiber fracture in tension
    - Fibers unable to carry load
  - Fiber buckling in compression
    - Major stiffness loss, however, it is still possible to transfer some load



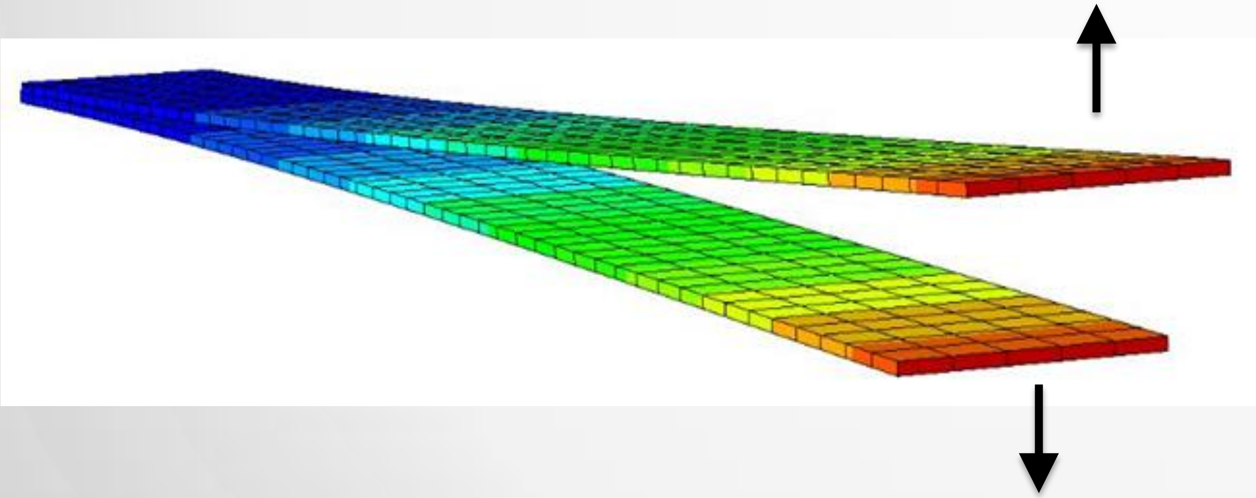


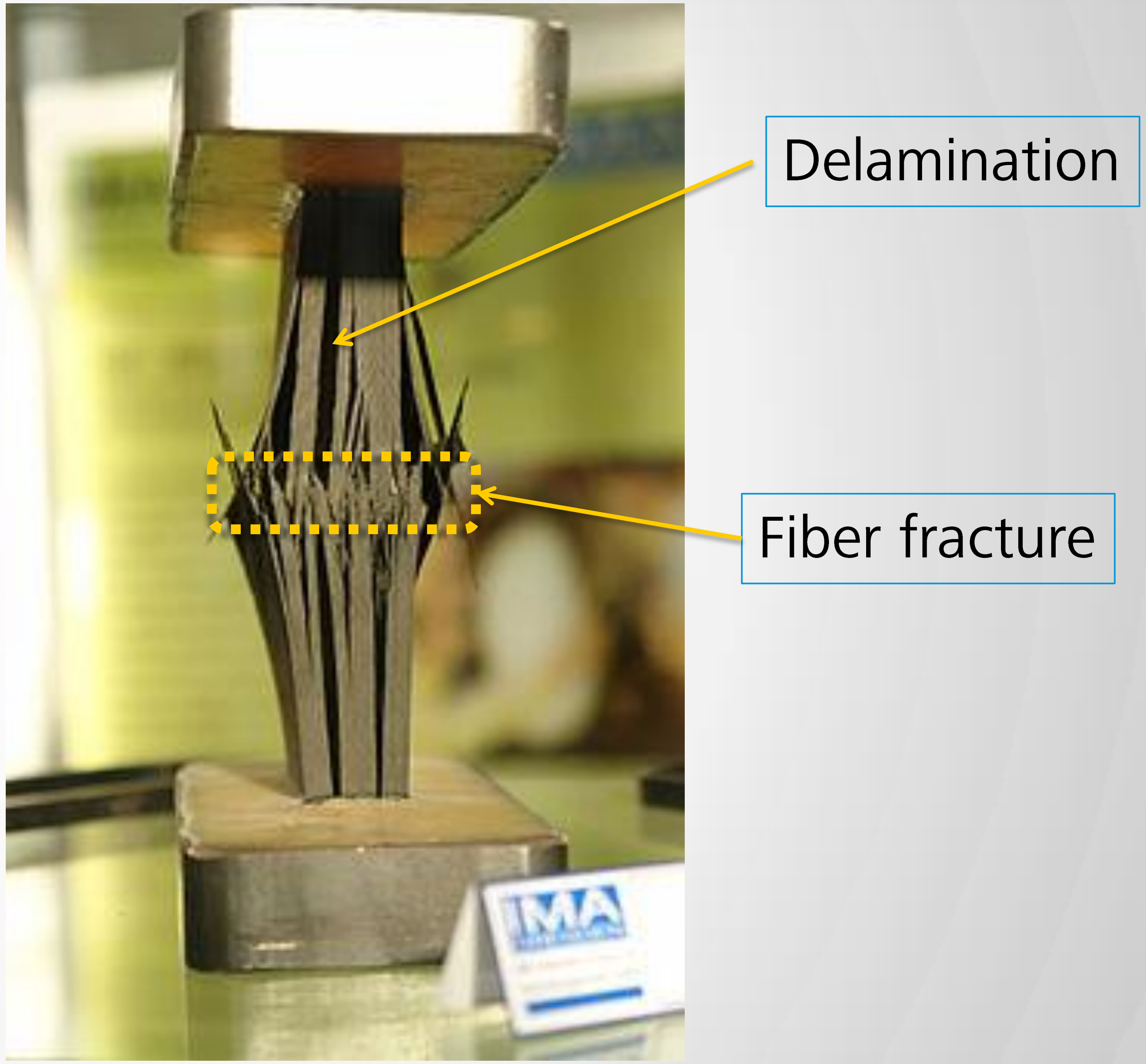
Laminate Failure Modes – Intra-Ply Failure



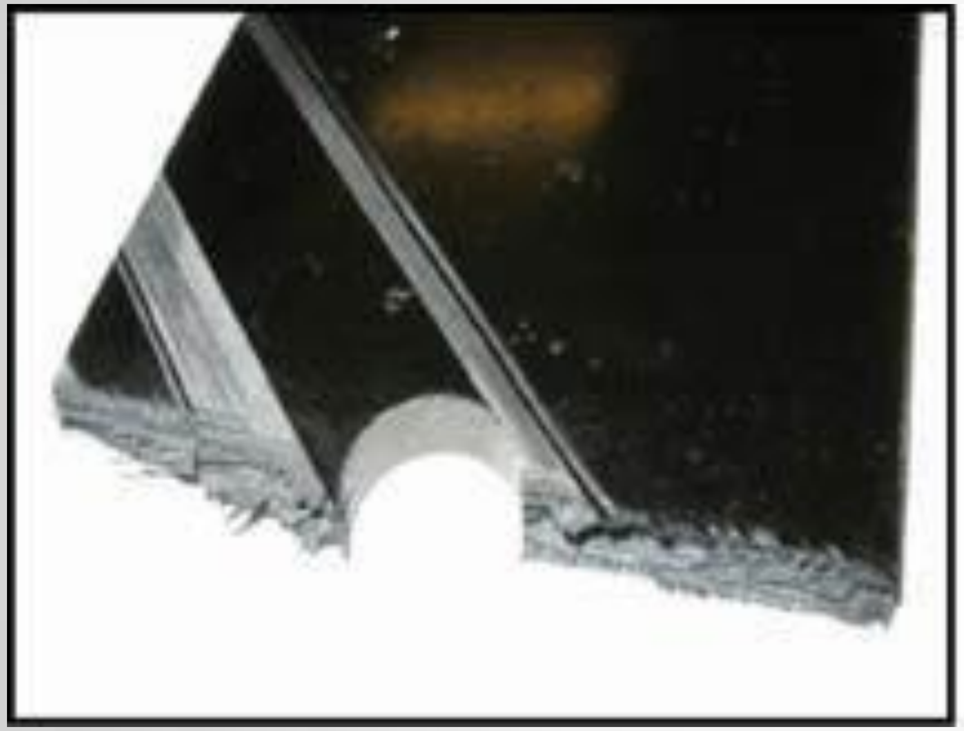
Laminate Failure Modes – Inter-Ply Failure

- Delamination
  - Plies debond and load transfer between adjacent plies is reduced
- Inter-ply and intra-ply failure are both typically present in a failed composite structure





Structural Failure - Examples



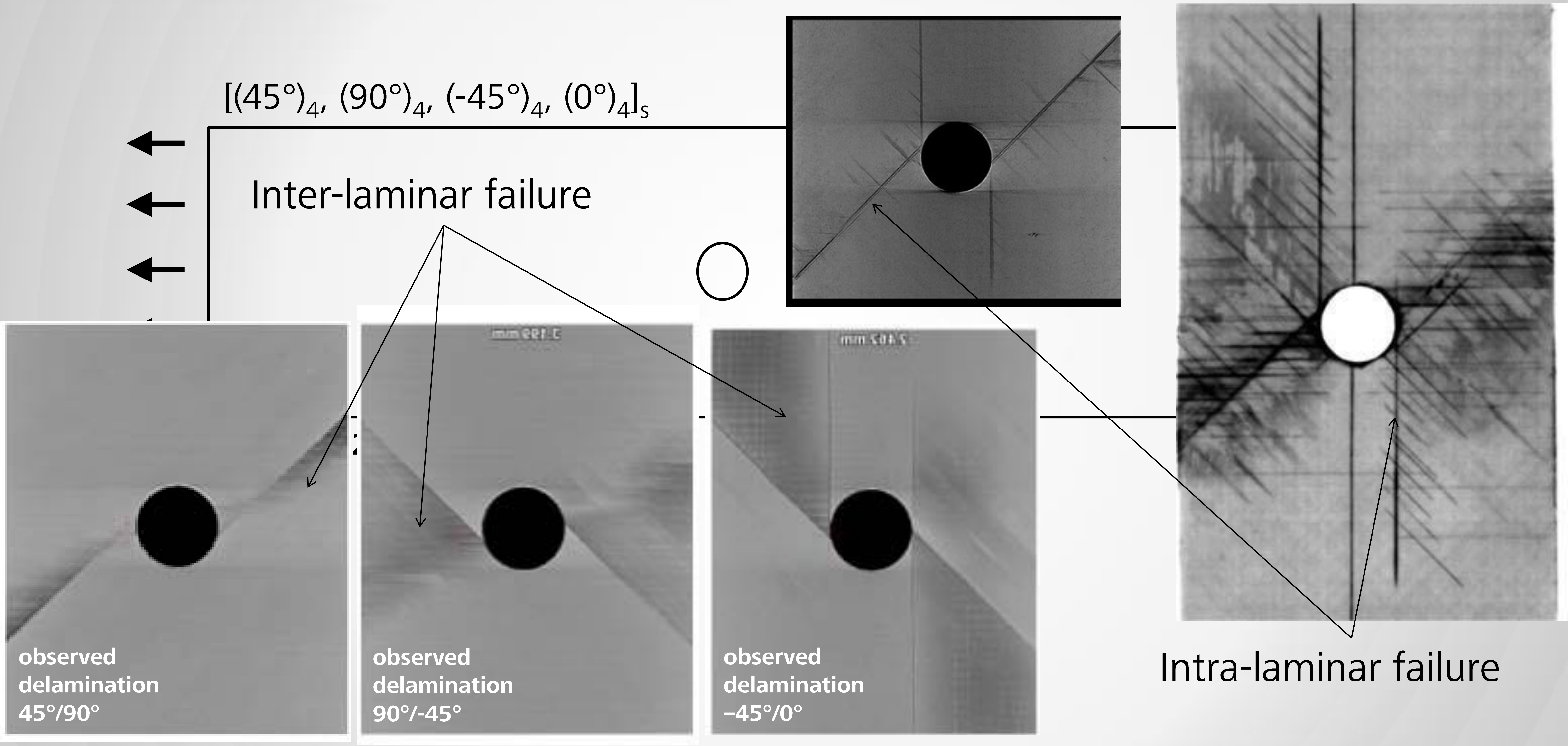
Fiber tensile

Fiber pull-out

Delamination

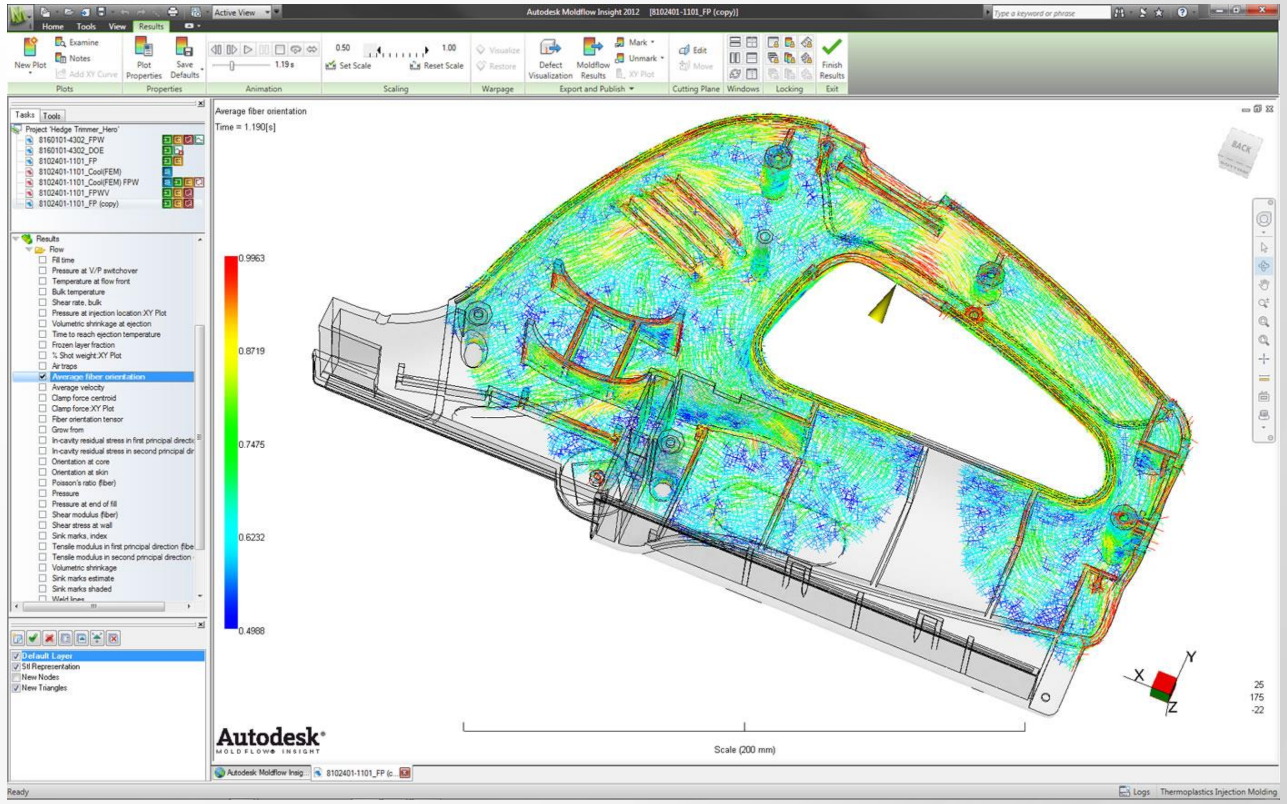
Song K., Li Y., and Rose C.A., "Continuum Damage Mechanics Models for the Analysis of Progressive Failure in Open-Hole Tension Laminates", 52nd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, 2011.

Structural Failure – Open-Hole Example



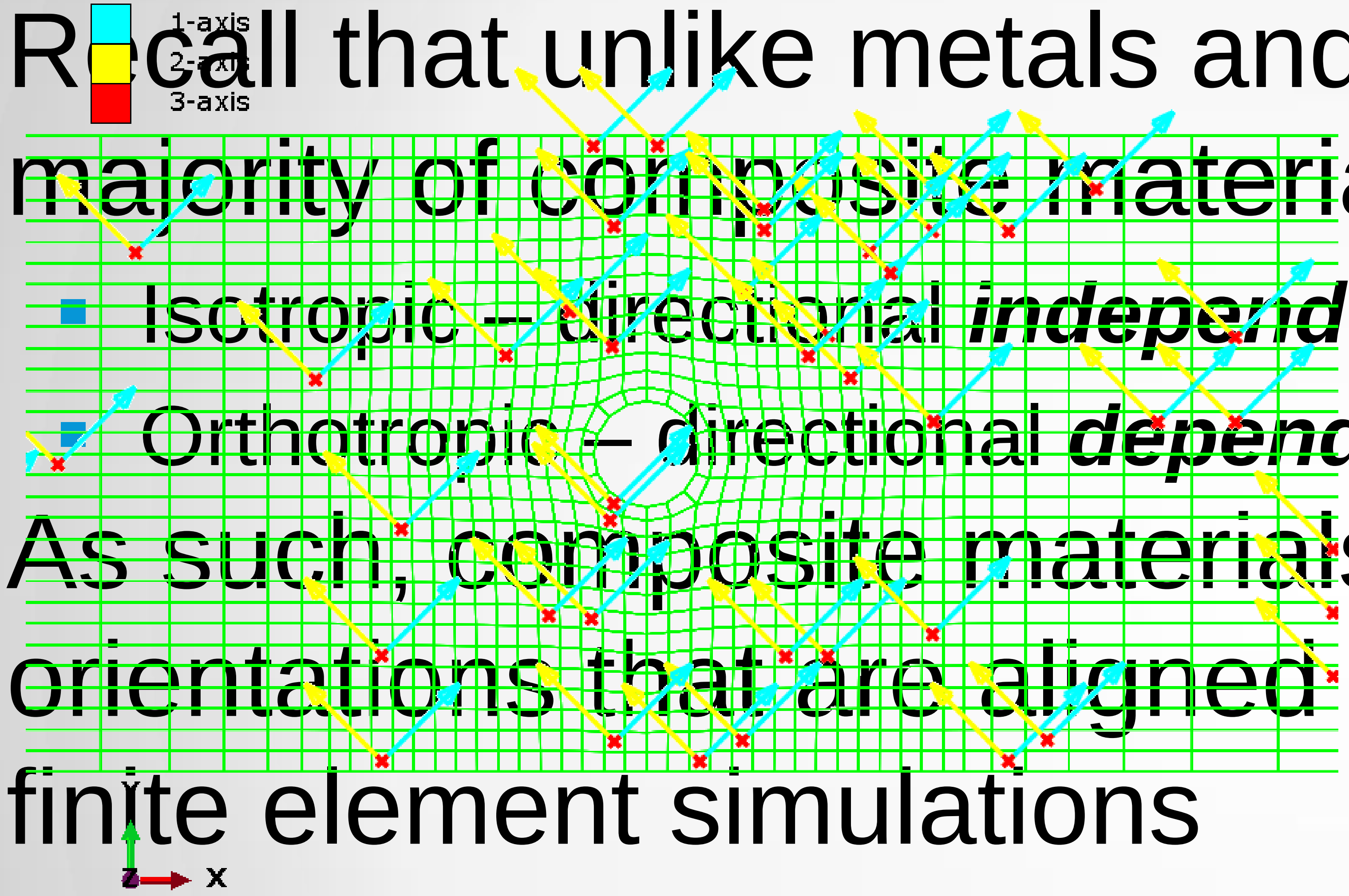
Analysis of Composites

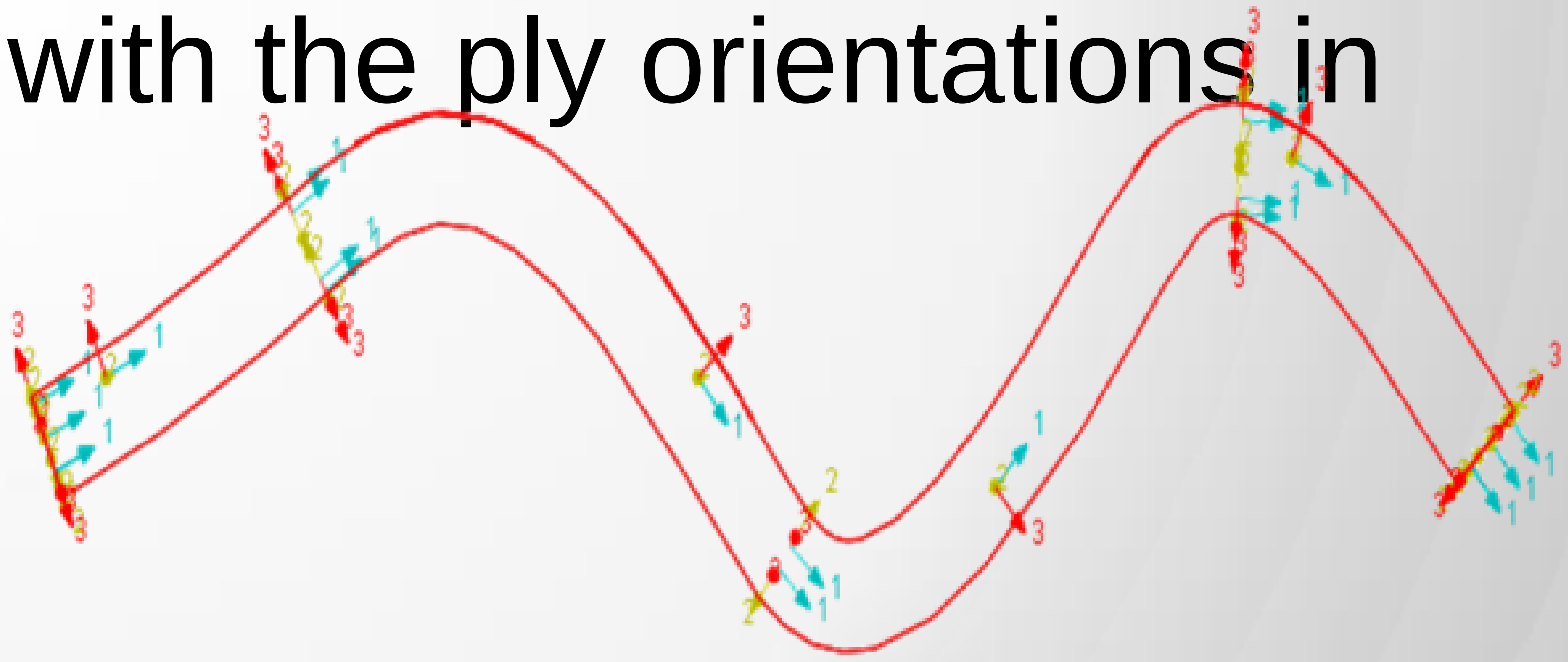
- Computational methods are used to analyze composite structures due to their inherent complexities
  - Finite Element Analysis – Simulates the response of structures
- With composites, we can simulate:
  - Stiffness response
  - Local and global failure
    - Ply failure
    - Delamination
  - Flow of injected composites



Orientations

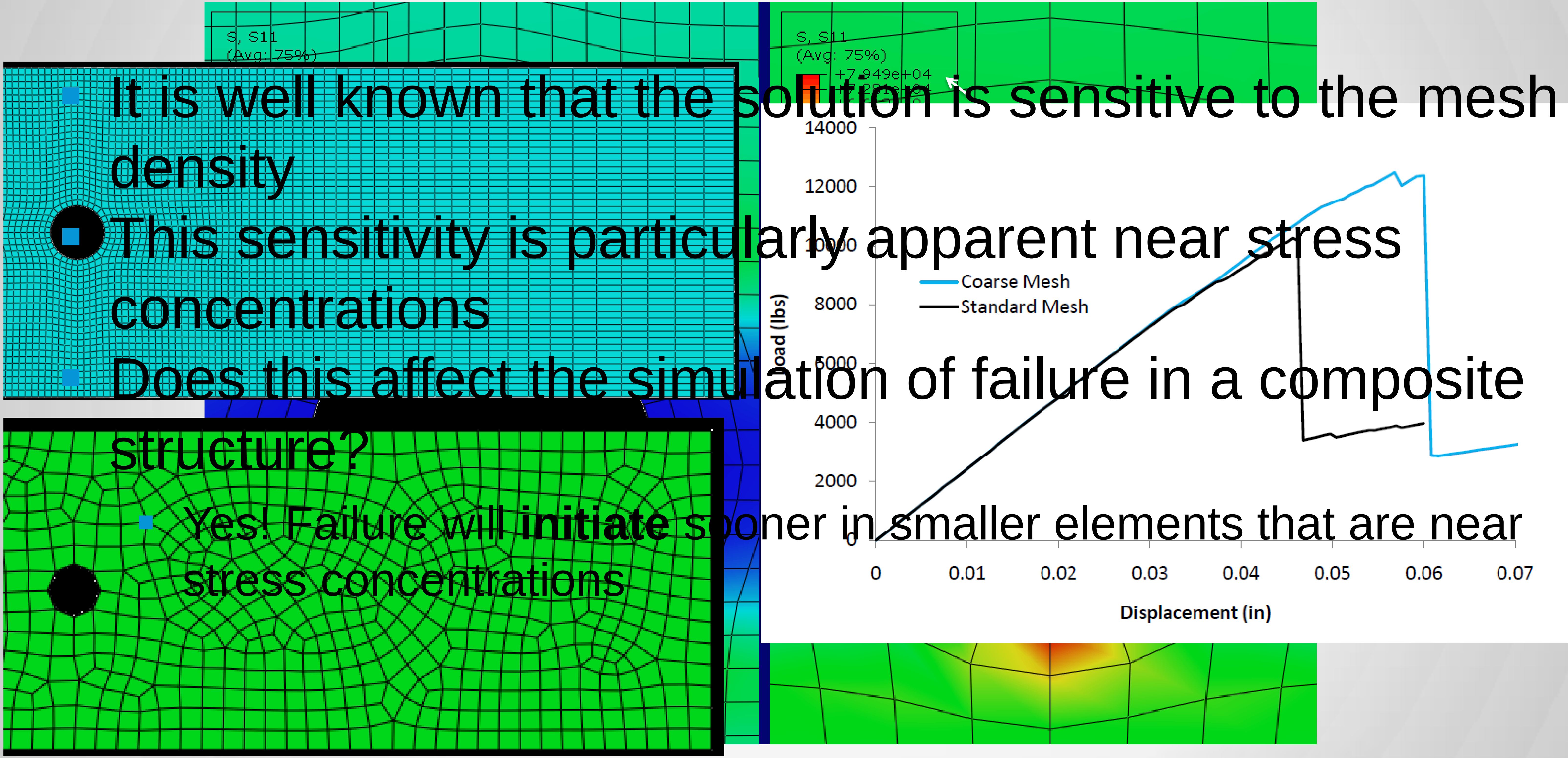
- Recall that unlike metals and plastics, for example, the majority of composite materials are orthotropic
  - Isotropic – directional ***independence***
  - Orthotropic – directional ***dependence***
- As such, composite materials must be assigned orientations that are aligned with the ply orientations in finite element simulations





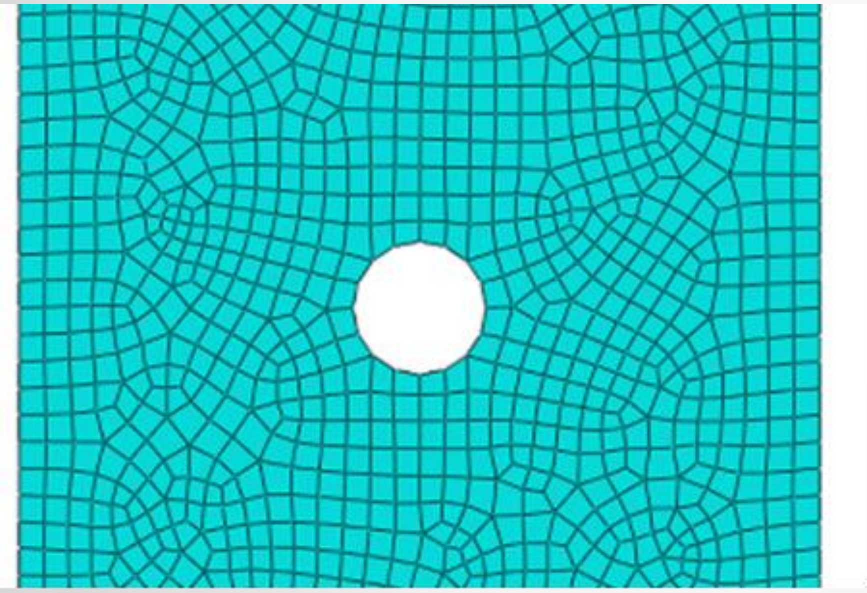
Element Size (Mesh Density)

- It is well known that the solution is sensitive to the mesh density
- This sensitivity is particularly apparent near stress concentrations
- Does this affect the simulation of failure in a composite structure?
  - Yes! Failure will **initiate** sooner in smaller elements that are near stress concentrations

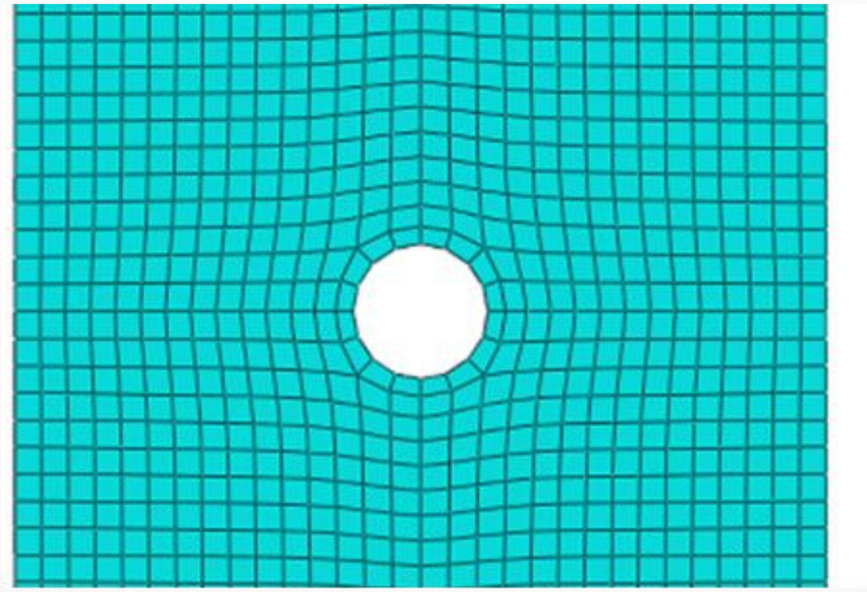


Element Arrangement

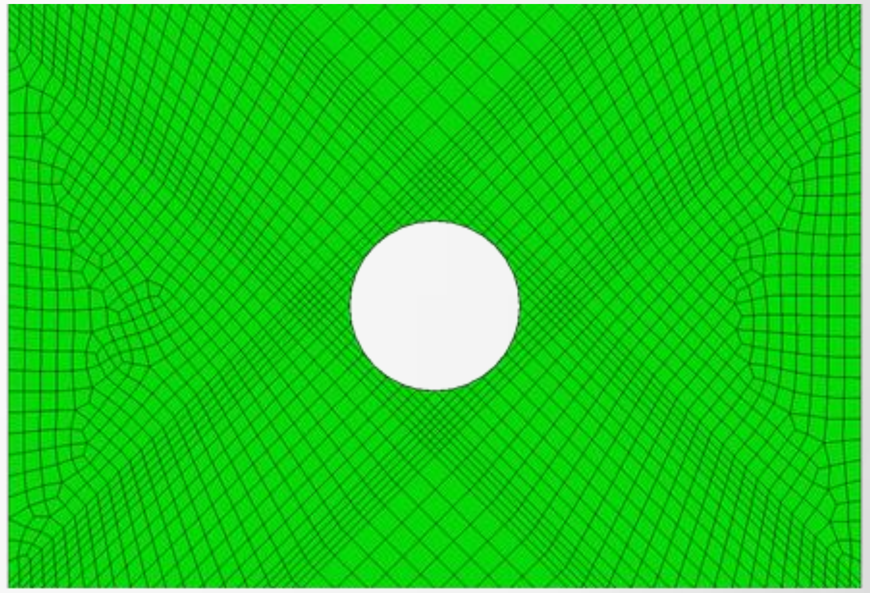
- We know that mesh size is important. What about mesh arrangement?



Arbitrary Mesh



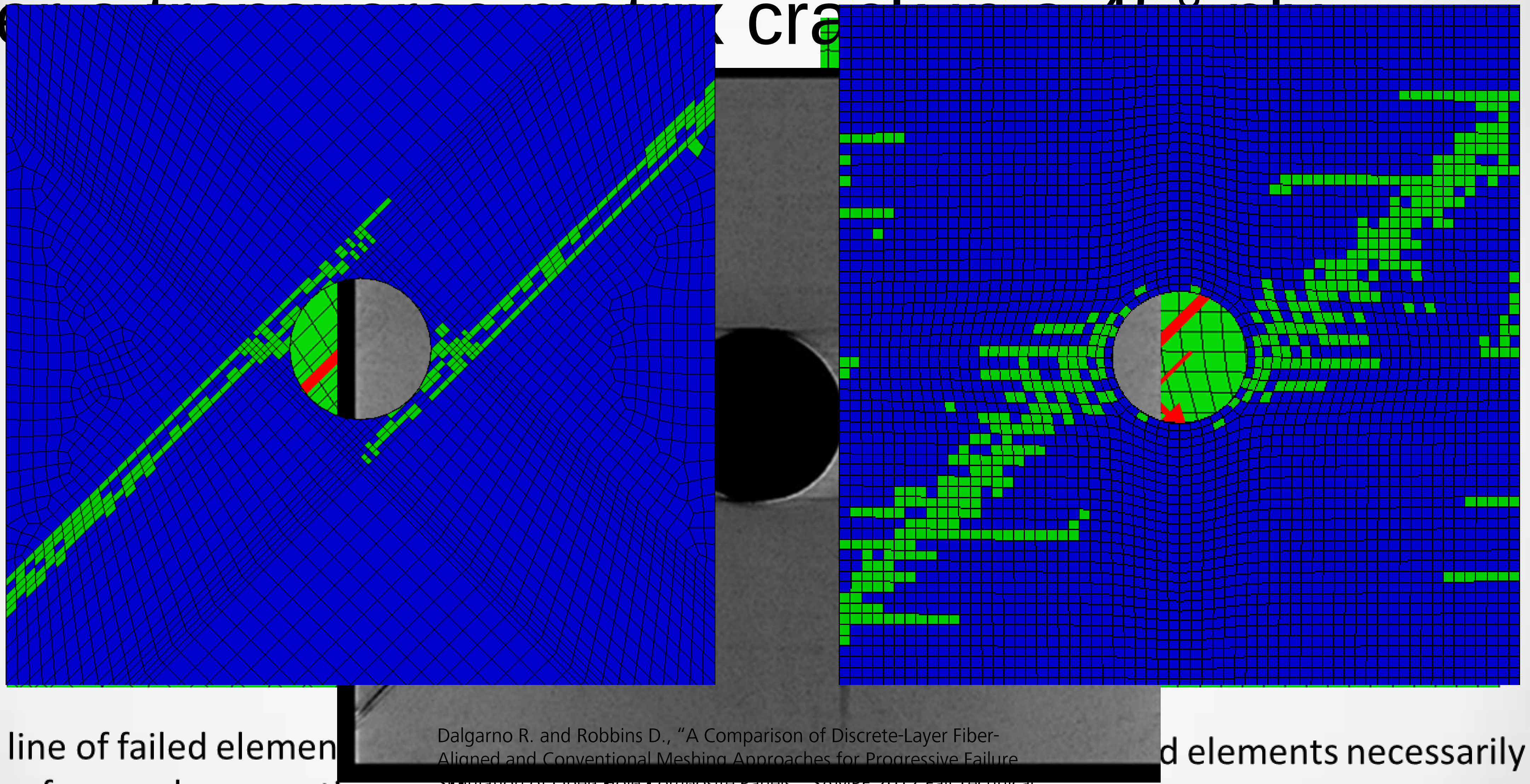
Notch-Centric Mesh



Fiber-Aligned Mesh

Element Arrangement

- Conside[...]k cra[...]



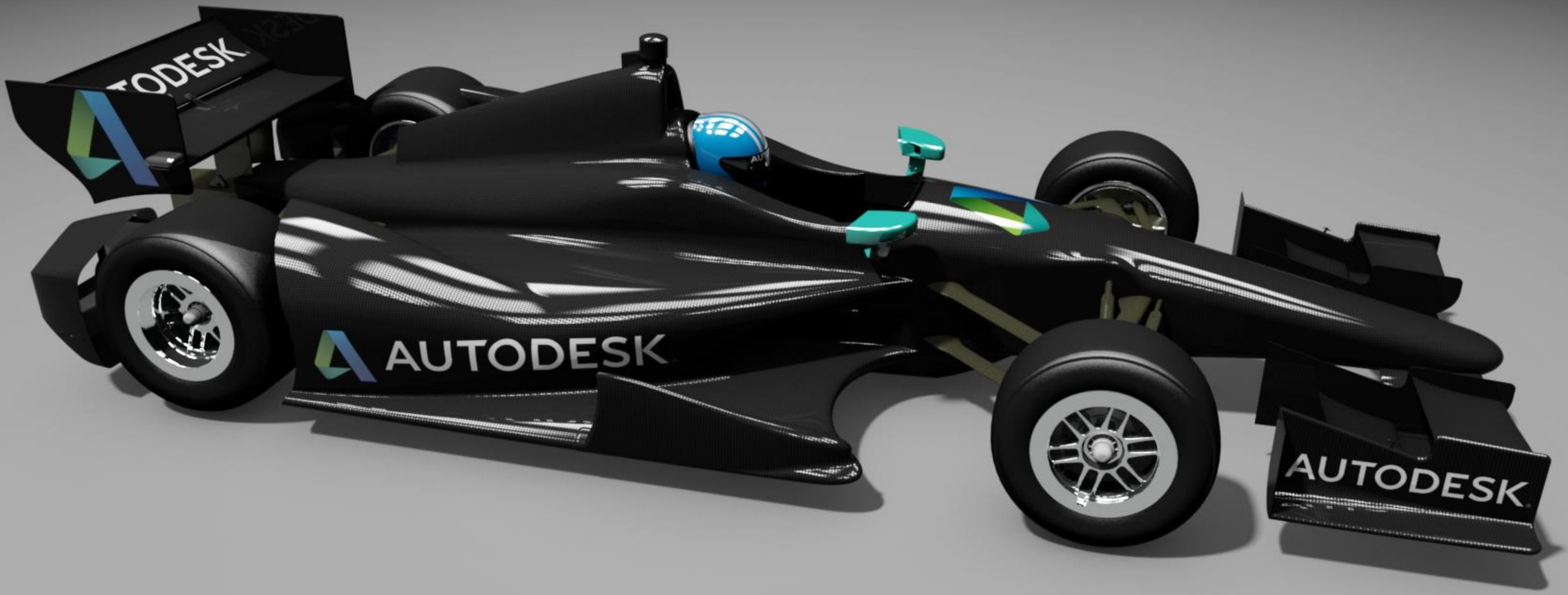
A line of failed elemen[...] can form a clean, contiguous linear path that provides complete disruption of load flow in matrix dominated directions

[...]d elements necessarily leaves many diagonal connections between un-failed elements, allowing spurious transfer of load across the transverse matrix crack.

Dalgarno R. and Robbins D., "A Comparison of Discrete-Layer Fiber-Aligned and Conventional Meshing Approaches for Progressive Failure Simulation of Open-Hole Composite Panels", SAMPE 2012 Fall Technical Conference, 2012.

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.

Composite Simulation at Autodesk



SOFTWARE SOLUTIONS

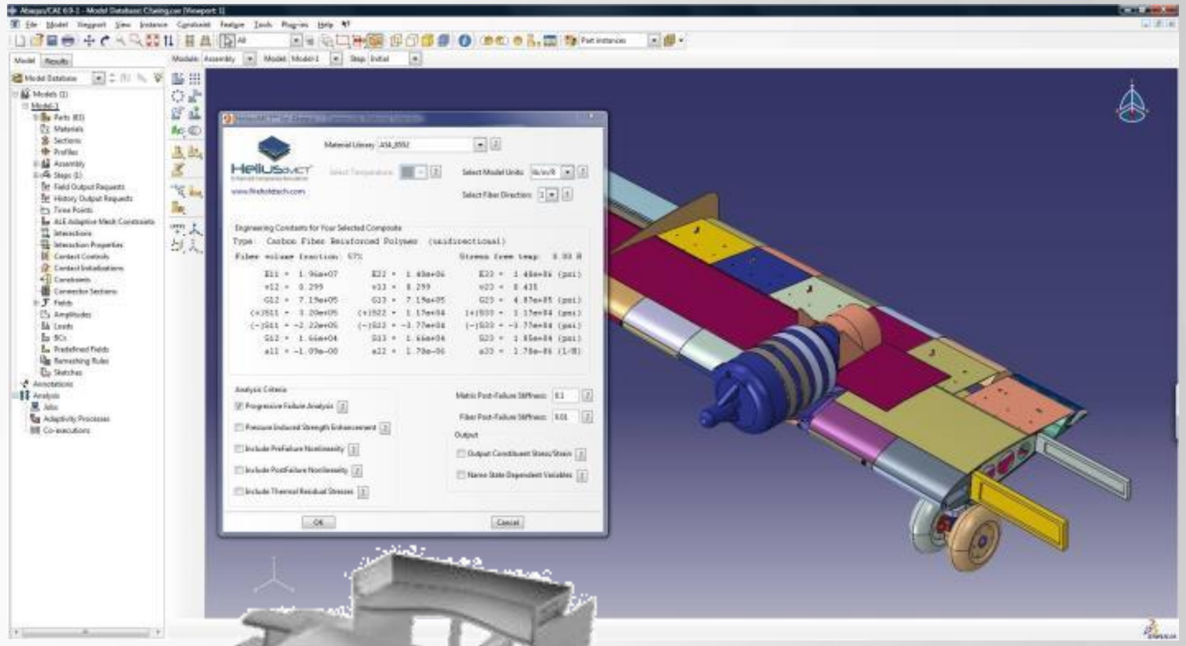
FOR DESIGN AND ANALYSIS OF COMPOSITE MATERIALS

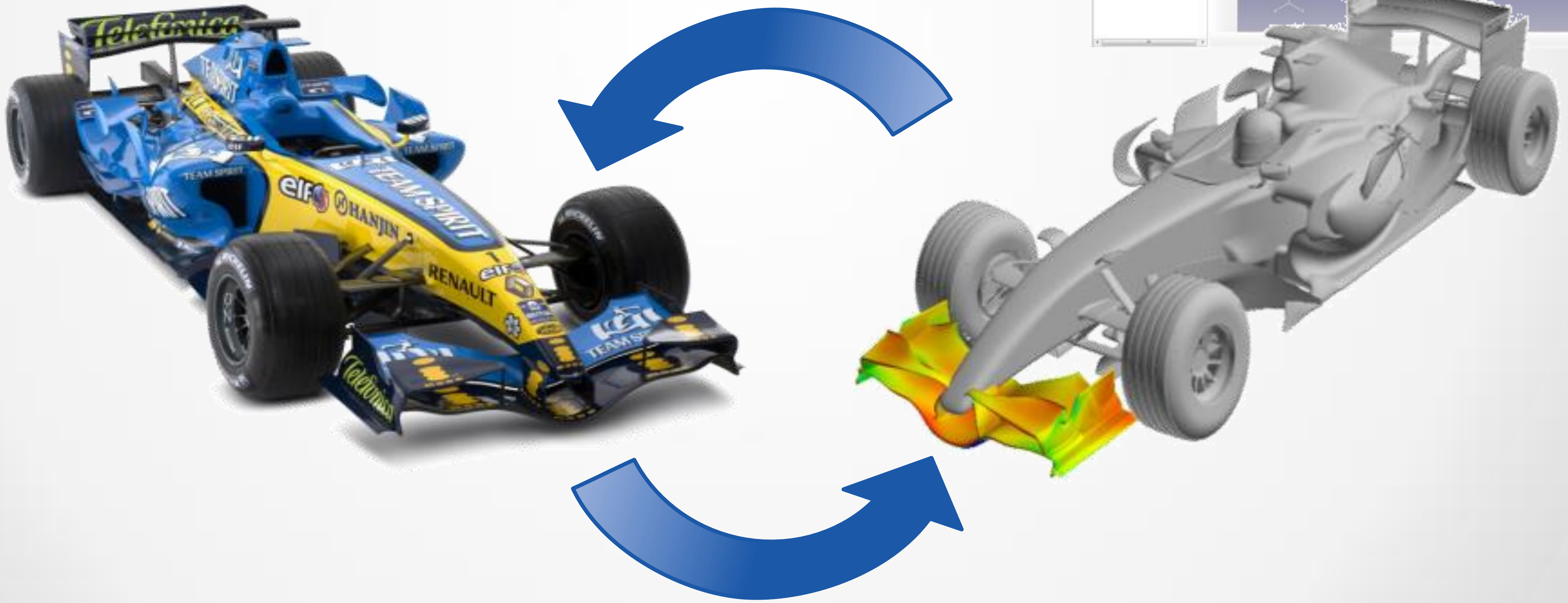
Autodesk's new Composites product line delivers:

Composites Specific Tools

Intuitive Interfaces

Exceptional Accuracy and Efficiency





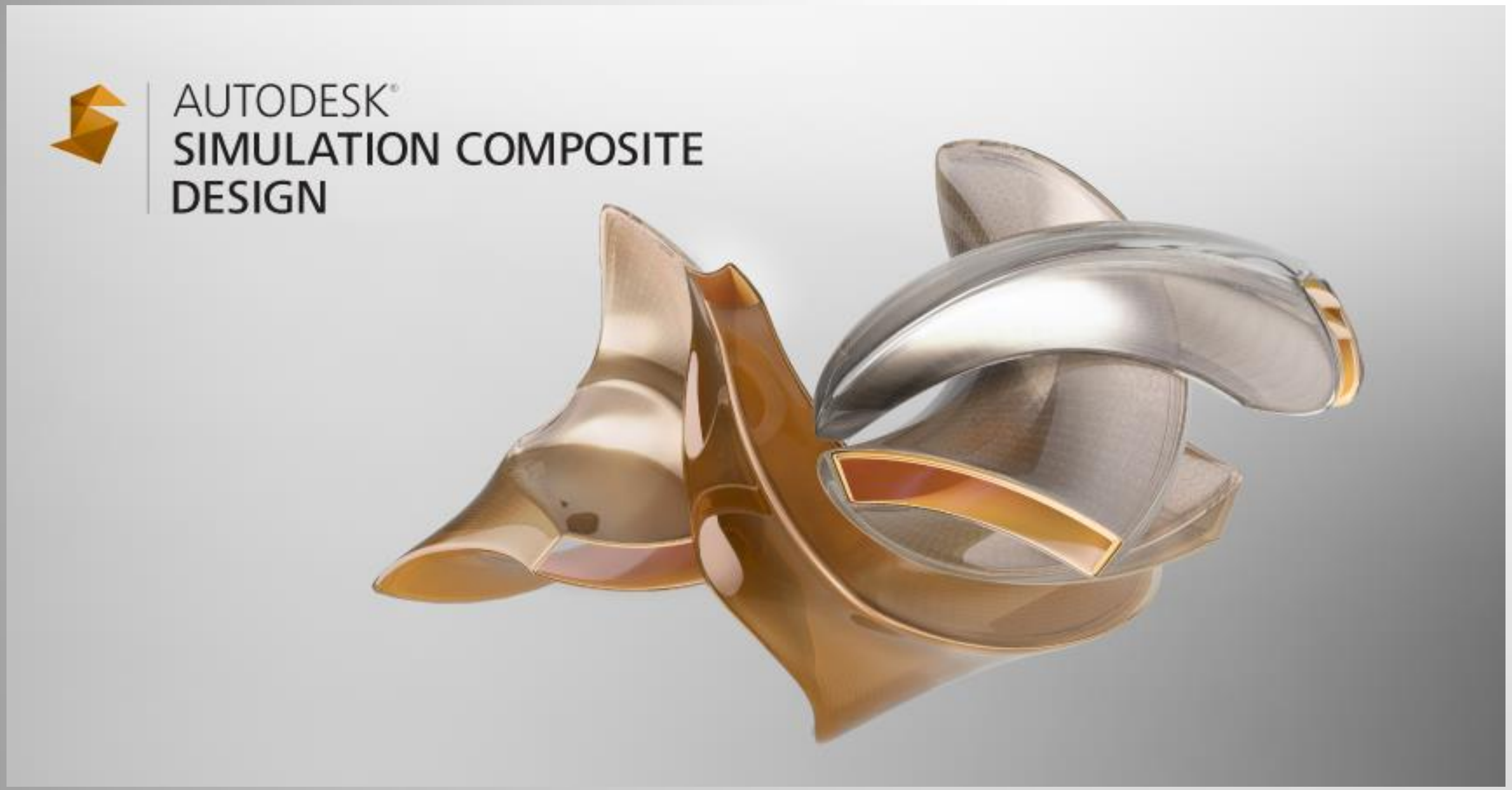
Enabling virtual prototyping for composites

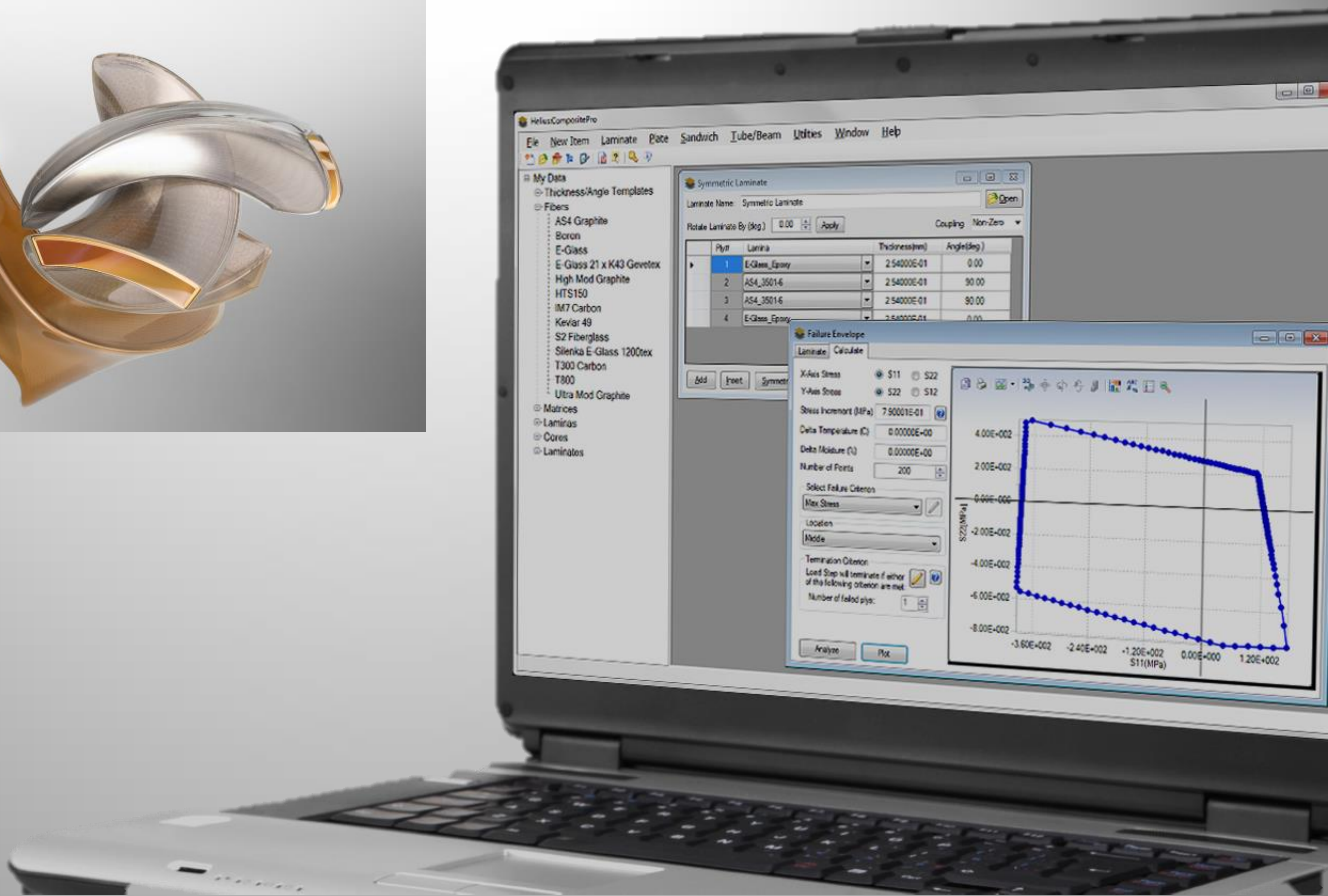
Composite Simulation Areas

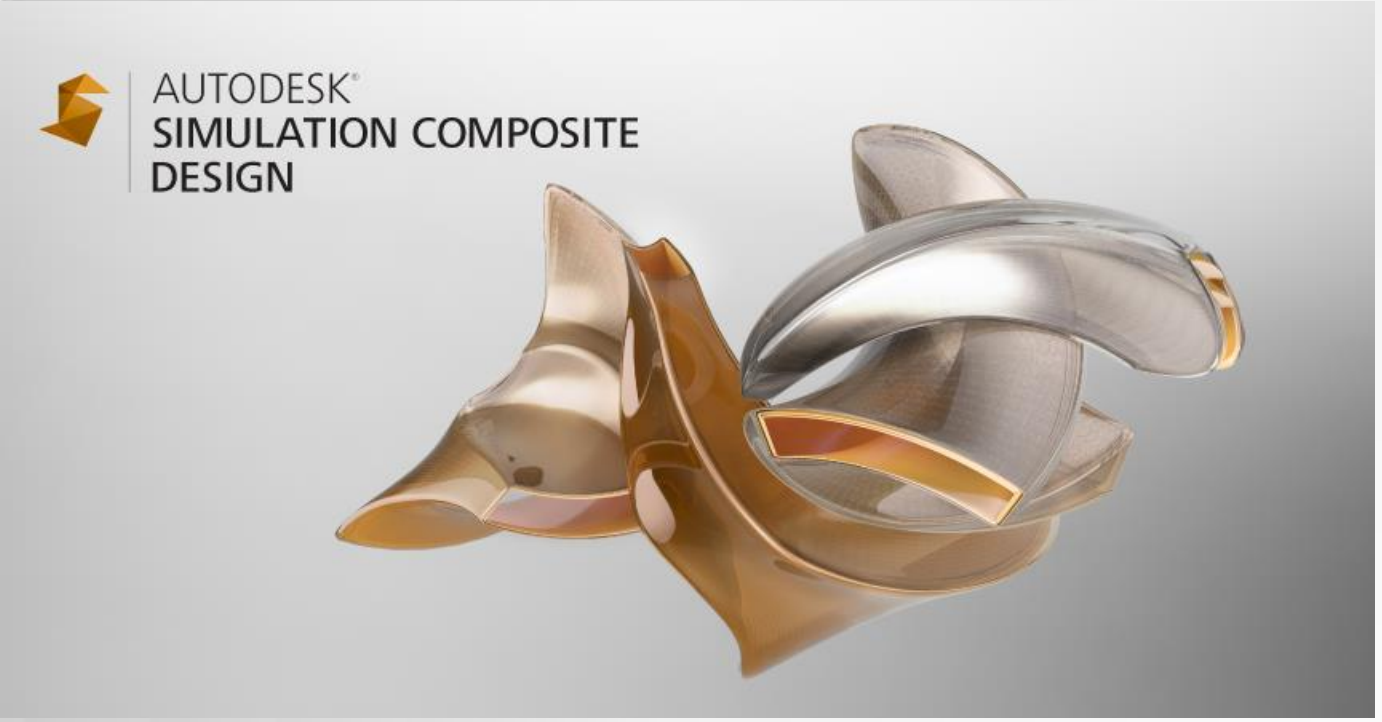
Design

Manufacturing

Analysis

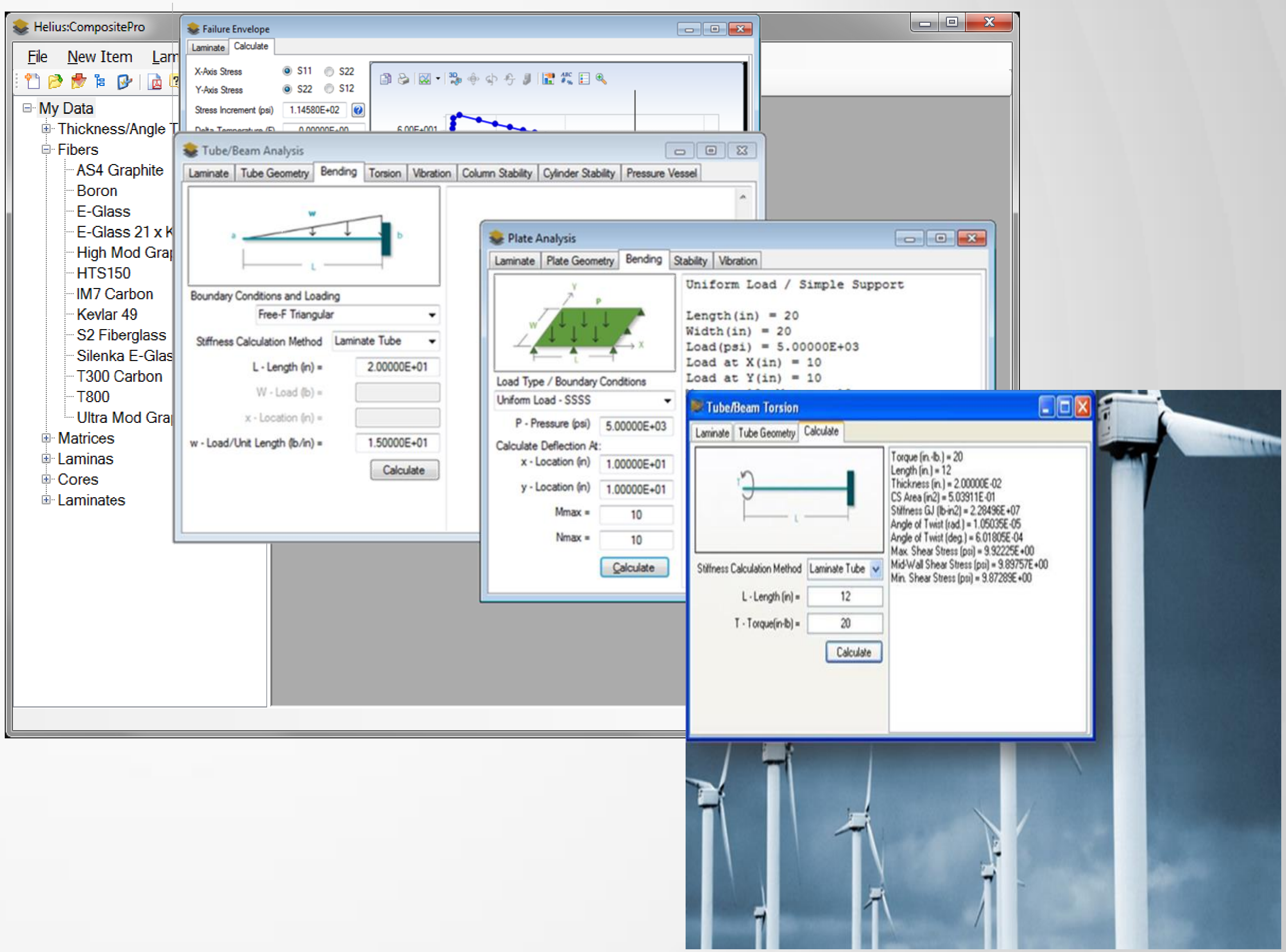

AUTODESK®
SIMULATION COMPOSITE
DESIGN


File New Item Laminate Plate Sandwich Tube/Beam Utilities Window Help
My Data
Thickness/Angle Templates
Fibers
AS4 Graphite
Boron
E-Glass
E-Glass 21 x K43 Gevetex
High Mod Graphite
HTS150
IM7 Carbon
Kevlar 49
S2 Fiberglass
Silenka E-Glass 1200tex
T300 Carbon
T800
Ultra Mod Graphite
Matrices
Laminas
Cores
Laminates
Symmetric Laminate
Failure Envelope



Composites design and engineering desktop tool

Quick, Efficient design of materials and simple structures for early design

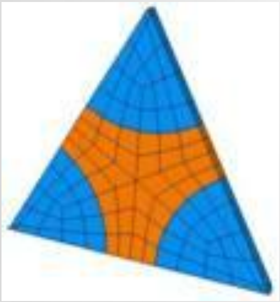


Material Analysis

Material Library:

- My Data
  - Thickness/Angle Templates
  - Fibers
  - Matrices
    - 3501-6 Epoxy
    - 5250-4 RTM
    - 5505 Epoxy
    - 8551-7 Epoxy
    - BSL914C Epoxy
    - LY556 Epoxy

Lamina from Micro Mechanics:



Input Fiber/Matrix, Lamina and/or Laminate data

Laminate Analysis

Equivalent Laminate Props:

Title	Value
Ex (psi)	1.32512E+07
Ey (psi)	1.76764E+07
Ez (psi)	9.16388E+06
Gxy (psi)	3.28911E+06
Gxz (psi)	3.17308E+06
Gyz (psi)	3.23109E+06
NUxy	1.58603E-01
NUyx	2.11567E-01
NUxz	3.93142E-01
NUzx	2.71878E-01
NUyz	3.67837E-01

Laminate Response

Factor of Safety

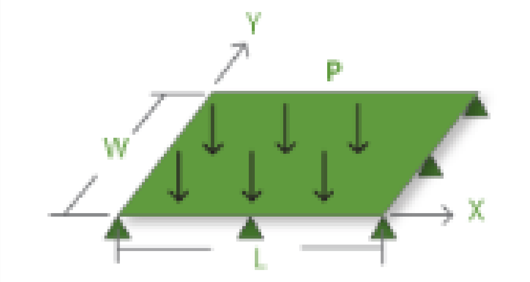
Composite Failure Criteria:

Max Stress

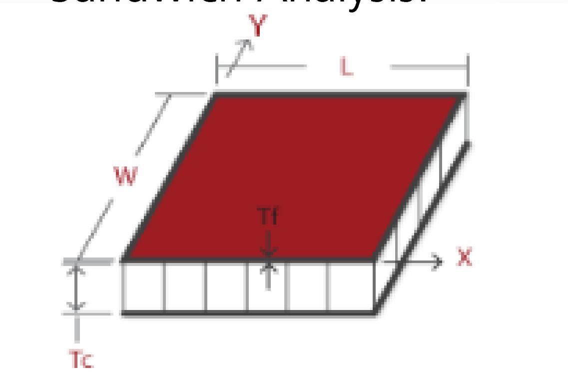
- Max Stress
- Max Strain
- Tsai-Wu
- Tsai-Hill
- Hashin
- Christensen
- Puck
- MCT

Simple Structural Analysis

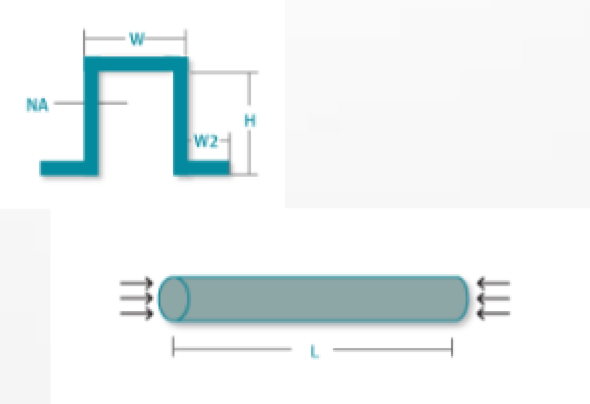
Plate Analysis:



Sandwich Analysis:



Beam/Tube Analysis:

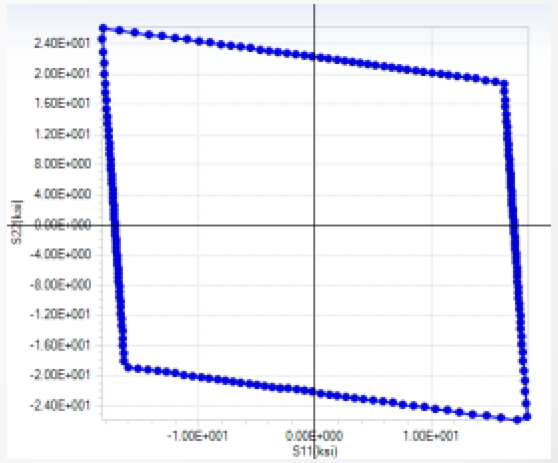


Advanced Laminate Analysis

Progressive Failure:

Inc.	SIGMAx (psi)	SIGMAy (psi)	SIGMAxy (psi)	EPSILONx (in/in)	EPS
1	2.00000E+03	-1.55431E-13	0.00000E+00	1.54778E-04	-2.
2	4.00000E+03	-3.10862E-13	0.00000E+00	3.09557E-04	-4.
3	6.00000E+03	-3.99680E-13	0.00000E+00	4.64335E-04	-6.
4	8.00000E+03	-6.21725E-13	0.00000E+00	6.19114E-04	-8.
5	1.00000E+04	-5.32907E-13	-9.86076E-30	7.73892E-04	-1.
6	1.20000E+04	-5.32907E-13	4.93038E-30	9.28671E-04	-1.
7	1.40000E+04	-3.55271E-13	9.86076E-30	1.08345E-03	-1.
8	1.60000E+04	-1.59872E-12	9.86076E-30	1.23823E-03	-1.
9	1.80000E+04	-2.99760E-13	6.16298E-31	1.42417E-03	-4.
10	2.00000E+04	-5.55112E-13	-3.38964E-30	1.58241E-03	-5.

Failure Envelopes:



Utilities

Export Lamina/Laminate to FEA:

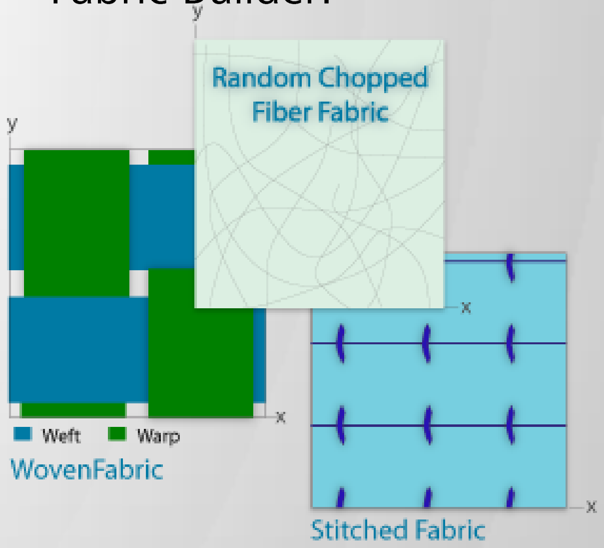
Abaqus Solution Partner

SIMULIA

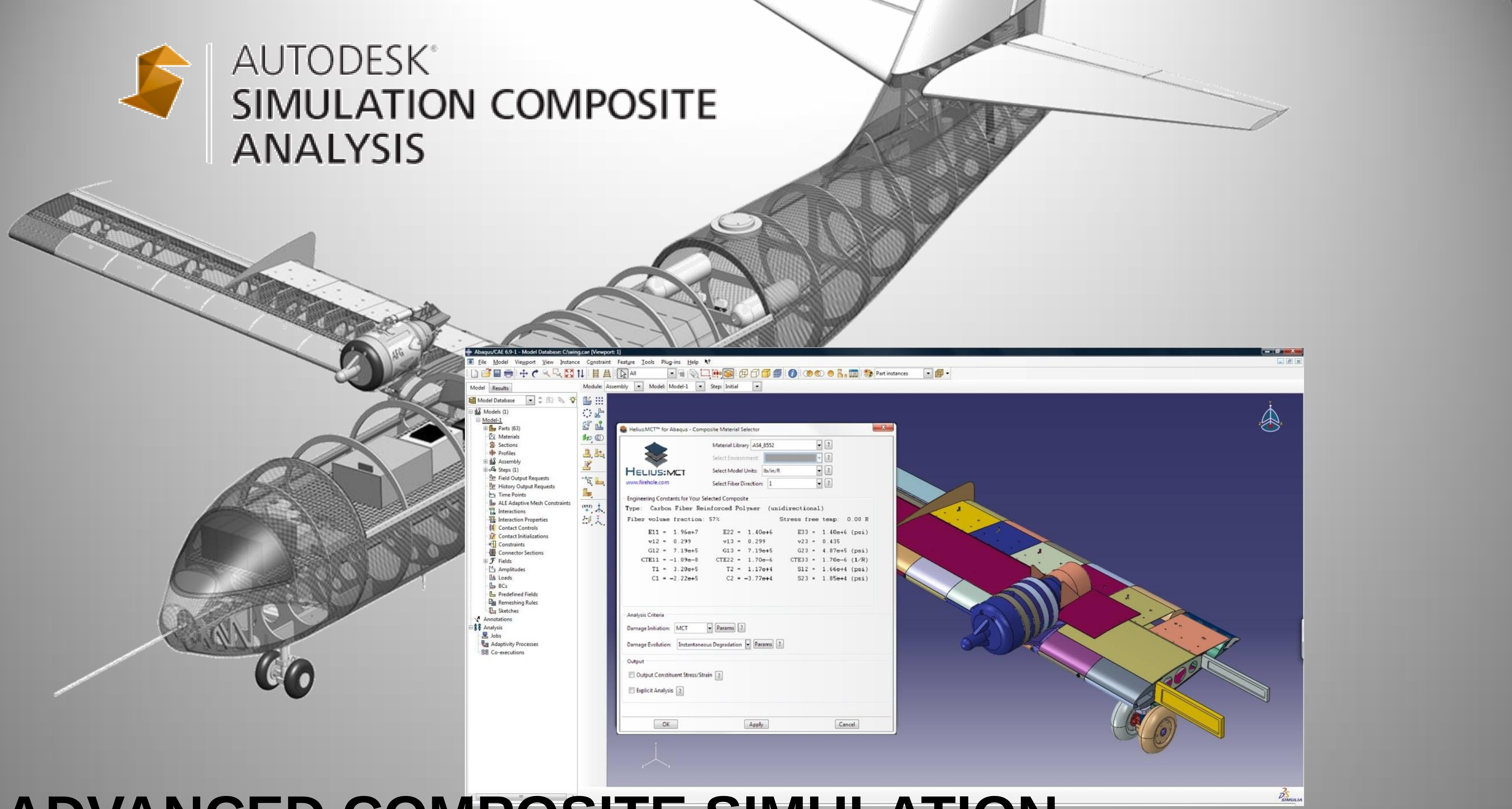
MSC Software Simulate More

ANSYS

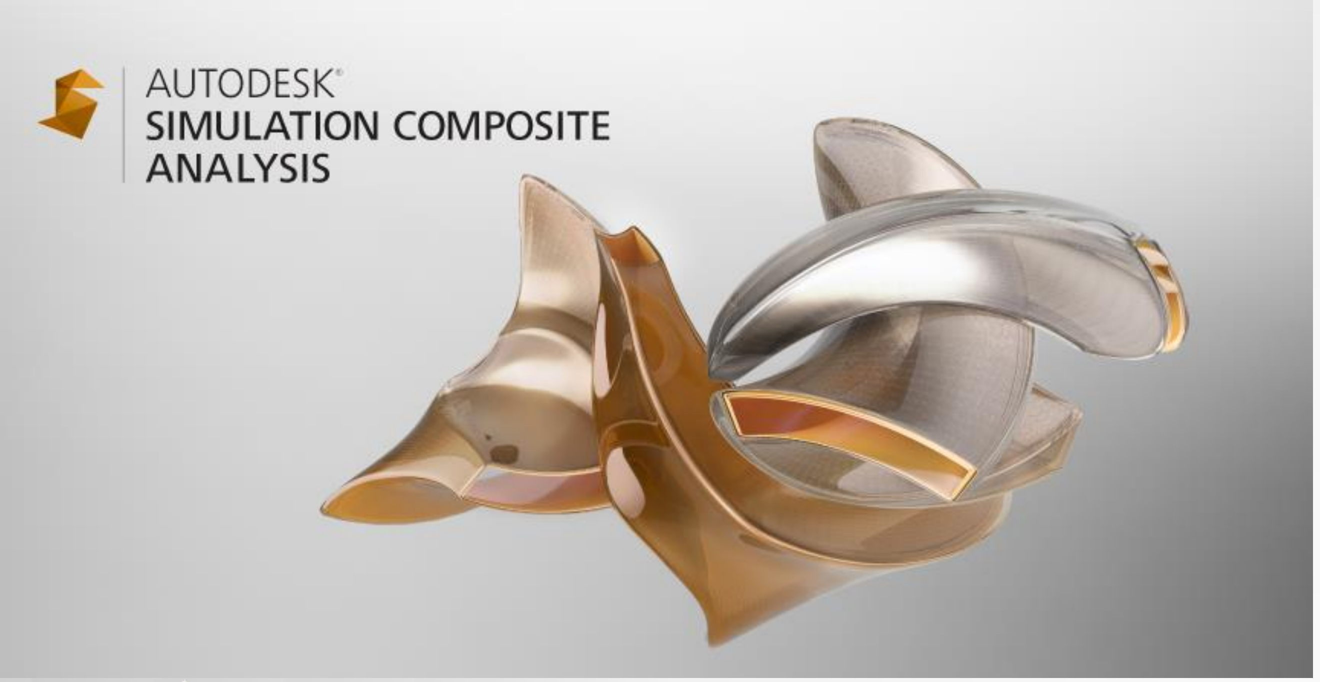
Fabric Builder:



AUTODESK®
SIMULATION COMPOSITE ANALYSIS

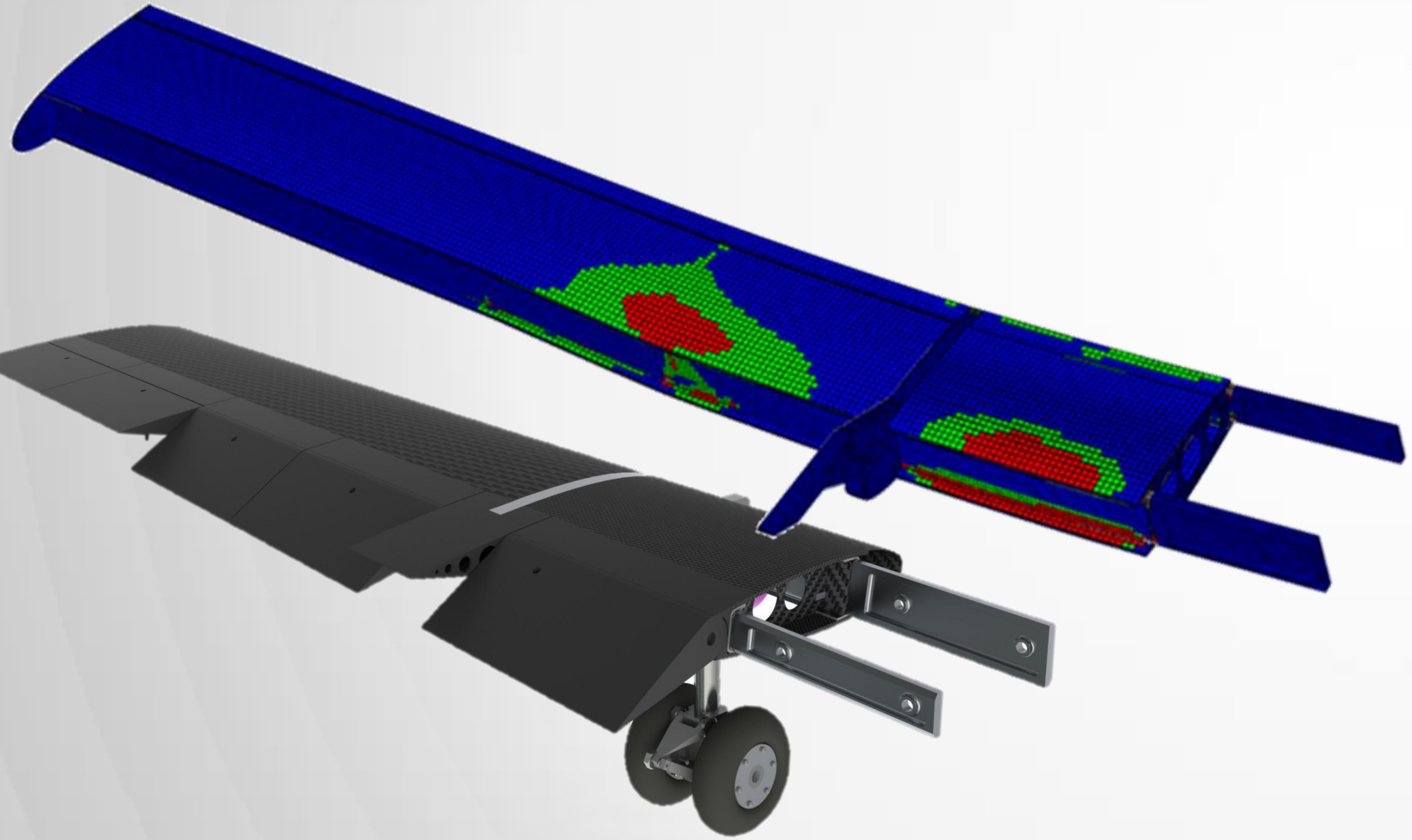


ADVANCED COMPOSITE SIMULATION



Composite-specific plug-in to FEA packages

ANSYS® | Abaqus Solution Partner – SIMULIA | LSTC Livermore Software Technology Corp. | NEi Nastran



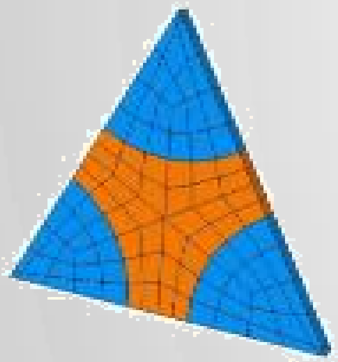
- Multi-scale, progressive failure FEA
- Functionality for In-plane & Delamination Failure
- Specific models for unidirectional and woven composites
- Multiple material Degradation Models
- Easy Material Property Characterization
- Superior Model Convergence
- Easy to use GUI's integrated directly into existing CAE platforms

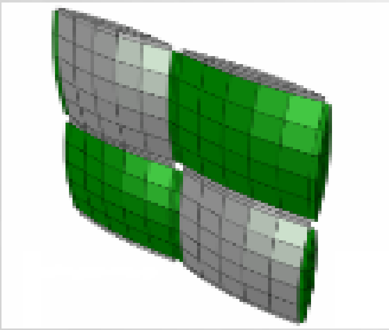
Material Management

Characterized constituent behavior from lamina inputs:

- Uses an iterative micromechanics based solver to calculate "in-situ" properties.

- Calculates constituent nonlinearity from lamina inputs.



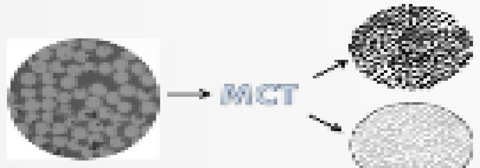


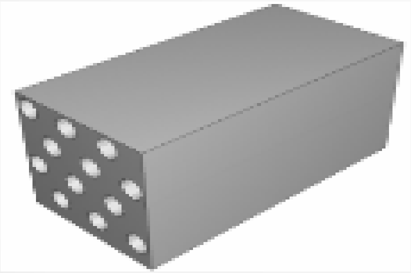
Multiscale Analysis

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





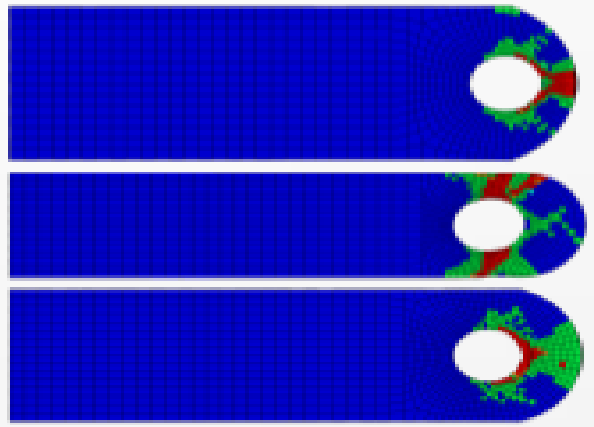
Failure, Damage & Fatigue

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