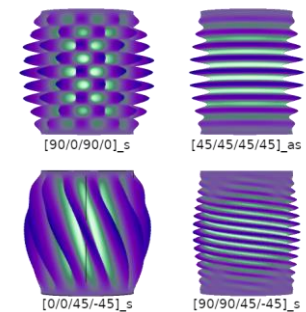
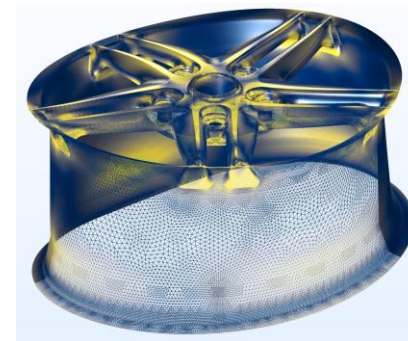
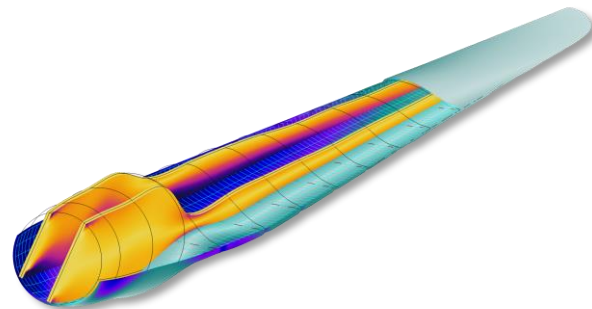
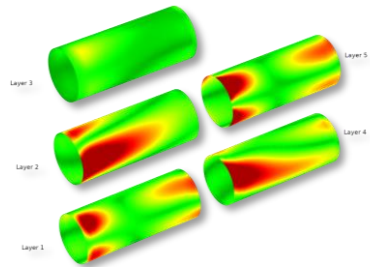


# Composite Materials Module: General Introduction



# The COMSOL<sup>®</sup> Software Product Suite

## COMSOL MULTIPHYSICS<sup>®</sup>

The platform product. Understand, predict, and optimize physics-based designs and processes with numerical simulation.

## DEPLOYMENT PRODUCTS

- COMSOL Compiler™
- COMSOL Server™

Distribute simulation applications created with COMSOL Multiphysics.

## ADD-ON PRODUCTS

### ELECTROMAGNETICS

- AC/DC Module
- RF Module
- Wave Optics Module
- Ray Optics Module
- Plasma Module
- Semiconductor Module

### FLUID & HEAT

- CFD Module
  - Mixer Module
- Microfluidics Module
- Porous Media Flow Module
- Subsurface Flow Module
- Pipe Flow Module
- Molecular Flow Module
- Metal Processing Module
- Heat Transfer Module

### STRUCTURAL & ACOUSTICS

- Structural Mechanics Module
  - Nonlinear Structural Materials Module
  - Composite Materials Module
  - Geomechanics Module
  - Fatigue Module
  - Rotordynamics Module
- Multibody Dynamics Module
- MEMS Module
- Acoustics Module

### CHEMICAL

- Chemical Reaction Engineering Module
- Batteries & Fuel Cells Module
- Electrodeposition Module
- Corrosion Module
- Electrochemistry Module

### MULTIPURPOSE

- Optimization Module
- Material Library
- Particle Tracing Module

### INTERFACING

- LiveLink™ for MATLAB®
- LiveLink™ for Excel®
- CAD Import Module
- Design Module
- ECAD Import Module
- LiveLink™ for SOLIDWORKS®
- LiveLink™ for Inventor®
- LiveLink™ for AutoCAD®
- LiveLink™ for Revit®
- LiveLink™ for PTC® Creo® Parametric™
- LiveLink™ for PTC® Pro/ENGINEER®
- LiveLink™ for Solid Edge®
- File Import for CATIA® V5

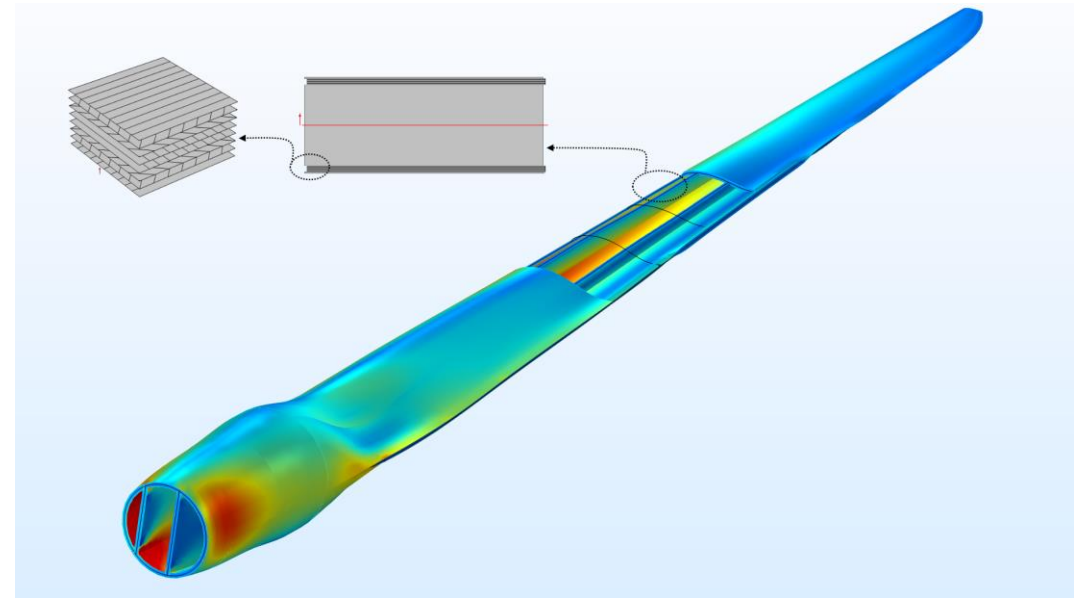
# COMSOL® Products for Composite Modeling

## Required products:

- COMSOL Multiphysics®
- Structural Mechanics Module (or MEMS Module)
- Composite Materials Module\*

## Possible extensions:

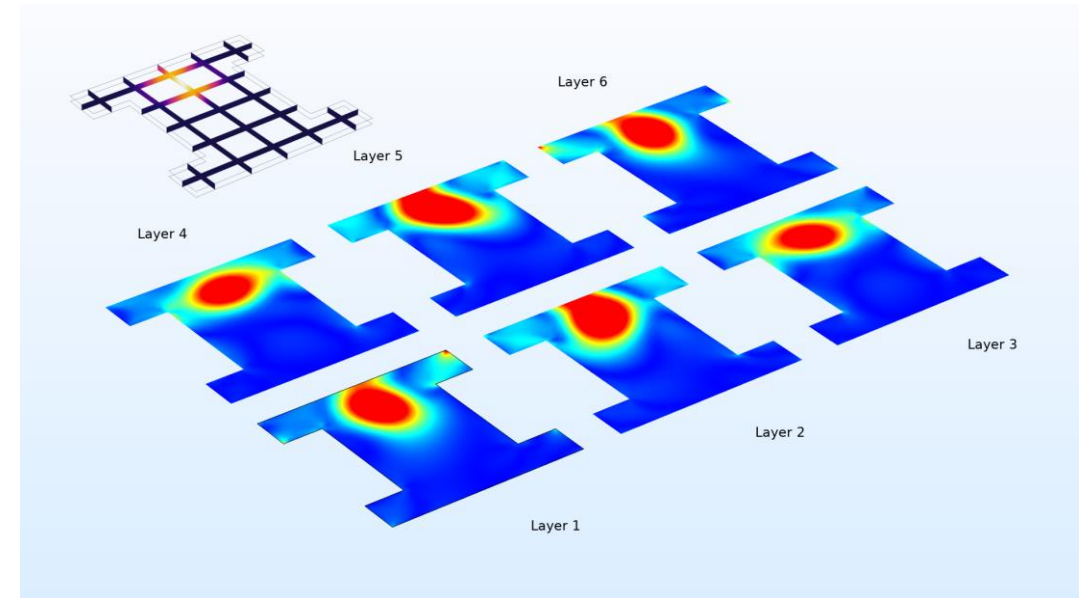
- Nonlinear Structural Materials Module
- Multibody Dynamics Module
- Fatigue Module
- For multiphysics
  - Heat Transfer Module
  - AC/DC Module
  - Acoustics Module
  - CFD Module



*Model of a wind turbine composite blade. The blade sandwich structure and stacking sequence are also shown.*

# Composite Materials Module

- Tool for analyzing layered composite structures or simple laminates made up of linear or nonlinear materials
- Uses the layered material technology
- Objective is to optimize the layup and other parameters of a laminate by performing multiscale, multiphysics, and various failure analyses



*Thermal stress in a composite laminate.*

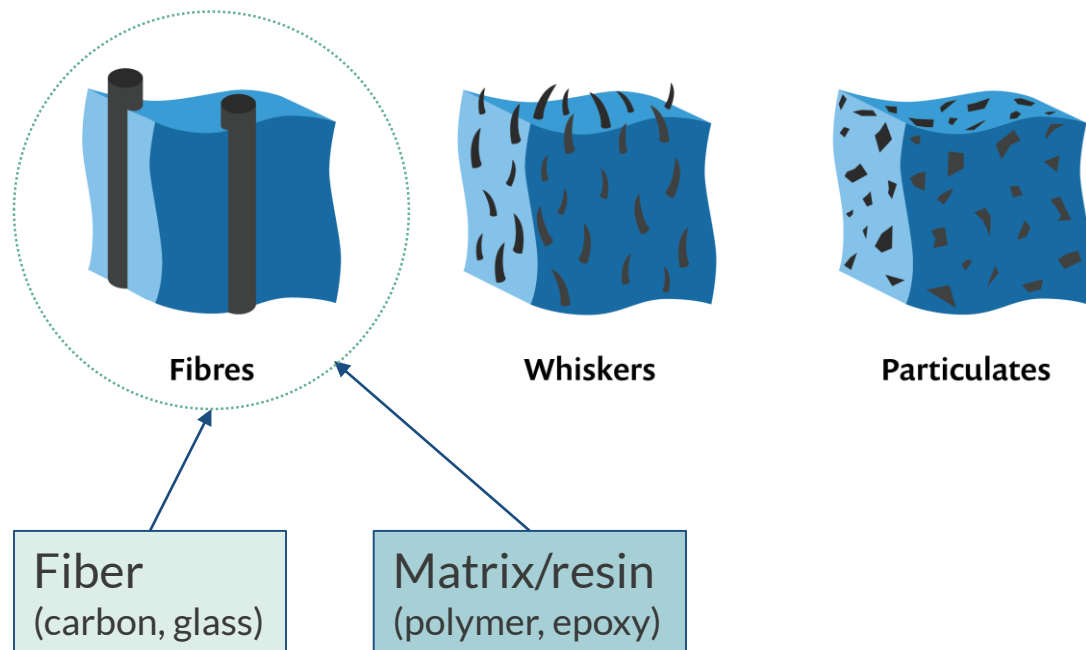
# Composite Materials Module Overview

- Layered shell element
  - Layerwise theory (mixed shape order possible)
  - Equivalent single layer theory (shell and membrane versions)
- Layered material
  - Layered material stack, preview plots, connection, ..
- Specialized tool for postprocessing
  - Layered material dataset, layered material slice plot, through thickness plot, ..
- Nonlinear material models <sup>\*</sup>
  - Plasticity, hyperelasticity, viscoplasticity, creep, ..
- Failure analysis
  - First-ply failure, delamination, linear buckling, ..
- Multiscale analysis
  - Micromechanics
  - Macromechanics
- Multiphysics analysis
  - Heat transfer, electromagnetics
  - Acoustics, fluid flow
- More
  - Layer activation
  - Variable thickness layers

# Introduction: Composite Materials and Laminate Theories

# What Is a Composite Material?

- A composite material is a heterogeneous material composed of two or more integrated constituents for enhanced structural performance



## Scope of Composite Materials Module:

- Fiber-based composites
  - CFRP (Carbon FRP)
  - GFRP (Glass FRP)
  - AFRP (Aramid FRP)
  - BFRP (Boron FRP)
- Laminated shells
- Sandwich panels

# Why Use Composite Materials?

## ■ Why use composite materials?

- High strength-to-weight ratio
- Material properties can be customized
- High resistance to fatigue and corrosion degradation
- Improved friction and wear properties
- Low thermal conductivity and low coefficient of thermal expansion

## ■ Why not replace metals then?

- High cost of raw materials and fabrication
- Difficulty in reuse and disposal
- Difficulty in joining different components
- Different types of failure modes
- Anisotropic materials – difficult to analyze

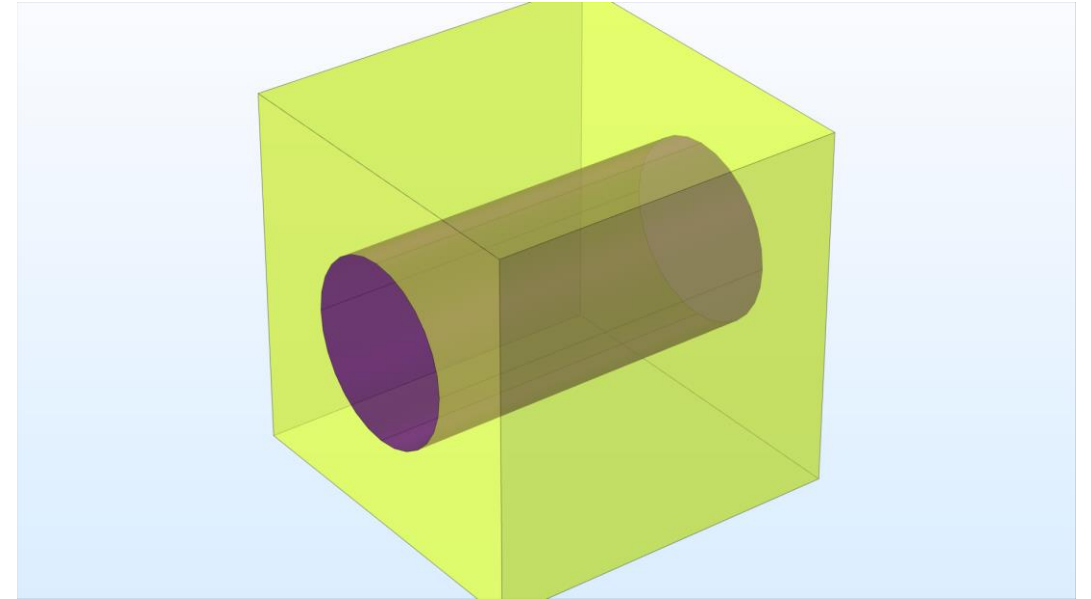


*Need for numerical simulations*



# Composite Materials Application Areas

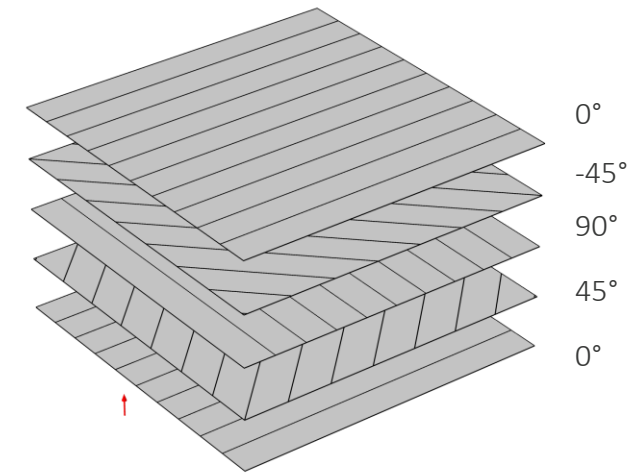
- Aircraft industry
- Defense industry
- Wind turbine industry
- Building and construction industry
  - Doors, panels, frames, bridges
- Chemical industry
  - Pressure vessels, storage tanks, piping, reactors
- Automobile and transportation industry
  - Bicycles, automobile components
- Marine and railway industry
  - Boat hulls, rail components
- Consumer and sports goods
  - Tennis racket, golf club shaft
- Electrical and electronics industry
  - Distribution pillars, link boxes
- Orthopedic aids
- Safety equipment



*Micromechanical model of ply having fiber and matrix.*

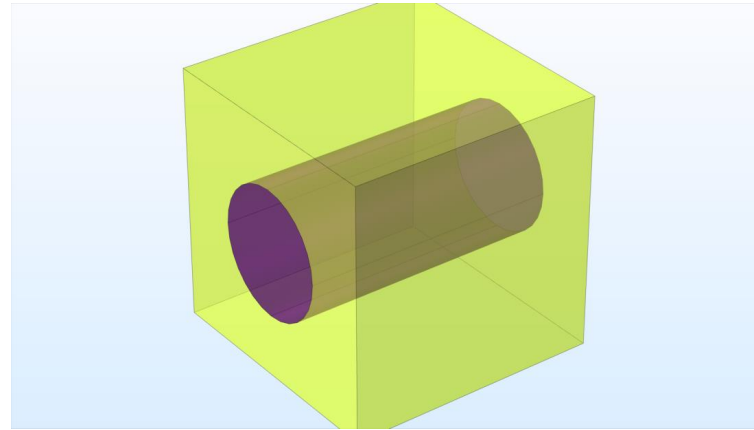
# Stacking Sequence and Laminate Types

- Stacking sequence is the fiber orientation in each ply with respect to the main axis of the laminate coordinate system
- Based on the stacking sequence, laminates can be classified as:
  - Angle-ply
  - Cross-ply
  - Balanced
  - Symmetric
  - Antisymmetric

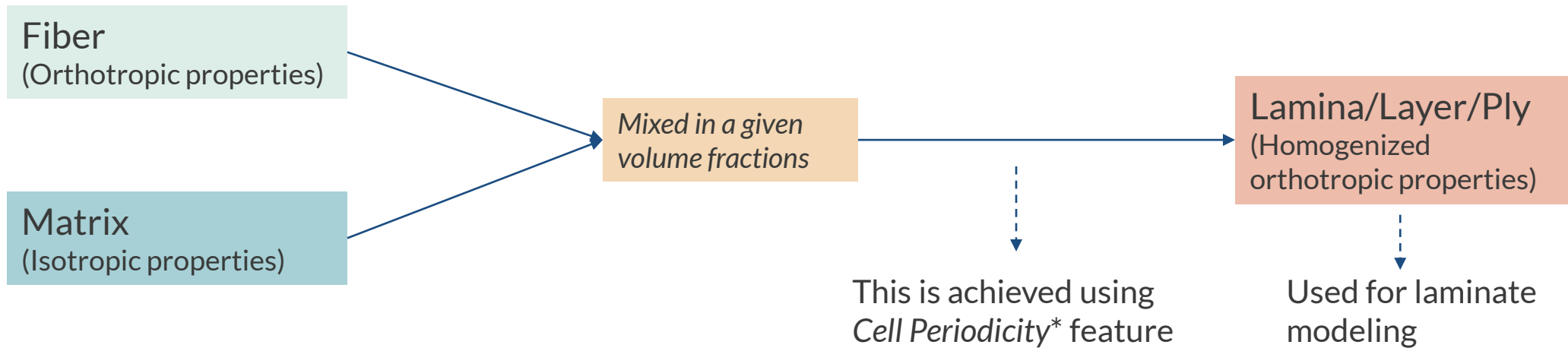


*Stacking sequence of an antisymmetric balanced laminate.*

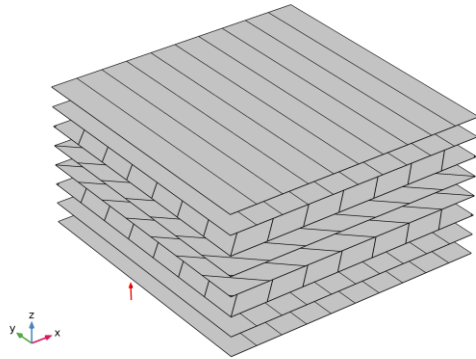
# Micromechanics: Fiber-Matrix Modeling



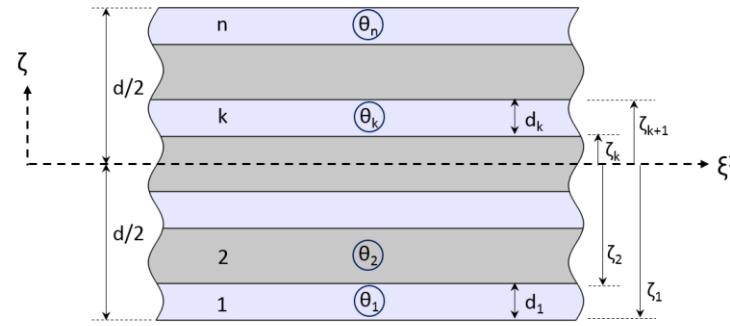
*Representative unit cell of a fiber composite layer having 20% fiber volume fraction.*



# Macromechanics: Laminate Modeling



Stacking sequence of a laminate



Cross section of a laminate

Stacking sequence

Material properties of each layer

Thickness of each layer

Number of sublayers in each layer



Step-1

Surface geometry

Laminate coordinate system

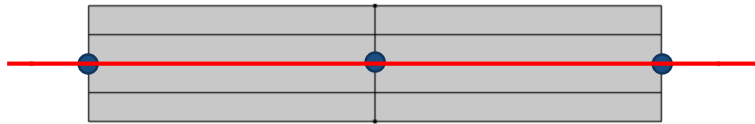
Physical offset



Step-2

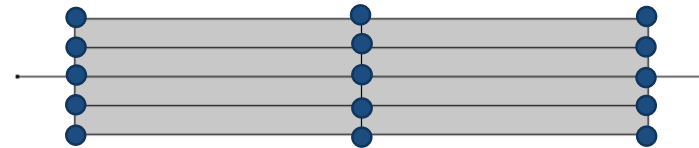
# Laminate Theories

- Equivalent Single Layer (ESL) theory:
  - Computes homogenized material properties of entire laminate and solves only at midplane



Available in *Layered Linear Elastic Material* node in *Shell* and *Membrane* interfaces.

- Layerwise (LW) Theory:
  - Solves also in thickness direction and can be used for very thick laminates including delaminated regions



Available in *Layered Shell* interface.

# Laminate Theories

## Equivalent Single Layer (ESL) theory

- Shell formulation
- Thin to moderately thick laminates
- Well suited for global responses
  - Maximum stresses, gross deflections, eigenfrequencies, buckling etc.
- Computationally inexpensive
  - Cost almost independent of number of layers (for linear materials)
- Shear correction factor needed for thicker laminates

## Layerwise (LW) theory

- Solid-like formulation
- Moderately thin to thick laminates
- Predicts interlaminar stresses
- Delamination modeling
- Supports piezoelectric layers
- Computationally expensive
  - Degrees of freedom grows with number of layers
- Shear is inherent in the formulation

# Assumptions/Restrictions in ESL Theory

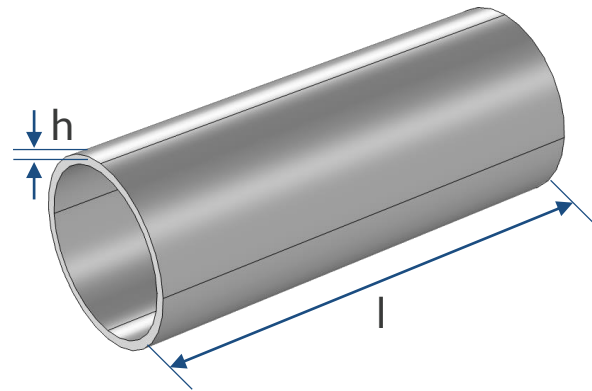
## ■ Assumptions:

- Straight lines perpendicular to the midsurface remain straight after deformation
- Plane stress condition is assumed
- The transverse normal strain is nonzero, but it is not part of the formulation and is ignored while expressing the energy of the system

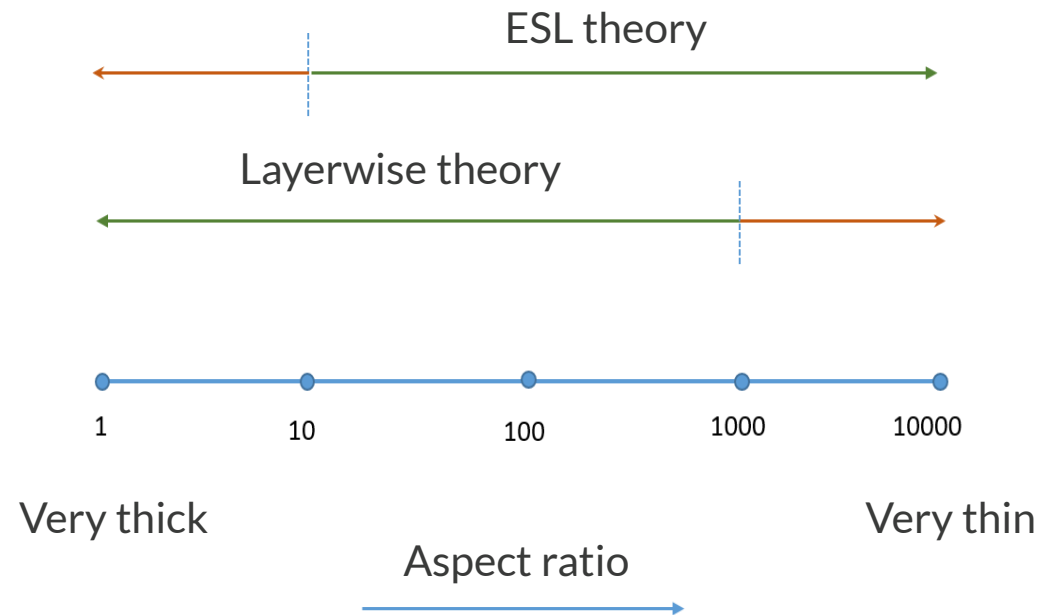
## ■ Restrictions:

- Material in each layer is assumed linear elastic and orthotropic
- Each layer has a uniform thickness
- All layers are perfectly bonded together
- Transverse shear stresses at the top and bottom surfaces of a laminate are zero

# Laminate Theory Validity



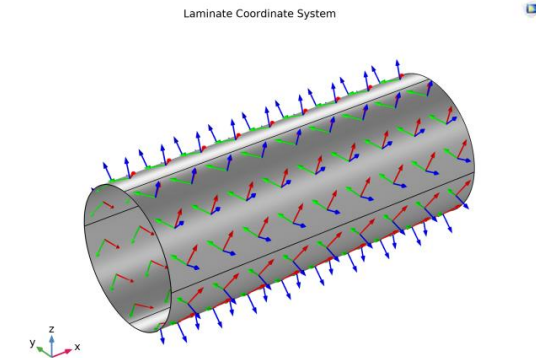
Aspect ratio =  $l/h$





# Benefits of Layerwise Theory over 3D Elasticity

- Easy to set up laminate coordinate system and built-in layer local coordinate system
- Possibility to have separate (either lower or higher) shape function order in thickness direction to avoid shear locking or to gain accuracy
- No need to build a 3D geometry with many thin layers
- In-plane finite element meshing is independent of the out-of-plane meshing
- Easy to handle layerwise and interfacial data



*Built-in laminate coordinate system and layer local coordinate system.*

Discretization
Displacement field:
Quadratic Lagrange
Linear
Quadratic Lagrange
Quadratic serendipity
Cubic Lagrange
Cubic serendipity
Quadratic-linear Lagrange
Quadratic-linear serendipity
Quadratic-cubic Lagrange
Quadratic-cubic serendipity

*Mixed shape order discretization.*

# Key Features: Composite Materials Module

# Layered Material

- Add required number of layers
- Define layer properties
  - Material, orientation, thickness, through-thickness mesh
- Input format
  - Directly enter in table, or load from a text file
- Interface materials (optional)
- Preview plots
  - *Layer Cross Section Preview*
  - *Layer Stack Preview*
- Saving and loading a layered material
- Sweeping over layered materials

Settings  
Layered Material

Label: Layered Material: [0/60/-60/0]\_s

Layer Definition

Layer	Material	Rotator	Thickness (m)	Mesh el
Layer 1	Material 1 (mat1)	0	th	1
Layer 2	Material 1 (mat1)	60	th	1
Layer 3	Material 1 (mat1)	-60	th	1
Layer 4	Material 1 (mat1)	0	th	1
Layer 5	Material 1 (mat1)	0	th	1
Layer 6	Material 1 (mat1)	-60	th	1
Layer 7	Material 1 (mat1)	60	th	1

Interface Property

Interface	Position (m)	Material
Layer 1 down	0	None
Layer 1-Layer 2	th	None
Layer 2-Layer 3	2*th	None
Layer 3-Layer 4	3*th	None
Layer 4-Layer 5	4*th	None
Layer 5-Layer 6	5*th	None
Layer 6-Layer 7	6*th	None

Preview Plot Settings

Distance between the orientation lines:  0.1

Thickness-to-width ratio: 0.5

Shows labels in cross section plot

Material Library Settings

User-Defined Library

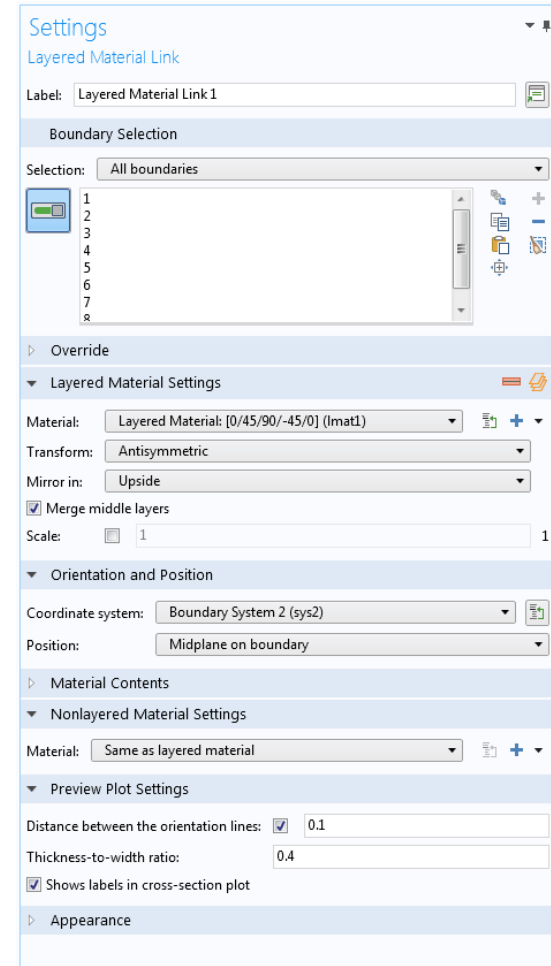
- composite cylinder buckling material
  - Material: Carbon-Epoxy
  - Layered Material: [0/0/45/-45]\_s

Switch 1 (sw1)

- Layered Material: [0/0/45/-45]\_s (sw1.lmat1)
- Layered Material: [90/90/45/-45]\_s (sw1.lmat2)
- Layered Material: [90/0/90/0]\_s (sw1.lmat3)
- Layered Material: [45/45/45/45]\_as (sw1.lmat4)

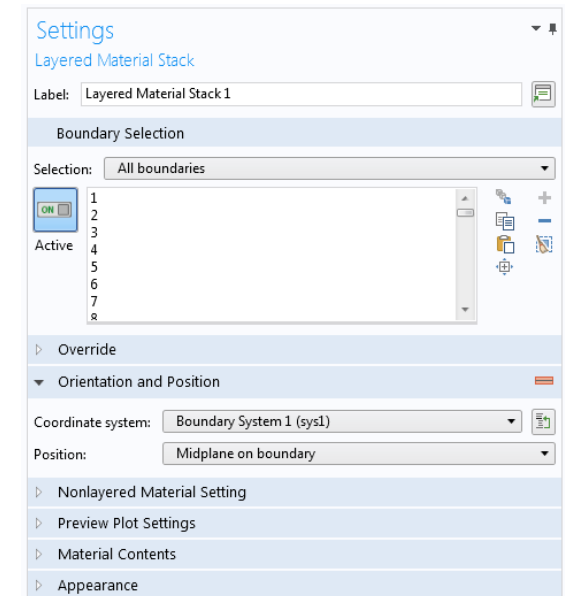
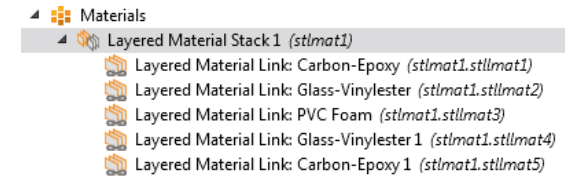
# Layered Material Link

- Define boundary selection
- Choose *Layered Material*
  - Choose a transform operation (optional)
  - Define a scale factor (optional)
- Orientation and position
  - Specify laminate coordinate system using *Boundary System*
  - Specify position of reference surface w.r.t. layered material
- This node allows the use of only single *Layered Material*



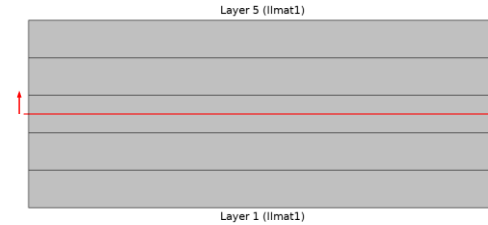
# Layered Material Stack

- Define boundary selection
  - Choose a transform operation (optional)
  - Define a scale factor (optional)
- Define new layered material or choose previously defined layered materials in the stacking order
  - Choose a transform operation (optional)
  - Define a scale factor (optional)
- Orientation and position
  - Specify laminate coordinate system using *Boundary System*
  - Specify position of reference surface w.r.t. layered material
- This node allows the use of multiple layered materials
  - Useful in modeling ply drop-off

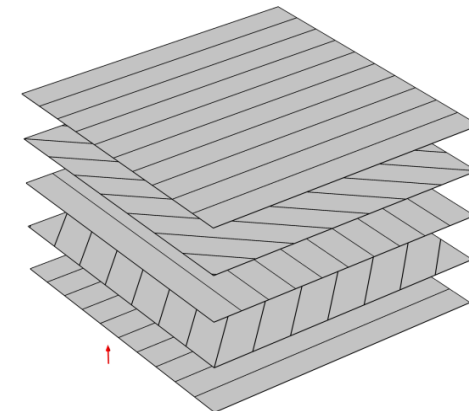


# Preview Plots

- Helps in visualizing layered material definition
  - Arrow (red) shows the stacking direction
  - Line (red) shows the position of the reference surface
- Customize preview plots
  - Change distance between orientation lines
  - Change thickness-to-width ratio



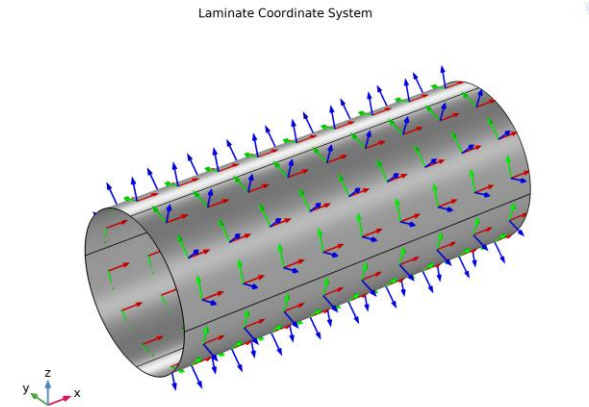
*Layer Cross Section Preview  
(Shows thickness of each layer  
and position of reference surface)*



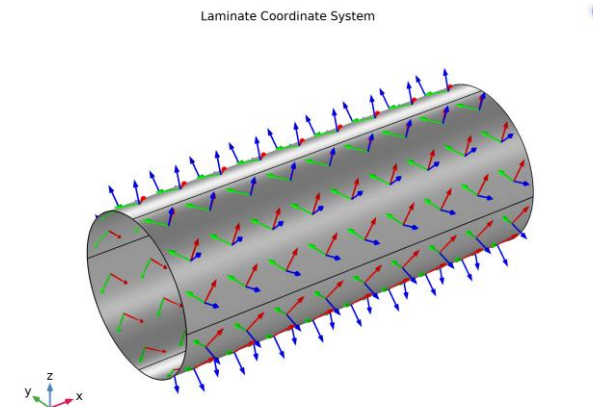
*Layer Stack Preview  
(Shows fiber direction in each layer)*

# Laminate Coordinate System

- Laminate coordinate system
  - Defined using Boundary System
  - The first tangent of the boundary system can be defined using other coordinate systems e.g. Cylindrical System
- Layer local coordinate system
  - Built-in
  - No need to setup curvilinear coordinate system for each layer

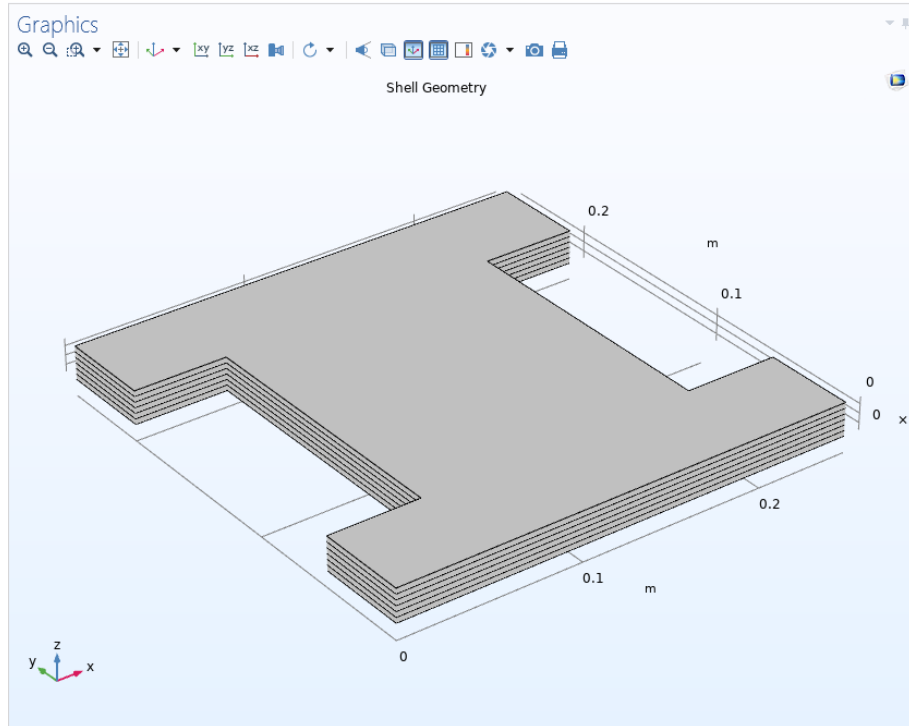


*Laminate coordinate system when the first axis is aligned with global x direction.*

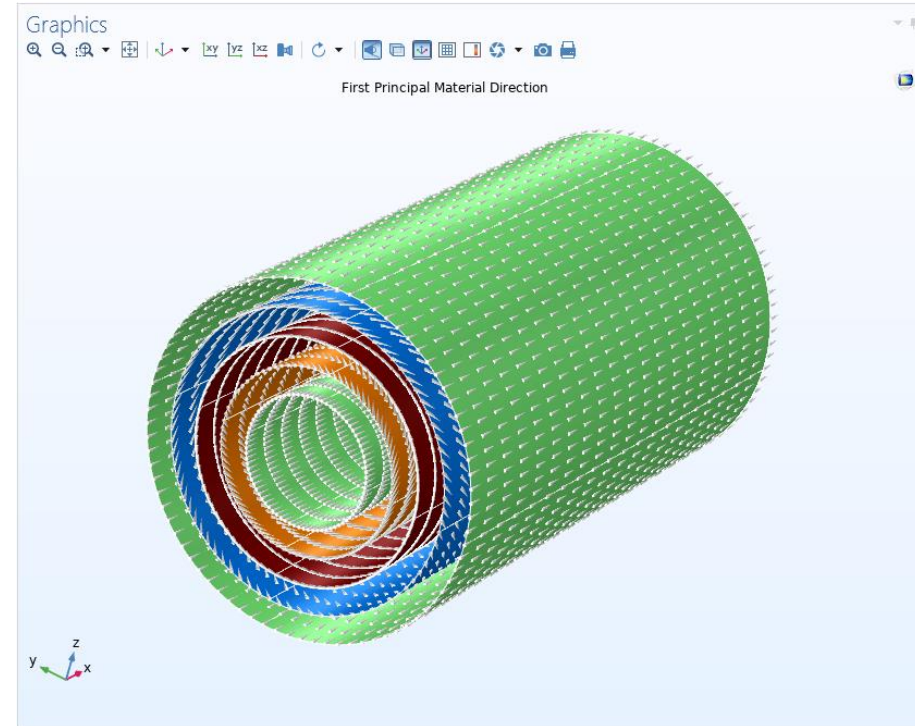


*Laminate coordinate system when the first axis is at 45° to the global x direction.*

# 3D Solid and Fiber Draping Visualization



*3D solid geometric representation (scaled in the thickness direction) of a composite laminate having six layers.*

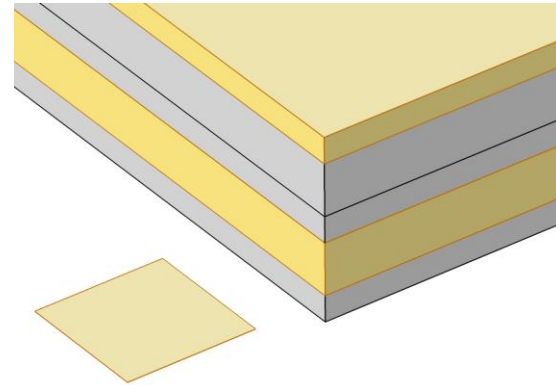


*First principal material direction showing the fiber draping direction in each layer of a composite cylinder.*



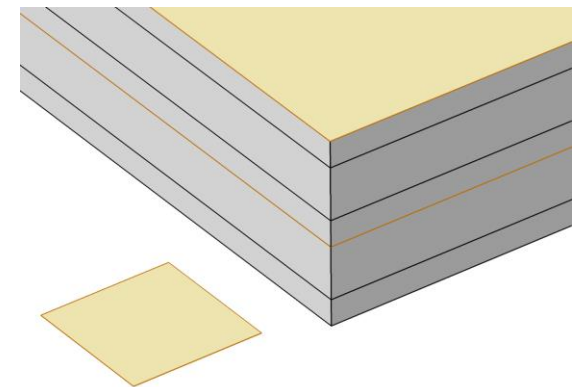
# Layer and Interface Selection

- In addition to geometric selections, the following selections can be made:
  - Layer selection
  - Interface selection
- There are six selections available:
  - Boundary + layer
  - Boundary + interface
  - Edge + layer
  - Edge + interface
  - Point + layer
  - Point + interface
- Material model is available on “boundary + layer” selection
- Different boundary conditions are available on different selections



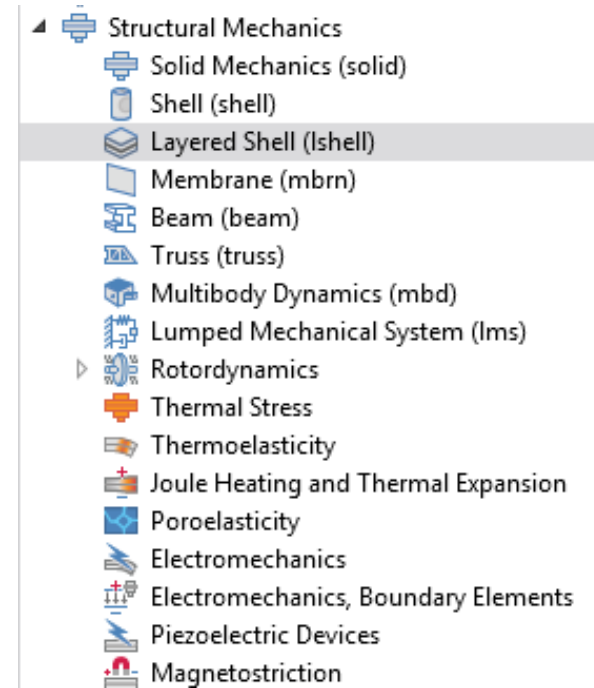
*Boundary + layer selection*

*Boundary + interface selection*



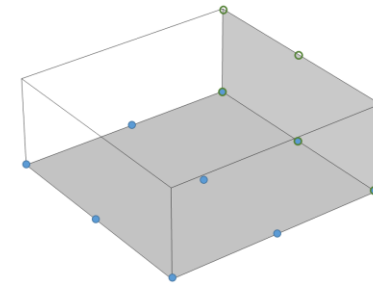
# Layered Shell Interface

- Available under Structural Mechanics in Model Wizard
- Based on *layerwise* laminate theory
- Supported space dimensions:
  - 3D
- Supported analysis types:
  - Stationary, Parametric
  - Time dependent
  - Eigenfrequency, Frequency domain
  - Linear Buckling
  - Random Vibration

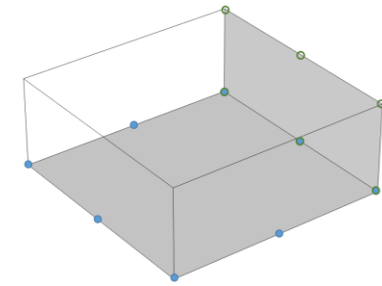


# Mixed Shape Discretization

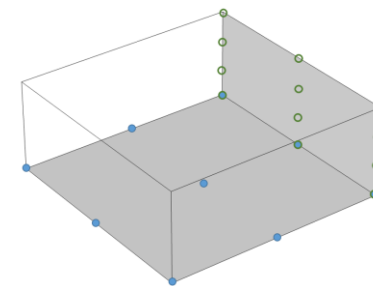
- The Layered Shell interface allows different shape order in base surface and thickness direction
- The four mixed shape elements available:
  - Quadratic-linear Lagrange
  - Quadratic-linear serendipity
  - Quadratic-cubic Lagrange
  - Quadratic-cubic serendipity
- Quadratic-linear shape
  - Faster simulation results
  - Can improve conditioning for thin shells
- Quadratic-cubic shape
  - Accuracy in through thickness results



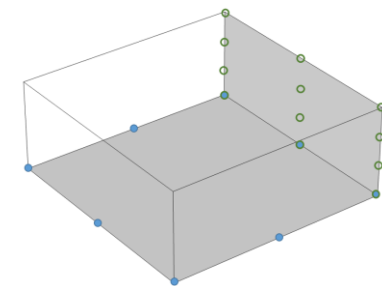
*Quadratic-linear Lagrange*



*Quadratic-linear serendipity*



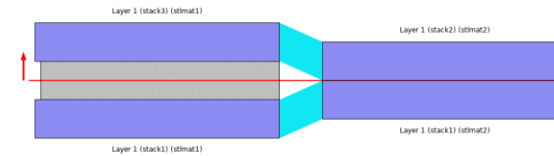
*Quadratic-cubic Lagrange*



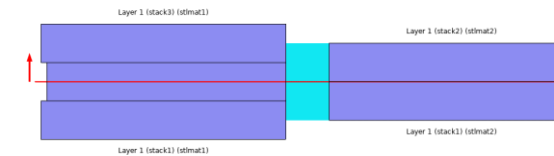
*Quadratic-cubic serendipity*

# Layered Material Continuity

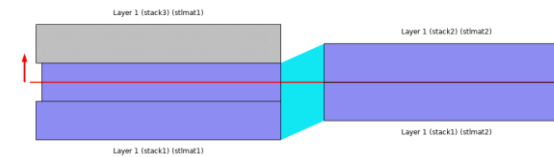
- Available through Continuity node in Layered Shell interface.
- Uses Layered Material Stack for modeling ply drop-off scenario.
- Possible to define offset in thickness direction while connecting two layered materials.



*Connecting the 1<sup>st</sup> and 3<sup>rd</sup> layer of left layered material to both the layers of right layered material. (ply drop-off scenario)*



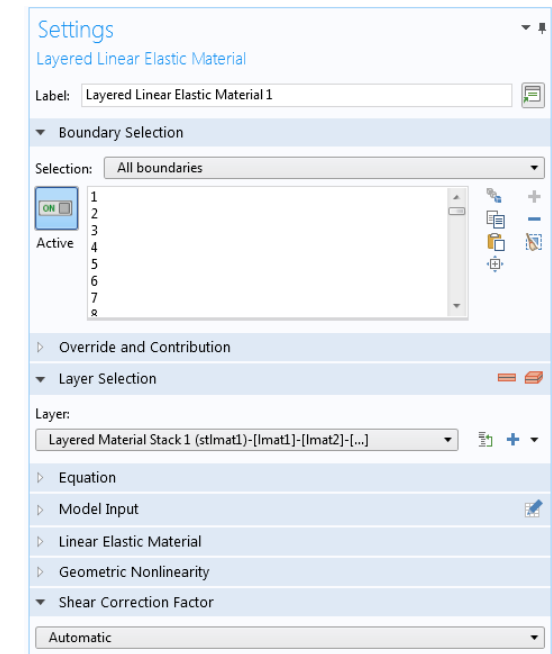
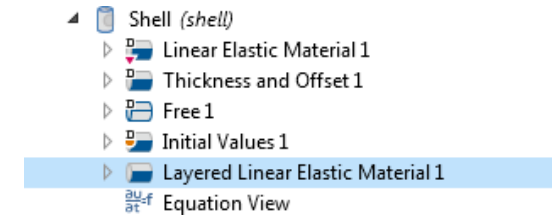
*Connecting the geometrically common area of both the layered materials.*



*Connecting the first two layers of left layered material to both the layers of right layered material.*

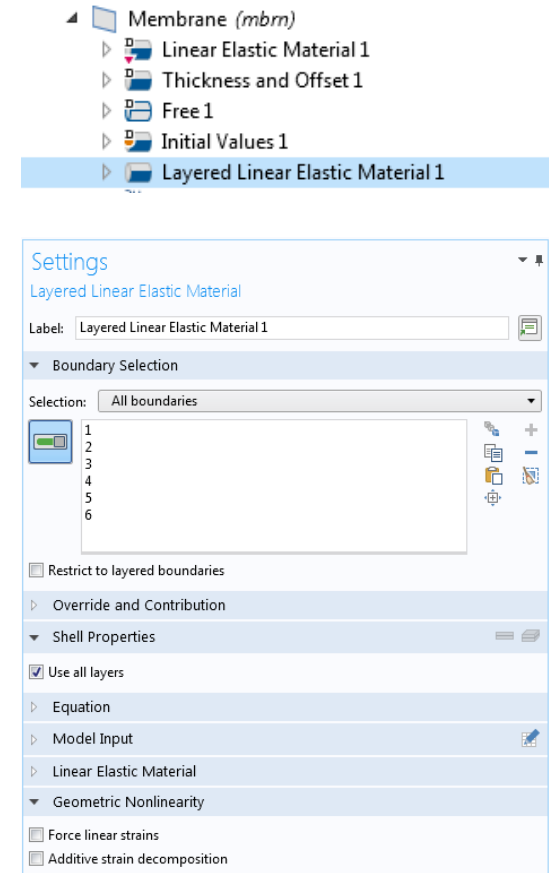
# Layered Linear Elastic Material (Shell)

- A material model in Shell interface
- Based on equivalent single layer laminate theory
  - First order shear deformation laminate theory
- Supported space dimensions:
  - 3D, 2Daxi
- Supported analysis types:
  - Stationary, Parametric
  - Time dependent
  - Eigenfrequency, Frequency domain
  - Linear Buckling
  - Random Vibration, Response Spectrum



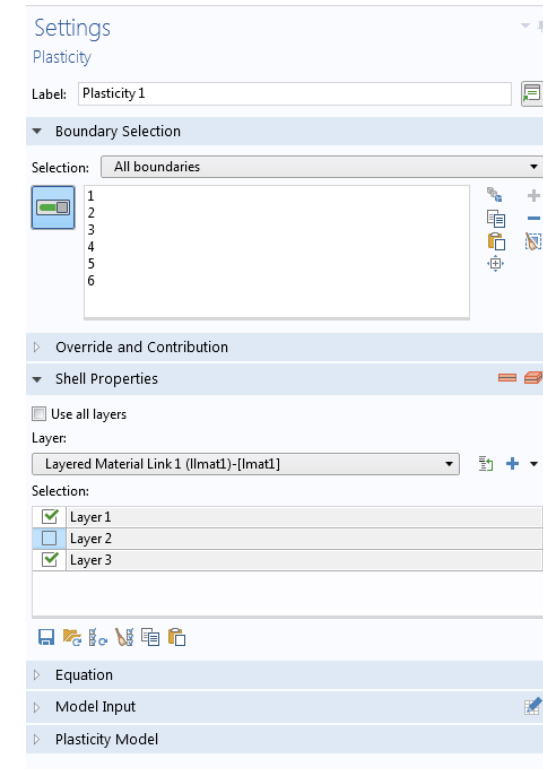
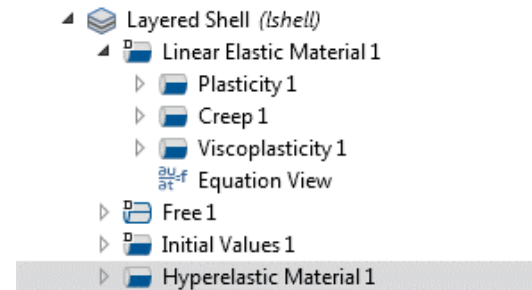
# Layered Linear Elastic Material (Membrane)

- A material model in Membrane interface
- Based on equivalent single layer laminate theory
  - Only membrane stresses
- Supported space dimensions:
  - 3D, 2Daxi
- Supported analysis types:
  - Stationary, Parametric
  - Time dependent
  - Eigenfrequency, Frequency domain
  - Random Vibration, Response Spectrum



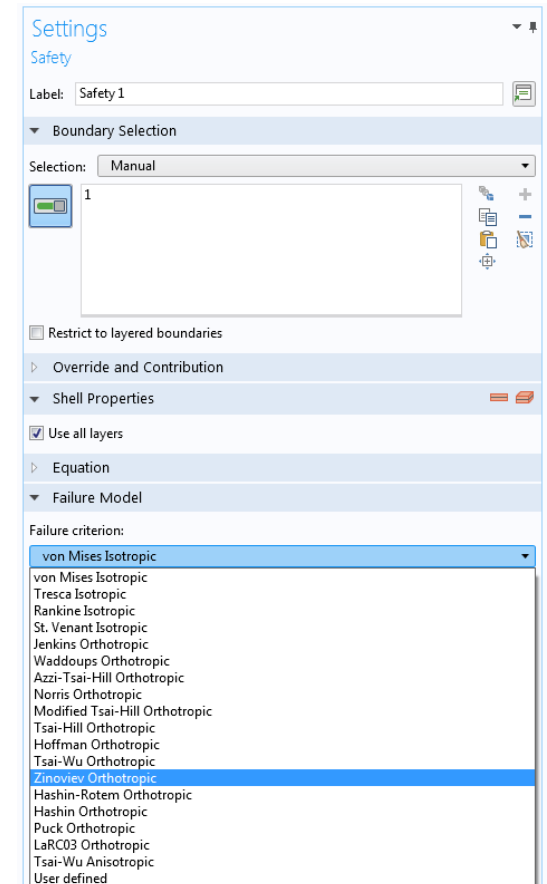
# Nonlinear Material Models

- Available in Layered Shell, Shell, and Membrane interfaces
- Linear Elastic Material
  - *Plasticity* \*
  - *Creep* \*
  - *Viscoplasticity* \*
- *Hyperelastic Material* \*
  - Only in Layered Shell interface
- Possible to have different material models in different layers of a laminate



# First Ply Failure (Safety)

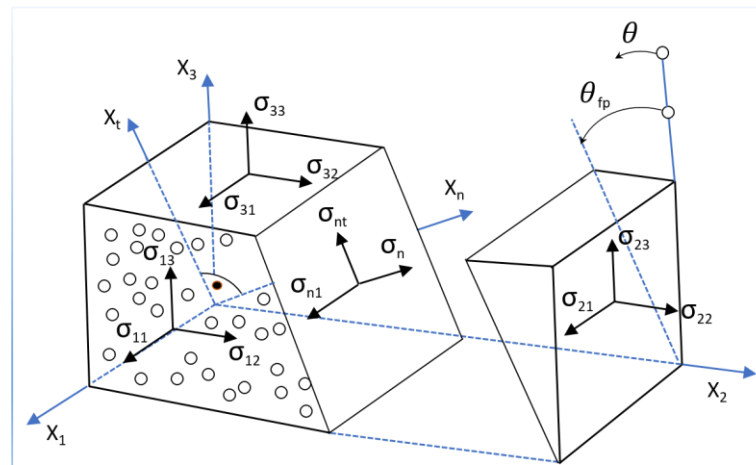
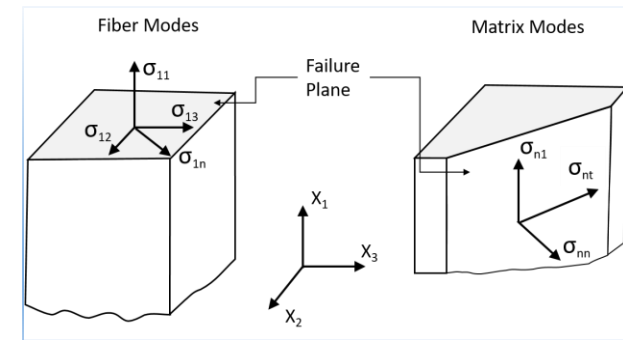
- The following failure criterion are available in both laminate theories:
  - von Mises
  - Tresca
  - Rankine
  - St. Venant
  - Jenkins
  - Waddoups
  - Tsai-Hill
  - Hoffman
  - Tsai-Wu
  - Tsai-Wu anisotropic
- Additionally, the equivalent single layer theory allows the following failure criteria:
  - Azzi-Tasi-Hill
  - Norris
  - Modified Tsai-Hill



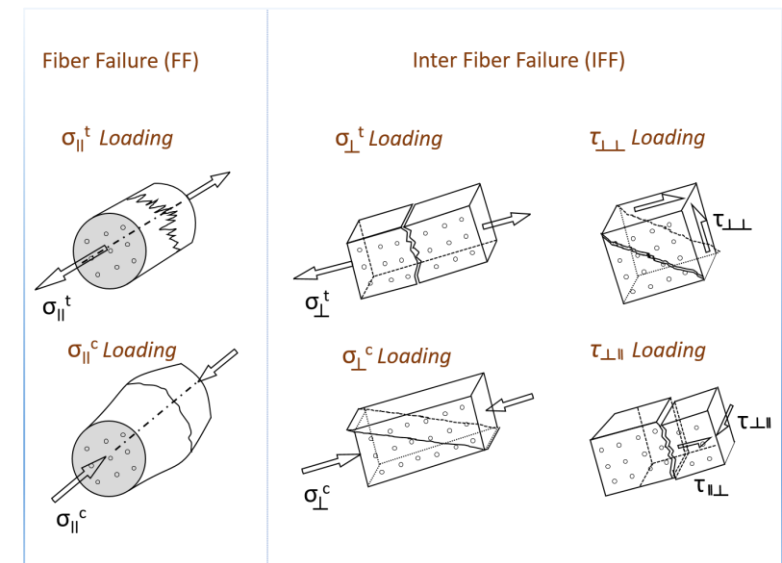


# First Ply Failure (Safety)

- Fiber composite specific failure criteria are available for both laminate theories:
  - Zinoviev
  - Hashin&Rotem
  - Hashin
  - Puck
  - LaRC03

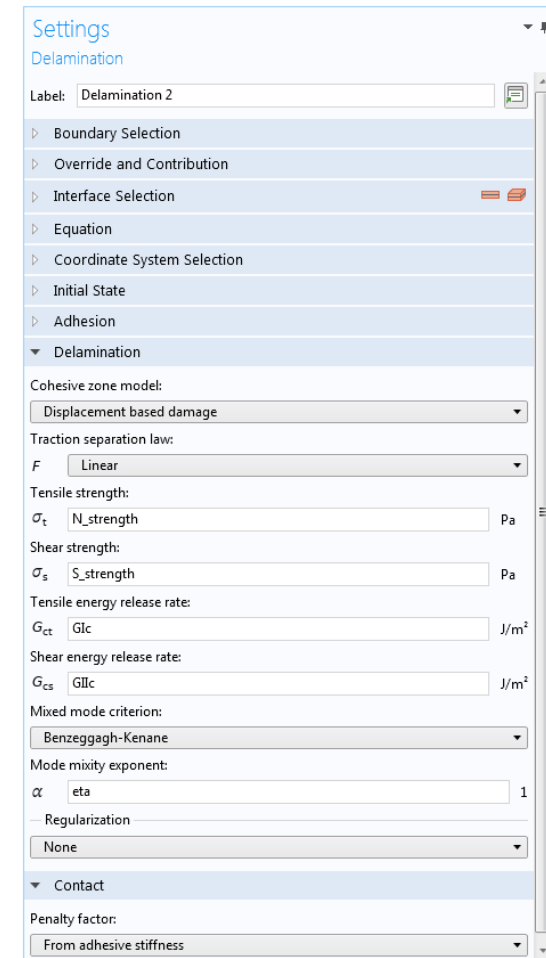
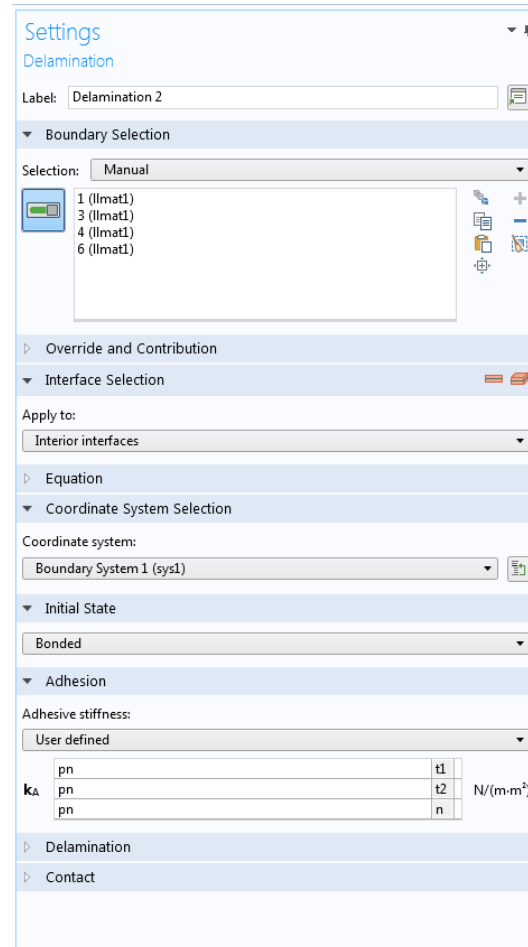


Failure modes in Puck criterion.



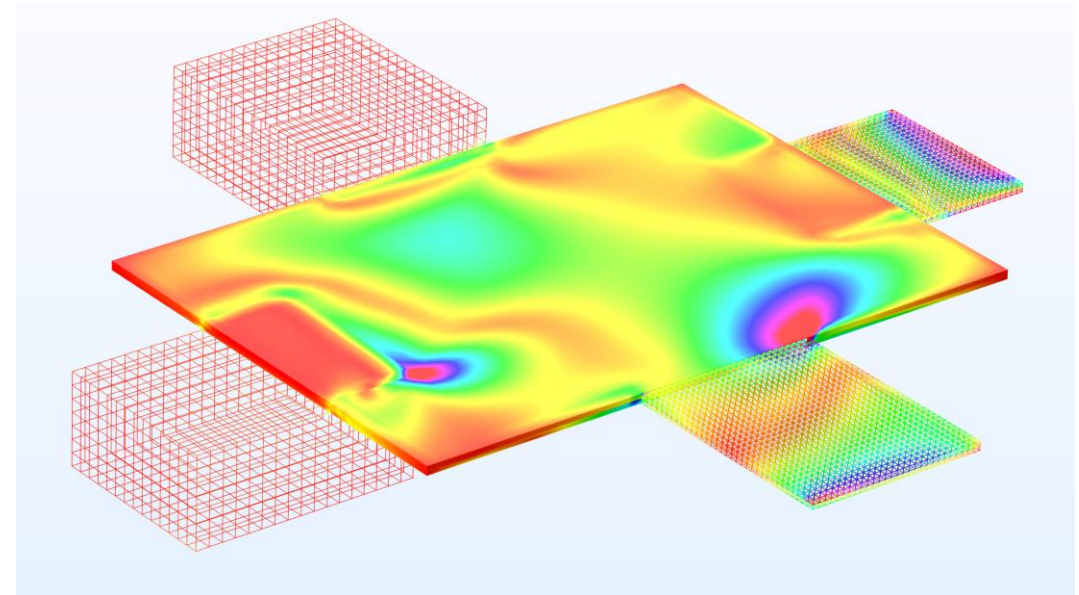
# Delamination

- Available in Layered Shell interface
- Initial state
  - Bonded or delaminated
- Adhesive stiffness
- Cohesive zone models
  - Displacement or energy based
- Traction-separation law
  - Linear, polynomial, exponential, ..
- Contact after delamination



# Structural Couplings

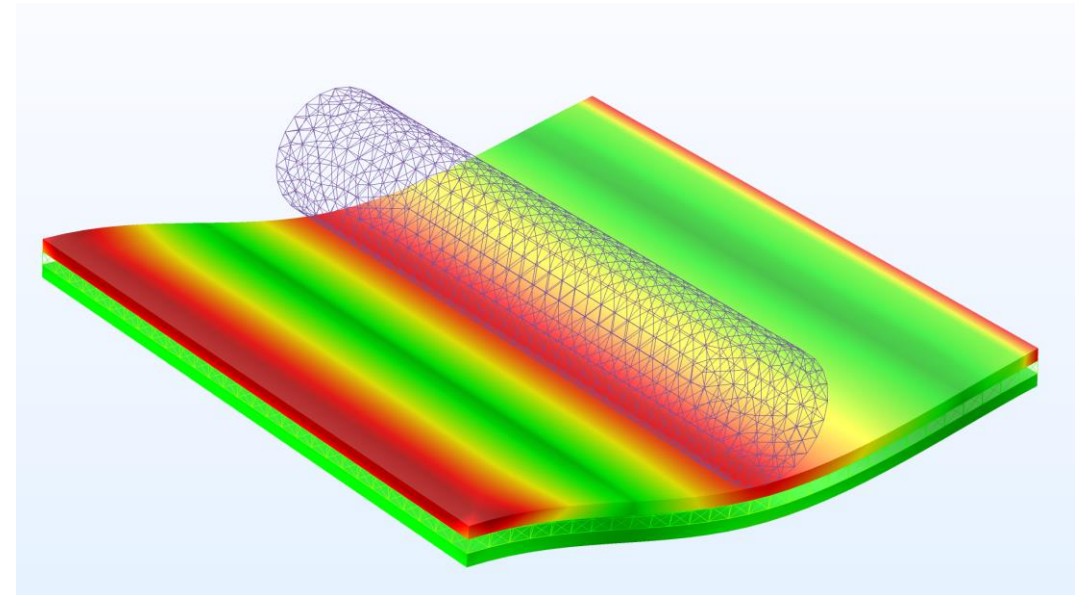
- *Layered Shell - Structure Cladding*
  - Couplings Layered Shell to Solid, Shell, or Membrane element
  - When two elements are in cladding configuration
- *Layered Shell - Structure Transition*
  - Couplings Layered Shell to Solid, or Shell, element
  - When two elements are in side-by-side configuration
- *Solid-Thin Structure Connection*
  - Couplings Shell, or Membrane to Solid element
  - When two elements are either in cladding or in side-by-side configuration



*Model of a layered shell connected to solid and shell elements in cladding and transition configurations. The results show the stress distribution in the layered shell (color plot) as well as in the solid and shell members (color wireframe plot).*

# Structural Contact

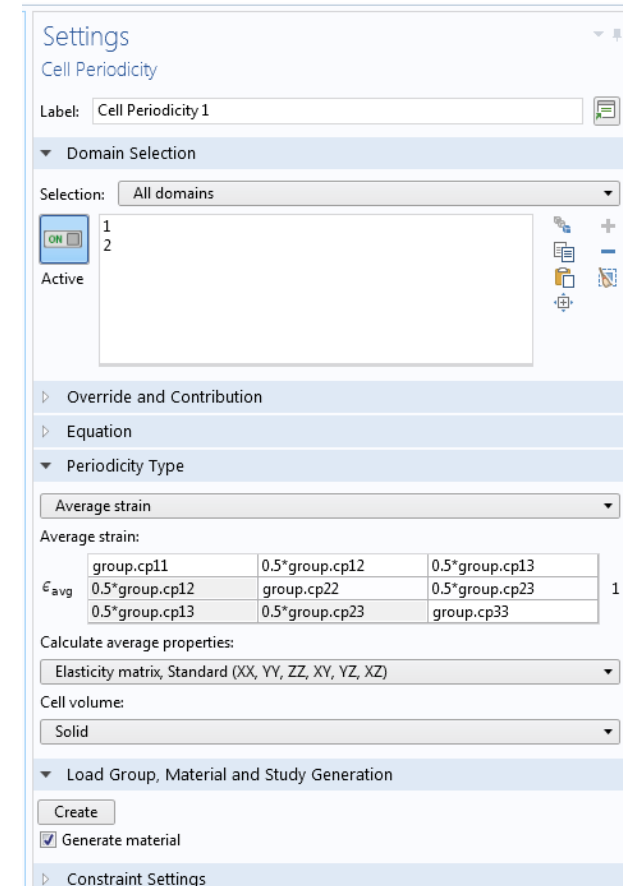
- Layered Shell to:
  - Layered Shell contact
  - Solid contact
  - Shell contact
  - Membrane contact
  - Meshed surface contact
  
- Shell/Membrane to:
  - Shell contact
  - Membrane contact
  - Layered Shell contact
  - Solid contact
  - Meshed surface contact



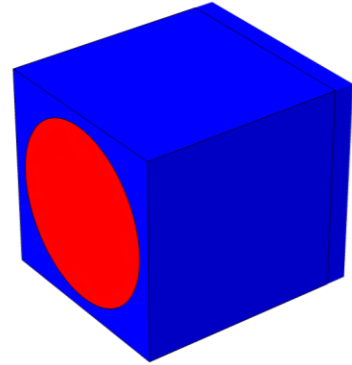
*Stress distribution in different layers of a composite laminate while modeling contact with a cylindrical surface.*

# Micromechanics (Cell Periodicity)

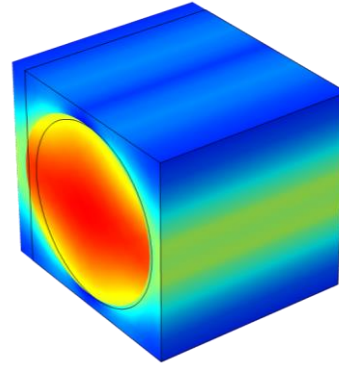
- Micromechanics analysis can be performed using Cell Periodicity node in Solid Mechanics interface.
- Needs 3D solid geometry of a unit cell (RVE) having fiber-matrix and their material properties.
- Solves for six load cases.
- Creates a node containing homogenized material data.



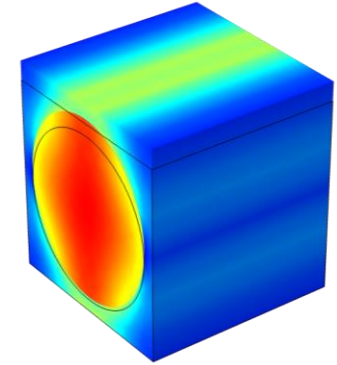
# Micromechanics (Cell Periodicity) (contd.)



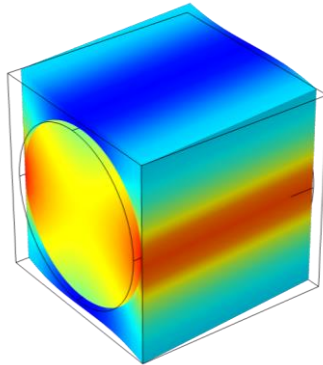
Load case 1  
Strain  $XX$



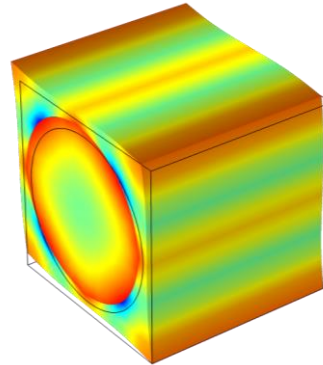
Load case 2  
Strain  $YY$



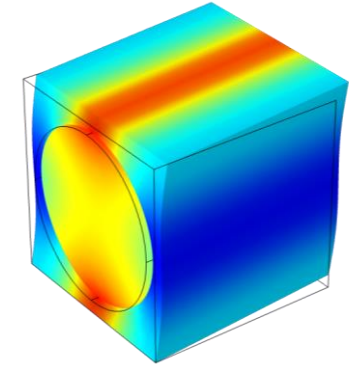
Load case 3  
Strain  $ZZ$



Load case 4  
Strain  $XY$



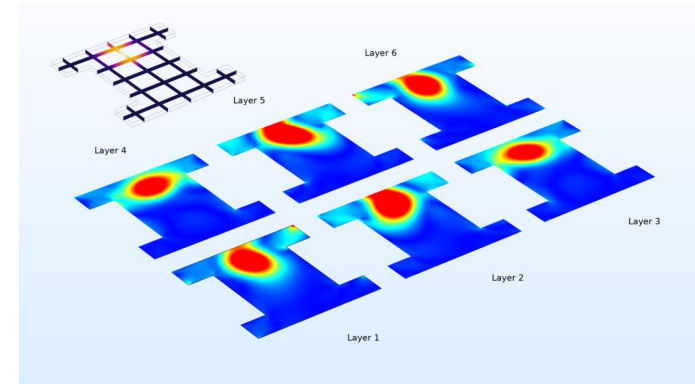
Load case 5  
Strain  $YZ$



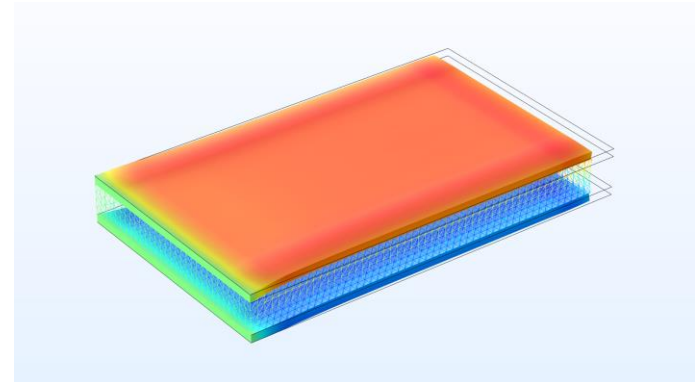
Load case 6  
Strain  $XZ$

# Multiphysics Couplings

- Multiphysics coupling nodes available for Layered Shell, Shell, Membrane interfaces:
  - Heat transfer
  - Acoustics
  - Fluid flow
  
- Piezoelectricity, Layered Shell\* interface:
  - *Layered Shell*
  - *Electric Currents in Layered Shells*
  - *Layered Piezoelectric Effect*



*Thermal stress in a composite laminate.*

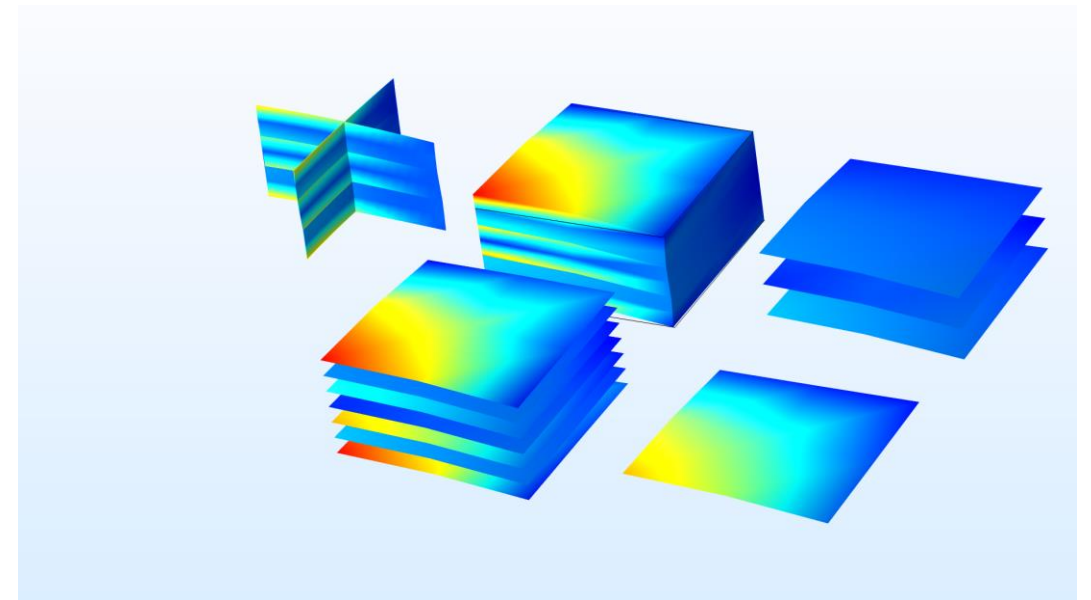


*Out-of-plane displacement in piezoelectric composite laminate.*



# Layered Material Data Set

- Visualize the results on a geometry with finite thickness
- Possible to scale the geometry in thickness direction
  - Select one or more layers
- Possible to plot the results on
  - Surface/volume on a 3D geometry
  - Slices in the 3D geometry
- Possible to evaluate results in thickness direction

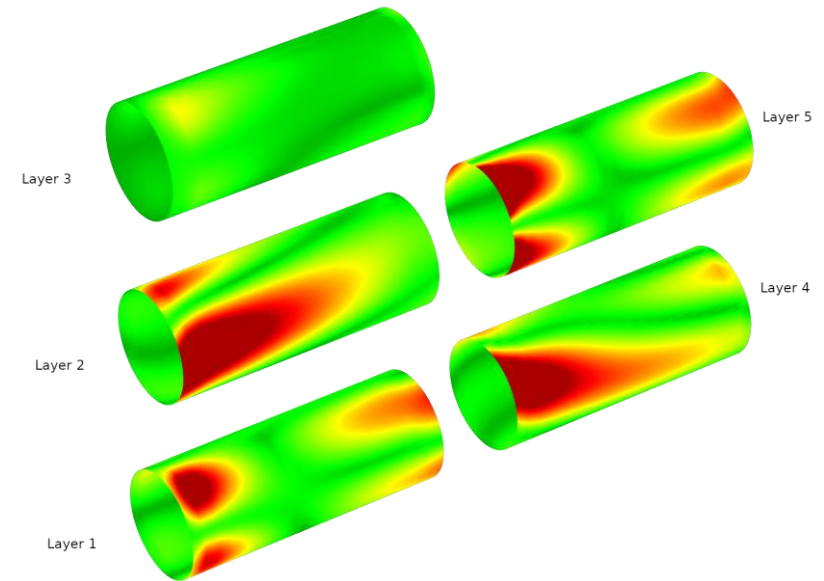


*Various plots created using layered material data set.*



# Layered Material Slice Plot

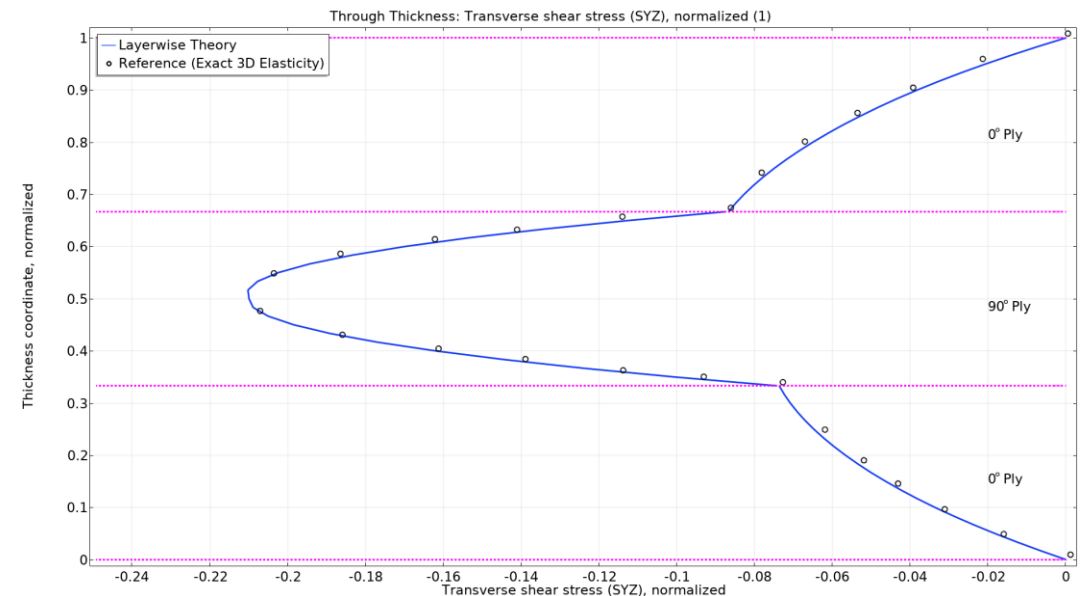
- Provides more freedom in terms of creating slices in a composite laminate:
  - Creating a slice only through one or a few selected layers
  - Creating a slice at a particular position within the layer that is not the midplane
  - Creating a slice through some or all layers, but not necessarily placing them in the through-thickness direction
  - Defining a layout when using multiple slices
  - Adding layer names to each slice



*von Mises stress in the middle of each layer plotted using layered material slice plot.*

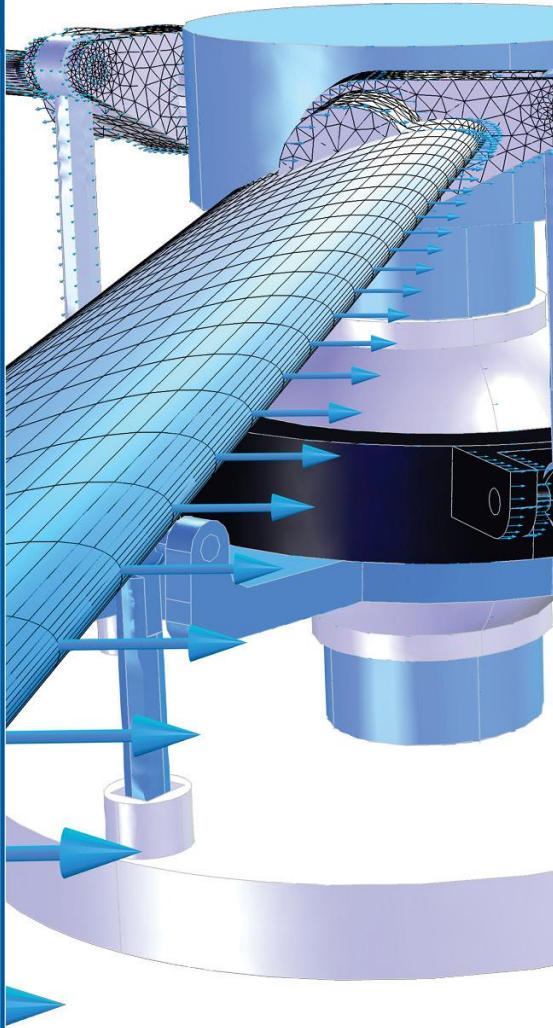
# Through Thickness Plot

- Visualize the variation of any quantity through the laminate thickness
- Select one or more geometric points on the boundary or optionally create cut point datasets
- Possible to enter the point coordinates directly
- The result quantity is plotted on the x-axis, while the thickness coordinate is plotted on the y-axis



*Transverse shear stress distribution in through thickness direction of a laminate.*

# Interfacing CAD & Mesh



## COMSOL MULTIPHYSICS®, COMSOL SERVER™, & STANDALONE APPLICATIONS

### LIVELINK™ INTERFACES

- ↔ LiveLink™ for AutoCAD®
- ↔ LiveLink™ for Inventor®
- ↔ LiveLink™ for PTC® Creo® Parametric™
- ↔ LiveLink™ for PTC® Pro/ENGINEER®
- ↔ LiveLink™ for Revit®
- ↔ LiveLink™ for SOLIDWORKS®
- ↔ LiveLink™ for Solid Edge®

### MESH FILE FORMATS

- ↔ 3MF
- ↔ NASTRAN®
- ↔ PLY
- ↔ STL
- ← VRML

### 2D CAD FILE FORMATS

- ↔ DXF™

### 3D CAD FILE FORMATS

- ↔ ACIS®
- ← AutoCAD®
- ← CATIA® V5 <sup>1</sup>
- ↔ IGES
- ← Inventor®
- ← NX™
- ↔ Parasolid®
- ← PTC® Creo® Parametric™
- ← PTC® Pro/ENGINEER®
- ← SOLIDWORKS®
- ↔ STEP

### OTHER PRODUCTS

- ← Mimics®
- ← Simpleware

### ECAD FILE FORMATS

- ← GDSII
- ← IPC-2581
- ← ODB++

### GEOGRAPHIC INFORMATION SYSTEM (GIS)

- ← Digital Elevation Map (DEM)

**KEY** ↔ ASSOCIATIVE READ & MODIFY    ↔ READ AND WRITE    ← READ

<sup>1</sup> Not supported with COMSOL Compiler™

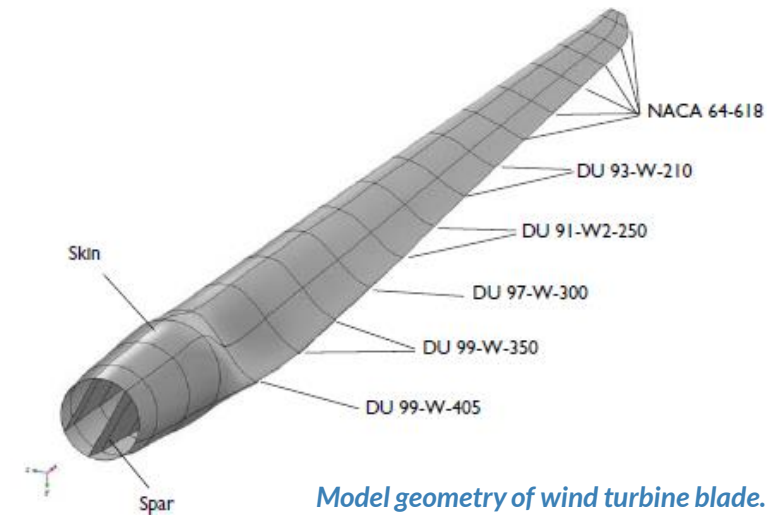
Support for implementation of the ODB++ Format was provided by Mentor Graphics pursuant to the ODB++ Solutions Development Partnership General Terms and Conditions ([www.odb-sa.com](http://www.odb-sa.com)).

For trademark ownership, see [www.comsol.com/trademarks](http://www.comsol.com/trademarks).

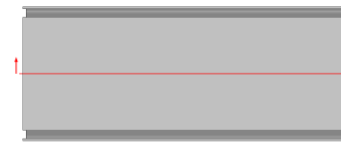
# Application Library

# Wind Turbine Composite Blade

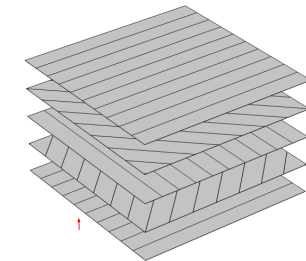
- A 61.5 m long wind turbine composite blade, having different airfoil sections, is modeled.
- The blade has a sandwich structure:
  - 10 Carbon fiber layers
  - 40 Glass fiber layers
  - 1 PVC foam layer
  - 40 Glass fiber layers
  - 10 Carbon fiber layers
- Stress distribution in skin and spar is computed under gravity and centrifugal forces.
- Natural frequencies and mode shapes at different speeds are also computed.



*Model geometry of wind turbine blade.*

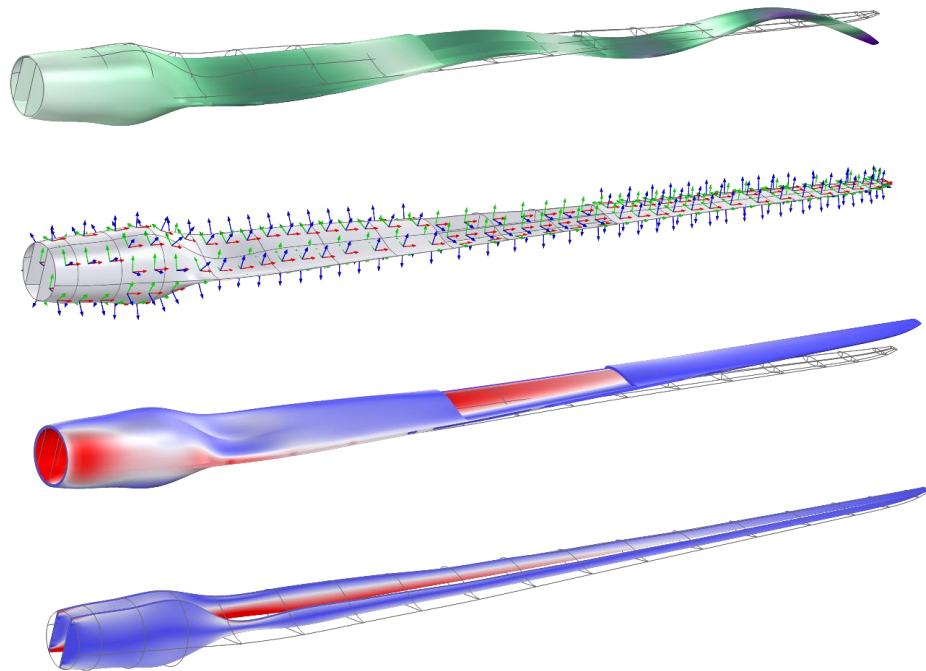


*Sandwich structure of the blade.*

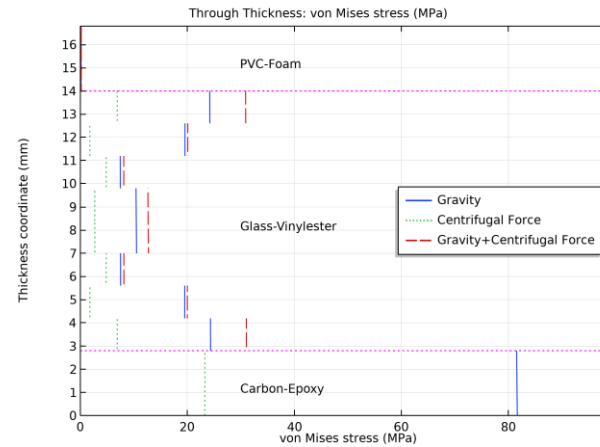


*Stacking sequence for carbon fiber layers.*

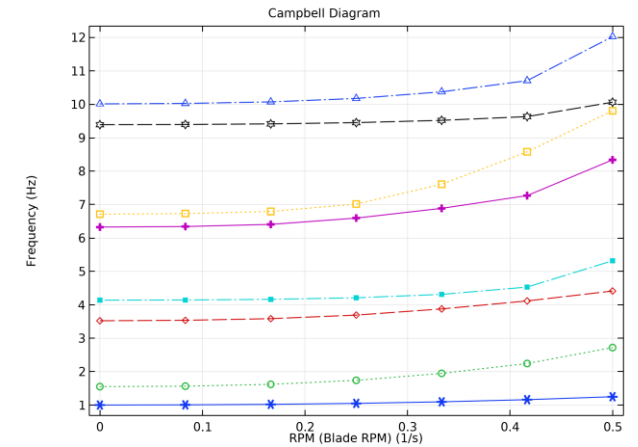
# Wind Turbine Composite Blade



One of the mode shapes, laminate coordinate system, stresses in skin, and stresses in spar (from top to bottom).



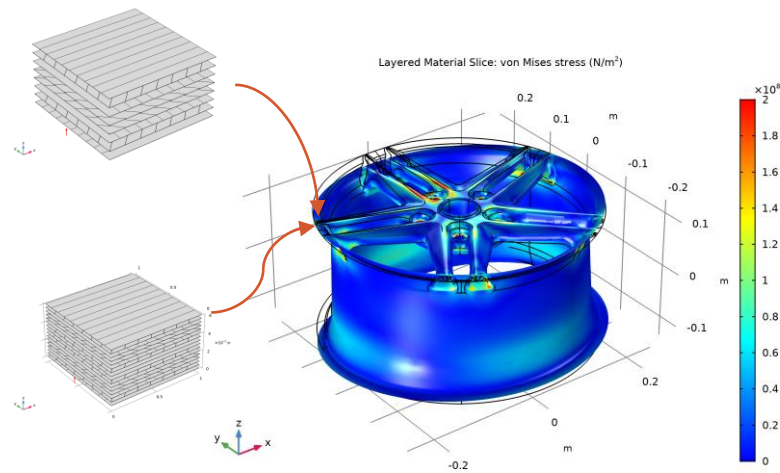
Through thickness stress variation.



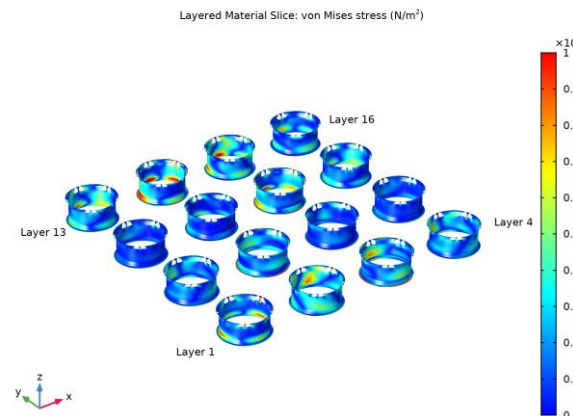
Campbell diagram.

# Composite Wheel Rim

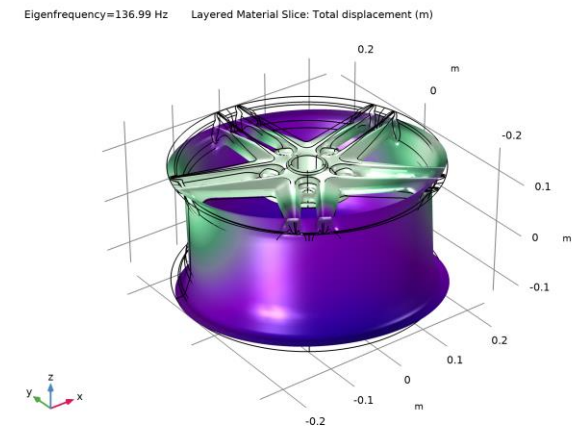
- Wheel rim made up of carbon-epoxy material, having different number of plies in different regions, is modeled.
- Stress analysis is performed when rim is subjected to inflation pressure and tire load.
- Natural frequencies and mode shapes are also computed when the rim is subjected to the rotating frame forces.



*Surface plot showing von Mises stress distribution in wheel rim.*



*Slice plot showing von Mises stress in each layer of rim.*

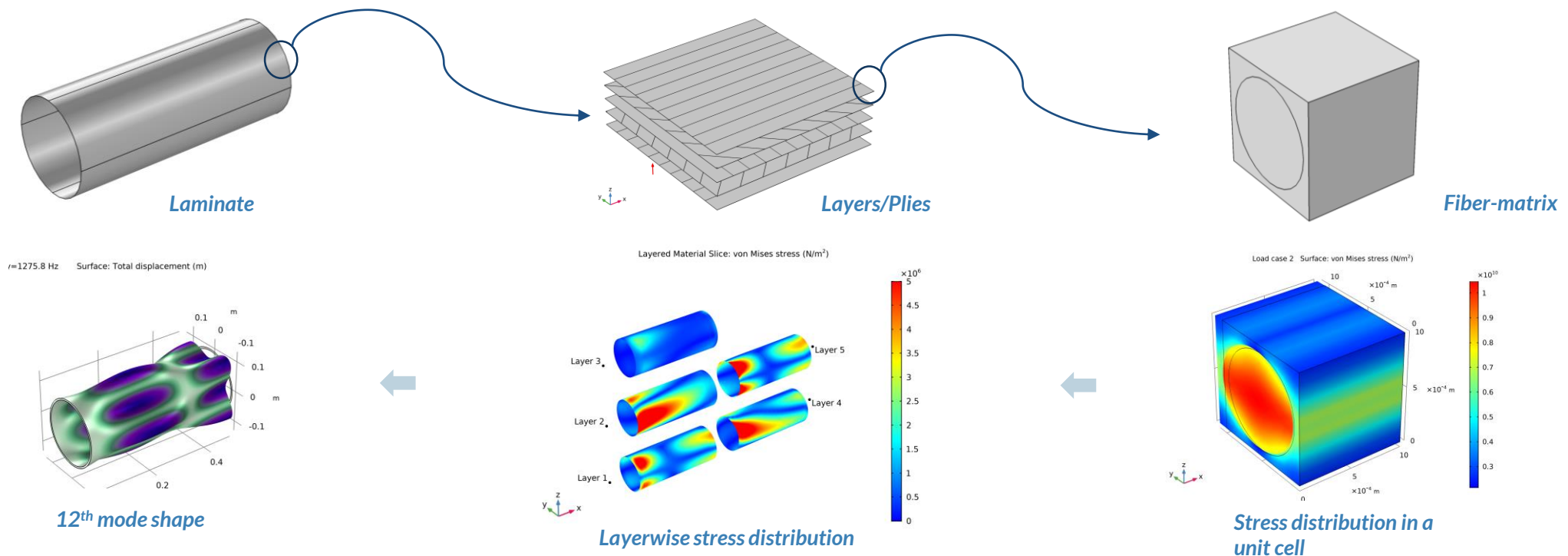


*First eigenmode.*



# Micromechanics and Stress Analysis

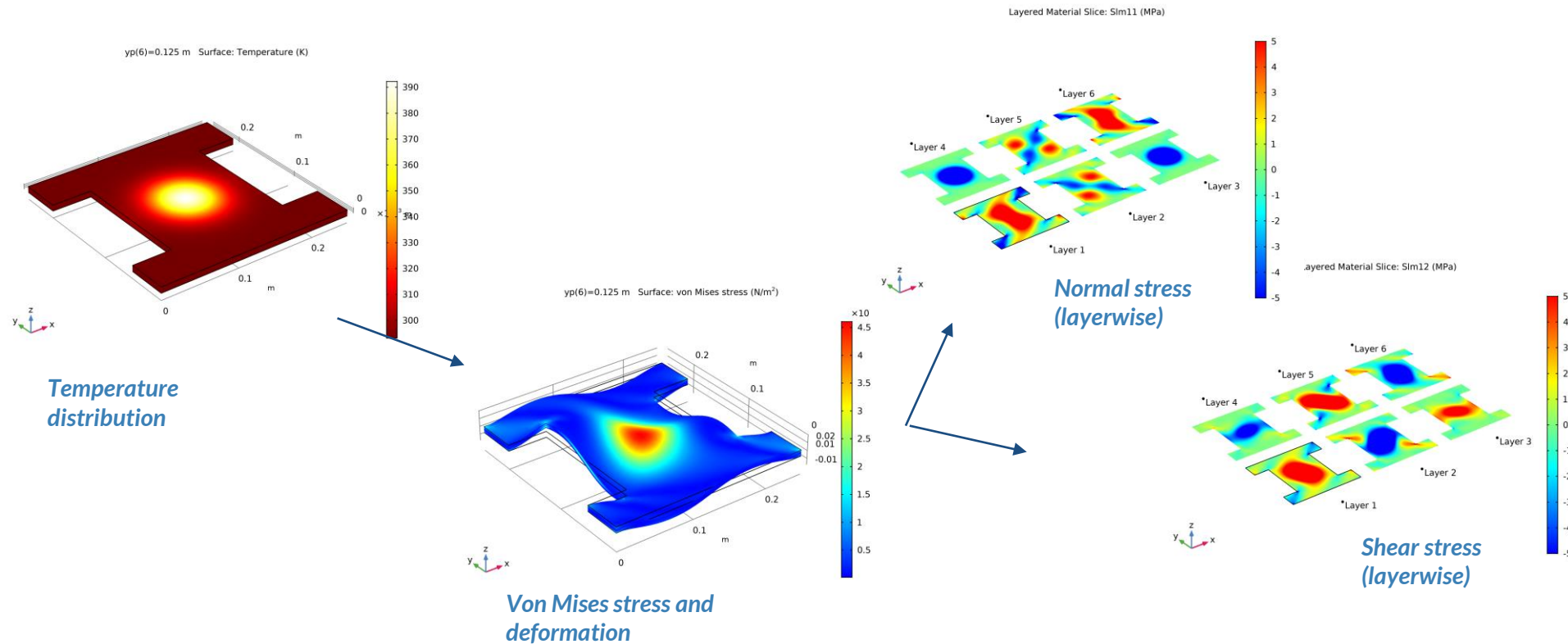
- Micromechanics analysis of a unit cell, made up of fiber and epoxy materials, is performed.
- Stress analysis of a composite cylinder is performed using *layerwise* theory and *equivalent single layer* theory.





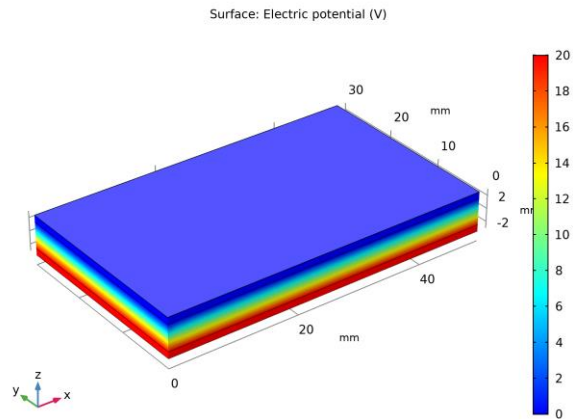
# Thermal Expansion of a Laminate

- Thermal expansion of a laminate, subjected to a deposited beam power heat source, is modelled.
- Laminate has six layers with [30/-45/75/-75/45/-30] stacking sequence.
- Layerwise theory is used in this model.

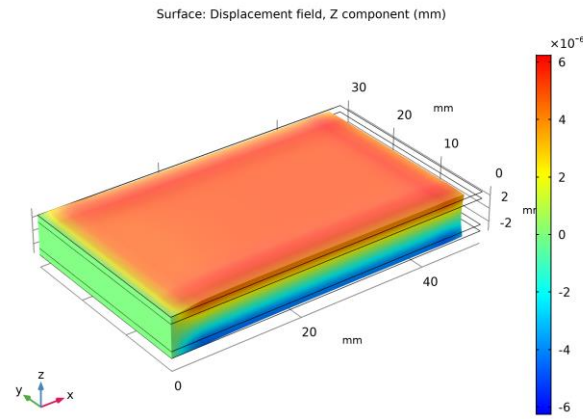


# Piezoelectricity in a Layered Shell

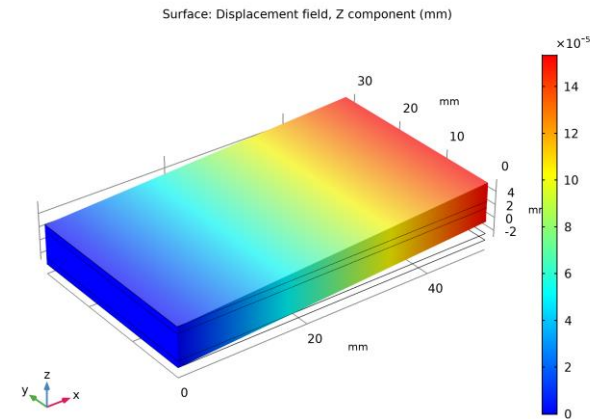
- Example demonstrates the modeling of piezoelectric devices using Layered Shell.
- Two cases of material orientation are studied:
  - Pole axis normal to the shell surface (leads to change in shell thickness)
  - Pole axis tangential to the shell surface (leads to shell bending)



*Electric potential distribution.*



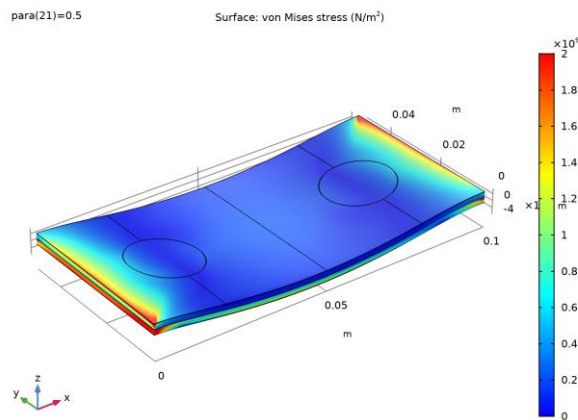
*Vertical displacement when pole axis is normal to the shell surface.*



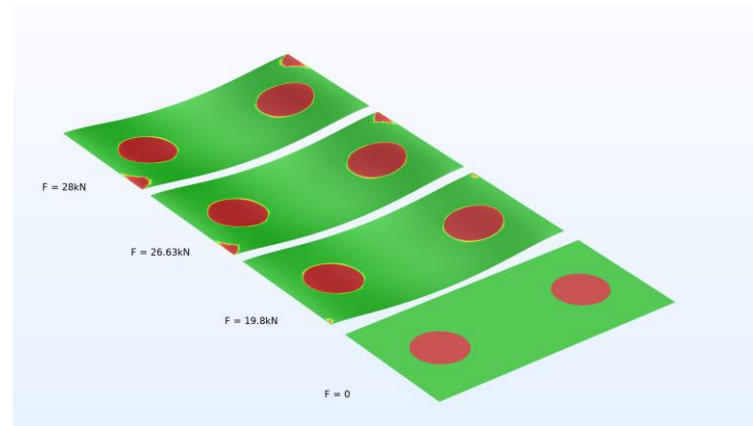
*Vertical displacement when pole axis is tangential to the shell surface.*

# Progressive Delamination in a Laminated Shell

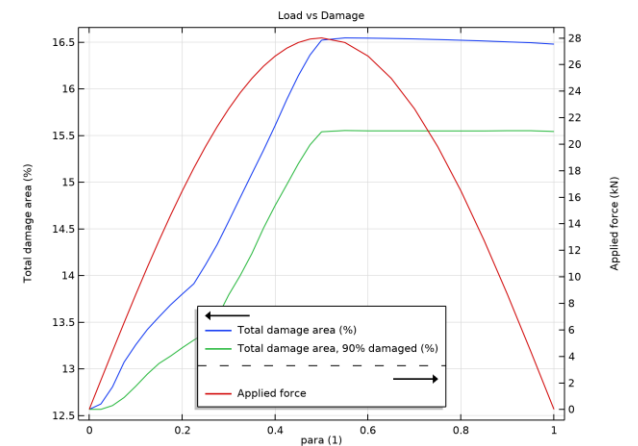
- Example illustrates the delamination initiation and propagation in a composite plate.
- There is an initial delaminated region at the interface between two layers.
- Compressive load is applied in order to predict the total interfacial damage in one load cycle.



Surface plot showing von Mises stress distribution.



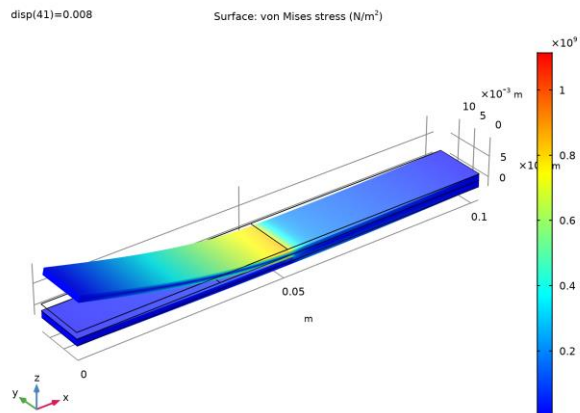
Slice plot showing damaged zone for different load values.



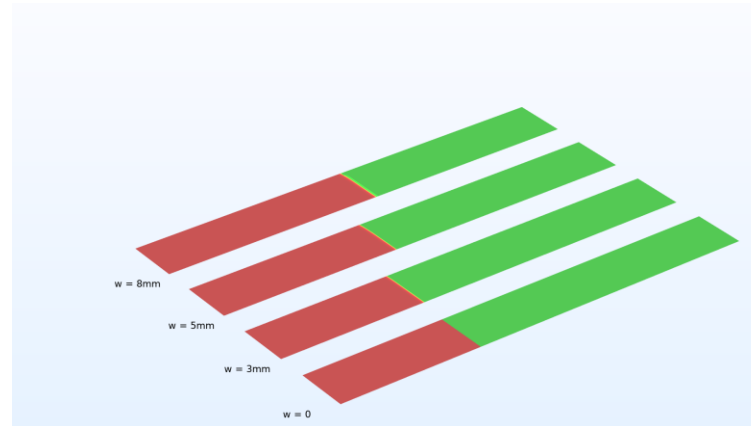
Total damage v/s applied load.

# Mixed-Mode Delamination of a Composite Laminate

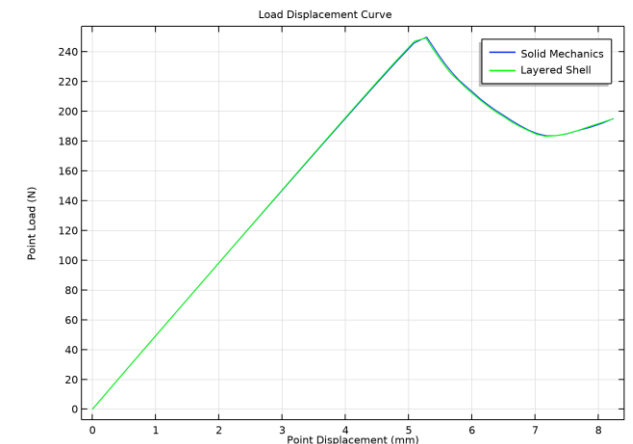
- Example shows the implementation of a CZM with a bilinear traction-separation law in a laminated composite.
- Models a mixed-mode debonding of a laminated composite.
- Results are compared with the model created using the Solid Mechanics interface.



Surface plot showing von Mises stress distribution in composite plate.



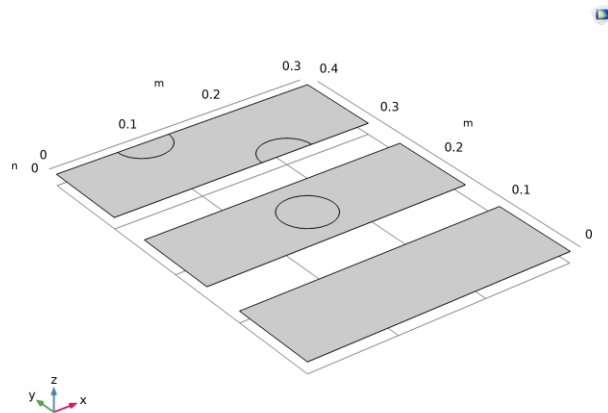
Slice plot showing damaged zone for different opening displacements.



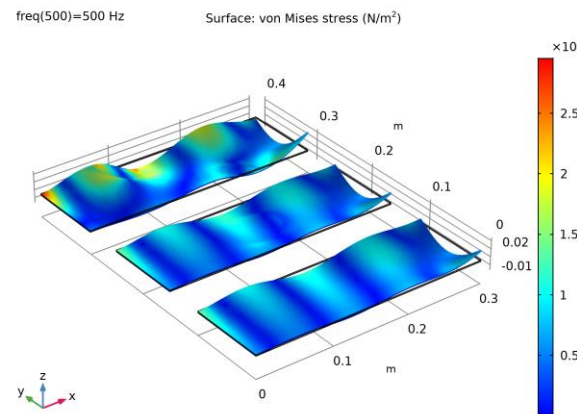
Load v/s displacement curve.

# Forced Vibration of a Laminate

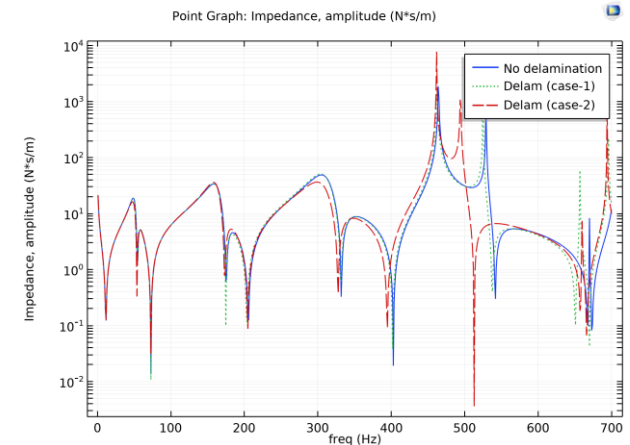
- Forced vibration analysis of a laminate subjected to bending and twisting loads.
- Laminate is analyzed for two different locations of delamination and compared with the healthy laminate without delamination.
- Three layers with [90/45/0] stacking sequence.
- Layerwise theory together with Thin Elastic Layer, Interface node is used to model debonded region.



*Composite laminate with and without delaminated region.*



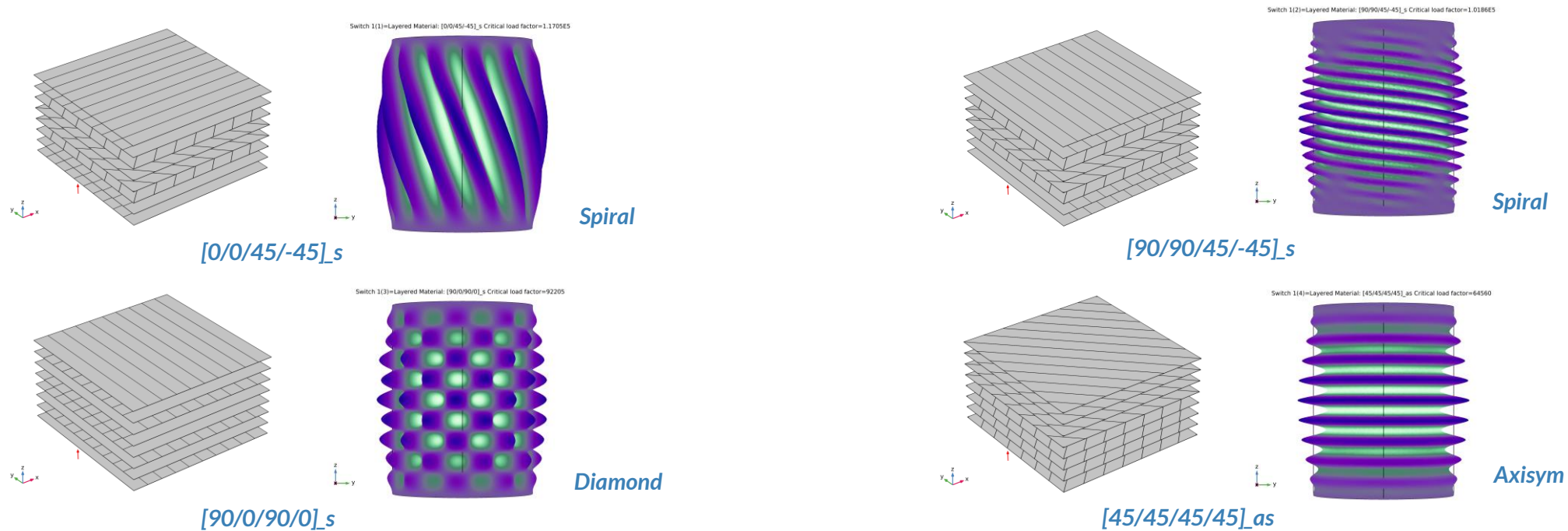
*von-Mises stress at 500 Hz when subjected to a bending load.*



*Impedance variation with frequency when subjected to a bending load.*

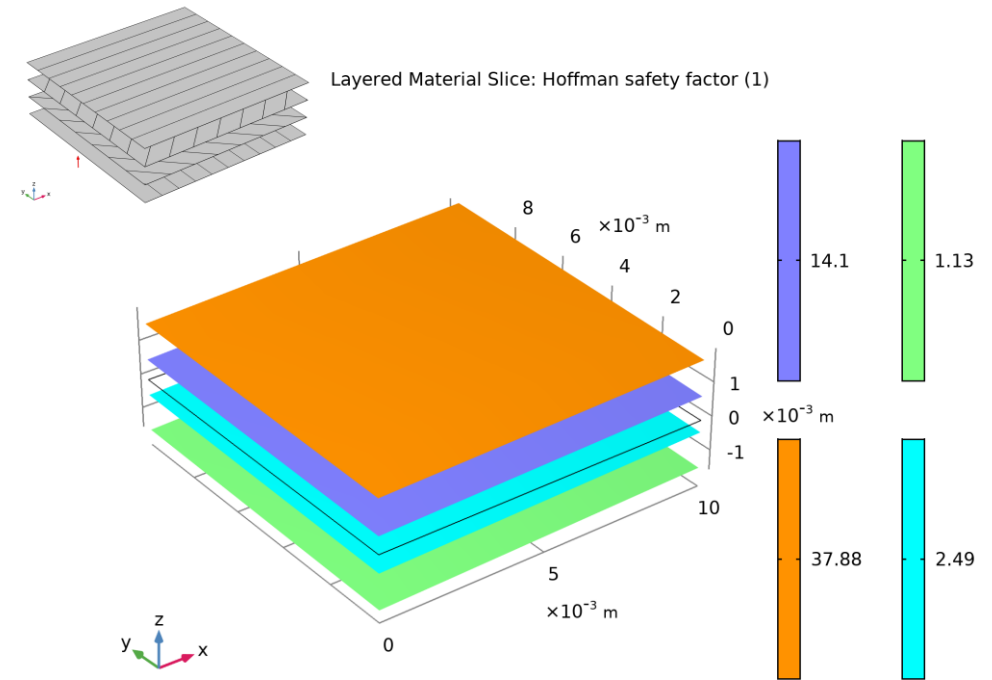
# Composite Cylinder Buckling

- Buckling analysis of a composite cylinder, under compressive loading and fixed-fixed end condition, is performed.
- Cylinder is made up of eight layers of carbon fiber reinforced epoxy material.
- The *equivalent single layer* theory is used in this model.



# Failure Prediction in a Laminate

- First ply failure analysis of a composite laminate, having 4 plies with [90/-45/45/0] stacking sequence, is performed.
- Failure Criteria used:
  - Tsai-Wu Anisotropic
  - Modified Tsai-Hill Orthotropic
  - Tsai-Wu Anisotropic
  - Tsai-Hill Orthotropic
  - Azzi-Tsai-Hill
  - Norris
  - Hoffman
- Results are compared with a benchmark.

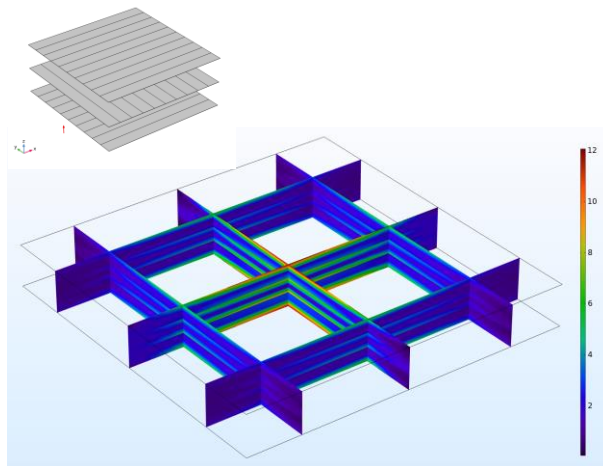


*Hoffman Safety Factor in all the plies of a laminate.*

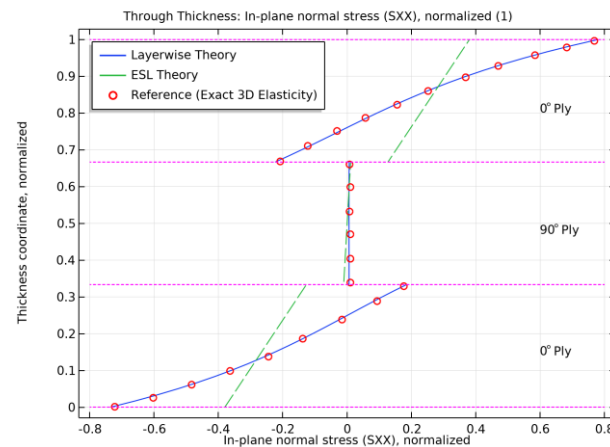


# Simply Supported Laminate

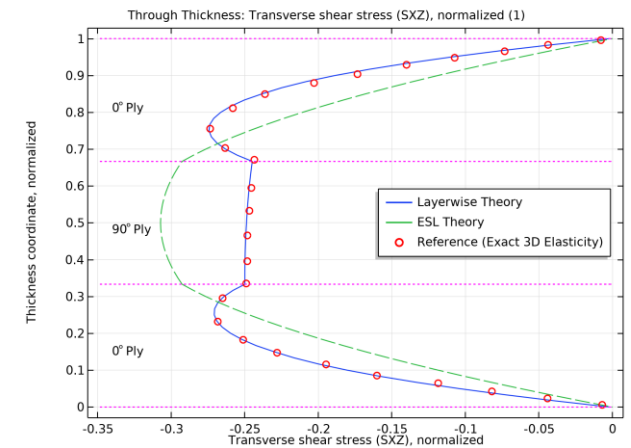
- Bending of a simply supported composite laminate subjected to transverse sinusoidal distributed load is modeled.
- Laminate has three layers with cross ply configuration [0/90/0].
- Both *layerwise* theory and *ESL* theory results are compared with exact 3D elasticity results given in the reference.



Slice plot showing von Mises stress distribution in through thickness direction.



Through thickness variation of normal stress (SXX).

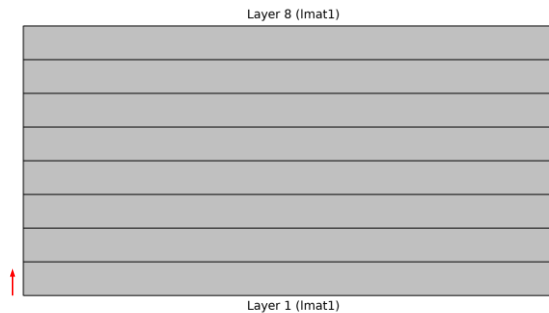


Through thickness variation of shear stress (SXZ).

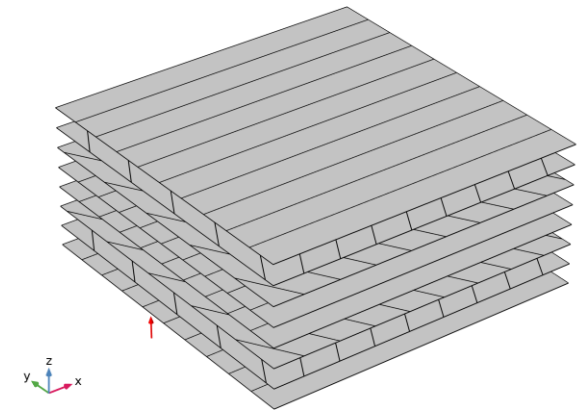


# Material Characteristics of a Laminate

- This example is a benchmark for equivalent single theory.
- The composite laminate considered here has eight layers with  $[0/60/-60/0/0/-60/60/0]$  stacking sequence.
- The following quantities are evaluated and compared :
  - Stiffness matrices (membrane and bending)
  - Flexibility matrices (membrane and bending)
  - Midplane strains for unit loading
  - Response to unit change in temperature



*Laminate cross section*



*Laminate stacking sequence*

# Thanks



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