Agenda

1. Intro to Composites
2. Demo of Model Build
3. Fighting Fidelity
4. Composite Optimization
5. Q&A
About Me

• University of Minnesota
  • Aerospace Engineering, 2019

• “Solar Rayces”
  • FSGP / ASC 2016, 2018,
  • WSC 2015, 2017

Joined Altair Engineering in 2019

• Structural FEA
• Composite Design & Optimization
What Is a Composite Material?

A composite material is one in which at least two distinct materials with significantly different material characteristics are joined to act as a single material.

Composite materials come in a variety of types, including:

- Particulate Composites (Particles + Matrix)
- Laminated Composites (Layers)
- Fibrous-Matrix Laminated Composites (Layers – “Long fiber + Matrix”)
- Core Stiffened Laminated Composites
Advantages of Composite Design

Why use composites for creating structural components?

- The material property of the composites can be engineered according to the application requirements.
- The ability to impart the required material property gives them great advantage when compared with traditional homogeneous materials like steel or aluminum.
- Composites have increased strength to weight ratios in use cases against isotropic metals.
Composite Designable Material Properties

Take the following example:
A simple square steel plate in tension needs to have displacement of 0.1 in x-direction.
- Designing for above requirement is a simple task
- What is the associated displacement of the part for the same loading in the y-direction?

What if the displacement in the y-direction needs to be no more than 0.025 units?
Composite Designable Material Properties

Using isotropic vs orthotropic materials force different approaches to this design problem

- Steel, being an isotropic material, can not change its properties in different directions. Hence different behavior in different directions needs to be achieved through changing the geometry.
- In case of composites, achieving the above is as simple as determining the correct number of plies in x and y directions.

- Ability to design the material property gives lot of freedom to the designers but increases the complexity of the design task.
- Orthotropic designs must take into account undesirable behaviors like extensional–shear coupling, bending-twist coupling, etc
Composite Designable Material Properties

Using isotropic vs orthotropic materials force different approaches to this design problem

- Steel, being an isotropic material, can not change its properties in different directions. Hence different behavior in different directions needs to be achieved through changing the geometry.
- In case of composites, achieving the above is as simple as determining the correct number of plies in x and y directions.

- Ability to design the material property gives lot of freedom to the designers but increases the complexity of the design task.
- Orthotropic designs must take into account undesirable behaviors like extensional–shear coupling, bending-twist coupling, etc.
Finite Element Simulation: Metals vs. Composites

FE of Metal Structures
- Geometry
- Material Properties (Isotropic)
- Loads and BC’s
- Visualization of Results on the Geometry
- Failure based on Invariants

FE of Composite Structures
- Geometry
- Material Properties (Non-Isotropic)
- Ply Orientations
- Constituent Properties
- Loads and Boundary Conditions
- Visualization of Results on Geometry, Thru-Laminate, and Constituent Level
- Failure is based on 3D Stress State, is Directional, and Dependent on Constituent Properties
Composite Material and Element Orientation and Ply Alignment

For shell elements using anisotropic materials, the x-axis of the material system defaults to the vector from G1-G2, parallel to the first and second nodes of the element definition

- Note that the element coordinate system and the material coordinate system are not the same concept
- The element coordinate system is always defined by the bi-section of vectors from G1-G3 and G2-G4
Understanding Composite Material Properties

The strain-stress relationship for isotropic linear elastic materials is given by:

\[
\begin{bmatrix}
\varepsilon_1 \\
\varepsilon_2 \\
\varepsilon_3 \\
\gamma_{12} \\
\gamma_{23} \\
\gamma_{13}
\end{bmatrix}
= \begin{bmatrix}
\frac{1}{E} & \frac{-v}{E} & \frac{-v}{E} & 0 & 0 & 0 \\
\frac{-v}{E} & \frac{1}{E} & \frac{-v}{E} & 0 & 0 & 0 \\
\frac{-v}{E} & \frac{-v}{E} & \frac{1}{E} & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{1}{G} & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{1}{G} & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{1}{G}
\end{bmatrix}
\begin{bmatrix}
\sigma_1 \\
\sigma_2 \\
\sigma_3 \\
\tau_{12} \\
\tau_{23} \\
\tau_{13}
\end{bmatrix}
\]

As shown, isotropic linear elastic materials have only two independent engineering constants. Any two of E, G, or \(v\) which are related by the equation:

\[
G = \frac{E}{2(1+v)}
\]
Understanding Composite Material Properties

Laminated composite material properties are generally modeled as orthotropic materials.

Thus, the strain-stress relationship can be rewritten as the following:

\[
\begin{bmatrix}
\varepsilon_1 \\
\varepsilon_2 \\
\varepsilon_3 \\
\gamma_{12} \\
\gamma_{23} \\
\gamma_{13}
\end{bmatrix} =
\begin{bmatrix}
\frac{1}{E_1} & -\frac{v_{12}}{E_2} & -\frac{v_{13}}{E_3} & 0 & 0 & 0 \\
-\frac{v_{12}}{E_1} & \frac{1}{E_2} & -\frac{v_{23}}{E_3} & 0 & 0 & 0 \\
-\frac{v_{13}}{E_1} & -\frac{v_{23}}{E_2} & \frac{1}{E_3} & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{1}{G_{12}} & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{1}{G_{23}} & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{1}{G_{13}}
\end{bmatrix}
\begin{bmatrix}
\sigma_1 \\
\sigma_2 \\
\sigma_3 \\
\tau_{12} \\
\tau_{23} \\
\tau_{13}
\end{bmatrix}
\]
Zone Based Data

Zone 1

<table>
<thead>
<tr>
<th>MID</th>
<th>T</th>
<th>THETA</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2) glass epoxy</td>
<td>0.18</td>
<td>45.0</td>
</tr>
<tr>
<td>(2) glass epoxy</td>
<td>0.18</td>
<td>-45.0</td>
</tr>
<tr>
<td>(1) carbon epoxy</td>
<td>0.2</td>
<td>0.0</td>
</tr>
<tr>
<td>(1) carbon epoxy</td>
<td>0.2</td>
<td>0.0</td>
</tr>
<tr>
<td>(2) glass epoxy</td>
<td>0.18</td>
<td>-45.0</td>
</tr>
<tr>
<td>(2) glass epoxy</td>
<td>0.18</td>
<td>45.0</td>
</tr>
</tbody>
</table>

Zone 2

<table>
<thead>
<tr>
<th>MID</th>
<th>T</th>
<th>THETA</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2) glass epoxy</td>
<td>0.18</td>
<td>45.0</td>
</tr>
<tr>
<td>(2) glass epoxy</td>
<td>0.18</td>
<td>-45.0</td>
</tr>
<tr>
<td>(1) carbon epoxy</td>
<td>0.2</td>
<td>0.0</td>
</tr>
<tr>
<td>(1) carbon epoxy</td>
<td>0.2</td>
<td>90.0</td>
</tr>
<tr>
<td>(1) carbon epoxy</td>
<td>0.2</td>
<td>90.0</td>
</tr>
<tr>
<td>(1) carbon epoxy</td>
<td>0.2</td>
<td>0.0</td>
</tr>
<tr>
<td>(2) glass epoxy</td>
<td>0.18</td>
<td>-45.0</td>
</tr>
<tr>
<td>(2) glass epoxy</td>
<td>0.18</td>
<td>45.0</td>
</tr>
</tbody>
</table>
Zone Based Data

### Zone 1

<table>
<thead>
<tr>
<th>MID</th>
<th>T</th>
<th>THETA</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2) glass_epoxy</td>
<td>0.18</td>
<td>45.0</td>
</tr>
<tr>
<td>(2) glass_epoxy</td>
<td>0.18</td>
<td>-45.0</td>
</tr>
<tr>
<td>(1) carbon_epoxy</td>
<td>0.2</td>
<td>0.0</td>
</tr>
<tr>
<td>(1) carbon_epoxy</td>
<td>0.2</td>
<td>0.0</td>
</tr>
<tr>
<td>(2) glass_epoxy</td>
<td>0.18</td>
<td>-45.0</td>
</tr>
<tr>
<td>(2) glass_epoxy</td>
<td>0.18</td>
<td>45.0</td>
</tr>
</tbody>
</table>

### Zone 2

<table>
<thead>
<tr>
<th>MID</th>
<th>T</th>
<th>THETA</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2) glass_epoxy</td>
<td>0.18</td>
<td>45.0</td>
</tr>
<tr>
<td>(2) glass_epoxy</td>
<td>0.18</td>
<td>-45.0</td>
</tr>
<tr>
<td>(1) carbon_epoxy</td>
<td>0.2</td>
<td>0.0</td>
</tr>
<tr>
<td>(1) carbon_epoxy</td>
<td>0.2</td>
<td>90.0</td>
</tr>
<tr>
<td>(1) carbon_epoxy</td>
<td>0.2</td>
<td>0.0</td>
</tr>
<tr>
<td>(1) carbon_epoxy</td>
<td>0.2</td>
<td>0.0</td>
</tr>
<tr>
<td>(2) glass_epoxy</td>
<td>0.18</td>
<td>-45.0</td>
</tr>
<tr>
<td>(2) glass_epoxy</td>
<td>0.18</td>
<td>45.0</td>
</tr>
</tbody>
</table>
Ply Based Data

<table>
<thead>
<tr>
<th>Name</th>
<th>ID</th>
<th>Orientation</th>
<th>Thickness</th>
<th>Material</th>
<th>Shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>laminate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>fiberglass_1</td>
<td>1</td>
<td>45.0</td>
<td>0.18</td>
<td>glass_epoxy</td>
<td>full</td>
</tr>
<tr>
<td>fiberglass_2</td>
<td>2</td>
<td>-45.0</td>
<td>0.18</td>
<td>glass_epoxy</td>
<td>full</td>
</tr>
<tr>
<td>carbon_uni_1</td>
<td>3</td>
<td>0.0</td>
<td>0.2</td>
<td>carbon_epoxy</td>
<td>full</td>
</tr>
<tr>
<td>carbon_uni_2</td>
<td>4</td>
<td>90.0</td>
<td>0.2</td>
<td>carbon_epoxy</td>
<td>partial</td>
</tr>
<tr>
<td>carbon_uni_3</td>
<td>5</td>
<td>90.0</td>
<td>0.2</td>
<td>carbon_epoxy</td>
<td>partial</td>
</tr>
<tr>
<td>carbon_uni_4</td>
<td>6</td>
<td>0.0</td>
<td>0.2</td>
<td>carbon_epoxy</td>
<td>full</td>
</tr>
<tr>
<td>fiberglass_3</td>
<td>7</td>
<td>-45.0</td>
<td>0.18</td>
<td>glass_epoxy</td>
<td>full</td>
</tr>
<tr>
<td>fiberglass_4</td>
<td>8</td>
<td>45.0</td>
<td>0.18</td>
<td>glass_epoxy</td>
<td>full</td>
</tr>
</tbody>
</table>
Ply Based Data

- Laminates (1)
  - laminate
    - new
      - ID: 9
      - Orientation: 0.0
      - Thickness: 0.2
      - Material: carbon_epoxy
    - fiberglass_1
      - ID: 1
      - Orientation: -45.0
      - Thickness: 0.18
      - Material: glass_epoxy
    - fiberglass_2
      - ID: 2
      - Orientation: -45.0
      - Thickness: 0.18
      - Material: glass_epoxy
    - carbon_uni_1
      - ID: 3
      - Orientation: 0.0
      - Thickness: 0.2
      - Material: carbon_epoxy
    - carbon_uni_2
      - ID: 4
      - Orientation: 90.0
      - Thickness: 0.2
      - Material: carbon_epoxy
    - carbon_uni_3
      - ID: 5
      - Orientation: 90.0
      - Thickness: 0.2
      - Material: carbon_epoxy
    - carbon_uni_4
      - ID: 6
      - Orientation: 0.0
      - Thickness: 0.18
      - Material: carbon_epoxy
    - fiberglass_3
      - ID: 7
      - Orientation: -45.0
      - Thickness: 0.18
      - Material: glass_epoxy
    - fiberglass_4
      - ID: 8
      - Orientation: 45.0
      - Thickness: 0.18
      - Material: glass_epoxy

- Card Image: PCOMP
- Laminates
- User Comments: +Z OPTIONS: 20
- NDM: 20
- SS: 20
- FT: 20
- TREF: 20
- GE_LIGMAT: 20

© Altair Engineering, Inc. Proprietary and Confidential. All rights reserved.
Typical Modeling Workflow

1) Laminate stacking direction (element normals)

2) Material orientation (0° fiber direction)

3) Ply creation (orientation, thickness, material, shape)

4) Laminate creation (ply stacking sequence, analysis settings)

5) Template property creation (solver specific attributes)

6) Draping simulation (calculate flat shape, fiber angle changes due to geometry curvature)
Orientations

In OptiStruct, the final fiber direction of a given ply is determined by as many as three rotations:

1. **Reference orientation** is a rotation from the element x axis (THETA field on element) at each element, or the x axis of a local system

2. **Orientation defined on a ply** applies an additional rotation on the reference orientation

3. **Drape table** (typically from a draping simulation) applies an additional rotation on the ply orientation
Advanced Material Model Development

Transition from Traditional Homogeneous Isotropic to Accurate Heterogeneous Anisotropic Material Models

Continuous Products (Unidirectional and Weaves)

Discontinuous Products (Injection Molding)

Reduce Time/Cost in the Design Process due to incomplete material understanding; Reduce experimental data requirements, Increase simulation accuracy!
What do we mean by Multiscale?

An example of a unidirectional material

The stress at any scale is the volume average stress of the scale below.

Example:

\[ \sigma_{\text{Ply}} = \frac{\sigma_{\text{Fiber}} + \sigma_{\text{Matrix}}}{2} \]

Scale0 (sConstituent MicroStructure)

Scale1 (sFiber/Matrix)

Scale2 (sPly)

Scale3 (sLaminate)
What do we mean by Multiscale?

An example of a metal

The stress at any scale is the volume average stress of the scale below.

Example:

$s_{\text{Metal}}$ is the volume average stress of $s_{\text{Grain}}$

$$\sigma_{\text{Metal}} = \sigma_{\text{Grain}} V_{\text{Grain}}$$

Currently perform simulations one scale above the constituent microstructure (Scale 1) to achieve predictive accuracy!
Multiscale Material Model Development (MMMD)

Develop Predictive Material Models from the Linear Regime to Ultimate Failure with Minimal Experimental Data Requirements by Extracting Properties at Scale 1 (Fiber/Matrix)

2-Scale, N-Phase Framework

**Scale 1 – Micromechanics**
- Matrix (Phase 1) Behavior
- Fiber (Phase 2) Behavior

**Scale 2 – Macromechanics**
- Composite Product Behavior

Matrix Stress vs. Matrix Strain
Fiber Stress vs. Fiber Strain
Homogenized Stress vs. Homogenized Strain

Scale 0 – Microstructure
Composite Design Optimization with OptiStruct

1. Initial Design Space

2. Topology Optimization
   (What is the most efficient part shape?)

3. Composite Free-Size / Size Optimization
   (What are the most efficient ply shapes?)
   (How many of each ply shape required?)

Repeat Laminate Technology
Double-Double
\((\theta/0/-\theta/90)_Ns\)
\((\theta/-\theta)_Ns\)
\((\theta/-\phi/-\phi)_Ns\)

Solves N for every element
Solves \(\theta, \phi\) for the global part
Composite Design Optimization with OptiStruct

Ply Shape Concepts and Final Design

Design Certification

Composite Design Optimization

Integrated Manufacturing & Structural Simulation

Advanced Material Model Development
Contact Us

My Email:
Soukup@altair.com  “Kory Soukup”

Solar Car Success Stories:
https://altairuniversity.com/solar-car-page/

For Competition & Sponsorship Info:
https://altairuniversity.com/sponsorship-competitions/
THANK YOU
altair.com

#ONLYFORWARD