Agenda
An Introduction to Composite FE Analysis
July 23rd, 2009
8am PDT (Seattle) / 11am EDT (New York) / 4pm BST (London)

Welcome & Introduction (Overview of NAFEMS Activities)
   Mr. Matthew Ladzinski, NAFEMS North America

An Introduction to Composite FE Analysis
   Mr. Tony Abbey, FETraining

Q&A Session
   Panel

Closing
An Overview of NAFEMS Activities

Matthew Ladzinski
NAFEMS
NAFEMS North America
Planned Activities

➢ Webinars

▪ New topic each month!

▪ Recent webinars:
  ▪ Composite FE Analysis
  ▪ 10 Ways to Increase Your Professional Value in the Engineering Industry
  ▪ Dynamic FE Analysis
  ▪ Modal Analysis in Virtual Prototyping and Product Validation
  ▪ Pathways to Future CAE Technologies and their Role in Ambient Intelligent Environments
  ▪ Computational Structural Acoustics: Technology, Trends and Challenges
  ▪ FAM: Advances in Research and Industrial Application of Experimental Mechanics
  ▪ CCOPPS: Power Generation: Engineering Challenges of a Low Carbon Future
  ▪ Practical CFD Analysis
  ▪ Complexity Management
  ▪ CCOPPS: Creep Loading of Pressurized Components – Phenomena and Evaluation
  ▪ Multiphysics Simulation using Implicit Sequential Coupling
  ▪ CCOPPS: Fatigue of Welded Pressure Vessels
  ▪ Applied Element Method as a Practical Tool for Progressive Collapse Analysis of Structures
  ▪ A Common Sense Approach to Stress Analysis and Finite Element Modeling
  ▪ The Interfacing of FEA with Pressure Vessel Design Codes (CCOPPS Project)
  ▪ Multiphysics Simulation using Directly Coupled-Field Element Technology
  ▪ Methods and Technology for the Analysis of Composite Materials
  ▪ Simulation Process Management
  ▪ Simulation-supported Decision Making (Stochastics)
  ▪ Simulation Driven Design (SDD) Findings

To register for upcoming webinars, or to view a past webinar, please visit: www.nafems.org/events/webinars
Proposed course offerings:

- Composite FE Analysis – August 25th, 2009 (four-week course)

Next courses:

- Dynamic FE Analysis – July 14th, 2009 (six-week course)
- Composite FE Analysis – August 25th, 2009 (four-week course)

Proposed course offerings:

- Non-linear – Fall 2009 (four-week course)
- Stochastics – Fall 2009
- Verification & Validation – Fall/Winter 2009

For more information, visit: www.nafems.org/e-learning
# NAFEMS Events

## Upcoming NAFEMS Events

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
<th>Location</th>
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<tbody>
<tr>
<td>Composite Products from Concept Design to Manufacturing</td>
<td>24th Jul 2009</td>
<td>Bangalore, India</td>
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<tr>
<td>Composites FE Analysis</td>
<td>25th Aug 2009</td>
<td>Course, e-Learning, Online</td>
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<tr>
<td>Practical Stress Analysis &amp; Finite Element Methods</td>
<td>15th Sep 2009</td>
<td>Course, Midlands, UK</td>
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<tr>
<td>Dynamics Testing &amp; Analysis Workshop</td>
<td>16th Sep 2009</td>
<td>Workshop, Bristol, UK</td>
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<td>Introduction au Calcul de Structures, aux Éléments Fini et à la Simulation Numérique</td>
<td>22nd Sep 2009</td>
<td>Course, Paris, France</td>
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<td>Analisi del comportamento a crash mediante test virtuale</td>
<td>22nd Sep 2009</td>
<td>Seminar, Bologna, Italy</td>
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<td>Introduction to FEA Analysis</td>
<td>22nd Sep 2009</td>
<td>Course, Orlando, FL, USA</td>
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<tr>
<td>Recent Advances in the Fatigue Analysis of Welded Structures</td>
<td>7th Oct 2009</td>
<td>Seminar, Gaydon, UK</td>
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<td>FEM Basic 1 - Praxisorientierte Strukturmechanik / Festigkeitslehre</td>
<td>19th Oct 2009</td>
<td>Course, Wiesbaden, Germany</td>
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</tbody>
</table>

**Let us know if you would like to schedule an on-site training course**

**For more information, please visit:**
[www.nafems.org](http://www.nafems.org)

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**Attend Events for Free**

NAFEMS Members are entitled to attend a number of seminars and workshops free of charge each year as part of their membership, as well as a library of free publications on joining. Members also receive significant discounts on NAFEMS courses, conferences and publications.

If you are a NAFEMS member, please login above to take advantage of these free places and discounted prices. If you are not a member, click here to read more about the benefits of getting involved.

**Get Involved, Join NAFEMS Today!**
Welcome and Agenda

Overview of the NAFEMS e-Learning Course

Introduction to Composites FE Analysis

Q and A
Composite FE Analysis
August 25th - September 15th, 2009
Four-Week Training Course

Members Price: £143 | €165 | $235
Non-Members Price: £228 | €264 | $375
Order Ref: el-003
Event Type: Course
Location: E-Learning, Online
Date: August 25, 2009

www.nafems.org/events/nafems/2009/el003/
Composites Analysis

Many designs now use composite structures or components, taking advantage of:

- Increased structural strength and stiffness to weight ratios
- Simpler manufacturing process
- More innovative design capability

The nature of the composite used can range from:

- Cheap and freely available glass fiber reinforced systems to
- Exotic and specifically tailored carbon, Kevlar or even metal/matrix systems

Many forms of manufacturing process available.
Overview of Composites e-Learning Class

Composites Analysis

The challenge for the designer and analyst is to determine the resulting stiffness and strength of the design.

Faced with the complexity of real world structural systems the analyst has to make decisions on the FEA analysis:

- the type of idealization
- level of detail required
- definition of failure

The design variations available with a composite material are immense; ply thickness, orientation and property can all be varied to tune the structural response.

A rational approach is needed to predict the strength and stiffness and how to use the FEA data to help design and verify the structure.
Composites Analysis

Your design may include thick composite sections with large numbers of plies, there may be regions of significant ply drop off.

Tee joints may be loaded in tension. In these cases the through thickness effects become very important for strength prediction.

The shape of the structure may imply changes in draping angle or layup thickness and it may be important to model this accurately.
Overview of Composites e-Learning Class

Composites Analysis

There are a wide range of failure theories, together with potentially large amounts of stress or strain data from a multi ply layup.

Due to the nature of the composite the stress components can include many more terms than a conventional metallic material for example.

*Whatever the nature of the challenge, this objective of this course is to break down the composite analysis process into clearly defined steps, give an overview of the physics involved and show how to successfully implement practical solutions using Finite Element Analysis.*
Overview of Dynamics e-Learning Class

Why an e-learning class?

In the current climate travel and training budgets are tight. To help you still meet your training needs the following e-learning course has been developed to complement the live class.

The e-learning course runs over a four week period with a single two hour session per week.

Bulletin Boards and Email are used to keep in contact between sessions, mentoring homework and allowing interchange between students.

E-learning classes are ideal for companies with a group of engineers requiring training. E-learning classes can be provided to suit your needs and timescale. Contact us to discuss your requirements.

We hope that small companies or individuals can now take part in the training experience.
1. What are composites?

Review of different forms and manufacturing processes.

2. How do composites vary from metallic structures?

Overview of material properties and the ABD matrix terms. Hints on practical design methods.

3. How do I set up a composite FEA?

Overview of typical processes. Keeping track of plies, mold lines etc.
Introductory Composites FE Analysis Webinar

Agenda

4. How good is my FEA idealization?
The importance of fiber orientation, draping and thickness effects.

5. How do I know whether the composite has failed?
Basic First Ply failure theories

6. How do I organize my results, where do I start looking?
Failure indices, Strength ratios.
Introductory Composites FE Analysis Webinar

Agenda

7. Through thickness and edge effects such as delamination

Usage of solid and thick shell elements.

8. Advanced failure methods

Progressive ply failure, cohesive elements, fracture mechanics methods (VCCT)
Agenda

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3. How do I set up a composite FEA?

Overview of typical processes. Keeping track of plies, mold lines etc.
1. What are composites?

Consider material types:

**ISOTROPIC** - the same material properties in all directions, steel is a typical example.

*Easy to measure properties*

**ANISOTROPIC** - different material properties in all directions, a chunk of volcanic rock is an example.

*Tough to measure or predict properties*

**ORTHOTROPIC** – special case of anisotropic, clear material directionality in 3 directions –represents a carbon fiber/resin system, for example, where the along axis, transverse axis and through thickness axis are different.

*Measurable and predictable properties – some challenges*
1. What are composites?

2D ORTHOTROPIC, A further simplification is where we ignore the through thickness stress. This is the usual starting point for what we call Classical Laminate Theory, the foundation of most FE solutions.

(a) Plane strain - Thick bodies
\[ \varepsilon_z = \gamma_{xz} = \gamma_{yz} = 0 \]
\[ \therefore \tau_{xz} = \tau_{yz} = 0 \]

(b) Plane Stress - Thin bodies
\[ \sigma_z = \tau_{xz} = \tau_{yz} = 0 \]
\[ \therefore \varepsilon_z = \gamma_{xz} = \gamma_{yz} = 0 \]

Direct through stress and shears assumed 0

* Note the limitations implied here – we will revisit this
1. What are composites?

The composite is a system which consists of fibers in a resin or similar medium (usually called the matrix)

The important strength and stiffness characteristics are provided by the high strength fibers

It is important to consider both the fibers and the matrix in the material stiffness and strength considerations
1. What are composites?

The fibers in isolation in a perfect test setup can have incredibly strong and stiff properties.

However they cannot be used in this form, they need a binding matrix.
1. What are composites?

The fibers are not perfect and may have varying levels of microscopic dislocation or cracking.

The matrix is relatively weak, but acts to link the fibers together.

The strength/stiffness is an aggregate of the two ingredients.
1. What are composites?

<table>
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<th>Fabric</th>
<th>Triaxial braid</th>
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<td>9.20</td>
<td>7.50</td>
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<td>Transverse modulus, $E_2$ (Msi)</td>
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<td>9.20</td>
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<tr>
<td>Lateral modulus, $E_3$ (Msi)</td>
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<td>1.30</td>
<td>****</td>
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<tr>
<td>In-plane shear modulus, $G_{12}$ (Msi)</td>
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<td>Transverse shear modulus, $G_{13}$ (Msi)</td>
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The table shows the stiffness of a group of Graphite – Epoxy systems

The directionality is clear

Convention is fiber/matrix as the system designation
A simple experiment using FEA to predict failing load in a coupon

Graph shows effect of ply angle in a single ply layup
1. What are composites?

In practice plies are rarely used individually, multiple angles are used to tailor the performance of the composite.

A stack up of plies is formed either by bonding sheets together or by some form of weaving.

However the FEA idealization usually assumes a ‘sheet-like’ equivalent.
1. What are composites?

‘Pre-preg layup‘ is a very common form of assembly where multiple dry unidirectional fiber/matrix sheets (pre-impregnated) are laid up and then wetted with a resin to achieve bonding between the sheets.

Pressure and temperature may be used to achieve good bonding or to achieve more complex shapes.
1. What are composites?

Resin Transfer molding (RTM). Cloth systems may be wetted externally and cured, or the system may be augmented by creating a vacuum in the part using a bagging system. Resin is then fed into the system and is absorbed into the composite.

Pressure applied between dies can be used as an alternative to creating a vacuum.

The cure may be at room temperature or elevated temperature dependent on the system.
1. What are composites?

Filament winding is used to create tubular based forms. With the use of sophisticated multi axis machines and CNC, spherical, conical and more complex shapes can be formed. It is suitable for very large components such as tunnel liners, rocket fuel tanks etc.

The resin may be added as the filament through a runs a bath, or it may be sprayed or applied later on the mandrel.

The mandrel and component may then be transferred to an oven for curing.
1. What are composites?

Other manufacturing processes

**Pultrusion** – a sock like woven shape is braided and then pulled through a heated die to form components such as drive shafts, stiffeners, rods etc.

**Automated tape placement** – a multi axis head under CNC control is able to lay individually programmed paths of tape across a flat bed or die shape. Very sophisticated ply orientations can be designed.
1. What are composites?

Many forms of composites are available, here a fabric is offered in a range of weights which control stiffness and strength.
1. What are composites?

Here a glass fiber and low strength carbon cloth are offered
Introductory Composites FE Analysis Webinar

Agenda

1. What are composites?

Review of different forms and manufacturing processes.

2. How do composites vary from metallic structures?

Overview of material properties and the ABD matrix terms. Hints on practical design methods.

3. How do I set up a composite FEA?

Overview of typical processes. Keeping track of plies, mold lines etc.
- Single Ply directions exposes weakness
- Ply layups used of multiple orientation

- Shorthand 0/45/-45/90
- Tuning the layup orientation, thickness and stacking order is key to optimum design
2. How do composites vary from metallic structures?

- Previous Single Ply replaced by 0/90/-45/45/45/-45/90/0
- Maximum Strength is reduced, but now very predictable
- No Optimization! Sometimes called ‘black’ isotropic material ....
why 0/90/-45/45/45/-45/90/0 choice?

BALANCED pairs - No Inplane Direct and Shear Coupling

SYMMETRIC plys - No Inplane and Out of Plane Coupling
2. How do composites vary from metallic structures?

Overview of material properties and the ABD matrix terms. Hints on practical design methods.

\[
\begin{bmatrix}
\sigma_1 \\
\sigma_2 \\
\tau_{12}
\end{bmatrix} =
\begin{bmatrix}
Q_{11} & Q_{12} & 0 \\
Q_{12} & Q_{22} & 0 \\
0 & 0 & Q_{66}
\end{bmatrix}
\begin{bmatrix}
\varepsilon_1 \\
\varepsilon_2 \\
\gamma_{12}
\end{bmatrix}
\]

\[Q_{11} = \frac{E_1}{1 - \nu_{12} \nu_{21}}, \quad Q_{12} = \frac{\nu_{21} E_1}{1 - \nu_{12} \nu_{21}}, \quad Q_{12} = \frac{\nu_{12} E_2}{1 - \nu_{12} \nu_{21}}\]

\[Q_{22} = \frac{E_2}{1 - \nu_{12} \nu_{21}}, \quad Q_{66} = G_{12}\]
2. How do composites vary from metallic structures?

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\[
\begin{bmatrix}
\sigma_x \\
\sigma_y \\
\tau_{xy}
\end{bmatrix} = \left[ T_1 \right] \begin{bmatrix} Q \end{bmatrix} \left[ T_2 \right]^{-1} \begin{bmatrix} \varepsilon_x \\
\varepsilon_y \\
\gamma_{xy}
\end{bmatrix}
\]

or

\[
\begin{bmatrix}
\sigma_x \\
\sigma_y \\
\tau_{xy}
\end{bmatrix} = \begin{bmatrix} \bar{Q} \end{bmatrix} \begin{bmatrix} \varepsilon_x \\
\varepsilon_y \\
\gamma_{xy}
\end{bmatrix}
\]

\[
T_1 = \begin{bmatrix}
\cos^2 \theta & \sin^2 \theta & -2\sin \theta \cos \theta \\
\sin^2 \theta & \cos^2 \theta & 2\sin \theta \cos \theta \\
\sin \theta \cos \theta - \sin \theta \cos \theta \cos^2 \theta & -\sin^2 \theta 
\end{bmatrix}
\]

\[
T_2 = \begin{bmatrix}
\cos^2 \theta & \sin^2 \theta & -\sin \theta \cos \theta \\
\sin^2 \theta & \cos^2 \theta & \sin \theta \cos \theta \\
2\sin \theta \cos \theta - 2\sin \theta \cos \theta \cos^2 \theta & -\sin^2 \theta 
\end{bmatrix}
\]

\[
\bar{Q} = \begin{bmatrix}
Q_{11} & Q_{12} & Q_{16} \\
Q_{12} & Q_{22} & Q_{26} \\
Q_{16} & Q_{26} & Q_{66}
\end{bmatrix}
\]
2. How do composites vary from metallic structures?

Overview of material properties and the ABD matrix terms. Hints on practical design methods.

For Arbitrary Coordinates, the Stress-Strain Relations for the $K^{th}$ Layer of a Multilayered Laminate Are:

\[
\begin{bmatrix}
\sigma_x \\
\sigma_y \\
\tau_{xy}
\end{bmatrix}_k =
\begin{bmatrix}
\bar{Q}_{11} & \bar{Q}_{12} & \bar{Q}_{16} \\
\bar{Q}_{12} & \bar{Q}_{22} & \bar{Q}_{26} \\
\bar{Q}_{16} & \bar{Q}_{26} & \bar{Q}_{66}
\end{bmatrix}_k
\begin{bmatrix}
\varepsilon_x \\
\varepsilon_y \\
\gamma_{xy}
\end{bmatrix}_k
\]

or in Reduced Form

\[
\{\sigma\}_k = [Q]_k \{\varepsilon\}_k
\]
2. How do composites vary from metallic structures?

Overview of material properties and the ABD matrix terms. Hints on practical design methods.
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\[
\begin{pmatrix}
\sigma_x \\
\sigma_y \\
\tau_{xy}
\end{pmatrix}_K =
\begin{bmatrix}
\bar{Q}_{11} & \bar{Q}_{12} & \bar{Q}_{16} \\
\bar{Q}_{12} & \bar{Q}_{22} & \bar{Q}_{26} \\
\bar{Q}_{16} & \bar{Q}_{26} & \bar{Q}_{66}
\end{bmatrix}_K
\begin{pmatrix}
\varepsilon_x \\
\varepsilon_y \\
\gamma_{xy}
\end{pmatrix} + Z
\begin{pmatrix}
K_x \\
K_y \\
K_{xy}
\end{pmatrix}
\]
2. How do composites vary from metallic structures?

Overview of material properties and the ABD matrix terms. Hints on practical design methods.
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The Force and Moment Resultants for an N-Layered Laminate Is Given as,

\[
\begin{align*}
\{N_x^z\} &= \frac{t}{2} \int_{-t/2}^{t/2} \{\sigma_x\} \, dz = \sum_{k=1}^{a} \frac{z_k}{z_{k-1}} \int_{z_{k-1}}^{z_k} \{\sigma_x\} \, dz \\
\{N_{xy}^z\} &= \int_{-t/2}^{t/2} \{\tau_{xy}\} \, dz \\
\{M_x^z\} &= \frac{t}{2} \int_{-t/2}^{t/2} \{\sigma_y\} \, z \, dz = \sum_{k=1}^{a} \frac{z_k}{z_{k-1}} \int_{z_{k-1}}^{z_k} \{\sigma_y\} \, z \, dz \\
\{M_{xy}^z\} &= \int_{-t/2}^{t/2} \{\tau_{xy}\} \, z \, dz
\end{align*}
\]

and

Where \( z_k \) and \( z_{k-1} \) Are Defined Below

![Diagram of laminate structure with layers and middle surface](image)
2. How do composites vary from metallic structures?

Overview of material properties and the ABD matrix terms. Hints on practical design methods.

The stiffness matrix, $\tilde{Q}_{ij}$, is constant within each lamina. Therefore, the stiffness matrix can go outside the integration over each layer, but is within the summation. Also, we recall that the strains and curvatures, $\varepsilon_x^o$, $\varepsilon_y^o$, $\gamma_{xy}^o$, $K_x$, $K_y$, $K_{xy}$ are middle surface values and are not functions of $Z$. Therefore, they can be removed from under both the integration and summation signs.

\[
\{N\} = \left[ \sum_{k=1}^{N} \left[ \tilde{Q}_k \int_{Z_{k-1}}^{Z_k} dz \right] \right] \begin{bmatrix} \varepsilon_x^o \\ \varepsilon_y^o \\ \gamma_{xy}^o \end{bmatrix} + \left[ \sum_{k=1}^{N} \tilde{Q}_k \int z dz \right] \begin{bmatrix} K_x \\ K_y \\ K_{xy} \end{bmatrix}
\]

\[
\{M\} = \left[ \sum_{k=1}^{N} \left[ \tilde{Q}_k \int_{Z_{k-1}}^{Z_k} z dz \right] \right] \begin{bmatrix} \varepsilon_x^o \\ \varepsilon_y^o \\ \gamma_{xy}^o \end{bmatrix} + \left[ \sum_{k=1}^{N} \tilde{Q}_k \int z^2 dz \right] \begin{bmatrix} K_x \\ K_y \\ K_{xy} \end{bmatrix}
\]
2. How do composites vary from metallic structures?

Overview of material properties and the ABD matrix terms. Hints on practical design methods.
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Overview of material properties and the ABD matrix terms. Hints on practical design methods.

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<td>1.00E-12 2.76E-12 6.55E-13 5.37E+01 5.10E+02 -3.37E+01</td>
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2. How do composites vary from metallic structures?

Overview of material properties and the ABD matrix terms. Hints on practical design methods.

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NAFEMS. The International Association for the Engineering Analysis Community Creating Awareness – Delivering Education and Training – Stimulating Standards

Composites E-Learning Course V1.0 Page 48
Introductory Composites FE Analysis Webinar

Agenda

1. What are composites?

Review of different forms and manufacturing processes.

2. How do composites vary from metallic structures?

Overview of material properties and the ABD matrix terms. Hints on practical design methods.

3. How do I set up a composite FEA?

Overview of typical processes. Keeping track of plies, mold lines etc.
3. How do I set up a composite FEA?

Overview of typical processes. Keeping track of plies, mold lines etc.

material property definitions

Component ply definitions

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<td>one layer of glass fibre</td>
<td>0.006</td>
<td>45</td>
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</tbody>
</table>
3. How do I set up a composite FEA?

Meshing

Setting up ply orientation
3. How do I set up a composite FEA?

Clear strategy needed to control order of ply layup to represent manufacturing process
3. How do I set up a composite FEA?

Good book keeping is essential!

- Either via spreadsheet
- Or FE software tools
4. How good is my FEA idealization?
3. How do I set up a composite FEA?

Visualization and control of components and layups is essential in the pre-processor.
3. How do I set up a composite FEA?
Account for Outer/Inner Mold Line continuity
3. How do I set up a composite FEA?

Two choices:
1. top surface on outer mold line
2. bottom surface on outer mold line

Account for Outer/Inner Mold Line continuity

- Orientate element normal
- Use global ply ids if available
Introductory Composites FE Analysis Webinar

Agenda

4. How good is my FEA idealization?

The importance of fiber orientation, draping, and thickness effects.

5. How do I know whether the composite has failed?

Basic First Ply failure theories

6. How do I organize my results, where do I start looking?

Failure indices, Strength ratios.
4. How good is my FEA idealization?

*The importance of fiber orientation, draping and thickness effects.*

As a ply is draped over a mold it will align the fibers into a net like pattern.

Each fiber would ideally like to form an minimum energy path, rather like a great circle on a globe.

The presence of the adjacent fibers, both in the same ply and throughout the lay up will inhibit this action.

- Two sections of cloth are shown draped over a conical shape.
- The flat pattern required to achieve the lay up geometry is shown.
4. How good is my FEA idealization?

*The importance of fiber orientation, draping and thickness effects.*

Here is an alternative manufacturing solution

- The layup is orientated to run along one edge
- The flat pattern adjusts to suit
- Notice the drift in angle as we go round the cone

Mapping the change in fiber orientation onto the FE mesh is important
4. How good is my FEA idealization?

Here is a section of an aircraft fuselage

The drift in the ply angles can be seen in the lay up data table
4. How good is my FEA idealization?

The draping around the neck of this component can be clearly seen.
4. How good is my FEA idealization?

Feasible draping angles depend on the shearing stiffness of the ply as it is laid over the mold. This will depend on the type of ply – pre-preg or cloth and its mechanical characteristics.

Most draping tools will allow the visualization of regions where the shearing action of the layup process is reaching practical limits, or where it is infeasible.
4. How good is my FEA idealization?

Here the analyst has introduced darts into the draping pattern to reduce the shearing action

Note the discontinuous plies
4. How good is my FEA idealization?

Here the analyst has forced the fibers to follow the flat cap of the stiffener.

This could be a specific design intent, or it may follow the known pattern of a pultrusion or molding.
4. How good is my FEA idealization?

For this type of FE software to be effective

- the analyst must be in the loop!
5. How do I know whether the composite has failed?

Basic First Ply failure theories
5. How do I know whether the composite has failed?

*Basic First Ply failure theories*

The initial approach we take in FEA analysis is to assume that as soon as a composite strength value is exceeded by the stress level present, then the structure has failed, or at least is not fit for further service.

This approach is called **First Ply Failure** mode.

However, it is a far from trivial task to establish the strength of a composite material.

Unlike isotropic materials the strength is dependent on the directional properties of an individual ply, which can vary longitudinally, transversely and in shear, and may well be different between tension and compression.

In addition the ply layup will also control the strength.

A great deal of research has been carried out to try to understand the failure mechanisms of a ply.
5. How do I know whether the composite has failed?

Probably the most intuitive ply failure mode is in tension. The sketch shows a typical failure appearance.

At the microscopic level there is a lot happening, with fiber pull out, fiber breaking and matrix cracking.

However the strength under this loading condition is repeatable for a given as supplied condition within a statistical variation.
5. How do I know whether the composite has failed?

Similarly the transverse tension is dominated by the strength of the matrix.

The microscopic level sees a surprisingly complex behavior with the fibers acting as stress raisers in the matrix stress field.
5. How do I know whether the composite has failed?

The failure under in plane shear can be assumed as a shear line failure along the matrix.

Again at a microscopic level the behavior is more complex with local cracking behavior building to a total failure.
5. How do I know whether the composite has failed?

However, in general in the tensile loading quadrant defined by both longitudinal and transverse tension is relatively straightforward.

Shear will play a strong role for all off axis loading directions.
A simple experiment using FEA to predict failing load in a coupon

Graph shows effect of ply angle in a single ply layup
Now the stress components are examined
Ply Angle 0 degrees

- full allowable axial fiber/matrix stress is obtained, 154,000 psi (1063MPa)
- This is a fiber failure mode
- fibers are carrying the load in the most favorable, axial direction
- resin is acting to stabilize the fibers, and not carrying any significant load (although resin does provide bridging mechanism for fiber gaps or breaks)
- transverse stress that will tend to pull the fibers apart is zero
- shear stress is zero
Ply Angle 90 degrees

- transverse properties of the material resisting the load

- transverse tension allowable is only 4,500 PSI (31 MPa), based mainly on matrix tensile strength – matrix failure

- (interestingly the fibers act as stress raisers in practice in the resin, so tensile strength is less than matrix alone)
even a few degrees from zero strength drops off rapidly
At 10 degrees the stress at failure is down to just over 40,000 psi (276 MPa)
fibers are now subjected to transverse stresses, fibers and the resin have to balance the applied stress state
weaker transverse strength of the resin reduces the strength.
longitudinal, transverse and shear stresses present
5-20 degrees shear dominates
30-90 degrees transverse dominates

\[ \sigma_1 = \frac{P}{A} \cos^2 \theta \]
\[ \sigma_2 = \frac{P}{A} \sin^2 \theta \]
\[ \tau_{12} = -\frac{P}{A} \sin \theta \cos \theta \]
How did we predict the strength of the single ply?

- A **failure theory** analogous to Von Mises stresses for Isotropic materials is used to predict failure

- Many failure theories exist, just using one here:

**Tsai-Wu Failure Theory**

\[
\left(\frac{1}{x_t} - \frac{1}{x_c}\right)\sigma_1 + \left(\frac{1}{y_t} - \frac{1}{y_c}\right)\sigma_2 + \frac{\sigma_1^2}{x_t x_c} + \frac{\sigma_2^2}{y_t y_c} + \frac{\tau_{12}^2}{S^2} + 2F_{12}\sigma_1\sigma_2 = F.I.
\]

- **Xt**  tension limit, along fiber
- **Xc**  compression limit, along fiber
- **Yt**  tension limit, transverse fiber
- **Yc**  compression limit, transverse fiber
- **S**   shear limit
- **F12** interaction term

Failure Index  > 1.0 is bad news
Other Failure Theories

Hill:
\[ \frac{\sigma_1^2}{x^2} - \frac{\sigma_1 \sigma_2}{x^2} + \frac{\sigma_2^2}{y^2} + \frac{\tau_{12}^2}{s^2} = F.I. \]

Hoffman:
\( \left(\frac{1}{x_t} - \frac{1}{x_c}\right)\sigma_1 + \left(\frac{1}{y_t} - \frac{1}{y_c}\right)\sigma_2 + \frac{\sigma_1^2}{x_t x_c} + \frac{\sigma_2^2}{y_t y_c} + \frac{\tau_{12}^2}{s^2} = \frac{\sigma_1 \sigma_2}{x_t x_c} \)

Max stress:
\[ \text{Max} \left[ \left(\frac{\sigma_1}{X_t}\right), \left(\frac{\sigma_2}{Y_t}\right), \left(\frac{\tau_{12}}{S}\right) \right] \]

Max strain:
\[ \text{Max} \left[ \left(\frac{\varepsilon_1}{X_t}\right), \left(\frac{\varepsilon_2}{Y_t}\right), \left(\frac{\gamma_{12}}{S}\right) \right] \]

- No account of tension/compression
- Interaction term
- No interaction between stresses
Other failure modes

As soon as the composite is put into compression then a rather different type of behavior occurs.

For **longitudinal compression** various local buckling and shear models have been suggested. The relative stiffness of the fiber and matrix is important as well as the spacing of the fibers and geometry within the matrix.

The sketch shows two local buckling forms and the photo shows evidence in practice.
5. How do I know whether the composite has failed?

**Transverse compression** is interesting because the strength is generally higher the transverse tension. The matrix tends to act to stabilize the fibers until some form of shear cracking occurs.

This behavior is not well understood in general and is the subject of much manipulation of the failure theories. As is shown on the next few slides the behavior is broken out as a separate phenomenon in some theories.
Tsai – Wu Explored

Consider stress state with no axial (with fiber) stress

Establish locus of failure stress

\[ \sigma_1 = 0.0 \]
F.I. = 1.0
\[ F_{12} = 0.0 \]
\[ \left( \frac{1}{y_t} - \frac{1}{y_c} \right) \sigma_2 + \frac{\sigma_2^2}{y_t y_c} + \frac{\tau_{12}^2}{s^2} = 1.0 \]
\[ \frac{\tau_{12}^2}{s^2} = 1.0 - \left( \frac{1}{y_t} - \frac{1}{y_c} \right) \sigma_2 - \frac{\sigma_2^2}{y_t y_c} \]
\[ \tau_{12}^2 = s^2 \left\{ 1.0 - \left( \frac{1}{y_t} - \frac{1}{y_c} \right) \sigma_2 - \frac{\sigma_2^2}{y_t y_c} \right\} \]
Hill Explored

Consider stress state with no axial (with fiber) stress

Establish locus of failure stress

\[
\sigma_1 = 0.0
\]

\[
\text{F.I.} = 1.0
\]

\[
\sigma_2 \frac{\sigma_2^2}{y^2} + \tau_{12} \frac{\tau_{12}^2}{s^2} = 1.0
\]

\[
\tau_{12} \frac{\tau_{12}^2}{s^2} = 1.0 - \sigma_2 \frac{\sigma_2^2}{y^2}
\]

\[
\tau_{12} \frac{\tau_{12}^2}{s^2} = s^2 \left\{ 1.0 - \sigma_2 \frac{\sigma_2^2}{y^2} \right\}
\]
This stress state zone is of great interest as it involves complex failure modes

On our test with 5 degrees off axis and higher $\sigma_1 \rightarrow 0.0$ MPa

- Tsai-Wu shows the effect of interaction when shear and compressive transverse stresses combine.

- Experimental evidence tends to confirm that Tsai-Wu predictions modify the simple stress limit values
Hill shows the limitation when the same strengths are used in Tension and Compression for transverse strength.

Experimental evidence shows a clear bias in the strength allowables and this affects the interaction.
For the FEA results using the Tsai-Wu criteria we can see the results for ply off axis > 10 degrees fit well into this reduced envelope as the axial stresses tend to zero.

In this case either Hill using transverse tension allowable, or Tsai-Wu would give the same results, which is intuitively correct.

We need to be aware that more complex loading states will not ‘fit’ Hill well.
Advanced failure modes:

The Tsai-Wu, Hill and Hoffman failure theories are just one of many that were developed using known failure points and then interpolating in stress space using quadratic relationships.

One of the limitations of this approach is that all failure is based on a full and continuous interaction between stress states.

It has been found experimentally that failure modes tend to be dominated by either fiber failure modes or matrix failure. There may be little interaction between them.

The continuous quadratic family of theories do not differentiate between these fundamental failure modes.

A class of failure theories has evolved which are sometimes described as ‘phenomenological’ to indicate the nature of the failure is implicit in the theory.
Advanced failure modes:

**Hashin-Rotem** failure criteria breaks up the assessment of failure into several sub criterion:

- **Tensile Fiber Failure:**
  \[
  \left( \frac{\sigma_1}{X_t} \right)^2 + \left( \frac{\tau_{12}}{S_{12}} \right)^2 = 1
  \]

- **Compressive fiber failure:**
  \[
  \left( \frac{\sigma_1}{X_c} \right)^2 = 1
  \]

- **Tensile Matrix failure:**
  \[
  \left( \frac{\sigma_2}{Y_t} \right)^2 + \left( \frac{\tau_{12}}{S_{12}} \right)^2 = 1
  \]

- **Compressive Matrix failure**
  \[
  \left( \frac{\sigma_2}{2S_{23}} \right)^2 + \left( \frac{Y_c}{2S_{23}} \right)^2 - 1 \left( \frac{\sigma_2}{Y_c} \right)^2 + \left( \frac{\tau_{12}}{S_{12}} \right)^2 = 1
  \]
Advanced failure modes:

Through thickness failure

\[ \left( \frac{\sigma_3}{Z_3} \right)^2 + \left( \frac{\tau_{23}}{S_{23}} \right)^2 + \left( \frac{\tau_{31}}{S_{31}} \right)^2 = 1 \]

Note that additional Stress and Strength definitions are made:

Through thickness direction

Transverse direction

Fiber direction
Advanced failure modes:

Each mode is assessed to see which has the highest failure index above 1.0, and hence which prompts the failure.

For our coupon we will ignore through thickness failure and assume inter laminar shear strength equals in plane shear strength:

\[ S_{23} = S_{12} \]

Only tensile axial stresses are present, and only tensile transverse stresses so only those two terms are considered.

The results show that the two failure modes are clearly defined:

- Fiber failure occurs up to at least 5 degrees off axis.
- Matrix failure occurs somewhere before 10 degrees and continues to 90.
- There is a very small reduction in failing load for the matrix failure.
It is interesting to compare the terms of the two failure criterion when the axial stresses are low and matrix failure is assumed to dominate.

Hashin

\[
\left( \frac{\sigma_2}{Y_t} \right)^2 + \left( \frac{\tau_{12}}{S_{12}} \right)^2 = 1.0
\]

Tsai-Wu

\[
\left( \frac{1}{y_t} - \frac{1}{y_c} \right)\sigma_2 + \frac{\sigma_2^2}{y_t y_c} + \frac{\tau_{12}^2}{S_{12}^2} = 1.0
\]

Each equation has an identical shear term. However, the Tsai-Wu first two terms appear to over contribute to a small extent and the compressive transverse strength is intuitively not likely to provide meaningful contribution.
Advanced failure modes:

Similarly if the transverse stress is ignored in the fiber failure region the equations can be compared

\[
\left( \frac{\sigma_1}{X_t} \right)^2 + \left( \frac{\tau_{12}}{S_{12}} \right)^2 = 1
\]

\[
\left( \frac{1}{X_t} - \frac{1}{X_c} \right) \sigma_1 + \frac{\sigma_1^2}{X_t X_c} + \frac{\tau_{12}^2}{S_{12}^2} = 1.0
\]

Note the Hashin method re-uses the shear term. The Tsai –Wu method cannot do this as it is continuous with no distinction. It is added here for comparison.

The Tsai-Wu direct terms are a balancing act and again there is no intuitive feel for their individual contributions

In both methods the shear term extends the domain of the pure fiber failure mode
Hashin Explored

Compressive Matrix failure

Consider stress state with no axial (with fiber) stress (implicit in matrix compressive term)

Establish locus of failure stress

\[
F.I. = 1.0
\]

\[
\left( \frac{\sigma^2}{2S_{23}} \right)^2 + \left( \frac{Y_c}{2S_{23}} \right)^2 - 1 \left[ \frac{\sigma^2}{Y_c} + \left( \frac{\tau_{12}}{S_{12}} \right)^2 \right] = 1
\]

\[
\left( \frac{\tau_{12}}{S_{12}} \right)^2 = 1 - \left( \frac{\sigma^2}{2S_{23}} \right)^2 - \left[ \frac{Y_c}{2S_{23}} \right]^2 - 1 \left[ \frac{\sigma^2}{Y_c} \right]
\]

\[
\tau_{12}^2 = S_{12} - \left( \frac{S_{12}\sigma^2}{2S_{23}} \right)^2 - \left[ \frac{Y_c}{2S_{23}} \right]^2 - 1 \left[ \frac{\sigma^2 S_{12}^2}{Y_c} \right]
\]
Advanced failure modes:

To better understand the failure Hashin failure mode in compression the failure locus under transverse stress and shear stress has been added to the Hill and Tsai-Wu curves

\[
\tau_{12}^2 = S_{12}^2 - \left( \frac{S_{12} \sigma_2}{2 S_{23}} \right)^2 - \left[ \left( \frac{Y_c}{2 S_{23}} \right)^2 - 1 \right] \frac{\sigma_2 S_{12}^2}{Y_c}
\]

- \( S_{23} = 0.5 \, s_{12} \)
- \( S_{23} = s_{12} \)
Test data

Strength data is available from suppliers, but needs to be treated with caution.

Test data costs a lot of resource to compile and is not widely available in industry.

Academic papers and text books tend to contain useful data.

Test if you can afford it, but is a complex process.

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<th>PHYSICAL PROPERTY</th>
<th>TEST METHOD</th>
<th>NOMINAL ULTIMATE VALUES</th>
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<td>3,434 psi</td>
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<tr>
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<td>MIL-P-26014F</td>
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Some of the test methods referenced
5. How do I know whether the composite has failed?

Basic First Ply failure theories

NAFEMS COMPOSITE BENCHMARKS Issue 2

TEST 1 - Laminated strip under three-point bending;
TEST 2 - Wrapped thick cylinder under pressure and thermal loading;
TEST 3 - Three-layer sandwich shell under normal pressure loading.

The purpose of these tests is to demonstrate that the program can carry out an effective composite analysis and :-

a) accurately predict displacements;
b) recover meaningful direct stresses;
c) recover meaningful interlaminar shear stresses;
using flat laminated plate, brick, curved shell and thick sandwich shell elements.
5. How do I know whether the composite has failed?

Basic First Ply failure theories
Introductory Composites FE Analysis Webinar

Agenda

4. How good is my FEA idealization?
The importance of fiber orientation, draping and thickness effects.

5. How do I know whether the composite has failed?
Basic First Ply failure theories

6. How do I organize my results, where do I start looking?
Failure indices, Strength ratios.
6. How do I organize my results, where do I start looking?

*Failure indices, Strength ratios.*

- Identify regions where F.I. shows failure in the layup
6. How do I organize my results, where do I start looking?

- Identify which plies are failing in the layup in that region
6. How do I organize my results, where do I start looking?

- Review Direct X, Direct Y and Shear XY ply stresses in the individual ply
- Assess major mode of failure
- Assess coupling through plies
- Redesign if required
6. How do I organize my results, where do I start looking?

Various stress sorting and filtering schemes are available dependent on solver and post processor used.

It is important to get familiar with these.

Use contour plots and any specific ply mapping tools.

The quantity of data can be immense.
6. How do I organize my results, where do I start looking?

The Failure Index is a quadratic term, it does not scale linearly with stress level.

Failure is when \( F.I \geq 1.0 \)

\[
\left( \frac{1}{x_t} - \frac{1}{x_c} \right) \sigma_1 + \left( \frac{1}{y_t} - \frac{1}{y_c} \right) \sigma_2 + \frac{\sigma^2_1}{x_t x_c} + \frac{\sigma^2_2}{y_t y_c} + \frac{\tau^2_{12}}{s^2} + 2F_{12} \sigma_1 \sigma_2 = F.I.
\]

For most Failure Criteria the F.I equation can be recast as a Strength Ratio of actual stress/allowable stress with F.I. set to 1.0.

Now Strength Ratio scales linearly with stress.

Failure is when \( S.R < 1.0 \)

Acts like a Reserve Factor as used in Europe \( MS = RF - 1 \).
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Agenda

7. Through thickness and edge effects such as delamination

Usage of solid and thick shell elements.

8. Advanced failure methods

Progressive ply failure, cohesive elements, fracture mechanics methods (VCCT)
7. Through thickness and edge effects such as delamination

*Usage of solid and thick shell elements*

We have not discussed the through thickness terms which include the interlaminar shears and the direct through thickness stress.
7. Through thickness and edge effects such as delamination

For thin shells in bending the interlaminar shears created by relative stretching between plies are approximated by assuming a simple through shear distribution analogous to classical shear solutions in solid isotropic sections.

Hence interlaminar shear stresses and strength assessment under simple bending is quite acceptable.
7. Through thickness and edge effects such as delamination

However, the thin shell theory assumes that the stresses are continuous within a ply and takes no account of any possible free edge effect where stresses go to zero.

In cases where this may be important it may be necessary to use thick shell or solid elements that can cater for this or to use a micro level element mesh where each ply is modeled with thick shells or solids.
7. Through thickness and edge effects such as delamination

Bending effect such as shown here will promote interlaminar shears and also direct through stresses.

Solids or thick shells are required.
7. **Through thickness and edge effects such as delamination**

This fitting will exhibit peel stresses, through thickness stresses and other stress patterns tending to act in a 3D sense through thickness.

For heavy fittings, plane strain may be a useful analysis method.
Introductory Composites FE Analysis Webinar

Agenda

7. Through thickness and edge effects such as delamination

Usage of solid and thick shell elements.

8. Advanced failure methods

Progressive ply failure, cohesive elements, fracture mechanics methods (VCCT)
8. Advanced failure methods

*Progressive ply failure, cohesive elements, fracture mechanics methods (VCCT)*

We saw the definition of First Ply Failure in a previous section.

**Progressive Ply Failure** takes this further by assuming that the stiffness of the failed ply can be reduced in some manner and the analysis continues.

Ply failures can continue to occur with subsequent reduction in stiffness.

A PPF strategy requires:

A failure criteria which can identify the mode of failure (such as Hashin, Puck, LARC02).

A rational strategy for reducing element stiffness based on the mode of failure seen.
8. Advanced failure methods

Progressive Ply Failure is sensitive to how the stiffness is reduced at each non-linear load step.

If the drop is too great then instabilities can occur, so usually a maximum percentage of stiffness in a particular orthotropic direction is used.

The user can elect to modify this to simulate more ductile composite materials.

Certain failure modes such as longitudinal tension may be classified as final failure in their own right.
8. Advanced failure methods

**Cohesive Element** methods aim to model specific debonding or delamination situations by inserting a layer of special elements between the plies or materials.
8. Advanced failure methods

The behavior of the crack or delamination front is controlled by an energy rate law to allow tuning for different types of material (e.g. brittle or ductile).

The actual failure method is still using a stress-based approach.
8. Advanced failure methods

**Virtual Crack Closure Technique** or VCCT use a fracture mechanics approach to delamination

Originally the method was used for cracks in isotropic materials and it has had great success

More recently it has been used to model delamination

The sketch at right shows a pair of nodes spanning a delamination that has just occurred.

The displacements of the nodes are known and the force required to oppose the opening action and close the crack back up can be deduced from the stress state.
8. Advanced failure methods

The force and displacements are known, so the energy required to close the crack is known.

This is equal to the energy required to produce the delamination.

The rate of change of energy with respect to the crack growth rate is analogous to the Stress Intensity Factor in isotropic materials.

The strain energy release rate can be compared to the fracture toughness of the material to establish whether a crack will propagate or not.
Q and A

e-learning @ nafems.org
Thank you!

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