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LAWRENCE BERKELEY NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY

Carbon Fiber Laminate Theory (Laminated Plate Theory)

LBNL Composites Workshop

February 29-March 3, 2016

Overview

Composites in Detectors, and background

What are composites and why we use them

Very brief introduction to design estimation

Common Laminates and Problems—ties to Fabrication

Q&A

For this discussion: 'Carbon Fiber' as a material, is Carbon Fiber Reinforced Plastic (CFRP)—a 'Composite'. Composites with other fibers and matrices are also broadly mentioned.

LBNL Composites Shop

Capability established to support construction of ATLAS Pixel Detector

Have since delivered many detectors…

Synergy of project requirements and contiguous R&D allows for bootstrap technology development

Techniques developed for ATLAS used on STAR

Materials developed on STAR (30gsm FAW) now used on ATLAS

Shop capabilities (large structures)

Design and Fabrication

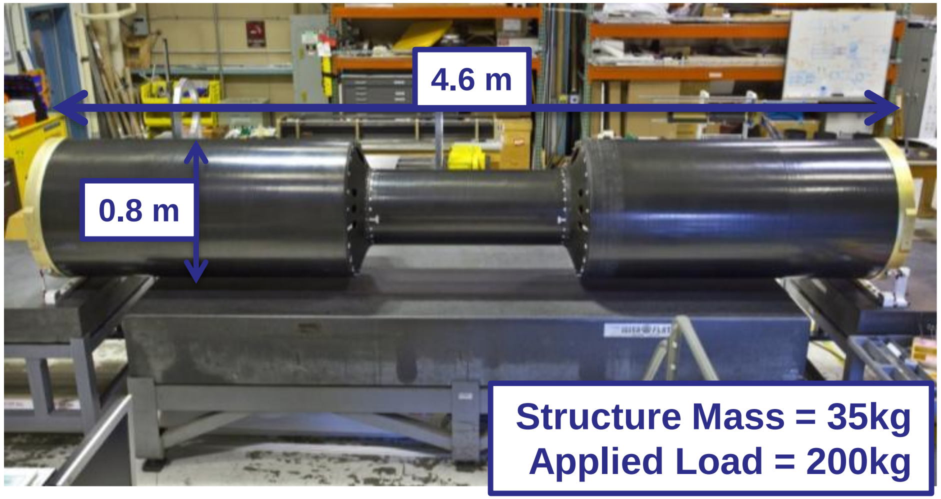
Low-mass, Stable Structures

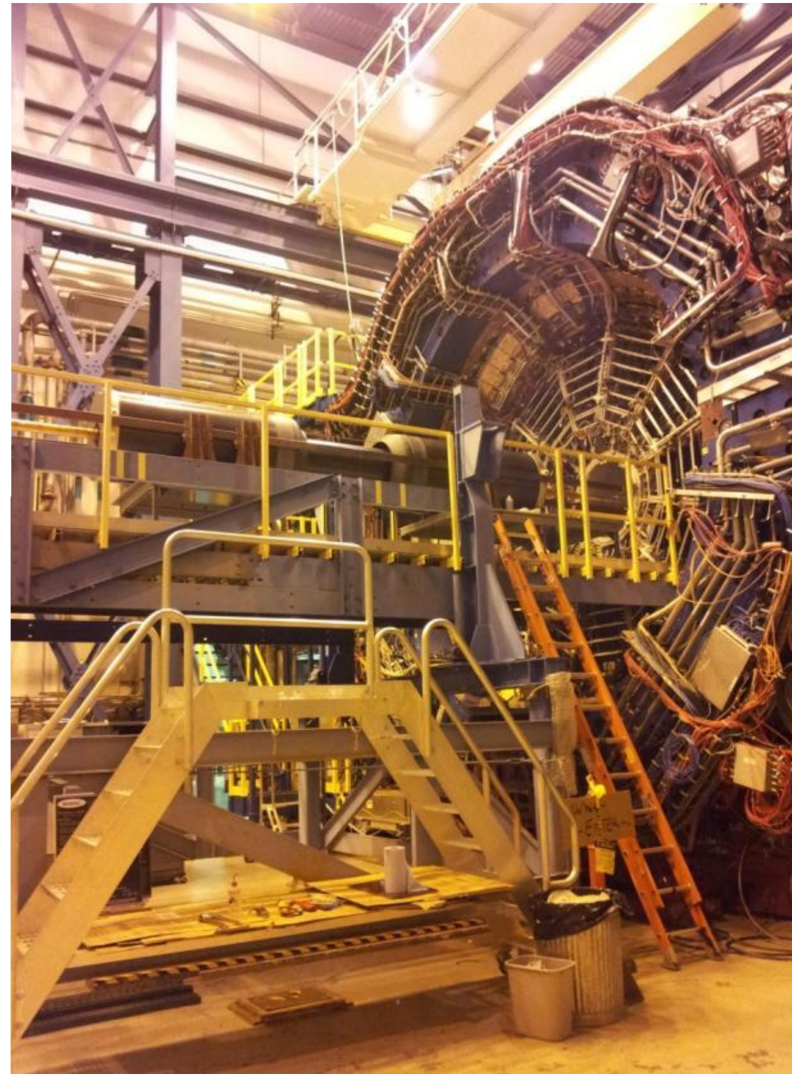
Precision Assembly of large structures (4-8m)

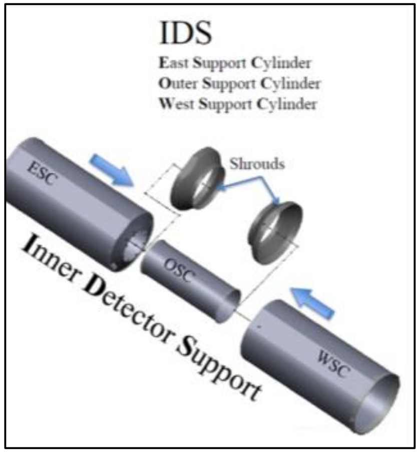
Developed for Global Support Structures of High Energy Physics Detectors

Useful for any structure requiring high precision/stability

STAR HFT Inner Detector Support (IDS)



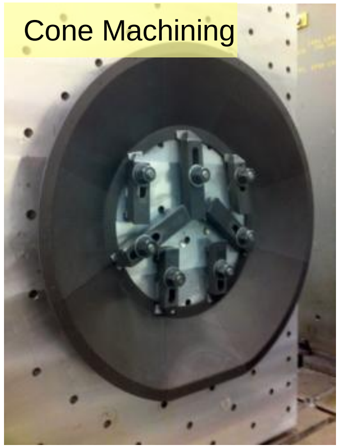


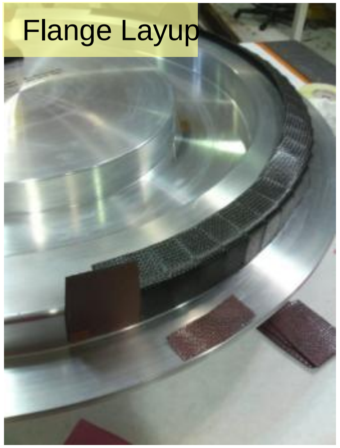


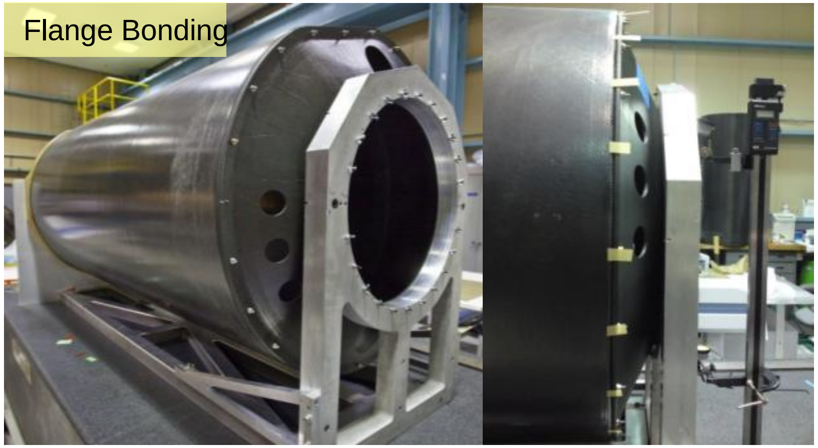

WSC/ESC Mandrel

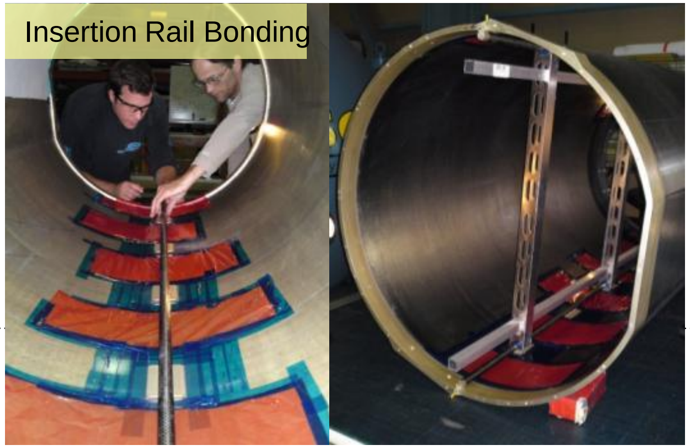

WSC/ESC Layup

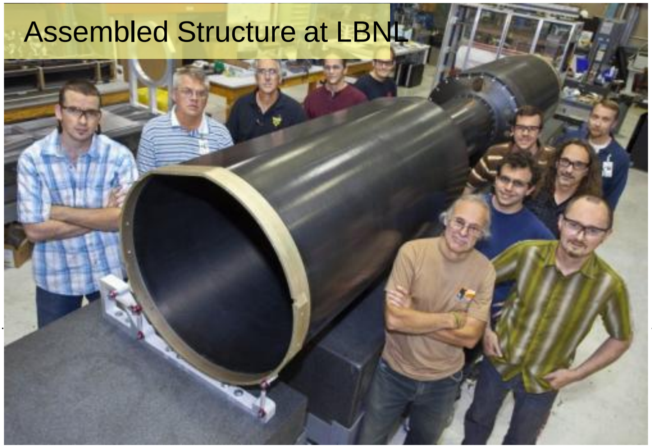

Cone Layup

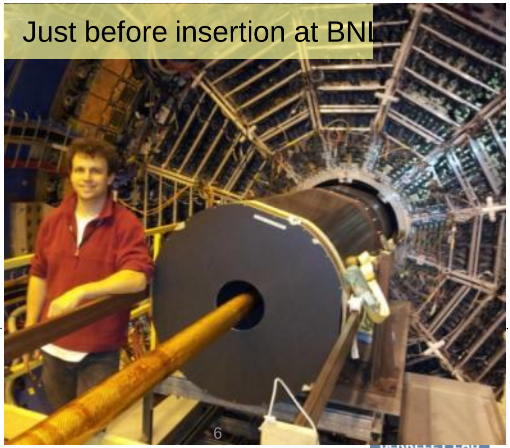

Cone Machining


Flange Layup


Flange Bonding


Insertion Rail Bonding


Assembled Structure at LBNL


Just before insertion at BNL

Composites are materials developed via a fabrication process

- Generally 2 components with vastly different properties that when combined yield superior qualities
- It is impossible to separate material properties from fabrication process in composites
- Ability to close loop on design, fabrication, and test is an important capability to develop and maintain
- It is important to understand aspects of fabrication at all stages, from pre-preg to layup to be able to properly specify design variables
- Over-use of ‘nominal’ values in design is common in our field and is what is taught in typical courses

Part manufacture is material design

Each of the stages of manufacture have some inter-relation and affect the overall product as deviations from ideal

Understanding these deviations allows you to modify the design, tool, and processes to best achieve intent and goals

Part and Process Design together are best viewed holistically

Of course, design of the laminate can have some peculiar ramifications to the manufacturing process…

Aim is to tie design and manufacture together both to show what’s easy to do/control and what’s difficult

Much of composite fab/design is simple, but tedious…

Some Design Background

Simple Lever rules can get you 80% of the way to understanding base properties of composite materials, say zeroth order properties like Moduli, Strength and CTE

Laminated Plate Theory is the basis for understanding higher order mechanical properties, and response of stresses on the materials

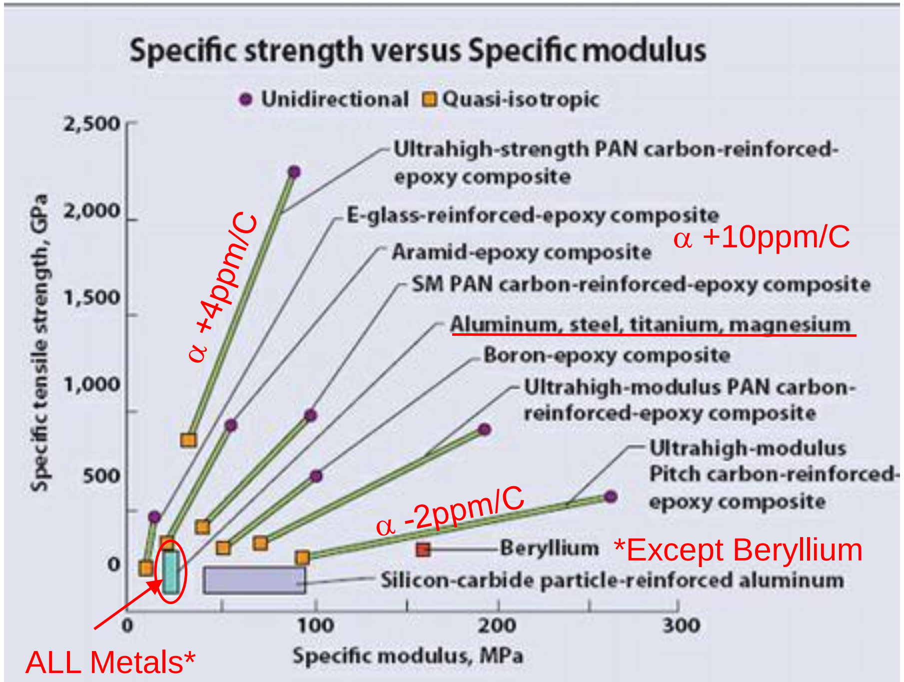
MOST of our laminates are designed 'Symmetric and Balanced' and further are designed to be 'Quasi-Isotropic'

- The sub-class of Symmetric isn't necessarily Quasi-Isotropic nor Balanced
- Symmetric, Balanced, QI (QIBS) laminates have the special property that many off-diagonal elements of the stiffness matrix are identically cancelled
- Off-Diagonal elements of the stiffness matrix are responsible for 'anti-clastic' behavior—bend-twist, and shear-extension coupling of induced strains

Symmetric Balanced Quasi-Isotropic laminates are the easiest to design with, and yield the most predictable parts

These terms will make more sense later…

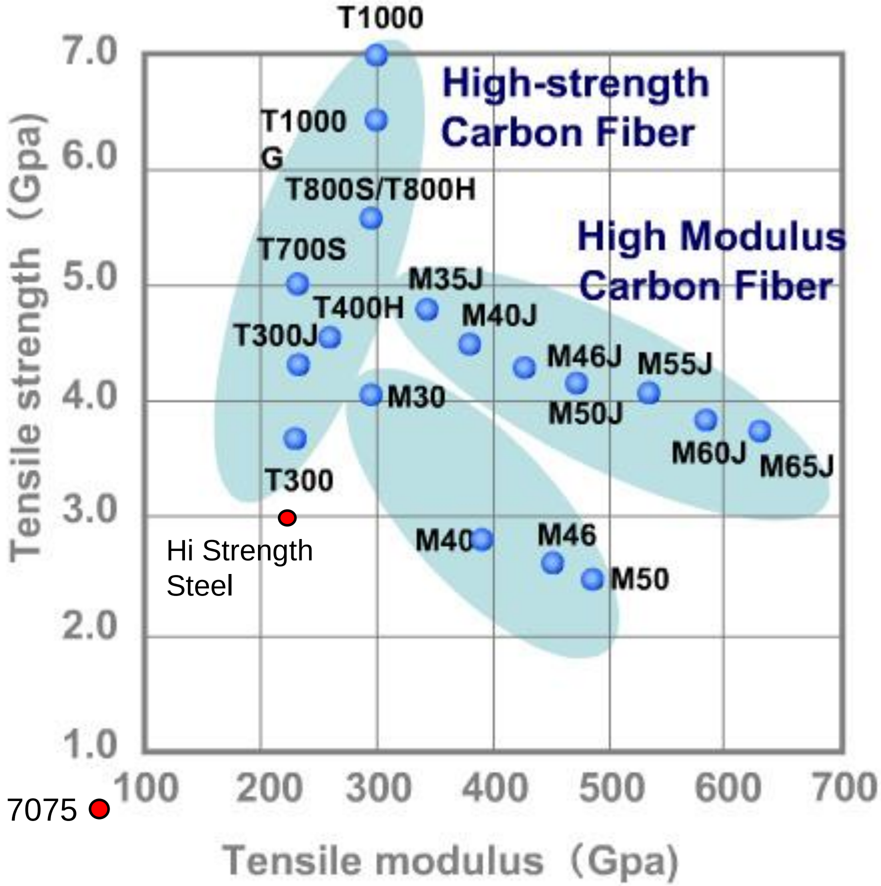
Why Composites: It’s not just mass



In units of E/ρ where Aluminum = 1 CFRP has a ρ ~60% of Al, GFRP similar; Modulus (E) of CFRP tunable from just under Aluminum to just over Titanium with Quasi-isotropic laminates. Oriented laminates can exceed Berylium in a desired direction.

- Clearly where mass is critical composite materials excel!
- Main competition is Be—not desired for several reasons
- Non-magnetic properties important in B-Field applications
- Glass fiber composites non-conductive for Hi-Voltage
- Thermal expansion tunable from near zero to Steel
- Matrix resin choice flexible based on other requirements

Carbon Fiber Properties



PAN (Poly Acrylo-Nitrile) is a polymer: (viscose). Pitch is geologic tar, a byproduct of oil extraction with very high carbon content and long polymer chains thus char ratio

- Carbon Fiber is not a material, it is a family of materials
- Other fibers such as Glass, PE, Kevlar, etc have more unique properties (tightly defined)
- CF properties vary based on their %-Graphitization—from mostly 'glassy' to 'crystalline'
- Also on 'precursor' material e.g. PAN versus Pitch
- Chart is for PAN based fibers
- Pitch based fibers can have modulus in excess of 1000GPa

Before going too far—Just in Case…

$$F = k\delta \quad F = EA\epsilon \quad \delta = \frac{Fl^3}{3EI} \quad \sigma = Mc/I$$

We are talking linear springs and beam theory here…

F = kx (δ in engineering); EA = k/l and ε is 'strain'

E is modulus; Stiffness normalized to area per unit length in applied force dimension (a material constant)

Physicists aren't the only ones that 'normalize' or abstract to convenient units…

"I" is areal moment of inertia of a section normal to the applied stress (not force), M is moment, σ is stress

If there are questions here—should resolve (quickly) before moving on…

Specific Language—Just in case…

Physics has ‘mass-less’, ‘point mass’, ‘frictionless’, ‘lossless’, etc. all of which convey a set of assumptions via an understanding of a particular phrase

They tell you what you can ignore immediately (or should pay attention…)

Engineering is the same, and also attributes specific meaning to colloquial terms (just like physics)

Strength and Stiffness are not the same; Strength is related to failure envelopes and Stiffness is related to performance in both linear and non-linear regimes

‘Elastic’ implies linear response, and pre-failure response

‘Plastic response’ implies failure and non-linear behavior

Composites are Plastics, and some ‘Plastic Behavior’ is expected…

A Brief word on 'Strength'

We tend to use composites in deflection driven designs, thus tend to use ultra-high modulus fibers

These fibers have low failure strains e.g. 0.3%

'High Strength' fibers have failure strains in excess of 1%

Matrices range from 1-5% failure strains

Strength models do exist to combine these in laminates, but require testing to use (Tsia-Hill or Tsai-Wu)—strain energy based like Von Mises…

For stiffness based designs, laminate strength is rarely an issue, but should be checked

Strength of composite materials will not be presented formally, but discussion is welcome

Consider using Fiber Strain as a metric to assess margins of safety

This technique is often referred to as ‘First Ply Failure’ and is rather conservate…

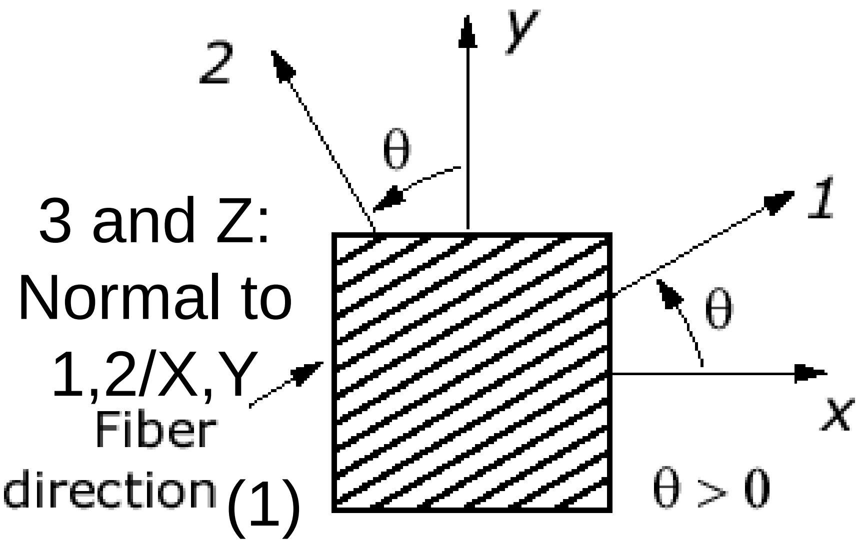
ACP Will report these values specifically

If you are using ANSYS without a composites package, do not use Von-Mises stresses…

Reporting principle strain of an isotropic solid is a quick estimate, but not proper.

Ultimately a more proper, full orthotropic analysis in ANSYS is required

Lamination: Additive manufacture



‘Carbon Fiber’ material is built layer by layer on a mold

Each layer has a fiber direction and ‘thickness’ specified by the design requirements (X,Y are Body Coordinates)

‘Thickness’ is a function of Fiber Areal Weight and Resin content—typically 55-60% Fiber Volume Fraction

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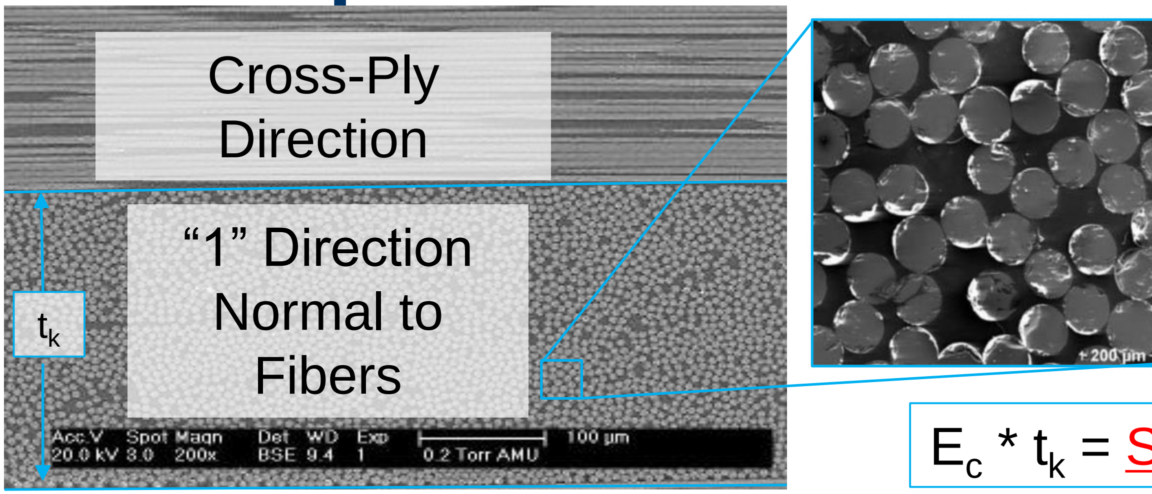
Composite Material 'Lever Rule'



Modulus of 'unit' section:

$$E_c = E_f{*}V_f + E_m{*}V_m + E_v{*}V_v$$

Where: Void Fraction

$$V_f + V_m + V_v = 1 \text{ (Unity)}$$

$E_c * t_k$ = Stiffness of lamina

- Volume fractions of Fiber, Matrix, and Void content map directly to 'lamina' engineering properties
- Various 'Volume Fractions' are a combination of material specification (FAW) and lamination process control
- Lamina are layers in a 'laminate' LPT is used to predict the structural performance of a sum of lamina
- Cured Ply Thickness (CPT = t_k)

Lamina Properties: Lever Rule in 2D

V_f = Fiber Volume Fraction ~ 0.50-0.60 depending on process

V_m = Matrix Volume Fraction ~$1-V_f$

Lamina Properties

$\boxed{\text{Cloth Compliance} := 13\%}$

Modulus Fiber (1) Direction

$$E_{11} := \frac{\left(E_{1f} \cdot V_f + E_m \cdot V_l\right)}{1 + \text{Cloth Compliance}}$$

Modulus Orthogonal 2/3 Direction

$$E_{22} := \frac{E_m}{1 - V_f \cdot \left(1 - \frac{E_m}{E_{2f}}\right)}$$

$$G_{12} := \frac{G_m}{1 - V_f \cdot \left(1 - \frac{G_m}{G_{12f}}\right)} \qquad G_{23} := \frac{G_m}{1 - V_f \cdot \left(1 - \frac{G_m}{G_{23f}}\right)} \qquad G_{13} := G_{12}$$

$$\nu_{12} := \nu_{12f} \cdot V_f + \nu_m \cdot V_l \qquad \nu_{23} := \frac{E_{22}}{2 \cdot G_{23}} - 1 \qquad \nu_{13} := \nu_{12} \qquad \nu_{21} := \nu_{12} \cdot \frac{E_{22}}{E_{11}}$$

~E_{fiber} * V_f Modified by Cloth Compliance

$$[C] = \begin{bmatrix} \frac{E_1}{1-\nu_{12}\nu_{21}} & \frac{\nu_{12}E_2}{1-\nu_{12}\nu_{21}} & 0 \\ \frac{\nu_{21}E_1}{1-\nu_{12}\nu_{21}} & \frac{E_2}{1-\nu_{12}\nu_{21}} & 0 \\ 0 & 0 & G_{12} \end{bmatrix}$$

~E_{matrix} * V_m

Actually C_{66}

Note: $(1+\nu_{12}\nu_{21})$ ~1.06-1.1

[C] represents *orthotropic* properties of one layer of composite material in 'Fiber Coordinates' (note not 6X6 due to orthotropic approximation)

"1" is fiber Direction, "2" is transvers to fiber (in plane), "3" is thru thickness dimension (ignored for orthotropic case)

Matrix moduli ~1-2 orders of magnitude less than fiber

ν_{12f} (fiber poisson ratio) not well published, ranges from 0.2-0.35

'Cloth Compliance' is empirical—not all fiber contributes to in-plane properties ranges from 8-15% base on weave ("0" for Uni-Directional Tape)

Lamina properties ~50% Fiber Properties in modulus, even less with cloth

Not all micromechanics use the same equations

Chou

Lamina Properties Cloth_Compliance := 0%

Modulus Fiber (1) Direction | Modulus Orthogonal 2/3 Direction

$$E_{11} := \frac{(E_{1f} \cdot V_f + E_m \cdot V_1)}{1 + \text{Cloth\_Compliance}} \qquad E_{22} := \frac{E_m}{1 - V_f \cdot \left(1 - \frac{E_m}{E_{2f}}\right)}$$

$$G_{12} := \frac{G_m}{1 - V_f \cdot \left(1 - \frac{G_m}{G_{12f}}\right)} \qquad G_{23} := \frac{G_m}{1 - V_f \cdot \left(1 - \frac{G_m}{G_{23f}}\right)} \qquad G_{13} := G_{12}$$

$$\nu_{12} := \nu_{12f} \cdot V_f + \nu_m \cdot V_1 \qquad \nu_{23} := \frac{E_{22}}{2 \cdot G_{23}} - 1 \qquad \nu_{13} := \nu_{12} \qquad \nu_{21} := \nu_{12} \cdot \frac{E_{22}}{E_{11}}$$

11.3 NOTE ON THE MICROMECHANICS MODELS

Kollar-Springer

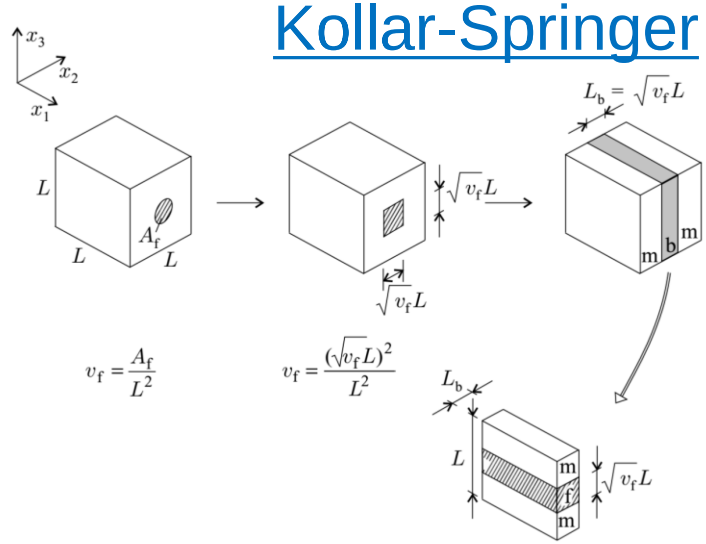
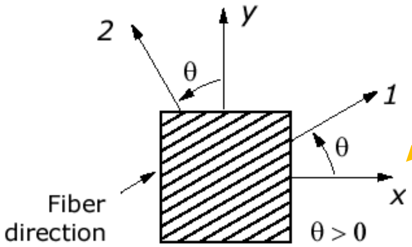


Figure 11.7: The model for the modified rule of mixtures (top) and the representation of the middle "b" layer (bottom).

$$E_{b2} = \sqrt{v_f}E_{f2} + (1 - \sqrt{v_f})\,E_m.$$

- Different methods to calculate E22 (transverse lamina modulus)
- Differ by ~6% but effect is small—E11>>E22

Oriented Lamina Properties: Transform



(Properties defined by [C] in fiber coordinates)

Primary Body Direction (X)

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

(Coordinate Transform Matrix)

$$[C_{body}] = [T]^{-1}[C][T]^{T}$$

$[T]^T$ (transpose) works out due to definition of [C] and mapping to 'engineering strain' via [R] factor 2 In G_{12} term

Theta (Degrees)	Cos^4(Theta) (Value)
5	0.984
10	0.941
15	0.840
45	0.250
60	0.063
90	0.000 (matrix)

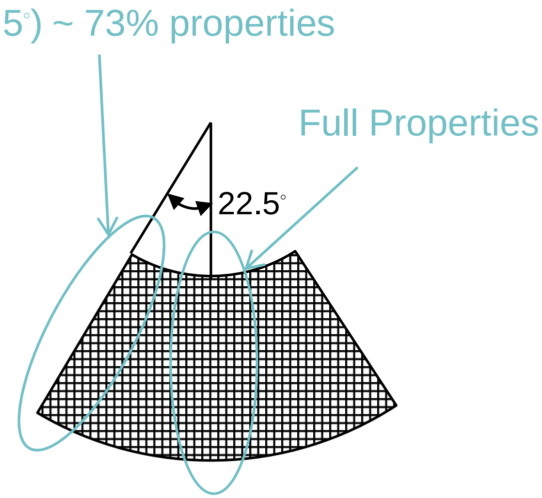
Sensitivity

Common Orientations

Transverse Direction

- **Transform to 'Body Coordinates' (X, Y) is ~ $\cos^4(\theta)$**
- **X is primary direction, Y is transverse**
- **Body Coordinates are aligned with physical structure, convention is θ = 0 is aligned with X**
- **Sensitivity shows accuracy required during lamination and/or design**

Properties dependent on orientation



Local analysis coordinate systems are important for material definition in ANSYS (FEM)

Flat plates and Cylinders are simple—body and fiber coordinates retain a unique mapping throughout the structure

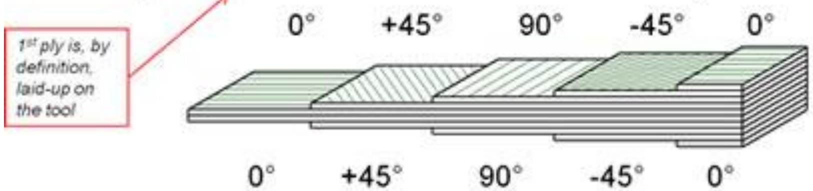
Transition elements: flanges or other non-planar structures are more complicated—fiber orientation thru volume needs to be accounted for

"Laminate" properties are an average over multiple layers

This can be done by hand calculation but software exists to aid in this

Laminate Properties: Multiple Lamina

- Laminates are often described by an orientation code
- Example: [0/-45/90/+45/0/0/+45/90/-45/0]



- Short hand: $[0/-45/90/+45]_S$ symmetric
- Short hand: $[0/-45/90/+45]_N$ Repeat N times
- Other Examples: $[0/+45/-45/90]_{2S}$ 16 total plies
  $[0_2/+45/-45/90_2]_S$ 12 total plies
  $[0_U/+45_{CL}]$ 2 total plies (1 uni @ 0° and 1 cloth @ ±45°)

http://www.quartus.com/resources/white-papers/composites-101/

The above laminate is QIBS
"Quasi-Isotropic Balanced Symmetric"
'Quasi-Isotropic' modulus in plane
'Balanced' about the mid-plane by area
'Symmetric' matched orientations about mid-plane
$[0,60,-60]_s$ and $[0,90]_s$ are also QIBS

Laminate nomenclature describes orientations of layers

Generally assumes all layers are the same material

Shorthand is not applicable for 'hybrid' materials e.g. materials with different fiber/thickness

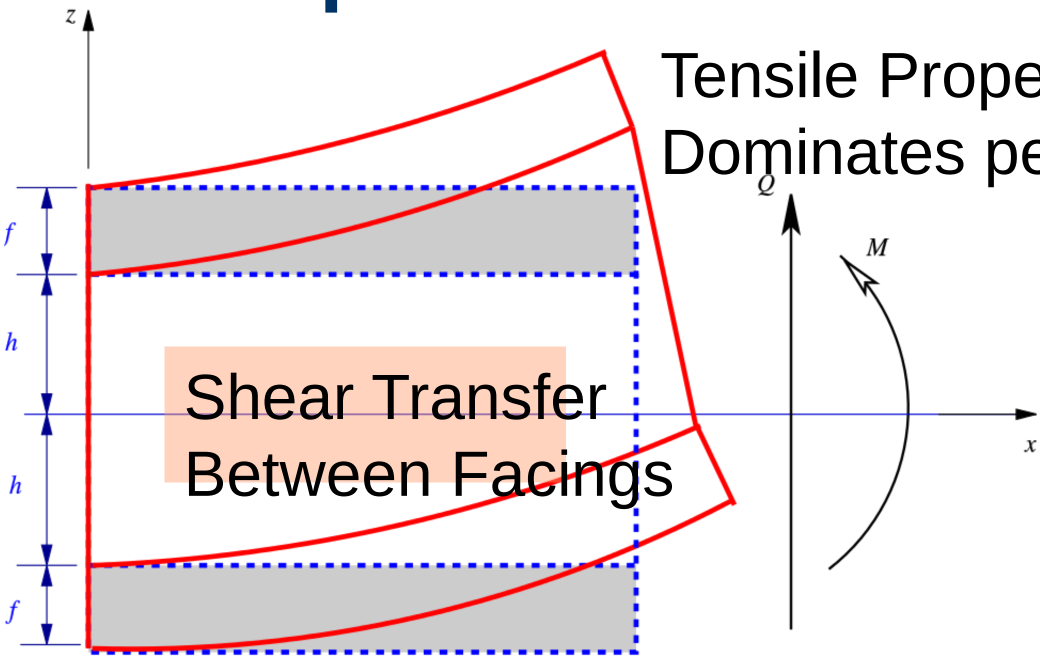
Later analysis assumes common material per layer/ply—generalization to hybrid materials is straightforward…

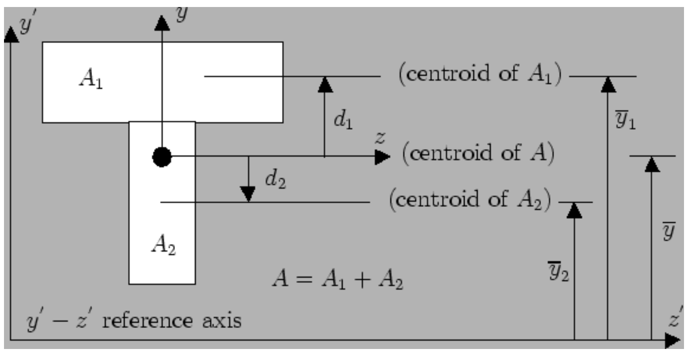
Sum of stiffness contributions of each layer: [A] matrix divided by thickness is the Modulus of the laminate

This is good for preliminary design

Composite Beam Theory

Tensile Properties of Facings Dominates performance





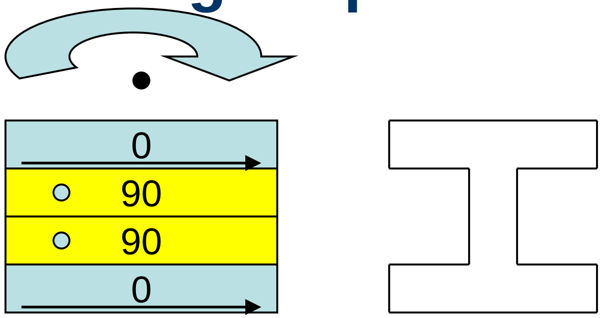
Composite Beam Theory is a method for adding various sections to calculate bending stiffness (weighted by offset from 'neutral axis')

Sectional inertia is also weighted by the stiffness of each section e.g. an Aluminum A_1 versus a Steel A_2 in the example above

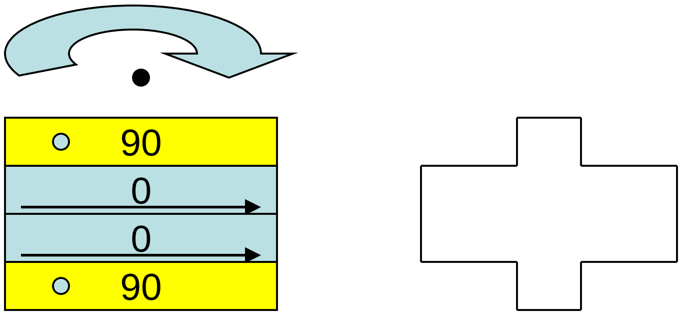
LPT is an identical formality—it simply sums smaller elements to arrive at similar section properties for tension, shear, and bending.

The matrix formalism of LPT is simply an accounting mechanism…

Stacking Sequence



Looks Like I-Beam when bent



Looks **NOT** Like I-Beam when bent on this axis

A Symmetric Laminate is symmetric wrt to ply orientation above and below the laminate mid-plane

- Example [0,+30,+30,0] sometimes written $(0,+30)_s$ is symmetric but not balanced

Balanced laminate is one where for every $+\theta$ there is also a $-\theta$ lamina

- Example [0, +30, -30, -30, +30, 0] or $[0, +30, -30]_s$

For a symmetric laminate, [B] = 0 always

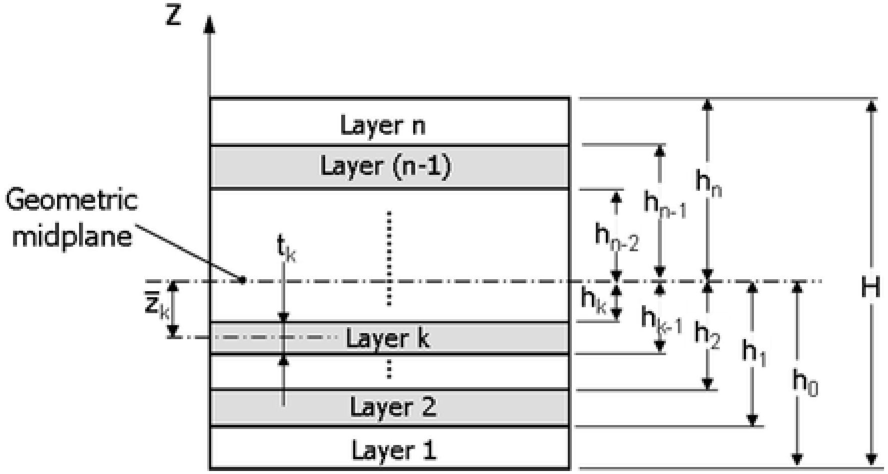
For Balanced laminates, $A_{16} = A_{26} = 0$ i.e. no shear extension coupling

Stacking sequence does not affect [A] matrix

- Both Laminates above have same Tensile properties—same [A] matrix

Laminate Plate Theory (nutshell)

Note: calculated from mid-plane *NOT* neutral axis…



Δh_k (ply thickness t_k of each ply) is constant here—unimportant for [A], important for [B], and [D].

$$A_{ij} = \sum_{k=1}^{N} \left(\bar{C}_{ij}\right)_k \left(z_k - z_{k-1}\right) = \sum_{k=1}^{N} \left(\bar{C}_{ij}\right)_k t_k$$

$$B_{ij} = \frac{1}{2} \sum_{k=1}^{N} \left(\bar{C}_{ij}\right)_k \left(z_k^2 - z_{k-1}^2\right) = \sum_{k=1}^{N} \left(\bar{C}_{ij}\right)_k t_k \bar{z}_k$$

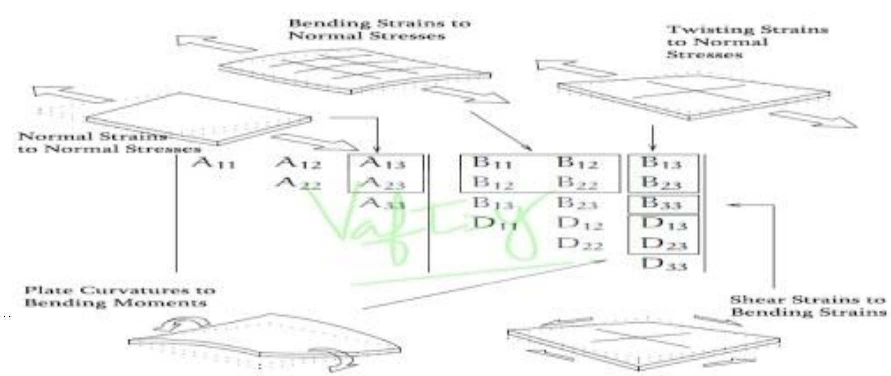
$$D_{ij} = \frac{1}{3} \sum_{k=1}^{N} \left(\bar{C}_{ij}\right)_k \left(z_k^3 - z_{k-1}^3\right) = \sum_{k=1}^{N} \left(\bar{C}_{ij}\right)_k \left(t_k \bar{z}_k^2 + \frac{t_k^3}{12}\right)$$

http://cae.vaftsycae.com/abd_matrix_composites.html

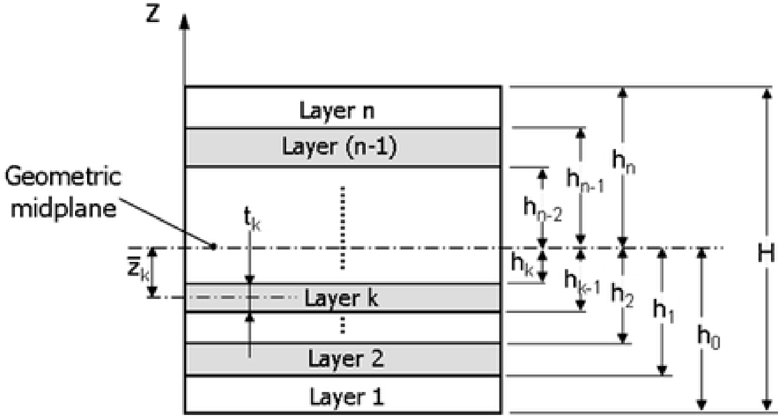
LPT has a matrix formalism which seems overtly complex:

- The ‘A’ matrix: Tensile Prop’s
- The ‘B’ matrix: Shear Coupling
- The ‘D’ Matrix: Plate Bending
- These are all about the mid-plane of the laminate (not section)

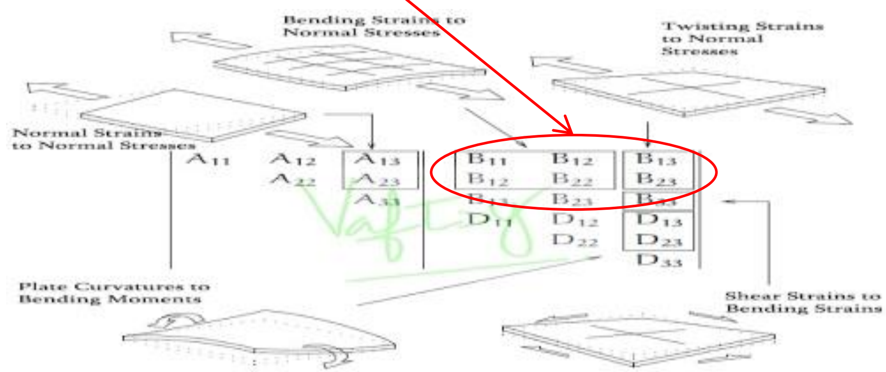
‘A’ matrix dominates for most ‘beam-like’ structures!



Balanced Symmetric laminates: no [B]



Ignore for Balanced Symmetric



$$B_{ij} = \frac{1}{2}\sum_{k=1}^{N}\left(\bar{C}_{ij}\right)_k\left(z_k^2 - z_{k-1}^2\right) = \sum_{k=1}^{N}\left(\bar{C}_{ij}\right)_k t_k \bar{z}_k$$

t_k is signed:
Negative below
Geometric mid-plane
Positive above

Balanced Symmetric Identically cancels all [B] matrix elements!

[B] is un-fun to deal with without specific expertise

Balanced Symmetric laminates render [A] and [D] essentially independent

B and D are second, even third, order problems for most structures—they mostly come into consideration for 'local' loading of structures

[A] (tensile properties) dominate for most applications

[A] Matrix properties (Tensile Properties)

Theta (Degrees)	Cos^4(Theta) (Value)
0	1
60	0.063
-60	0.063
-60	0.063
60	0.063
0	1
Average:	0.375

6-ply QIBS Laminate

Theta (Degrees)	Cos^4(Theta) (Value)
0	1
45	0.250
90	0
-45	0.250
-45	0.250
90	0
45	0.250
0	1
Average:	0.375

8-ply QIBS Laminate

Average assumes all layers are equal thickness thus stiffness in the laminate coordinates

Both examples are QIBS: *ALL* examples of QIBS will have the same body modulus

Tables indicate orientation knockdown—still need to include Fiber Volume Fraction (V_f) knockdown

- Tables above show fractional contributions of each layer in “X” direction (body coordinate) based on orientation “θ” of fibers to body
- Each layer should also be knocked down by Vf ~50-60%
- Including V_f, E_X and E_Y for a QIBS laminate range from 18-22% of E_{fiber}
- QIBS laminates can be estimated as ‘black’ metal with some caveats

‘Black Aluminum’ and other estimates

‘High Strength’ CF ranges from 220-300GPa

‘Intermediate Modulus’ CF from 280-500GPa

Pitch based fibers start at 500 and goes to ~1000GPa

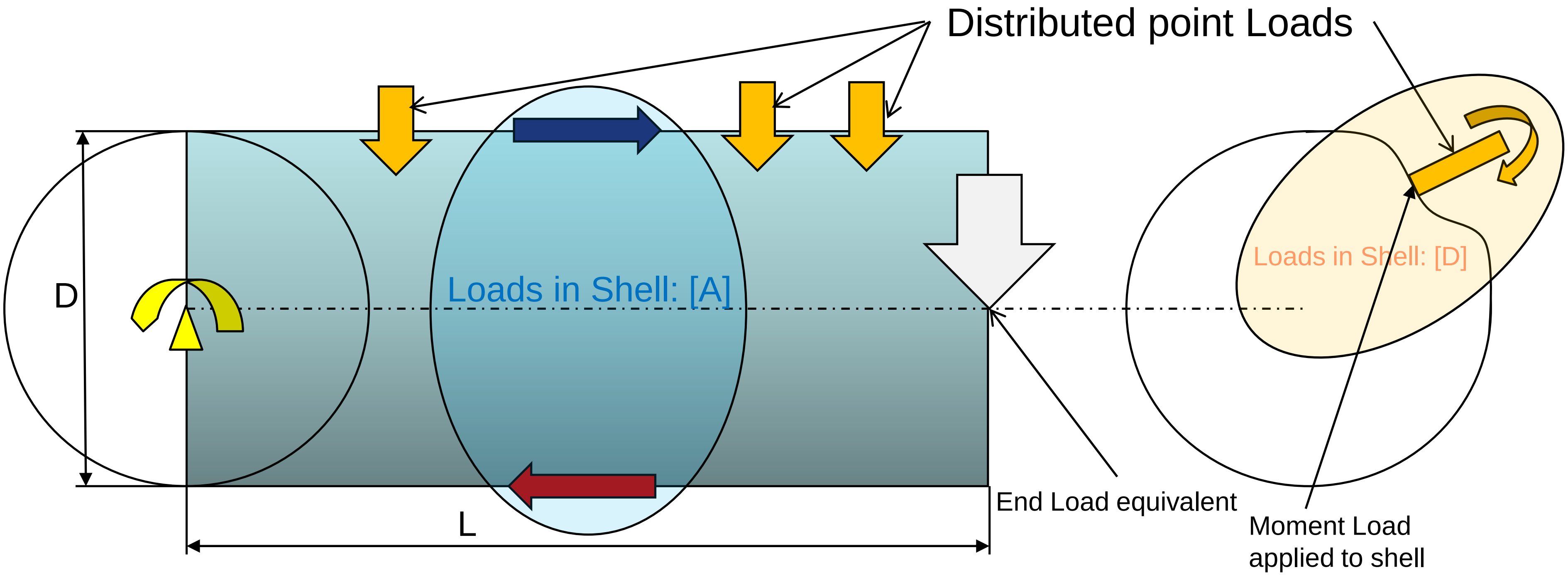
Considering the QIBS estimate of ~20% fiber modulus there exists both an Al and Ti equivalent quite trivially

‘Black Aluminum’ is a pejorative term aimed at a design that took no other advantage other than density by using a CFRP component (since the early ‘80’s)

On the other hand, using an Aluminum or Titanium analog (with lower density) in analysis is a quick way to asses if a composite structure is beneficial in an FEM

As with any mechanical assembly, it’s usually the joints and local loads that screw with the design…

Global versus Local Deflections



Deflections may be dominated by local flexure for thin walled structures

L / D > 8 is required for ‘beam like’ behavior; else: ‘shear’ properties dominate global deflection relative to supports

Introducing loads into thin shells requires some expertise

Expert advice: when it's needed

Use of 'Black' isotropic analogs are useful for design studies

- Approximations are truly valid for tensile (in-plane) loads
- Conceptual design studies, nominal sizing, first order mass…
- Feature or load rich locales are where approximations break

Normal loads/local moments need expertise to asses

- Localized load transfer into shell is important to understand

Joint compliance is significant for bolted/mechanical joints

- More than expected compared to metallic grips, however metallic joints are not frequently modelled properly…

Composites cannot always replace metallic solutions

An intermediate goal is to disseminate what's easy to do, but also what's hard…

Composites Engineering at LBNL

As with many disciplines at the lab; expert resources are matrixed, but available

Similarly, Composite Design is not broadly taught in an engineering curriculum (more in the past decade)

Cryogenics and Vacuum technology are similar examples:

- Engineering and Technical staff new to the lab become proficient quickly thru exposure
- Training is available both off and on-site
- Some problems still require an expert to solve—knowing who to talk to is important onsite and within the industry

Eng Div is looking to put together some seminars at various technical levels to teach Composite Design/Fab

Conclusion

The material is intended to give an idea of whether composites are useful for a design

Also, with the limitation of when to seek experts

Hand Calculations will get you rather close, but ultimately detailed FEA is required to ‘get to the next level’

Resources are available at LBNL, CERN

Design Resources

COMPOSITES ENGINEERING

- Home
  - R&D Projects
  - Composites DB
  - Composites DB Prototype
  - Design Resources
  - Administration
  - Log Out

Composites Engineering

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These slides are exerpts of talks given by

Neal Hartman, Joseph Silber, and myself—feel free to contact me in the context of this course for clarification