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U.S. DEPARTMENT OF ENERGY

Elements of Fabrication II -
Material Properties Developed and Testing

ESI-PAP Composites

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These are the typical symbols used for composite properties

Property	Meaning
E	tensile modulus
G	shear modulus
ν	poisson ratio
ρ	volume fraction
α	coefficient of thermal expansion
β	coefficient of moisture expansion
V	volume fraction
M	mass fraction
FAW	fiber areal weight
PAW	prepreg areal weight
CPT	cured ply thickness

Subscript	Meaning
1, 2, 3	ply directions
x, y, z	laminate directions
f	fiber property
m	matrix property
v	void

A few examples:

E_{1f} … fiber modulus along fiber direction
E_{11} … ply modulus along fiber direction
ν_{12} … poisson ratio in-plane
M_m … matrix mass fraction
V_v … void volume fraction

Micromechanics calculations give us the linear properties, for *one* ply

- Goal is to get correct values for:
  - E_{11}, E_{22}, E_{33} … tensile moduli
  - G_{12}, G_{23}, G_{13} … shear moduli
  - ν_{12}, ν_{23}, ν_{13} … poisson ratios
  - ρ … density
  - α_1, α_2, α_3 … CTE
- These are *dependent* properties
- These are the inputs for finite element analysis or laminated plate theory hand calcs

There are many *independent* material properties to find, measure, or estimate

- Vendors typically give us only:
  - E_{1f} … modulus in fiber's long direction
  - ρ_f, ρ_m … fiber and matrix densities
  - α_{1f} … CTE in fiber's long direction
  - α_m … CTE of matrix
- We are often left to estimate or analogize:
  - E_{2f} … fiber modulus transverse
  - E_m … matrix modulus
  - ν_{12f}, ν_{23f} … poisson ratios of fiber in and out of plane
  - ν_m … poisson ratio of matrix
  - α_{2f} … fiber CTE transverse

There are also several fabrication properties to know

- To get V_f and V_m, we need:
  - M_m … matrix mass fraction
  - V_v … void fraction
- V_v is often treated as negligible *if* there is guaranteed sufficient compaction, as in an autoclave.
- Spoiler: You can check V_f experimentally if you know the fiber areal weight (FAW) and measure the cured-ply thickness (CPT)

Micromechanics calculation example

M55J Lamina Properties from Micromechanics

Fiber and Matrix Properties (INPUT)

	Property	Source
Modulus	$E_{1f} := 540GPa$	CN Series Data Sheet
	$E_{2f} := 8.9GPa$	By analogy to P-75S fibers
	$E_m := 4.4GPa$	Kollar&Springer. Approx value for structural epoxies
Poisson Ratio	$\nu_{12f} := 0.23$	By analogy to P-75S fibers
	$\nu_{23f} := 0.74$	By analogy to P-75S fibers
	$\nu_m := 0.35$	Kollar&Springer. Approx value for structural epoxies
Density	$\rho_f := 1910\frac{kg}{m^3}$	M55J Data Sheet
	$\rho_m := 1170\frac{kg}{m^3}$	EX-1515 Data Sheet
CTE	$\alpha_{1f} := -1.1\cdot\frac{10^{-6}}{K}$	M55J Data Sheet
	$\alpha_{2f} := 12.5\cdot\frac{10^{-6}}{K}$	By analogy to P-75S fibers
	$\alpha_m := 61\cdot\frac{10^{-6}}{K}$	EX-1515 Data Sheet
WEAVE	weave_reduction_factor := 0%	

Prepreg / Cure Properties (INPUT)

$M_m := 40.3\%$ matrix mass fraction (mean value from 2013-03-29 Tencate report)

$V_v := 0.5\%$ void fraction

$FAW := 31.3\frac{gm}{m^2}$ (mean value from 2013-03-29 Tencate report)

Ply Properties (CALCULATED, NO BLEED)

$$V_f := \frac{1 - V_v}{1 + \frac{\rho_f}{\rho_m}\cdot\frac{M_m}{1 - M_m}} = 47.3\%$$

$$CPT\_estimate := \frac{FAW}{\rho_f\cdot V_f} = 35\cdot\mu m$$

$$V_m := 100\% - V_f - V_v = 52.2\%$$

Fiber and Matrix Shear Moduli (CALCULATED)

$$G_{12f} := \frac{E_{1f}}{2\cdot(1 + \nu_{12f})} = 219.5\cdot GPa \qquad G_{23f} := \frac{E_{2f}}{2\cdot(1 + \nu_{23f})} = 2.6\cdot GPa \qquad G_m := \frac{E_m}{2\cdot(1 + \nu_m)} = 1.6\cdot GPa$$

Lamina Properties (CALCULATED, per Kollar & Springer)

$$E_{11} := (1 - weave\_reduction\_factor)\cdot(E_{1f}\cdot V_f + E_m\cdot V_m) = 257.9\cdot GPa$$

$$E_{22} := \left[\frac{\sqrt{V_f}}{E_{2f}\sqrt{V_f} + E_m\cdot(1 - \sqrt{V_f})} + \frac{1 - \sqrt{V_f}}{E_m}\right]^{-1} = 6.1\cdot GPa$$

$$E_{33} := E_{22} = 6.1\cdot GPa$$

$$G_{12} := \left[\frac{\sqrt{V_f}}{G_{12f}\sqrt{V_f} + G_m\cdot(1 - \sqrt{V_f})} + \frac{1 - \sqrt{V_f}}{G_m}\right]^{-1} = 5.1\cdot GPa$$

$$G_{23} := \left[\frac{\sqrt{V_f}}{G_{23f}\sqrt{V_f} + G_m\cdot(1 - \sqrt{V_f})} + \frac{1 - \sqrt{V_f}}{G_m}\right]^{-1} = 2\cdot GPa$$

$$G_{13} := G_{12} = 5.1\cdot GPa$$

$$\nu_{12} := \nu_{12f}\cdot V_f + \nu_m\cdot V_m = 0.291$$

$$\nu_{23} := \frac{E_{22}}{2\cdot G_{23}} - 1 = 0.521$$

$$\nu_{13} := \nu_{12} = 0.291$$

Density

$$\rho := \rho_f\cdot V_f + \rho_m\cdot V_m = 1514\frac{kg}{m^3}$$

Thermal Properties

$$\alpha_1 := \frac{V_f\cdot E_{1f}}{E_{11}}\cdot\alpha_{1f} + \frac{V_m\cdot E_m}{E_{11}}\cdot\alpha_m = -5.47\times 10^{-7}\frac{1}{K}$$

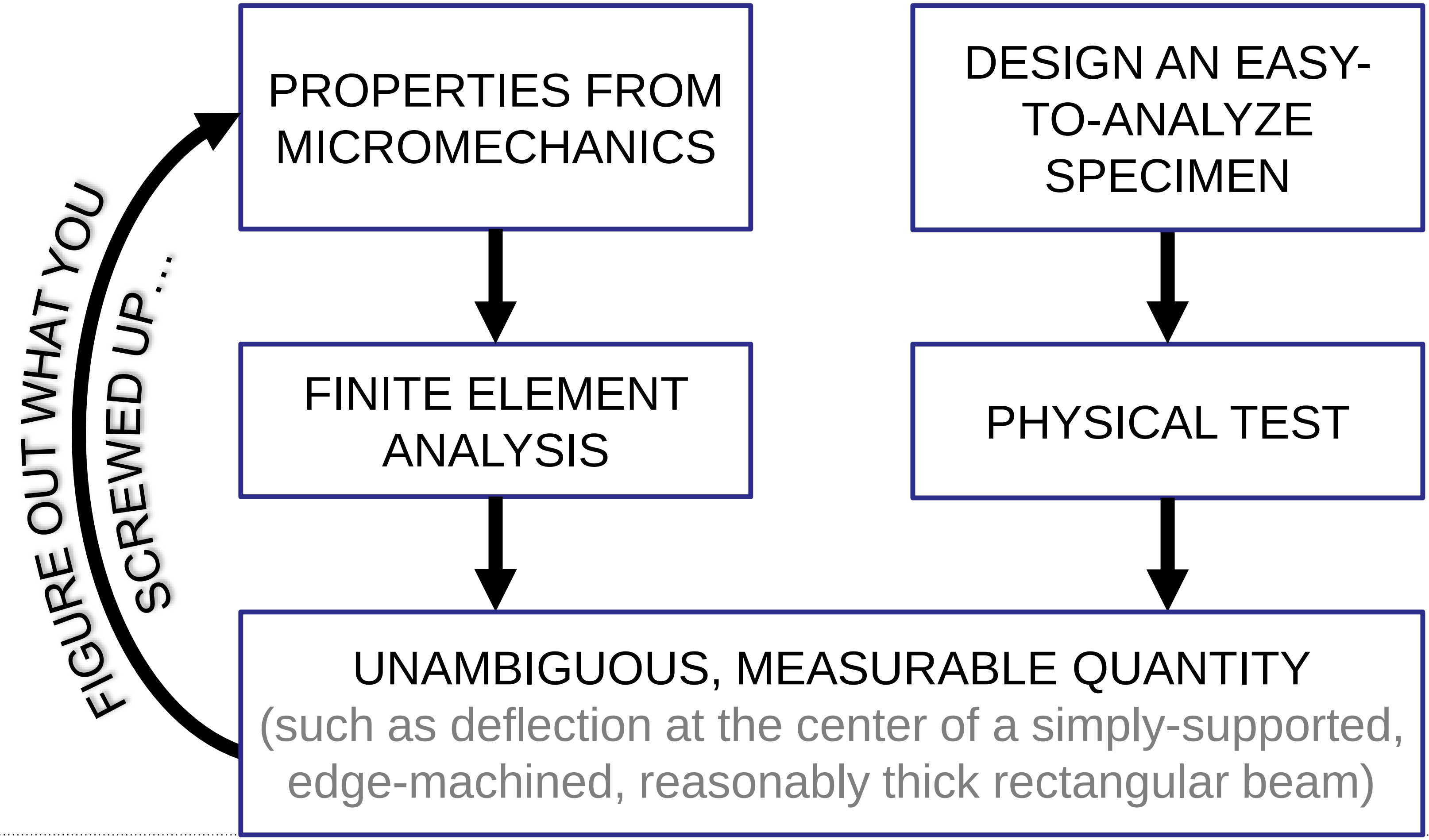
$$\alpha_2 := V_f\cdot\alpha_{2f} + V_m\cdot\alpha_m + V_f\cdot\nu_{12f}\cdot(\alpha_{1f} - \alpha_1) + V_m\cdot\nu_m\cdot(\alpha_m - \alpha_1) = 4.89\times 10^{-5}\frac{1}{K}$$

$$\alpha_3 := \alpha_2 = 4.89\times 10^{-5}\frac{1}{K}$$

There are simple in-the-shop tests to check *some* properties from micromechanics

- 4 point bend test:
  - pure bending
  - depends mainly on E_{11} and CPT
- 3 point bend test:
  - combined bending and shear
  - depends mainly on E_{11}, G_{13}, and CPT
- Measure the laminate thickness:
  - sensitive to surface texture, bleed, and compaction
  - compare to M_m via V_f, if we're careful with mass tracking

Opinion: the least interpretative dance is when simple test validates a simple FEA



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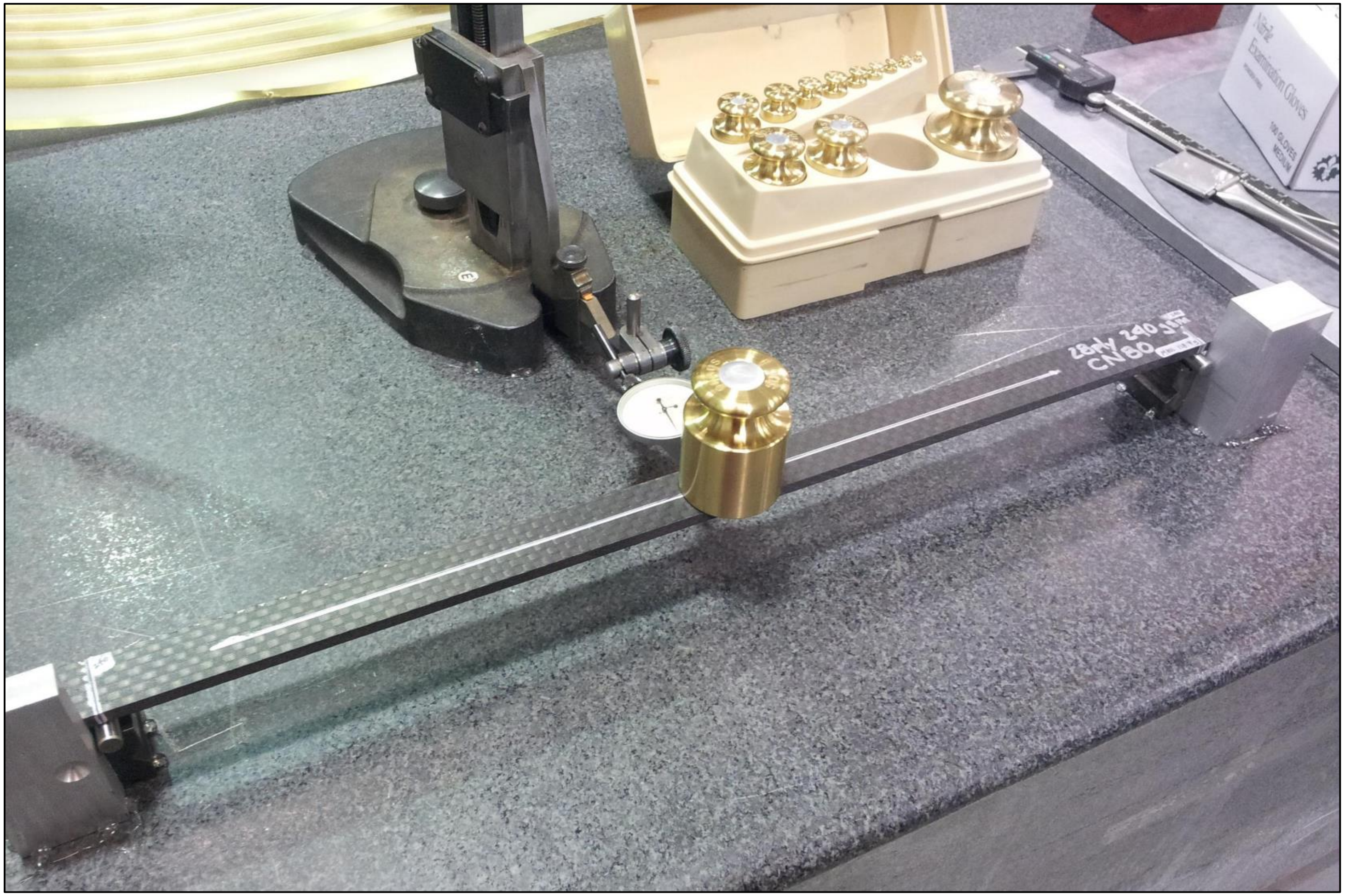
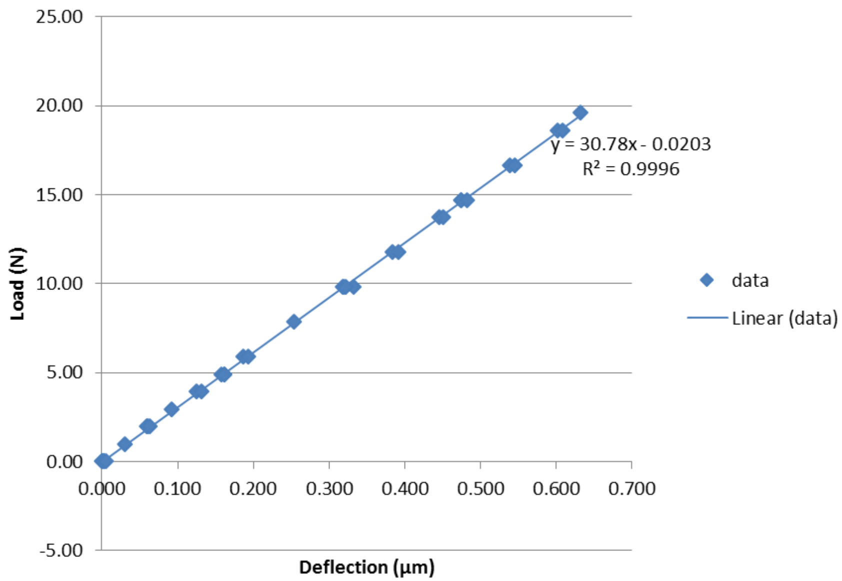
3-point bend test

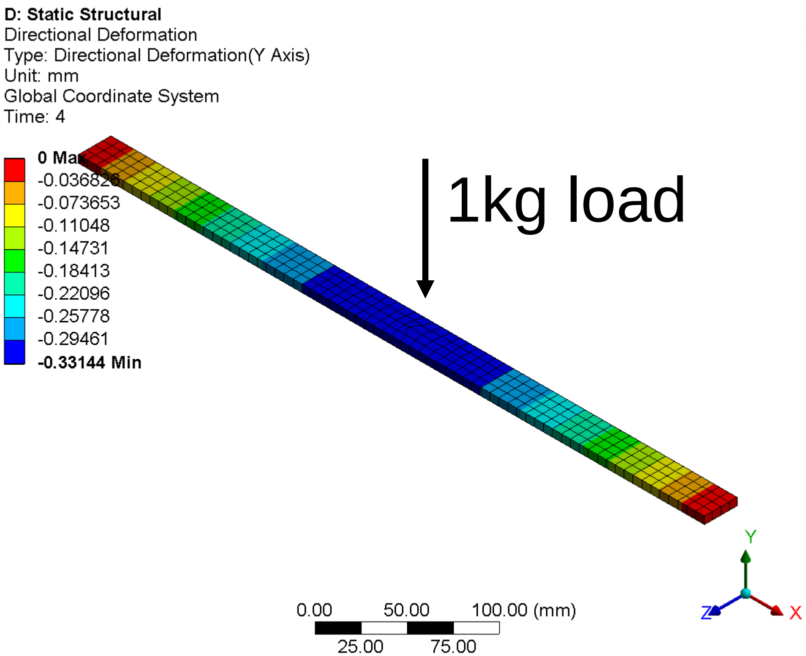


Compare test data to finite element analysis to validate the properties

Test data
30.8 N/mm



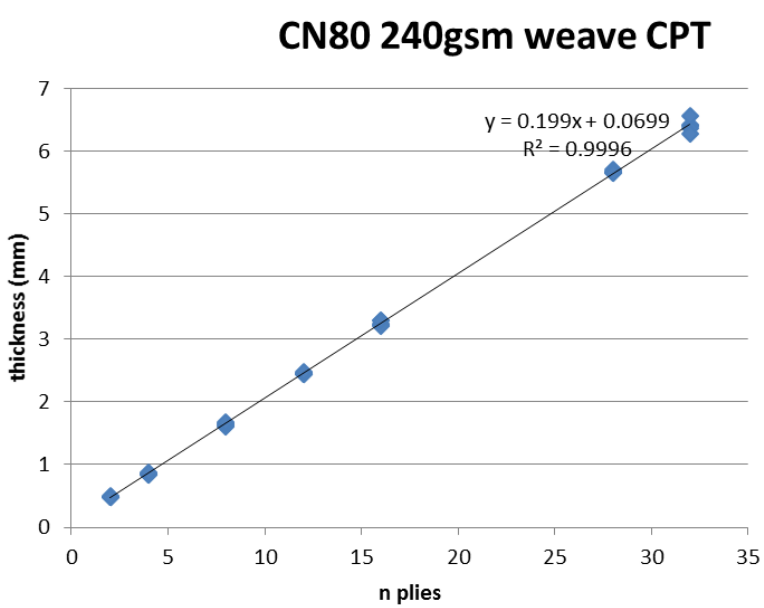
FEA
31.8 N/mm (3% error)



NOTE: we always also do a similarly-sized aluminum beam in the test and FEA to validate the overall methodolgy

Cured ply thickness (CPT)

- CPT is *essential* for
  - knowing bending stiffness (goes as ~ t^3)
  - process control over thickness dimension
- need multiple samples, multiple number of layers
- in this example:
  slope = CPT = 199um
  offset = surface texture = 70 um



Part	Meas Location	N layers	Thickness
-		-	mm
3"x3" sample	corner1	2	0.494
3"x3" sample	corner2	2	0.488
3"x3" sample	corner3	2	0.479
3"x3" sample	corner4	2	0.483
3"x3" sample	middle	2	0.487
3"x3" sample	corner1	4	0.864
3"x3" sample	corner2	4	0.859
3"x3" sample	corner3	4	0.846
3"x3" sample	corner4	4	0.847
3"x3" sample	middle	4	0.874
3"x3" sample	corner1	8	1.652
3"x3" sample	corner2	8	1.633
3"x3" sample	corner3	8	1.604
3"x3" sample	corner4	8	1.647
3"x3" sample	middle	8	1.672
3"x3" sample	corner1	12	2.455
3"x3" sample	corner2	12	2.439
3"x3" sample	corner3	12	2.443
3"x3" sample	corner4	12	2.451
3"x3" sample	middle	12	2.483
3"x3" sample	corner1	16	3.231
3"x3" sample	corner2	16	3.299
3"x3" sample	corner3	16	3.25
3"x3" sample	corner4	16	3.215
3"x3" sample	middle	16	3.303
1"x19.5" beam	end1	28	5.66
1"x19.5" beam	mid1	28	5.677
1"x19.5" beam	mid2	28	5.717
1"x19.5" beam	mid3	28	5.671
1"x19.5" beam	end2	28	5.656
3"x3" sample	corner1	32	6.425
3"x3" sample	corner2	32	6.412
3"x3" sample	corner3	32	6.367
3"x3" sample	corner4	32	6.286
3"x3" sample	middle	32	6.564

Fiber areal weight (FAW) is the key spec we give a pre-pregger

- FAW is an immutable property
- Regardless of how much resin we bleed or how many bubbles we form…

  … there is exactly as much fiber in the laminate as FAW says there is.

- We rely on an having an accurate FAW in the calculations below.

In addition to impact of total material on physics, very good reason why we always carefully track mass during production:

We need M_m to get V_f and CPT…

$$V_f := \frac{1 - V_v}{1 + \frac{\rho_f}{\rho_m} \cdot \frac{M_m}{1 - M_m}}$$

$$\text{CPT\_estimate} := \frac{\text{FAW}}{\rho_f \cdot V_f}$$

If you know the total ply area well, then it's no problem:

$$M_m = 1 - \text{FAW} * A / m_{final}$$

where "final" means after curing.

But total area can be *much* more difficult to measure than total mass for many ply shapes, especially in complex, overlapping stackups…

Hence we want another set of confirming measurements that normalize out area

Mass of resin removed during cure:

$m_{initial} = m_{raw} - m_{backing}$

note: $m_{bleed} = m_{initial} - m_{final}$

note: *always* weigh the backing paper after taking it off the raw prepreg!

Matrix mass fraction (M_m):

$\mathbf{M_m} = 1 - (FAW / PAW) * (m_{initial} / m_{final})$

note: this calculation can be thrown off by lack of attention to resin flash (excess matrix mass) or post-cure trimming (deficient fiber mass)!

Iteration is generally required to get properties right

1. Estimate / lookup as much as possible
2. Get real material, with vendor data on the particular prepreg batch's FAW and M_m
3. Make samples with no resin bleed to confirm M_m of prepreg and CPT
4. Make samples and compare stiffness to FEA with
    - bend tests (3 or 4 pt beam)
    - pull tests (Instron)
5. Recalculate micromechanics. For woven materials, estimate E_{11} reduction due to out-of-plane cross-over.
6. Re-FEA until properties agree.
7. Make samples with varying resin bleed and measure M_m and CPT again.

A few more comments regarding modulus and cured ply thickness…

- E_{ij} and CPT are *dependent* properties:
  - E_{ij} = function(V_f)
  - CPT = function(FAW, V_f)
- In general, E_{ij} is only meaningful when there is a CPT attached to it.
- If we quote a ply modulus without also giving a CPT, we are inherently giving incomplete, and often misleading, data.
- Both E_{ij} and CPT are required inputs to any FEA.
- Both E_{ij} and CPT always have to be kept up-to-date with V_f (the volume fraction, depends on processing) and FAW (the fixed, total amount of fiber).

Strength is a whole other subject

- This talk has been mainly about elastic properties
- It typically requires FEA to do any useful analyses of strength
  - because strength needs to be checked ply-by-ply throughout the laminate, with strains rotated into each ply's layup direction
- The simplest strength properties to use are the 2D max fiber strains to failure:
  - ε_{1ut}, ε_{1uc} … tensile and compressive along fiber
  - ε_{2ut}, ε_{2uc} … tensile and compressive transverse
  - γ_{12u} … shear
- Generally the matrix (low E, high ε) is along for the ride and does not fail
- Note that interlaminar shear strength (ILSS) is a key property for thick composites, particular at edge boundary conditions
  - And you cannot get interlaminar shear stress out of a 2D analysis!