IBEX 2006 Session 101

Design Basics for Composite Structures

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What are composites?

General term:

Any combination of materials bonded together to act as one engineering unit, including, for example:

- METALS
- WOOD
- FOAM
- PLASTIC
- F.R.P
- Where your imagination goes….

Specific term:

(As used in this talk)

F.R.P. –

FIBER reinforced PLASTICS

F.R.P. usually used as solid *laminate* or as laminated "sandwich"

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Familiar Materials vs. Composites

- METALS

Isotropic- Uniform properties in all directions

Yield (permanent bend) before failure

- WOOD

Nature's unidirectional: has a grain, and is much stronger in line with grain

- PLYWOOD

Laminated wood, bi-directional

- PLASTICS

Homogenous

Usually relatively weak

Soft or hard

Non-linear stress/strain

COMPOSITE LAMINATE

- Chopped strand mat

Quasi isotropic

- Other composite fabrics are *directional*

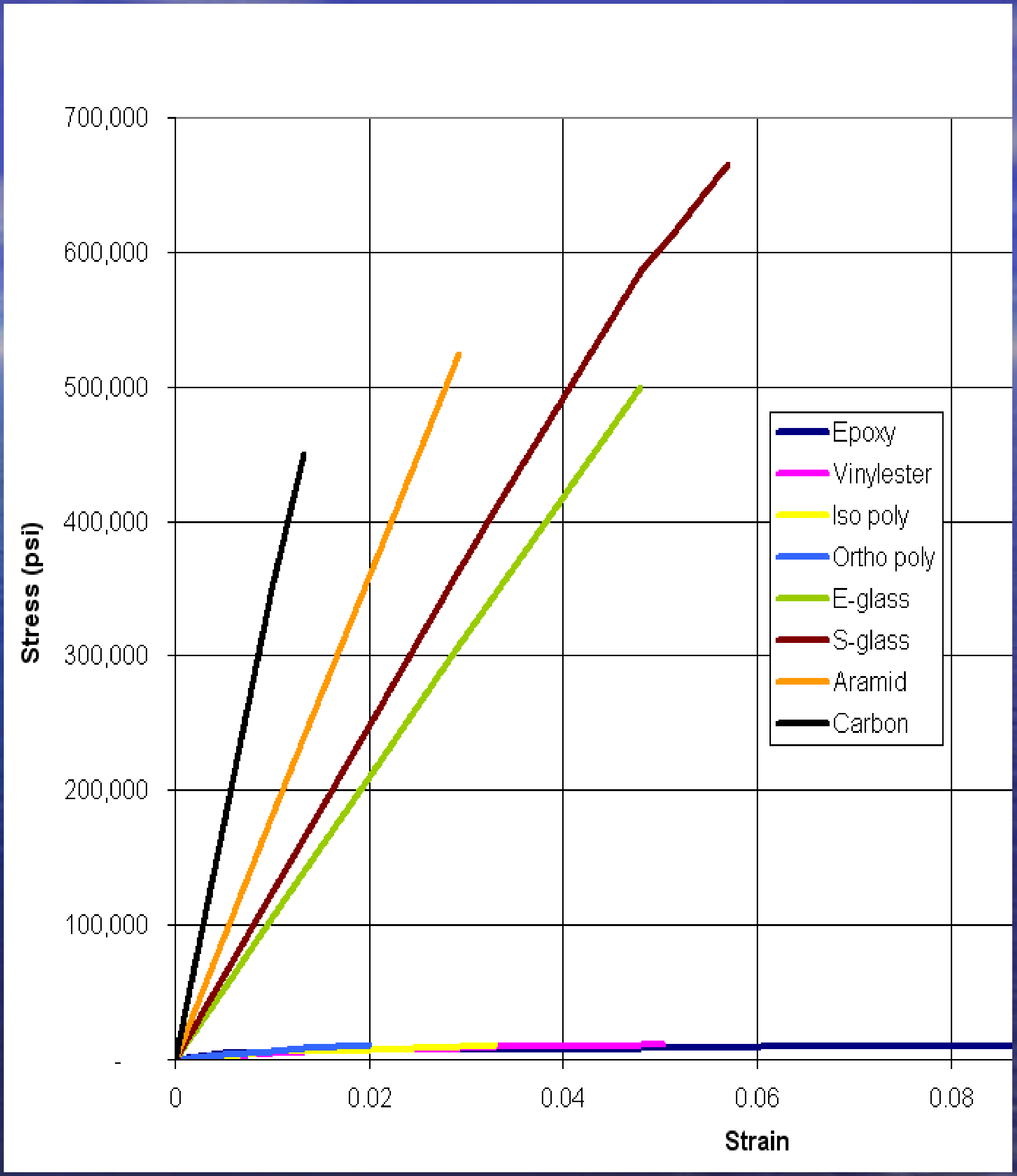
One-directional rovings or fibers combined with weaving, stitching, and/or layering

Think of the fiber direction as *grain* (as in wood)

It is both FIBER REINFORCED PLASTIC and PLASTIC BONDED FIBERS

Stress/Strain for Fibers & Resin. (Isolated, not in a laminate)

- Fibers do not yield
- Fibers are vastly stronger than resin. This is why "grain" direction is important
- Stiff fibers (e.g. carbon) carry high load at low strain (low stretch)
- Lower quality resins fail before fibers – fatigue & laminate strength limiting
- High quality resin have high strain. Fatigue is greatly reduced. Fibers can reach load capacity



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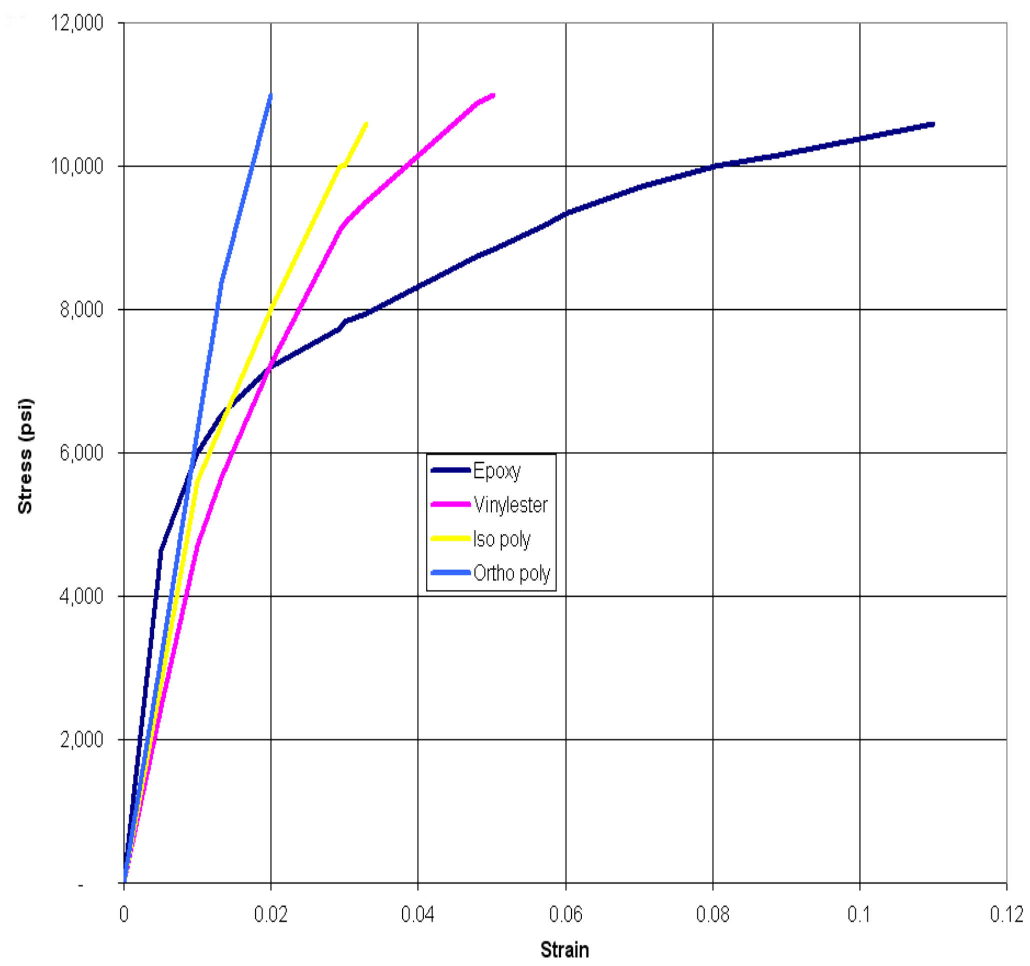
Stress/Strain for various resin types

- Same plot as previous
- These are generic. Properties can vary significantly
- Ortho polyesters are typically stiff/more brittle. Strain to failure less than most fibers
- Vinylesters and Epoxies have much higher strain to failure, therefore less fatigue in a laminate
- More fiber strength is available when resin matrix has higher strain at failure



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Use composites effectively

- Align fibers ("grain") with the load
- Even when load path is well known, 100% unidirectional laminate is rarely wise.

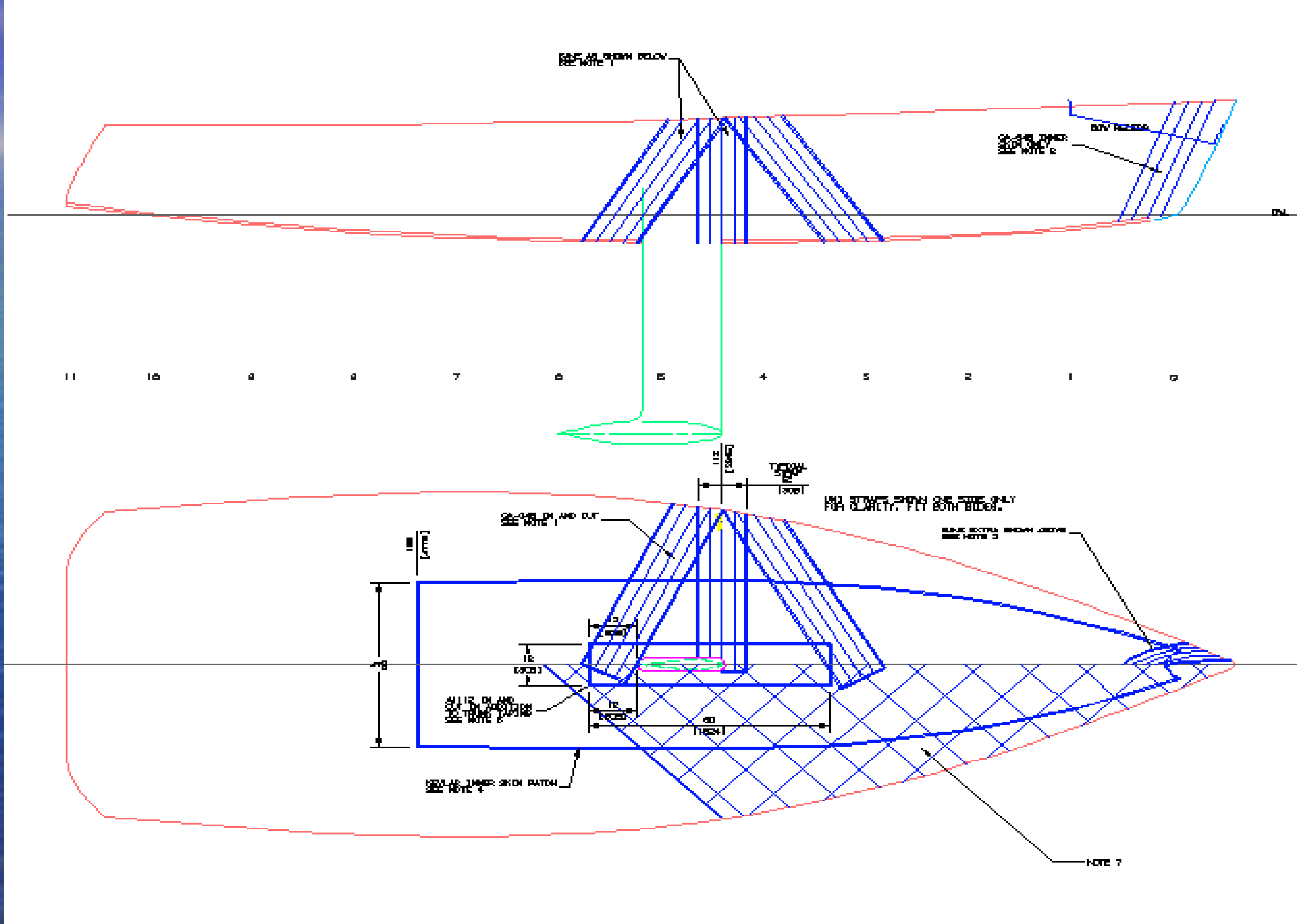
(Due to Poisson effects, at least 20% of fibers off axis is usually desirable when load path is clearly defined.)

- For panels, primary grain should run in the short direction across framing.

(For a wood floor, would you lay your planking across the frames or parallel to them?)

- Exotic, expensive material where it is most effective

Effective use of reinforcements in Ultimate 24 Sportboat



- Carbon uni strap aligned with primary loads: chainplate to keel, etc.

- Kevlar grounding patch in bottom

- Extra E-glass +/-45 biaxial in bow for collision and shear due to rig loads

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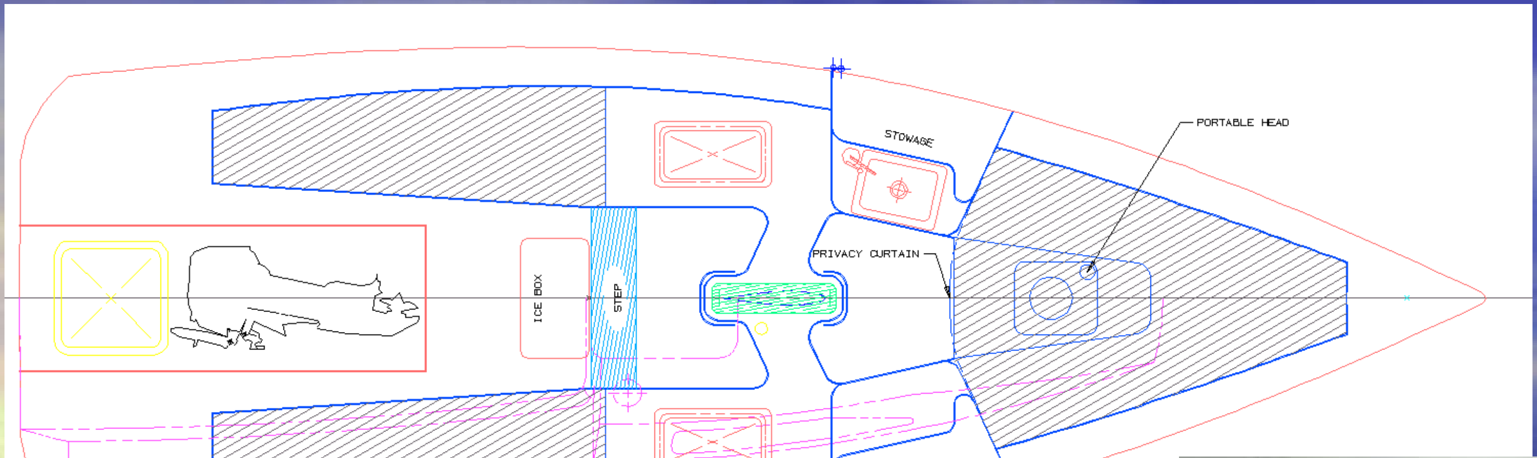
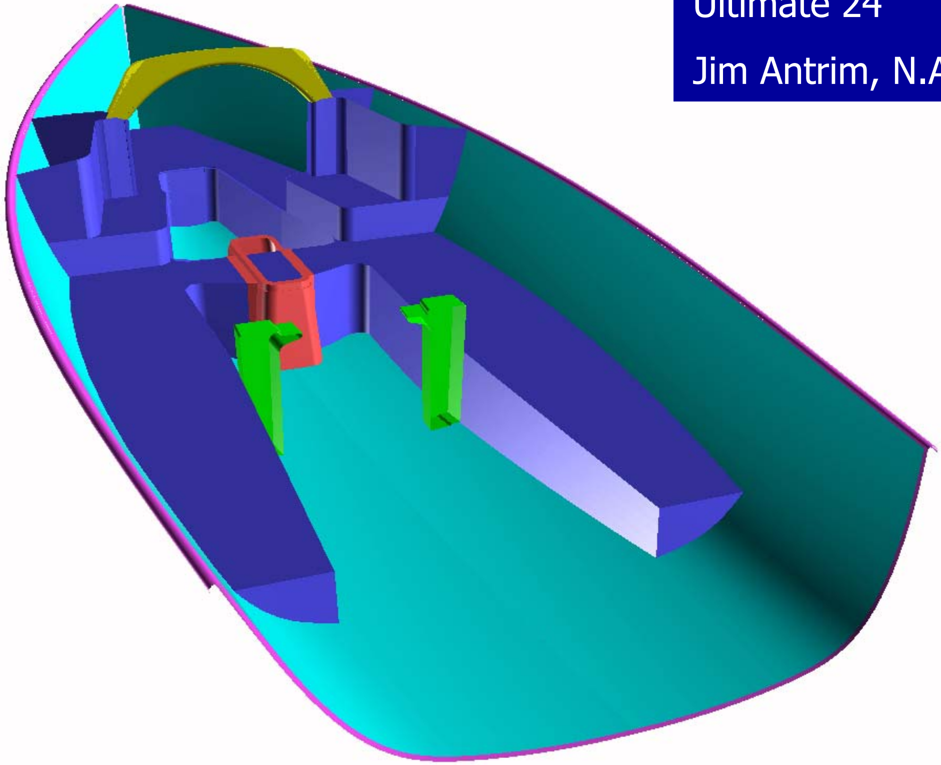
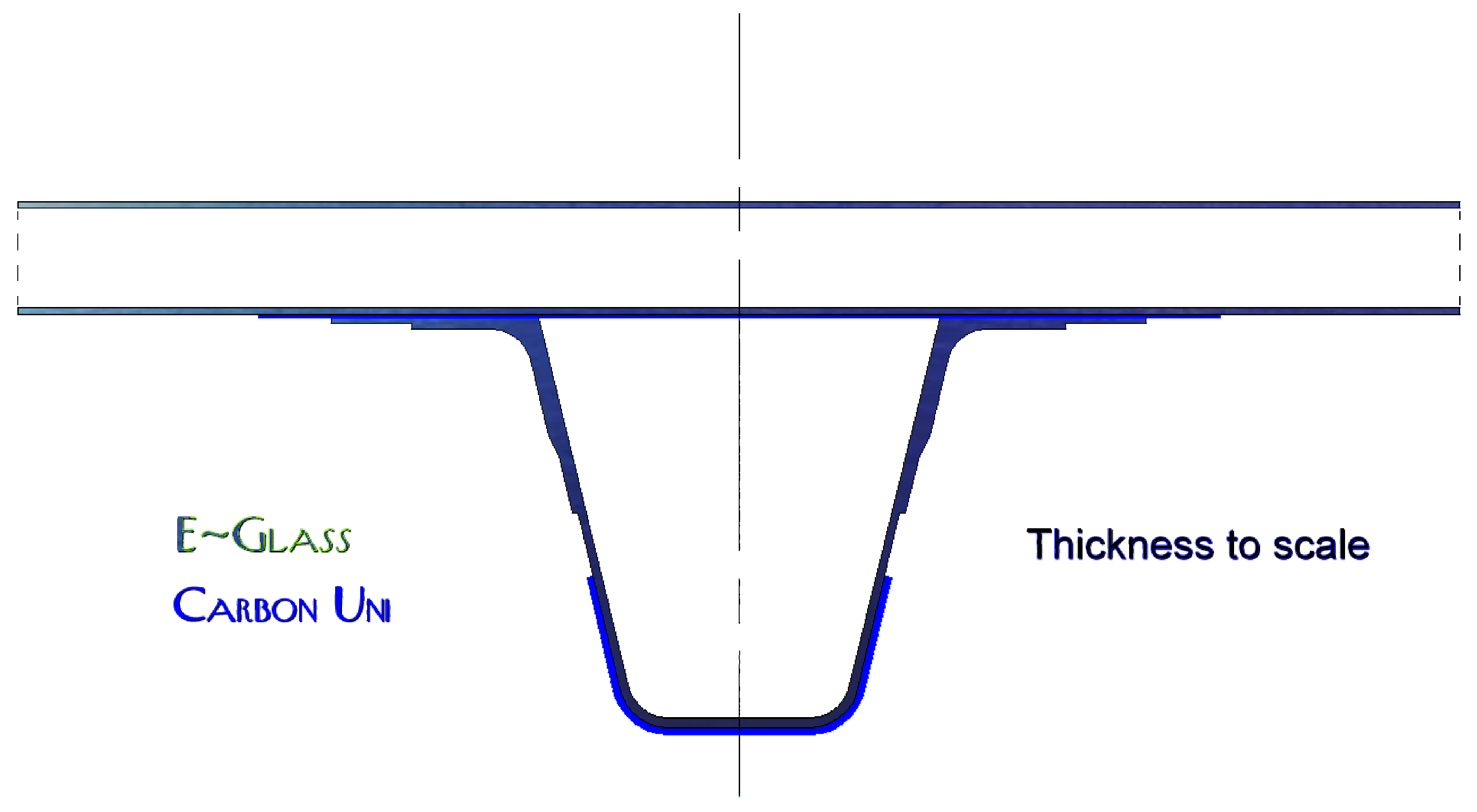


Ultimate 24

Jim Antrim, N.A.



Effective use of high tech composites
Hat Section example



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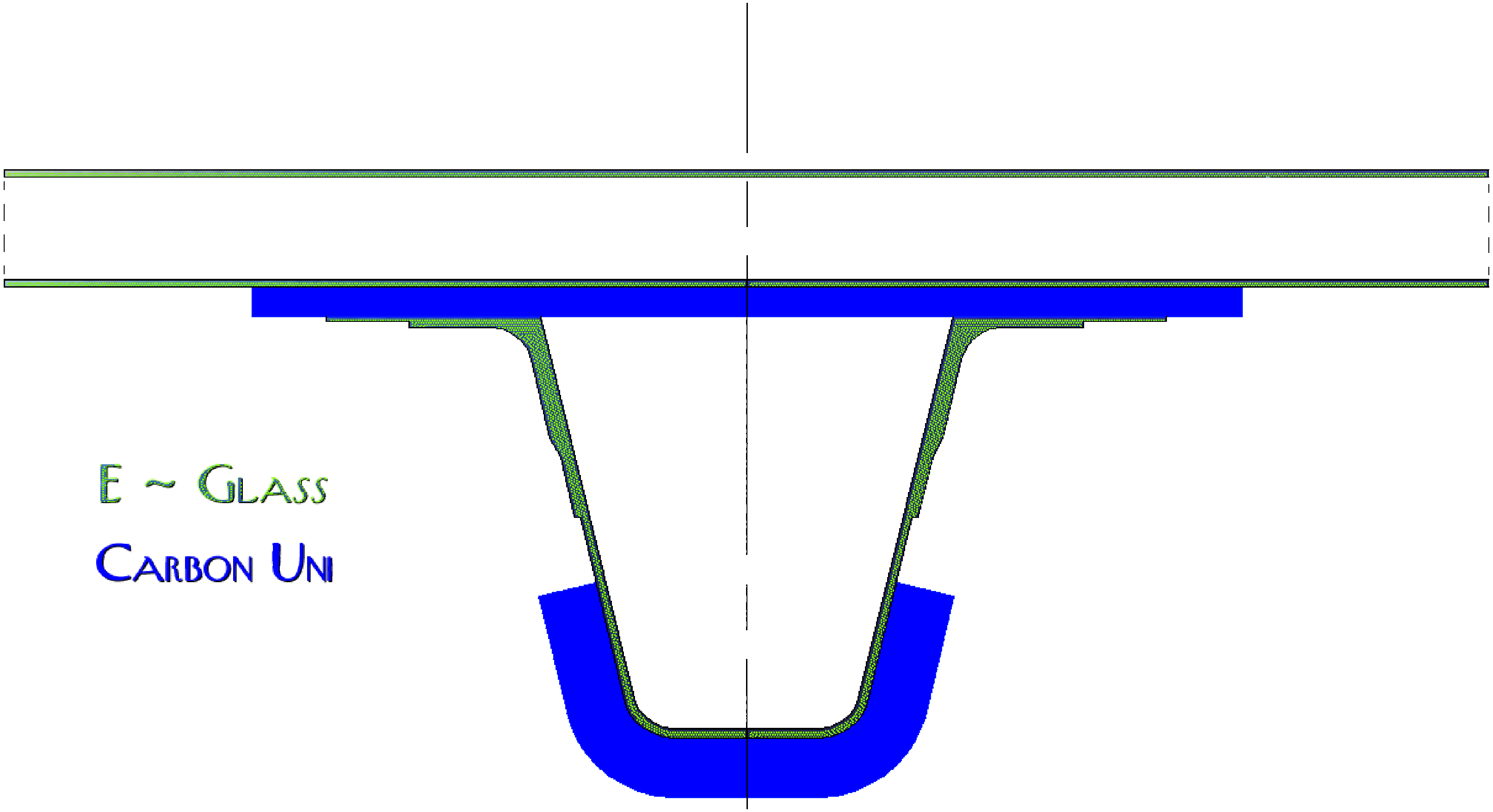
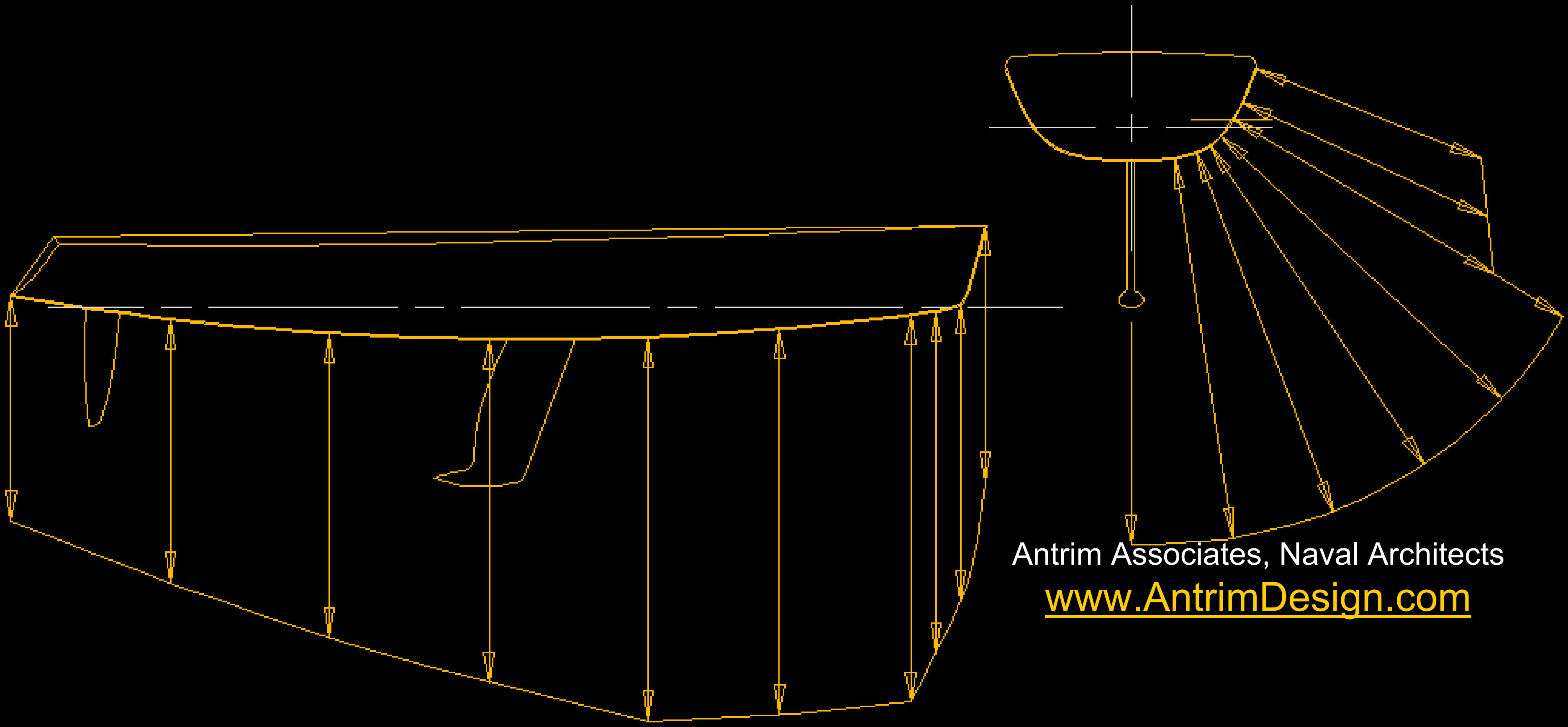
Thickness adjusted to EFFECTIVE area
(Area times Young's Modulus)



Water head (pressure) on a monohull sailboat



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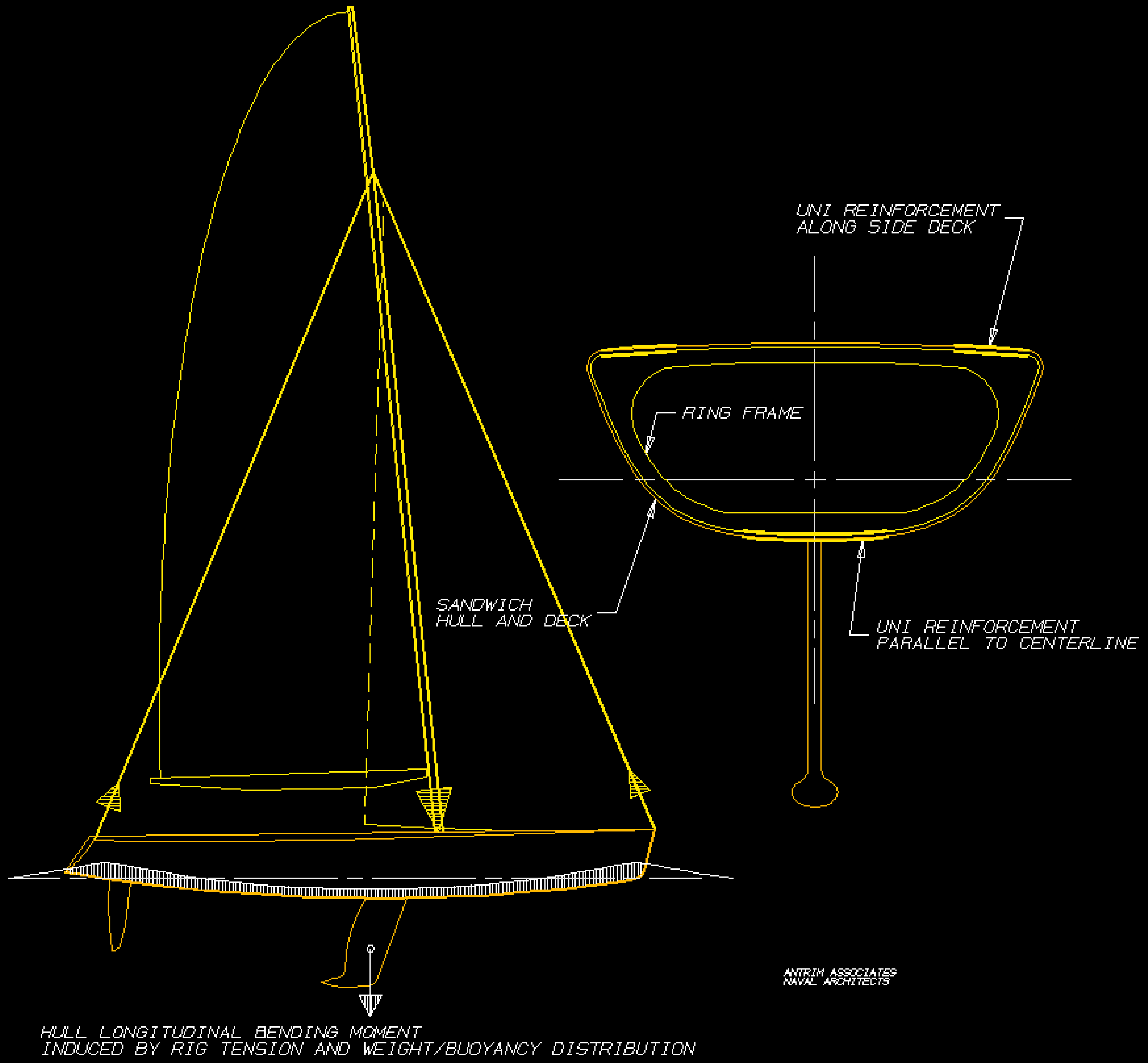
Hull bending in a sailboat under imposed rig loads, wave loads, & keel weight



Perhaps we underestimated the hull bending loads?

Not Antrim Associates, Naval Architects

(though we have had mishaps on occasion too)

Orienting fibers to the load

Many parts have obvious load path

- Tubes, such as mast, boom, bowsprit, rudder post, multihull crossbeams.
- Hull framing

Hull/Deck shell has varied loading

- Water pressure, crew & gear loads perpendicular to panel surface
- Hull bending loads in plane with panel

Bulkheads & ring frames have varied edge loading, shear

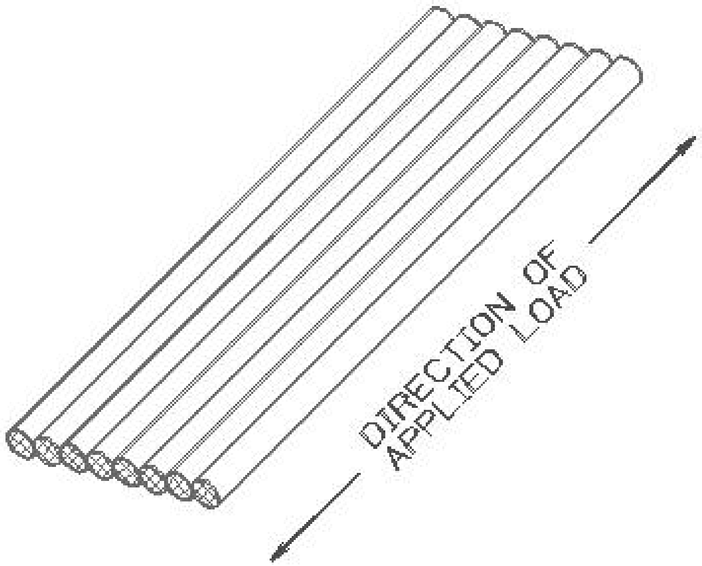
Billy Black photo

Antrim 40 trimaran *Zephyr*

Ideal Composite Structure

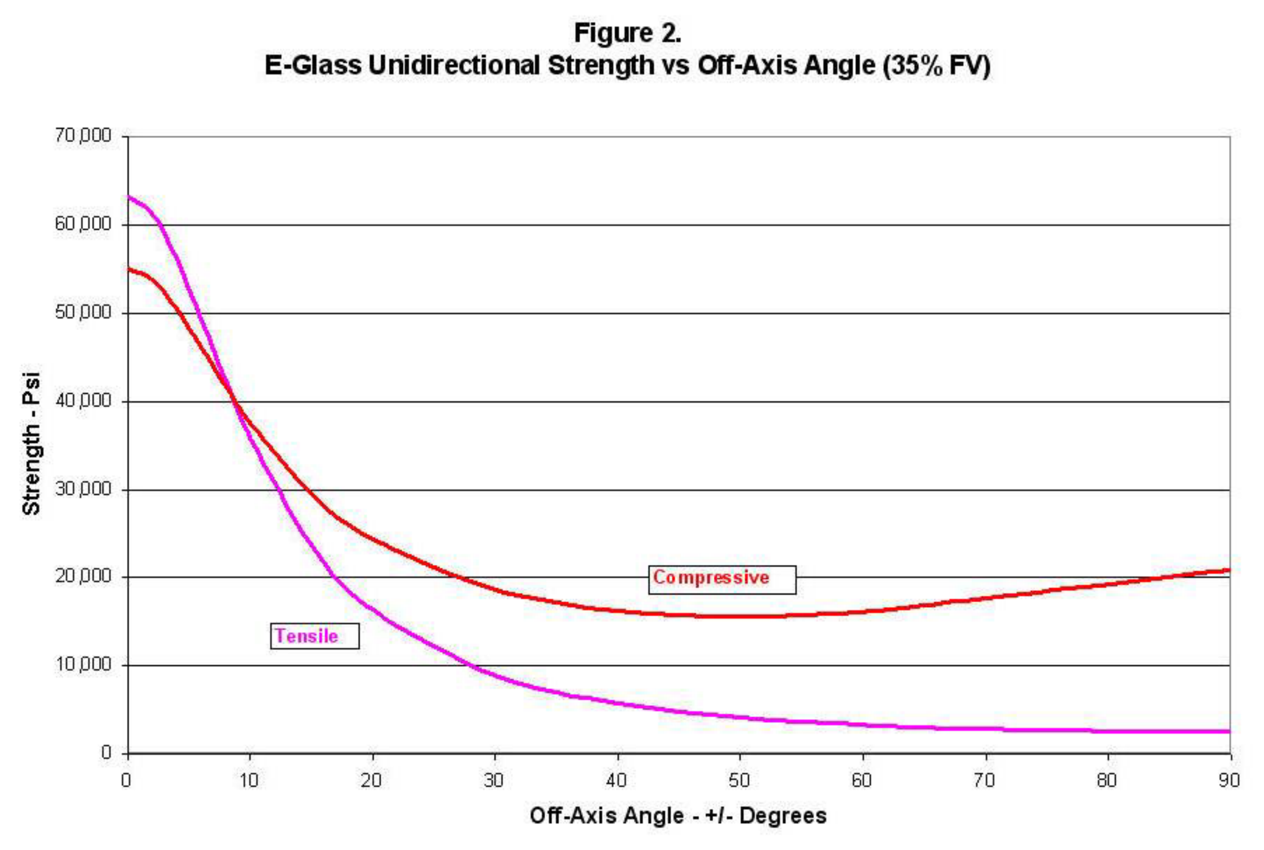
FIGURE 1

THE IDEAL COMPOSITE STRUCTURE

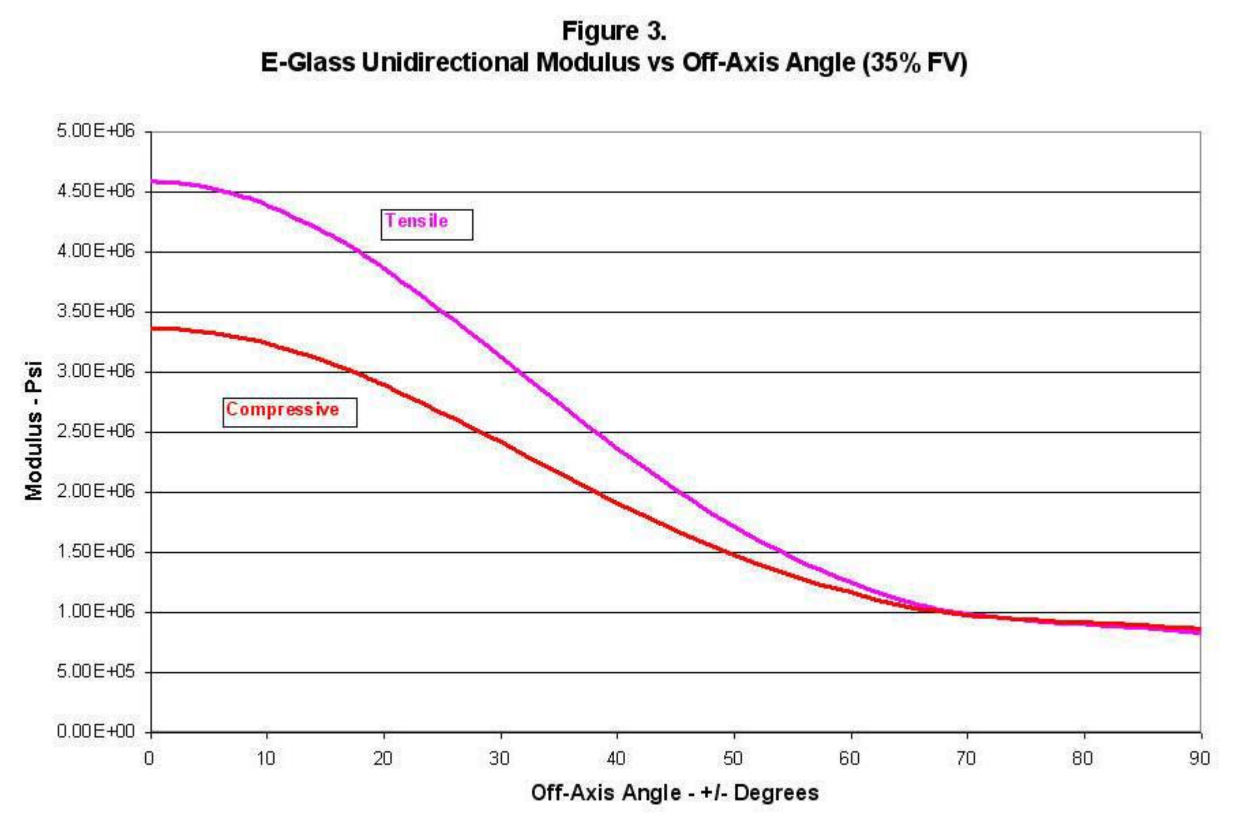


- *ALL FIBERS RUN IN SAME DIRECTION*
- *MINIMUM RESIN ABOUT EACH FIBER*
- *NO CRIMPS, TWISTS, OR WAVINESS*
- *FIBERS ORIENTED IN DIRECTION OF LOAD*

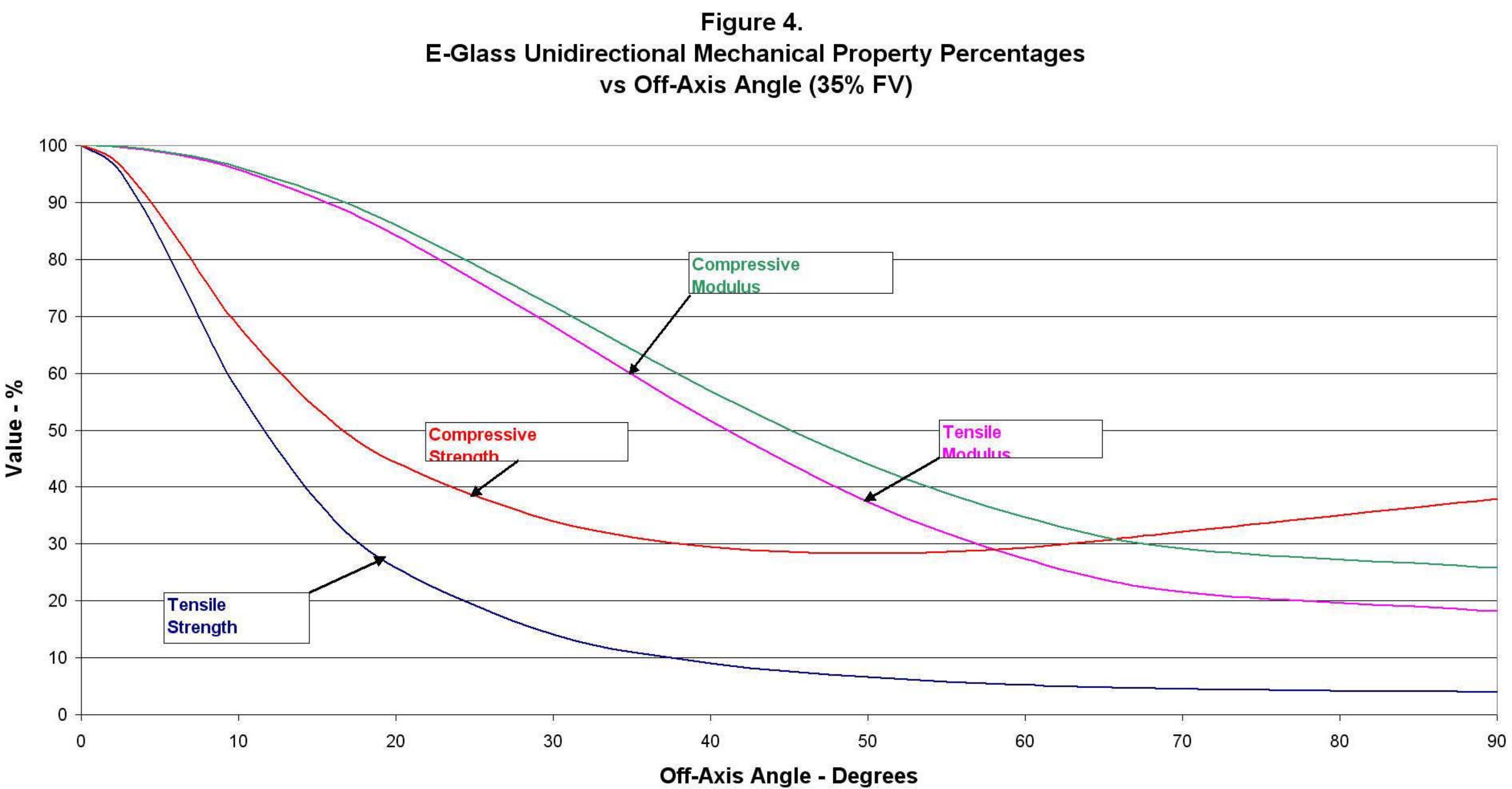
E-Glass Unidirectional vs. Off-Axis Strength



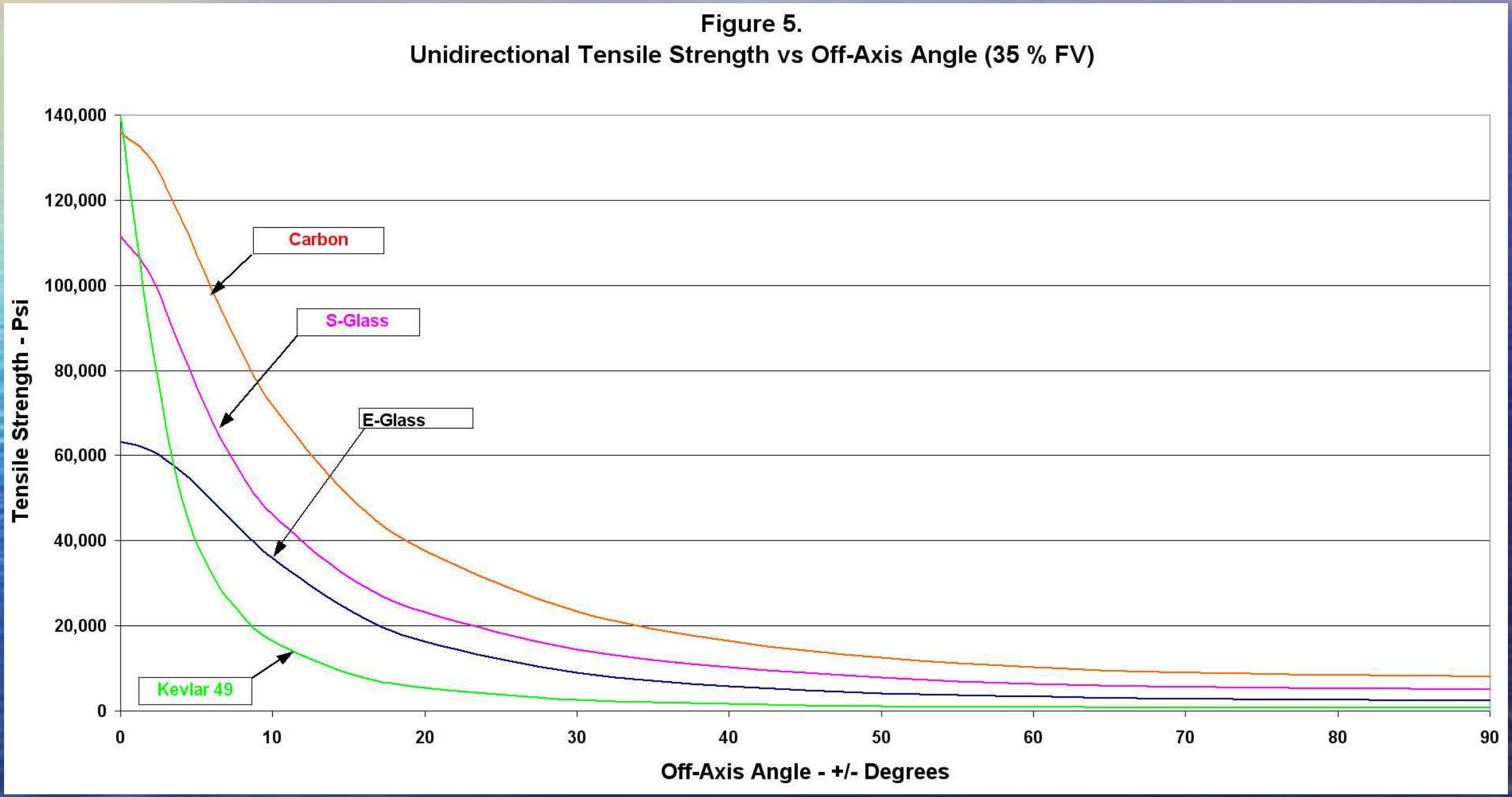
E-Glass Unidirectional vs. Off-Axis Modulus



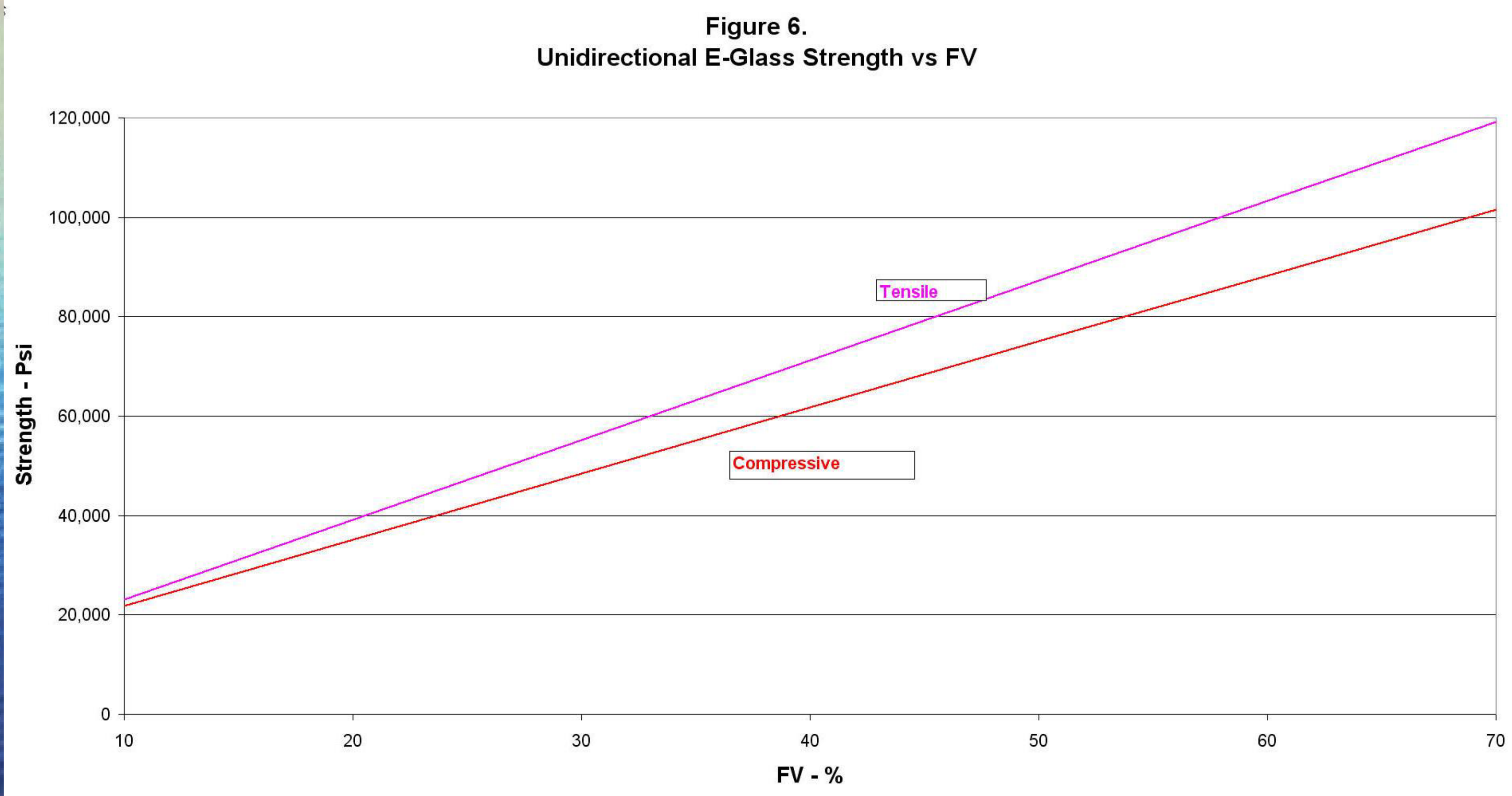
E-Glass Unidirectional Mechanical Property % vs. Off Axis Angle



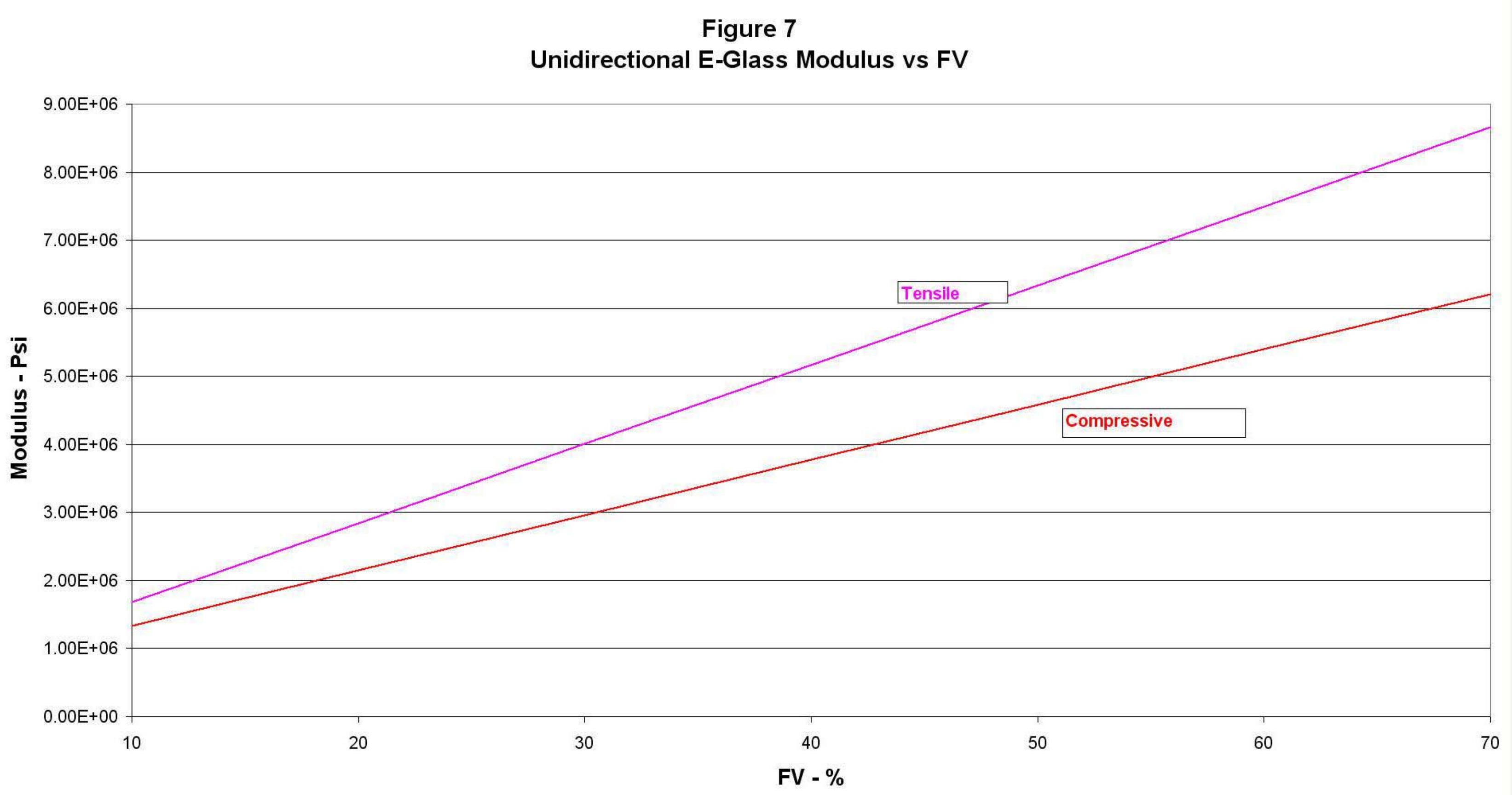
Unidirectional Tensile Strength vs. Off Axis Angle



E-Glass Unidirectional Strength vs. Fiber Volume

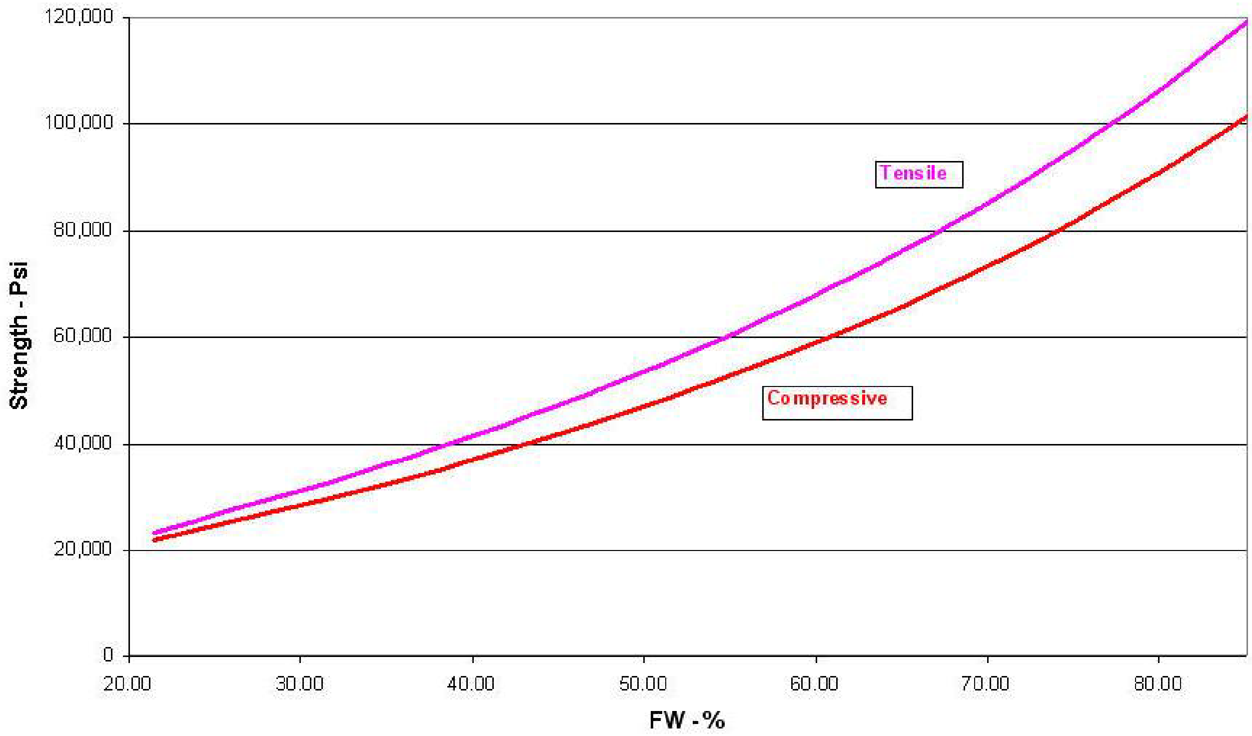


E-Glass Unidirectional Modulus vs Fiber Volume



E-Glass Unidirectional Strength vs. FW

Figure 8.
Unidirectional E-Glass Strength vs FW



Unidirectional E-Glass Modulus vs FW

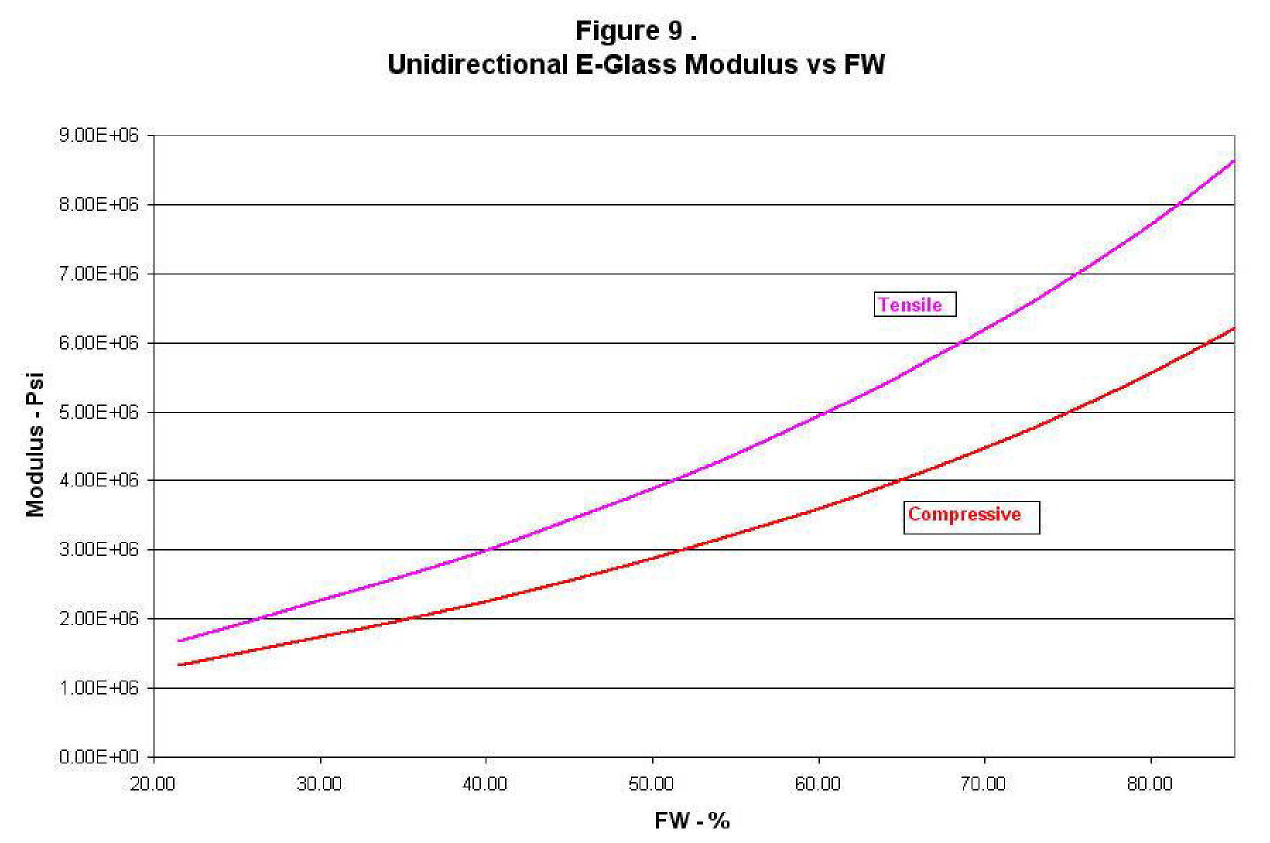
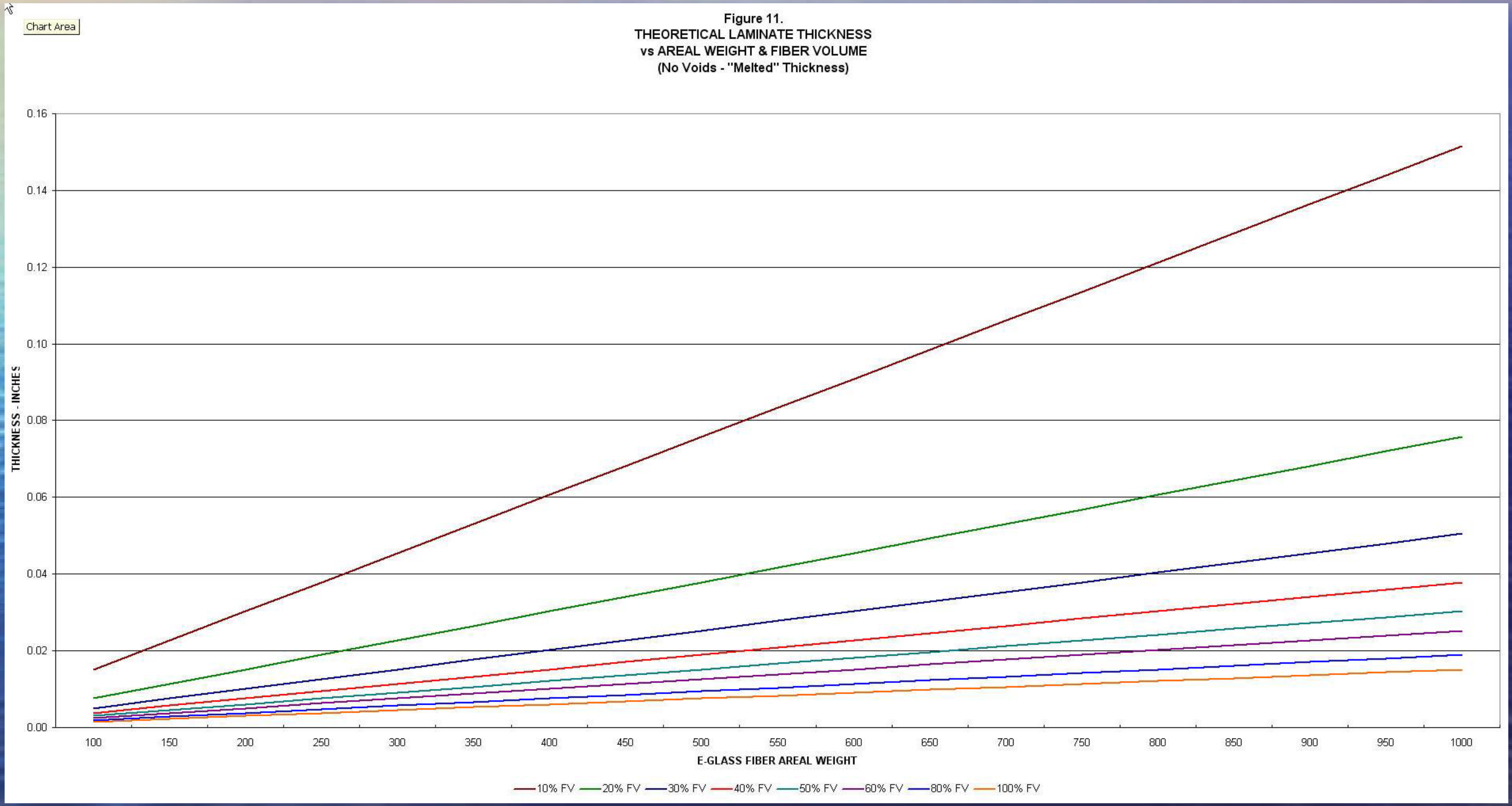


Figure 9 .
Unidirectional E-Glass Modulus vs FW

Theoretical Laminate Thickness



Variation of Tensile Strength with Fiber Format

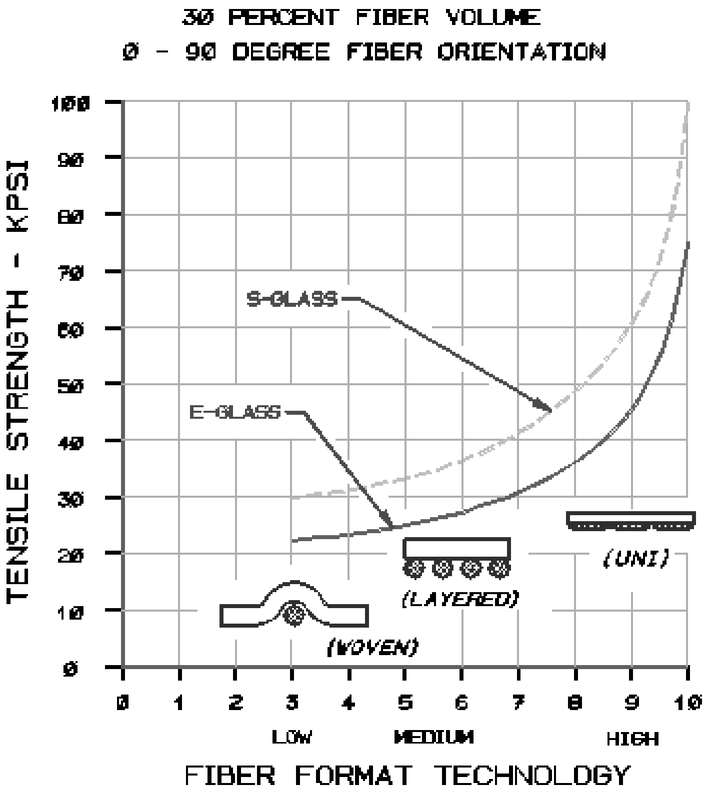


FIGURE 12

VARIATION OF TENSILE STRENGTH WITH FIBER FORMAT

Knockdown Factors for Woven Fabrics

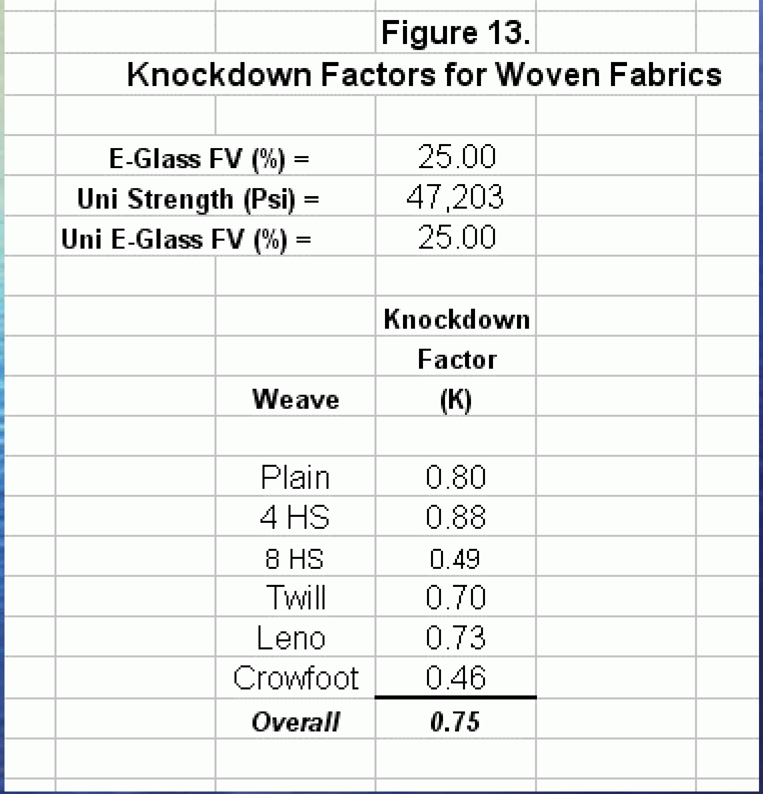


Figure 13.

Knockdown Factors for Woven Fabrics

E-Glass FV (%) = 25.00

Uni Strength (Psi) = 47,203

Uni E-Glass FV (%) = 25.00

Weave	**Knockdown Factor (K)**
Plain	0.80
4 HS	0.88
8 HS	0.49
Twill	0.70
Leno	0.73
Crowfoot	0.46
Overall	***0.75***

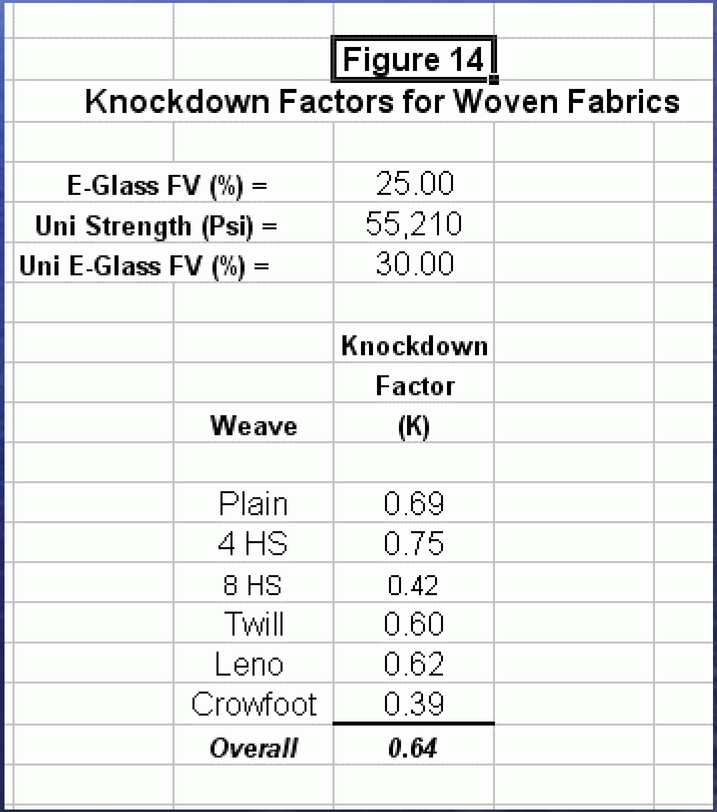


Figure 14

Knockdown Factors for Woven Fabrics

E-Glass FV (%) = 25.00

Uni Strength (Psi) = 55,210

Uni E-Glass FV (%) = 30.00

Weave	**Knockdown Factor (K)**
Plain	0.69
4 HS	0.75
8 HS	0.42
Twill	0.60
Leno	0.62
Crowfoot	0.39
Overall	***0.64***

Sandwich Laminate under Load

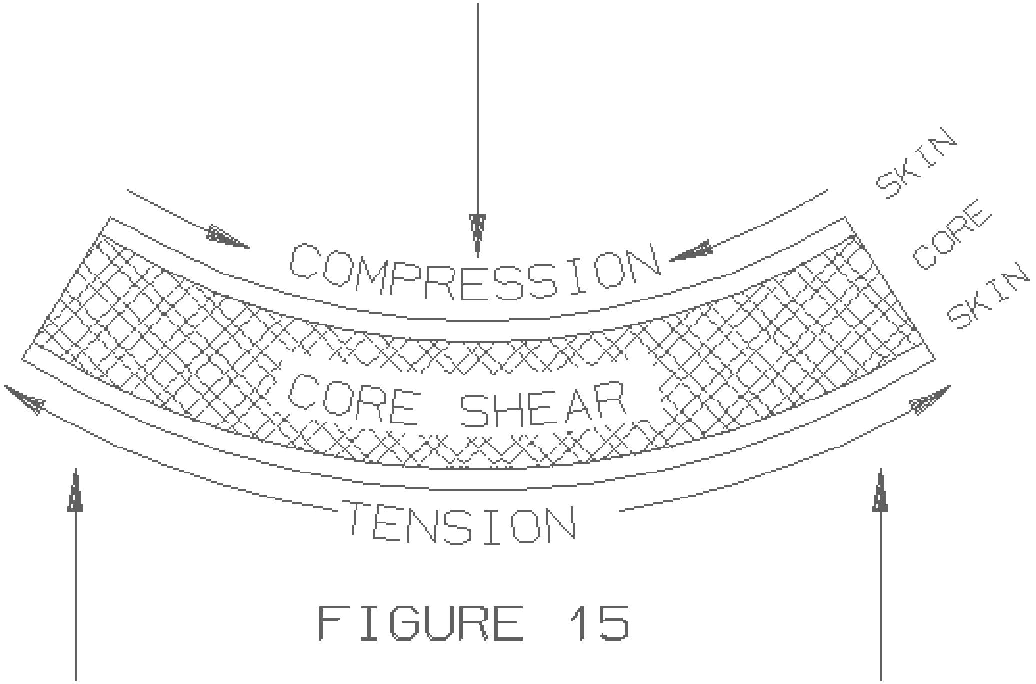


FIGURE 15

Determining Composite Density & Thickness

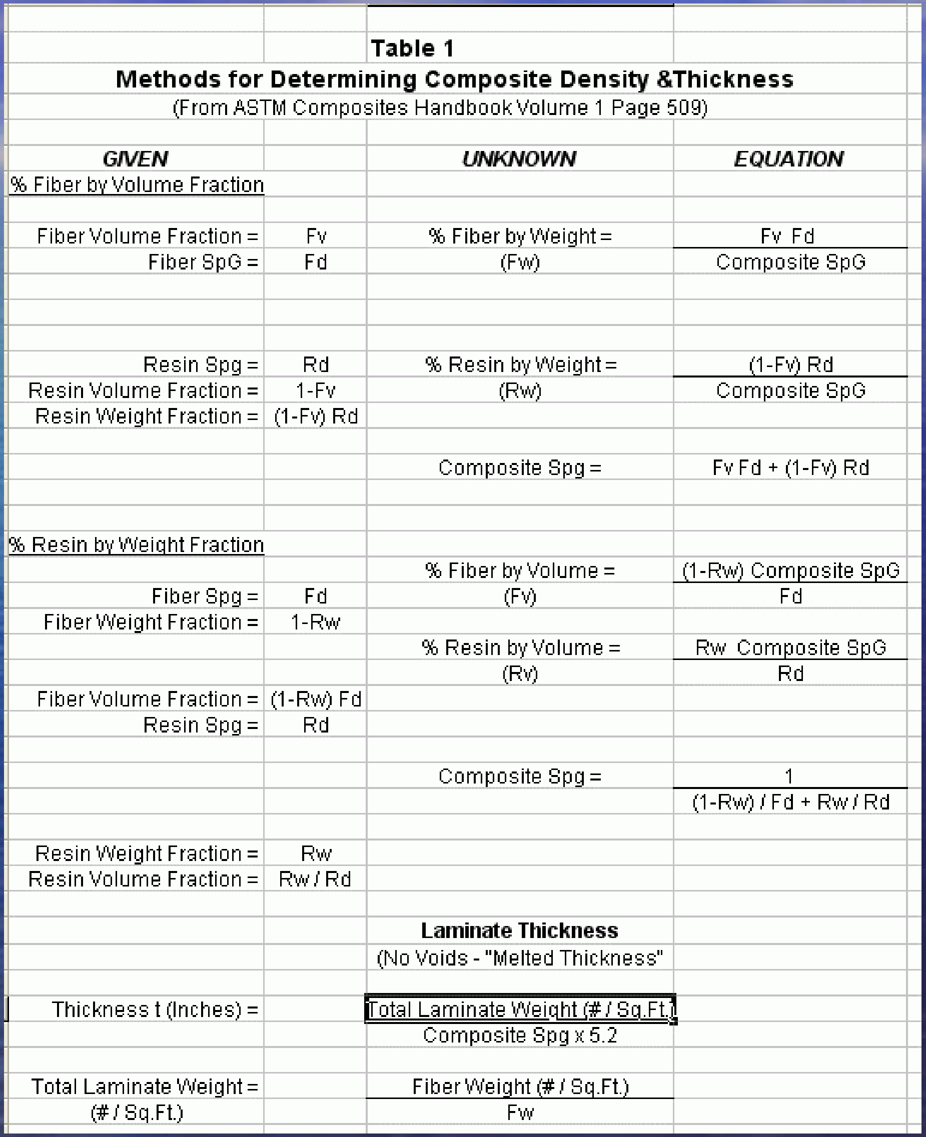


Table 1

Methods for Determining Composite Density &Thickness

(From ASTM Composites Handbook Volume 1 Page 509)

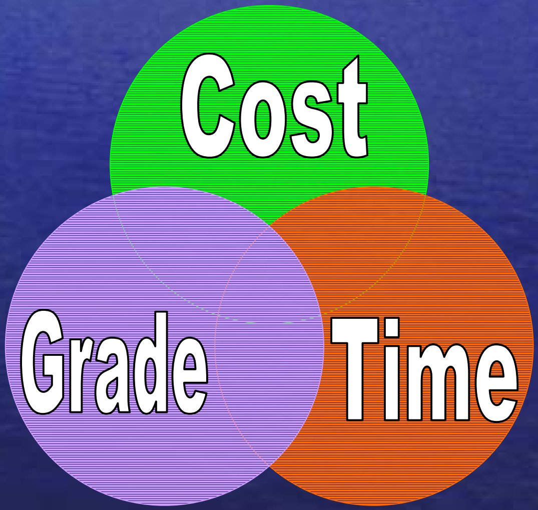
GIVEN		***UNKNOWN***	***EQUATION***
% Fiber by Volume Fraction			
Fiber Volume Fraction =	Fv	% Fiber by Weight =	Fv Fd
Fiber SpG =	Fd	(Fw)	Composite SpG
Resin Spg =	Rd	% Resin by Weight =	(1-Fv) Rd
Resin Volume Fraction =	1-Fv	(Rw)	Composite SpG
Resin Weight Fraction =	(1-Fv) Rd		
		Composite Spg =	Fv Fd + (1-Fv) Rd
% Resin by Weight Fraction			
		% Fiber by Volume =	(1-Rw) Composite SpG
Fiber Spg =	Fd	(Fv)	Fd
Fiber Weight Fraction =	1-Rw		
		% Resin by Volume =	Rw Composite SpG
		(Rv)	Rd
Fiber Volume Fraction =	(1-Rw) Fd		
Resin Spg =	Rd		
		Composite Spg =	1
			(1-Rw) / Fd + Rw / Rd
Resin Weight Fraction =	Rw		
Resin Volume Fraction =	Rw / Rd		
		Laminate Thickness	
		(No Voids - "Melted Thickness"	
Thickness t (Inches) =		Total Laminate Weight (# / Sq.Ft.)	
		Composite Spg x 5.2	
Total Laminate Weight =		Fiber Weight (# / Sq.Ft.)	
(# / Sq.Ft.)		Fw	

E-Glass Composite Density & Thickness

	Table 2.		
E-Glass Composite Density & Thickness			
GIVEN		*UNKNOWN*	
Resin by Weight Fraction			
Fiber Volume Fraction	0.350	% Fiber by Weight	53.846
Fiber Density (Spg)	2.600		
Fiber Weight Fraction	0.910		
Fiber Weight (# / Cu.In.)	0.033		
Resin Density (Spg)	1.200	% Resin by Weight	46.154
Resin Volume Fraction	0.650		
Resin Weight Fraction	0.780		
Resin Weight (# / Cu.In.)	0.028		
		Composite Density (Spg)	1.690
		(# / Cubic Inch)	0.0610
Resin by Weight Fraction			
		% Fiber by Volume	35.000
Fiber Density (Spg)	2.600		
Fiber Weight Fraction	0.538		
Fiber Weight (# / Cu.In.)	0.014		
Fiber Volume Fraction	0.150		
		% Resin by Volume	65.000
		Composite Density (Spg)	1.690
		(# / Cubic Inch)	0.0610
Resin Density (Spg)	1.200		
Resin Weight Fraction	0.462		
Resin Weight (# / Cu.In.)	0.037		
Resin Volume Fraction	0.850		
		Laminate Thickness	
		(No Voids - "Melted Thickness")	
Fiber Areal Weight (Grams / Meter^2)	300		
Fiber Weight (Oz./Yd.^{2})	8.850		
Fiber Weight (# / Sq.Ft.)	0.0615		
Resin Weight (# / Sq.Ft.)	0.0527		
Laminate Weight (# / Sq.Ft.)	0.1141		
Thickness t (Inches) =	0.0130		

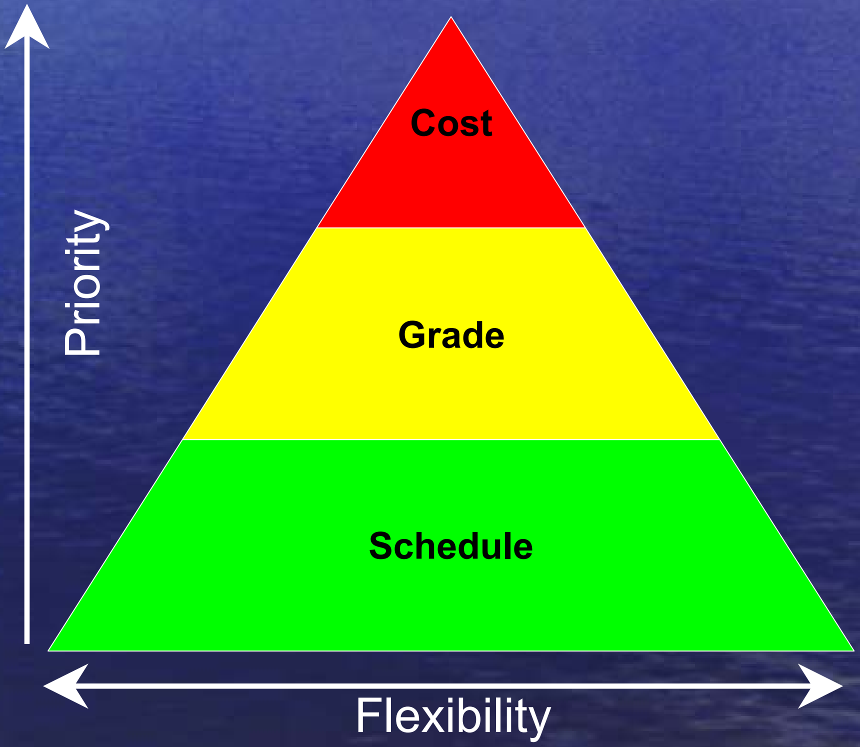
Triple Constraint

- Cost / Resources
  - Amount of $, materials or personnel to support the project
- Schedule
  - Amount of time to complete the project
- Quality / Grade / Performance
  - Quality = Fit for purpose
  - Grade = Degree of luxury
    - (Product) Performance – For yachts, this can be a sub-category of grade



Client Priorities

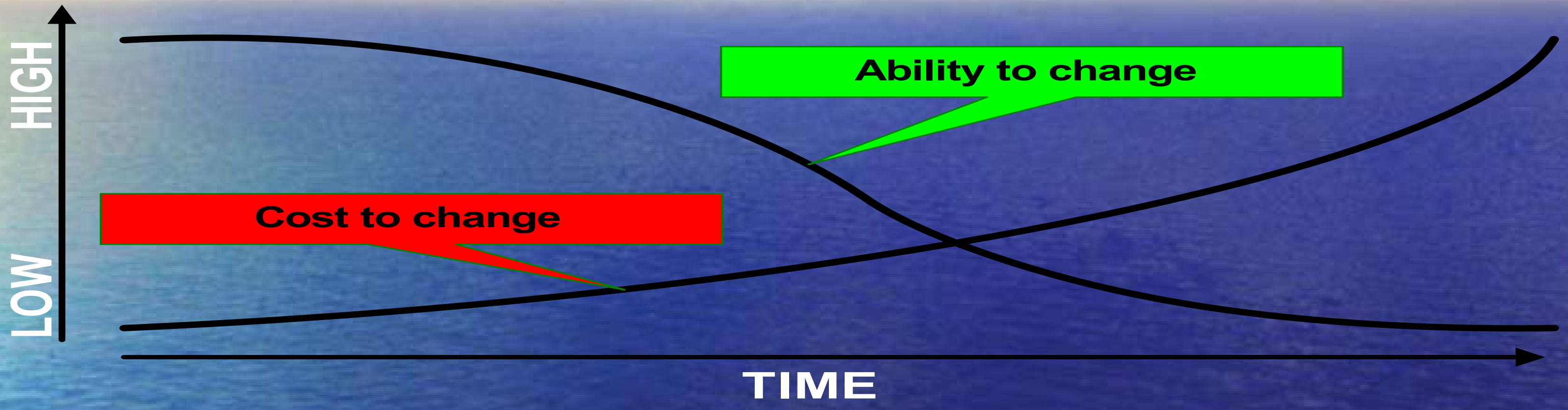
- Client priorities will determine how tradeoffs should be prioritized
  - If Cost is the primary driver (fixed) there should be some flexibility to “grade” and / or schedule
  - If Schedule is the driver, there may be increased cost and compromises on “grade”
  - If Quality / Grade is the driver, there may be increased cost and compromises on schedule



Applying Priorities

- If Cost is the primary driver
  - Exotic or expensive materials can be avoided
    - i.e. E-Glass instead of Carbon would be a compromise on "grade"
- If Schedule is the primary driver
  - You may invest additional resources (people or $) to finish the job quicker
- If Grade is the driver
  - It may take longer to get the materials (teak decking?)
  - It will cost more than a comparable vessel without the "options"

Planning ahead



- By determining what the primary driver is during the early phases of the design process, costly and time consuming changes can be avoided later
- Every project follows a lifecycle
  - Initiating → **Planning** → Executing → Monitor/Control → Close[1]
  - A clear plan will help the client, designer and builder understand each other's perspective, constraints and requirements

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[1] Project Management Institute PMBOK 3rd edition

Estimating Schedule

- Expert Judgment
  - Work with the builder to estimate how long a project will take
    - Break the project into phases: tooling, hull, deck, joining, assembly, finishing, etc.
    - Take into account that if there are multiple projects or production lines, there will be interruptions!
- Analogous Estimating
  - If you have done similar projects previously:
    - Refer to how long each step took
    - Refer to the "lessons learned" from the project (you did write them down, right?)
- Parametric Analysis
  - Duration = Amount of Work x Productivity
    - i.e. Each ply takes 30 minutes and we have 6 plies to lay up…
- Three Point Estimate
  - (Pessimistic + 4 x Most Likely + Optimistic) / 6

Estimating Cost (and weight)

- Bottoms-Up Estimate
  - An accurate weight analysis provides:
    - A Bill of Materials (BOM) for constructing the boat
      - Each of the BOM components should detail both weight and cost
    - A listing of the "standard" equipment for the boat
      - This will determine "empty" displacement
      - Adding cost information will verify if you are within budget constraints
    - A listing of the "optional" as well as personal gear for a standard weekend
      - This will determine "light" displacement
    - A listing of what an owner would provision for a long trip
      - This will determine "loaded" displacement
- Analogous Estimate
  - What have similar projects cost in the past (+ inflation)?
- Parametric Estimating (good for hardware)
  - Cost = Component Cost x Quantity
- Vendor Bid Analysis