Marine Composites

Webb Institute
Senior Elective

Design Process for Marine Composite Structures

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Composite Materials
Design Summary

- The physical properties of composite materials are a function of processed reinforcement and resin combinations

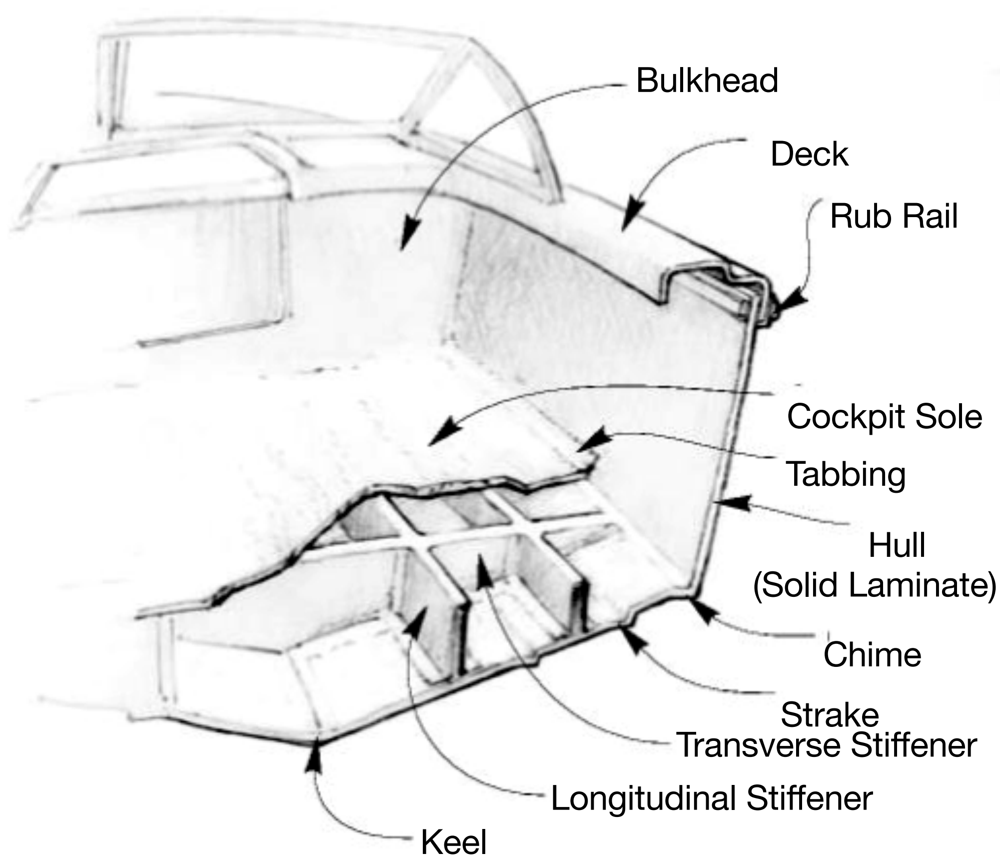
- Metals are isotropic with equal properties in all directions - composites have properties that vary with direction

- Carbon fibers have excellent in-plane properties when loads align with fibers - E-glass laminates are more damage tolerant

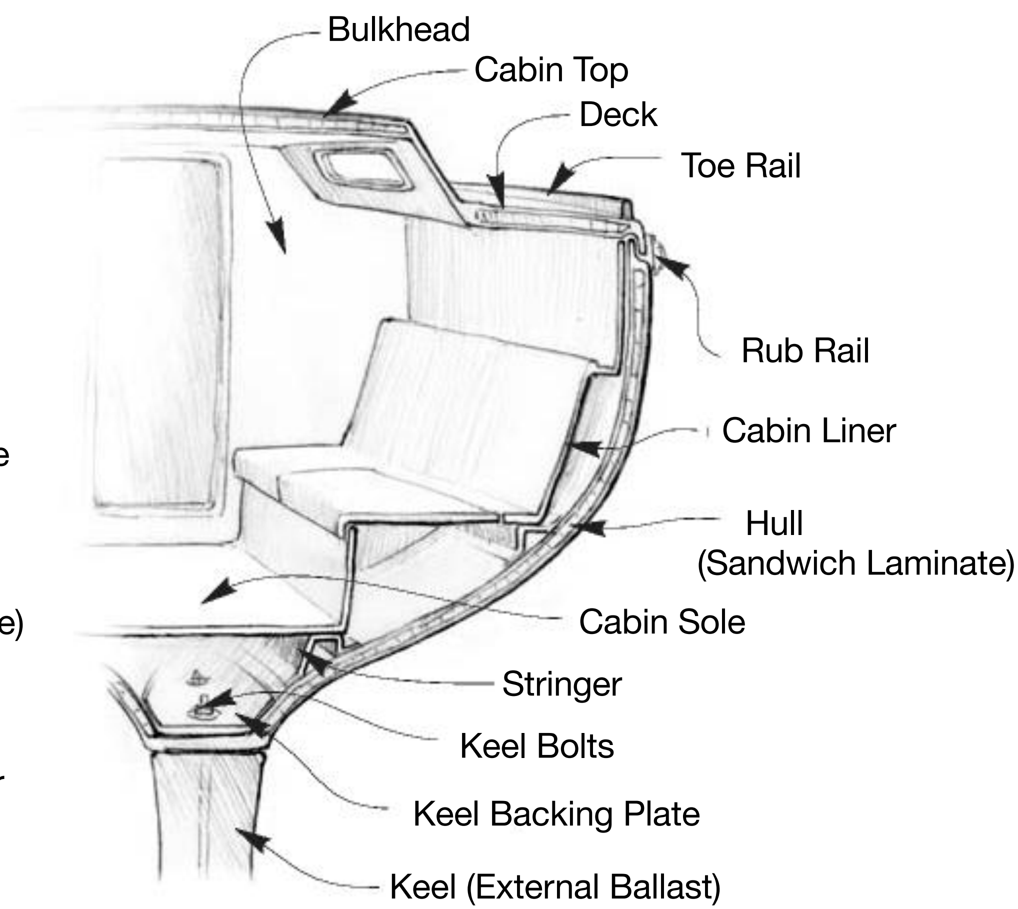
- Large marine structures have traditionally been built with E-glass - long-term experience with carbon fiber is limited, although fatigue properties of carbon laminates does seem to be better than E-glass

Composite Boat Nomenclature

Powerboats

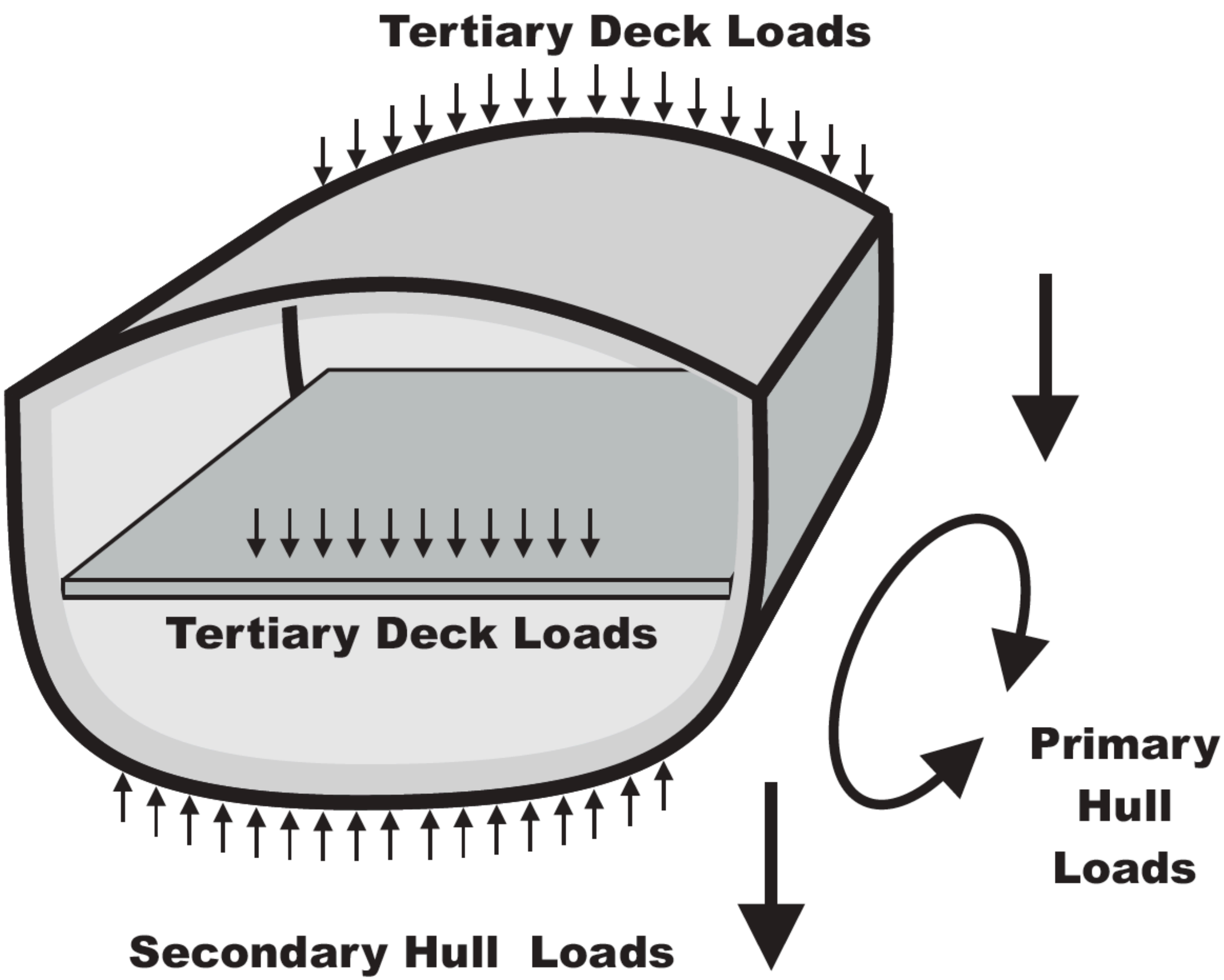


Sailboats



Gougeon Brothers, Inc., Bay City, MI

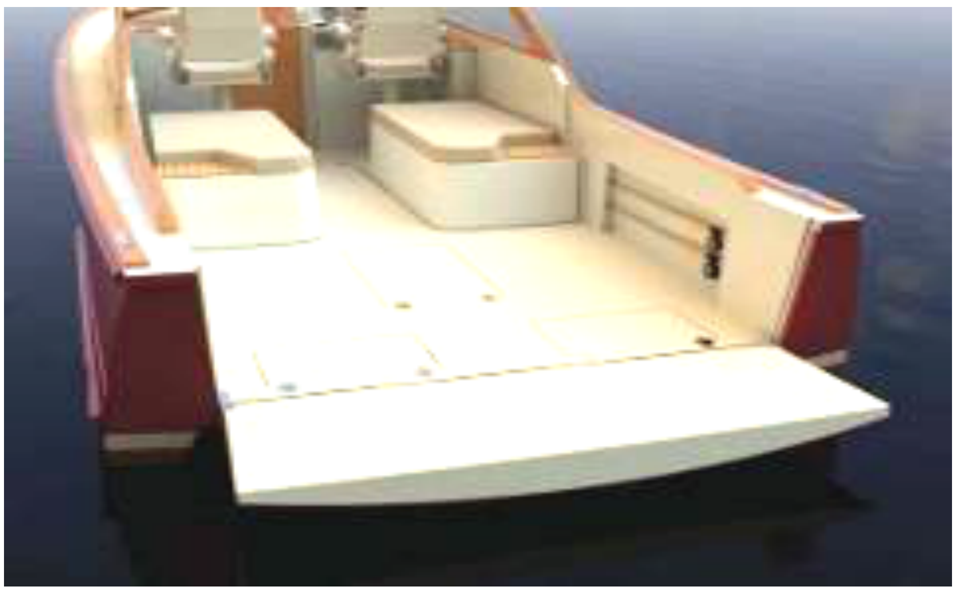
Loading



Overview of Primary (Overall Hull Bending), Secondary (Hydrostatic and Hydrodynamic Forces Normal to Hull Surface) and Tertiary (Local Forces) Loads

Hull Structure with Large Cutouts

Greg Kolodziejzyk



C.H. Marine Yachts

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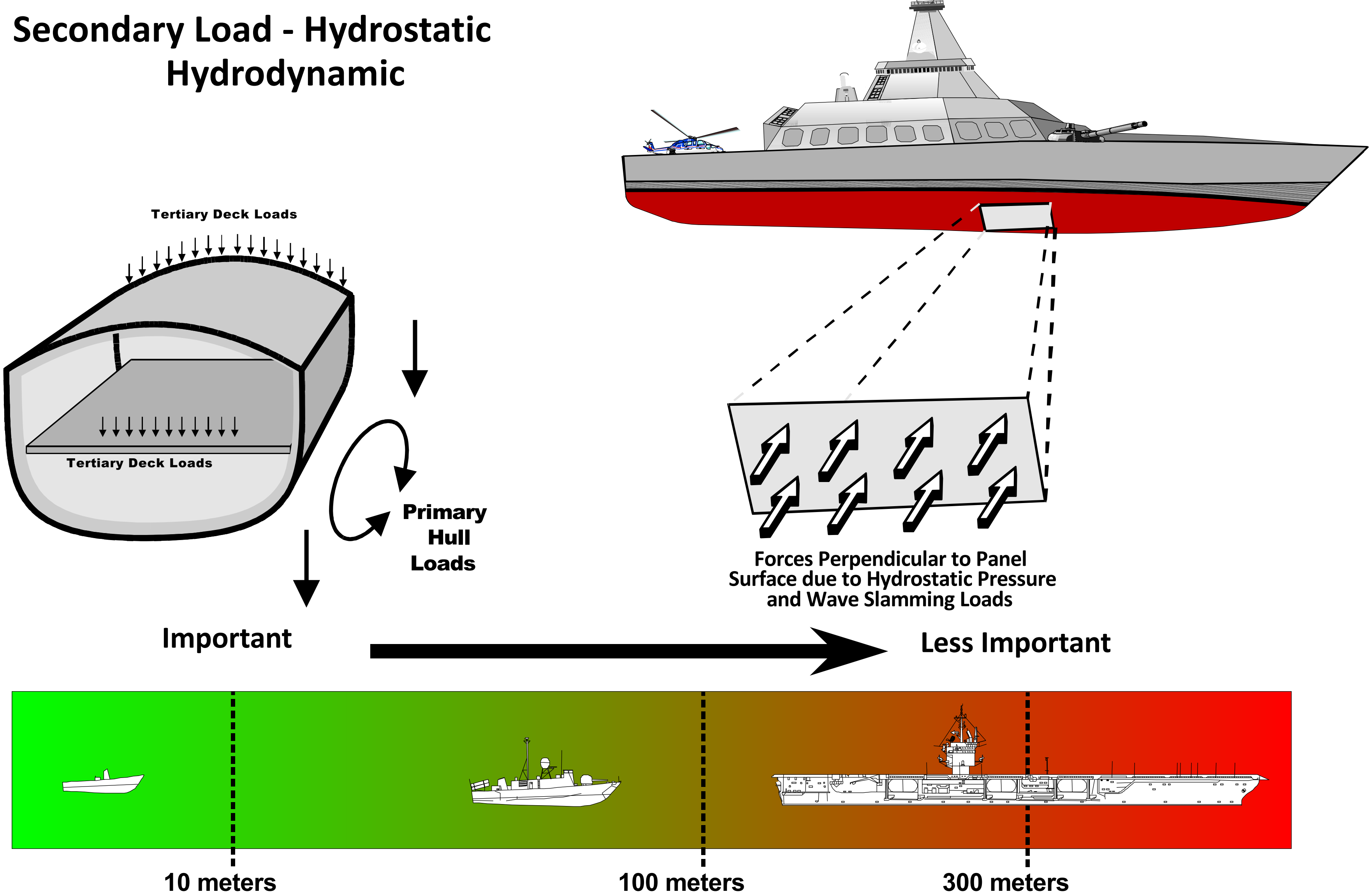
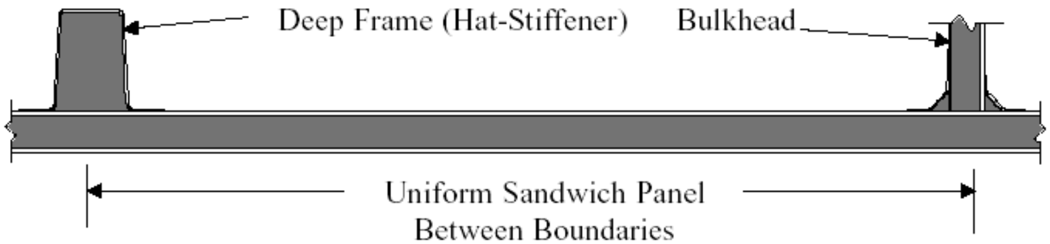
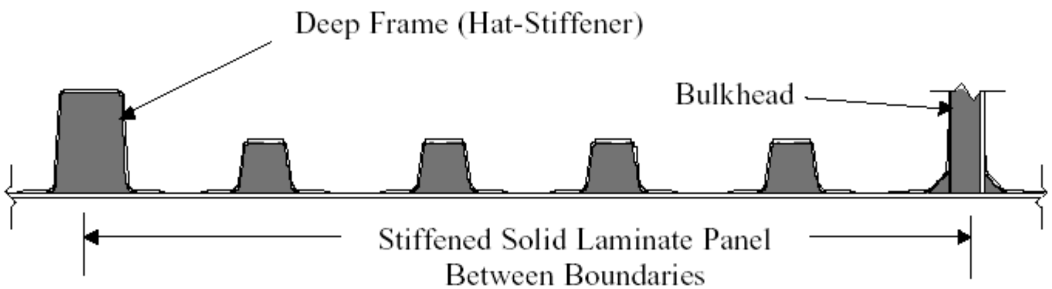
Out-of-Plane Loading

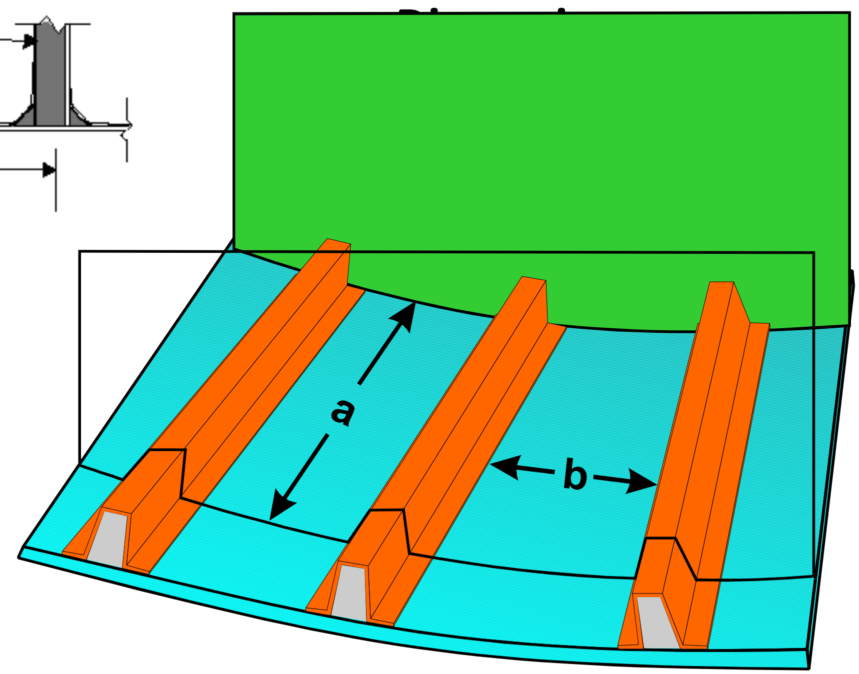


Composite Panel Configurations





Panel Deflection Primarily Dependent on Short Span (b)

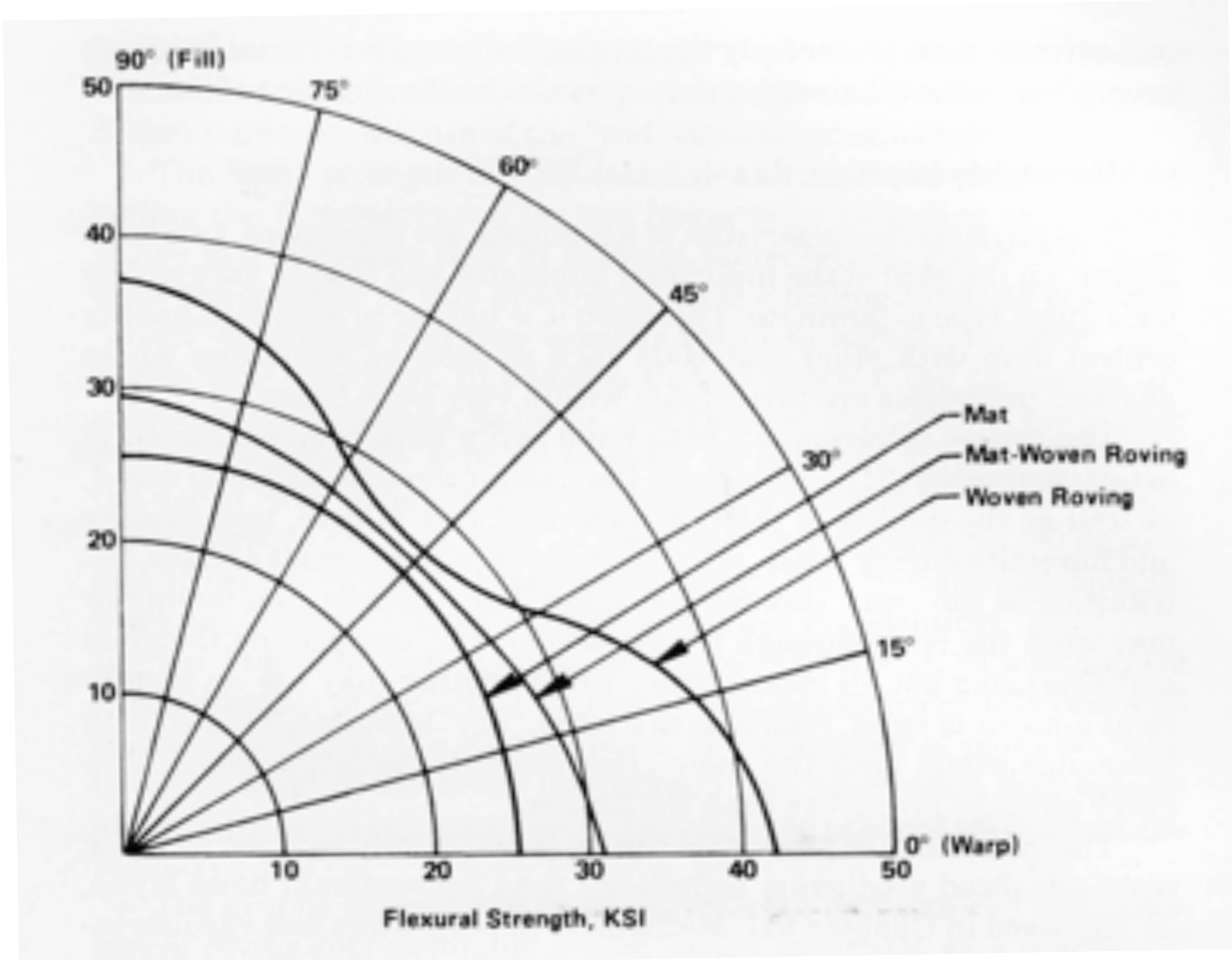


Typical Laminate Properties

Material	Fibre Volume Fraction V_f	Specific Gravity (SG)	Young's Modulus E (GPa)	Shear Modulus (GPa)	Tensile Strength σ_{UT}(MPa)	Comp. Strength (MPa)	Shear Strength (MPa)
E-glass polyester (CSM)	0.18	1.5	8	3	100	140	75
E-glass polyester (balanced WR)	0.34	1.7	15	3.5	250	210	100
E-glass polyester (unidirectional)	0.43	1.8	30	3.5	750	600	
Carbon/epoxy (high strength balanced fabric)	0.5	1.5	55	12	360	300	110
Carbon/epoxy (high strength unidirectional)	0.62	1.6	140	15	1500	1300	
Carbon/epoxy (high modulus unidirectional)	0.62	1.7	300	20	700	650	
Kevlar 49/epoxy (unidirectional)	0.62	1.4	50	8	1600	230	

data from C.S. Smith, "*Design of Marine Structures in Composite Materials*," 1990.

Directional Strength of Fiberglass



Robert J Scott, “Fiberglass Boat Design and Construction,” pg 43, 2nd edition, 1996, SNAME.

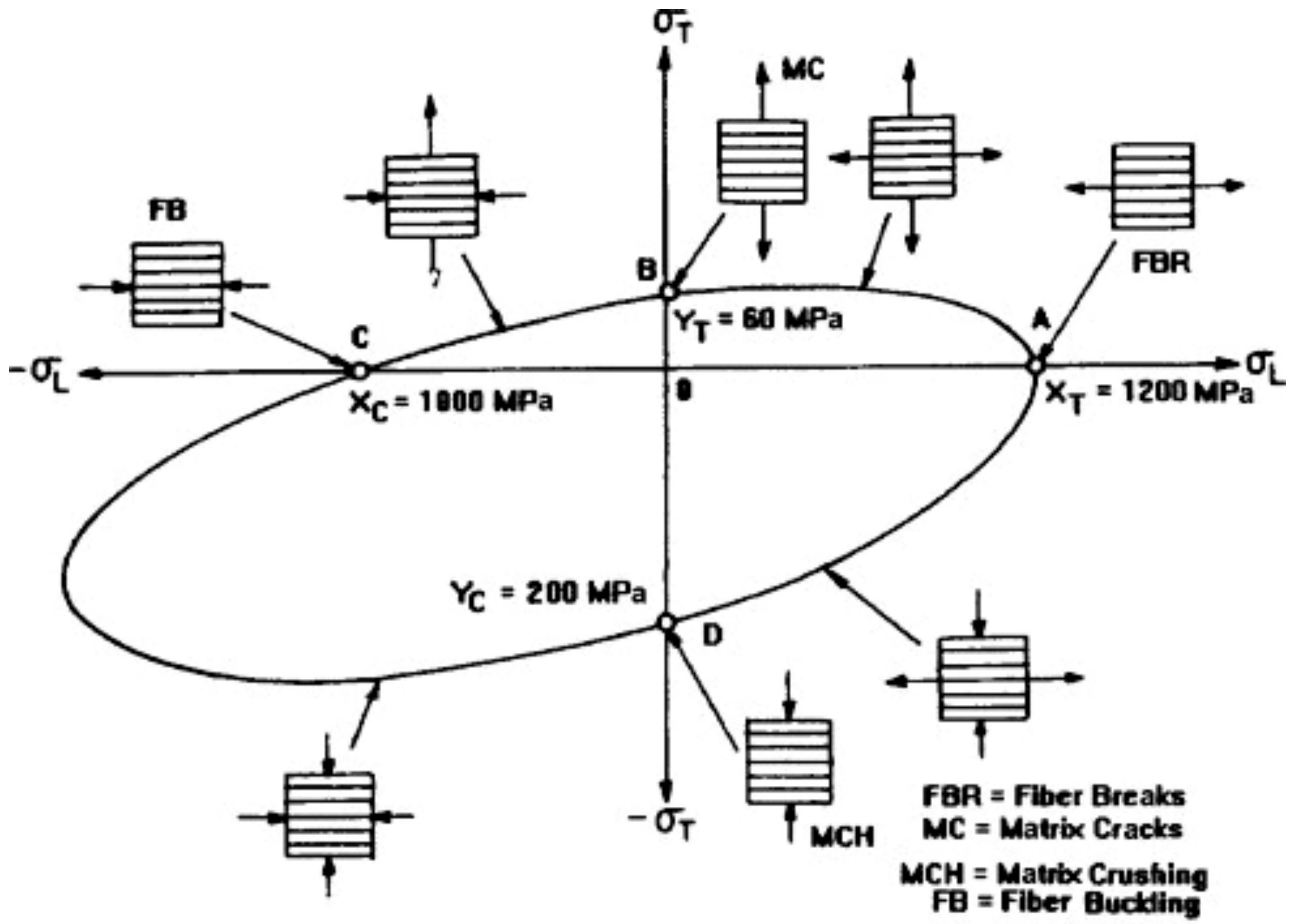
Material Property Comparison

	Material	Density gms/cm³	Tensile Strength MPa	Tensile Modulus GPa	Ultimate Elongation %
Resins	Orthophthalic Polyester	1.229	48.3	4.07	1
	Isophthalic Polyester	1.210	71.1	3.90	2
	Vinyl Ester	1.120	76-83	3.38	4-5
	Epoxy (Gougeon Proset)	1.200	48-76	3.66	5-6
	Phenolic	1.150	35.2	3.66	2
Fibers	E-Glass (24 oz WR)	2.602	3450	72.45	4.8
	S- Glass	2.491	4589	86.94	5.7
	Kevlar® 49	1.442	3623	124.2	2.9
	Carbon-PAN	1.757	2415-4830	227-393	0.38-2.0
Cores	End Grain Balsa (SB 100)	0.152	9.11	2.55	n/a
	Linear PVC (Airex R62.80)	0.088	1.38	0.06	30
	Cross-Linked PVC (Diab H-100)	0.096	3.11	0.12	n/a
	Honeycomb (Nomex® HRH-78)	0.096	n/a	0.41	n/a
	Honeycomb (Nidaplast H8PP)	0.077	n/a	n/a	n/a
Laminates	Solid Glass/Polyester, hand lay-up	1.538	138	9.66	n/a
	Glass/Polyester Balsa Sandwich	0.384	41	2.76	n/a
	Glass/VE PVC Sand, SCRIMP	0.288	41	2.76	n/a
	Solid Carbon/Epoxy fil wound	1.554	607	60	n/a
	Carbon/Epoxy Nomex prepreg	0.144	62	3.45	n/a
Metals	ABS Grd A (ASTM 131)	7.861	400	204	21
	ABS Grd AH (ASTM A242)	7.861	490	204	19
	Aluminum (6061-T6)	2.712	310	69	10
	Aluminum (5086-H34)	2.658	304	69	9
Wood	Douglas Fir	0.391	90	13.46	n/a
	White Oak	0.630	101	12.28	n/a
	Western Red Cedar	0.340	52	7.66	n/a
	Sitka Spruce	0.340	90	10.83	n/a

Note: The values used in this table are for illustration only and should not be used for design purposes. In general, strength is defined as yield strength and modulus will refer to the material's initial modulus. A core thickness of 1" with appropriate skins was assumed for the sandwich laminates listed.

Mechanical Behavior of Orthotropic Materials

Typical quadratic failure envelope with condition of stress state and possible initiating failure mechanisms at different points on the failure envelope



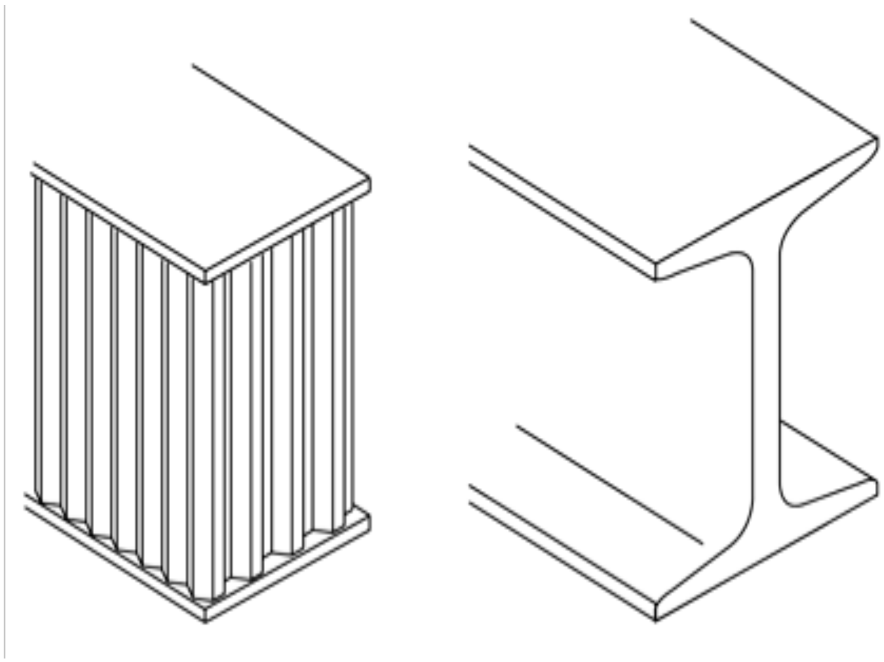
G. Narayana Naik, S. Gopalakrishnan, , Ranjan Ganguli, "Design optimization of composites using genetic algorithms and failure mechanism based failure criterion," Composite Structures, Volume 83, June 2008

Solid and Sandwich Laminate Comparison

- Hat-stiffened, solid laminates built as monolithic structures offer the greatest amount of primary axis reinforcements to resist hull girder bending moments
- Solid laminates are easier to inspect for structural damage
- Sandwich laminates are the most efficient structures for resisting out-of-plane loads
- Sandwich laminates offer good insulation properties and a reserve inner skin to prevent flooding

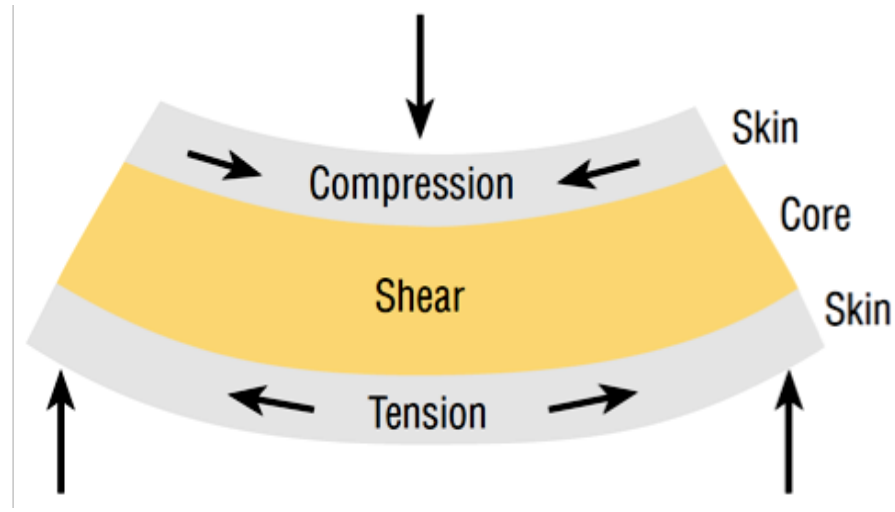
Sandwich Laminates

Sandwich Laminate as I-beam



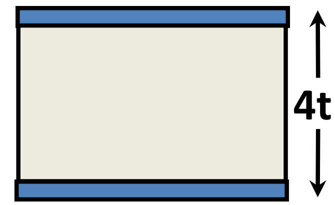
Hexcel, Prepreg Technology, Publication No. FGU 017b, March 2005.

Stresses from Flexural Loading



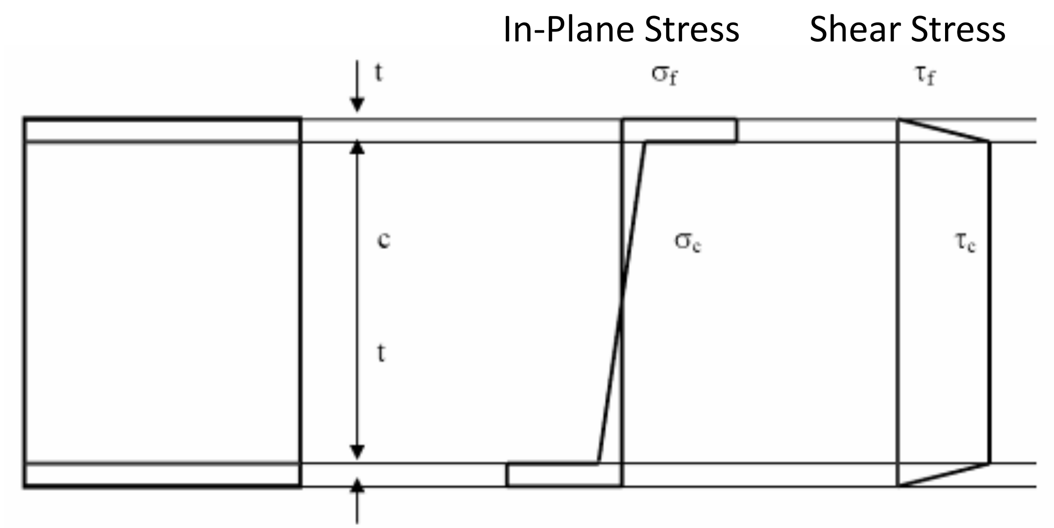
SP Gurit, SP Guide to Composites, GTC-1-1098, Feb 2008.

Comparison of Solid & Sandwich Laminates for Out-of-Plane Loads

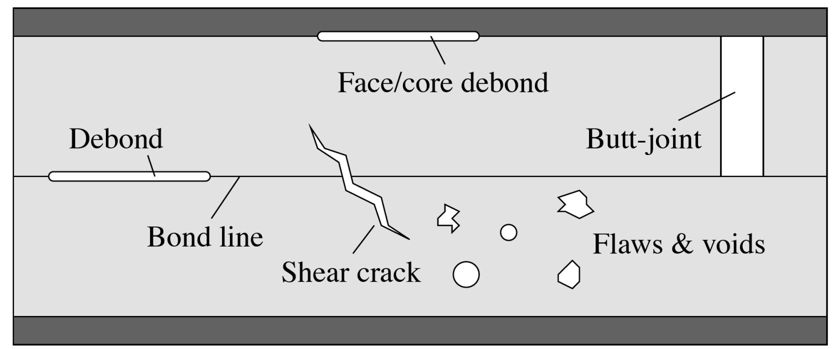
	 t	 2t	 4t
Relative Stiffness	**100**	**700**	**3700**
Relative Strength	**100**	**350**	**925**
Relative Weight	**100**	**103**	**106**

Stresses in Sandwich Laminates

Sandwich Laminate Beam subject to Bending



Defects and imperfections in sandwich structure

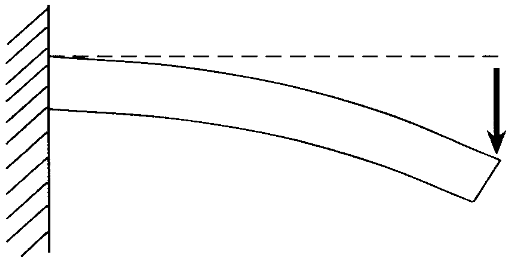


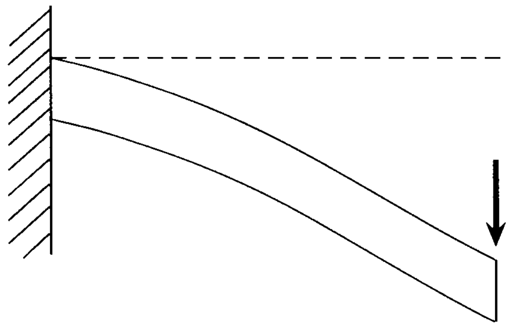
<u>Skins or Faces</u>
Skin stresses are primarily tensile or compressive during bending. Skins must also resist local impact loads.

<u>Core</u>
The core must transfer the loads between the skins via shear. Cores must also resist compressive stress from out of plane loads and hardware.

<u>Bonding Layer</u>
The bonding layer must ensure that the skins remain bonded to the core by resisting shear and peeling loads.

Sandwich Laminate Rigidity

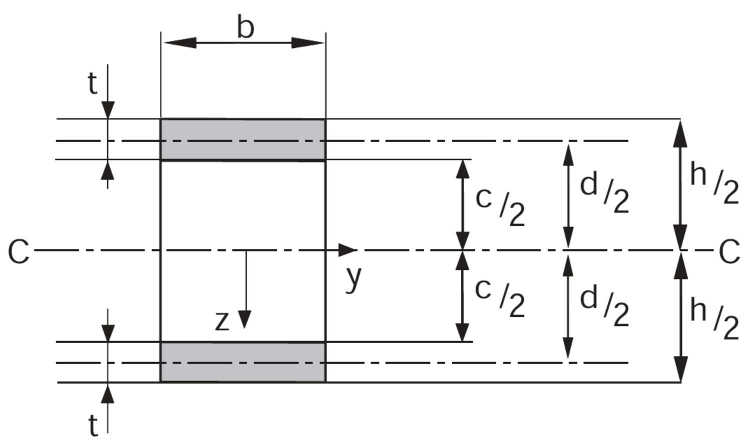




$$D = E_f \frac{bt^3}{6} + E_f \frac{btd^2}{2} + E_c \frac{bc^3}{12}$$

for sandwiches with relatively thin skins:

$$\frac{d}{t} > 5.77 \qquad D \approx E_f \frac{btd^2}{2} + E_c \frac{bc^3}{12}$$

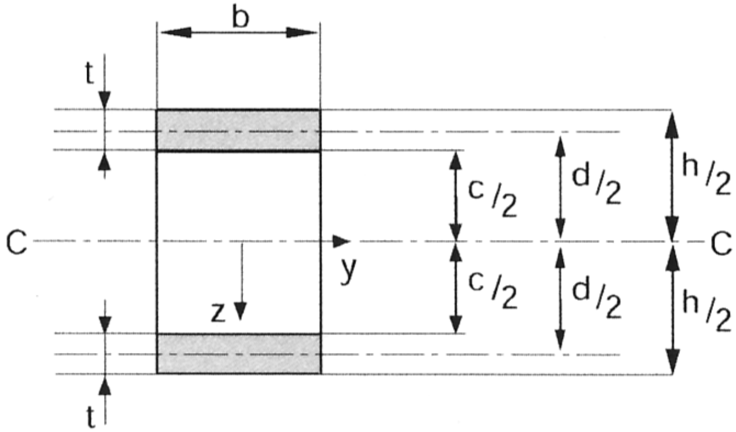


for sandwiches with relatively stiff skins:

$$\frac{E_f}{E_c} \cdot \frac{td^2}{c^3} > 16.7 \qquad D \approx E_f \frac{btd^2}{2}$$

from DIAB Sandwich Handbook

Stresses in Sandwich Laminates

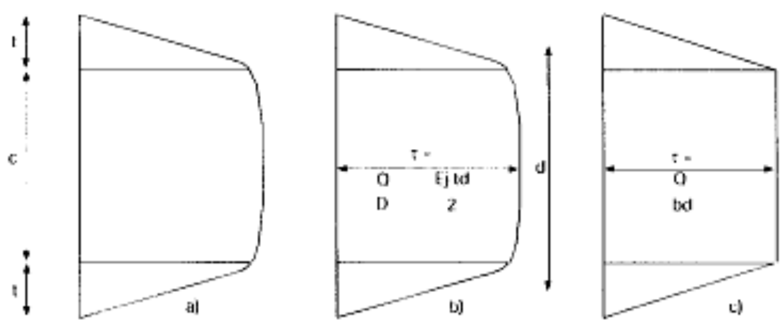


In-plane stresses for faces and core:

$$\sigma_f = \frac{Mz}{D} E_f \left(\frac{c}{2} \le z \le \frac{h}{2} ; -\frac{h}{2} \le z \le -\frac{c}{2} \right)$$

$$\sigma_c = \frac{Mz}{D} E_c \left(-\frac{c}{2} \le z \le \frac{c}{2} \right)$$

Shear stress distribution:



a) Typical stress distribution
b) Effect of “soft” cores
c) Soft core ignoring skin flexural rigidity

Maximum shear stress in the core:

$$\tau = \frac{Q}{D} \left(E_f \frac{td}{2} + \frac{E_c}{2} \frac{c^2}{4} \right)$$

where Q is the local shear force

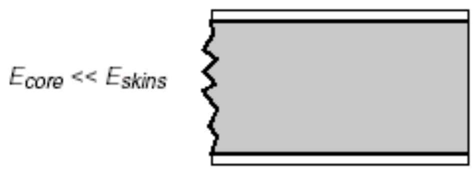
Constant core shear stress for “soft” cores:

$$\tau = \frac{Q}{D} \frac{E_f td}{2}$$

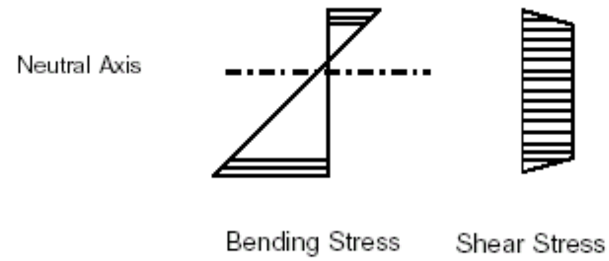
from DIAB Sandwich Handbook

Effect of Skin Thickness on Sandwich Stresses

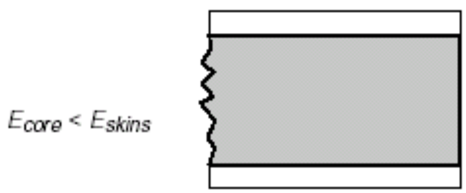
Thin Skins and Stiff Core



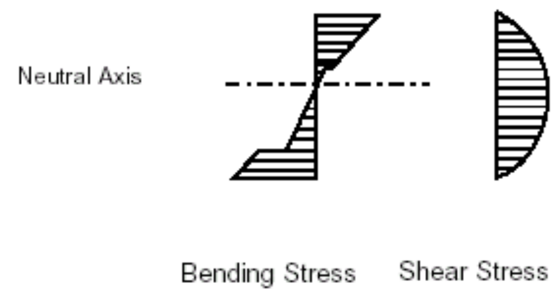
Thin skins with axially soft and shear rigid core



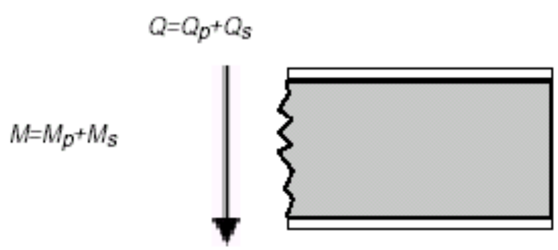
Thick Skins and Stiff Core



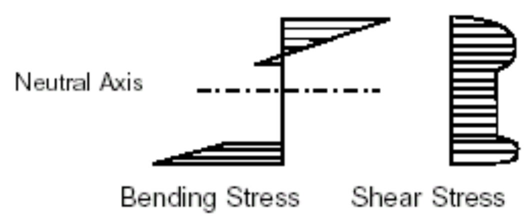
Thick skins with axially stiff and shear rigid core



Thin Skins and Soft Core



Combined Bending Moment and Shear Force



Damage Tolerance of Solid & Sandwich Laminates

Damage Mechanism	Solid Laminate	Sandwich Laminate
Wave Impact	Rely on good bond to stiffener; damage easily visible; may deflect a lot before failure	Good out-of-plane mechanical properties; delaminations may be difficult to detect; deck & bulkhead attachment points critical
Point Loads	Thicker skins resist failure; toughness dependent on reinforcement & resin selection	Easier to puncture but holing difficult; susceptible to damage at transition to solid & at hard spots
Fatigue	Usually good due to low working stress – beware of large deflections and machinery attachment points	Dependent on skin and core modulus: attention to hardware mounting detail necessary
Delamination	Function of resin interlaminar shear strength	Skin-to-core bond is weakest link – fabrication QA critical
Fire	Dependent on resin system; skins self-insulating; dissipates heat off back side; more resin = more fuel	Core makes hot skin burn faster; balsa will char and stop fire after first skin is gone

Takeaway Sandwich Concepts

When laminates are designed to resist out-of-plane loads:

- Skins are primarily in compression (load side) and tension (interior side)
- Core shear strength and stiffness properties are critical laminate parameters
- Shear strength of bond between skin and core is critical to performance
- Beam analysis may not accurately represent “end conditions” or off-axis characteristics of panel structures
- Dynamic performance of sandwich laminates primarily dependent on core “strain rate” dependent properties

Laminate Stacking Programs Based on Classical Laminate Theory

- Programs have a database of constituent materials and can also accept user supplied materials with appropriate mechanical properties
- Panel design loads can be input as forces & moments or based on vessel parameters if software is tied to classification society rules that dictate design pressure
- User needs to know how laminate will be built to estimate fiber content
- Stacking sequence and ply orientation can be altered and output usually compares several laminates at one time
- Program outputs typically include:
  - Laminate weight, thickness, density and cost
  - Modulii for 0° & 90° Tensile, Compressive, Flexural and Shear
  - Ultimate stress for 0° & 90° Tensile, Compressive, Flexural and Shear
  - In-plane (EA) and bending (EI) stiffness
  - Ultimate in-plane (load per unit width) and bending (moment) strength

VectorLam

Step 1
Laminate Construction

Laminate Construction

Laminate # ->	1	2	3
Name	**Current Bottom**	**LaborSaver Bottom**	**VectorFusion Bottom**
Layer 1	Gelcoat - 20 mil	Gelcoat - 20 mil	Gelcoat - 20 mil
Layer 2	Chopped Mat - 1.5 oz	Chopped Mat - 1.5 oz	Chopped Mat - 1.5 oz
Layer 3	Chopped Mat - 1.5 oz	Chopped Mat - 1.5 oz	Chopped Mat - 1.5 oz
Layer 4	E-LTM 2415	E-LTM 3615	E-3LTi 10800 - infused
Layer 5	E-LTM 2415	E-LTM 3615	E-3LTi 10800 - infused
Layer 6	E-LTM 2415	Chopped Mat - 1.5 oz	E-3LTi 10800 - infused
Layer 7	E-LTM 2415	E-LTM 3615	
Layer 8	E-LTM 2415	E-LTM 3615	
Layer 9	E-LTM 2415		
Layer 10	E-LTM 2415		

The laminate page shows layer-by-layer comparison of current practice to two alternatives. In this example the builder is shown a comparison between current open mold practice, a reduced labor cost using LaborSaver reinforcements, and an infused option using VectorFusion, infusion specific reinforcements.

http://www.vectorply.com/lam-example.html

VectorLam

Step 2
DNV (Det Norske Veritas): Laminate design to International standards

Name :	Current Bottom	LaborSaver Bottom	VectorFusion Bottom	Units
Properties of the Craft :				
Length in meters (ft x 0.3048 = m)	12.32	12.32	12.32	m
Service Speed (> 25 knots for "high speed" craft.)	18.0	18.0	18.0	knots
Displacement (1 tonne = 1000 kg = 2205 lb)	12.70	12.70	12.70	tonnes
Maximum draft - baseline to wl - T	1.73	1.73	1.73	m
Draft at L/2 at speed (0 - Max. Draft) TL/2	0.87	0.87	0.87	m
Draft at forepeak, at speed - TL	1.52	1.52	1.52	m
Maximum beam, Bmax	5.94	5.94	5.94	m
Maximum beam at water line, Bwl	5.33	5.33	5.33	m
Water line beam at mid-ship, Bwl2	5.33	5.33	5.33	m
Deadrise at LCG (10-30 degrees)	15	15	15	Deg.
Service area restriction notation	R0	R0	R0	
Type and service notation	Yacht	Yacht	Yacht	
Hull Type	Monohull	Monohull	Monohull	
Number of hulls	1	1	1	
DnV Minimum Design Vert. Accelleration, acg,min (in g's)	1.42	1.42	1.42	g's
Safety Factor on DNV Minimum Vertical Accelleration	1.30	1.30	1.30	>= 1
Design Vertical Acceleration in g's, acg = DNVmin x SF	1.85	1.85	1.85	g's
Properties of a Specific Plating Area:				
Panel Location - hull bottom or side.	Bottom	Bottom	Bottom	
Station Fwd (0=AP, 1=FP)	0.70	0.70	0.70	
Vertical distance from panel center to WL, ho (>=0)	0.45	0.45	0.45	m
Local deadrise angle - bottom panels only. (10-30 deg.)	20.00	20.00	20.00	Deg.
Panel shorter dimension	0.81	0.81	0.81	m
Panel longer dimension	1.83	1.83	1.83	m
Laminate for Single Skin or Outer Skin of Sandwich	Current Bottom	LaborSaver Bottom	VectorFusion Bottom	
Outer Skin 0 Degree Direction Span	Long	Long	Long	
Core Material (Leave blank for single skin)				
Core Thickness (mm)				mm
Inner Skin Laminate (Leave blank for single skin)				
Inner Skin 0 Degree Direction Span	Long	Long	Long	
Sandwich or Single Skin (Solid) Construction	S. Skin	S. Skin	S. Skin	
Panel Edge Support Conditions	Fixed	Fixed	Fixed	
Design Pressure in kN / sq.m :	34.92	34.92	34.92	kN/sq.m
in PSI units	5.06	5.06	5.06	PSI
Controlled By:	Slamming	Slamming	Slamming	

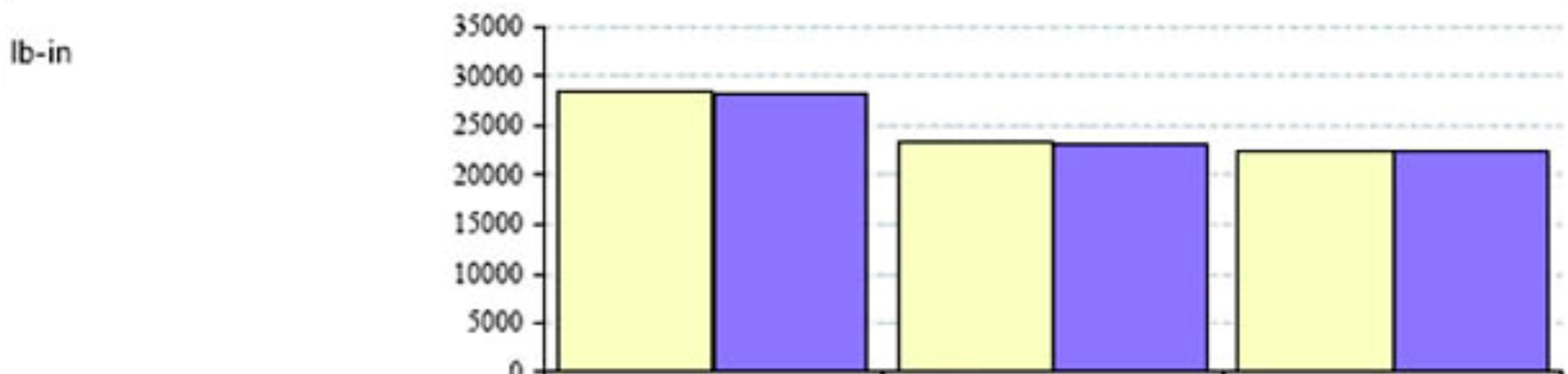
Existing laminates and new designs can be verified by DNV, an international design standard. Hull dimensions, displacement, service speed, largest unsupported panel, and intended service use are part of the equation to generate bottom pressures, vertical acceleration and other data that help engineers design the most appropriate laminate.

http://www.vectorply.com/lam-example.html

eric greene associates

VectorLam

Step 3
Compare the basics: stiffness, strength, weight, & cost



	Current Bottom	LaborSaver Bottom	VectorFusion Bottom
0º Flex. Stiffness	28,588	23,392	22,410
90º Flex. Stiffness	28,145	23,187	22,450

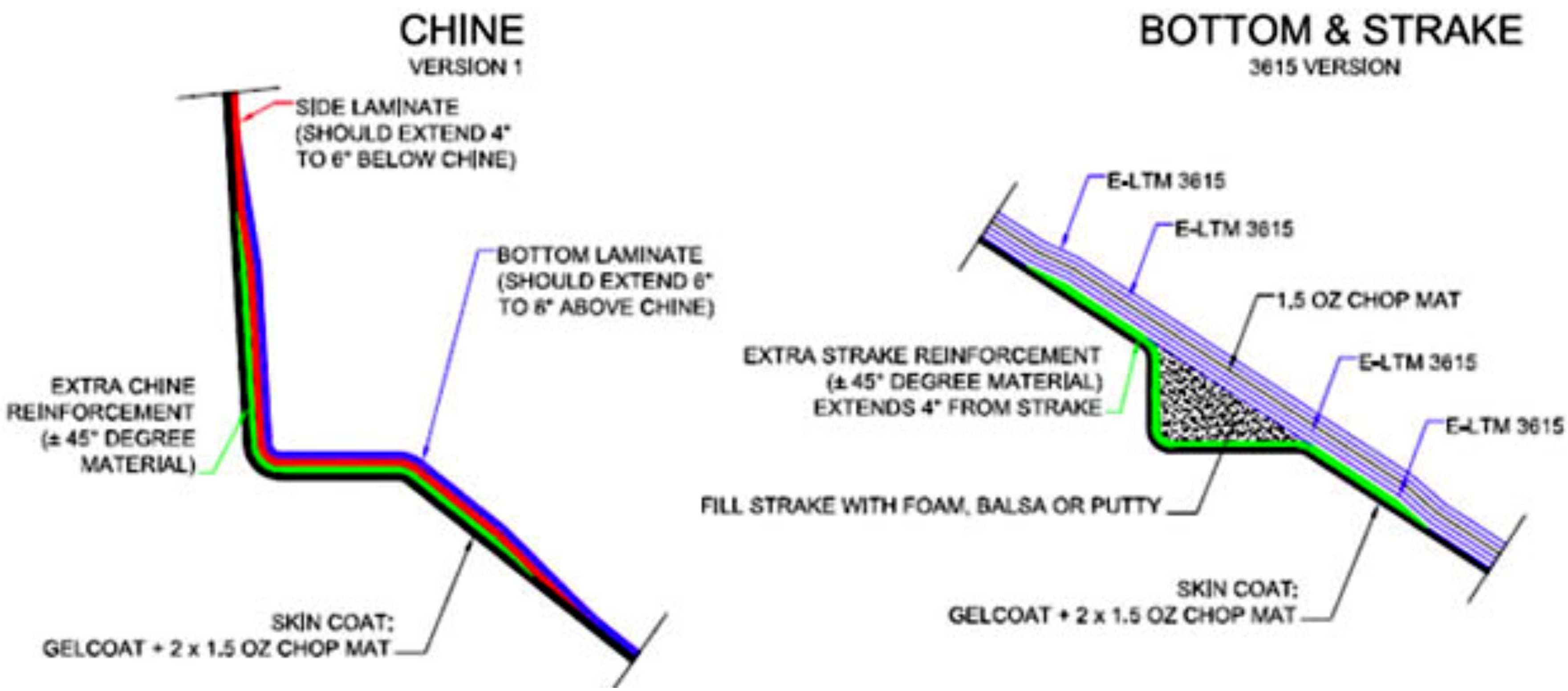
Stiffness,"EI"

Graphs like this "Stiffness, EI" illustration, compare laminates on the basis of stiffness, strength, weight, and cost. This allows designers and builders to play "what if" scenarios with laminate design long before the building process begins. In this scenario, the current bottom laminate is well overbuilt, and both labor and weight can be reduced with the other options while still providing sufficient stiffness and strength. Laminate weight is reduced 8% in the LaborSaver Bottom and 10% in the VectorFusion Bottom. The number of layers is also reduced by 2 and 4, respectively.

http://www.vectorply.com/lam-example.html

VectorLam

Step 4
Construction detail

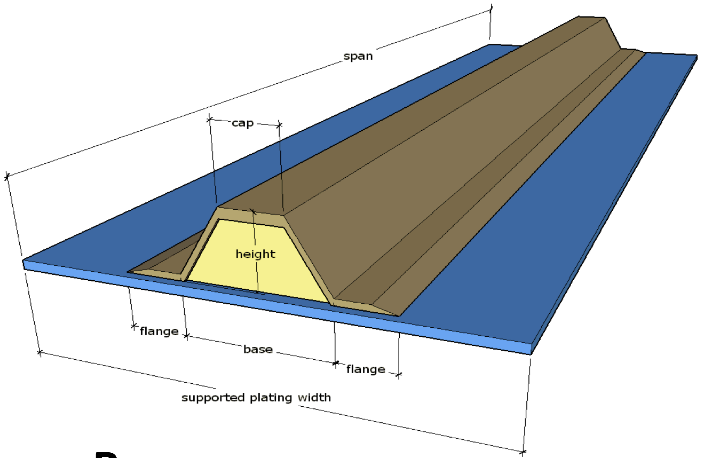


Each laminate report includes construction suggestions for the major components such as strakes, stringers, and hull bottom to side intersection. Laminate reports are available in hard copy or electronic file format.

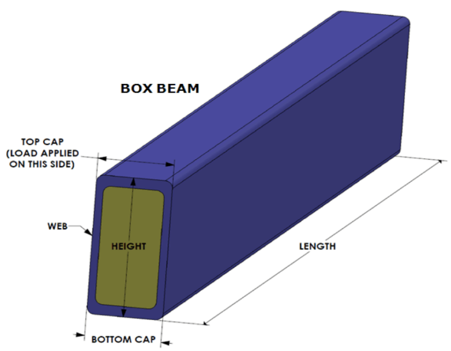
http://www.vectorply.com/lam-example.html

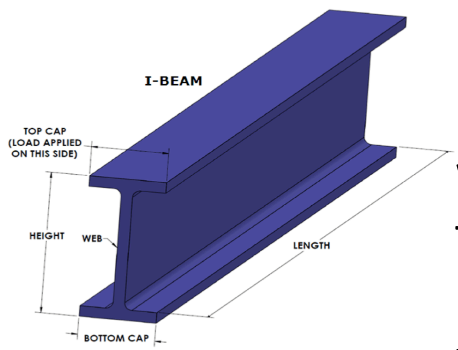
Safety Factors

Stiffeners

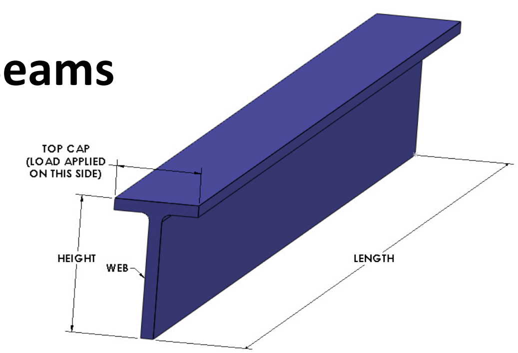


Beams





T-Beams



Safety factors used in VectorLam program

Parameter	Safety Factor
Deflection	1.0
First Ply Failure	2.0
Ultimate Skin Failure	3.0
Core Shear Failure	2.5
Moment at ends	3.33
Moment at middle of distributed load	3.33
Moment at point load	3.33
Web shear	4.0
Top cap compression buckling	2.5
Bottom cap compression buckling	2.5
Web shear buckling	2.5
Global buckling	3.33

Levels of Uncertainty in Marine Composite Design

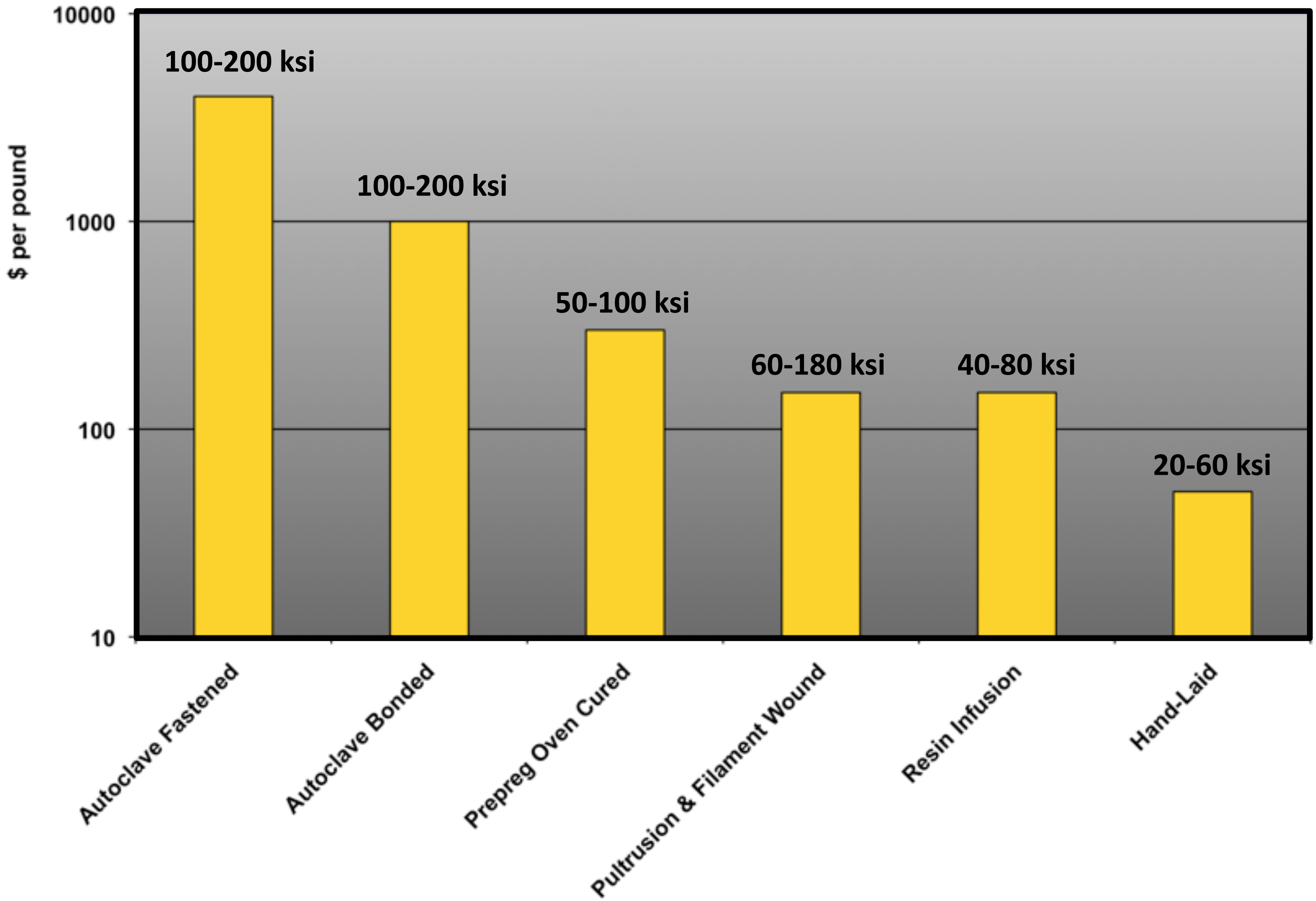
Type of Uncertainty	Coefficient of Variation
Wave Loads	20% – 100%
Buckling Analysis	100%
Structural Analysis	10%
Elastic Modulus	5%
Yield Strength	8%
Mechanical Test of Quality Marine Laminate	5% - 8%

from Det Norske Veritas’ (DNV's) "*Structural Reliability Methods*" and Chamis, C.C. and M.C. Shiao, “*Probabilistic Assessment of Composite Structures*,” 1993, NASA

Design Tool Summary

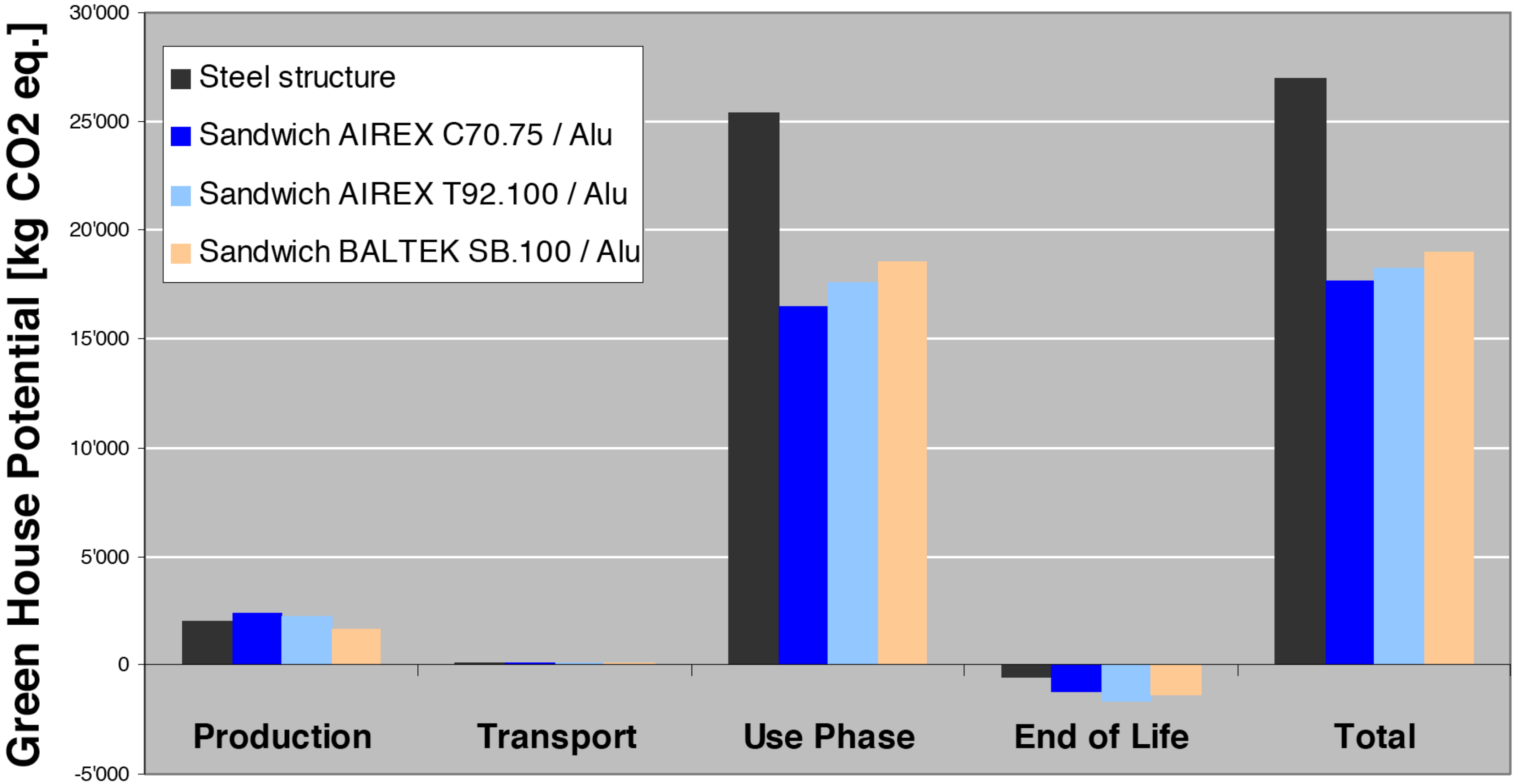
- Design tools for large marine structures are more mature for metals than composites
- Composite laminates have 26 engineering parameters that need to be characterized with mechanical testing
- Composites do not have a “plastic” failure region – interlaminar failures and cracking precedes catastrophic failure
- There are numerous shear, tensile and compressive failure modes for composite structures

Strength/Cost Paradigm



Green House Potential

Graph showing the Green House Gas Potential for different construction alternatives of an upper floor bus section over its life cycle



3A Composites, "Life Cycle Inventory Analysis for sandwich structures," Sins, Switzerland

Design Summary

- Composites offer the potential to "highly engineer" a structure when load paths are well defined
- Long-term experience with large, composite marine structures is limited to E-glass laminates
- In-plane loads dominate for ships - out-of-plane loads drive the design of boats
- Sophisticated design tools for composite structures have been developed for the aerospace industry but are immature for large, marine structures