Marine Composites

Webb Institute
Senior Elective

Core Materials and Adhesives

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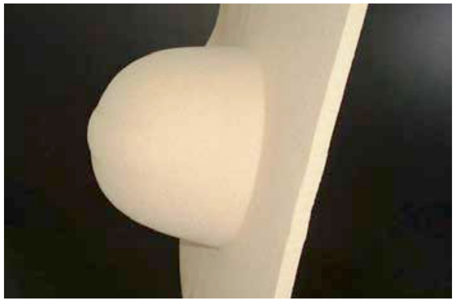
Types of Cores

End-Grain Balsa

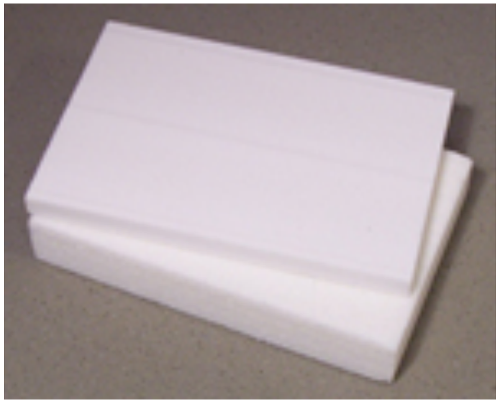
SAN Foam



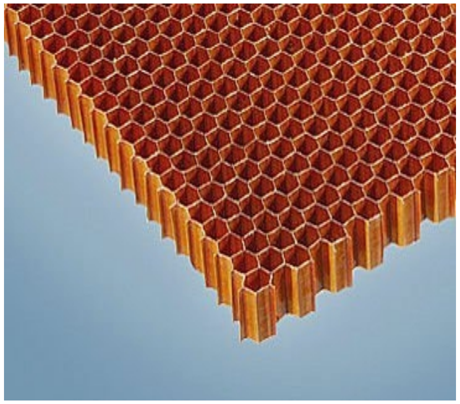
Linear PVC Foam

Aromatic Polyester Foam

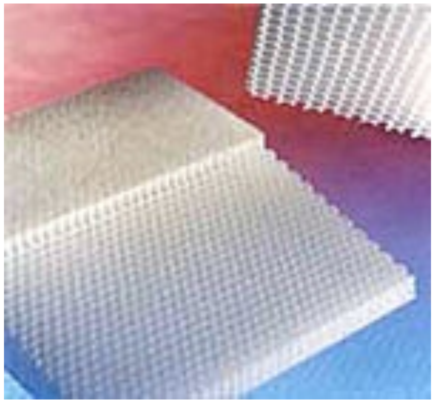
Cross-Linked PVC Foam



PET Foam

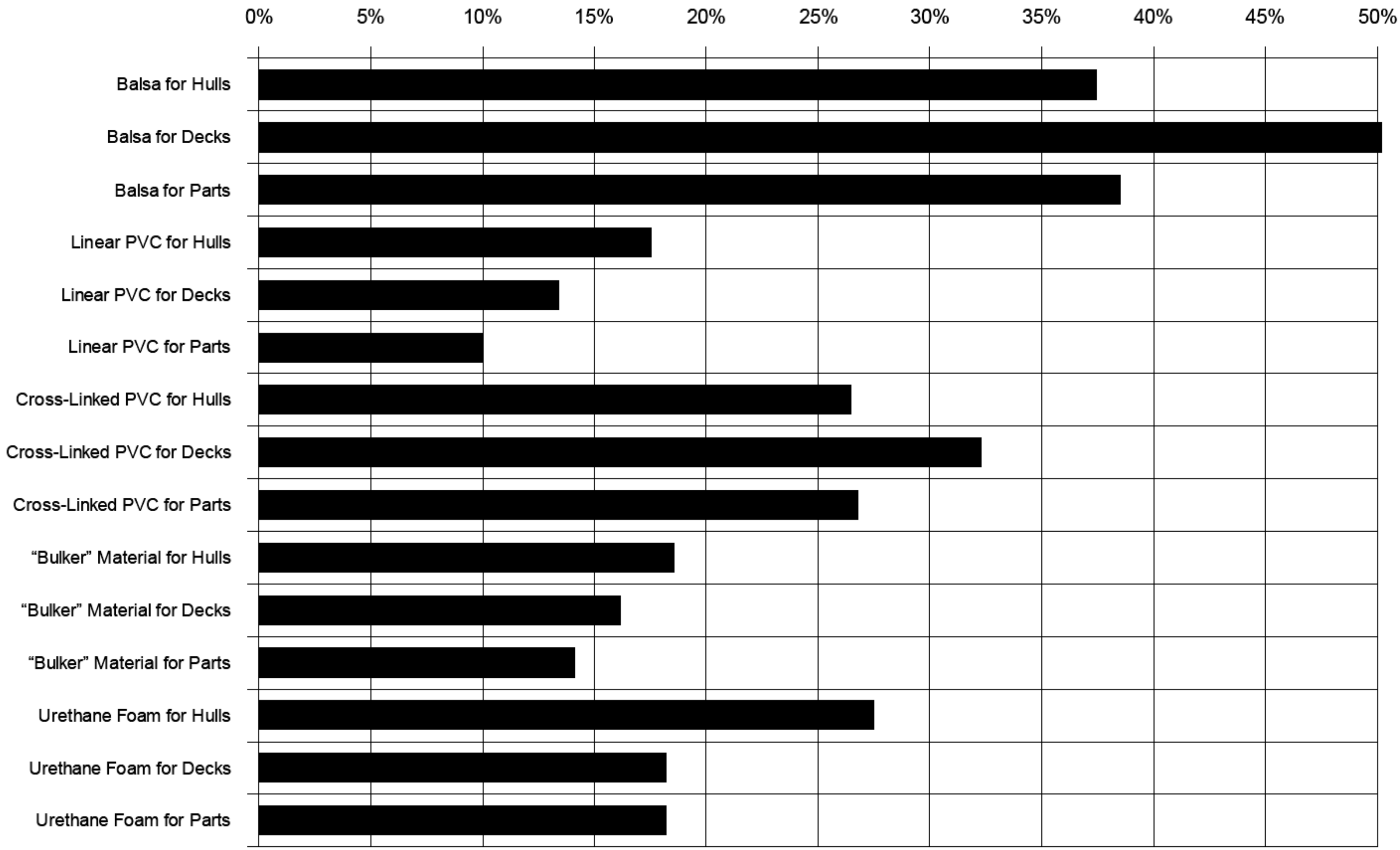


Aramid Honeycomb



Polypropylene Honeycomb

Boatbuilder's Core Usage



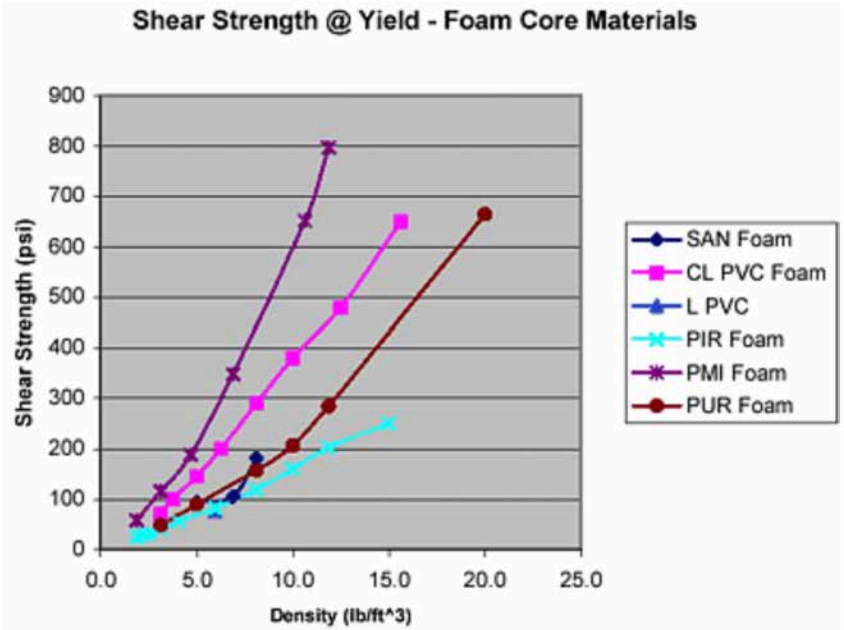
data from Eric Greene Associates 1995 survey

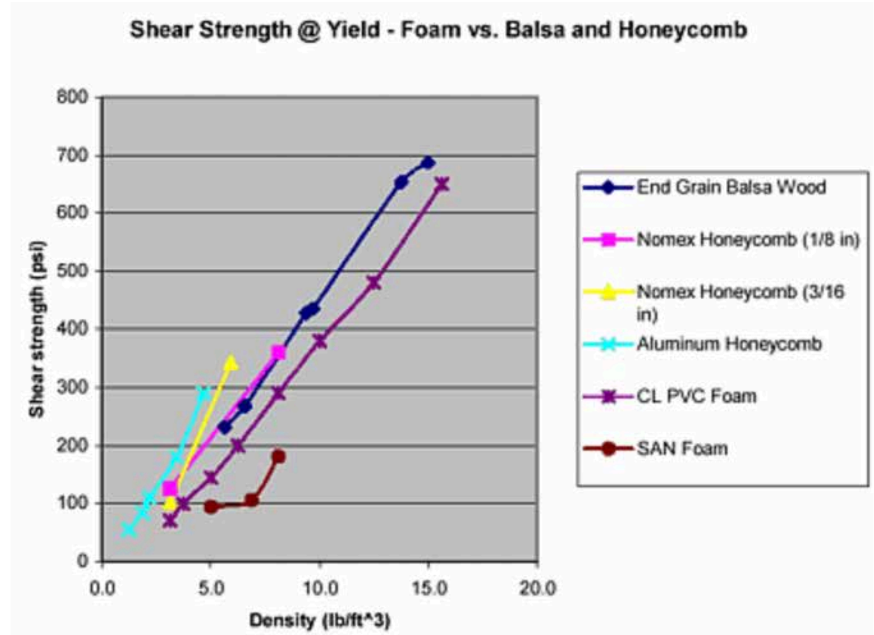
Comparison of Core Material Data

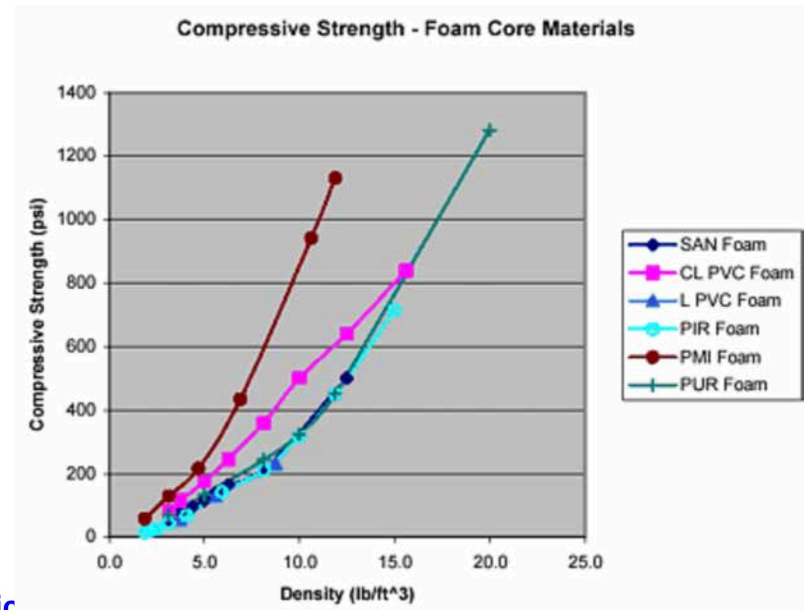
Core Material		Density		Tensile Strength		Compressive Strength		Shear Strength		Shear Modulus	
		lbs/ft^3	g/cm^3	psi	Mpa	psi	Mpa	psi	Mpa	psi x 10^3	Mpa
End Grain Balsa		7	112	1320	9.12	1190	8.19	314	2.17	17.4	120
		9	145	1790	12. 3	1720	11.9	418	2.81	21.8	151
Cross-Linked	Termanto, C70.75	4.7	75	320	2.21	204	1.41	161	1.11	1.61	11
PVC Foam	Klegecell II	4.7	75	175	1.21	160	1.1			1.64	11
	Divinycell H-80	5	80	260	1.79	170	1.17	145	1	4.35	30
	Termanto C70.90	5.7	91	320	2.21	258	1.78	168	1.16	2.01	13
	Divinycell H-100	6	96	360	2.48	260	1.79	217	1.5	6.52	45
Linear Structural Foam	Core-Cell	3.0-4.0	55	118	0.81	58	0.4	81	0.56	1.81	12
		5-5.5	80	201	1.39	115	0.79	142	0.98	2.83	20
		8.0-9.0	210	329	2.27	210	1.45	253	1.75	5.1	35
Airex Linear PVC Foam		5.0-6.0	80-96	200	1.38	125	0.86	170	1.17	2.9	20
PMI Foam	Rohacell 71	4.7	75	398	2.74	213	1.47	185	1.28	4.3	30
	Rohacell 100	6.9	111	493	3.4	427	2.94	341	2.35	7.1	49
Phenolic Resin Honeycomb		6	96	n/a	n/a	1125	7.76	200	1.38	6	41
Polypropylene Honeycomb		4.8	77	n/a	n/a	218	1.5	160	1.1	n/a	n/a

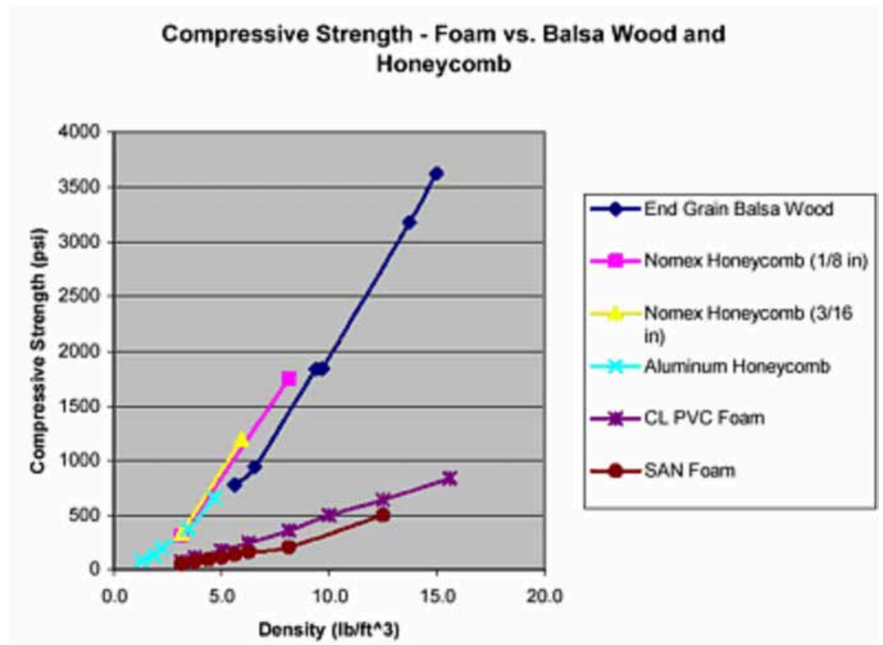
Comparative Data for Some Sandwich Core Materials

Core Properties vs Density



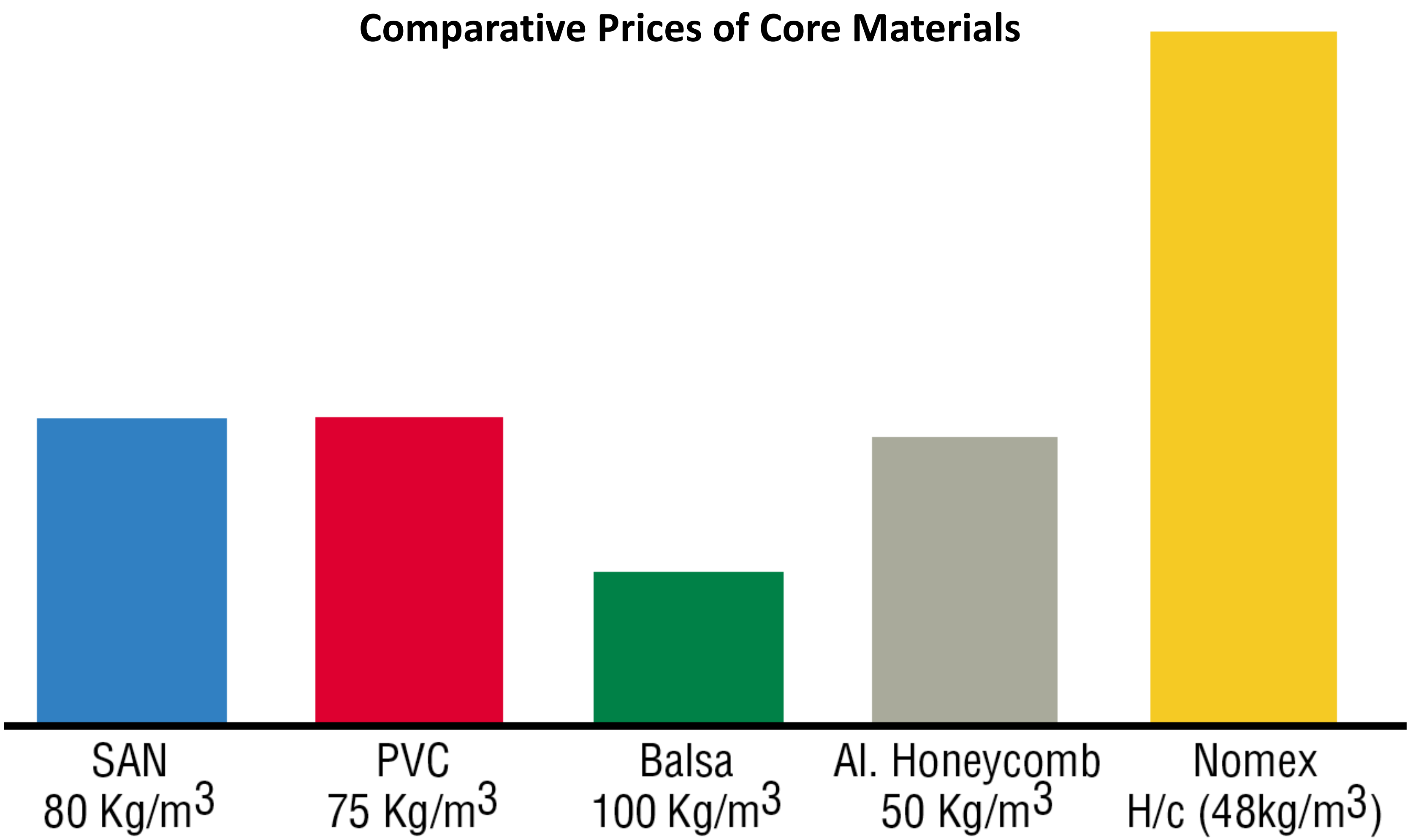






eric greene associates

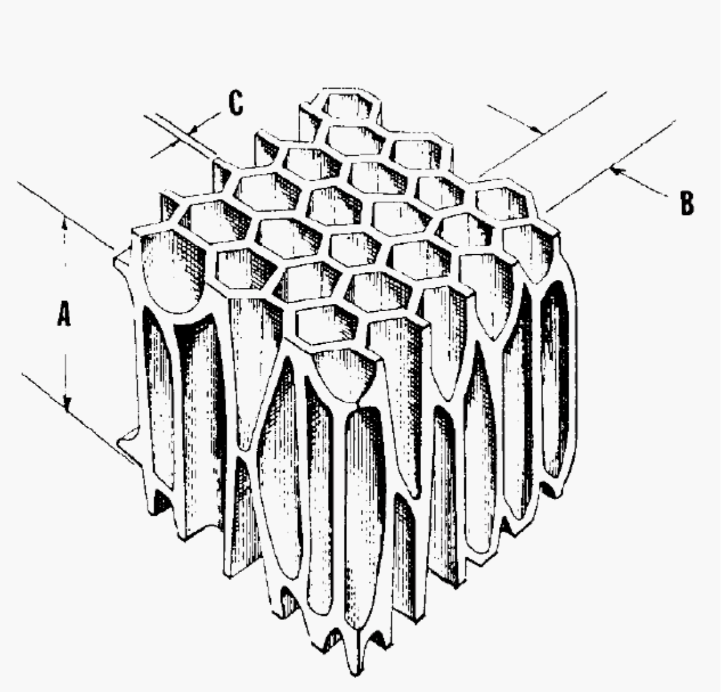
Comparative Core Costs



SP Systems, Guide to Composites," GTC-1-1098

Balsa Core Construction & Shear Properties

Balsa Core Structure



Balsa Cell Geometry with A = Average Cell Length = .635mm; B = Average Cell Diameter = .032mm; C = Average Cell Wall Thickness = .002mm [Baltek Corporation]

Shear Strength Reduction with Core Thickness

The core shear properties should be derated according to below table when core thickness of more
than 12.7 mm is used. The table is based on a good interface between the core and skin laminate.

Core thickness, (mm):	Multiply specified core shear strength by the following factor:
12.7	1.05
19.0	1.00
25.4	0.95
38.1	0.86
50.8	0.77

Det Norske Veritas Type Approval Certificate NO. K-2859

Balsa Structural Properties

Typical properties for BALTEK® SB			SB.50	SB.100	SB.150
Apparent nominal density	ASTM C 271	kg/m^3 lb/ft^3	94 5.9	153 9.5	247 15.4
Compressive strength perpendicular to the plane	ASTM C 365	N/mm^2 psi	6.3 917	12.9 1878	26.3 3813
Compressive modulus perpendicular to the plane	ASTM C 365	N/mm^2 psi	1993 289098	4005 580914	7982 1157714
Tensile strength perpendicular the plane	ASTM C 297	N/mm^2 psi	7.4 1073	13.2 1920	23.5 3413
Tensile modulus perpendicular the plane	ASTM C 297	N/mm^2 psi	2200 319131	3570 517774	5759 835277
Shear strength	ASTM C 273	N/mm^2 psi	1.8 262	3.0 433	4.9 712
Shear modulus	ASTM C 273	N/mm^2 psi	106 15364	160 23191	309 44786
Thermal conductivity at room temperature	ASTM C 177	W/m.K $BTU.in/ft^2.hr.°F$	0.048 0.331	0.066 0.456	0.084 0.581

BALTEK® SB Structural End-Grain Balsa, Alcan Composites, 2005

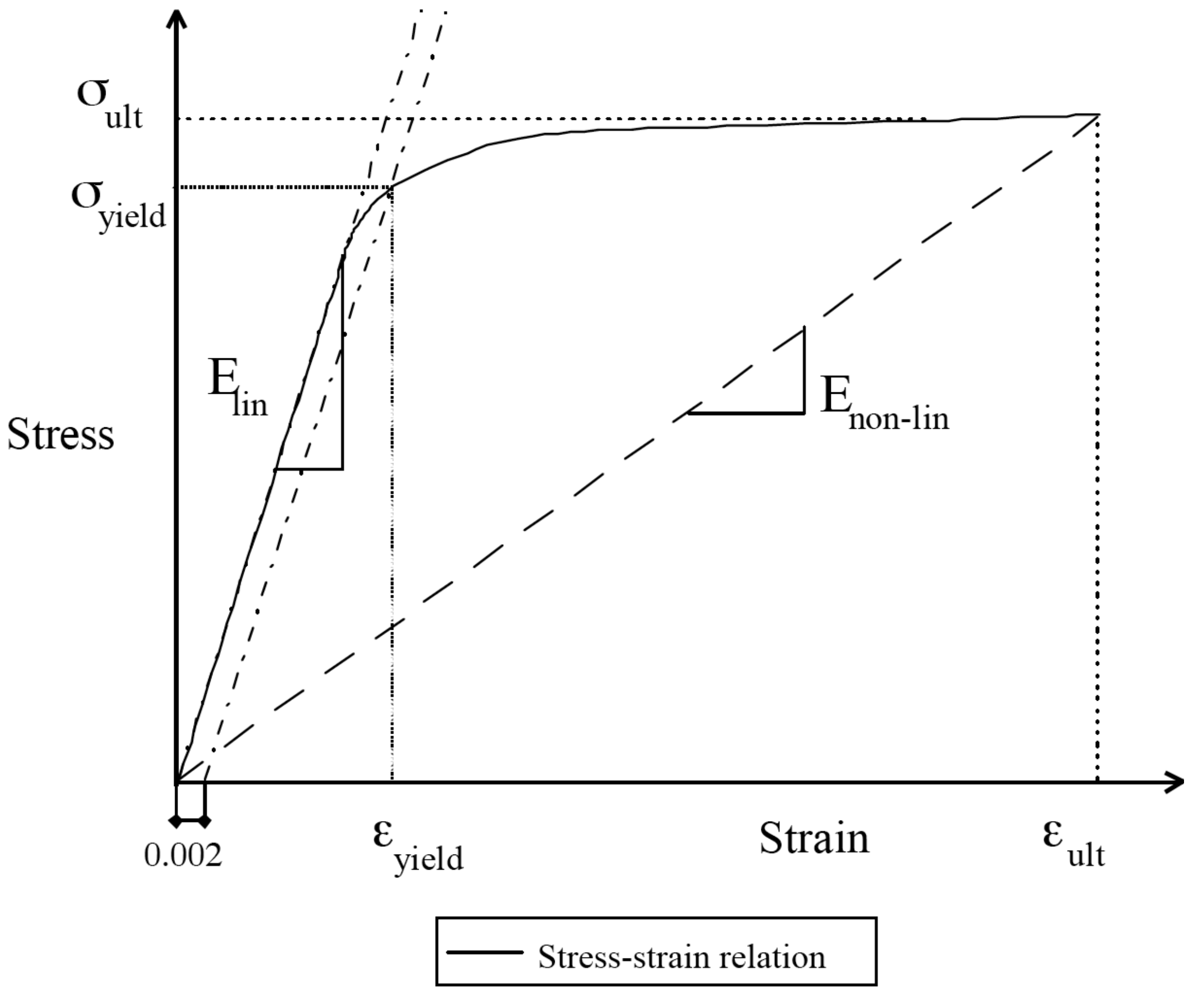
History of Foam Cores

The first foam material specifically formulated for a marine environment was a poly vinyl chloride (PVC) and isocyanate blend (simply called PVC foam) created in Germany by Dr. Lindemann in the late 1930's and 40's. It has been rumored that this early version of PVC foam was used in the German E-boats and even in the famous 'Bismarck' battleship. After World War II, France acquired the formula as part of its war reparations. From there, the formula was licensed out to companies in Sweden, Switzerland, and Germany, who kept developing the original recipe in their own distinct ways. After many years of different formula offshoots and company consolidations two main suppliers of PVC foam remain, DIAB and Airex/Herex.

Other foams based on chemical components other than PVC have also been developed over the years, including: linear PVC (also originally formulated by Dr. Lindemann), polystyrene (PS), styreneacrylonitrile (SAN), polyurethane (PUR), polyisocyanurate (PIR), polymethylmethacrylate (PMI), polyetherimide (PEI), and many others.

Core "Plastic" Behavior

Properties to be measured on a non-linear stress-strain curve for a plastic core materials

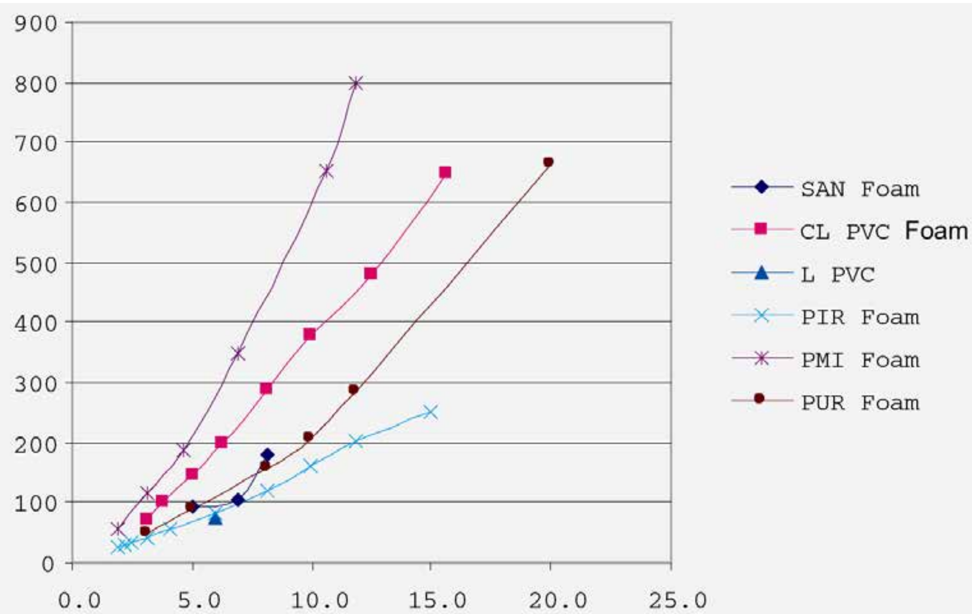


The offset strain to determine the yield point is defined here as 0.2% strain. Its recommended to calculate the modulus according to ISO 527 as the slope of the curve between 0.05% and 0.25% strain.

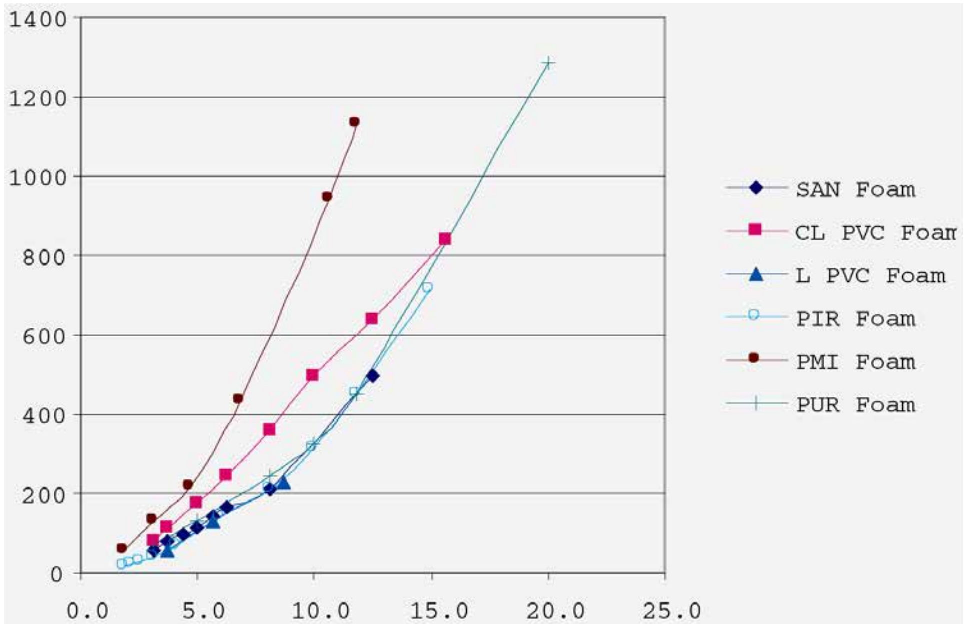
Det Norske Veritas, Project Recommended Standard for Composite Components, January 2002

Foam Core Mechanical Properties

Shear Strength (psi) at Yield vs. Density (lbs/ft³)



Compressive Strength (psi) at Yield vs. Density (lbs/ft³)



Divinycell H

Average Physical Properties

Property	Unit	H 45	H 60	H 80	H 100	H 130	H 200	H 250
Nominal Density [1)] ISO 845	lb/ft^3	3.0	3.8	5.0	6.3	8.1	12.5	15.6
Compressive Strength [2)] ASTM D 1621	psi	87 (72)	130 (102)	203 (167)	290 (239)	435 (348)	696 (609)	899 (783)
Compressive Modulus [2)] ASTM D 1621	psi	7,250 (6,525)	10,150 (8,700)	13,050 (11,600)	19,575 (16,675)	24,650 (21,025)	34,800 (29,000)	43,500 (34,809)
Tensile Strength [2)] ASTM D 1623	psi	203 (160)	261 (218)	363 (319)	508 (362)	696 (508)	1,030 (914)	1,334 (1,160)
Tensile Modulus [2)] ASTM D 1623	psi	7,975 (6,525)	10,875 (8,265)	13,775 (12,325)	18,850 (15,225)	25,375 (19,575)	36,250 (30,450)	46,400 (37,710)
Shear Strength ASTM C 273	psi	81 (67)	110 (91)	167 (138)	232 (203)	319 (276)	508 (464)	653 (566)
Shear Modulus ASTM C 273	psi	2,175 (1,740)	2,900 (2,320)	3,915 (3,335)	5,075 (4,060)	7,250 (5,800)	12,325 (10,875)	15,080 (12,763)
Shear Strain ASTM C 273	%	12 (8)	20 (10)	30 (15)	40 (25)	40 (30)	40 (30)	40 (30)

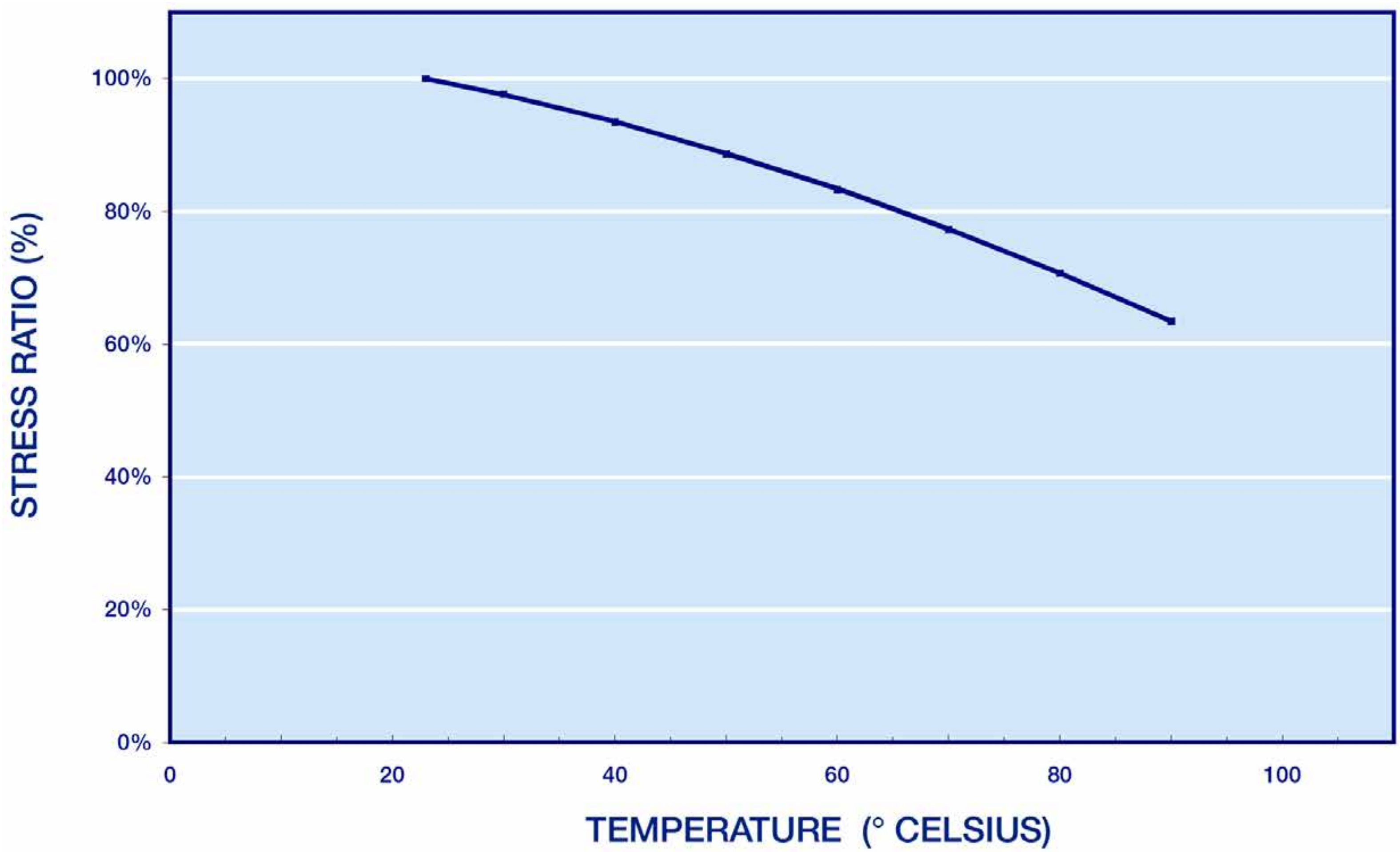
1) Typical density variation +/– 10%.

2) Perpendicular to the plane. All values measured at +73.4°F.

Divinycell H Technical Manual, DIAB, November, 2007.

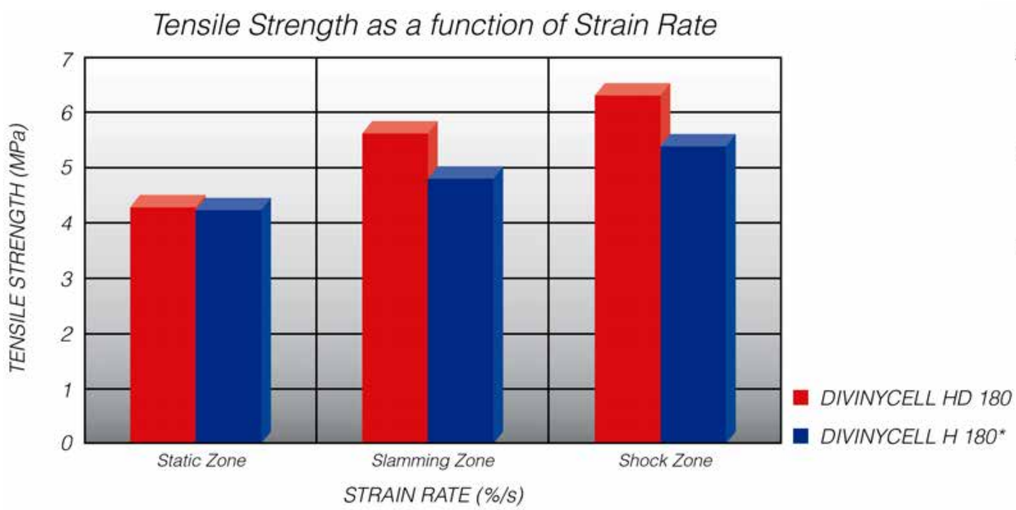
Divinycell H

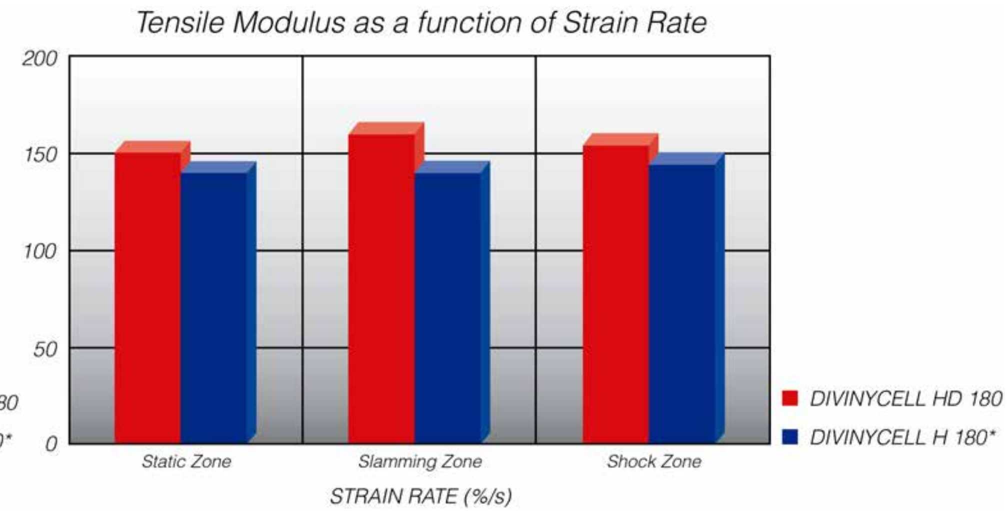
Shear performance of Divinycell H PVC foams as a function of temperature

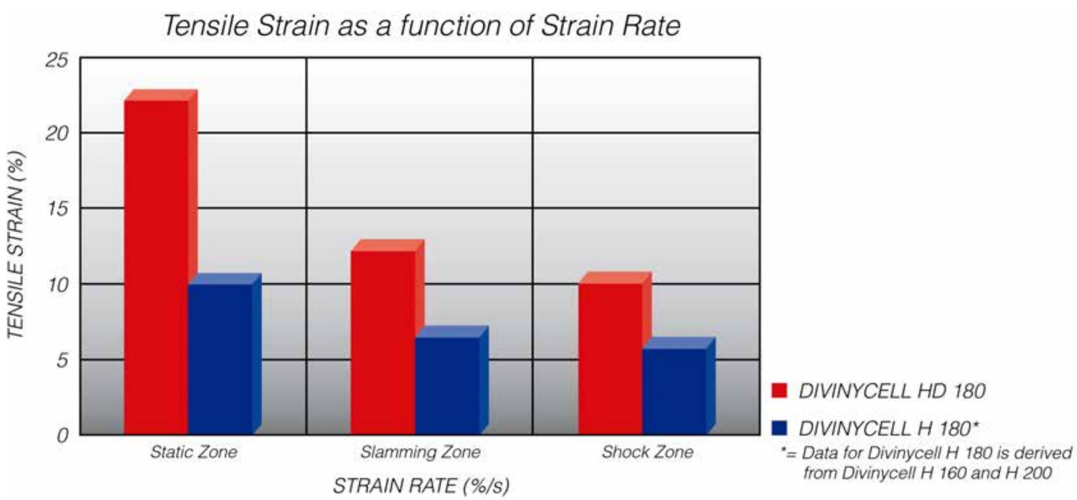


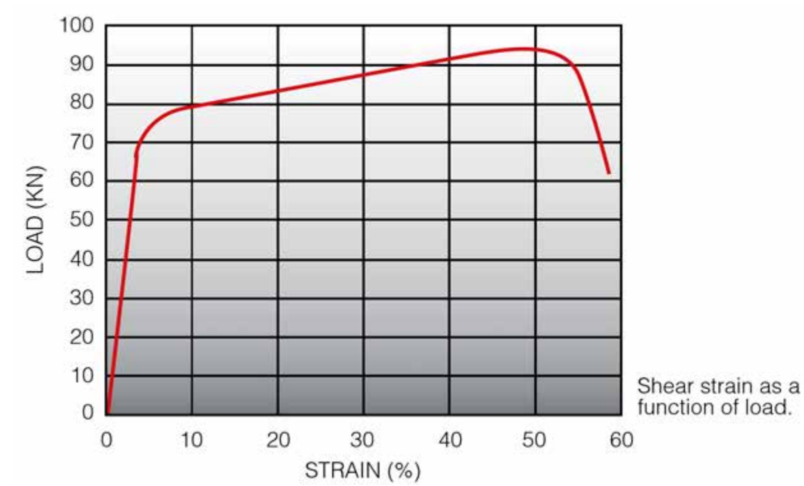
Divinycell H Technical Manual, DIAB, November, 2007.

Divinycell HD Grade





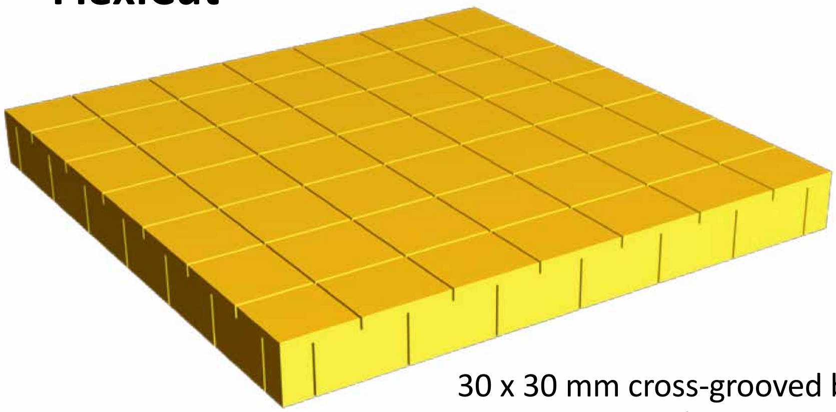




Divinycell HD Technical Manual, DIAB, March, 2004.

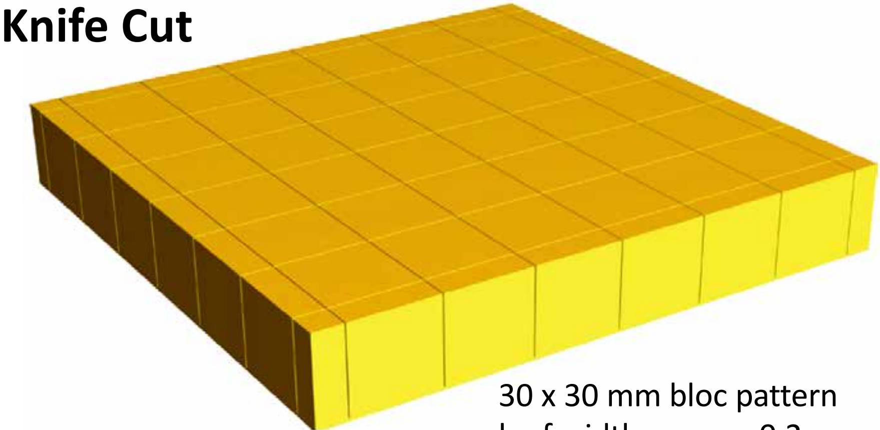
Core Finishing Options

FlexiCut



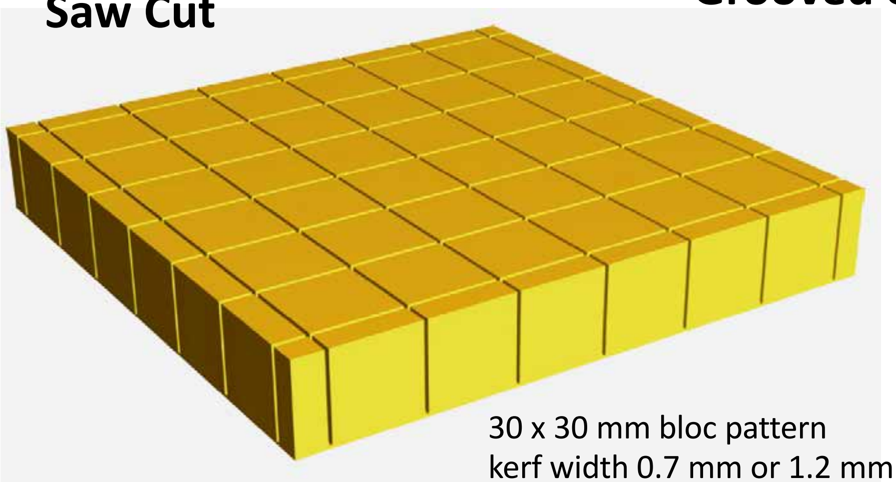
30 x 30 mm cross-grooved both sides
kerf depth 85% / 20% of thickness
kerf width 0.7 mm or 1.2 mm

Knife Cut



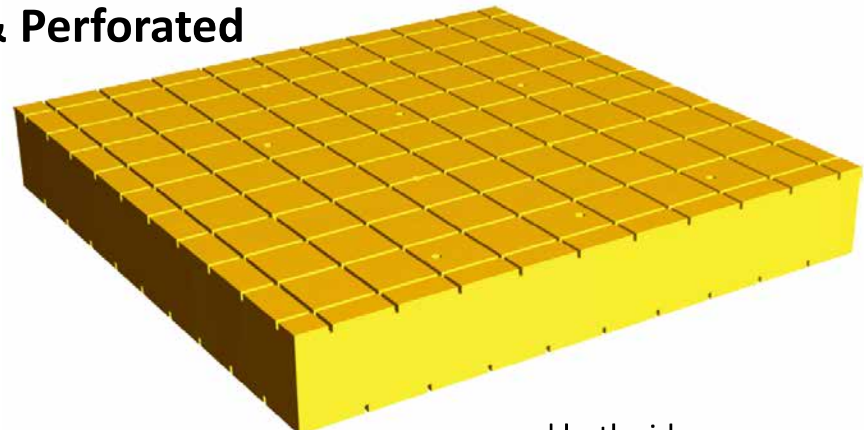
30 x 30 mm bloc pattern
kerf width approx. 0.2 mm
glass fiber cloth on bottom side of sheet
blocs are cut almost down to cloth

Saw Cut



30 x 30 mm bloc pattern
kerf width 0.7 mm or 1.2 mm
glass fiber cloth on bottom side of sheet
blocs are cut almost down to cloth

Grooved & Perforated



cross-grooved both sides
groove width 1.2 mm, depth approx. 2.5 mm
grooving distance 20 mm
grooving offset both sides 10 mm
perforated (drilled), hole diameter 3 mm
hole distance 45 mm (32 x 64 mm pattern)
holes may not be aligned with grooves

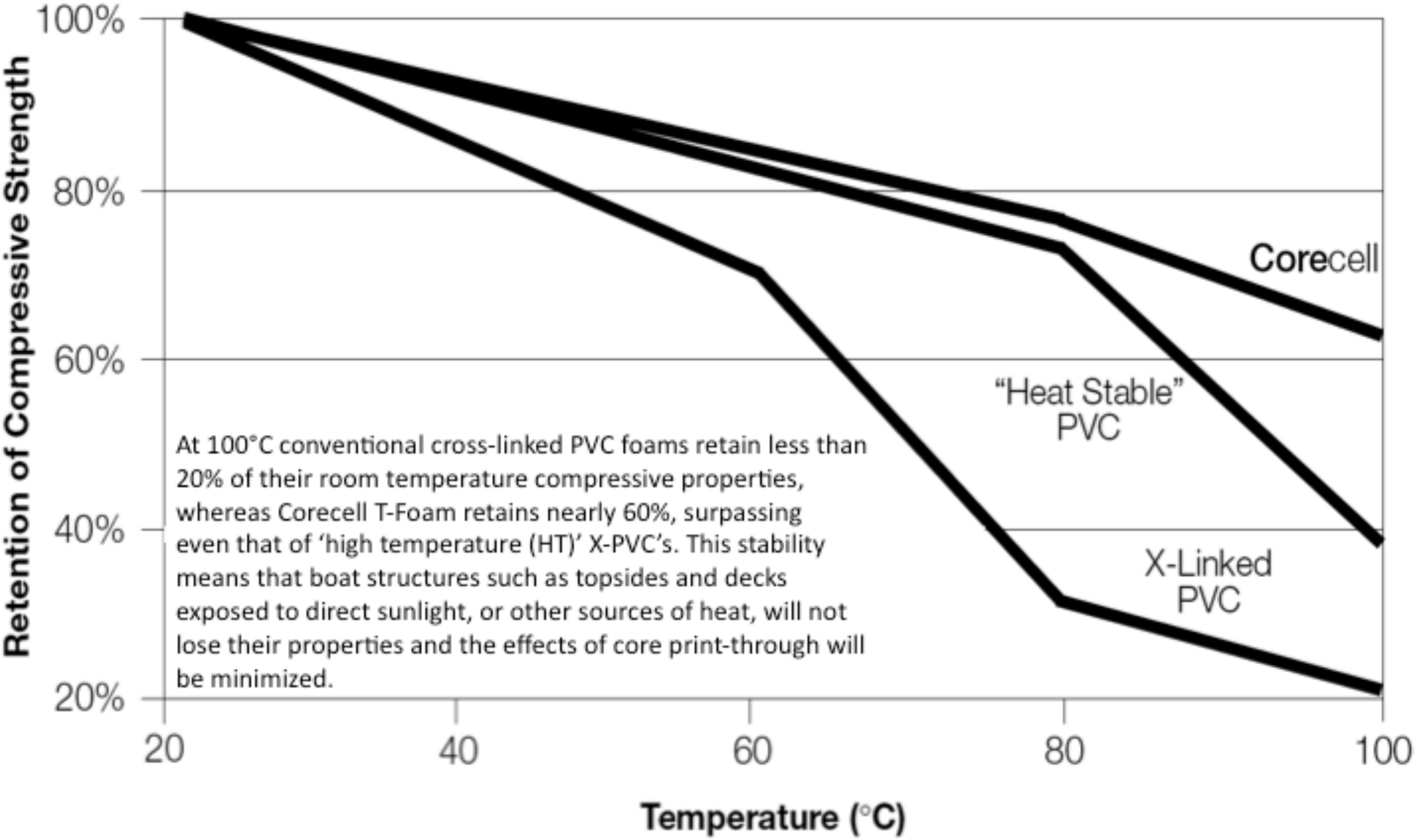
3A Composites, “Overview of Finishing Options,” Jan 2012

SAN Foam

Built-in Toughness – SAN is an inherently tough polymer. In the case of Corecell A-Foam, this creates ultra-tough and damage resistant foam. Other Corecell grades also benefit from this SAN characteristic, demonstrating robustness in handling and final service that exceeds other more rigid polymer foams. Whereas Corecell's toughness is inherent in its polymer backbone, more rigid foams can only be slightly toughened through the addition of plasticisers, which can leach out with time.

Corecell is manufactured in blocks of foam that are later sliced to the required thickness for use. The manufacturing process used for Corecell produces foam that is extremely consistent from one block to another. Since mechanical properties are proportional to density, this tight and consistent density range translates to tight and consistent mechanical properties as well as weight from one block to another. For example, the stated density range of X-PVC from block to block is -10 to +15%. For balsa it is typically ±18-20%. For Corecell it is ±5-7%

SAN Foam at Elevated Temperature



At 100°C conventional cross-linked PVC foams retain less than 20% of their room temperature compressive properties, whereas Corecell T-Foam retains nearly 60%, surpassing even that of 'high temperature (HT)' X-PVC's. This stability means that boat structures such as topsides and decks exposed to direct sunlight, or other sources of heat, will not lose their properties and the effects of core print-through will be minimized.

SAN Foam Properties

Impact Resistance

Single Skin Fiberglass

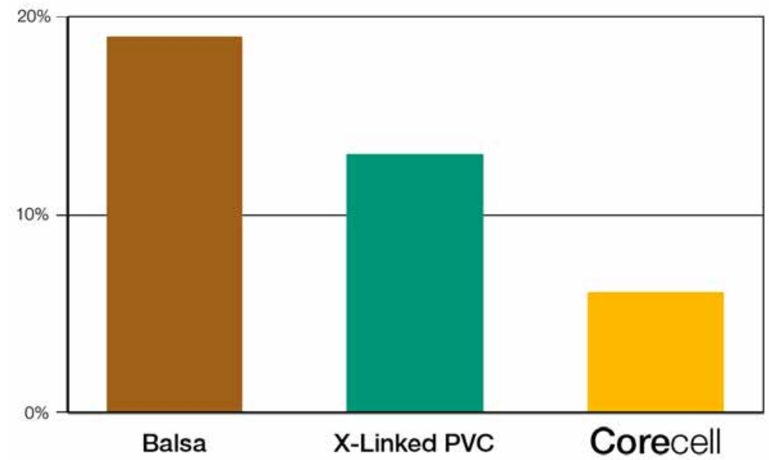
Cross Linked PVC Foam

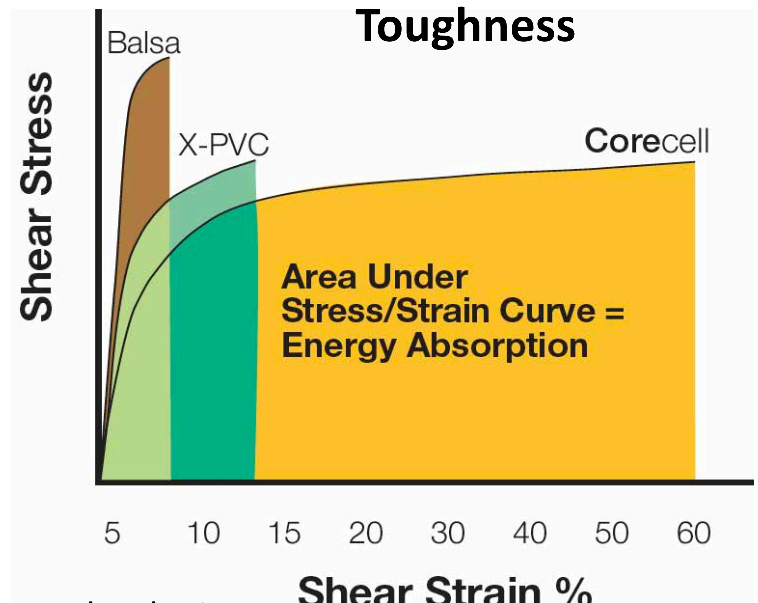
Balsa

SAN Foam

Corecell A-Foam
For hulls and other dynamically loaded structures
Corecell P-Foam
Heat-stabilized A-Foam for prepreg processing
Corecell T-Foam
For superstructures, decks and interiors
Corecell S-Foam
Specialist core for sub sea applications

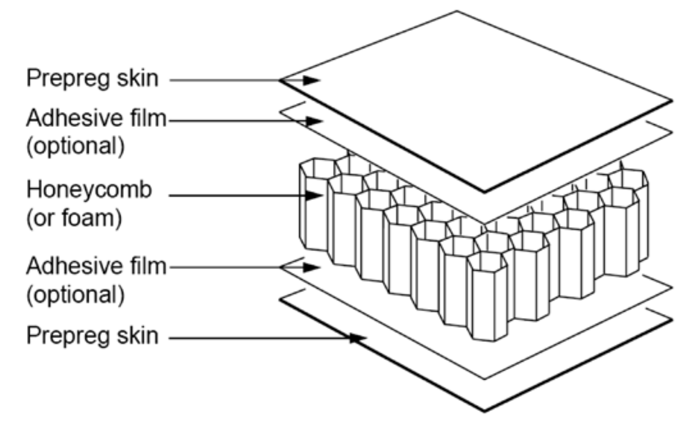
Density Variation

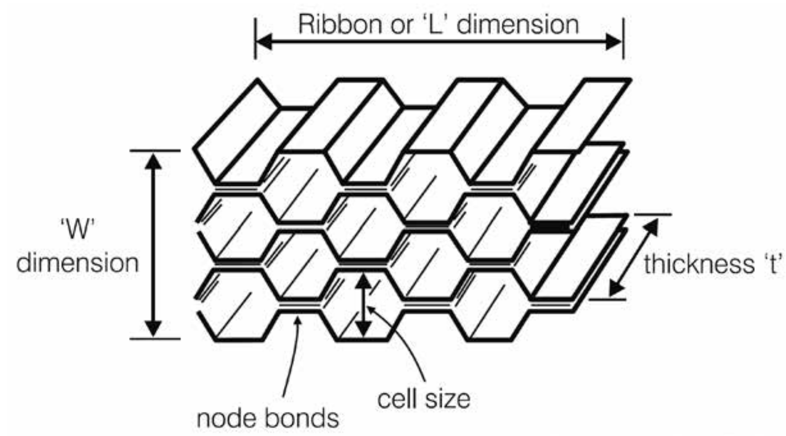




Corecell brochure from Gurit Composite Technologies

Honeycomb Construction & Orthotropic Shear Properties

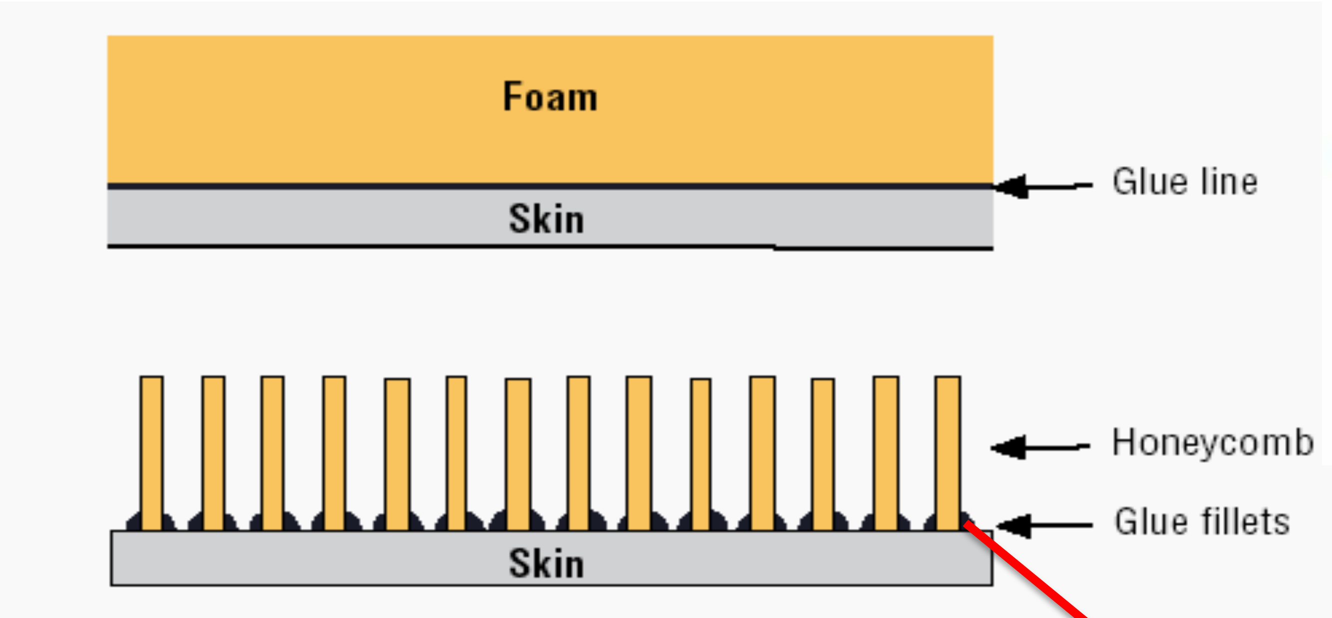




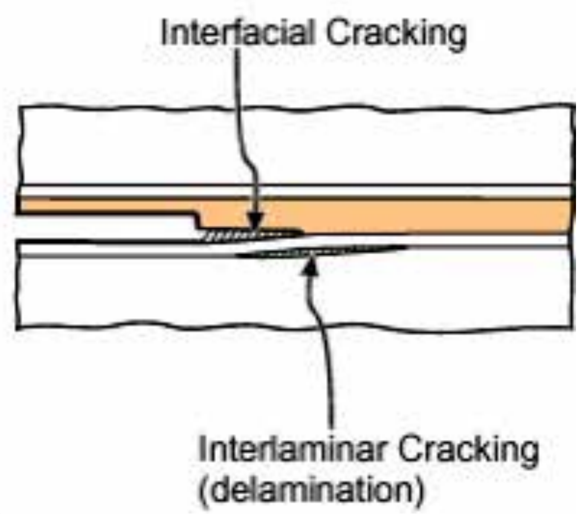
PRODUCT CONSTRUCTION		COMPRESSION		PLATE SHEAR			
Density	Cell Size*	Stabilized		L Direction		W Direction	
kg/m³ (lb/ft³)	mm (in)	Strength MPa	Modulus MPa	Strength MPa	Modulus MPa	Strength MPa	Modulus MPa
HRH10 Nomex (Aramid)							
29 (1.8)	3 (1/8)	0.9	60	0.5	25	0.35	17.0
32 (2.0)	5 (3/16)	1.2	75	0.7	29	0.4	19.0
32 (2.0)	13 (1/2)	1.0	75	0.75	30	0.35	19.0
48 (3.0)	3 (1/8)	2.4	138	1.25	40	0.73	25.0
48 (3.0)	5 (3/16)	2.4	140	1.2	40	0.7	25.0
64 (4.0)	3 (1/8)	3.9	190	2.0	63	1.0	35.0
64 (4.0)	6 (1/4)	5.0	190	1.55	55	0.86	33.0
80 (5.0)	3 (1/8)	5.3	250	2.25	72	1.2	40.0
96 (6.0)	3 (1/8)	7.7	400	2.6	85	1.5	50.0
123 (7.9)	3 (1/8)	11.5	500	3.0	100	1.9	60.0
144 (9.0)	3 (1/8)	15.0	600	3.5	115	1.9	69.0
29 (1.8)	5 OX (3/16)	1.0	50	0.4	14	0.4	21.0
48 (3.0)	5 OX (3/16)	2.9	120	0.8	20	0.85	35.0

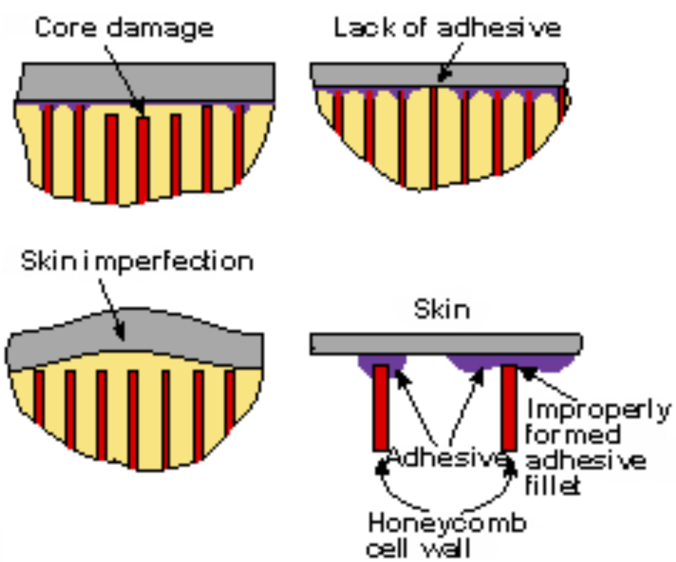
from HexWeb™ Honeycomb Sandwich Design Technology

Bondline Comparison

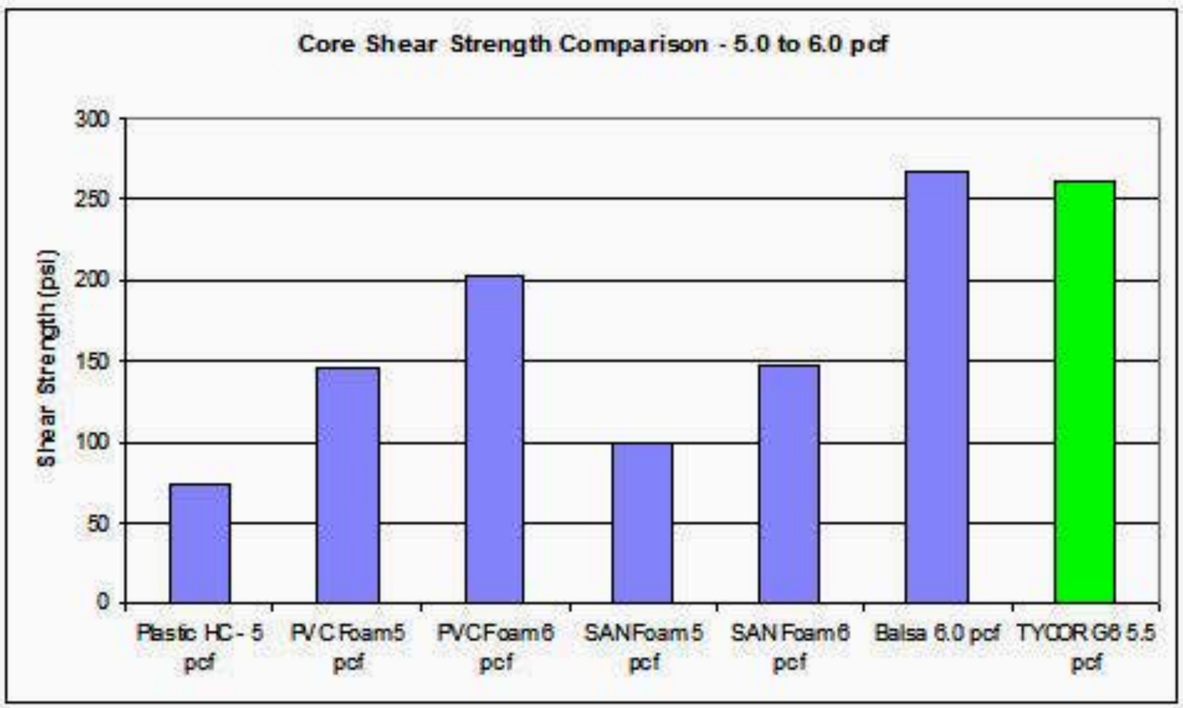


Core/Laminate Bond for Foams and Honeycombs

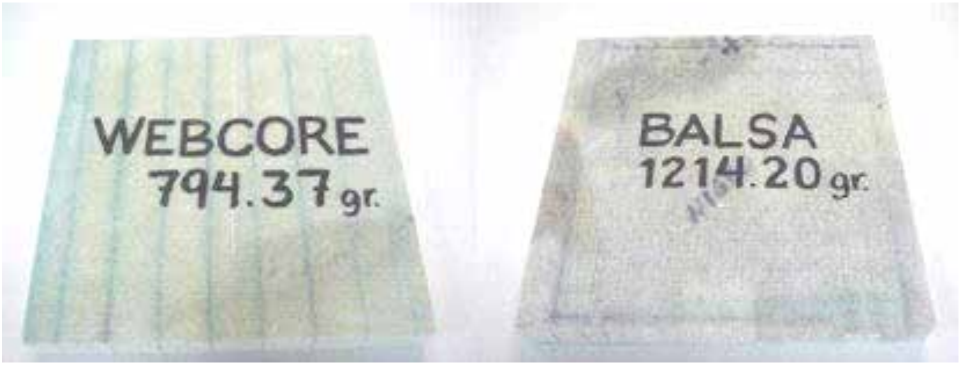


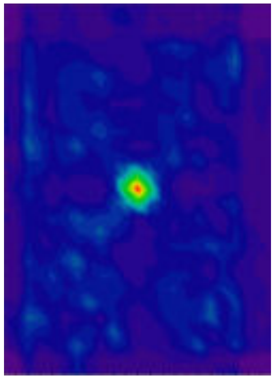


Foam Core with Shear Ties



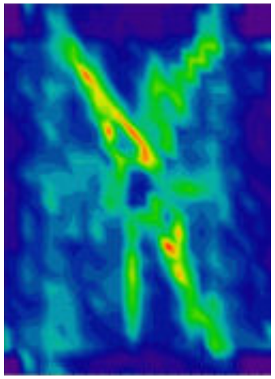
TYCOR from is based on a patented fiber reinforcing technology that places glass fiber reinforcements through the thickness of closed cell foam sheets to produce a web and truss structure. [Webcore Technologies]





TYCOR Panel
1344 ft-lb impact
No delamination,
localized damage

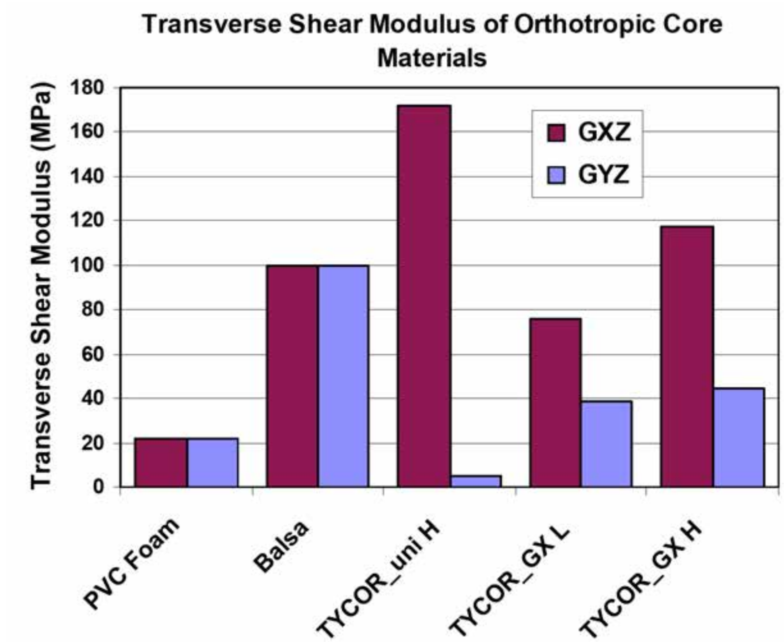
PVC Foam Core Panel
1344 ft-lb impact
Extensive delamination



Foam Core with Shear Ties

TYCOR® Fiber Reinforced Core (FRC) Unidirectional FRC (left), Bi-directional (right)

Foam removed to display webs

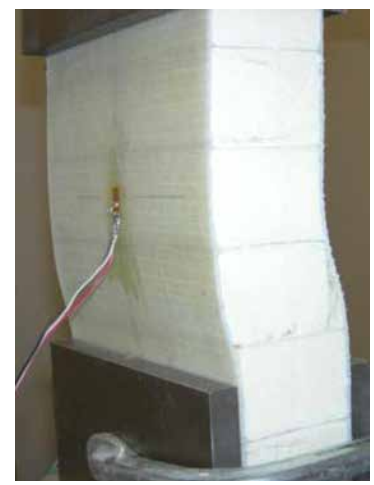


ASTM C 364/C Edgewise Compression Failure Modes

Face Compression

Local Face Buckling

Face Buckling/Debond from Core



Core Shear Instability

Fred Stoll, Scott Cambell and Rob Banerjee, WebCore Technologies, May, 2008

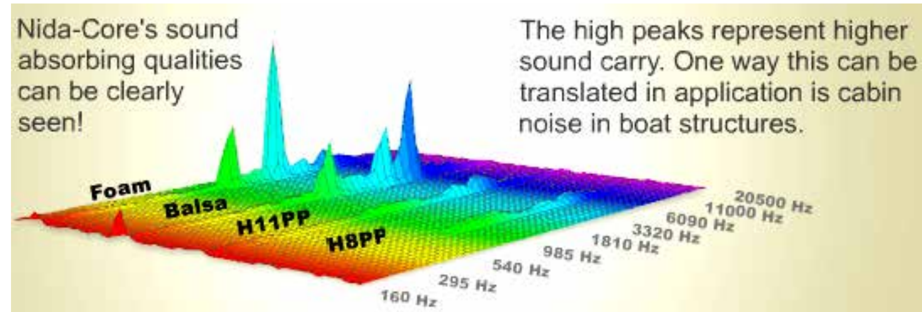
eric greene associates

Thermoplastic Honeycomb

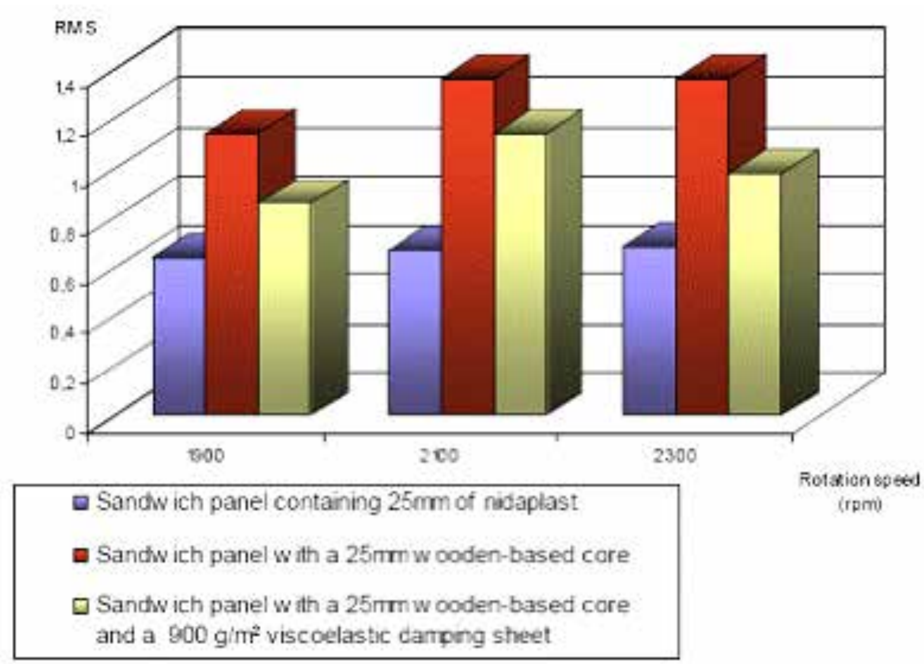
Mechanical Properties of 3M Nida Core Structural Honeycomb Core

Parameter	H8PP	H8HP	H11PP-45	H11-60 PP
Compressive Strength, psi	188	348	58	175
Compressive Modulus, psi	2175	7250	1305	1820
Tensile Strength, psi	72.5	87	44	37
Shear Strength, psi	72.5	87	44	78
Shear Modulus, psi	725	1305	435	580
Density, lbs/ft^3	5.0	6.9	2.8	3.7

Sound Transmission



Bulkhead Vibration Levels



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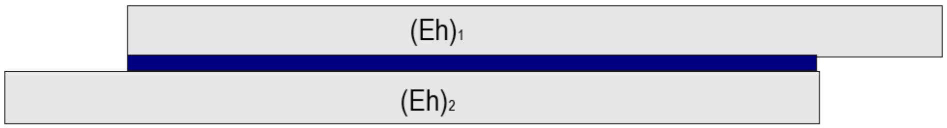
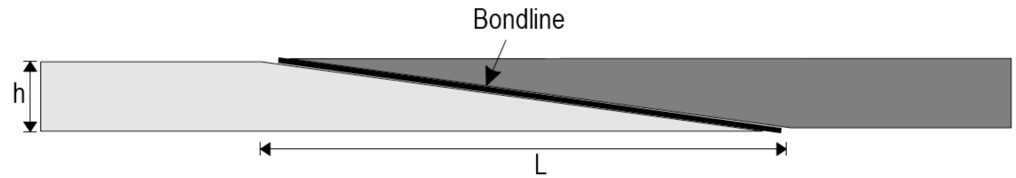
Bonded Joints

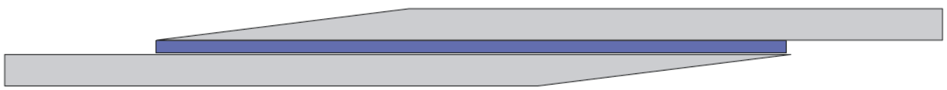
Lap Joint



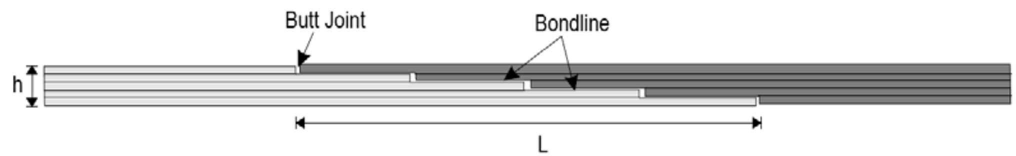
Scarf Joint



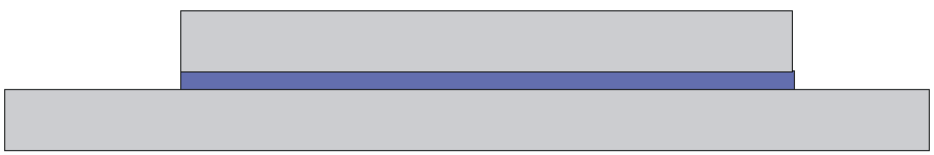
Tapered Lap Joint



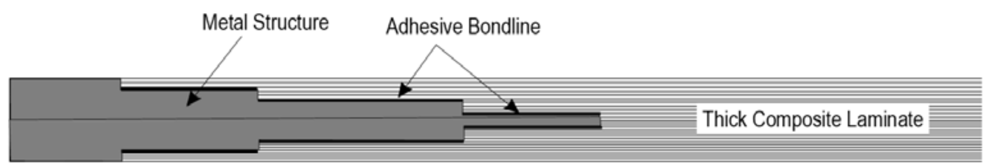
Scarf Joint Constructed by Stepping Back Individual Plies



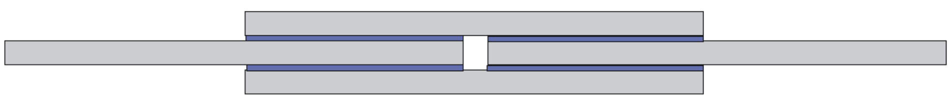
Doubler (or Strap) Joint



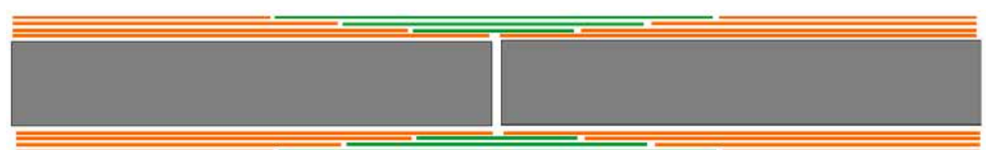
Stepped-Lap Joint for Thick Composite-to-Metal Joint



Double Strap Joint



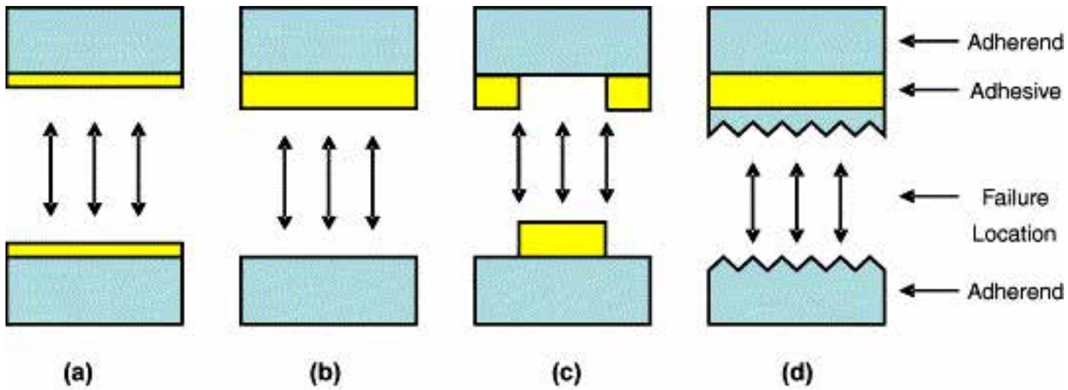
Scarf Joint in Sandwich Structure



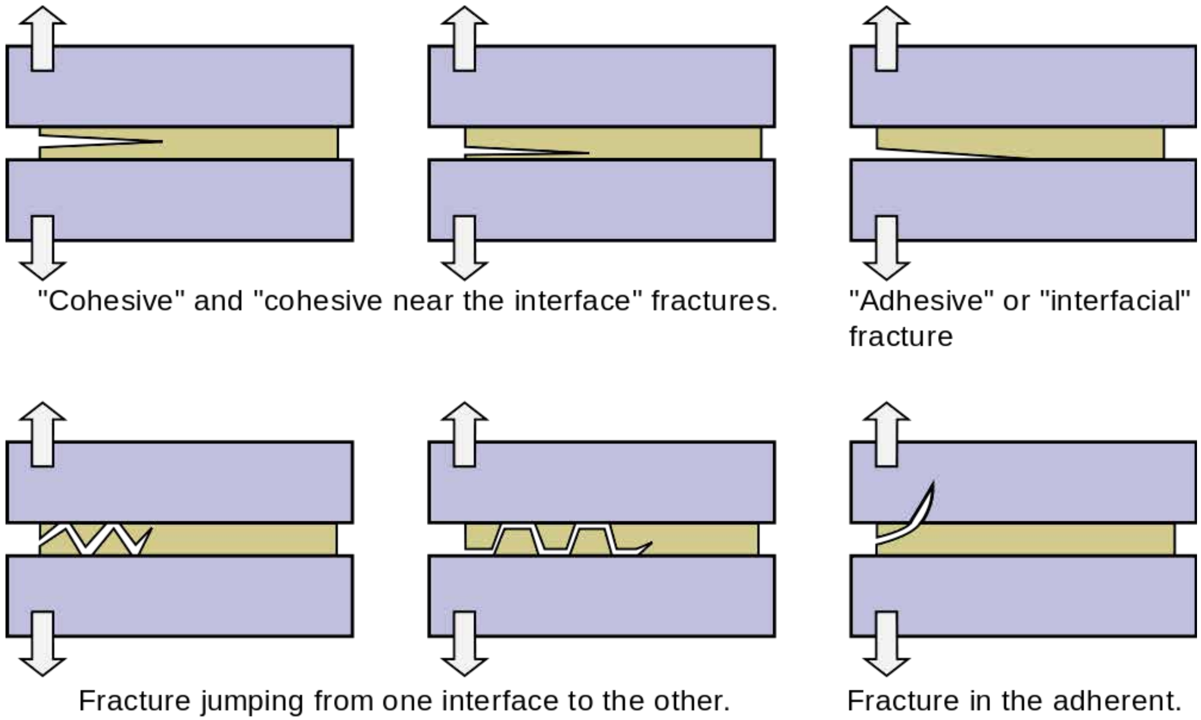
Bonded Joint Guidelines

- Bonding works best for thin structures. The length of single overlap joints should be 100 times the adherend thickness.
- Thick bonded structures need complex stepped lap joints to develop adequate efficiency.
- Proper surface preparation is critical.
- Adhesive may become brittle in cold environments.
- Some of the adhesive must be lightly stressed to resist creep and improve durability
- Taper ends of bonded overlaps down to 0.020” with a 1-in-10 slope, to minimize induced peel stresses.
- Adhesives work best in shear and are poor in peel. Design joints to minimize out-of-plane stresses.
- Balanced adherend stiffnesses improve joint strength.
- For simple, uniformly thick bonded splices: use 30t overlap in double shear, 80t overlap for single-lap joints, 1-in-50 slope for scarf joints.
- Minimize bond line thickness
- It is often desirable to use mechanical fasteners to pull adherend together and hold them in place while the adhesive cures

Adhesive Bond Failure Modes

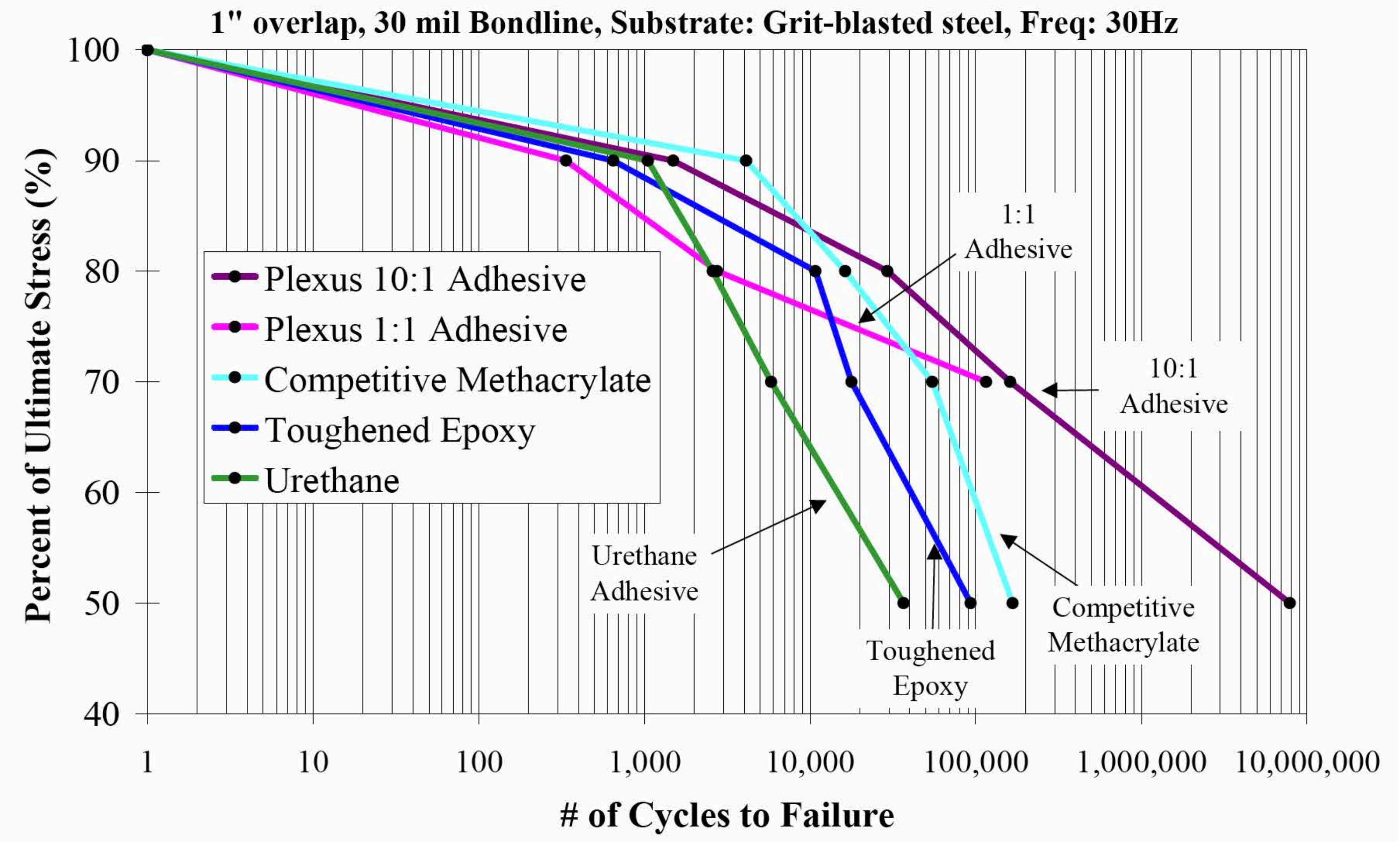


Schematic diagram for the failure mode definition of an adhesive bonded joint: (a) cohesive failure, (b) adhesive failure, (c) mixed failure and (d) adherend failure.



Adhesive Fatigue

S/N Fatigue Curves for Various Adhesives



Adhesives Classification Society Guidance

- Adhesives for structural applications are to be used in accordance with the manufacturer's recommendations.
- The details of all structural adhesives are to be specified on the Material Data Sheet and on the construction plans submitted.
- Details concerning the handling, mixing and application of adhesives are to form part of the Builders Process Instruction. Particular attention is to be given to the surface preparation and cleanliness of the surfaces to be bonded.
- Where excessive unevenness of the faying surfaces exists, a suitable gap-filling adhesive is to be used or local undulations removed by the application of additional reinforcements.
- The Builder Process Description is to identify the level of training required for personnel involved in the application of structural adhesives.

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Specific Adhesives Guidance

- The minimum shear strength of the adhesive is to be between 6.9 N/mm^2 and 10 N/mm^2. This shear strength is to be achieved in temperatures ranging from ambient to 49°C. All failures of test samples are to be either cohesive or fiber tear.
- The adhesive is to be tested in fatigue at 50% of the ultimate tensile strength and is to last for a minimum of one million cycles at 30 Hz.
- The process for the application of the adhesive is to be submitted for review and is to include the maximum bondline thickness, nondestructive testing methods and maximum creep.
- The elastic modulus of the adhesive is to be considerably less than that of the FRP skin to which it is being adhered
- The strain of failure ratio of the adhesive is to be much larger than the surrounding structure.
- The mechanical properties of the adhesive are achieved rapidly, such that the use of screws or bolts will not be necessary to hold the substrates together while the adhesive cures.
- The adhesive is to be compatible with the lamination resin.

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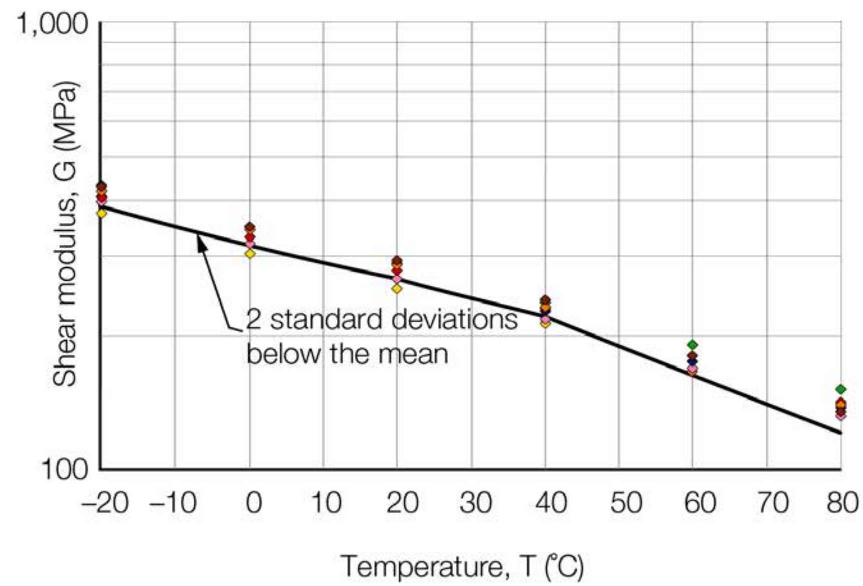
Elastomer Properties

Required Adhesive Mechanical Properties based on Polyurethane Technology

Test	Standard	Criteria
Density	ISO 845	≥ 1000 kg/m^3 at RT
Hardness	DIN 53505	Shore D≥65 at RT
Shear modulus	Torsion pendulum test –20°C to +80°C DIN EN ISO 6721-2	G≥312-2.4T (°C)
Tensile stress	ISO 527 or ASTM D412	≥20MPa at RT ≥5MPa at +80°C
Elongation	ISO 527 or ASTM D412	Min. 10% at –20°C Min. 20% at RT
Bond shear strength	ASTM D429-81	≥2.7MPa (shot blasted) ≥4MPa (grit blasted)
RT = Room temperature in °C		



LLOYD'S REGISTER, PROVISIONAL RULES FOR THE APPLICATION OF SANDWICH PANEL CONSTRUCTION TO SHIP STRUCTURE, April 2006, Material Manufacture and Construction Procedures

Adhesive Best Practices

- Abrade or energize the surfaces to be bonded
  - Raise surface energy without damaging fibers in the laminate (ScotchBrite or sandpaper abrasion)
- Clean surfaces free from dust or debris
- Use appropriate adhesive for the application
- Goal is to apply slightly more adhesive than required and close the joint in a timely fashion
- Provide uniform bondline thickness
- Provide constant clamping pressure along bondline
  - Typical bonding pressures range from 5-50psi
  - Vacuum bagging can provide uniform pressure (avoid frothing)
- Cure adhesive to achieve structural properties
  - Room temperature curing systems usually take several days to achieve good structural properties
  - High performance adhesives usually require an elevated temperature cure