ENVIRONMENTAL EFFECTS

HYGROTHERMAL STRAINS AND STRESSES

$$\epsilon_{xx} = \epsilon_{xx}^{M} + \epsilon_{xx}^{T} + \epsilon_{xx}^{H}$$

$$\epsilon_{yy} = \epsilon_{yy}^{M} + \epsilon_{yy}^{T} + \epsilon_{yy}^{H}$$

$$\epsilon_{xy} = \epsilon_{xy}^{M} + \epsilon_{xy}^{T} + \epsilon_{xy}^{H}$$

$\epsilon^{T} = \alpha \Delta T$ (coeff of expansion)

$\epsilon^{H} = \beta \Delta H$

M, T, and H denote the mechanical, thermal, and hygroscopic strains respectively.

Moisture may cause swelling or contraction by moisture absorption or desorption.

Residual stresses may develop due to a mismatch of thermal expansion of the laminae during cure and cause intralaminar cracks. [2]

FREE THERMAL EFFECTS

- Require that $N = M = 0$ no mechanical external loading
  - Therefore

temperature

$$\begin{pmatrix} 0 \\ 0 \end{pmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \begin{pmatrix} \epsilon^o \\ k \end{pmatrix} + \begin{pmatrix} N^T \\ M^T \end{pmatrix}$$

[5]

- Inversion yields the free thermal strain and curvatures vectors for the laminate

$$-\begin{bmatrix} A & B \\ B & D \end{bmatrix}^{-1} \begin{pmatrix} N^T \\ M^T \end{pmatrix} = \begin{pmatrix} \epsilon^o \\ k \end{pmatrix}$$

- The strain in any ply may be written as

$$(\epsilon_x)^i = (\epsilon^o) + z^i(k)$$

- Stresses in the laminate coordinates are written as

$$(\sigma_x)^i = [\overline{Q}^i](\epsilon_x)^i - (\Gamma_x)^i \Delta T^i$$

  - Transforming to the principal material coordinates

$$(\sigma_l)^i = [\theta^i]^{-1}(\sigma_x)^i$$

- Transforming the strains

$$(\epsilon_l)^i = [\theta^i]^{-1}(\epsilon_x)^i$$

[5]

For Uniform Temperature Fields and Symmetric Laminates

- $[B] = (M^T) = 0$

$$(\epsilon^o) = (\alpha_x)\Delta T$$

$$(k) = 0$$

- Strains in the laminate coordinates are identical in each ply

$$(\epsilon_x)^i = (\epsilon^o) = (\alpha_x)\Delta T$$

$$(\sigma_x)^i = [\overline{Q}^i]((\alpha) - (\alpha_x)^i)\Delta T$$

The stresses induced by the free thermal expansion of a laminate are related to the differences between the laminate and the ply thermal expansion vectors.

[5]

For Laminates Displaying Isotropic Thermal Expansion

- When subjected to a uniform temperature change, the stresses in the principal material coordinates are identical in every ply.

$$(\epsilon_l) = \frac{E_{11}(\alpha_{22} - \alpha_{11})\Delta T}{1 - 2\nu_{12} + \frac{E_{11}}{E_{22}}} \begin{pmatrix} 1 \\ -1 \\ 0 \end{pmatrix}$$

Where the transverse direction stress is equal and opposite to the fiber direction stress.

- The previous discussion is also applicable to moisture swelling.

[5]

DISPLACEMENT FIELD

$$u(y,z) = \sum_{i=1}^{8} N_i U_i \qquad v(y,z) = \sum_{i=1}^{8} N_i V_i \qquad w(y,z) = \sum_{i=1}^{8} N_i W_i$$

The field is altered in the following manner to incorporate loading terms into the planar element

$$U(x,y,z) = \epsilon_0 x + kxz + u(y,z)$$

$$V(x,y,z) = Cxz + v(y,z)$$

$$W(x,y,z) = -\frac{1}{2}kx^2 - Cxy + w(y,z)$$

Where ϵ_0 is the uniform extension, k is the longitudinal curvature, and C is one-half the twisting curvature.

[23]

$$K_x = - \frac{\delta^2 W}{\delta x^2} = k$$

$$K_y = - \frac{\delta^2 W}{\delta y^2}$$

$$K_{xy} = -2 \frac{\delta^2 W}{\delta x \delta y} = 2C$$

[23]

STRAIN FIELD

$$(\epsilon) = (\epsilon)_0 + (\epsilon)_L$$

Where $(\epsilon)_0$ is the conventional strain vector and $(\epsilon)_L$ is

$$(\epsilon)_L = \begin{pmatrix} kz + \epsilon_0 \\ 0 \\ 0 \\ 0 \\ -Cy \\ Cz \end{pmatrix}$$

[23]

EXPANSIONAL STRAINS IN A LAMINATE (MOISTURE, TEMPERATURE)

$$\begin{bmatrix} \sigma_x^k \\ \sigma_y^k \\ \tau_{xy}^k \end{bmatrix} = \begin{bmatrix} Q_{11}^k & Q_{12}^k & Q_{16}^k \\ Q_{12}^k & Q_{22}^k & Q_{26}^k \\ Q_{16}^k & Q_{26}^k & Q_{66}^k \end{bmatrix} \begin{bmatrix} \epsilon_x^o \\ \epsilon_y^o \\ \gamma_{xy}^o \end{bmatrix}$$

$$+ z \begin{bmatrix} Q_{11}^k & Q_{12}^k & Q_{16}^k \\ Q_{12}^k & Q_{12}^k & Q_{26}^k \\ Q_{16}^k & Q_{26}^k & Q_{66}^k \end{bmatrix} \begin{bmatrix} K_x \\ K_y \\ K_{xy} \end{bmatrix} - \begin{bmatrix} Q_{11}^k & Q_{12}^k & Q_{16}^k \\ Q_{12}^k & Q_{22}^k & Q_{26}^k \\ Q_{16}^k & Q_{26}^k & Q_{66}^k \end{bmatrix} \begin{bmatrix} \epsilon_1^{E^k} \\ \epsilon_2^{E^k} \\ \epsilon_6^{E^k} \end{bmatrix}$$

[3]

THERMAL FORCE RESULTANTS

$$N_x^E = \int_{-h/2}^{h/2} (\epsilon_1^{E^k} Q_{11}^k + \epsilon_2^{E^k} Q_{12}^k + \epsilon_6^{E^k} Q_{16}^k)\, dz$$

$$N_y^E = \int_{-h/2}^{h/2} (\epsilon_1^{E^k} Q_{12}^k + \epsilon_2^{E^k} Q_{22}^k + \epsilon_6^{E^k} Q_{26}^k)\, dz$$

$$N_{xy}^E = \int_{-h/2}^{h/2} (\epsilon_1^{E^k} Q_{16}^k + \epsilon_2^{E^k} Q_{26}^k + \epsilon_6^{E^k} Q_{66}^k)\, dz$$

THERMAL MOMENT RESULTANTS

$$M_x^E = \int_{-h/2}^{h/2} (\epsilon_1^{E^k} Q_{11}^k + \epsilon_2^{E^k} Q_{12}^k + \epsilon_6^{E^k} Q_{16}^k)\, z\, dz$$

$$M_y^E = \int_{-h/2}^{h/2} (\epsilon_1^{E^k} Q_{12}^k + \epsilon_2^{E^k} Q_{22}^k + \epsilon_6^{E^k} Q_{26}^k)\, z\, dz$$

$$M_{xy}^E = \int_{-h/2}^{h/2} (\epsilon_1^{E^k} Q_{16}^k + \epsilon_2^{E^k} Q_{26}^k + \epsilon_6^{E^k} Q_{66}^k)\, z\, dz$$

[3]

FOR FREE EXPANSION

$$N_x = N_y = N_{xy} = 0$$

$$\begin{bmatrix} \epsilon_x^0 \\ \epsilon_y^0 \\ \gamma_{xy}^0 \end{bmatrix} = \begin{bmatrix} A_{22}/D & -A_{12}/D & 0 \\ -A_{12}/D & A_{22}/D & 0 \\ 0 & 0 & 1/A_{66} \end{bmatrix} \begin{bmatrix} N_x^E \\ N_y^E \\ 0 \end{bmatrix}$$

WHERE $D = A_{11}A_{22} - A_{12}^2$

STRAINS ARE EFFECTIVE EXPANSIONAL STRAINS

$$\epsilon_x^0 = \bar{\epsilon}_x^E, \quad \epsilon_y^0 = \bar{\epsilon}_y^E$$

[3]

RESIDUAL STRESSES

FOR BALANCED SYMMETRIC LAMINATES

$$\epsilon_x^0 = \alpha_x \Delta T \, , \; \epsilon_y^0 = \alpha_y \Delta T$$

$$\gamma_{xy}^0 = K_x = K_y = K_{xy} = 0$$

PLY EXPANSIONAL STRAINS

$$\epsilon_1^{E^k} = \alpha_1^k \Delta T \, , \; \epsilon_2^{E^k} = \alpha_2^k \Delta T \, , \; \epsilon_6^{E^k} = \alpha_6^k \Delta T$$

[3]

LAMINATE EXPANSIONAL STRAINS (SYMMETRIC, BALANCED LAMINATES)

$$\epsilon_x^E = \frac{A_{22}N_x^E - A_{12}N_y^E}{A_{11}A_{22} - A_{12}^2} \quad , \quad \bar{\epsilon}_y^E = \frac{A_{11}N_x^E - A_{12}N_y^E}{A_{11}A_{22} - A_{12}^2}$$

THERMAL EXPANSION

$$\bar{\epsilon}_x^E = \alpha_x \, \Delta T \; , \quad \bar{\epsilon}_y^E = \alpha_y \, \Delta T$$

$$\alpha_y = \frac{A_{11}N_x^T - A_{12}N_y^T}{(A_{11}A_{22} - A_{12}^2)\;\Delta T} \quad , \quad \alpha_x = \frac{A_{22}N_x^T - A_{12}N_y^T}{(A_{11}A_{22} - A_{12}^2)\;\Delta T}$$

[3]

FOR SYMMETRIC, BALANCED LAMINATES

$$M_x^E = M_y^E = M_{xy}^E = 0 \quad \text{FOR} \quad \epsilon^E \neq f(z)$$

$$\epsilon_6^E(-\theta) = -\epsilon_6^E(\theta) \; ; \quad N_{xy}^E = 0$$

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & 0 \\ A_{12} & A_{22} & 0 \\ 0 & 0 & A_{66} \end{bmatrix} \begin{bmatrix} \epsilon_x^0 \\ \epsilon_y^0 \\ \gamma_{xy}^0 \end{bmatrix} - \begin{bmatrix} N_x^E \\ N_y^E \\ 0 \end{bmatrix}$$

[3]

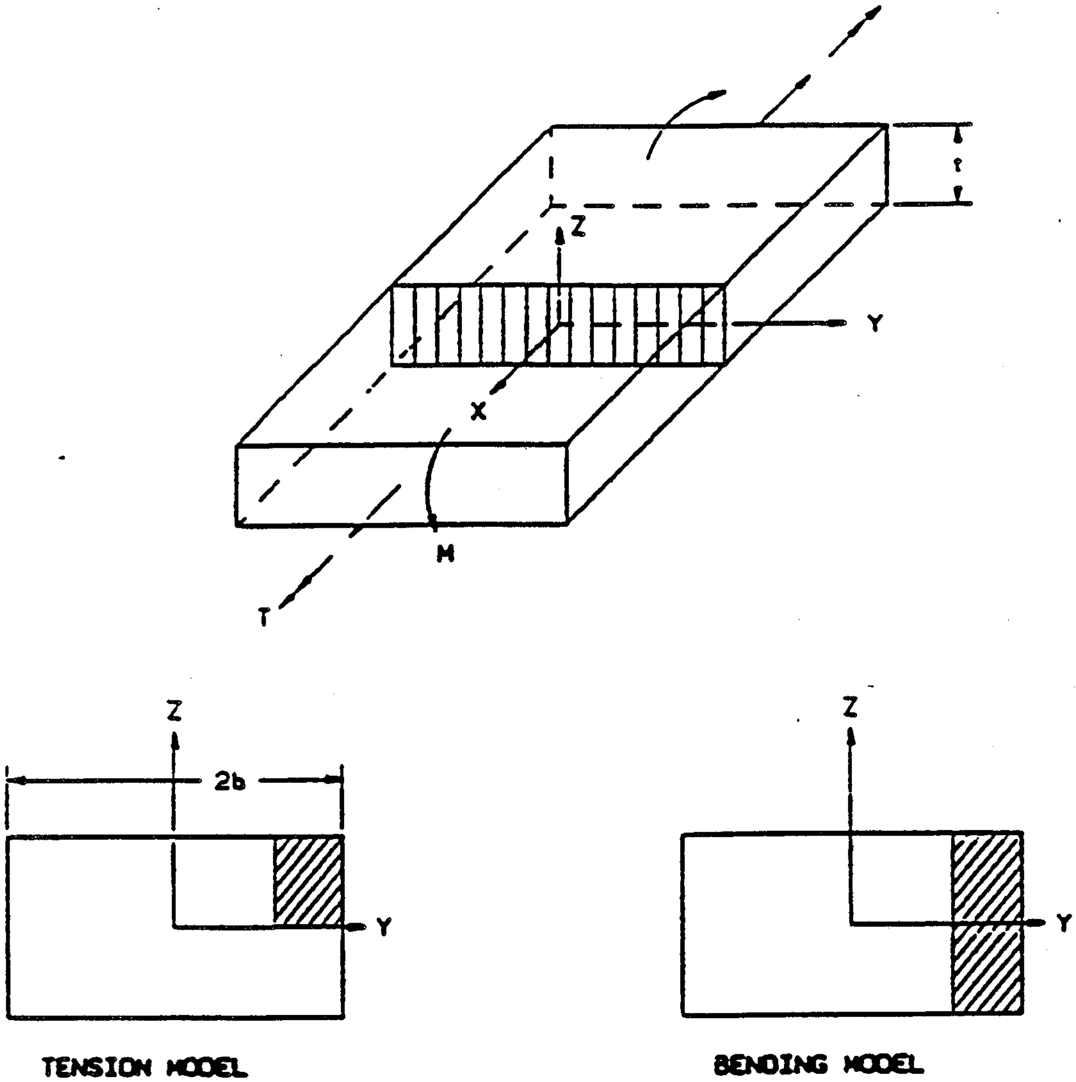
LAMINATE CONSTITUTIVE RELATIONS

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \\ \hdashline M_x \\ M_y \\ M_{xy} \end{bmatrix} = \left[\begin{array}{ccc:ccc} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ \hdashline B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{array}\right] \begin{bmatrix} \epsilon_x^0 \\ \epsilon_y^0 \\ \gamma_{xy}^0 \\ \hdashline K_x \\ K_y \\ K_{xy} \end{bmatrix} - \begin{bmatrix} N_x^E \\ N_y^E \\ N_{xy}^E \\ M_x^E \\ M_y^E \\ M_{xy}^E \end{bmatrix}$$

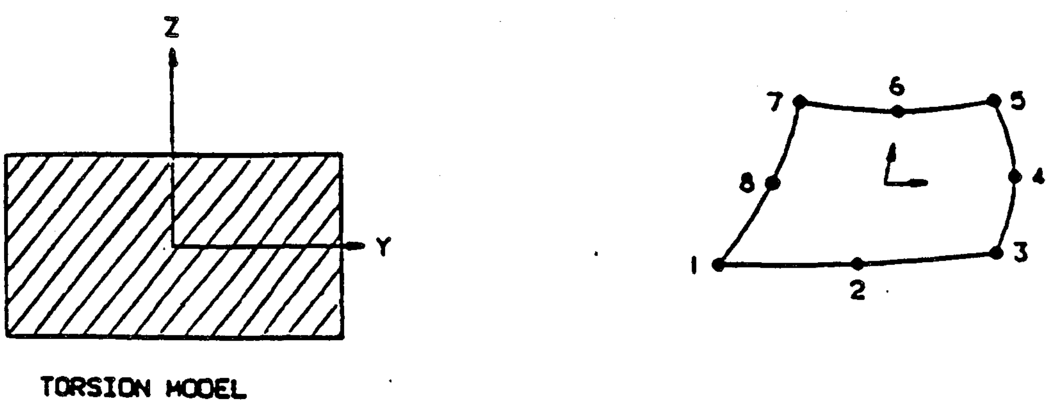
[3]

$$\begin{Bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{Bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \begin{Bmatrix} \varepsilon_x^\circ + \alpha_x \Delta T + \beta_x \Delta H \\ \varepsilon_y^\circ + \alpha_y \Delta T + \beta_y \Delta H \\ \varepsilon_{xy}^\circ + \alpha_{xy} \Delta T + \beta_{xy} \Delta H \\ K_x \\ K_y \\ K_{xy} \end{Bmatrix}$$

[24]



Only shaded areas are considered in the finite element model



Schematic of a quasi three-dimensional finite element model [23]

MATERIAL PROPERTIES

Layup $[+35/-35/0/90]_S$

Material $AS4/3501-6$

$\Delta T = -200^o F$ $\Delta H = 0.4$

Ply thickness = 0.0055 inches

Number of plies = 4

$E_1 = 1.93x10^7$ psi

$E_2 = E_3 = 1.62x10^6$ psi

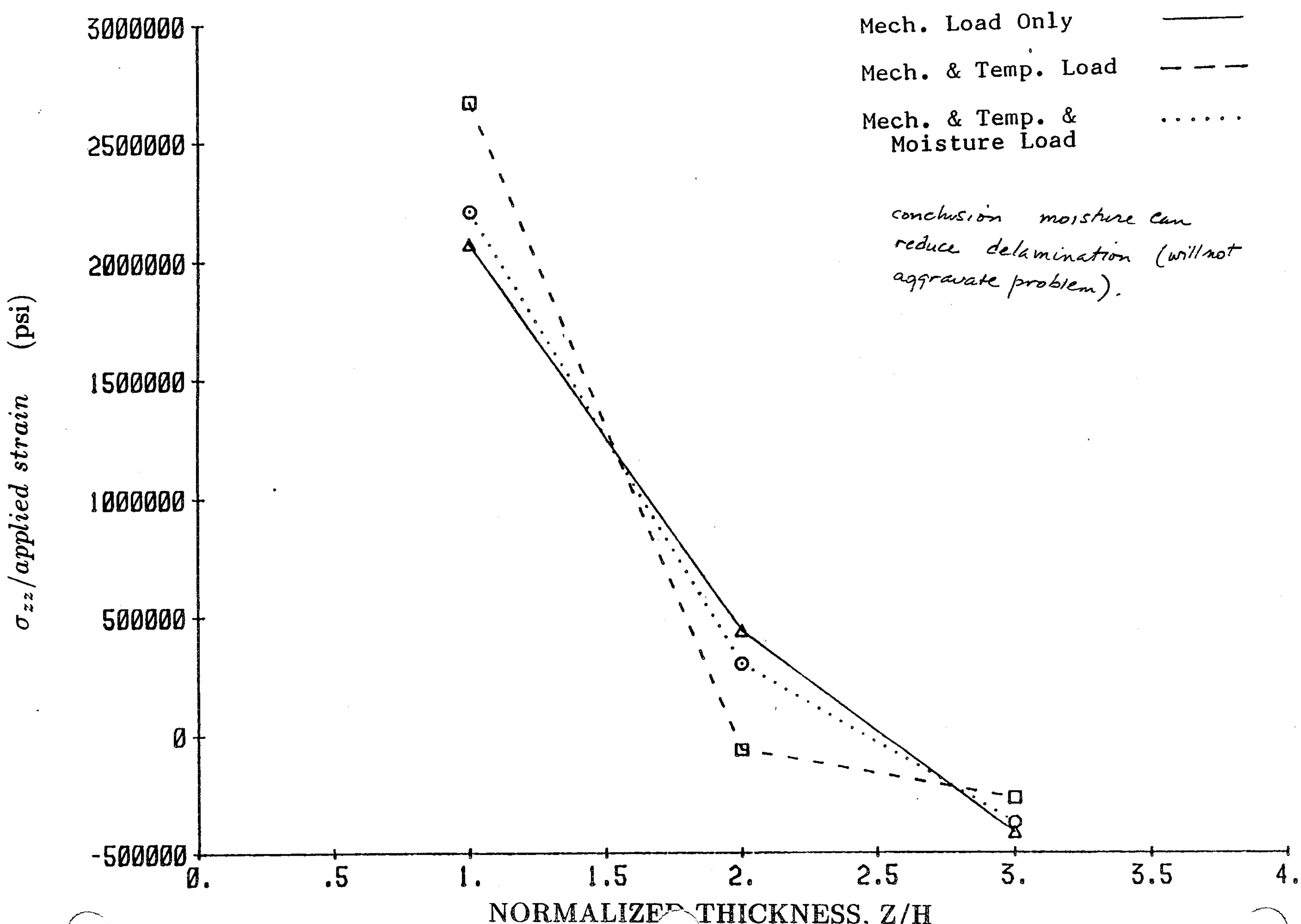
$\nu_{12} = 0.288$

$G_{12} = 1.02x10^6$ psi

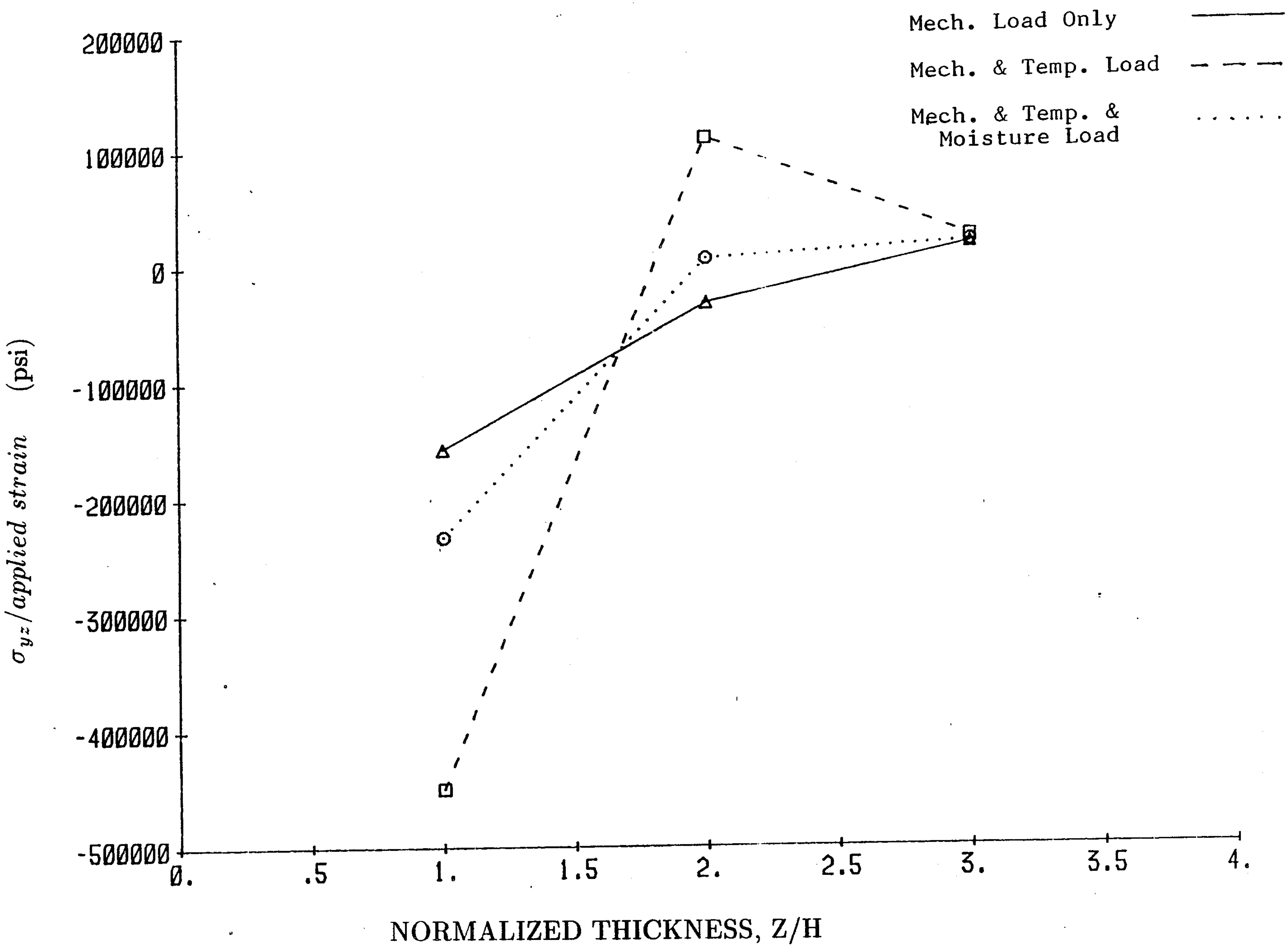
$\alpha_1 = -2.3x10^{-7}$ in/in /°F $\beta_1 \cong 0$

$\alpha_2 = \alpha_3 = 1.49x10^{-5}$

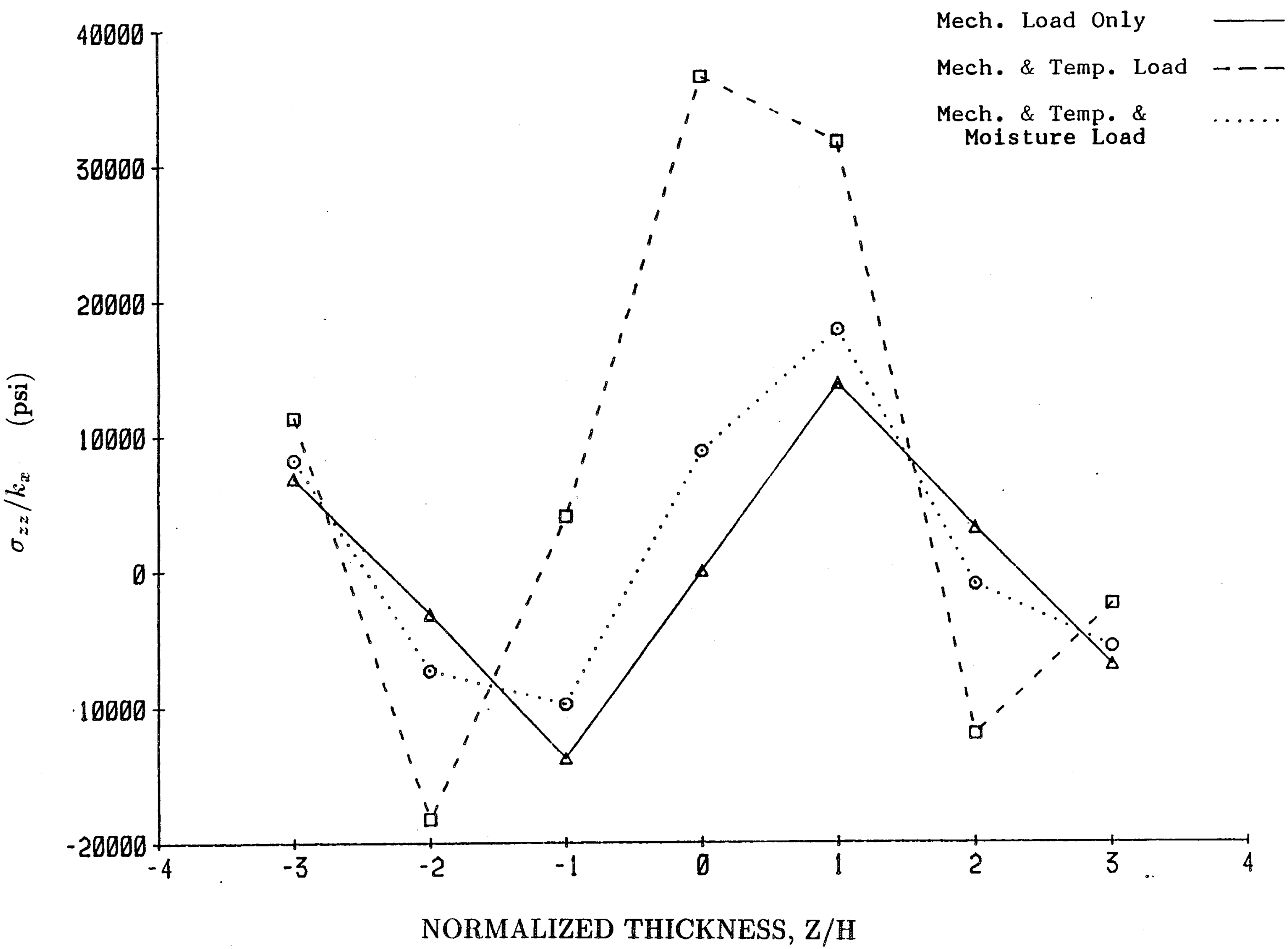
$\beta_2 = \beta_3 = 5.56x10^{-3}$



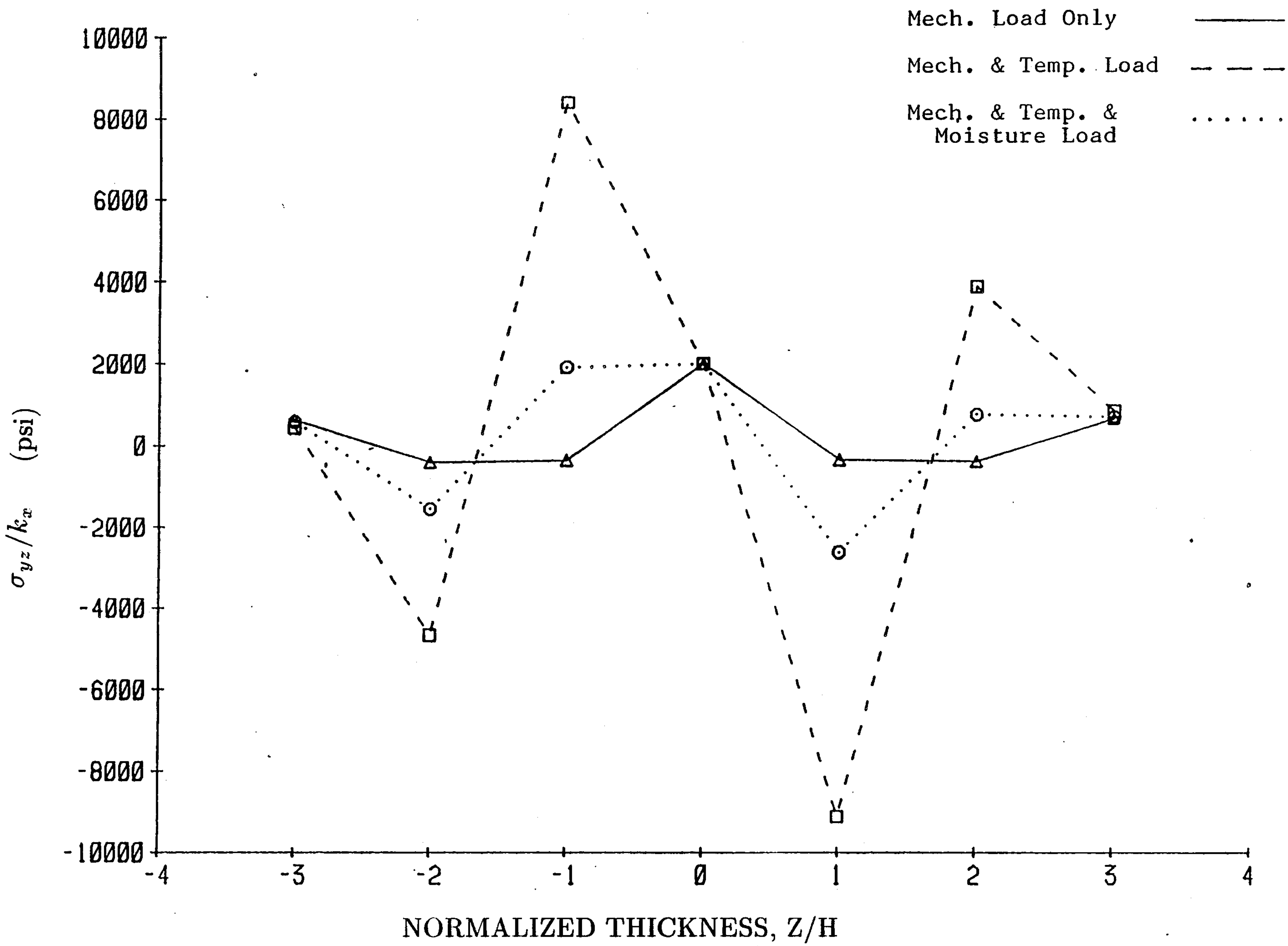
Interlaminar Normal Stress Distribution for Tension Loads [24]



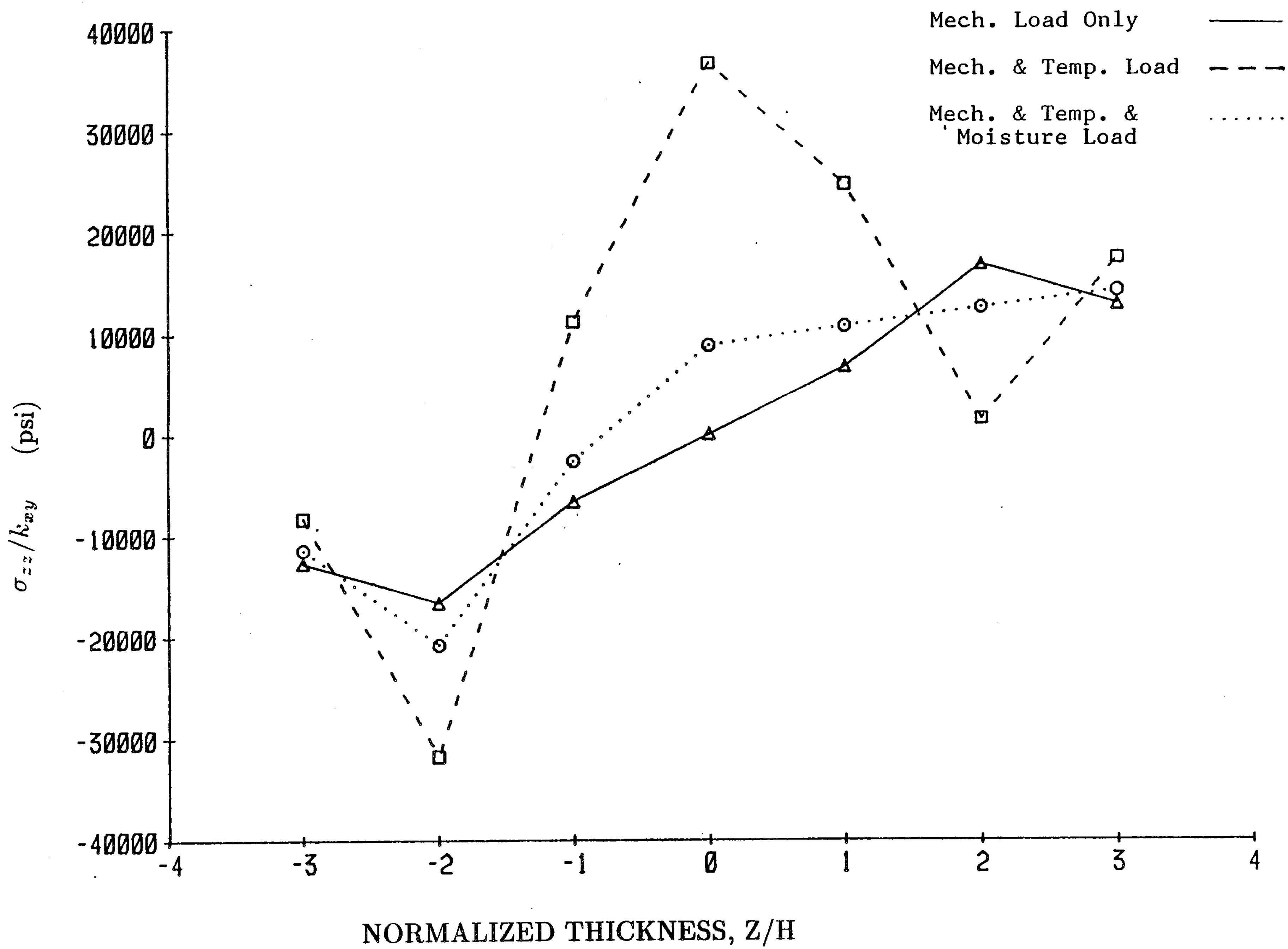
Interlaminar Shear Stress Distribution for Tension Loads [24]



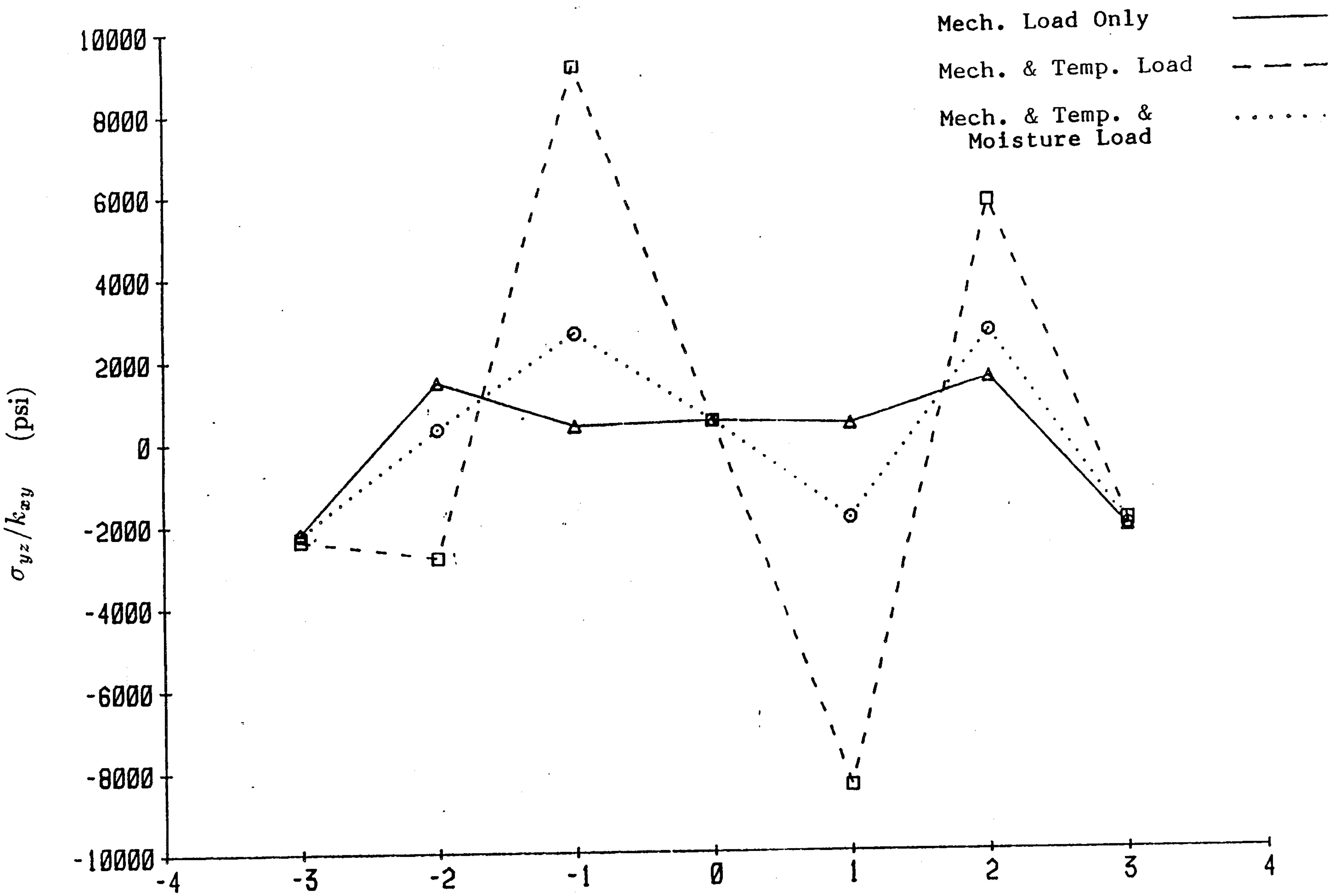
Interlaminar Normal Stress Distribution for Bending Loads [24]



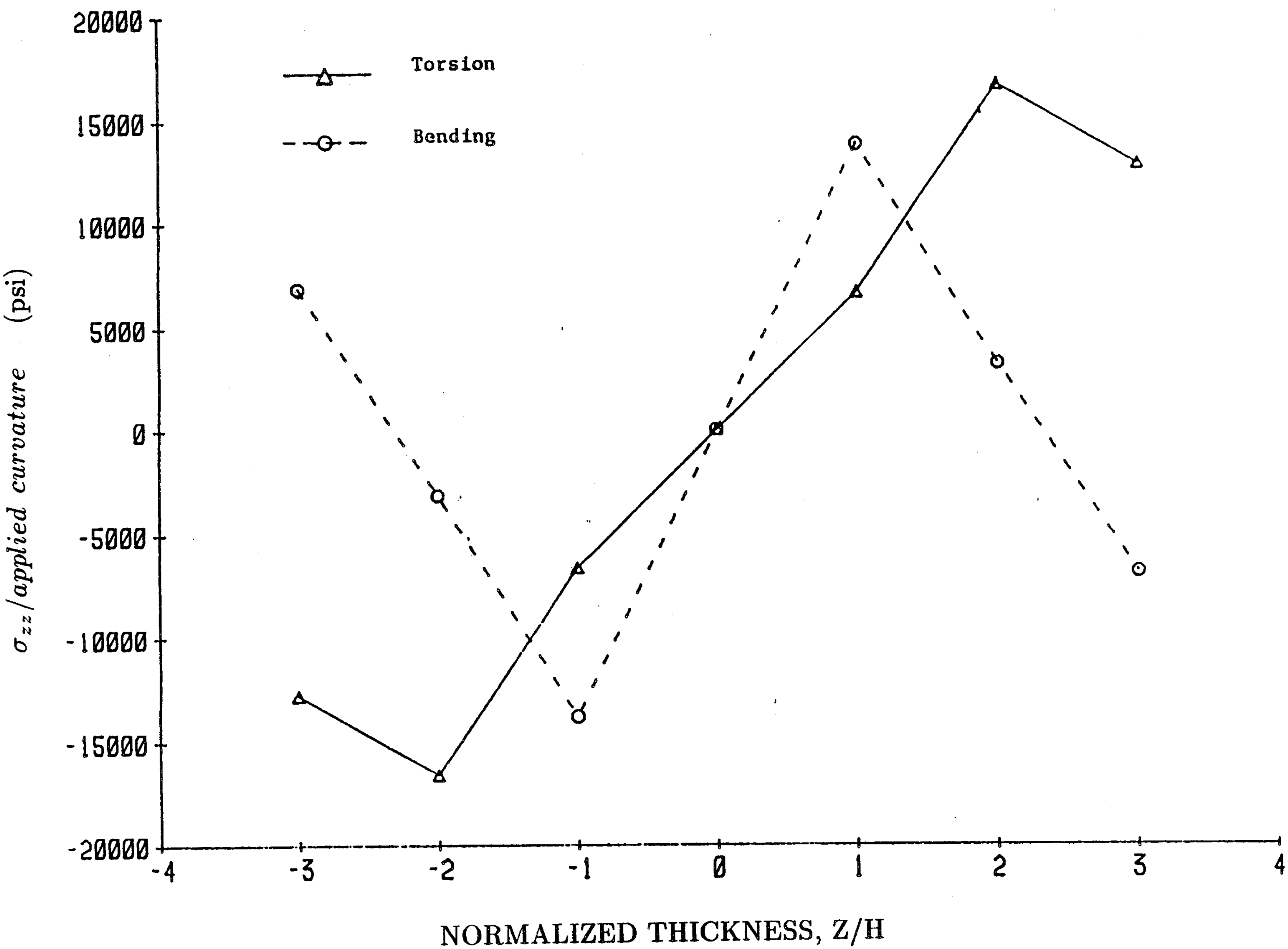
Interlaminar Shear Stress Distribution for Bending Loads [24]



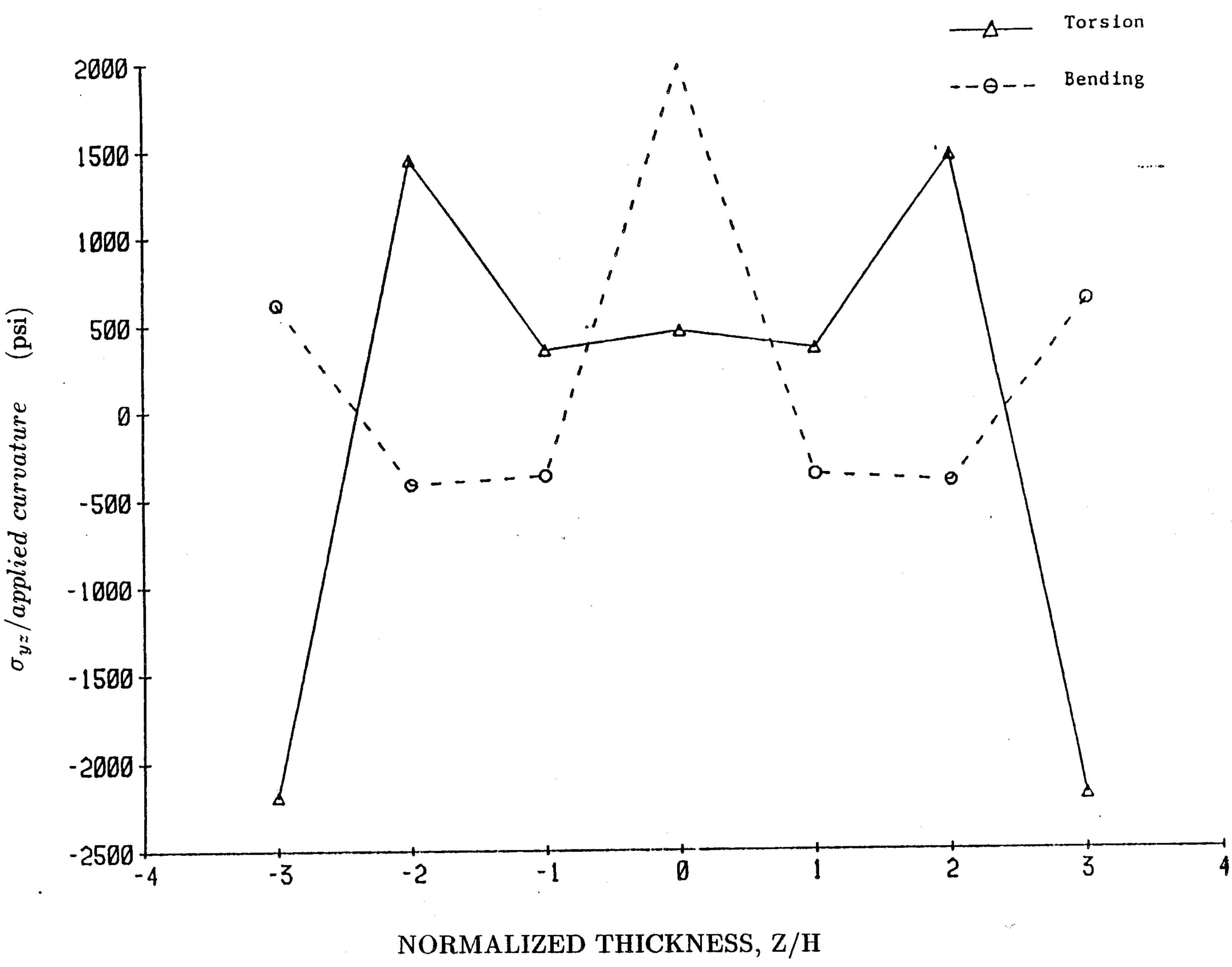
Interlaminar Normal Stress Distribution for Torsion Loads [24]



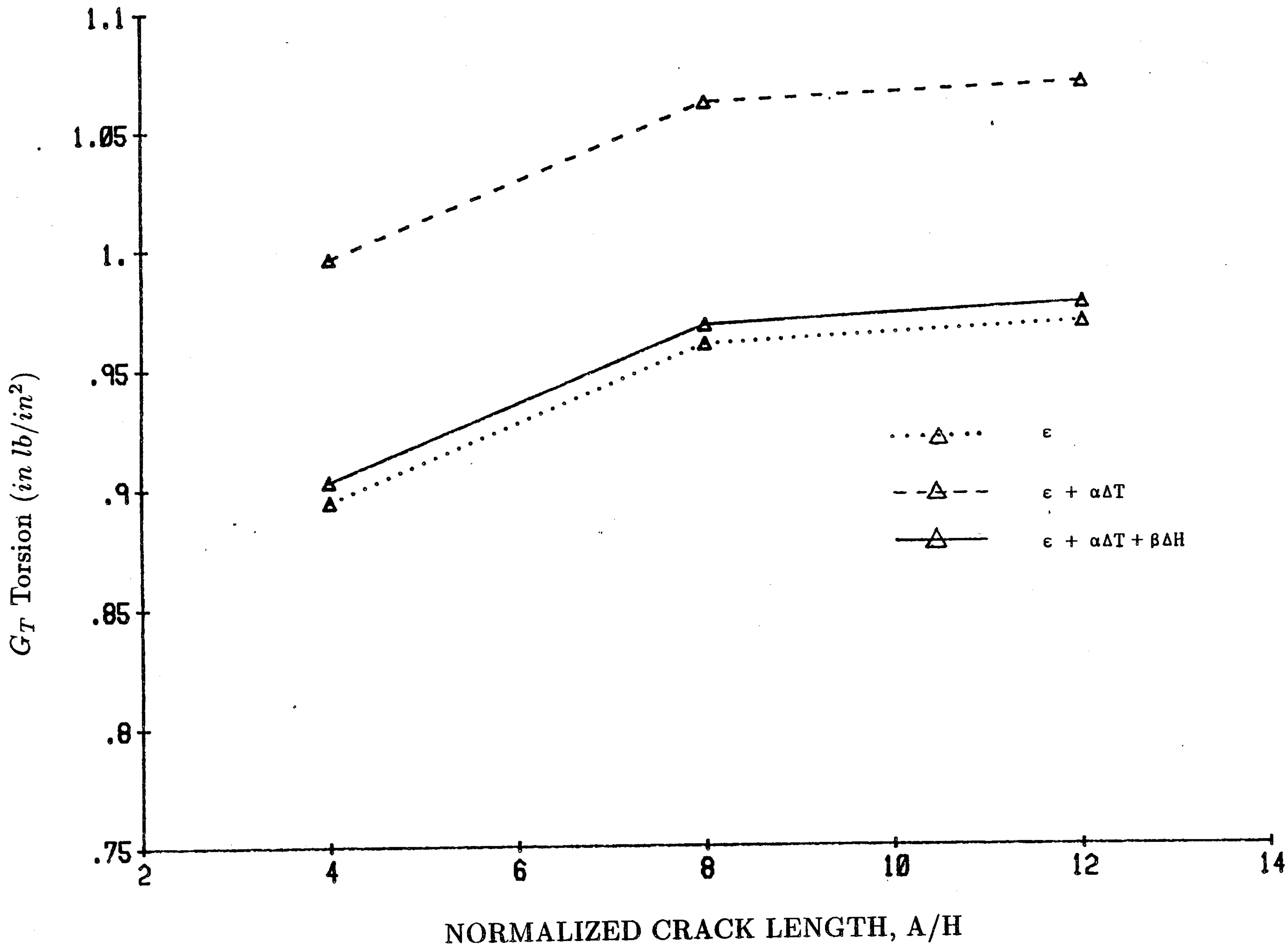
Interlaminar Shear Stress Distribution for Torsion Loads [24]



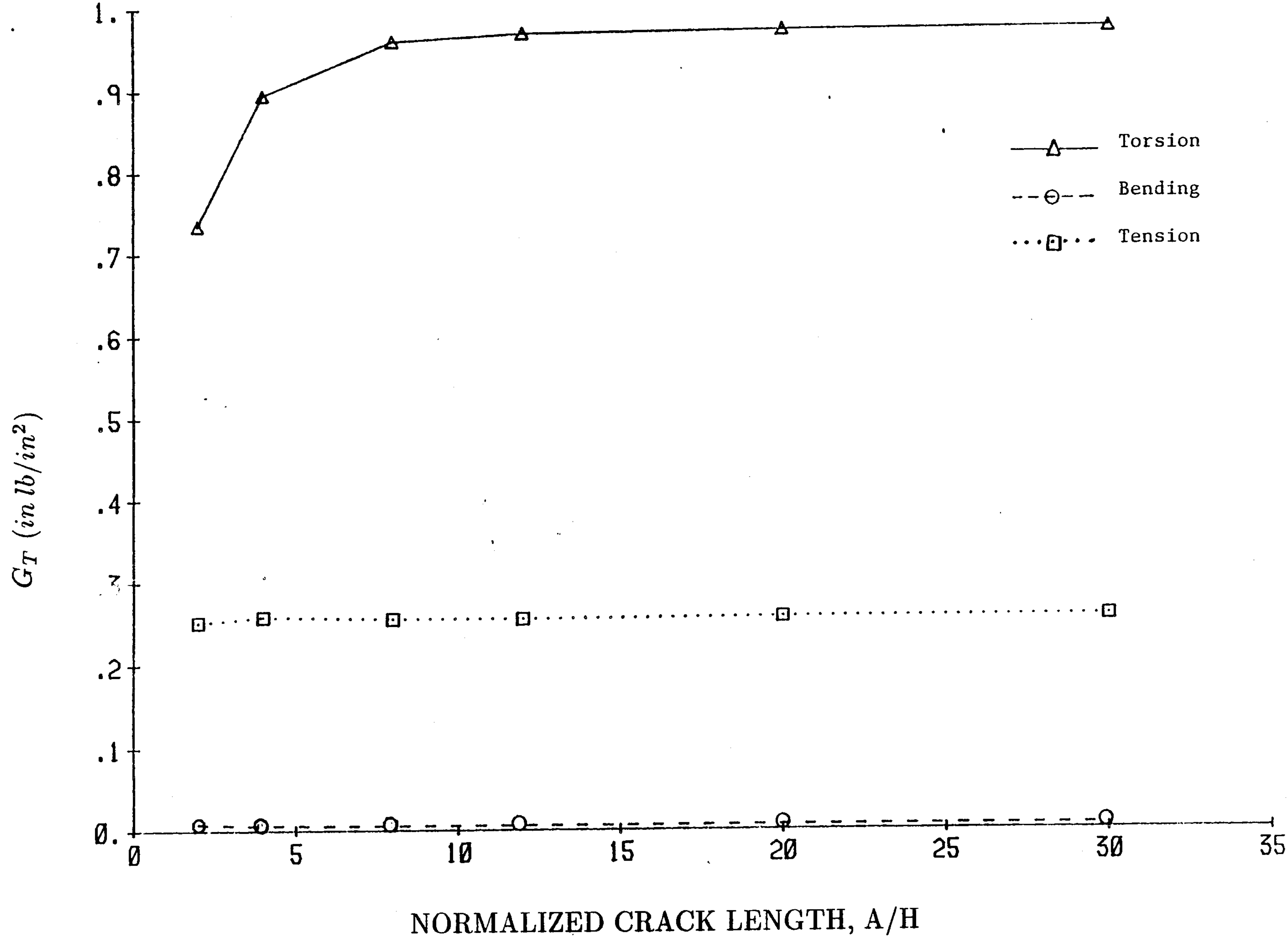
Interlaminar Normal Stress Distribution for Bending and Torsion Loads [24]



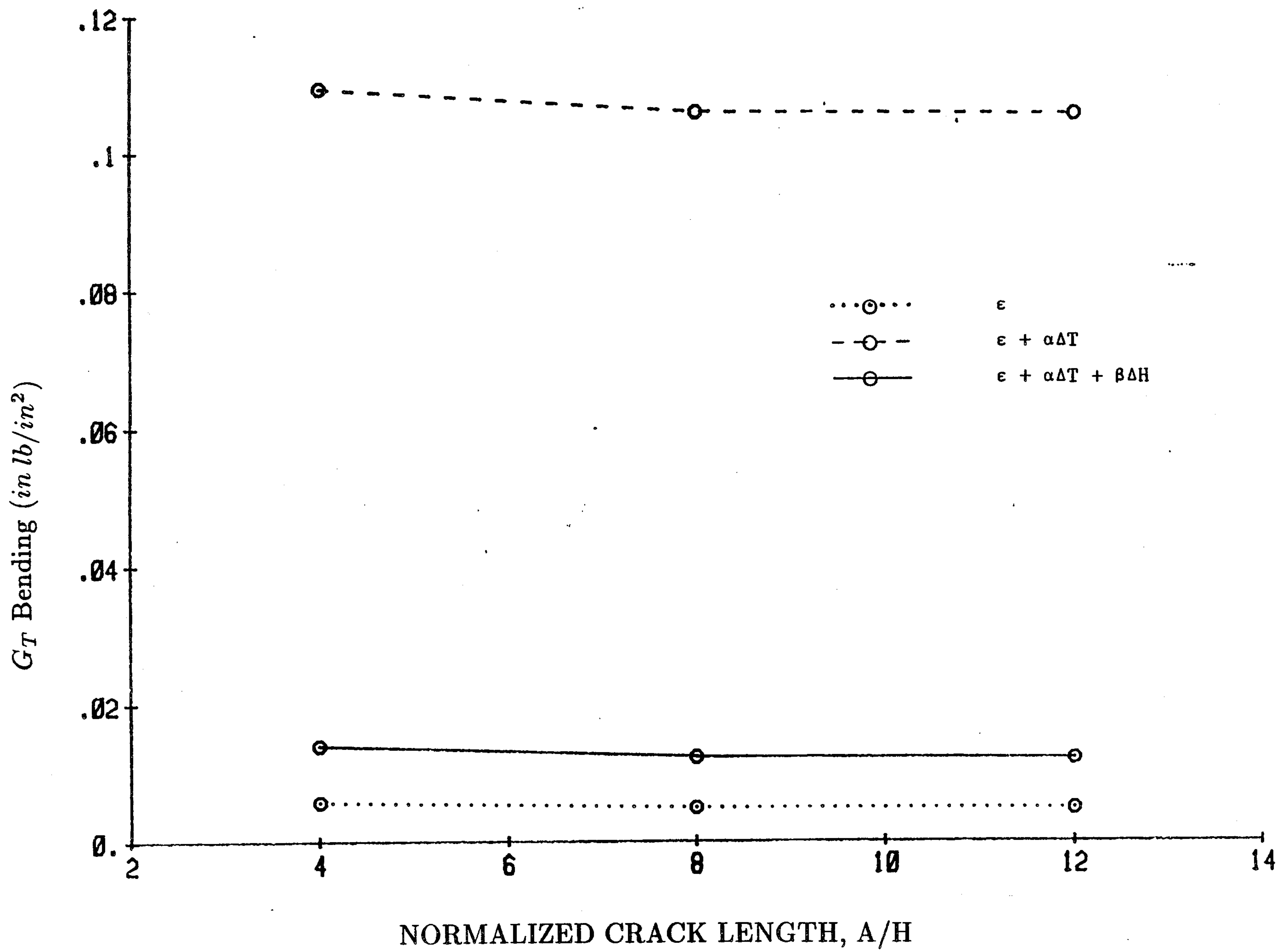
Interlaminar Shear Stress Distribution for Bending and Torsion Loads [24]



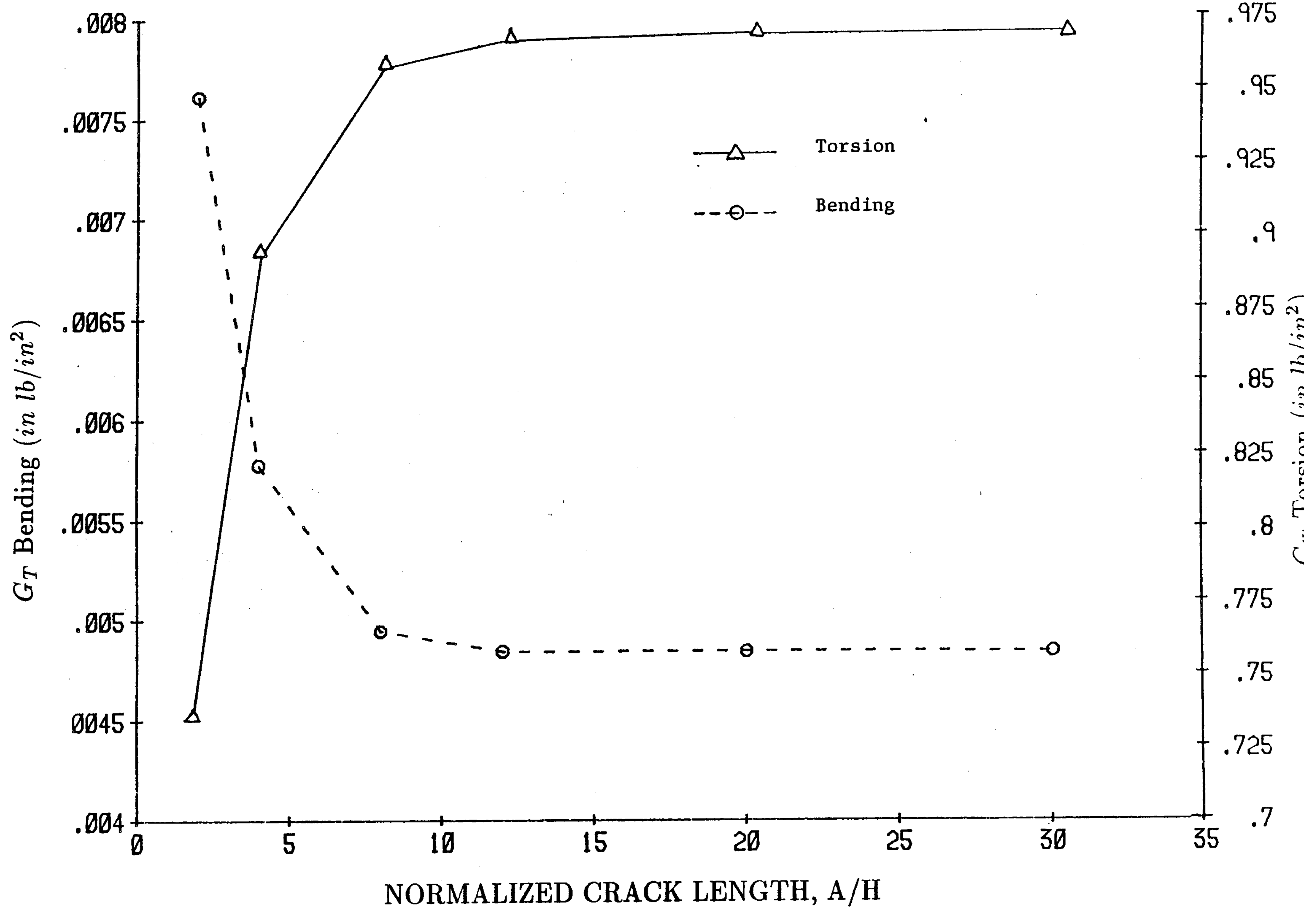
Total Strain Energy Release Rate as a F ction of Normalized Crack Length for Torsio oads [24]



Total Strain Energy Release Rate as a Function of Normalized Crack Length for Torsion, Bending, and Tension Loads [24]



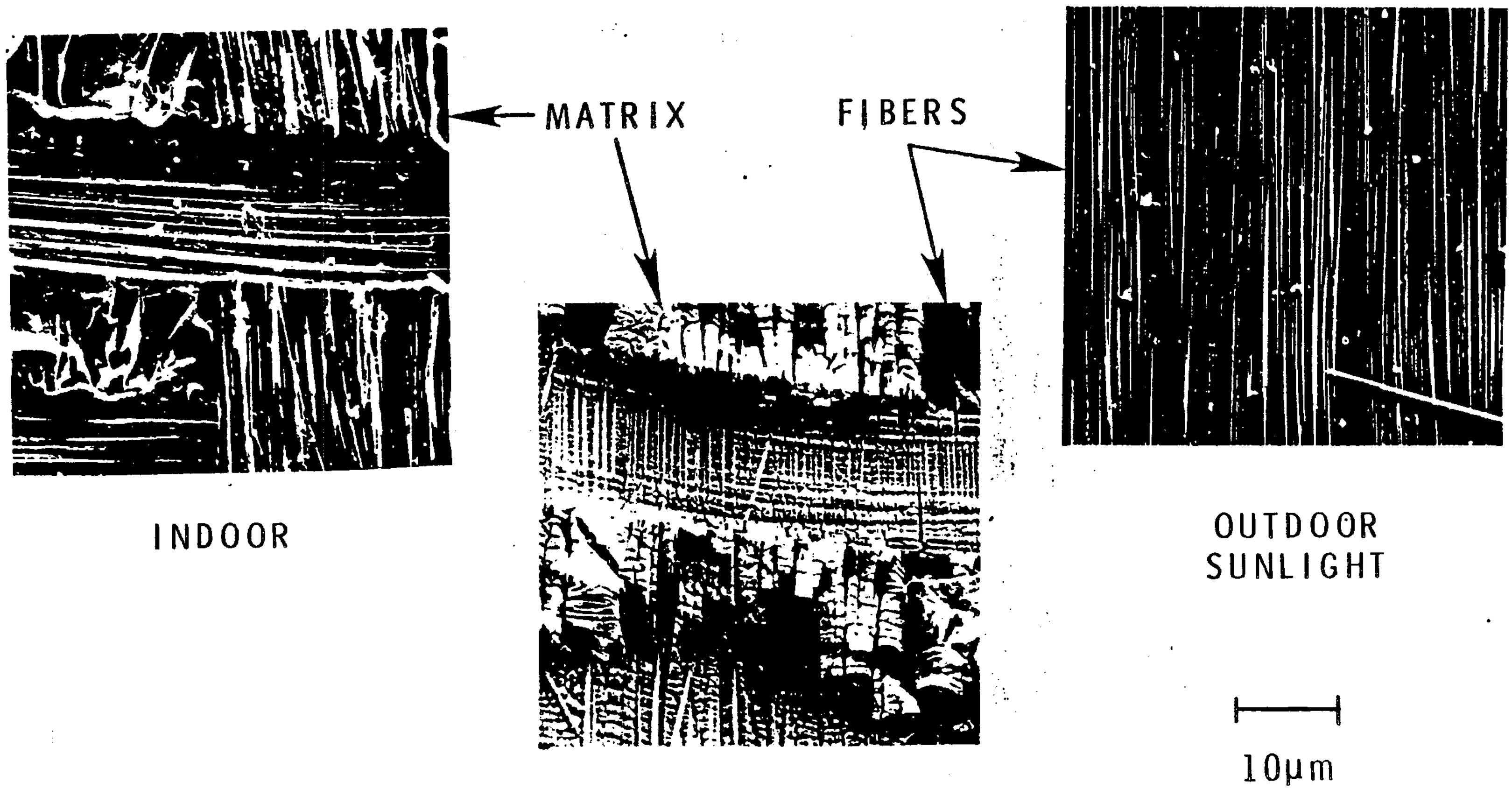
Total Strain Energy Release Rate as a Fun[illegible]on of Normalized Crack Length for Bending [illegible]ads [24]



Total Strain Energy Release Rate as a Function of Normalized Crack Length for Torsion and Bending Loads [24]

MATRIX DETERIORATION FROM OUTDOOR EXPOSURE

GR/EP 5208-T300 2 YEARS



[25]

References: 3, 5, 23, 24, 25

DESIGN

IMPORTANT ASPECTS IN DESIGN

- Anisotropy
- Data Base
- Environmental Effects
- Damage Tolerance
- Assembly, Attachments
- Manufacturing
- Inspection
- Repair
- Cost

ENVIRONMENTAL CONSIDERATIONS

- Temperature
- Flammability + toxicity
- Heat Transfer
- Acoustics
- Moisture/Humidity
- Adhesive Solvents or Outgassing
- Jet Fuel

[26]

STRUCTURAL CONSIDERATIONS

- Strength
- Fatigue
- Stiffness
- Adhesive Performance

ECONOMIC CONSIDERATION

- Value Analysis

[26]

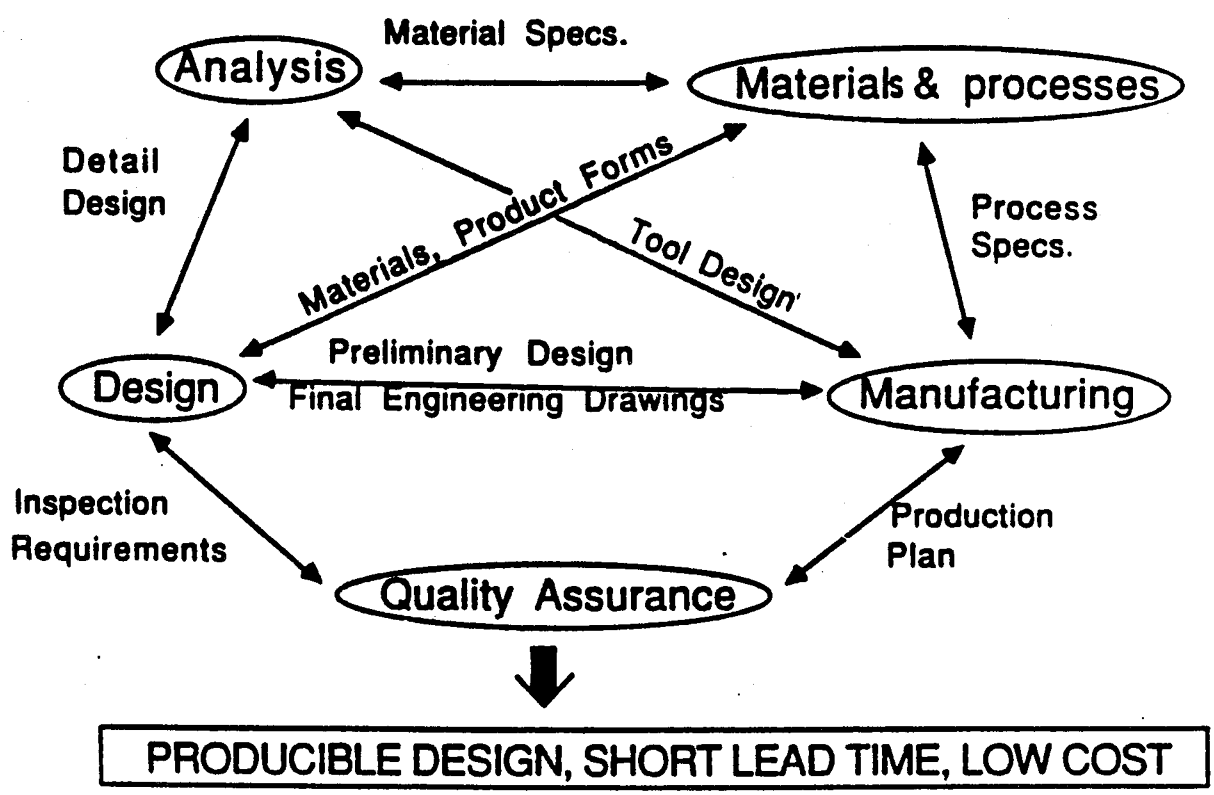
MOST EFFICIENT DESIGN

- Produced at minimum cost
- Remains within design constraints
- Makes optimum use of resources

[28]

SIMULTANEOUS ENGINEERING

- Design for Strength
- Design for Stiffness
- Joint Design
- Sandwich Structures



[27]

ORGANIZATIONAL FUNCTIONS

- Designer
  - On board conceptual design phase
  - Definitive development phase
  - Preliminary design release
  - Incorporate inputs
  - Finalize design
  - Approvals

    Stress

    Weights

    Design checker

    Materials and Process

    Producibility
  - Design release

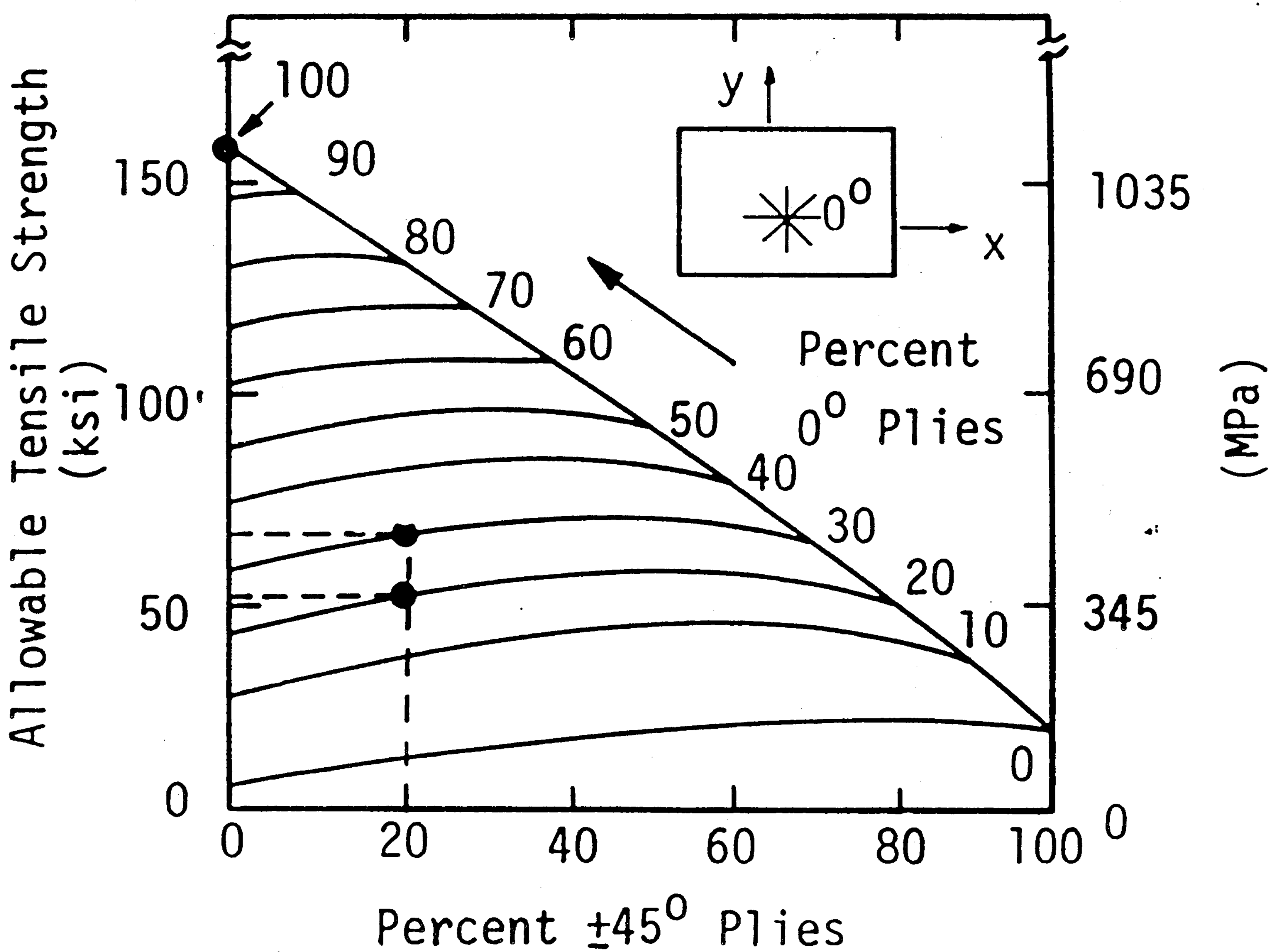
- Manufacturing Engineering
  - Review for equipment capabilities
  - Forcast tooling plan
  - Guide designer to least costly tooling configuration
  - On-going design surveillance *
  - Review preliminary design
  - Perform design tradeoff studies
  - Determine make or buy
  - Feedback to design
  - Approve design

- Material and Process
  - Recommend material selection
  - Evaluate alternate materials
  - Review preliminary design
  - Feedback to design
  - Approve design

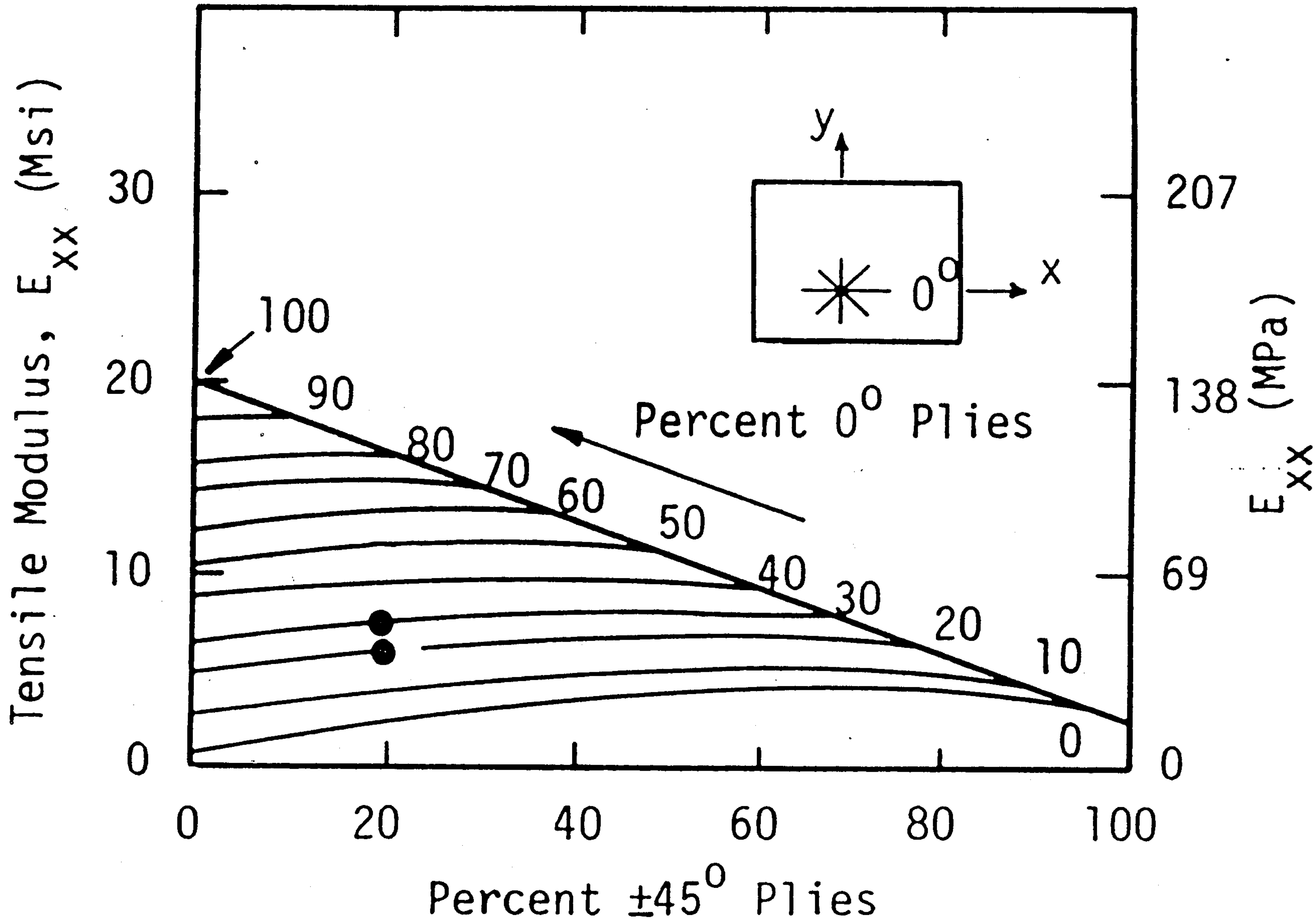
[28]

DESIGN FOR STRENGTH

- Assume state of stress is known
- Evaluate stress resultants
- Find principal directions (Mohr's Circle) from
- Align laminae in major load direction *
- Carpet plots



Carpet plot for tensile strength σ_{xx} of a ca[illegible] fiber-epoxy $[0/90/+45/-45]_S$ laminate f[illegible]ly [2]



Carpet plot for tensile modulus E_{xx} of a carbon fiber-epoxy $[0/90/+45/-45]_S$ laminate family [2]

DESIGN FOR STIFFNESS

For isotropic systems

- Axial stiffness $= EA_0$
- Bending stiffness $= EI_c$
- Torsional stiffness $= GI_c$

DESIGN STEPS FOR BEAMS

- Define loads
- Define beam type (BC's)
- Determine required maximum deflection
- Select skin material
- Calculate first approximation
- Select skin thickness
- Select core SANDWICH CONSTRUCTION
- Re-check deflection
- Face wrinkling and intracell damping

[26]

FITTINGS AND CLOSE-OUTS

- Act as structural tie to adjoining or supporting structure
- Allow two panels to be joined straight or at right angles
- Incorporate a hinge or be detachable
- Provide edge protection against inpact damage
- Seal the panel joint
- Provide a smooth, continuous extension of the facings
- Decorative

[26]

FASTENERS

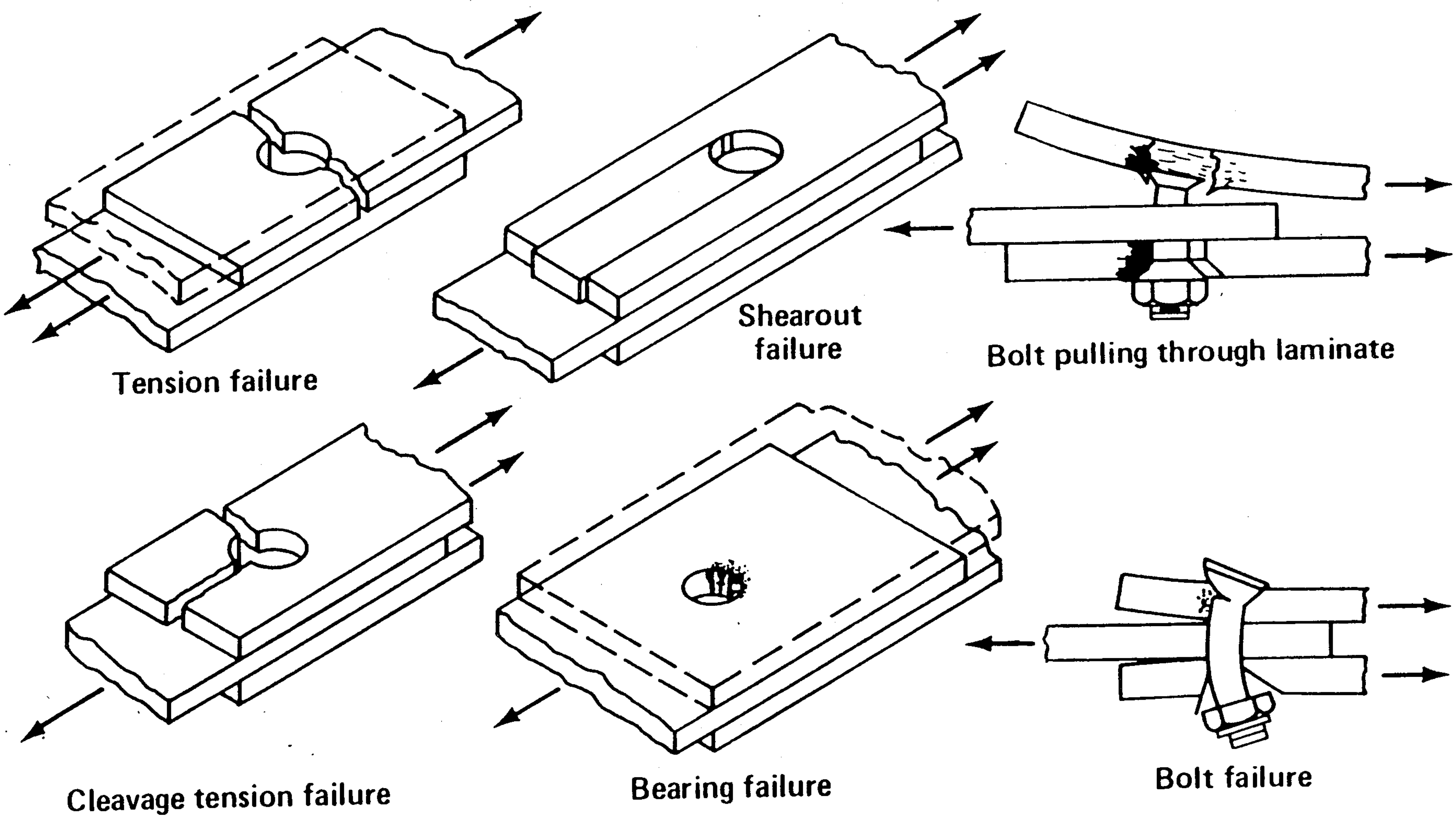
- Molded-in
  - Provide the best structural strength
  - Add more weight to the panel
  - Are time consuming to install

- Grommet type
  - Weigh less than molded-in fasteners

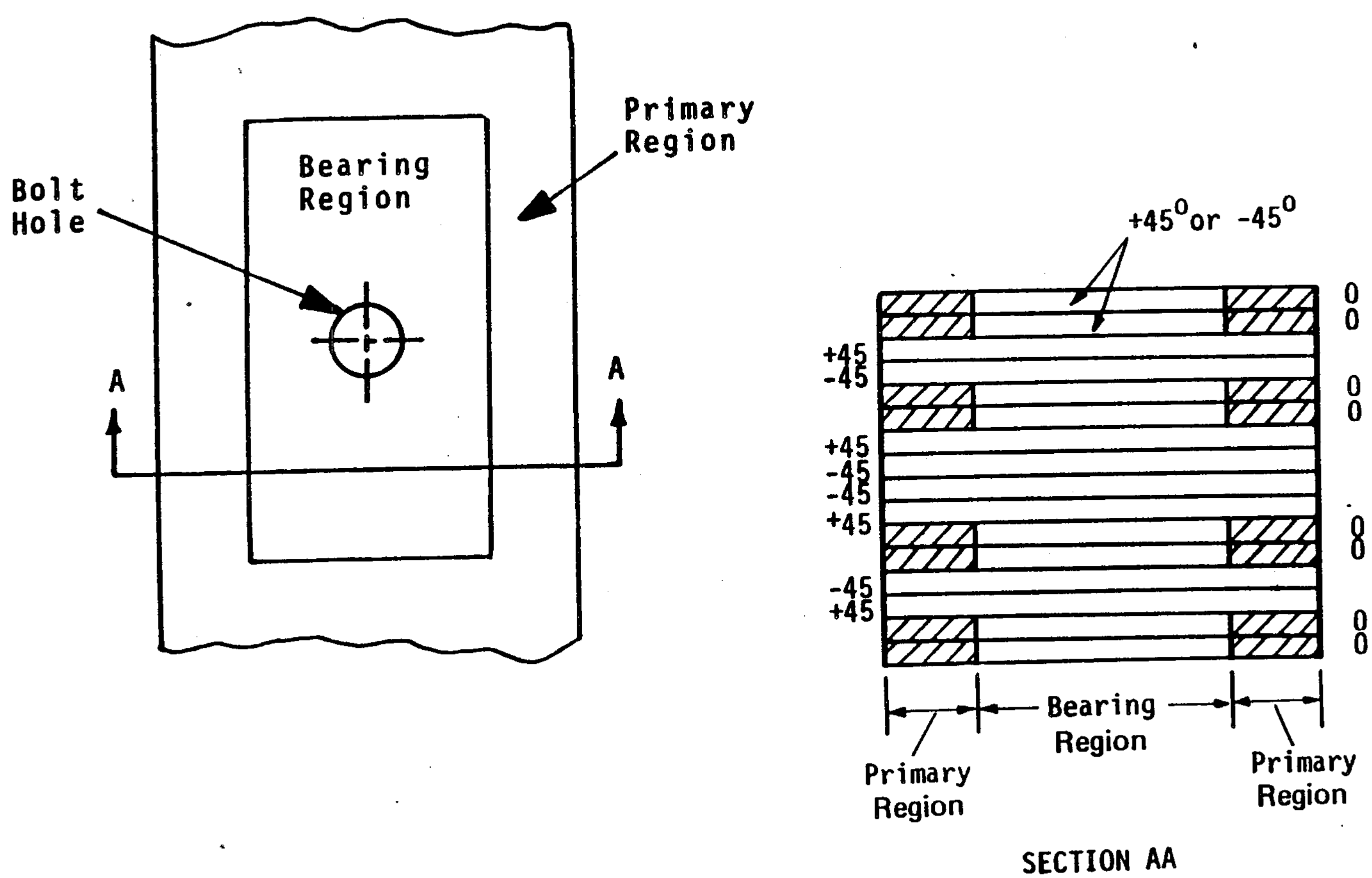
- Variations of each type of fastener include:
  - Flush, raised or countersunk heads
  - Clearance hole or threaded through
  - Blind, threaded - with or without self-locking device
  - Floating nuts which simplify critical alignment
  - Materials include Aluminum, Stainless Steel, Carbon Steel, and special alloys

JOINTS

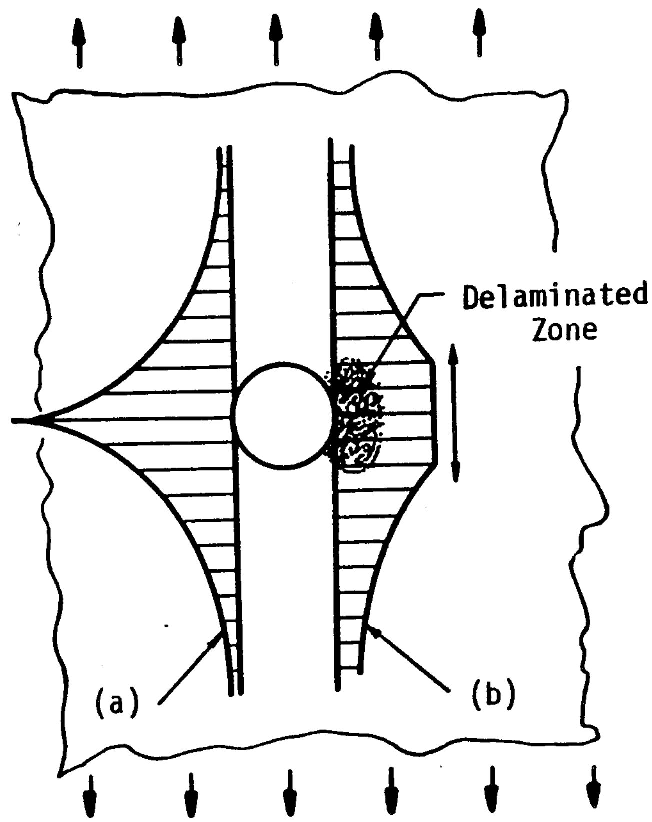
- Mechanical
  - Bolted
- Bonded
  - Single lap
  - Double lap
  - Single strap joint
  - Double strap joint
  - Stepped lap joint
  - Scarf joint



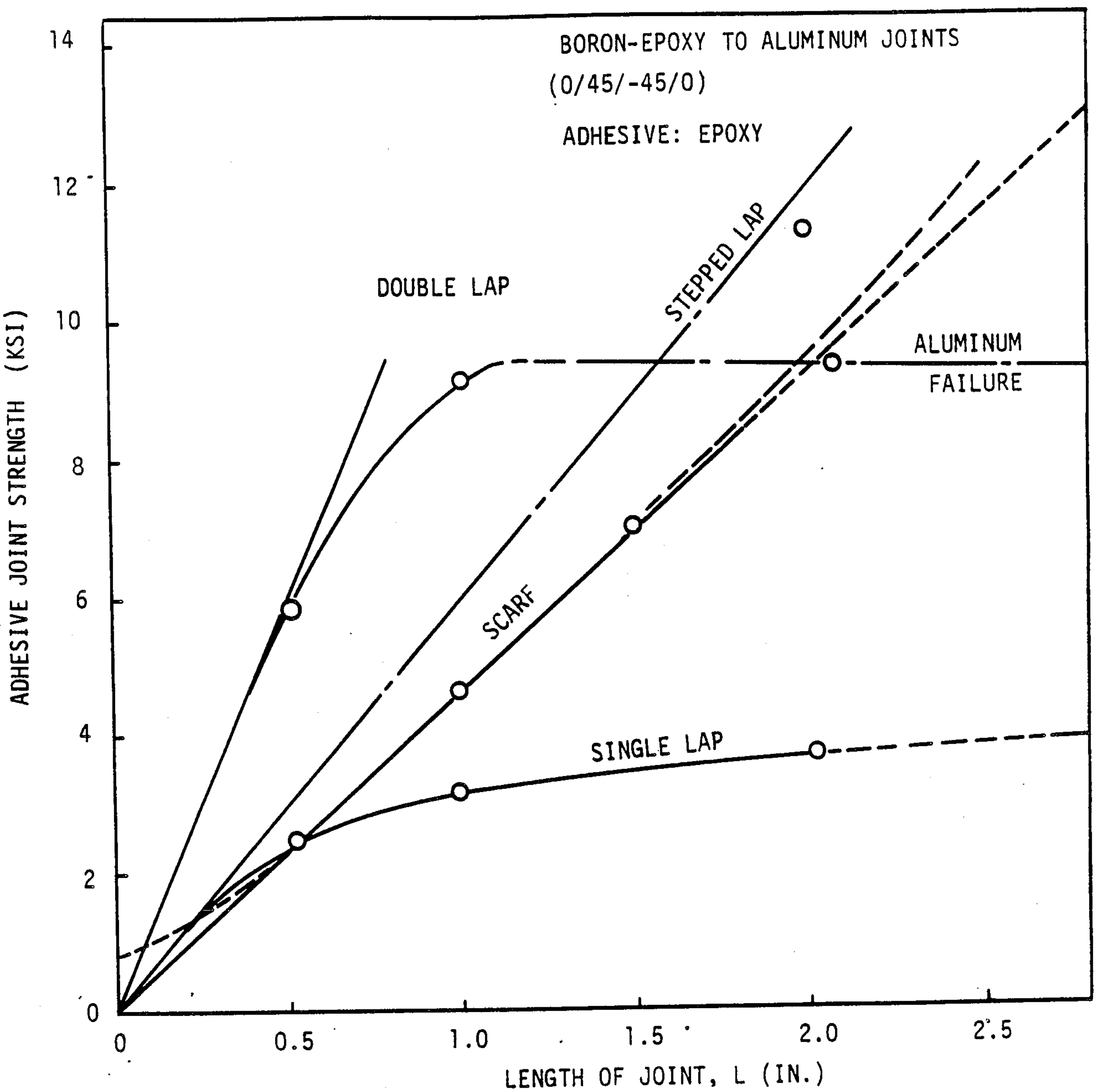
Modes of failure for bolted joints in advanced composites [5]



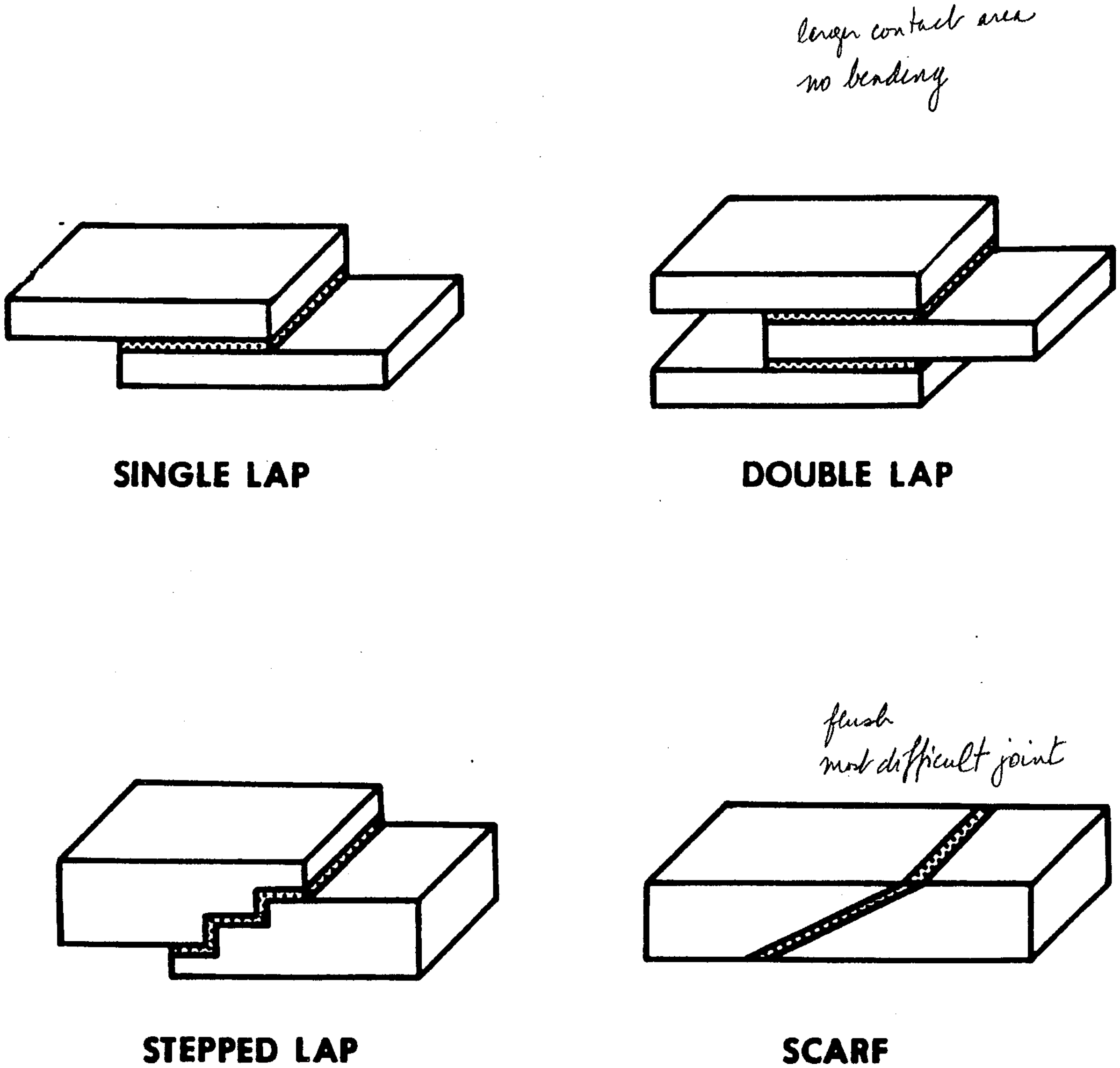
Laminate tailoring method for improving bolted joint strength [2]



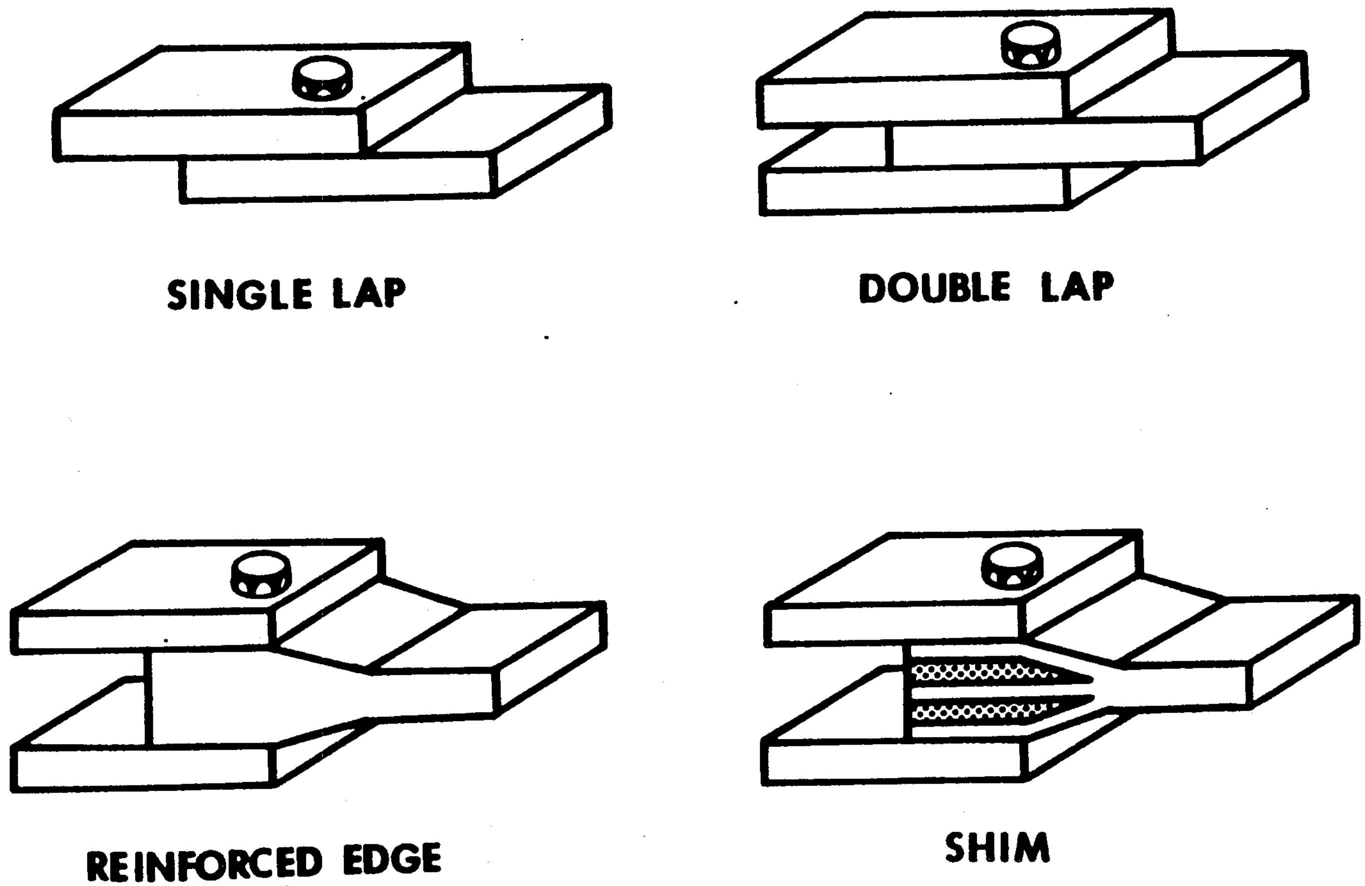
Stress distributions in areas adjacent to a bolt hole with (a) no delaminated zone and (b) a delaminated zone. [29]



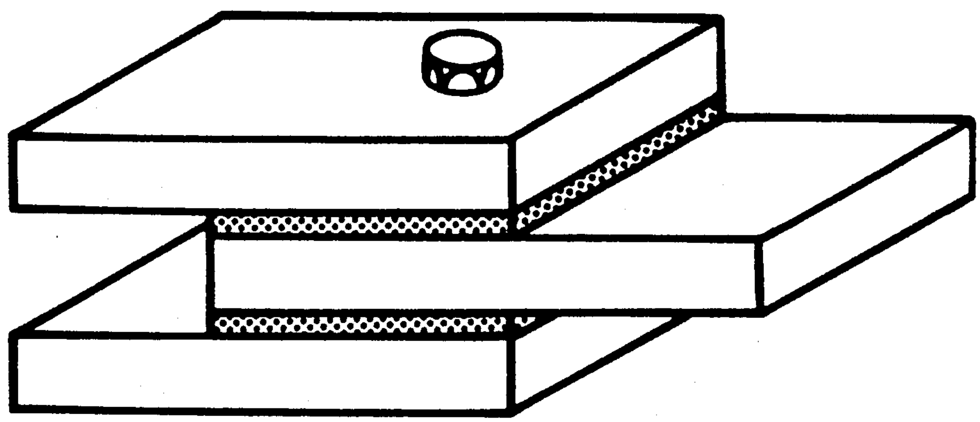
Comparison of joint strengths of various bonded joint configurations [30]



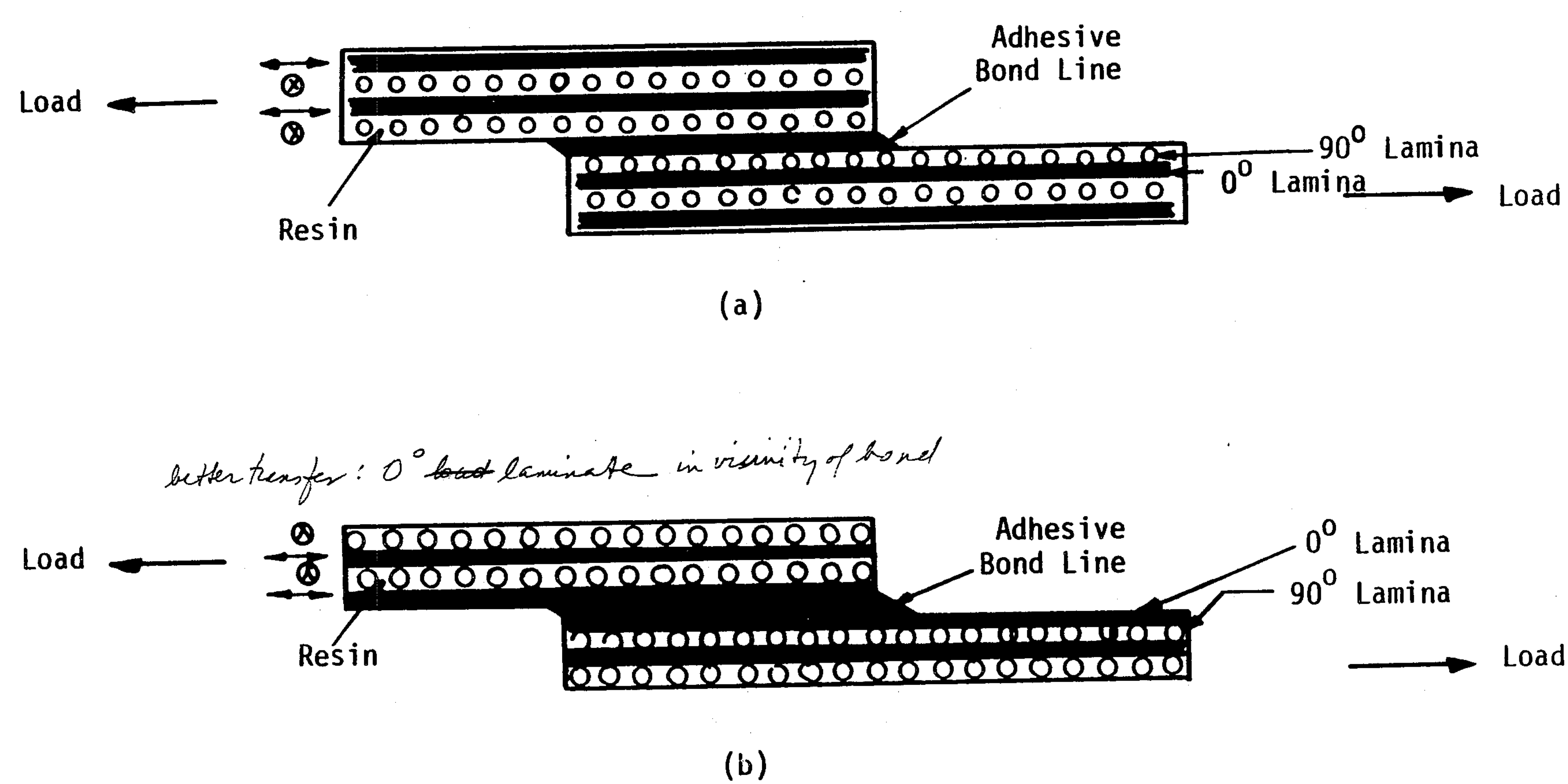
Bonded Joints [12]



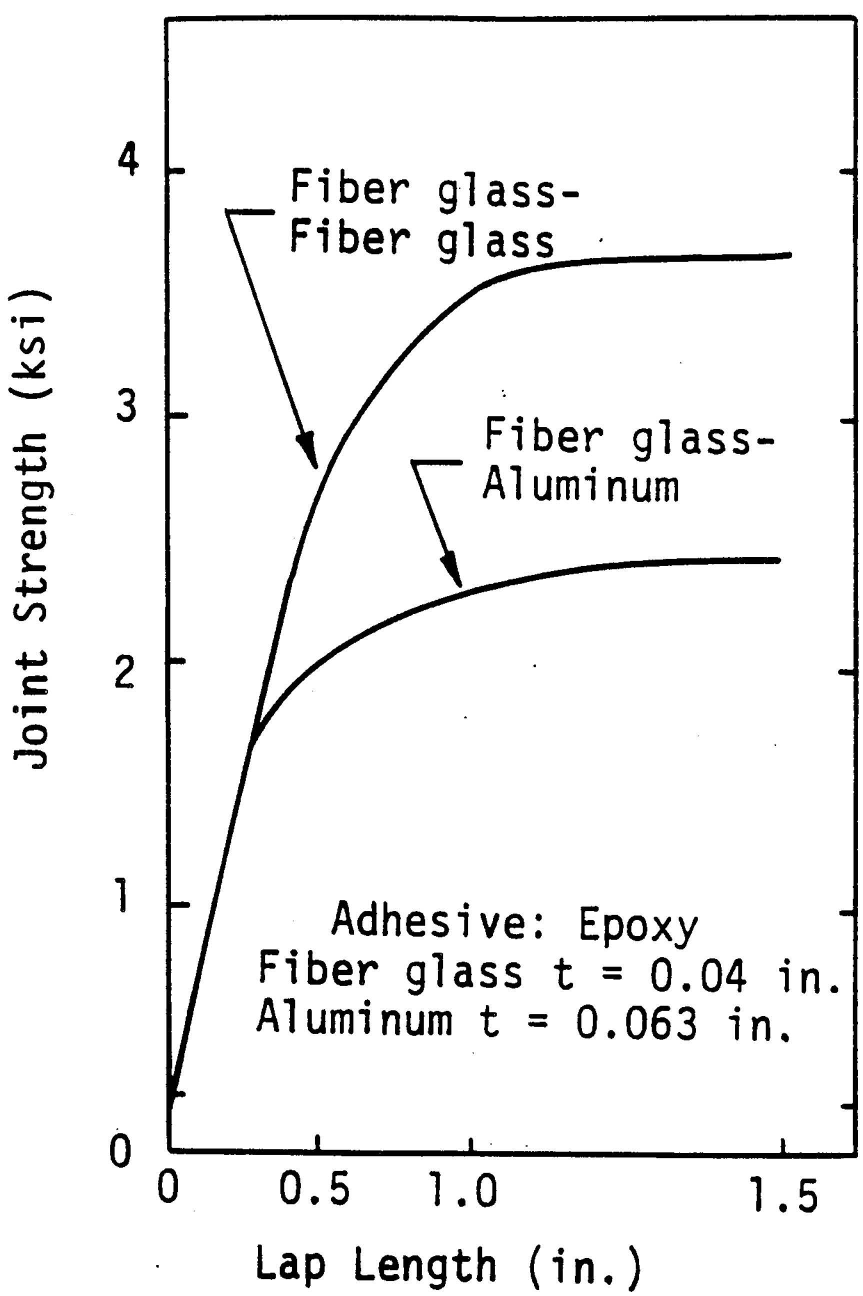
Bolted Joints [12]



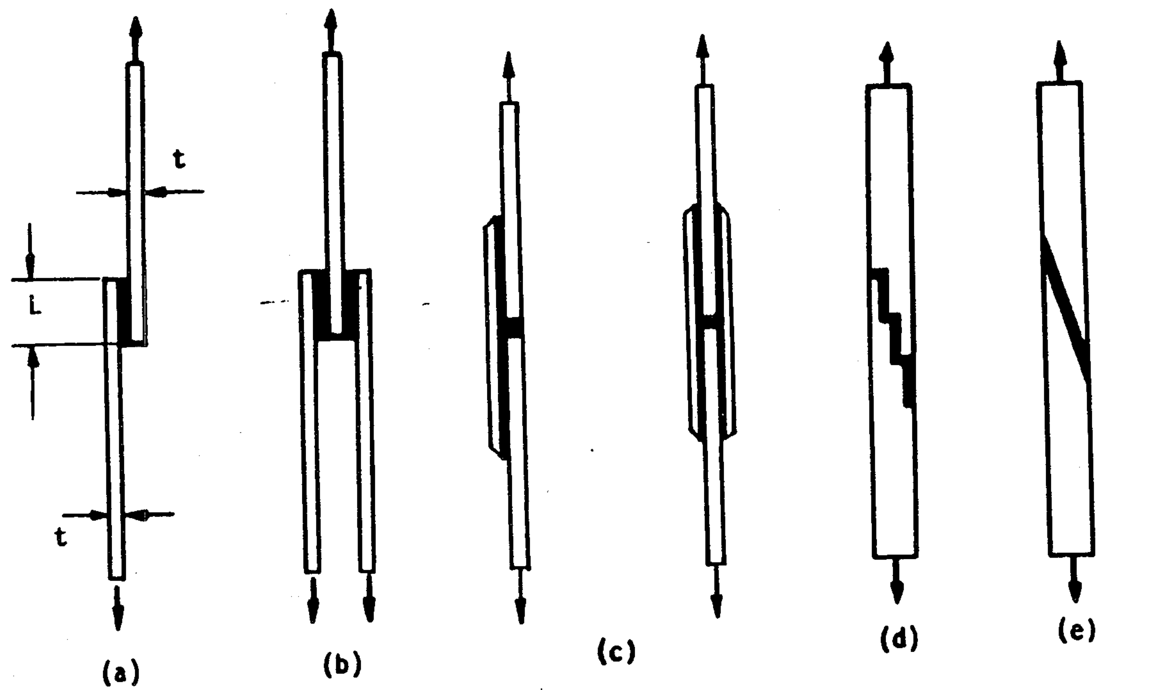
Bonded-bolted Double Lap Joint [12]



Examples of (a) poor and (b) good laminate designs for bonded joints [30]



Increase in the joint strength of single-lap bonded joint with lap length [30]



Basic bonded joint configurations: (a) single-lap joint, (b) double-lap joint, (c) single- and double- strap joints, (d) stepped lap joint, and (e) scarf joint. [2]

ADHESIVE MATERIALS

- Fillet Forming
- Bond Line Control
- Toughness

Toughness is often determined by a peel test for sandwich structures.

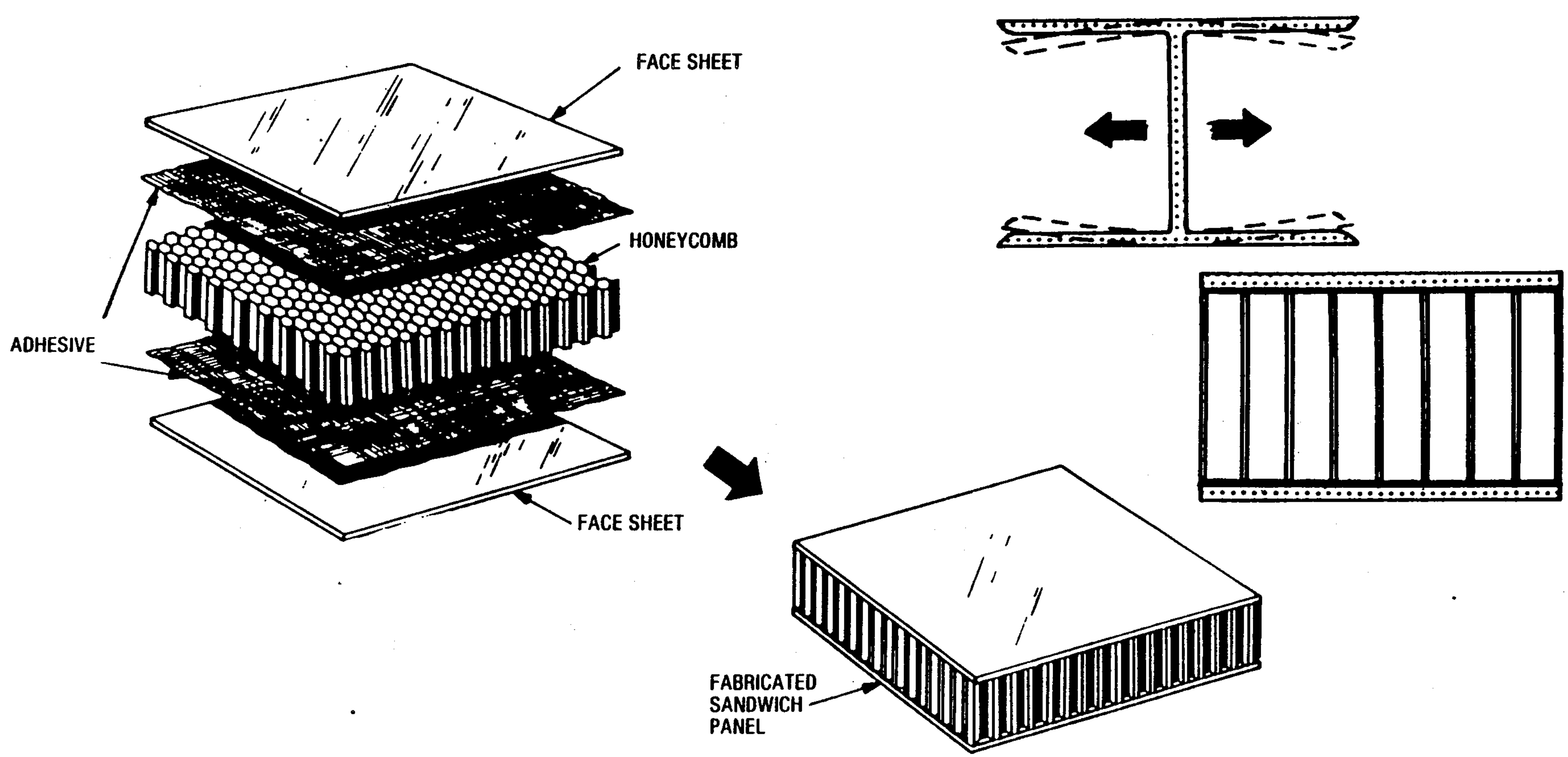
- Peel Strength Depends On:
  - Strength of facing
  - Toughness of adhesive
  - Amount of adhesive used
  - Density of the core
  - Cell size of the core
  - Direction of the peel
  - Surface preparation
  - Degradation of the adherent surface subsequent to bonding

[26]

SANDWICH DESIGN

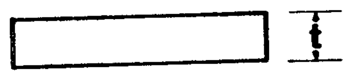
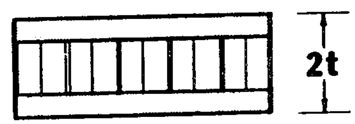
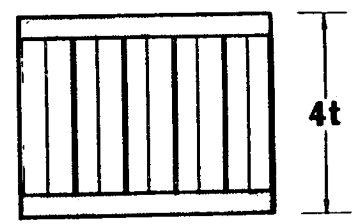
- Understand the fabrication sequence/method
- Use the right core
- Simplify tooling by allowing post-bonding structural additions
- Do not hesitate to use several joining methods in the same part
- Use bolts and rivets for carrying loads
- Use doublers where needed

Doublers are facing reinforcements put into or on a sandwich panel in areas of high stress. [26]



SANDWICH CONSTRUCTION

[26]

			
Relative Stiffness (D)	100	700	3700
Relative Strength	100	350	925
Relative Weight	100	103	106

AN EXAMPLE OF HOW HONEYCOMB STIFFENS A STRUCTURE WITHOUT INCREASING ITS WEIGHT [26]

COMPARISON OF TYPICAL PROPERTIES OF HONEYCOMB CORE MATERIALS [26]

Considerations	5052 5056 CR 111	2024 CR 111	ACG CR 111	HRP	HFT	NP	HRH 327	HRH 10	WR II
Cost	Mod.	High	Low	Mod.	Mod.	Mod.	High	Mod.	Low
Max. Service Temp.	350°F	420°F	350°F	350°F	375°F	180°F	500°F	350°F	180°F
Flamability	E	E	E	E	E	E	E	E	P
Impact Resistance	G	G	G	F	G	F	F	E	F
Moisture Resistance	E	E	E	E	E	E	E	E	G
Fatigue Strength	G	G	G	G	G	G	G	E	F
Heat Transfer	High	High	High	Low	Low	Low	Low	Low	Low

EXAMPLE OF MECHANICAL PROPERTY TABLES FROM TSB 120

The following tables contain a sampling of mechanical properties of the various honeycomb core types for which Hexcel has developed data. See TSB120 for more complete information.

5052 ALLOY HEXAGONAL ALUMINUM HONEYCOMB

HEXCEL HONEYCOMB DESIGNATIION Cell-Material-Gage	Nominal Density pcf	COMPRESSIVE					Crush Strength psi	PLATE SHEAR					
		Bare		Stabilized				"L" Direction			"W" Direction		
		Strength psi		Strength psi		Modulus ksi		Strength psi		Modulus ksi	Strength psi		Modulus ksi
		typ	min	typ	min	typ	typ	typ	min	typ	typ	min	typ
1/8-5052-.0007	3.1	285	200	300	215	75	130	210	155	45.0	130	90	22.0
1/8-5052-.001	4.5	550	375	570	405	150	260	340	285	70.0	220	168	31.0
1/8-5052-.0015	6.1	1000	650	1040	680	240	450	550	455	98.0	320	272	41.0
1/8-5052-.002	8.1	1485	1000	1515	1100	350	750	725	670	135	455	400	54.0
3/16-5052-.001	3.1	315	200	335	215	75	130	210	155	45.0	130	90	22.0
3/16-5052-.0015	4.4	560	360	590	385	145	250	330	280	68.0	215	160	30.0
3/16-5052-.002	5.7	820	560	860	600	220	390	460	410	90.0	300	244	38.5
1/4-5052-.001	2.3	210	120	230	130	45	75	140	100	32.0	85	57	16.2
1/4-5052-.0015	3.4	375	240	385	250	90	150	235	180	50.0	150	105	24.0
1/4-5052-.002	4.3	500	350	560	370	140	230	320	265	66.0	210	155	29.8
1/4-5052-.004	7.9	1420	970	1490	1050	340	725	700	650	130	440	390	52.8
3/8-5052-.0007	1.0	45	20	50	20	10	25	45	32	12.0	30	20	7.0
3/8-5052-.001	1.6	300	190	315	200	20	40	85	60	21.0	50	32	11.0

5056 HEXAGONAL ALUMINUM HONEYCOMB

1/8-5056-.0007	3.1	340	250	360	260	97	170	250	200	45.0	155	110	20.0
1/8-5056-.001	4.5	670	475	700	500	185	320	425	350	70.0	255	205	28.0
3/16-5056-.001	3.1	405	250	420	260	97	170	255	200	45.0	155	110	20.0
1/4-5056-.001	2.3	240	145	265	155	58	100	170	130	32.0	105	62	15.0

2024 HEXAGONAL ALUMINUM HONEYCOMB

1/8-2024-.0015	5.0	810	525	840	620	200	425	500	400	82.0	315	250	33.0
1/8-2024-.003*	9.5	2375	1475	2500	1725	480	1120	1150	950	170	650	585	64.0
3/16-2024-.0015	3.5	400	250	500	290	86	200	290	230	55.0	180	143	23.0
1/4-2024-.0015	2.8	290	165	320	175	40	110	200	140	42.0	120	88	19.0

5052 ALUMINUM FLEX-CORE

5052/F40-.0013	2.1	300	126	225	157	65	80	90	63	18	50	37	10
5052/F40-.0019	3.1	370	238	400	280	125	165	180	126	32	110	75	13
5052/F80-.0019	6.5	1000	700	1050	735	310	—	440	308	72	240	180	24
5052/F80-.0025	8.0	1790	1100	1850	1120	400	—	620	434	98	345	260	31

HONEYCOMB MATERIALS

ALUMINUM COMMERCIAL GRADE—ALUMINUM NAVAL GRADE HEXAGONAL HONEYCOMB

HEXCEL HONEYCOMB DESIGNATION Material-Cell-Gage	Nominal Density pcf	COMPRESSIVE			Crush Strength psi	PLATE SHEAR			
		Bare	Stabilized			"L" Direction		"W" Direction	
		Strength psi	Strength psi	Modulus ksi		Strength psi	Modulus ksi	Strength psi	Modulus ksi
		typ.	typ.	typ.	typ.	typ.	typ.	typ.	typ.
ACG 1/4-.003	5.2	620	650	148	245	345	63	215	31
ACG 3/8-.003	3.6	325	340	92	120	210	40	130	20
ACG 1/2-.003	2.5	165	170	40	60	130	25	70	15
ACG 3/4-.003	1.8	110	120	24	45	95	16	55	8.0
ACG 1- -.003	1.4	75	80	16	25	55	14	40	7.0
ANG-2 3/8	3.7	370	390	105	180	260	55	170	26

HRP GLASS REINFORCED PHENOLIC HONEYCOMB

HEXCEL HONEYCOMB DESIGNATION Material-Cell-Density	COMPRESSIVE					PLATE SHEAR					
	Bare		Stabilized			"L" Direction			"W" Direction		
	Strength psi		Strength psi		Modulus ksi	Strength psi		Modulus ksi	Strength psi		Modulus ksi
	typ	min	typ	min	typ	typ	min	typ	typ	min	typ
HRP-3/16-4.0	500	350	560	480	57	290	210	11	160	130	5.0
HRP-3/16-5.5	800	570	870	750	95	435	350	19	240	200	8.5
HRP-1/4-3.5	375	280	455	400	46	230	170	11	130	100	3.5
HRP-3/8-3.2	320	260	440	350	38	200	160	11	105	85	3.0

HFT GLASS REINFORCED PHENOLIC HONEYCOMB

HEXCEL HONEYCOMB DESIGNATION Material-Cell-Density	COMPRESSIVE			PLATE SHEAR					
	Stabilized			"L" Direction			"W" Direction		
	Strength psi		Modulus ksi	Strength psi		Modulus ksi	Strength psi		Modulus ksi
	typ	min	typ	typ	min	typ	typ	min	typ
HFT-1/8-5.5	890	640	69	460	360	40	230	180	14
HFT-3/16-4.0	590	430	44	275	210	30	140	115	14

HRH-327 GLASS REINFORCED POLYIMIDE HONEYCOMB

HRH 327-3/16-4.5	520	400	58	320	220	33	150	110	11
HRH 327-3/16-8.0	1210	1000	126	700	490	62	420	300	22

WR II SHELTER CORE

HEXCEL HONEYCOMB DESIGNATION Material-Cell-Density	COMPRESSIVE			PLATE SHEAR			
	Bare	Stabilized		"L" Direction		"W" Direction	
	Strength psi	Strength psi	Modulus ksi	Strength psi	Modulus ksi	Strength psi	Modulus ksi
	typ	typ	typ	typ	typ	typ	typ
WR II-3/8-2.5	260	340	33	170	13	100	7.0
WR II-3/8-3.8	515	570	55	255	19	175	9.0

HONEYCOMB MATERIALS

HRH-10 ARAMID FIBER REINFORCED HONEYCOMB

HEXCEL HONEYCOMB DESIGNATION	COMPRESSIVE					PLATE SHEAR					
	Bare		Stabilized			"L" Direction			"W" Direction		
	Strength psi		Strength psi		Modulus ksi	Strength psi		Modulus ksi	Strength psi		Modulus ksi
Material-Cell-Density Gage Hexagonal	typ	min	typ	min	typ	typ	min	typ	typ	min	typ
HRH10-1/8-1.8(1.5)	110	70	130	85	—	90	65	3.7	50	36	2.0
HRH10-1/8-6.0(3)	1075	800	1125	825	60	370	260	13.0	200	135	6.0
HRH10-3/16-3.0(2)	300	210	370	270	20	160	130	5.8	90	70	3.5
HRH10-3/8-2.0(2)	150	80	170	105	11	110	72	4.2	55	36	2.2
HRH10/OX-3/16-3.0(2)	365	255	400	270	17	125	95	3.0	140	105	6.0
FLEX-CORE											
HRH10/F35-2.5(3)	200	140	235	175	12^{p}	130	105	4.0^{p}	65	40	1.9^{p}
HRH10/F50-3.5(3)	355	245	435	340	24	190	125	5.7^{p}	80	55	4.0

COMMON ADHESIVES IN CURRENT USE

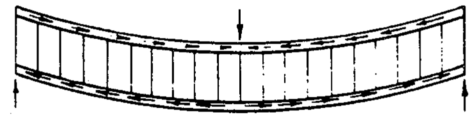
ADHESIVE TYPE	TRADE DESIGNATION	MANUFACTURER
Nitrile Phenolic Films	FM 238, FM 47	American Cyanamid
	AF 30, AF 31, AF 32	3M Company
	Metlbond 402	Narmco
	Plastilock 655, 638, 620, 650	BF Goodrich
Modified Epoxy Liquid and Pastes	M-6803, M-6860	Narmco
	R471	Ciba-Geigy
	EA 9320, EA 9309, EA 934	Hysol
	MA 1015, MA 2021	McCann Adhesives
	Crest 142, 471,3181, 3135	Crest Products
	EC 2216	3M Company
	A1396B, A1444B, A1446B	BF Goodrich
	Strucol R380	Hexcel SA, Belgium
	HP 326	Hexcel Corporation
Modified Epoxy Film 250°F Cure and Below	EA 9601, EA 9602.3, EA 9628	Hysol
	MA 229, MA 429, MA 456	McCann Adhesives
	FM 24, FM 53, FM 73, FM 123, FM 137	American Cyanamid
	Metlbond 117, M1113, M1133, M1137, M1204	Narmco
	Plastilock 717B	BF Goodrich
	R393, R7114	Ciba-Geigy
	AF 126, AF 126-2	3M Company
	HP 347 (Cell Edge) (Hexabond®)	Hexcel Corporation
	Structufilm R382	Hexcel SA, Belgium
	F 185	Hexcel Corporation
Modified Epoxy Film 350°F Cure	Metlbond 328, 329, 329-1, 1515	Narmco
	AF 130, AF 143, AF 147	3M Company
	FM 61, FM 96, FM 150-2, FM 300, FM 400, HT 424	American Cyanamid
	Plastilock 729-3	BF Goodrich
	MA 529	McCann Adhesives
	EA 9649	Hysol
	Structufilm R398	Hexcel SA, Belgium
Epoxy/Polyimide Film	A1177B, A1273B	BF Goodrich
	EA 951	Hysol
	FM 1000	American Cyanamid
Polyimide Films	FM 34B-18	American Cyanamid
	HP 955, HP 956	Hexcel Corporation
Modified Urethane Pastes, Liquids	Crest 7410, 7450, 7395	Crest Products
	Metlbond 6872, 6875, 6876	Narmco
	EC 3549	3M Company
	Plastilock 550	BF Goodrich
	Morad 336	Morton Chemical
Core Splicing Adhesives Pastes and Tapes	Crest 3181, 3158	Crest Products
	Metlbond 6602, 6607, 6601, 6603	Narmco
	FM 37, FM 39, FM 40, FM 41, FM 47-Type 0, FM 404	American Cyanamid
	MA 550, MA 2150	McCann Adhesives
	EA 9815, Thermofoam 3050, Thermofoam 3056	Hysol
	AF 3002, AF 3015	3M Company
	HP 905, HP 906	Hexcel Corporation
	Plastilock 654, 658	BF Goodrich
	Strucol 370, 370B	Hexcel SA, Belgium

NOTE: The use of a corrosion inhibiting primer on metal facings is strongly advised. This step improves resistance to bond-line corrosion and greatly increases durability. It also allows for lengthy storage of ready-to-bond details, or making them into riveted sub-assemblies, without the need for re-cleaning immediately prior to bonding. One corrosion inhibiting primer, BR 127 (American Cyanimid), seems to have gained acceptance for use with a number of adhesive systems. However, conditions of use must be very carefully controlled and be consistent with recommendations of both the adhesive supplier and the primer supplier if optimum results are to be achieved. FM 47 is also used as a primer for some services. PPG corrosion inhibiting primer UC 40485 has also proved successful.

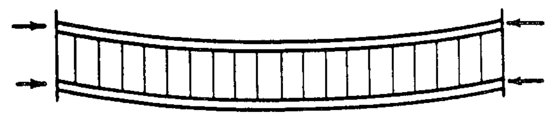
DESIGN REQUIREMENTS, MODES OF LOADING AND FATIGUE

Sandwich structures should be designed to meet the basic structural criteria listed below when these criteria pertain to the type of loading under consideration.

FIGURE 3

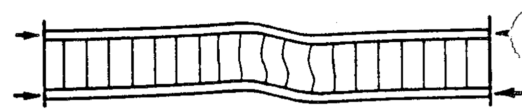


1) The facings should be thick enough to withstand the tensile, compressive, and shear stresses induced by the design load.

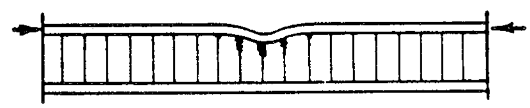


2) The core should have sufficient strength to withstand the shear stresses induced by the design loads. Adhesive must have sufficient strength to carry shear stress into core.

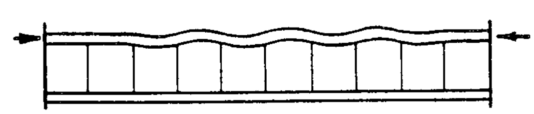
3) The core should be thick enough and have sufficient shear modulus to prevent overall buckling of the sandwich under load, and to prevent crimping.



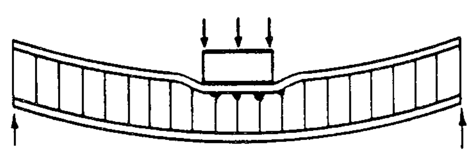
4) Compressive modulus of the core and the compressive modulus of the facings should be sufficient to prevent wrinkling of the faces under design load.



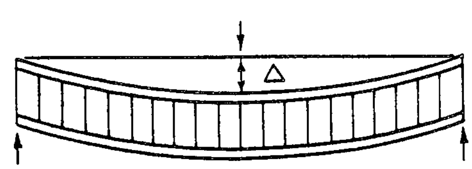
5) The core cells should be small enough to prevent intra-cell dimpling of the facings under design load.



6) The core should have sufficient compressive strength to resist crushing by design loads acting normal to the panel facings or by compressive stresses induced through flexure.



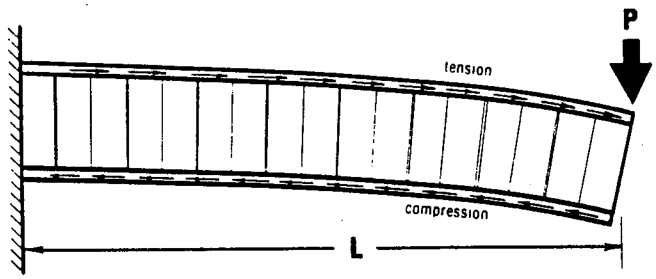
7) The sandwich structure should have sufficient flexural and shear rigidity to prevent excessive deflections under design load.



HOW SANDWICH BEAMS WORK

FIGURE 4

BENDING:



Consider, for example, a cantilever beam one inch wide with a length, L, and a load, P, at its end, as shown in Fig. 4. This load creates a moment, M, which in this case is equal to P × L at the fixed end. It also sets up tension and compression stresses within the structure. The magnitude of these induced stresses is related to the moment. For the sandwich beam the tensile and compressive force in the facing times the distance between the facing centroids equals the moment. Or the facing stress equals:

$$\text{The bending stress in the facings} = \frac{\text{Moment M}}{\text{thickness of a facing x distance between facing centroids}}$$

SHEAR:

The load also imparts a shearing action within the structure. This shear force is taken up by the honeycomb which prevents the top and bottom facings from slipping. The shear force, V, may vary along the beam if a uniform load is applied. The maximum shear force for various load and support conditions is shown in Fig. 7. The shear stress in the core is related to V by the distance between the facing centroids.

$$\text{The shear stress in the core} = \frac{\text{Shear Load V}}{\text{distance between facing centroids}}$$

DEFLECTION:

The total deflection of a honeycomb sandwich structure is calculated by adding the deflection caused by the bending reaction and the shear reaction within the structure. Fig. 5 demonstrates the individual deflection and shows that the deflection in each case is the result of the basic elastic properties of the stressed materials involved. Thus the bending deflection is related to the modulus of elasticity of the facings, and the shear deflection is related to the core shear modulus.

NOTE: Deflections of cantilever beams may vary considerably from the basic formula depending upon core characteristics, and the details of anchoring the beam.

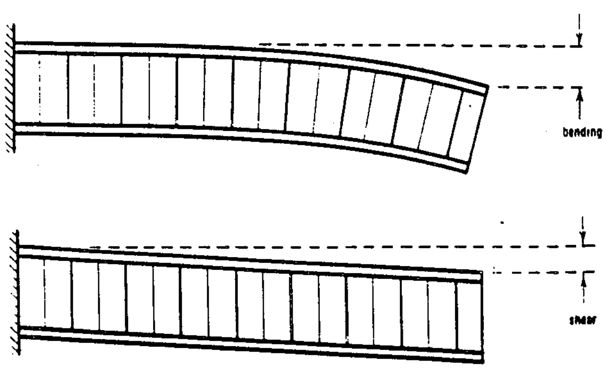
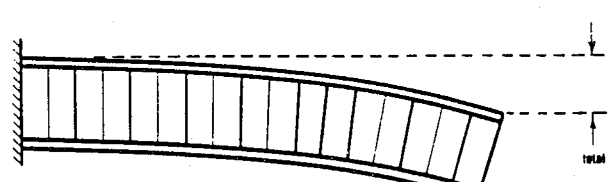


FIGURE 5

Total deflection = bending deflection + shear deflection.



ANALYSIS OF FLAT RECTANGULAR SANDWICH BEAMS

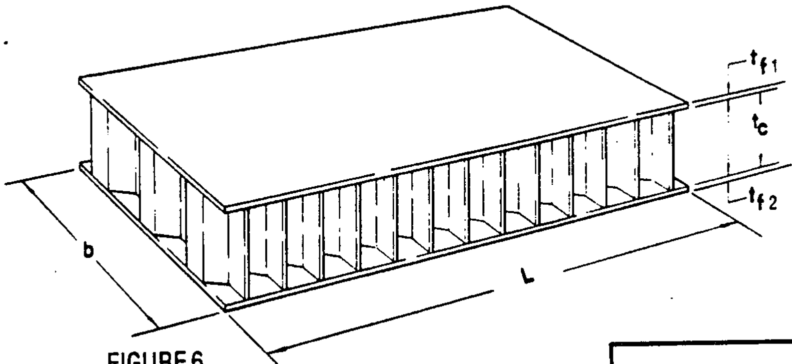


FIGURE 6

$$h = \frac{t_{f1}}{2} + \frac{t_{f2}}{2} + t_c$$

BENDING STRESS IN FACINGS

$$\sigma_{fi} = \frac{M}{t_{fi} h b} \quad i = 1 \text{ or } 2$$

where M is determined by Figure 7

CORE SHEAR STRESS

$$\tau_c = \frac{V}{hb}$$

V is from Figure 7

DEFLECTION K_b and K_s from Figure 7

$$\Delta = \frac{2K_b P L^3 \lambda}{E_f t_f h^2 b} + \frac{K_s P L}{h G_c b} \quad \text{(for same skin materials)}$$

or

$$\Delta = \frac{K_b P L^3}{D} + \frac{K_s P L}{h G_c b} \quad \text{(see D below)}$$

(For most long beams, the second term is relatively small, but should be checked if deflection is critical.)

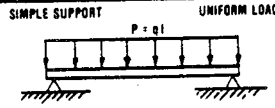
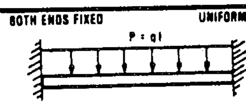
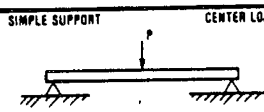
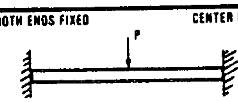
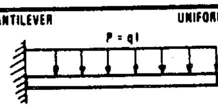
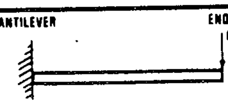
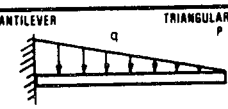
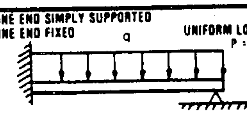
FACE DIMPLING

$$\sigma_{CR} = \frac{2E_f}{\lambda}\left[\frac{t_f}{s}\right]^2$$

FACE WRINKLING

$$\sigma_{CR} = 0.82\,E_f\left[\frac{E_c t_f}{E_f t_c}\right]^{1/2}$$

FIGURE 7
BEAM CHART

BEAM TYPE	MAXIMUM SHEAR FORCE V	MAXIMUM BENDING MOMENT M	BENDING DEFLECTION CONSTANT K_b	SHEAR DEFLECTION CONSTANT K_s
SIMPLE SUPPORT, UNIFORM LOAD, P = ql 	0.5P	0.125PL	0.01302	0.125
BOTH ENDS FIXED, UNIFORM LOAD, P = ql 	0.5P	.08333PL	.002604	0.125
SIMPLE SUPPORT, CENTER LOAD, P 	0.5P	0.25PL	0.02083	0.25
BOTH ENDS FIXED, CENTER LOAD, P 	0.5P	0.125PL	.00521	0.2[illegible]
CANTILEVER, UNIFORM LOAD, P = ql 	P	0.5PL	0.125	0.5
CANTILEVER, END LOAD, P 	P	PL	0.3333	1
CANTILEVER, TRIANGULAR LOAD, q, P = ½ql 	P	0.3333PL	0.06666	0.3333
ONE END SIMPLY SUPPORTED, ONE END FIXED, UNIFORM LOAD, q, P = ql 	0.625P	0.125PL	0.005405	.07042

*If deflections are critical, actual deflections should be verified by tests

$$D = \frac{E_1 t_1 E_2 t_2 h^2 b}{E_1 t_1 \lambda_2 + E_2 t_2 \lambda_1} \quad \text{or} \quad \frac{E t_1 t_2 h^2 b}{(t_1 + t_2)\lambda} \quad \text{or} \quad \frac{E t h^2 b}{2\lambda}$$

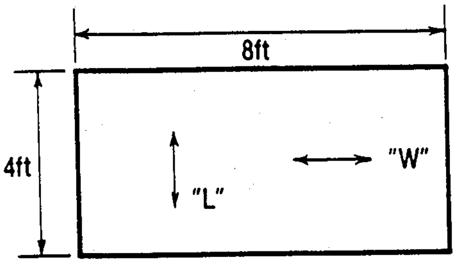
LIST OF TERMS

- P = Total Load
- L = Span
- σ_f = Facing Stress
- t_f = Skin Thickness
- h = Centroid Distance
- τ_c = Core Shear Stress
- Δ = Deflection
- E_f = Facing Modulus
- G_c = Core Shear Modulus
- b = Width
- σ_{CR} = Critical Facing Stress
- D = Panel Stiffness
- $\lambda = 1 - \mu^2$
- μ = Facing Poisson's Ratio
- S = Cell Size
- E_c = Core Compression Modulus
- t_c = Core Thickness
- I = Moment of Inertia

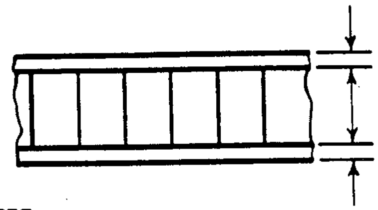
SAMPLE PROBLEMS

Examples are shown for these cases:

A. Simply Supported Column. B. Simply Supported Beam. C. Simply Supported Plate



PANEL TO BE ANALYZED

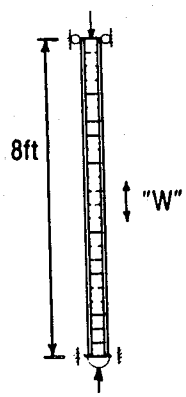


0.020" Al. 5052-H34
1.000" 3/8-5052-.002-3.0
0.020" Al. 5052-H34

MATERIAL PROPERTIES

Facings, Al. 5052-H34: F_{cy} = 24 ksi, E_f = 10.1 msi, λ = 0.89
Core, 3/8-5052-.002-3.0: σ_c = 200 psi, E_c = 70 ksi, τ_L = 145 psi,
G_L = 43.0 ksi, τ_W = 85 psi, G_W = 21.2 ksi

A. Simply Supported Column



P = 4000 lbs.

b = 4 ft.

$$\text{PANEL STIFFNESS, } D = \frac{E_f t_f h^2 b}{2\lambda} = \frac{(10.1 \times 10^6)(0.020)(1.020)^2(48)}{2(0.89)} = 5.67$$

$$\text{PANEL RIGIDITY, } U_W = h\, G_c^W\, b = (1.020)(21{,}200)(48) = 1.04 \times 10^6$$

$$U_L = h\, G_c^L\, b = (1.020)(43{,}000)(48) = 2.11 \times 10^6$$

1. **CHECK FACING YIELDING —**

$$\sigma_f = \frac{P}{2t_f b} = \frac{4000}{2(0.020)(48)} = 2{,}083 \text{ psi}$$

$$F.S. = \frac{24{,}000}{2{,}083} = 11.5$$

2. **CHECK COLUMN BUCKLING —**

$$P_{CR} = \frac{\pi^2 D}{L^2 + \frac{\pi^2 D}{U}}$$

$$P_{CR} = \frac{\pi^2\,(5.67 \times 10^6)}{(96)^2 + \frac{\pi^2 (5.67 \times 10^6)}{1.04 \times 10^6}} = 6040 \text{ lbs.}$$

$$F.S. = \frac{6040}{4000} = 1.5$$

3. **CHECK SHEAR CRIMPING —**

$$P_{CR} = t_c G_c b = (1.00)(21{,}200)(48) = 1.02 \times 10^6 \text{ lbs.}$$

$$F.S. = \frac{1.02 \times 10^6}{4000} = 254$$

4. **CHECK FACING DIMPLING —**

$$\sigma_{CR} = \frac{2E_f}{\lambda}\left[\frac{t_f}{s}\right]^2$$

$$\sigma_{CR} = \frac{2(10.1 \times 10^6)}{0.89}\left[\frac{0.020}{0.375}\right]^2 = 64{,}560 \text{ psi}$$

64,560 psi > 24,000 ∴ NOT CRITICAL!

5. **CHECK FACING WRINKLING —**

$$\sigma_{CR} = 0.82\, E_f \left[\frac{E_c t_f}{E_f t_c}\right]^{1/2}$$

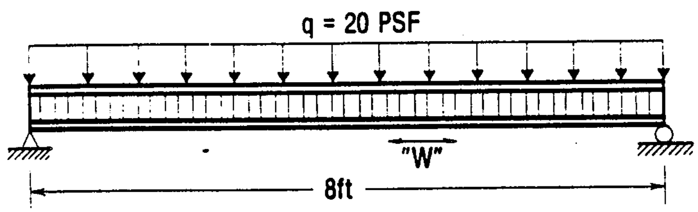
$$\sigma_{CR} = 0.82(10.1 \times 10^6)\left[\frac{(70{,}000)(0.020)}{(10.1 \times 10^6)(1.000)}\right]^{1/2} = 97{,}500 \text{ p}$$

97,500 psi > 24,000 ∴ NOT CRITICAL!

6. **CHECK FACTOR-OF-SAFETY —**

MINIMUM F.S. (COLUMN BUCKLING) = 1.5

B. Simply Supported Beam



b = 4 ft.

$P = 20(8)(4) = 640$ lbs.

$V_{max} = 0.5P = 0.5(640) = 320$ lbs.

$M_{max} = 0.125PL = 0.125(640)(96) = 7680$ in-lbs.

CHECK FACING YIELDING —

$$\sigma_f = \frac{M}{t_f h b} = \frac{7680}{(0.020)(1.020)(48)} = 7{,}843 \text{ psi}$$

$$F.S. = \frac{24{,}000}{7{,}843} = 3.1$$

2. CHECK CORE SHEAR STRESS —

$$\tau_c = \frac{V}{h b} = \frac{320}{(1.020)(48)} = 6.54 \text{ psi}$$

$$F.S. = \frac{85(0.93)^*}{6.54} = 12.1$$

*Correction Factor for 1" Thick Al. H/C, TSB 120

3. CHECK BEAM DEFLECTION —

$$\Delta = K_b \frac{PL^3 2\lambda}{E_f t_f h^2 b} + K_s \frac{PL}{h G_c b}$$

$$\Delta = \frac{(0.0130)(640)(96)^3(2)(0.89)}{(10.1 \times 10^6)(0.020)(1.020)^2(48)} + \frac{(0.125)(640)(96)}{(1.020)(21{,}200)(48)} = 1.31''$$

1.30" 0.01"

If this deflection is excessive, see step 7.

4. CHECK FACING DIMPLING —

$$\sigma_{CR} = \frac{2E_f}{\lambda}\left[\frac{t_f}{s}\right]^2 = \frac{2(10.1 \times 10^6)}{0.89}\left[\frac{0.020}{0.375}\right]^2 = 64{,}560$$

64,560 psi > 24,000 ∴ NOT CRITICAL!

5. CHECK FACING WRINKLING —

$$\sigma_{CR} = 0.82 E_f \left[\frac{E_c t_f}{E_f t_c}\right]^{1/2}$$

$$\sigma_{CR} = 0.82(10.1 \times 10^6)\left[\frac{(70{,}000)(0.020)}{(10.1 \times 10^6)(1.000)}\right]^{1/2} = 97{,}500$$

97,500 psi > 24,000 ∴ NOT CRITICAL!

6. CHECK FACTOR-OF-SAFETY —

MINIMUM F.S. (FACE YIELDING) = 3.1

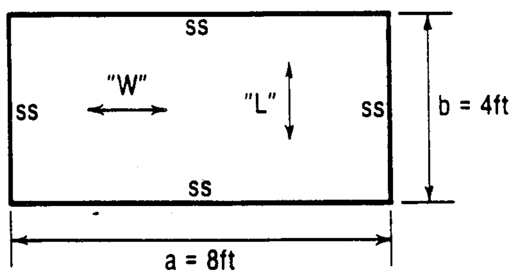
7. REDUCE DEFLECTION — USE 2" THICK CORE

$$\Delta = \frac{(0.0130)(640)(96)^3(2)(0.89)}{(10.1 \times 10^6)(0.020)(2.020)^2(48)} + \frac{(0.125)(640)(96)}{(2.020)(21{,}200)(48)} = 0$$

0.33" 0.00"

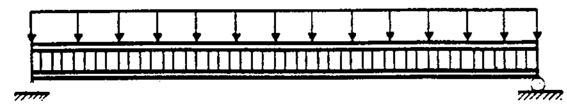
SAMPLE PROBLEMS

C. Simply Supported Plate (from MIL HDBK-23)



a > b

UNIFORM LOAD,
$p = 20 \text{ psf} = 0.139 \text{ lbs/in}^2$



Simply supported all four edges

1. DETERMINE PLATE COEFFICIENTS —

$$\frac{b}{a} = \frac{48}{96} = 0.50$$

$$R = \frac{G_b}{G_a} = \frac{43{,}000}{21{,}200} = 2.03$$

USE R = 2.5 (see Figure 8)

$$V = \frac{\pi^2 E_f t_f h^2}{2b^2 h G_c \lambda}$$

$$V = \frac{\pi^2(10.1 \times 10^6)(0.020)(1.020)^2}{2(48)^2(1.020)(21{,}200)(0.89)} = 0.023$$

FROM FIGURE 8 $K_1 = 0.0105$
FIGURE 9 $K_2 = 0.103$
FIGURE 10 $K_3 = 0.37$

2. CHECK PANEL DEFLECTION —

$$\Delta = \frac{2K_1 p b^4 \lambda}{E_f t_f h^2}$$

$$\Delta = \frac{2(0.0105)(0.139)(48)^4(0.89)}{(10.1 \times 10^6)(0.020)(1.020)^2} = 0.066$$

3. CHECK FACING STRESS —

$$\sigma_f = \frac{K_2 p b^2}{h t_f} = \frac{(0.103)(0.139)(48)^2}{(1.020)(0.020)} = 1{,}617 \text{ psi}$$

$$F.S. = \frac{24{,}000}{\ } = 14.8$$

4. CHECK CORE SHEAR STRESS —

$$\tau_c^w = \frac{K_3 p b}{h} = \frac{(0.37)(0.139)(48)}{1.020} = 2.42 \text{ psi}$$

$$F.S. = \frac{85(0.93)^*}{2.42} = 32.7$$

* Correction Factor for 1" thick Al. H/C, TSB 120

5. CHECK FACING DIMPLING —

$$\sigma_{CR} = \frac{2E_f}{\lambda}\left[\frac{t_f}{s}\right]^2$$

$$\sigma_{CR} = \frac{2(10.1 \times 10^6)}{0.89}\left[\frac{0.020}{0.375}\right]^2 = 64{,}560 \text{ psi}$$

64,560 psi > 24,000 ∴ NOT CRITICAL!

6. CHECK FACING WRINKLING —

$$\sigma_{CR} = 0.82\, E_f \left[\frac{E_c t_f}{E_f t_c}\right]^{1/2}$$

$$\sigma_{CR} = 0.82(10.1 \times 10^6)\left[\frac{(70{,}000)(0.020)}{(10.1 \times 10^6)(1.000)}\right]^{1/2} = 97{,}500$$

97,500 psi > 24,000 ∴ NOT CRITICAL!

7. CHECK FACTOR-OF-SAFETY —

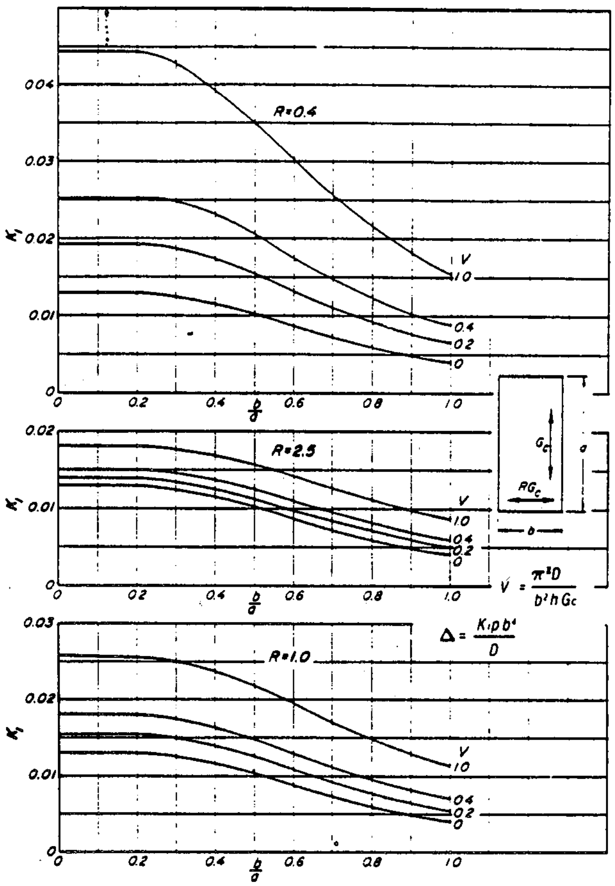


Figure 8 -- K_1, for determining maximum deflection, Δ, of flat rectangular sandwich panels $a > b$

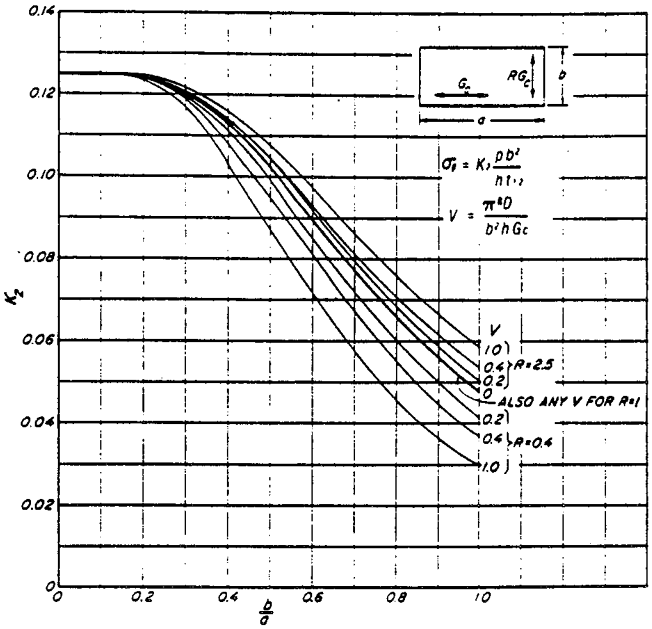


Figure 9 -- K_2, for determining facing stress, σ_f, of flat rectangular sandwich panels $a > b$

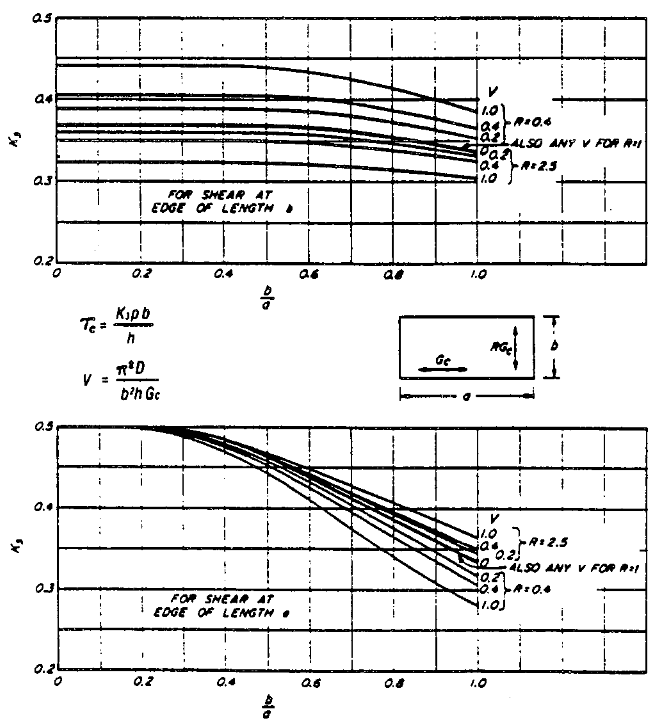
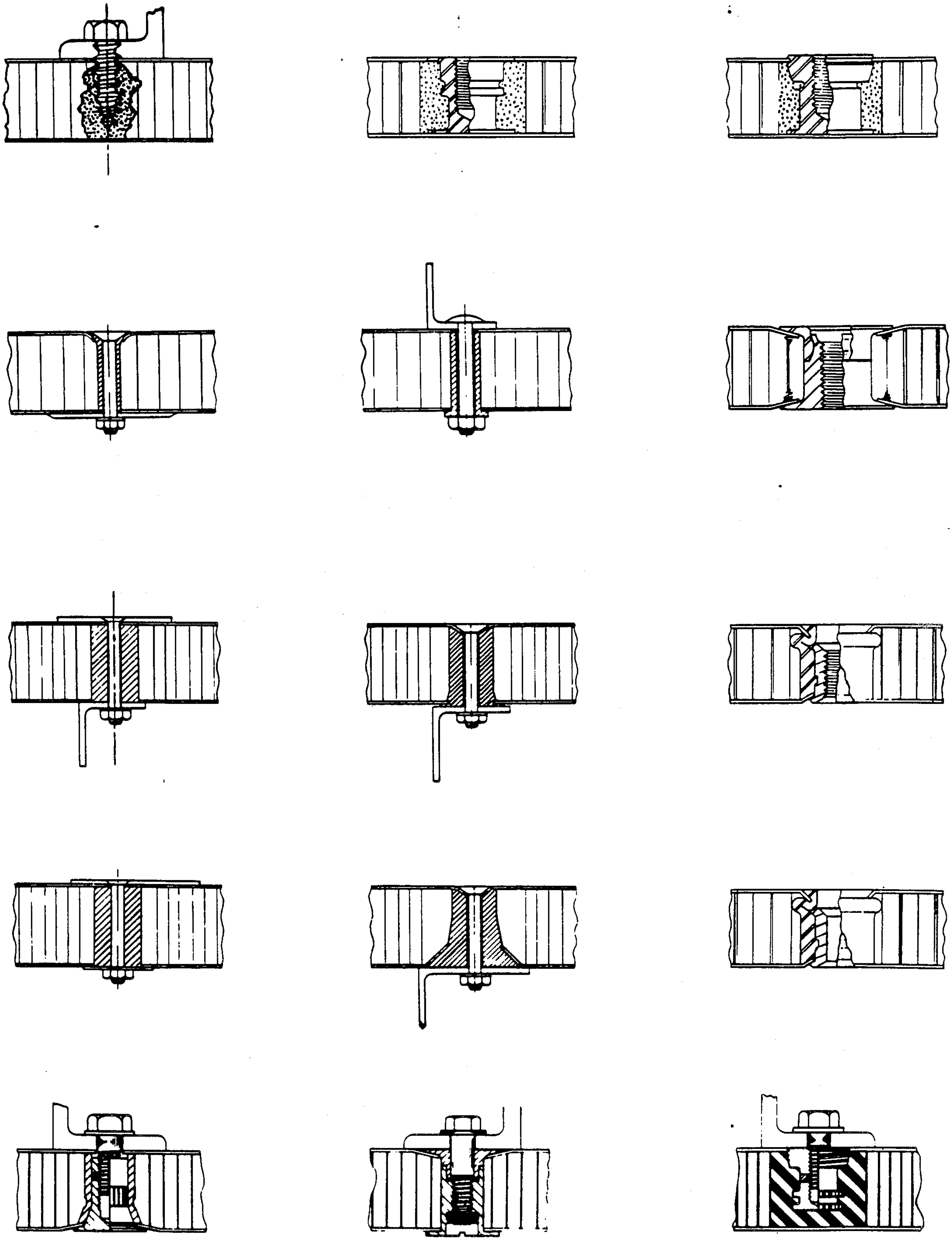


Figure 10 -- K_3, for determining core shear stress, τ_c, for flat rectangular sandwich panels $a > b$

SANDWICH DESIGN (continued)



PROPERTIES OF TYPICAL SANDWICH FACING MATERIAL [26]

Facing Material	Yield Strength f_f — psi	Modulus of Elasticity E_f — psi	$\frac{\lambda_f}{1-\mu^2}$	Weight per Mil Thickness lbs./ft²	Comments
Aluminum					
1100 — H14	13,000C	10.0×10^6	.89	.014	Mod. cost, workable, exc. chemical resistance, scars easily
3003 — H16	18,000C	10.0×10^6	.89	.014	Fair strength, good weather resist., mod. cost
5052 — H34	24,000C	10.1×10^6	.89	.014	Better strength, good weather resist., mod. cost
6061 — T6	35,000C,T	10.0×10^6	.89	.014	Good strength, workable, only heat-treatable alloy easily welded
2024 — T3	42,000T	10.5×10^6	.89	.014	Exc. strength, heat-treatable, soft stage for working, fair corrosion resist.
7075 — T6	66,000T	10.3×10^6	.89	.014	High strength, fair corrosion resist.
Mild Carbon Steel	50,000	29×10^6	.91	.040	Low cost, high weight, good availability
Stainless Steel:					
304 annealed	35,000	28×10^6	.94	.040	
316 annealed	35,000	28×10^6	.94	.040	High cost, corrosion resistant
17-7 ph	155,000	29×10^6	.94	.040	High strength, heat treatable
Graphite Woven	85,000	8.1×10^6	.99	.008 †	High cost, strength & modulus
Graphite Unidirectional	187,000	18.3×10^6	.99	****	High cost, strength & modulus
Fiberglass Prepreg:					
Epoxy F155**	62,000	3.3×10^6	.98	.0095	Exc. strength, low temp. cure
Epoxy F161**	57,900	3.7×10^6	.98	.0090	Heat resist., good strength
Phenolic F120**	48,000	3.5×10^6	.98	.0088	High temp., good strength
Polyester F141**	48,000	3.5×10^6	.98	.0090	Good strength, low cost
Polyimide F174**	60,000	3.5×10^6	.98	.0085	High temp. resistant
Epoxy Unidirectional F155	100,000	6.5×10^6	.98	****	Highest strength
Kevlar F155***	32,000C	4.1×10^6C	1.00	.007	High cost, high tensile
Kevlar F155***	70,000T	4.1×10^6T			Low weight, tough, low compression
Fiberglass Mat., Polyester resin	14,000	0.92×10^6	.98	.007	Very low cost
Woven roving, polyester resin	38,000	1.85×10^6	.98	.007	Very low cost
Ext fir plywood	2,650	1.8×10^6	.99	.003	
Pine plywood	3,000	1.8×10^6	.99	.003	(See Note)
Luan plywood	2,250	1.8×10^6	.99	.002	
Tempered hardwood 70 lb/cu.ft.	3,600	0.65×10^6	.99	.005	Good hardwood, low cost, smooth surface
Gypsum board	120	0.30×10^6	.98	.004	Fire resistant, low cost

*Yield strength is the lower of tensile or compressive.

**All values are with 1581 fabric and autoclave cure.

***Both compressive ("C") and tensile ("T") shown for 285 styles.

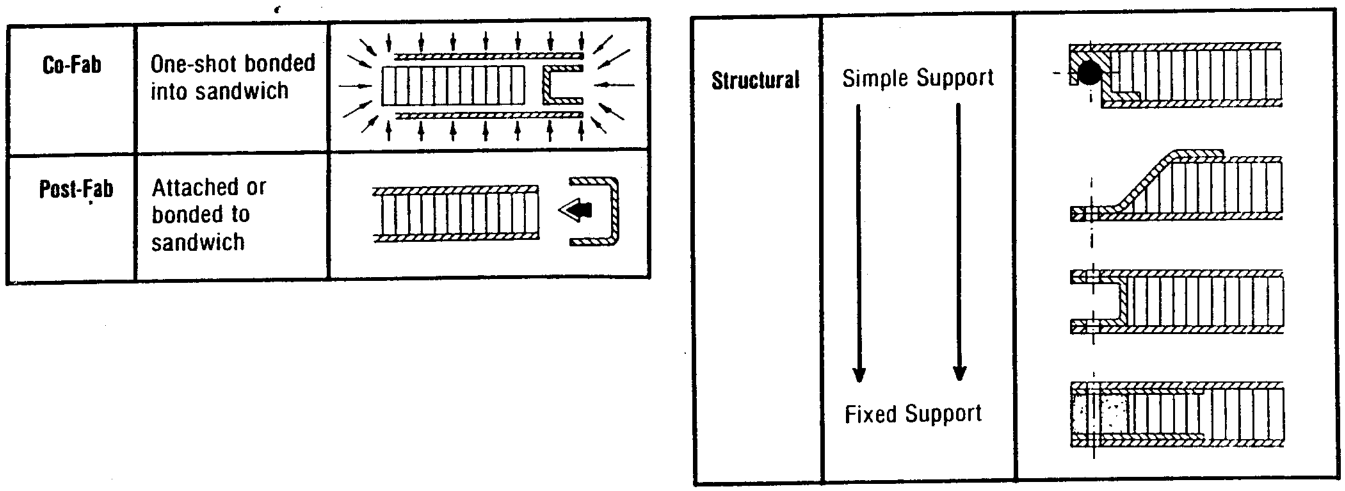
****Dependent on fiber areal weight of 145 g/m².

†3K-70-PU (12" × 12"; Thornel 300/3000 Tow 7 mil/ply)

NOTE: For calculations involving plywood, "Effective thickness" should be used except for locating centroid.

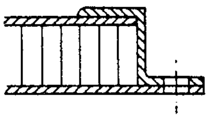
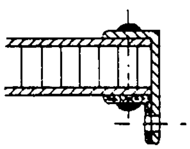
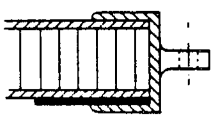
Actual Thickness	Effective Thickness
[illegible]" (.250)	0.14"
[illegible]" (.375)	0.14"
[illegible]" (.500)	0.26"

CLOSE-OUTS AS DEFINED BY THE FABRICATION TECHNIQUE AS WELL AS END-USE

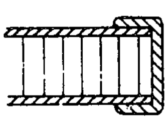
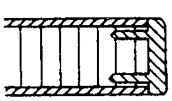
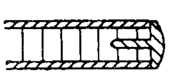
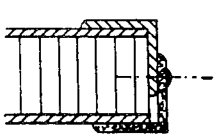


TYPICAL PANEL CLOSE-OUT DESIGNS

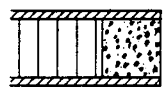
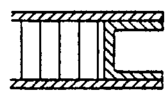
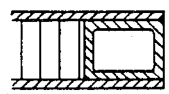
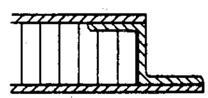
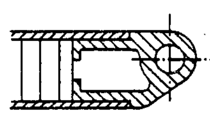
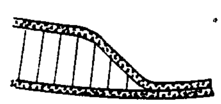
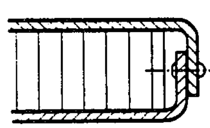
POST-FAB

	Simple support. Special extrusion. Panel is smooth one side.
	Strong. Low cost using standard angle. Pop rivet and bond.
	Special extrusions or castings bonded to panel. Could include doublers.

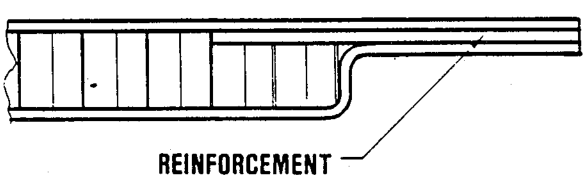
POST-FAB

	Low cost. Simple channel. Can be formed around bends and corners.
	Smooth edge. Special shape. Route core and bond in the legs of extrusion.
	Smooth finish. Low cost. For thin panels. Can be bent by notching legs.
	Standard angles for thick panels and low volume. Pop rivet and bond.

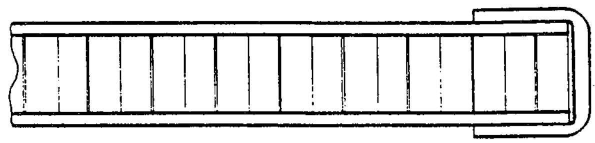
CO-FAB

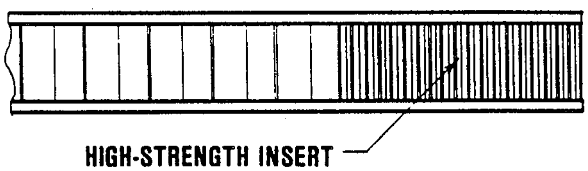
	Low cost. Wood, foam or particle board bonded into panel: or high strength materials. Solid.
	Strong. Low cost. Core bonded to channel for added strength.
	Very strong. Smooth surfaces. More costly.
	Moderate strength. Costly. Requires routing honeycomb.
	Special extrusions castings. Do not project beyond top and bottom
	Chamferred close out. Good for fiberglass prepreg on curved surfaces.
	Low cost. No extra pieces. also with only one side formed.

SANDWICH DESIGN (continued)

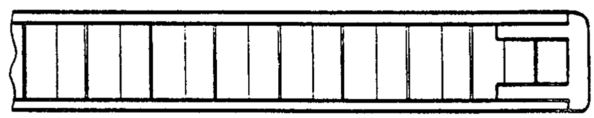


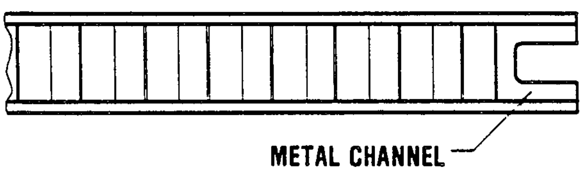
A



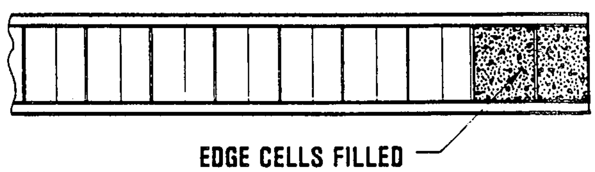


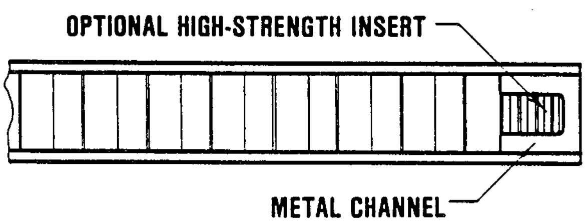
B



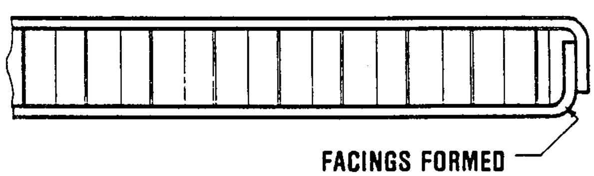


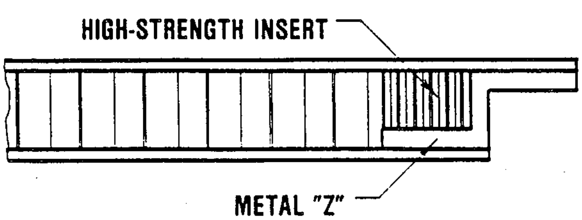
C



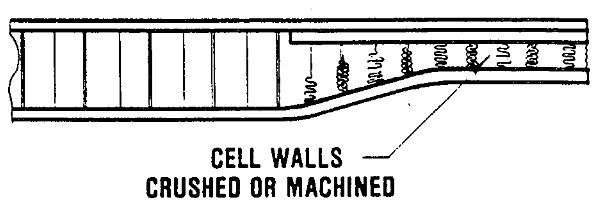


D





E



SANDWICH DESIGN (continued)

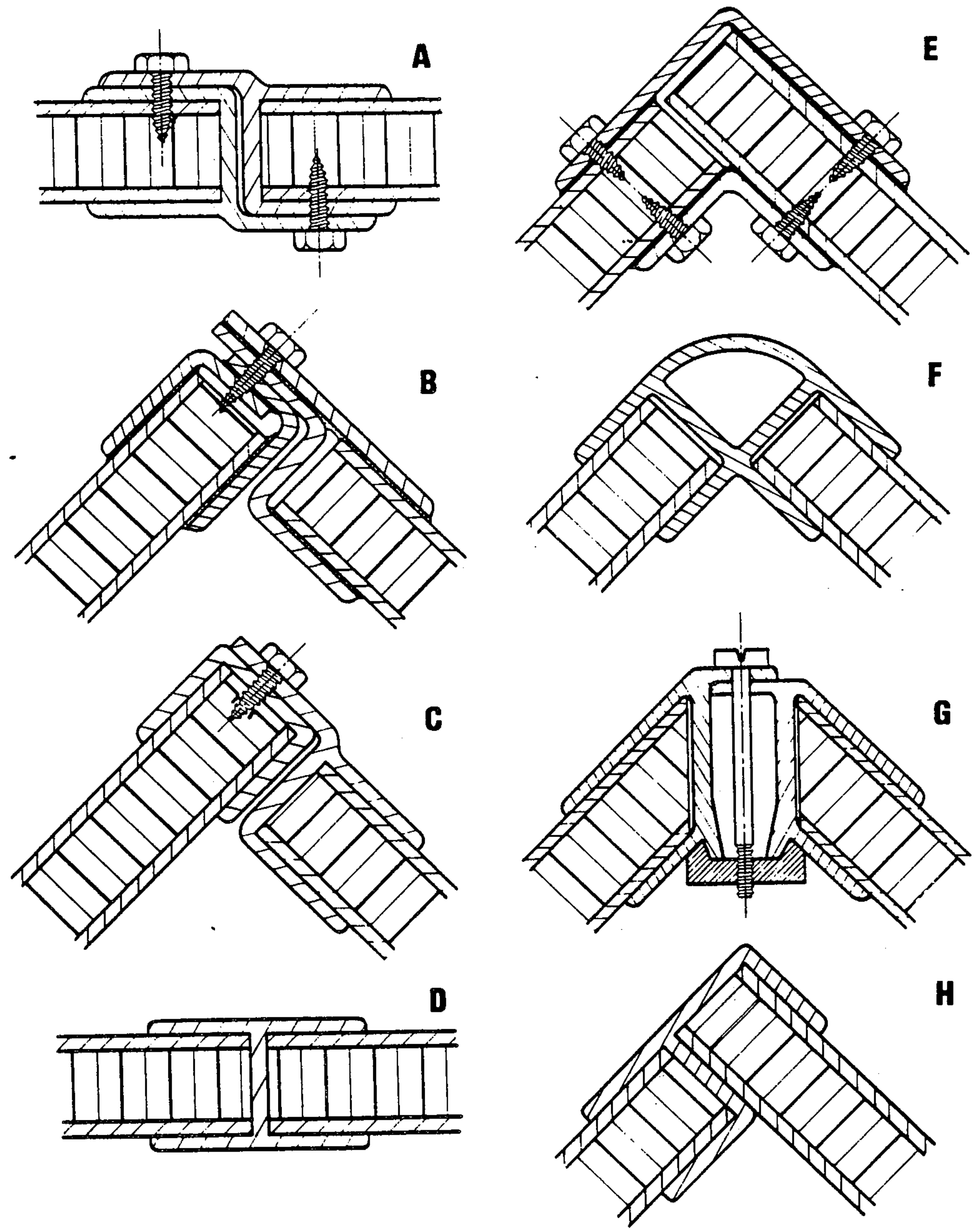
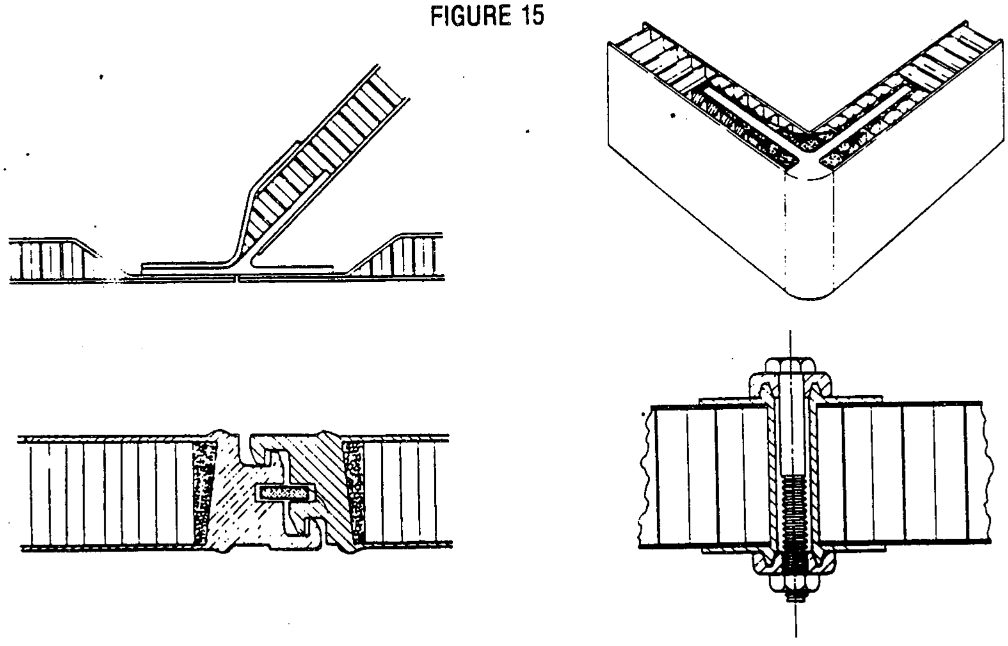


FIGURE 15



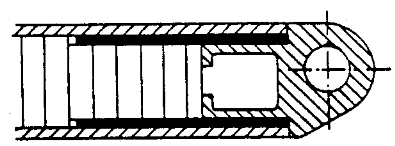
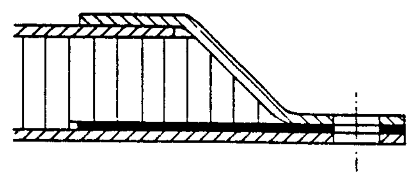
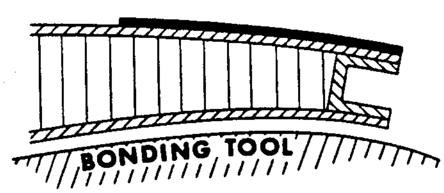
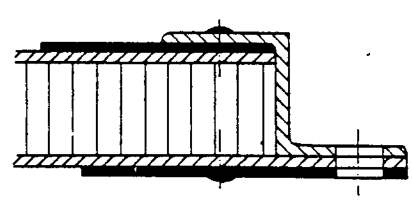
SANDWICH DESIGN (continued)

DOUBLERS

Doublers are facing reinforcements put into or on a sandwich panel in areas of high stress considerations. A doubler should not only distribute high local forces over a larger area, but also should do this as gradually as possible.

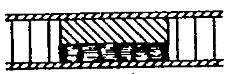
Just like close-outs, a doubler can be incorporated during the panel bonding or be added afterwards. They can be internal or external. However, note that internal doublers, usually require extra machining of the honeycomb. The exception could be when prepreg facings are used and the extra layer(s) of reinforcement are simply added and co-cured.

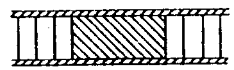
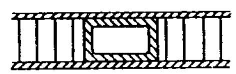
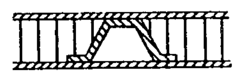
DOUBLERS IN A SANDWICH PANEL

Internal Co-Fab	Doublers on one or both sides. Requires doubler relief cuts in core.	
	Allow ample clearance to position doubler and account for adhesive thickness	
External Co-Fab	Doublers located on "bag" side of the assembly. Co-cured with facings.	
External Post-Fab	Doublers bonded to one or both sides of panel. Pop rivet for alignment.	

SANDWICH DESIGN (continued)

PANEL REINFORCEMENTS FOR CONCENTRATED LOADS

	Foam or epoxy filled. For small, localized areas. Can be drilled.
	High density honeycomb spliced into panel. Low weight and strong.
	Solid block crushed and bonded into core. Reduces shear strength.

	Solid block of foam, metal or plastic bonded in place.
	Extruded shapes for continuous ribs. Very strong. Edge bond core.
	Formed sheet metal for tapered panels. Requires core carving.
	Floor tie-down ring.

PRODUCIBILITY FABRICATION PROCESSES CHECKLIST

- Have proper design specifications been used?
- Do design specifications unduly restrict manufacturing processes?
- Is expensive special tooling or equipment required for manufacturing?
- Have the most economical manufacturing processes been specified?
- Is the design consistent with normal shop flow?
- Is the equipment and tooling list complete?
- Can a simplified manufacturing process be used?
- Are finish requirements clearly understandable?
- Are processes consistent with production quantity requirements?
- Are alternate processes possible within design constraints?

[28]

PRODUCIBILITY ANALYSIS CHECKLIST

Producibilty Objectives in Design

Simultaneous Engineering

- To maximize:
  - Simplicity of design
  - Use of economical materials
  - Standardization of materials and processes
  - Confirmation of design adequacy
  - Process repeatability
  - Product inspectability
  - Acceptable material and processes
  - Alternate methods of manufacture

[28]

- To minimize:
  - Procurement lead time
  - Generation of scrap
  - Pollution
  - Total part count
  - Manufacturing skill levels
  - Use of proprietary items
  - Use of material or process without alternatives

[28]

Producibilty in Composites Design

Objectives:

- Early involvement in design concept
- Design simplicity
- Maximize use of economical methods
- Standardization of materials and components
- Process repeatability
- Product inspectability
- Reduce total part count
- Optimize use of co-cure
- Cost reduction in manufacturing
- Reduced tooling costs
- Cost avoidance through design
- Reduce number of engineering changes

[28]

connects
connects

Effective Producibilty Tools

- Producibility check lists
- Estimates
- Trade studies
- Value Engineering
- Risk reduction testing
- Make or Buy decisions
- Maintainability evaluations
- Collaboration between participants

The fundamental ingredient for an optimal design is a willingness to compromise. [28]

FOR SUCCESS OF DESIGN PRODUCIBILITY EFFORTS

Objectives:

- Early involvement
- Contribute to desgn development and be imaginative
- Conduct risk reduction tests, before funding is committed to a questionable concept
- Utilize checklists
- Be flexible
- Coordinate with all support organizations for back-up data
- Be cost and schedule conscious in an ongoing effort
- Never lose sight of the objective of optimizing design producibility while remaining within design constraints

[28]

SUGGESTED FORMAT FOR PRODUCIBILTY TEAM

- Co-locate team with Design Group
  - Designers
  - Manufacturing Engineers
  - Materials and Processes Engineers

[28]

ORGANIZATIONAL RESPONSIBILTY

- Materials and Processes reporting to Engineering

- Manufacturing Engineering teamed with Materials and Processes reporting to their respective divisions

- Production Engineering reporting to Operations supported by Materials and Processes, Manufacturing Engineering, Value Engineering and Tooling

[28]

Producibility is defined as the inherent elements of a design by which a component or part, while meeting all of its performance objectives within the design constraints, may be produced in the shortest time, at the lowest cost, utilizing the most readily available materials, with the most advantageous processes, equipment and manufacturing methods.

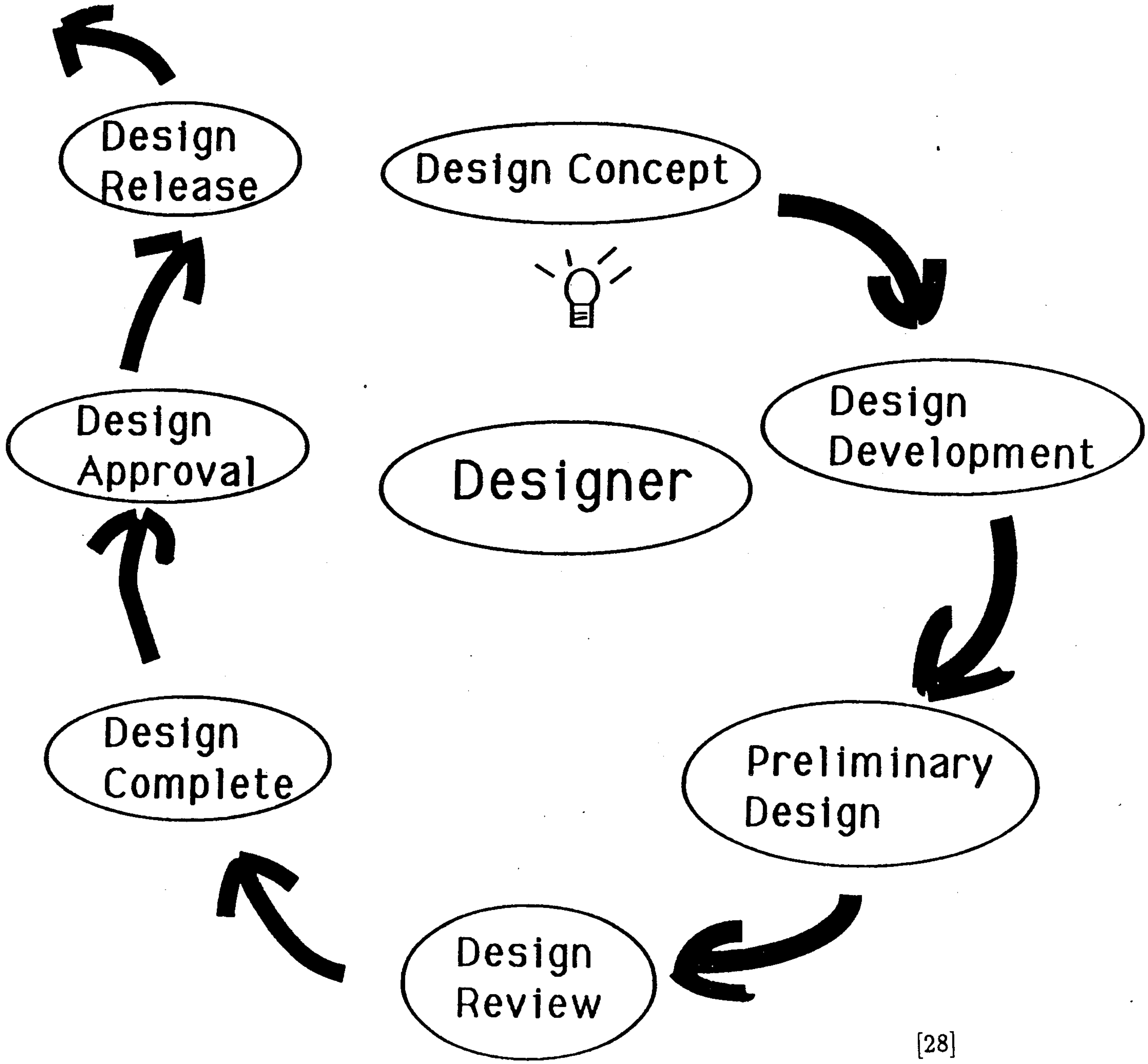
CONSIDERATION OF OBJECTIVES

- Design concept
- Cost reduction through Value Engineering
- Quality improvements through better workmanship and improved Quality Assurance
- Advancements in materials
- Optimum utilization of available equipment

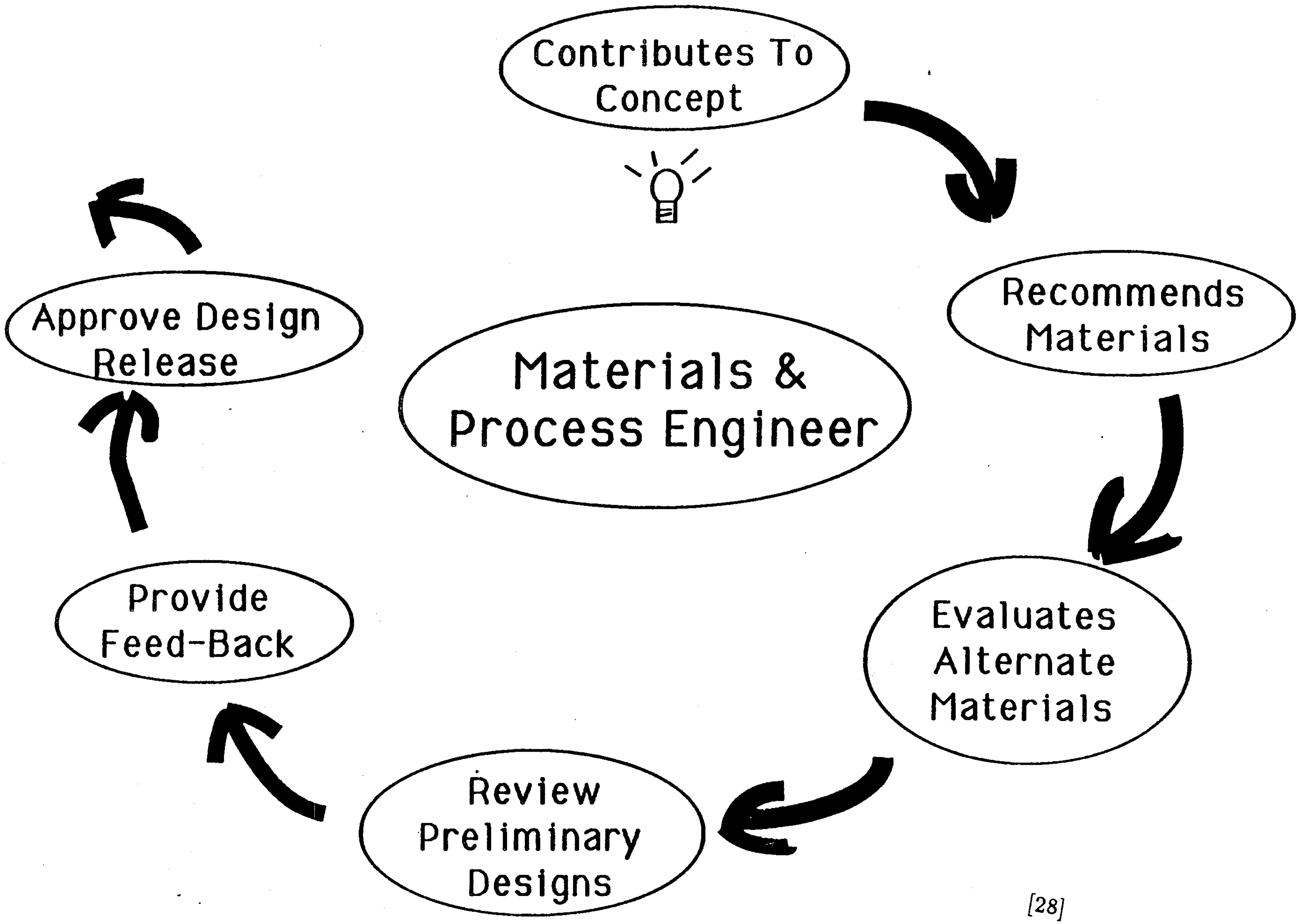
DESIGN PRODUCIBILITY TEAM MUST CONSIDER

- Available equipment
- Tooling requirements
- Available processes
- Available materials
- Cost
- Quality
- Simplicity of design

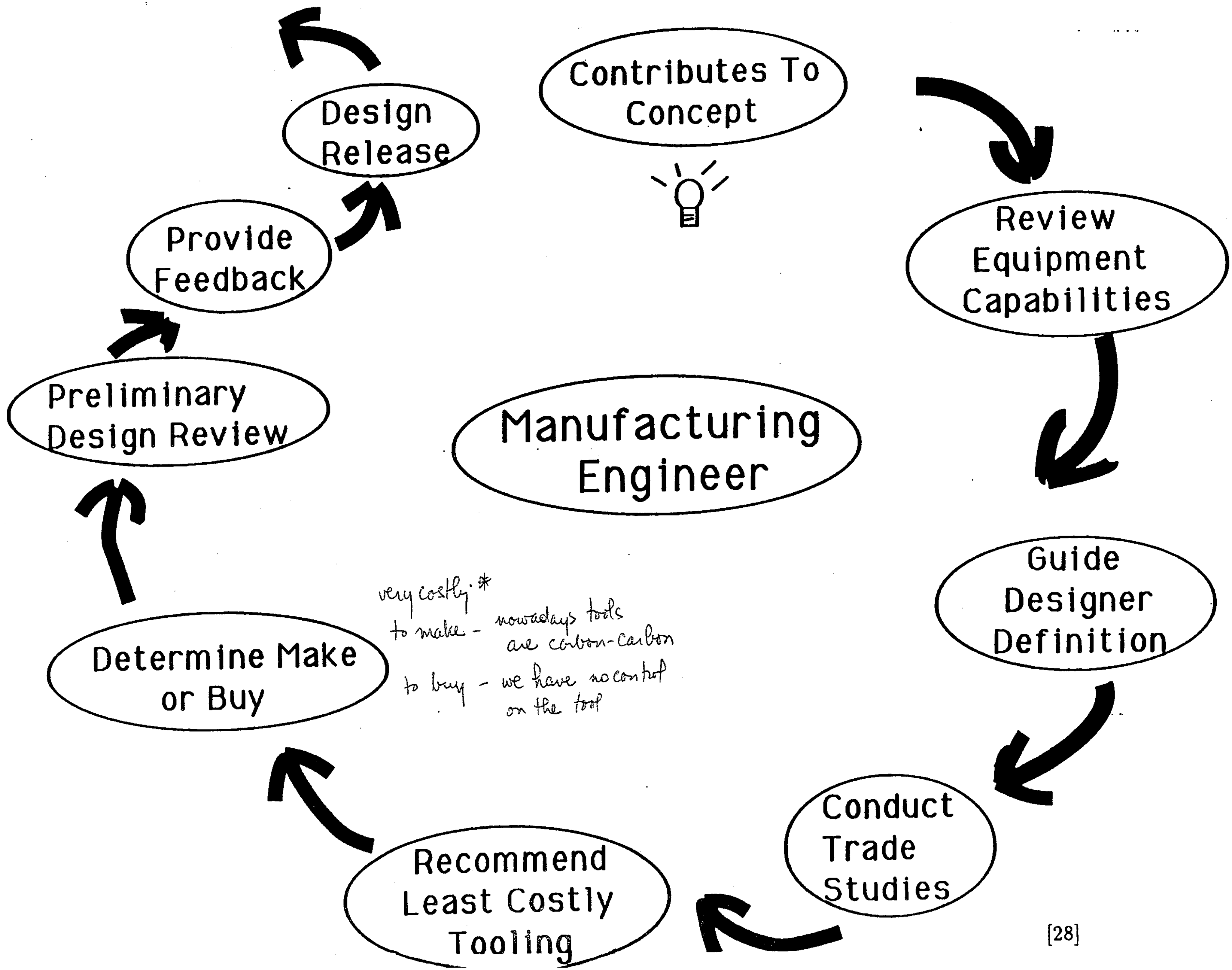
[28]


Design Concept
Design Development
Preliminary Design
Design Review
Design Complete
Design Approval
Design Release
Designer

[28]


Contributes To Concept
Recommends Materials
Evaluates Alternate Materials
Review Preliminary Designs
Provide Feed-Back
Approve Design Release
Materials & Process Engineer

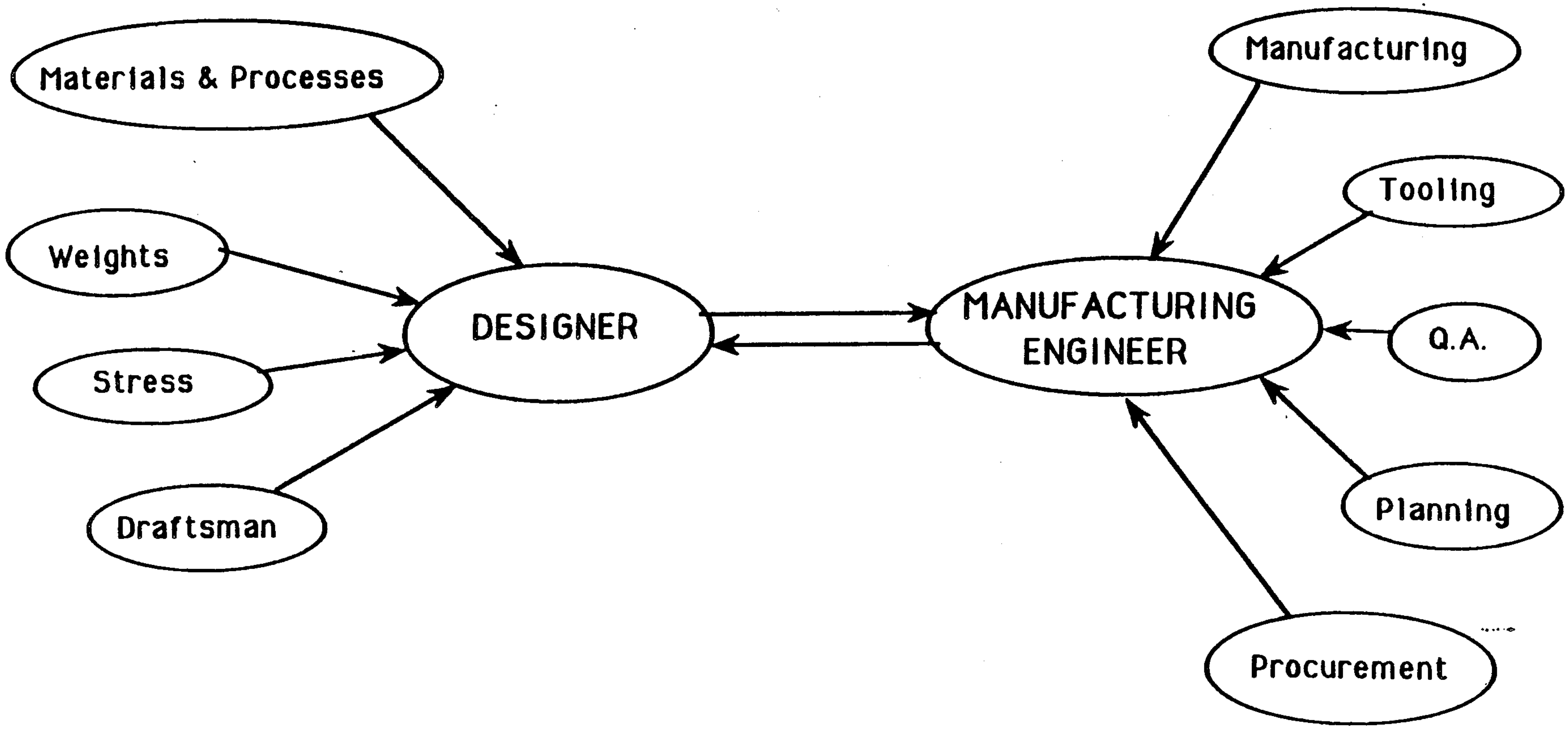
[28]


Contributes To Concept
Review Equipment Capabilities
Guide Designer Definition
Conduct Trade Studies
Recommend Least Costly Tooling
Determine Make or Buy
Preliminary Design Review
Provide Feedback
Design Release
Manufacturing Engineer
very costly *
to make - nowadays tools are carbon-carbon
to buy - we have no control on the tool

[28]

SOURCES OF BACK-UP DATA

SOURCES OF BACK-UP DATA



<u>Governing Guidelines</u>

Make Or Buy → Tooling Policy → Manufacturing Policy

[28]

CONSTRAINTS:

WEIGHTS

MAINTAINABILITY

RELIABILITY

STRESS

CONSIDERATIONS:

ASSEMBLE ABILITY

INSPECT ABILITY

ACCESSIBILITY

PRIMARY DRIVERS:

WEIGHTS

COST

TOOLING COSTS

SCHEDULE

SECONDARY DRIVERS:

TOOL TYPE

LIMITED LIFE

EXTENDED LIFE

CURE

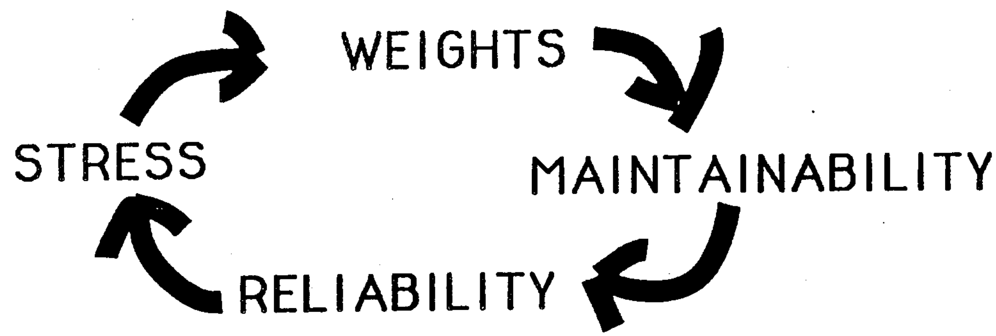
AUTOCLAVE

OVEN

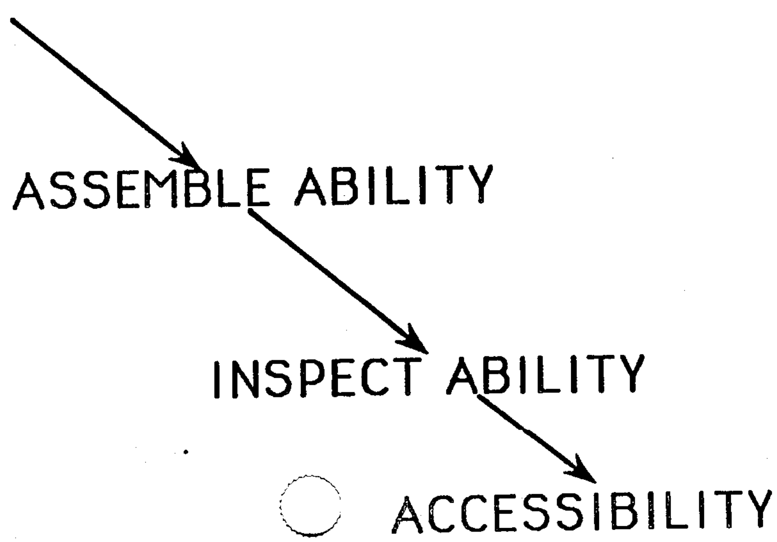
PRESS

[28]

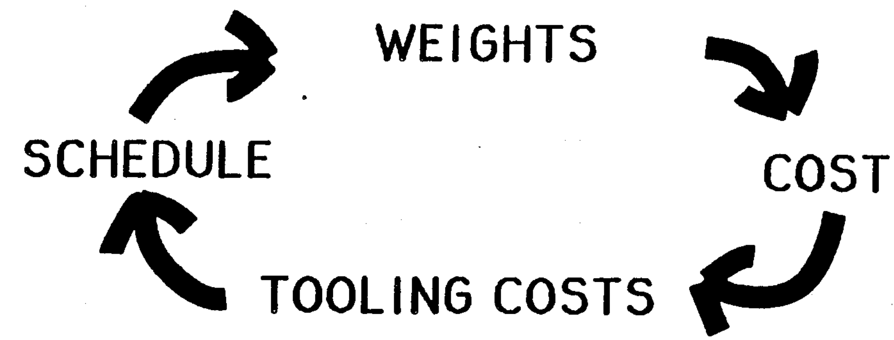
<u>CONSTRAINTS:</u>



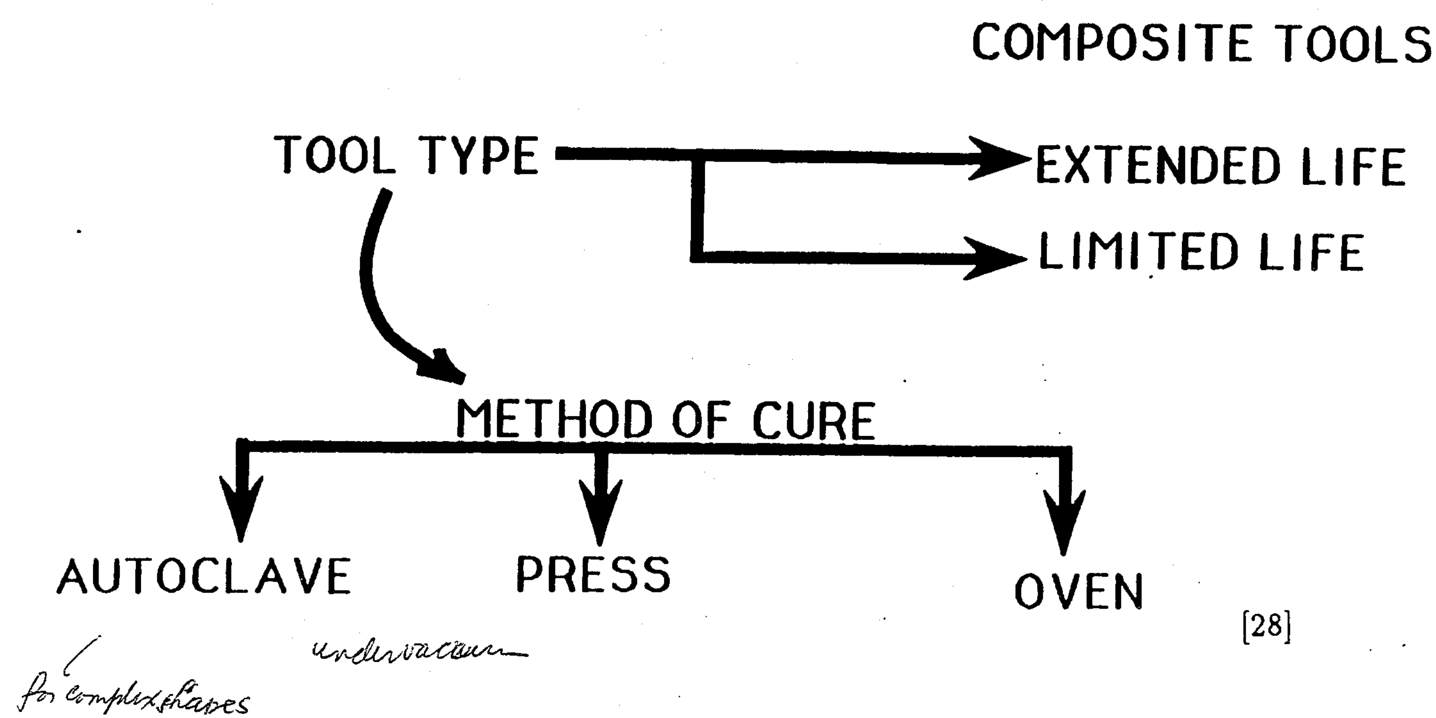
<u>CONSIDERATIONS:</u>



PRIMARY DRIVERS:

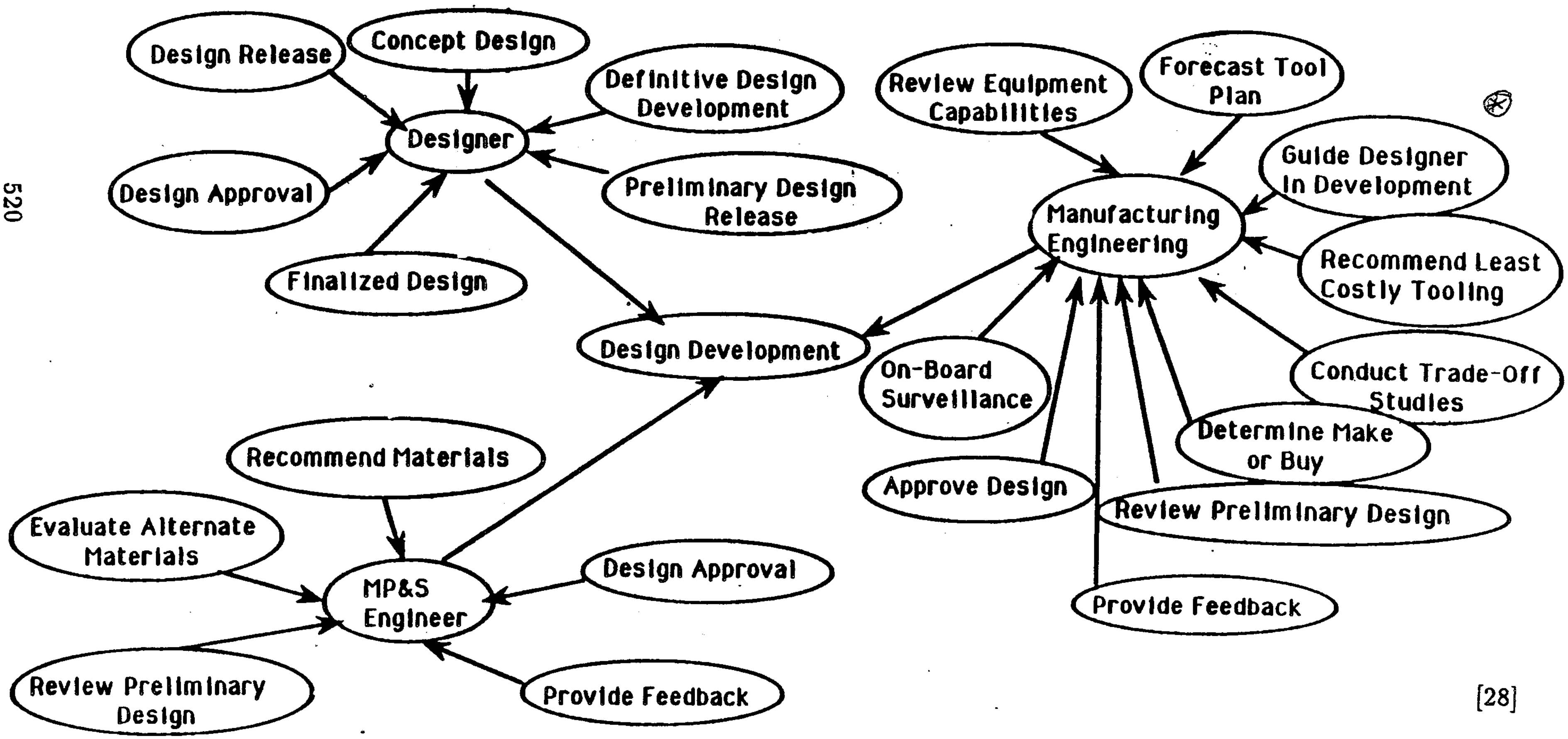


SECONDARY DRIVERS:



[28]

SUGGESTED FORMAT - PRODUCIBILITY TEAM



[28]

References: 2, 5, 12, 26, 27, 28, 29, 30, 31, 32

References: 2, 5, 12, 26, 27, 28, 29, 30, 31, 32

MANUFACTURING

MANUFACTURING FUNDAMENTALS

- Transformation of uncured or partially cured fiber-reinforced thermosetting polymers into parts involves curing the material at elevated pressures and temperatures.

- High cure temperatures are required to initiate and sustain the chemical reaction.

- High pressures provide the force needed for the flow of the highly viscous fiber-resin in the mold.

- The cure cycle is the length of time required to cure a part. [2]

CURE CYCLE

- Depends on:
  - Resin chemistry
  - Catalyst reactivity
  - Cure temperature
  - Presence of inhibitors/accelerators

additives, toughners and fillers

DEGREE OF CURE

- Generally increases with time and temperature
- Rate of cure is decreased as the degree of cure approaches a maximum value - material dependent
- If temperature is too low, degree of cure may not reach 100 percent level in any reasonable time.

[2]

must adjust cure cycle to ensure little residual stress (R.S.) while avoiding the void content.
keeping low temp will cause voids. but little RS.
keeping high temps will " high RS but low voids

NDE testing ultrasonic is used in degree of cure.

VISCOSITY

- Viscosity is a measure of a fluid's resistance to flow under shear stresses

- In general, polymer melts are shear thinning fluids since their viscosity decreases as shearing intensity increases

- For polymers, viscosity increases with time. This increase is faster at higher temperatures.

- Gel time is the time at which the resin viscosity increases at a very rapid rate.

- A B-staged or thickened resin has a much higher viscosity than a neat resin

- Fillers increase viscosity and the rate of viscosity increase

GEL TIME TEST

- Gel time is the time when the reacting material no longer adheres to the end of a clean stick
- After the gel time is reached, the polymer solidifies quickly

SHRINKAGE

- High shrinkage is desirable for easy release from the mold surface
- High resin shrinkage may cause warpage and/or sink marks

[2]

- Thermoplastic additives tend to reduce the rate of viscosity increase

- Increase in viscosity is less at higher shear rates

- Viscosity is a function of temperature, shear rate, and degree of cure

- Activation energy for viscous flow increases with degree of cure

[2]

Typical Applications

- Sucker rod guides
- Avionics housing

Trends

- Automated loading/unloading of press
- Increasing part sizes [31]

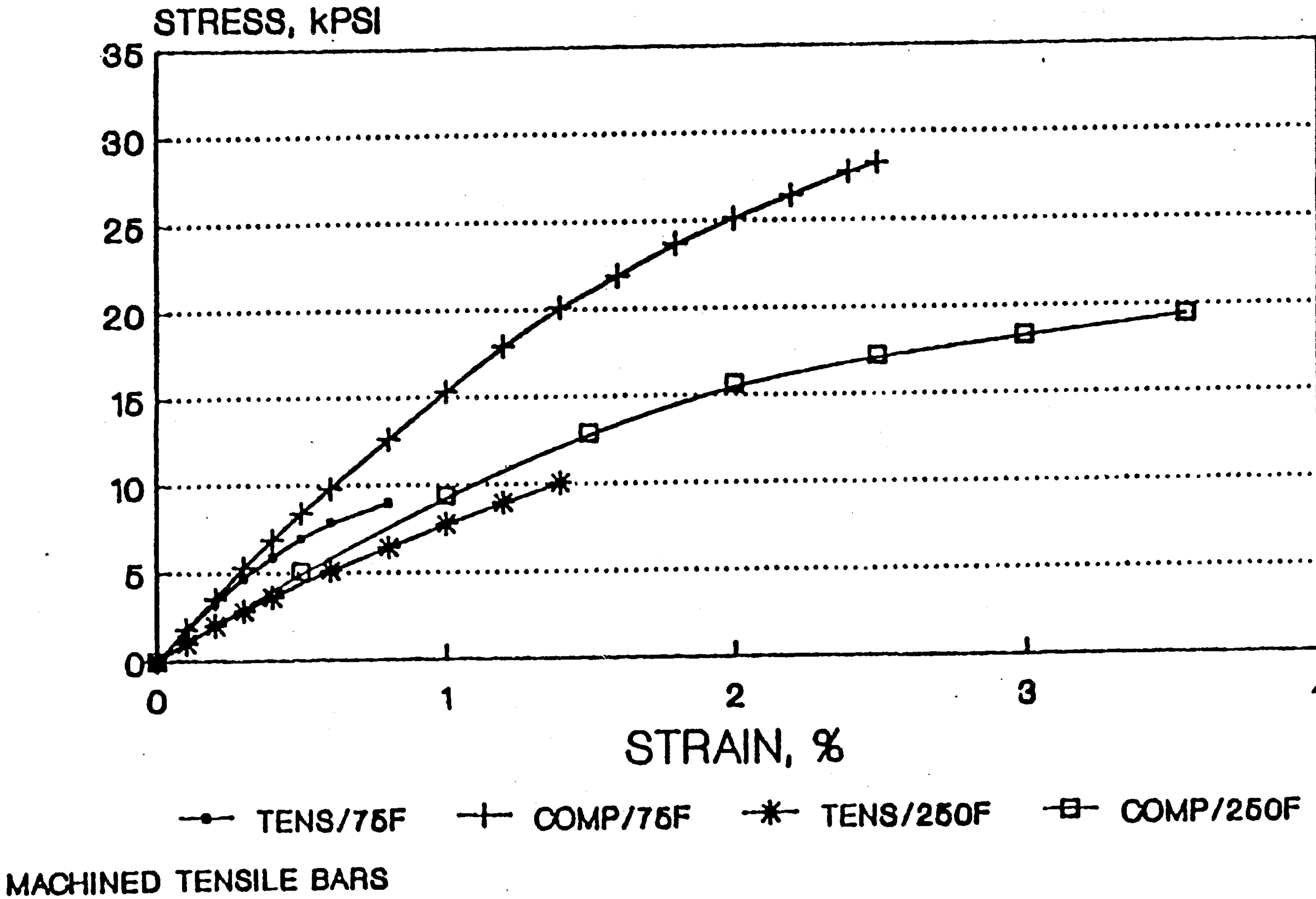
STAMP MOLDING

Process

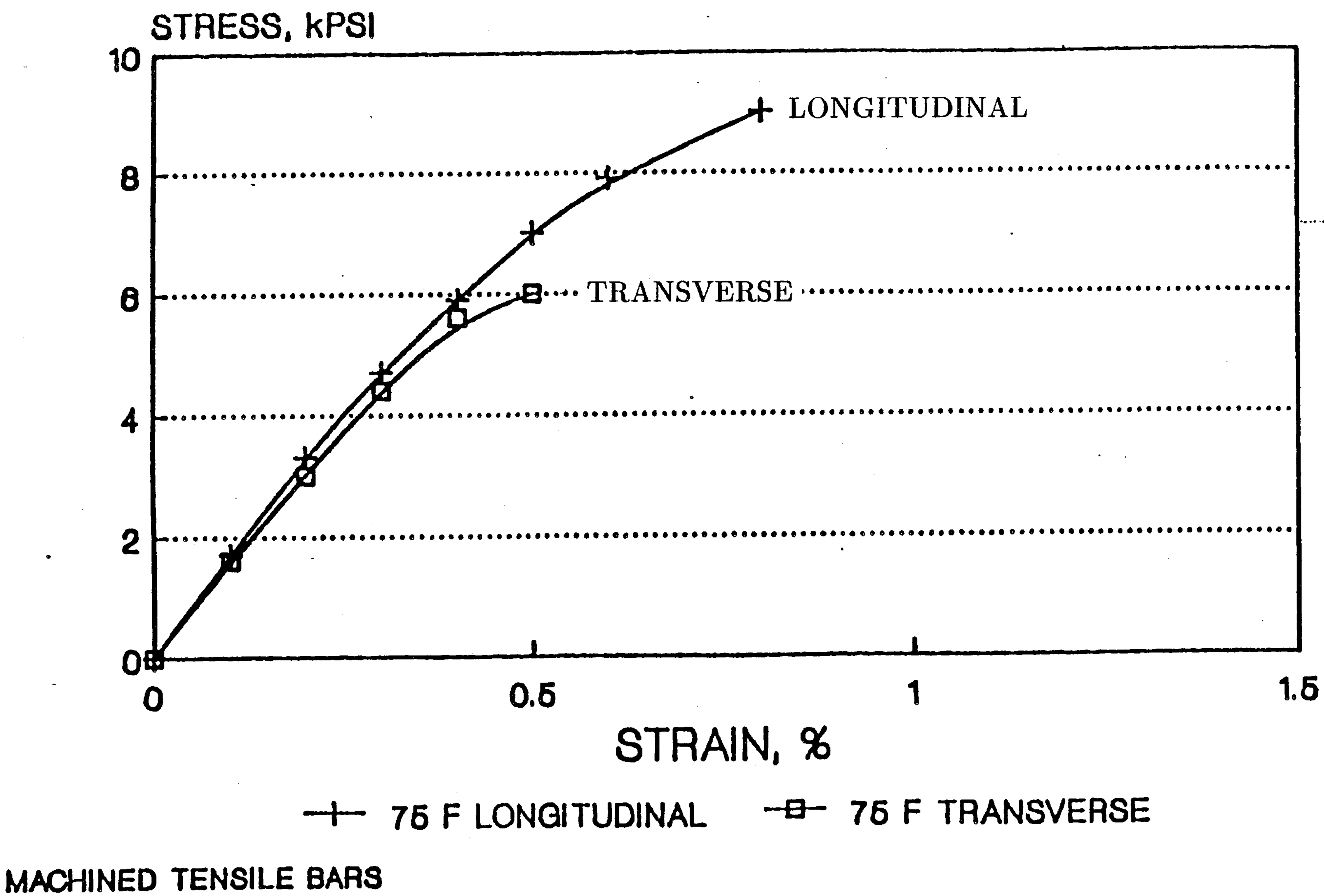
- Pre-heated material blanks
- Low cycle times
- Typical Material reinforced with fiber mat
- Comparable to compression molded properties

State-of-the-art

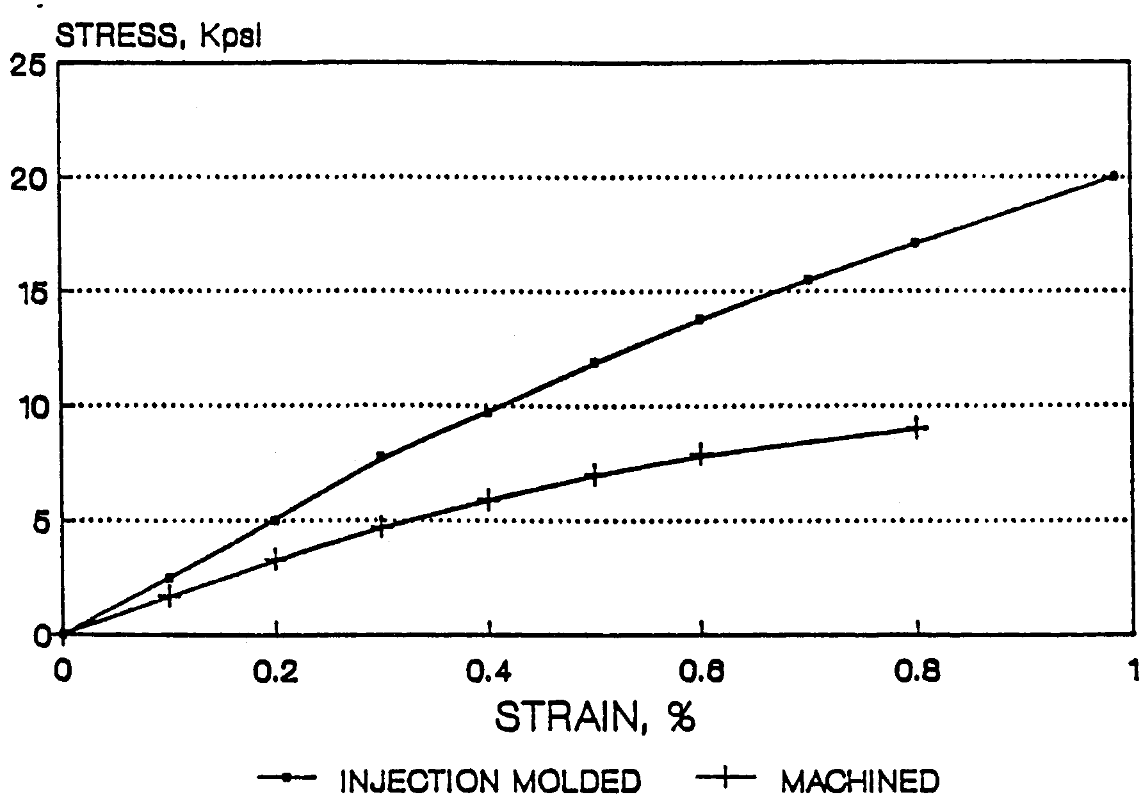
- Use CAD and FEA to design molds and parts
- Use CAM to make molds



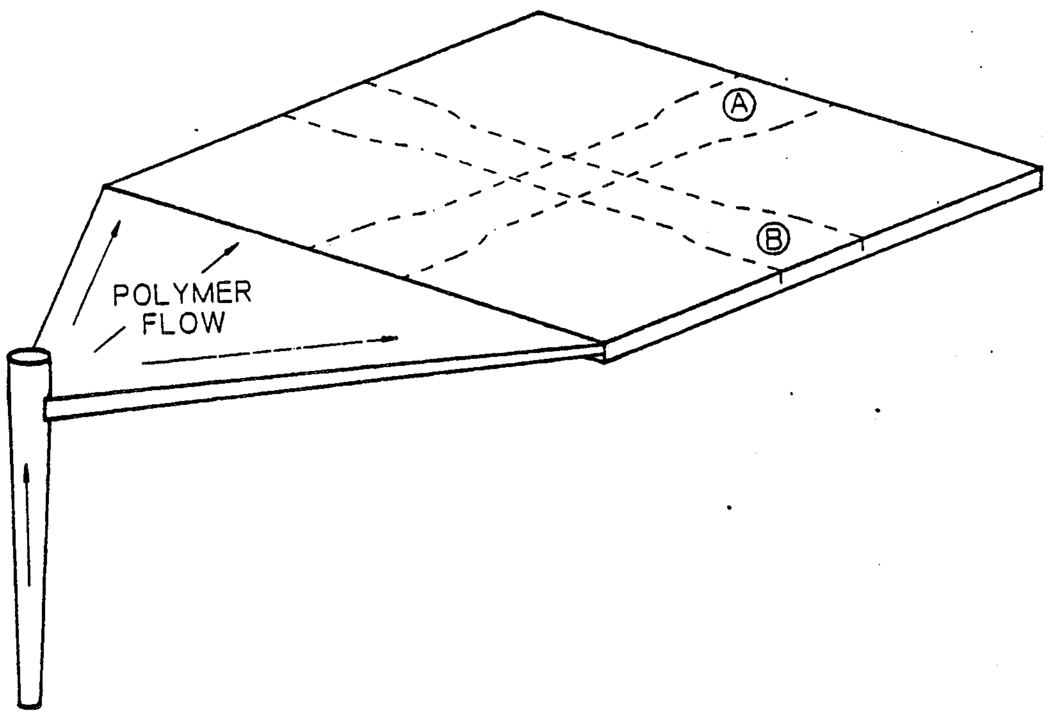
Temperature Effect at 75°F and 250°F Longitudinal Tensile and Compressive Properties [31]



Anisotropic Characteristic Tensile Properties at 75°F [31]



Injection Molded vs. Machined Specimens Tensile Stress-Strain at 75^oF [31]



Test Specimen Orientation [31]

Typical Applications

- Electronics encapsulation
- Chemical resistant pump components
- Underhood products

Trends

- Better prediction of fiber orientation in part
- Co-injection molding

[31]

INJECTION MOLDING

Process

- Large volume process
- Reduces part count, machining, and assembly time compared to metals
- Good tolerance control
- Inexpensive materials
- Strength sensitive to mold flow

State-of-the-art

- Use mold flow software to estimate fiber orientation in part and provide FEA input
- Use CAD and FEA to design molds and parts
- Input results to CNC milling machine to cut net shape molds

Typical Applications

- Cylindrical sections

Trends

- Improved on-line consolidation
- Improved winding speeds
- Commercial application

[31]

FILAMENT WINDING

Process

- Slit-tape or tow prepreg material
- In-situ heating required
- In-situ consolidation or post-consolidation
- Strength comparable to press molded TPC

State-of-the-art

- Winding speeds generally slower than thermosets at present
- Usually single tow windings
- Helical winding
- Thin and thick walled winding

Typical Applications

- Orthotics
- Fasteners

Trends

- Improved line speeds
- Experimental postforming

[31]

PULTRUSION

Process

- Complex constant cross-sections
- In-line inpregnated or prepreg feedstock
- Comparable line speed to thermosets
- Off-axis reinforcement

State-of-the-art

- Rods, bars
- Channels
- T and I beams
- Off-axis ply orientation
- Hollow shapes

NEAT RESIN PROPERTIES OF HIGH PERFORMANCE THERMOPLASTICS

POLYMER	T_G, °C	TENSILE PROPERTIES AT 25°C STRENGTH (YIELD), KSI	MODULUS, KSI	STRAIN (BREAK), %	FRACTURE ENERGY (G_{IC}), IN-LB/IN	NOTCHED IZOD, FT. LB/IN
POLYETHERETHERKETONE (PEEK)	143	14.5	450	> 40	> 23	1.6
POLYARYLENE KETONE (APC-HTX)	205	–	–	–	–	–
POLYARYLENE KETONE (PXM 8505)	265	12.7	360	13	–	–
POLYPHENYLENE SULFIDE (PPS)	90	12.0	630	5	–	3.0
POLYARYLENE SULFIDE (PAS-2)	215	14.5	470	7.3	–	0.8
POLYARYLAMIDE (J-POLYMER)	120	–	–	–	–	–
POLYAMIDEIMIDE (TORLON)	275	9.2	667	1.4	19.4	2.7
POLYAMIDEIMIDE (TORLON PIX638)	243	13.0	400	30	20	–
POLYETHERIMIDE (ULTEM 1000)	217	15.2	430	60	19	1.0
POLYIMIDE (AVIMID K-III)	251	14.8	546	14	11	–
POLYIMIDE (LARC-TPI)	264	17.3	540	4.8	–	–
POLYMIDESULFONE ($PISO_2$)	273	9.1	719	1.3	8	–
POLYSULFONE (UDEL P-1700)	190	10.2	360	> 50	14	1.2
POLYARYLSULFONE (RADEL A400)	220	10.4	310	60	20	12
POLYETHERSULFONE (VICTREX PES 41006)	230	12.2	380	> 40	11	1.6
POLYESTER (XYDAR SRT-300)	350	20.0	2400	4.9	6.9	2.4

[31]

- Fiber wet-out depends on
  - Viscosity of resin bath
  - Number of strands in roving
  - Fiber tension
  - Speed of winding and length of bath

- Common defects are
  - Voids
  - Delaminations
  - Fiber wrinkles

[2]

FILAMENT WINDING

- A band of continuous resin-impregnated rovings or monofilaments is wrapped around a rotating mandrel and cured to produce axisymmetric hollow parts

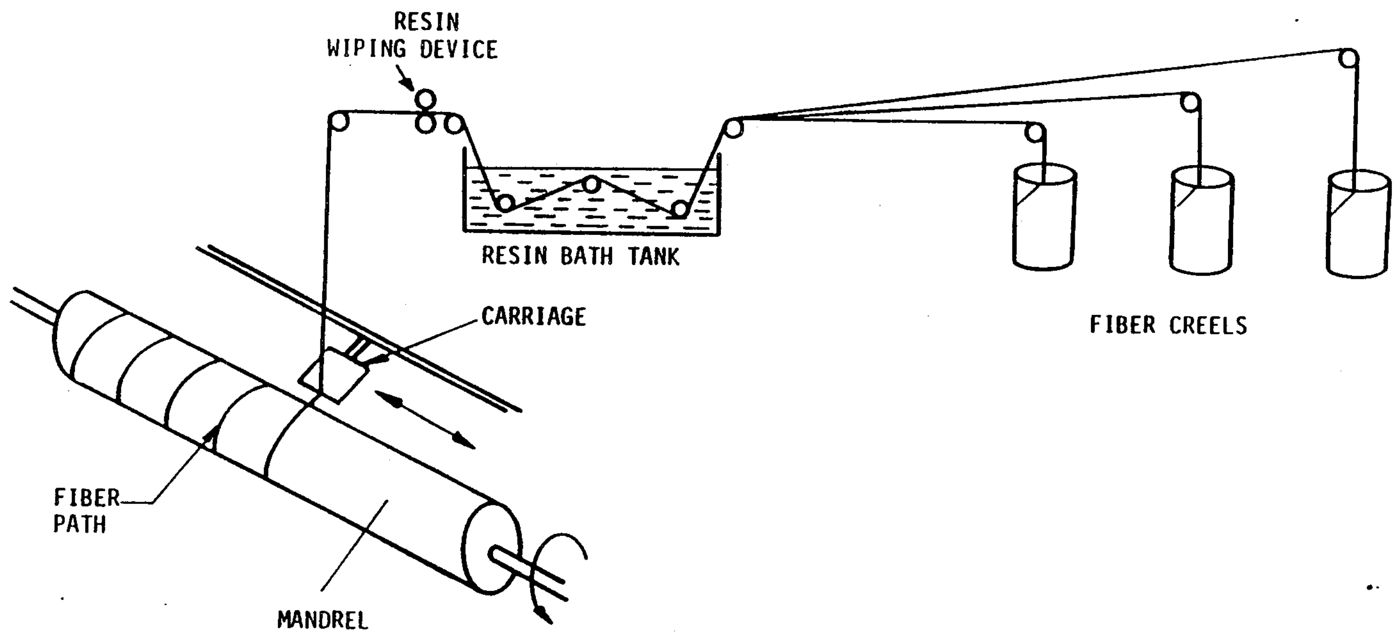
- Also used to produce prepreg sheets or continuous fiber-reinforced sheet molding compounds by slitting the wound shape parallel to the mandrel axis

- Fiber breakage slows production

- Part is cured on mandrel

- Fiber angles achieved by varying mandrel translation

- Pulling causes pre-tension in fibers


RESIN
WIPING DEVICE
RESIN BATH TANK
CARRIAGE
FIBER CREELS
FIBER
PATH
MANDREL

[2]

- Defects include
  - Fiber bunching and shifting
  - Wrinkling
  - Folding of mats or woven rovings

- Tensile modulus and strength increase as fiber content increases

- Most important factor in controlling the mechanical performance is the fiber wet-out

[2]

ABILITY TO WET-OUT FIBERS

- Depends on:
  - Initial resin viscosity
  - Time in bath
  - Bath temperature
  - Mechanical action on fibers in bath

WET-OUT FOR A GIVEN VISCOSITY

- Improves as:
  - Time in bath increases
  - Bath temperature is increased
  - Mechanical action on fibers in bath is increased [2]

- Preformers distribute the fiber bundles evenly,squeeze out the excess resin, and bring the material into its final configuration
- Final shaping, compaction, and curing take place in the die
- The die has a tapering section along its length
- Die temperature, length, and pulling speed are controlled to allow complete curing before exiting the die

- No external pressure is applied
- Speeds range from 2-15 ft/min
- Pulling force must overcome
  - Friction force of fibers against die walls
  - Shear viscous force between the resin and die walls
  - Drag resistance

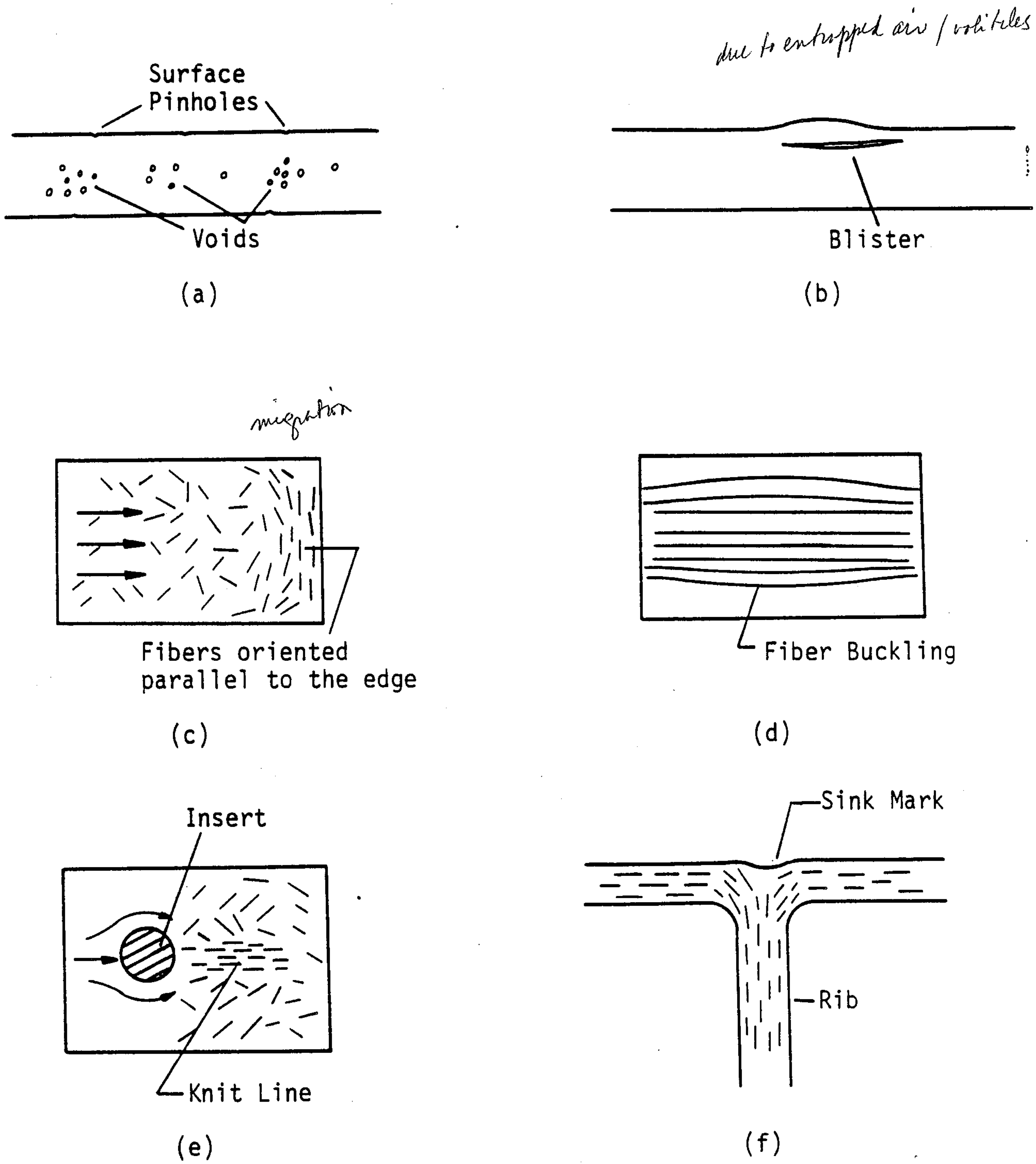
PULTRUSION

- Continuous molding process used to produce long, straight structural members of constant cross-sectional area

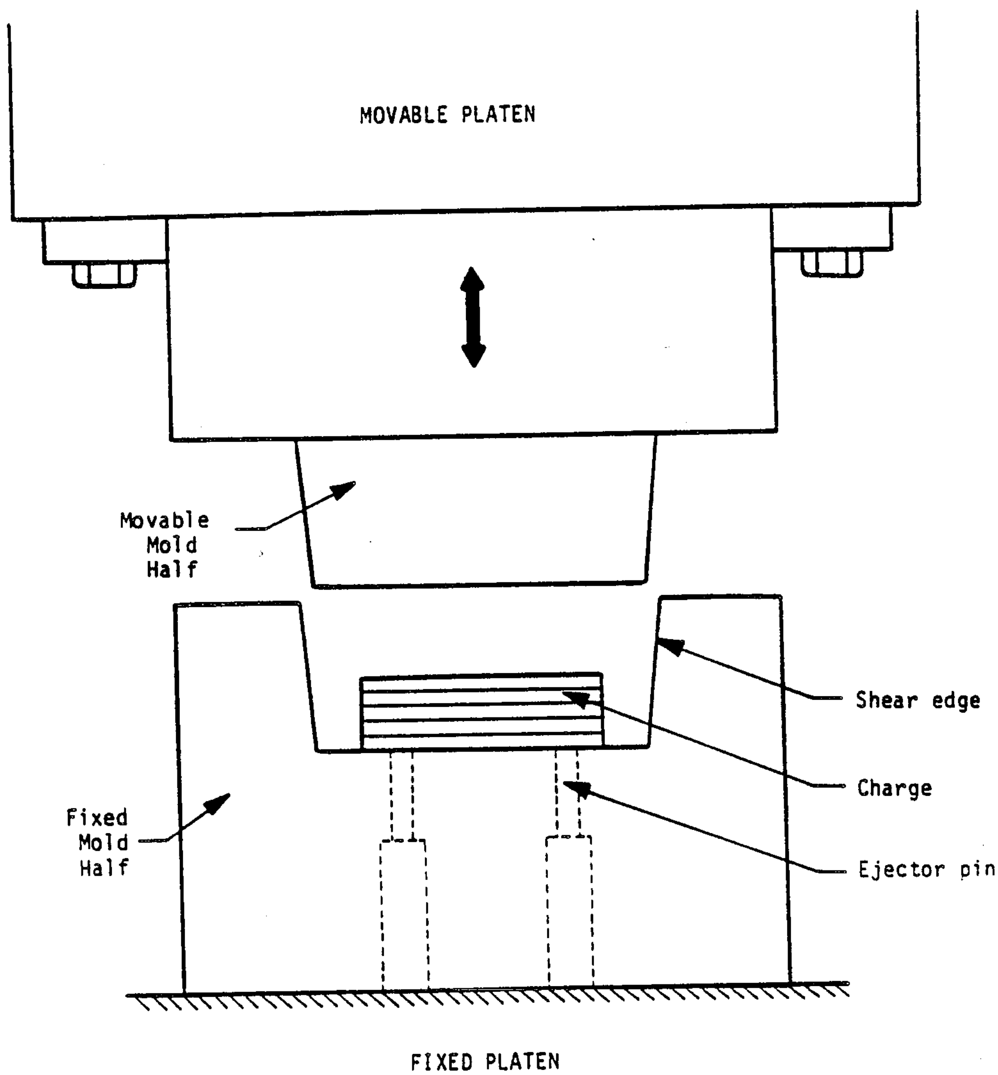
- Major constituent is longitudinally oriented strand rovings

- Steps

  - Continuous strand rovings and mats are pulled from one end of the line into a resin bath containing liquid resin, curing agent, etc.
  - Viscosity, residence time, and mechanical action on the fibers are adjusted to ensure complete fiber wetting



Various defects in a compression-molded SMC part [2]



Schematic of a compression molding process [2]

- Defects

  - Random fibers may not be distributed evenly
  - Porosity caused by trapped air
  - Blistering due to excessive gas pressure in the interior region of the part

Blistering may be reduced by

- Minimizing trapped air

- Increasing interlaminar shear strength by:

  Changing resin
  Using coupling agents
  Decreasing mold temperature
  Assure proper cure before opening mold

[2]

- The entire assembly is cured in a preheated autoclave under heat and pressure
- Cure pressure and temperature are selected to meet the following requirements:
  - Resin is uniformly cured
  - Resin is cured in shortest possible time
  - Temperature does not exceed a prescribed limit during cure
  - Pressure is high enough to squeeze out all excess resin before the resin gels

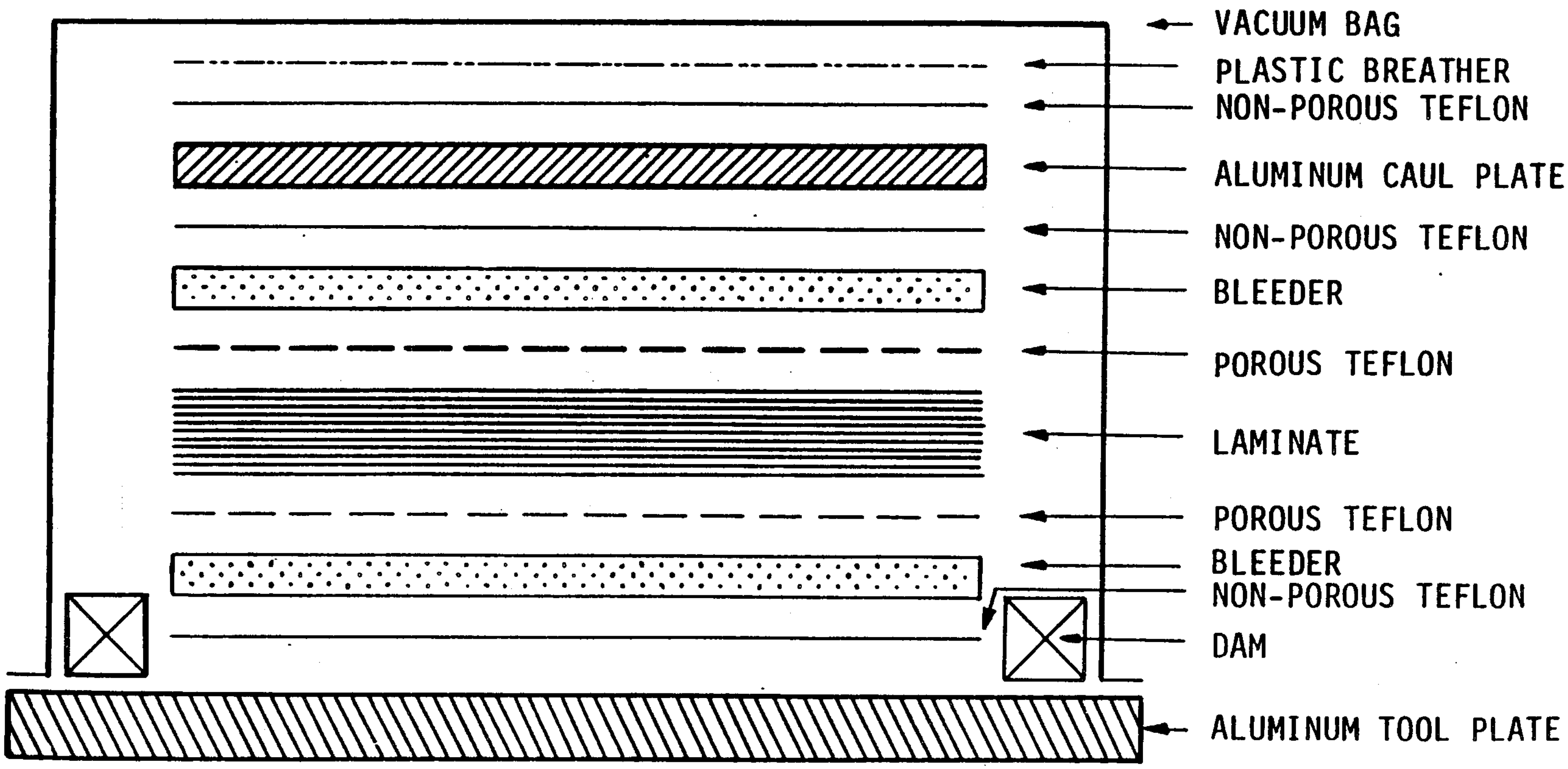
[2]

COMPRESSION MOLDING

• shopped fibers
• wiskers

- Used for forming sheet molding compounds into finished products in matched molds
- Can produce complex shapes quickly
- Suitable for high-volume production
- Steps
  - Place pre-cut and weighed amount of SMC on bottom of preheated mold cavity
  - Mold is closed quickly
  - Top of mold is lowered at a constant rate until pressure reaches a preset level
  - Flow of material is required to expel air in the mold and charge

if not done under the right conditions fibers migrate to bottom and the resin to top



Schematic of a bag molding process [2]

BAG MOLDING PROCESS

- Mold surface is covered with a teflon-coated glass fabric separator to prevent sticking
- Prepreg plies are laid up
- Porous release cloth and a few layers of bleeder papers are placed on top of the prepreg stack
- The bleeder papers are used to absorb the excess resin
- Complete layup is covered with another sheet of Teflon-coated glass fabric separator, a caul plate,and then a thin heat-resistant vacuum bag [2]

- Air may be trapped between layers during lamination

- Much of the air or volatiles may be removed by

  - Degassing the liquid resin
  - Applying a vacuum during the molding process
  - Allowing the resin to flow freely in the mold

[2]

VOIDS

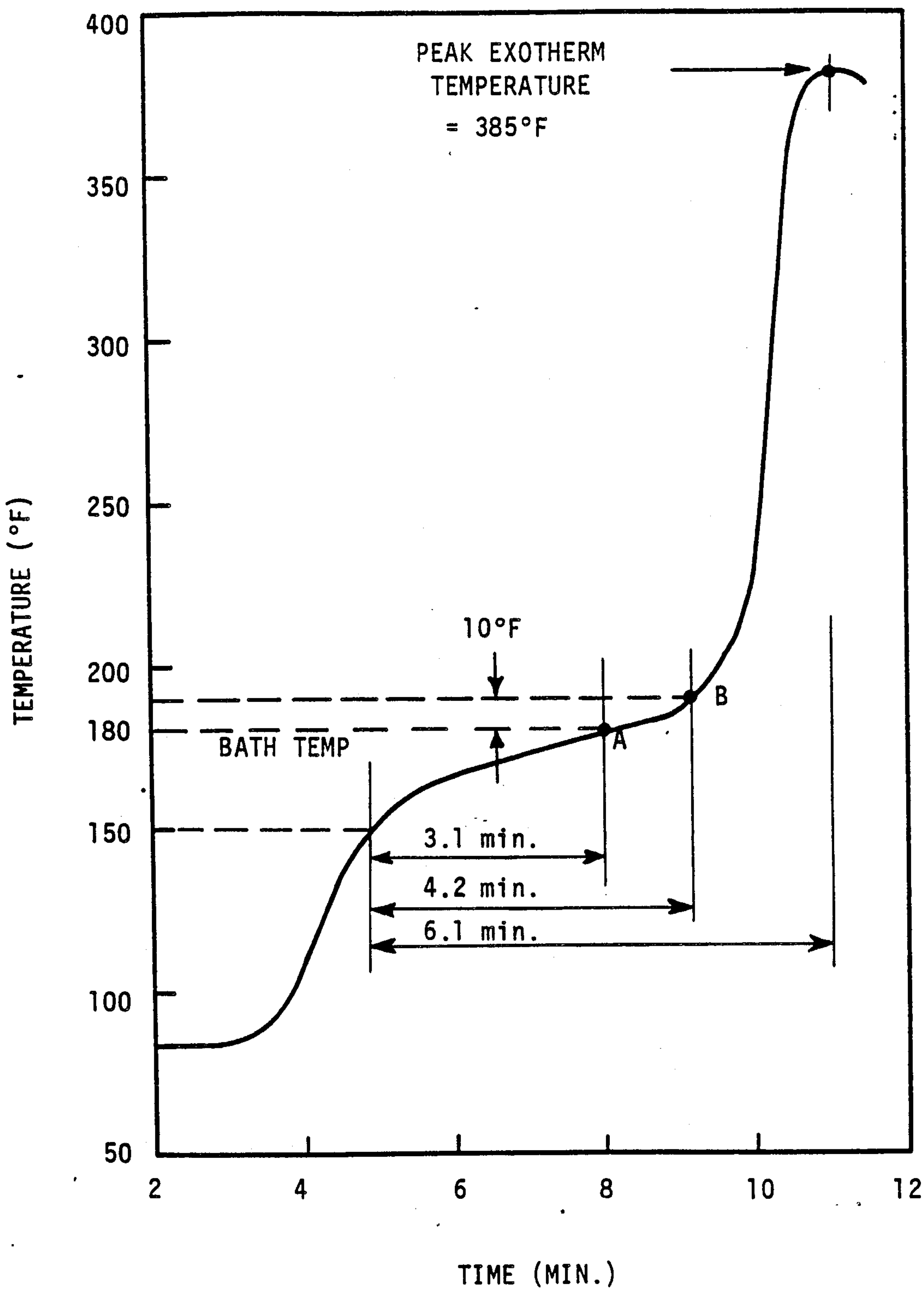
- Considered the most critical defect in influencing mechanical properties

- Most common cause is the inability of the resin to displace air from the fiber surface when the fibers are coated with the liquid resin

- Air entrapment is affected by

  - Rate at which fibers are pulled through resin
  - Relative values of fiber/resin surface energies
  - Mechanical manipulation of the fibers in the resin

- Voids may be caused by the entrapment of air bubbles and volatiles in the liquid resin



Typical temperature-time curve obtained in a gel-time test [2]

AUTOCLAVE PROCESSING

Process

- Processing similar to thermosets
- Temperature requirements are higher 350-450 thermoset 700-800 thermoplastic
- No exotherm problems 85 psi " set 330 psi " plastic

State-of-the-art

- Large panels ($5ft x 10ft$)
- Thicknesses up to 0.5 *inch*

Typical Applications

- Experimental panels
- Feedstock for thermoforming

Trends

- Simplified bagging procedures
- Automated material handling
- Larger panels
- Thicker panels

[31]

AEROSPACE

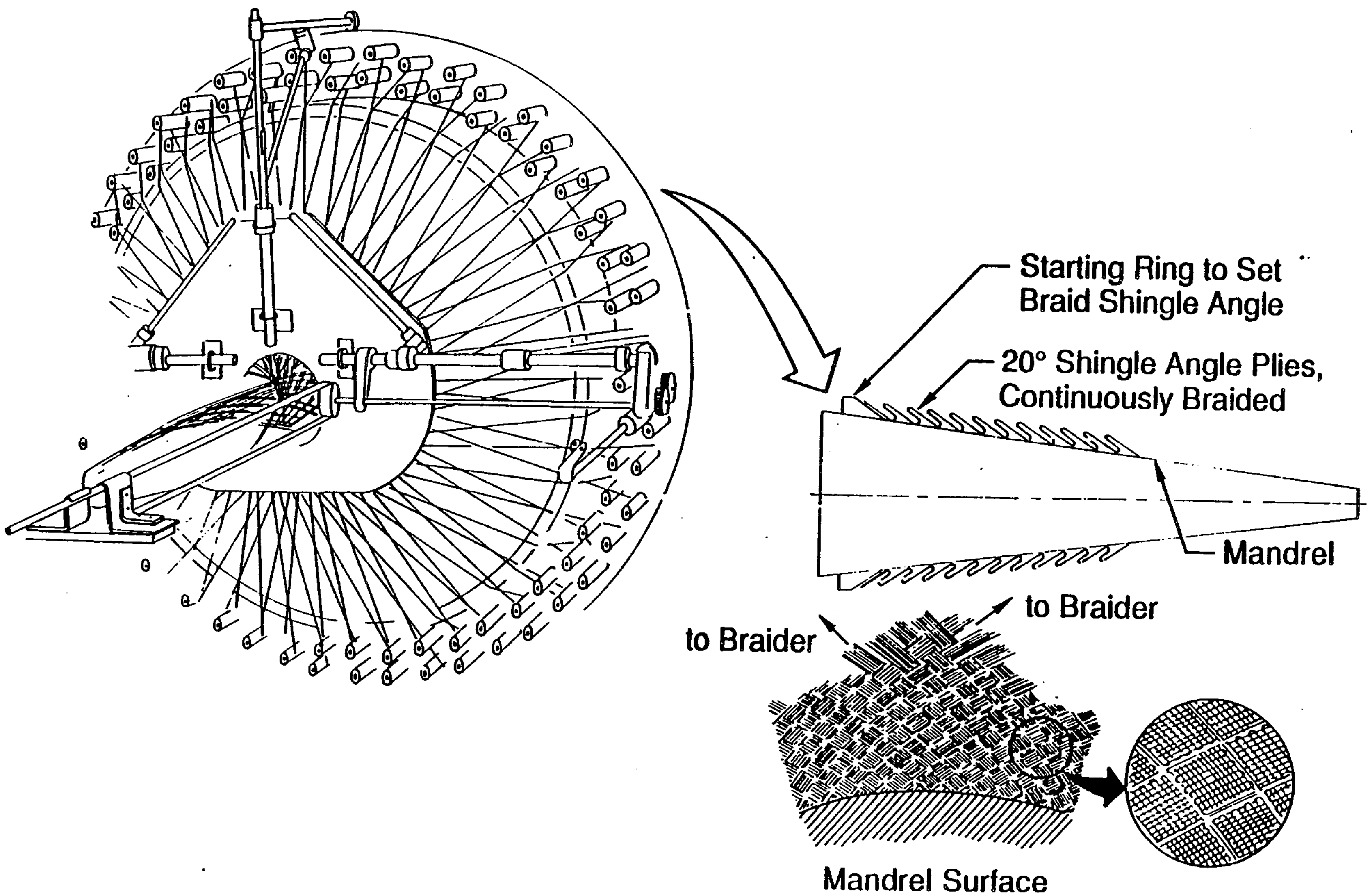
Aircraft

- Hand layup
- Tape laying

Missiles

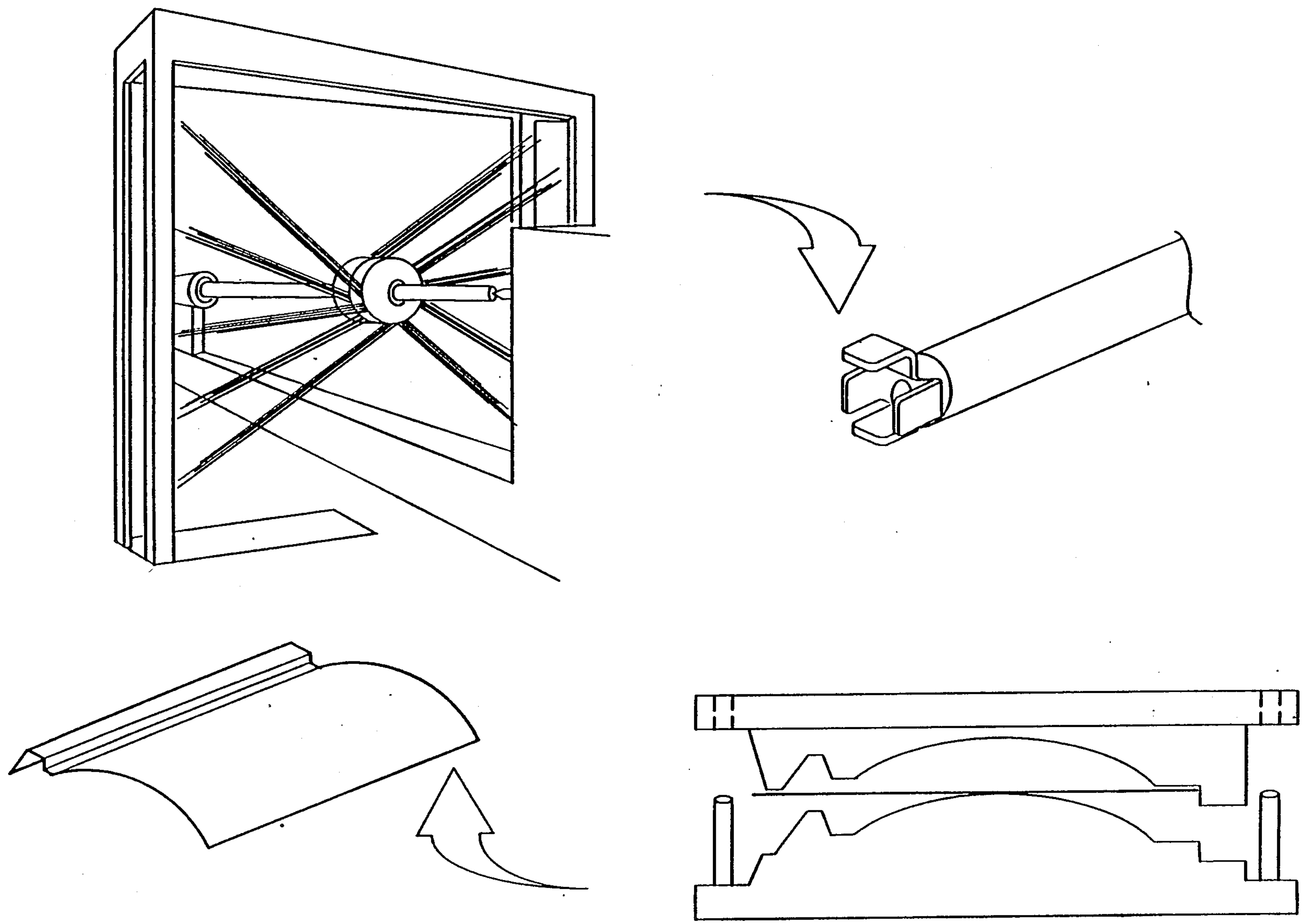
- Filament winding
- Braiding

Braiding

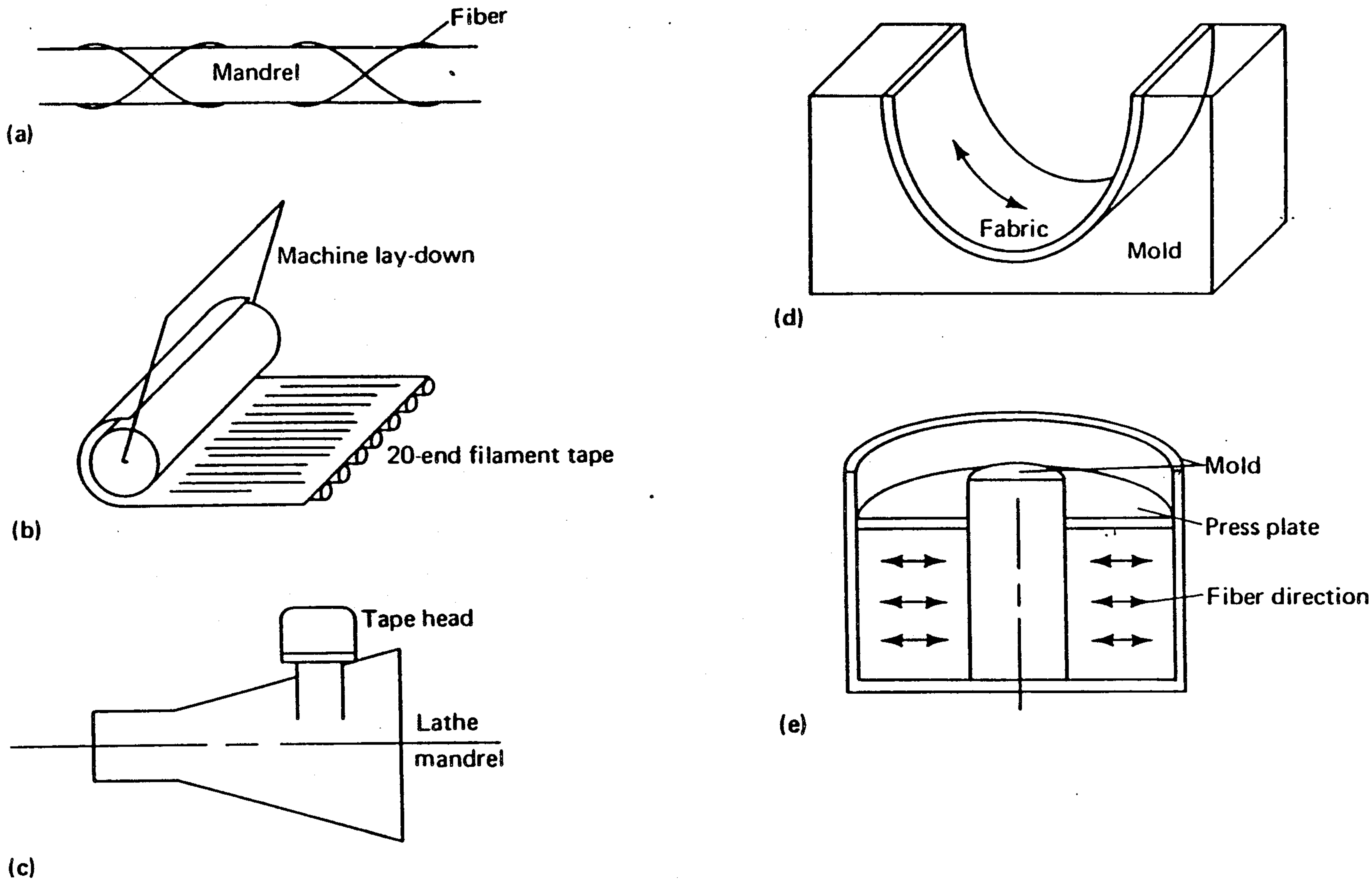

Starting Ring to Set
Braid Shingle Angle
20° Shingle Angle Plies,
Continuously Braided
Mandrel
to Braider
to Braider
Mandrel Surface

[32]

Transportation

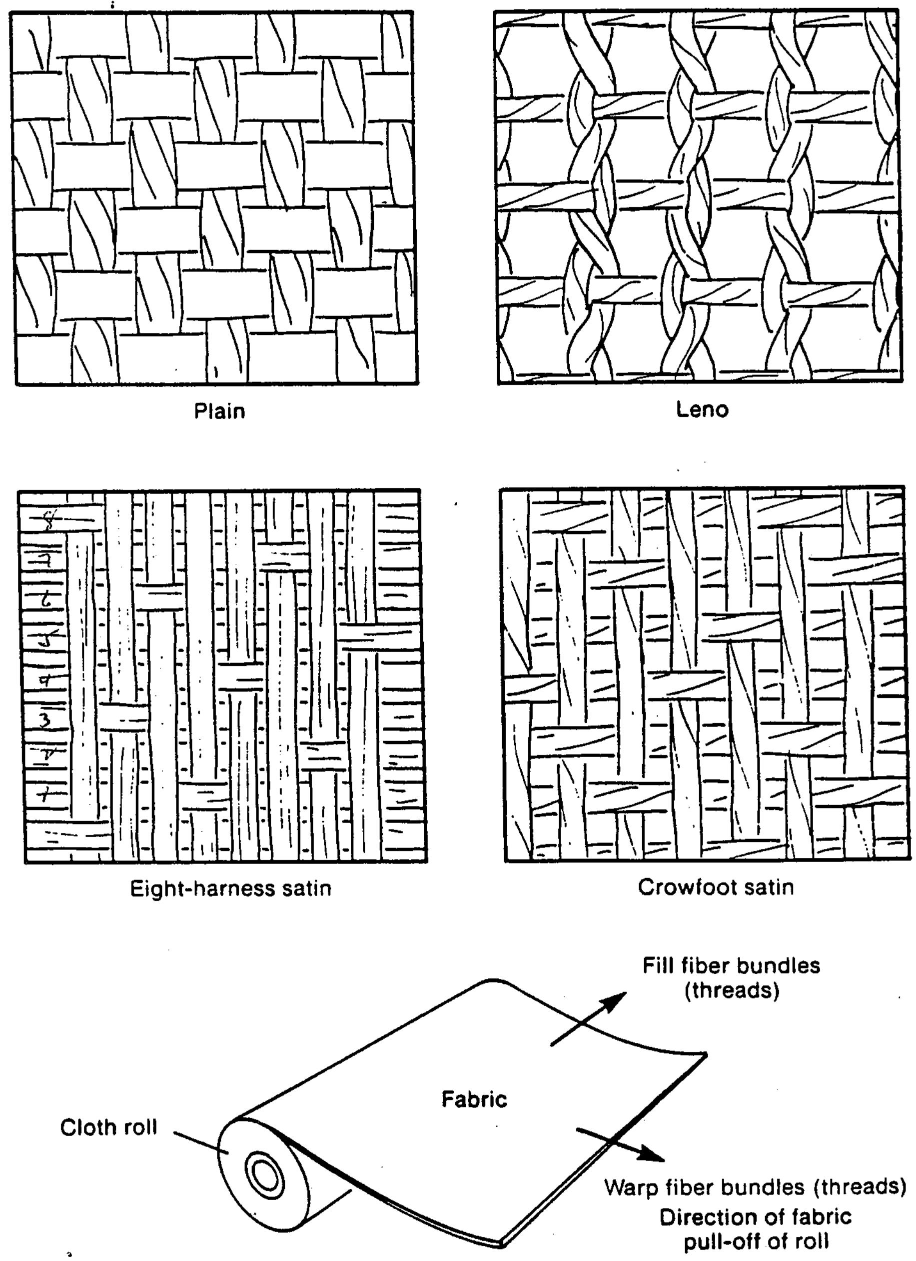


[32]



Typical fiber-resin applications. (a) Filament winding of pipe or rocket motor case. (b) Unidirectional tape lay-down for aircraft panel. (c) Tape-wrapping cone for rocket motor nozzle. (d) Lay-up of fabric resin for boat hull. (e) Molding of hollow cylinder for rocket motor nozzle.

[5]



Typical fabric weaves [5]

INTEGRALLY CURED COMPOSITE WING DESIGNS

Benefits

- Reduced assembly costs
- Reduced assembly fit-up problems
- Reduced fuel leakage paths

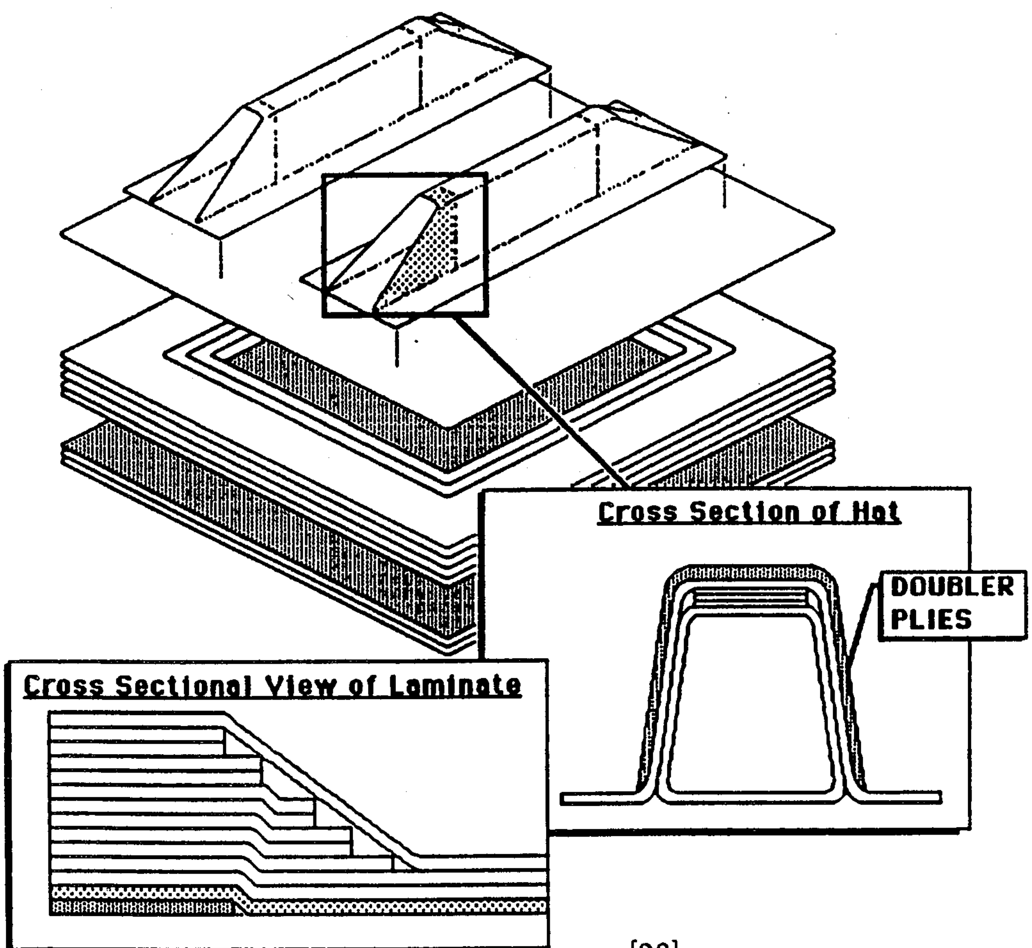
Concerns

- Increased tooling costs and time span
- Increased life cycle tooling costs
- Increased composite part fabrication time [32]

QUALITY CONTROL

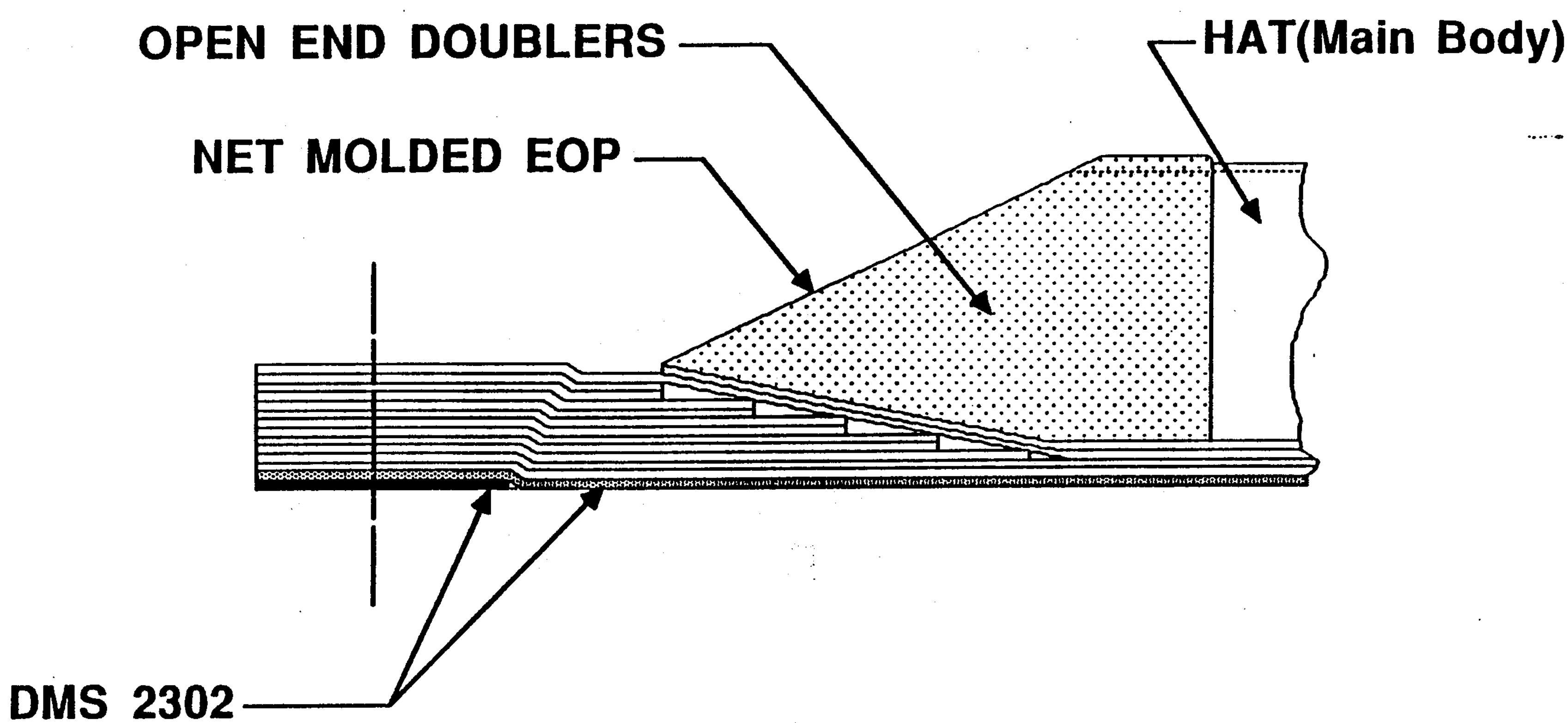
- Inspect raw materials
- Monitor cure cycle
- Inspect cured part
  - X-ray, voids appear as dark spots and resin rich areas appear as light streaks
  - Ultrasonics
  - Neither method gives depth information

GENERIC HAT PANELS



[28]

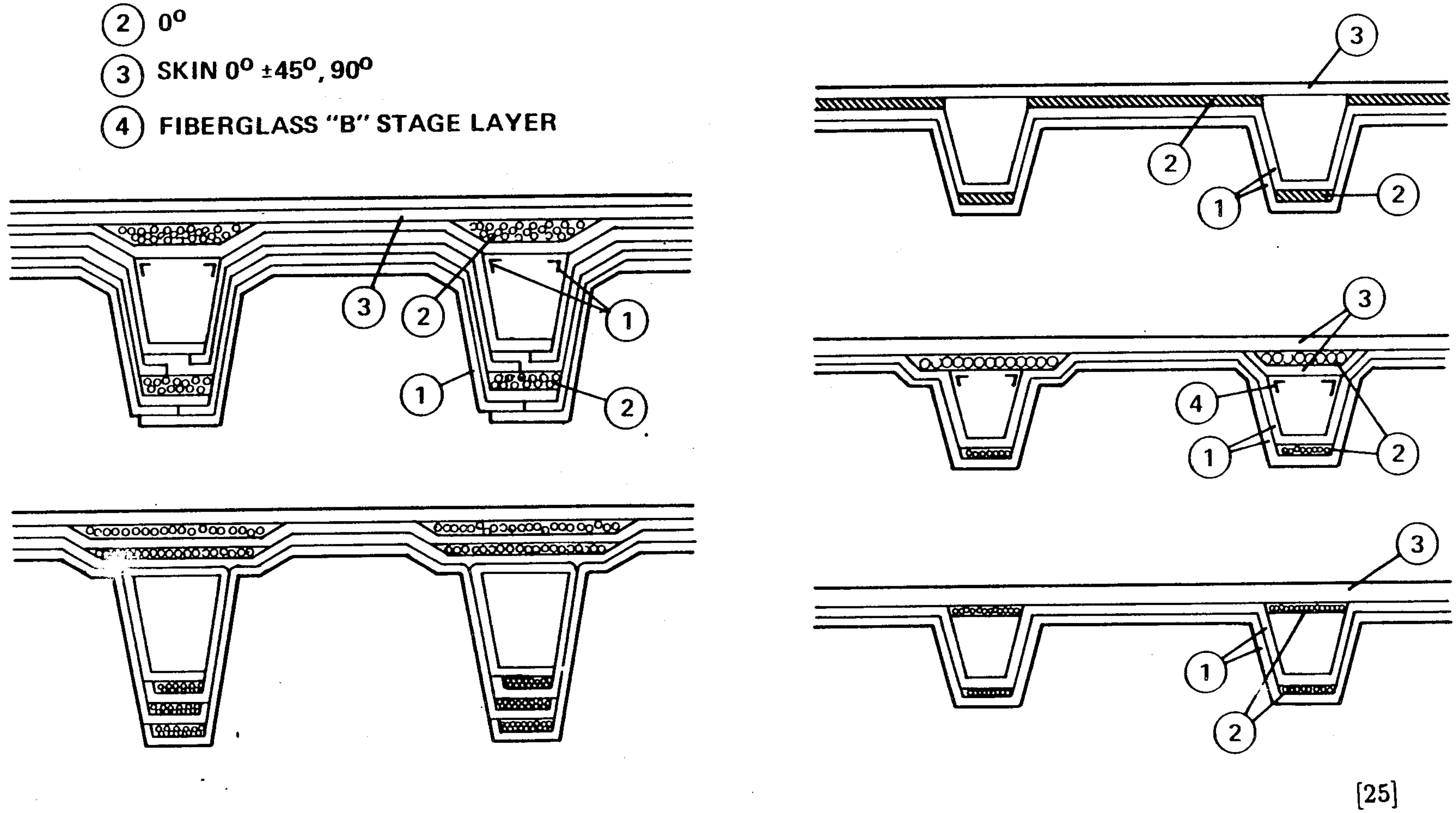
HAT AND DOUBLER: CROSS SECTION



[28]

HAT STIFFENED PANELS

1. MAINLY $\pm 45^{\circ}$
2. 0°
3. SKIN 0° $\pm 45^{\circ}$, 90°
4. FIBERGLASS "B" STAGE LAYER



HAT STIFFENED

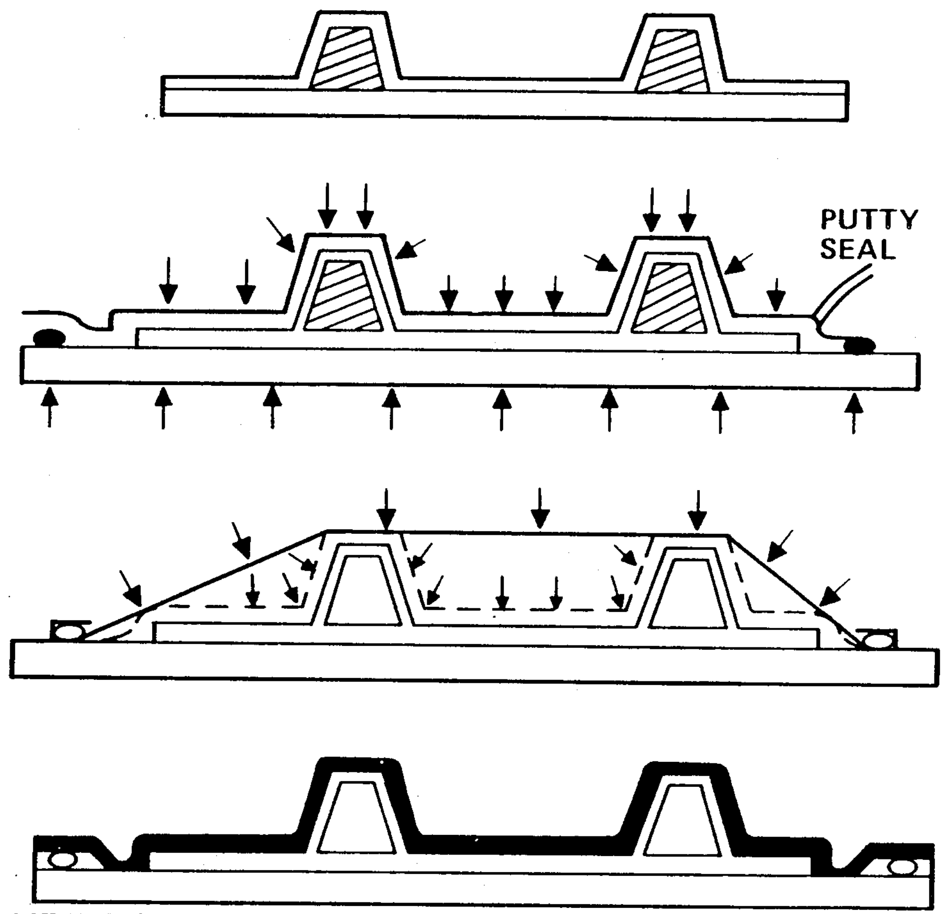
TOOLING CONCEPTS—LIGHT STRUCTURE CAPS

SOLID MADRELS
- CAST SILICONE
- ALUMINUM
- TEFLON
- WASH OUT PLASTER
- FOAM

PRESSURE BAG
- NYLON

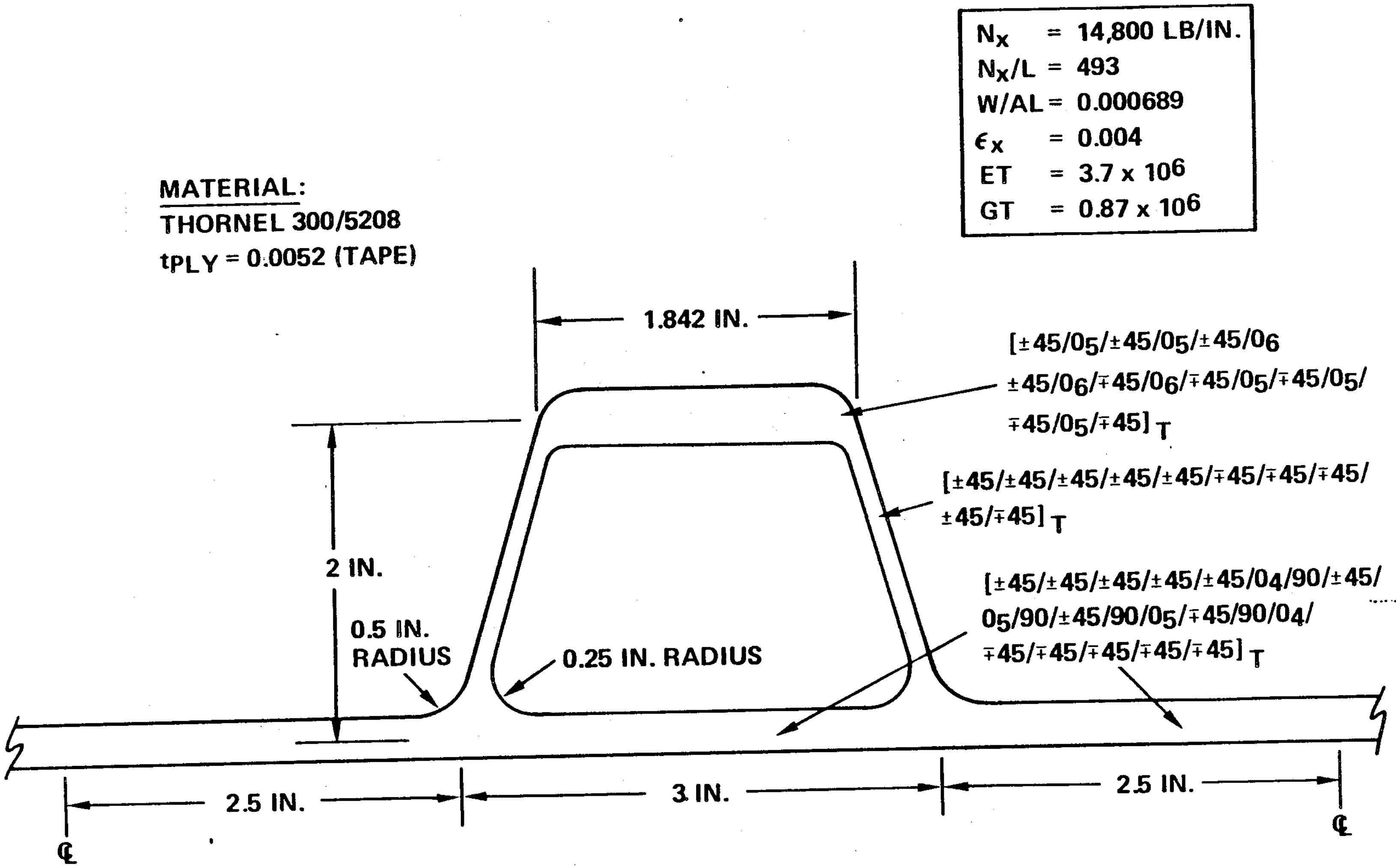
HIGH ELONGATION SILICONE

FORMED SILICONE



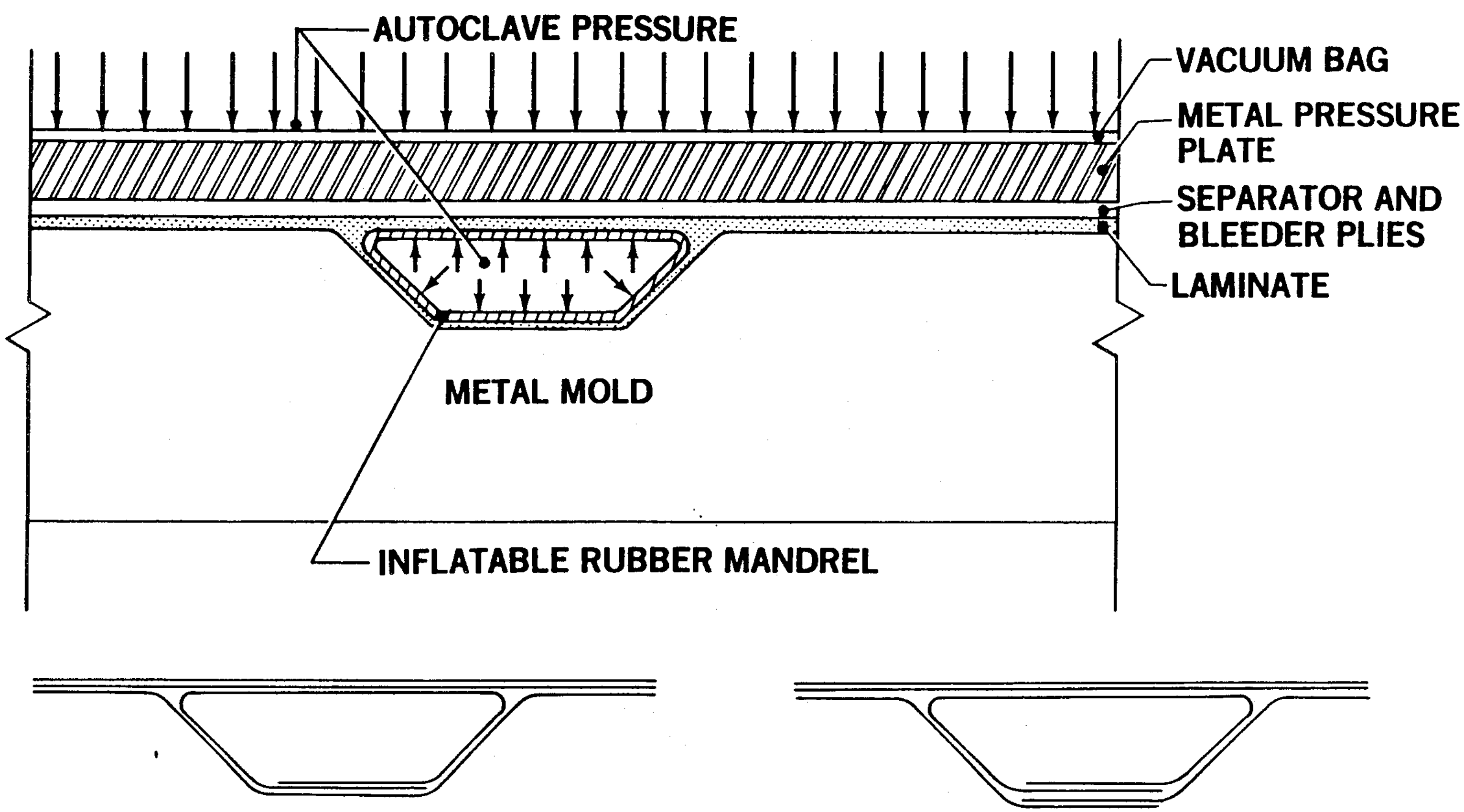
SUITABLE PROCEDURE FOR THIN STRUCTURE

[25]


MATERIAL:
THORNEL 300/5208
tPLY = 0.0052 (TAPE)
Nx = 14,800 LB/IN.
Nx/L = 493
W/AL = 0.000689
εx = 0.004
ET = 3.7 x 10^6
GT = 0.87 x 10^6
1.842 IN.
[±45/05/±45/05/±45/06
±45/06/∓45/06/∓45/05/∓45/05/
∓45/05/∓45] T
[±45/±45/±45/±45/±45/∓45/∓45/∓45/
±45/∓45] T
[±45/±45/±45/±45/±45/04/90/±45/
05/90/±45/90/05/∓45/90/04/
∓45/∓45/∓45/∓45/∓45] T
2 IN.
0.5 IN.
RADIUS
0.25 IN. RADIUS
2.5 IN.
3 IN.
2.5 IN.
℄
℄

[25]

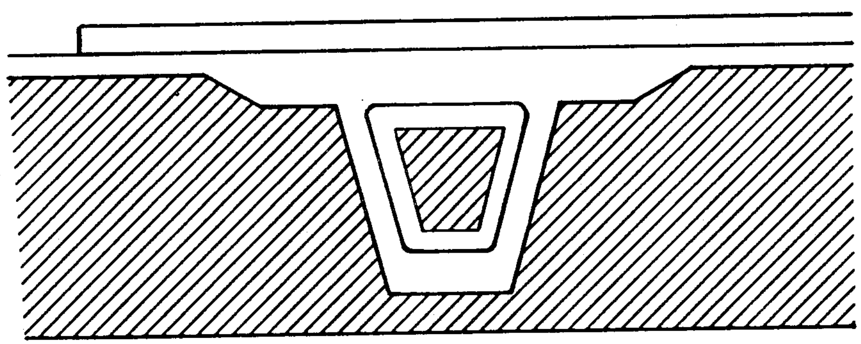
HAT-STIFFENED PANEL FABRICATION



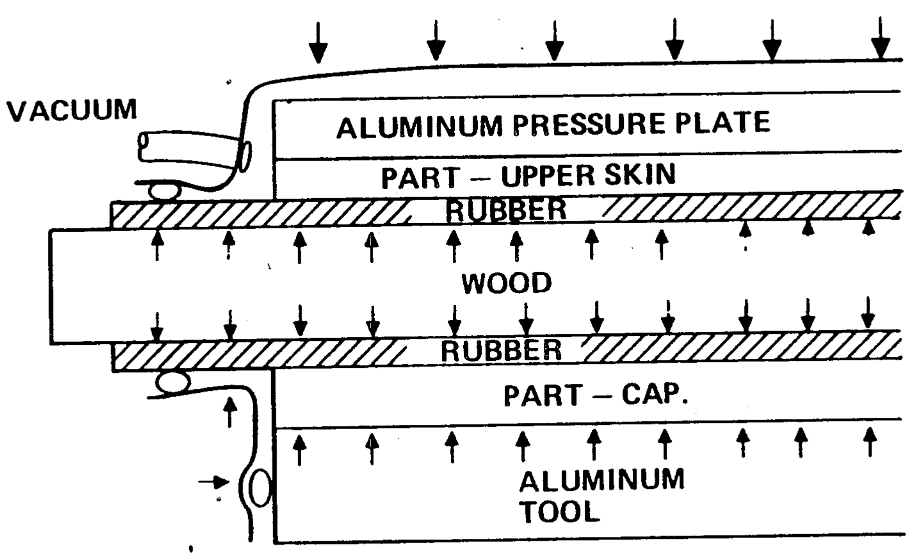
[25]

HAT STIFFENED PANEL

TYPICAL BAG PROCEDURE FOR INFLATED MANDREL CONCEPT



LOCATE OUTER SKIN IN PLACE



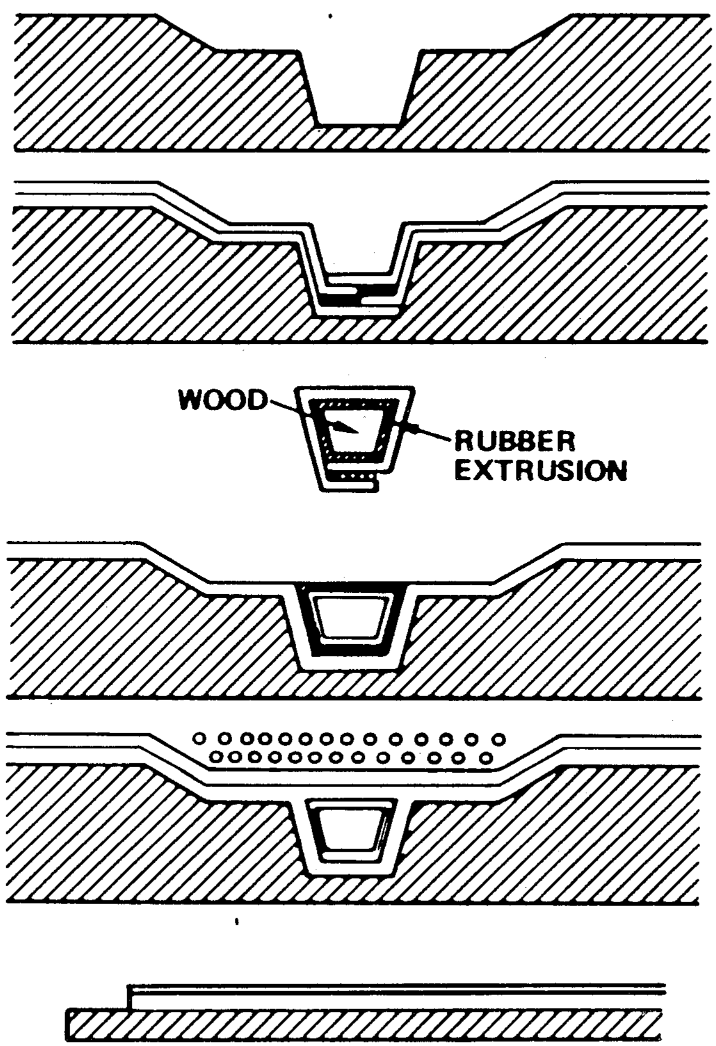
LOCATE NYLON VACUUM BAG AND SEAL BAG TO ENDS OF RUBBER EXTRUSIONS

DRAW VACUUM AND REMOVE WOOD SUPPORTS

[25]

HAT STIFFENED PANEL

TYPICAL LAYUP PROCEDURE FOR WRAPAROUND WEB CONCEPT



ALUMINUM FEMALE TOOL

LAYUP FIRST PORTION OF HAT/SKIN PATTERN

LOCATE EXTRUDED SILICONE INFLATABLE ON WOOD SUPPORT TOOL LAYUP FLAT PLY AND WRAP ON MANDREL

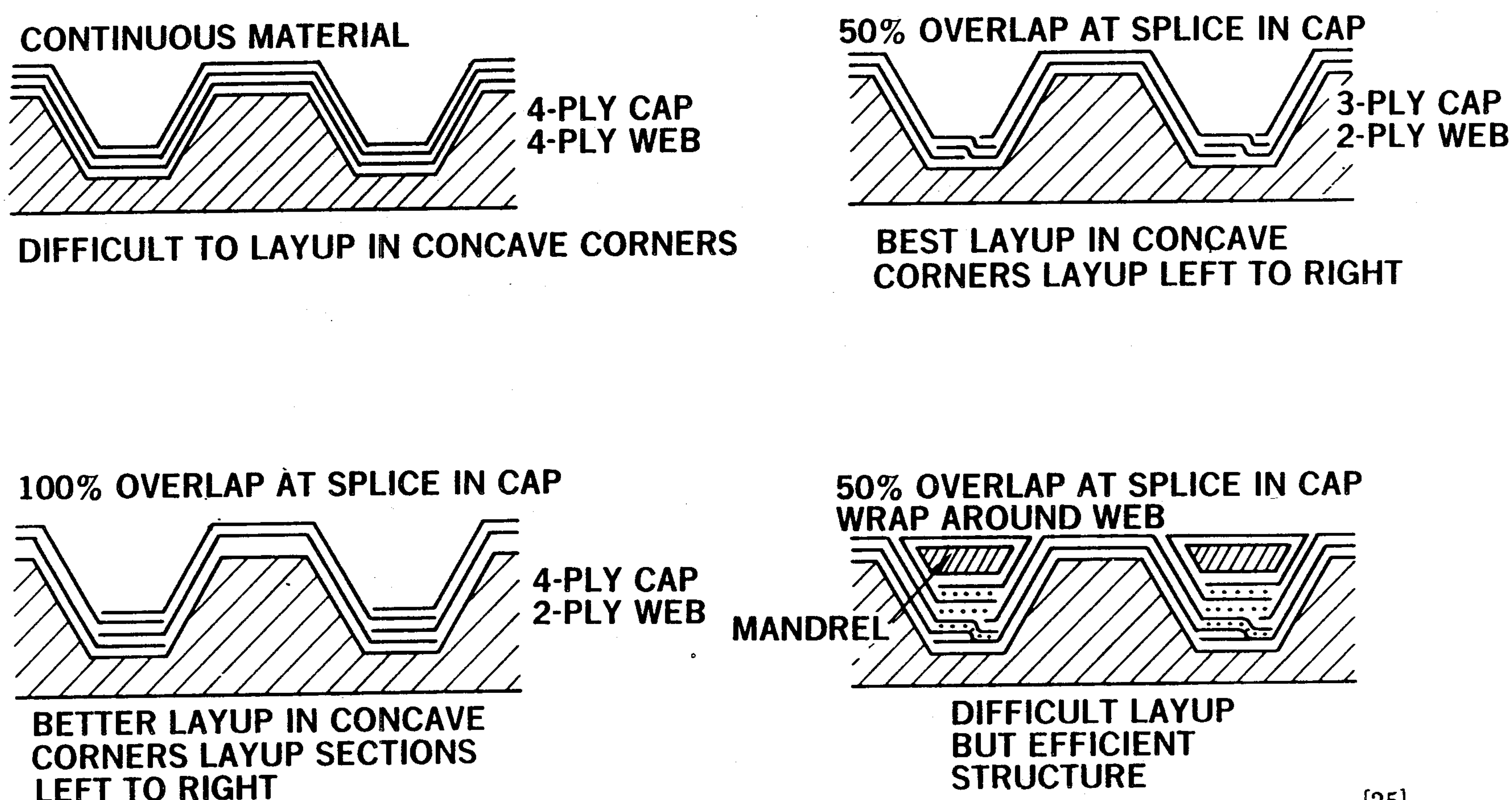
LOCATE WRAPAROUND PORTION OF WEB/CAP DETAIL IN CAVITY

LAYUP SKIN SIDE DOUBLER

LAYUP OUTER SKIN ON FLAT TOOL [25]

HAT STIFFENED PANELS

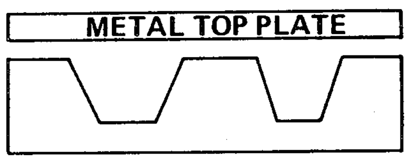
TYPICAL LAYUP PATTERNS



[25]

HAT STIFFENED

TOOLING CONCEPT—THICK STRUCTURAL CAPS



SOLID EXTERNAL TOOL

ALUMINUM, STEEL, GRAPHITE } MACHINED
FIBERGLASS/HONEYCOMB
SILICONE RUBBER, CERAMIC, PLASTER } CAST

INTERNAL MANDRELS

FOAM (URETHANE) REMAINS

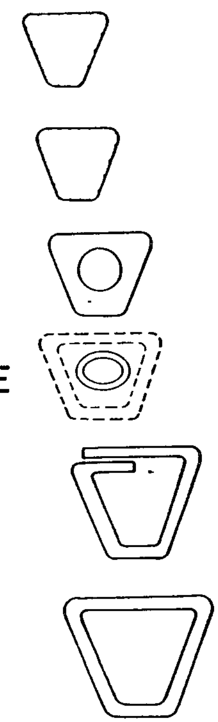
SOLID SILICONE—CAST—EXPANSION

HOLLOW SILICONE—CAST—INFLATABLE

ROUND EXTRUDED SILICONE—INFLATABLE

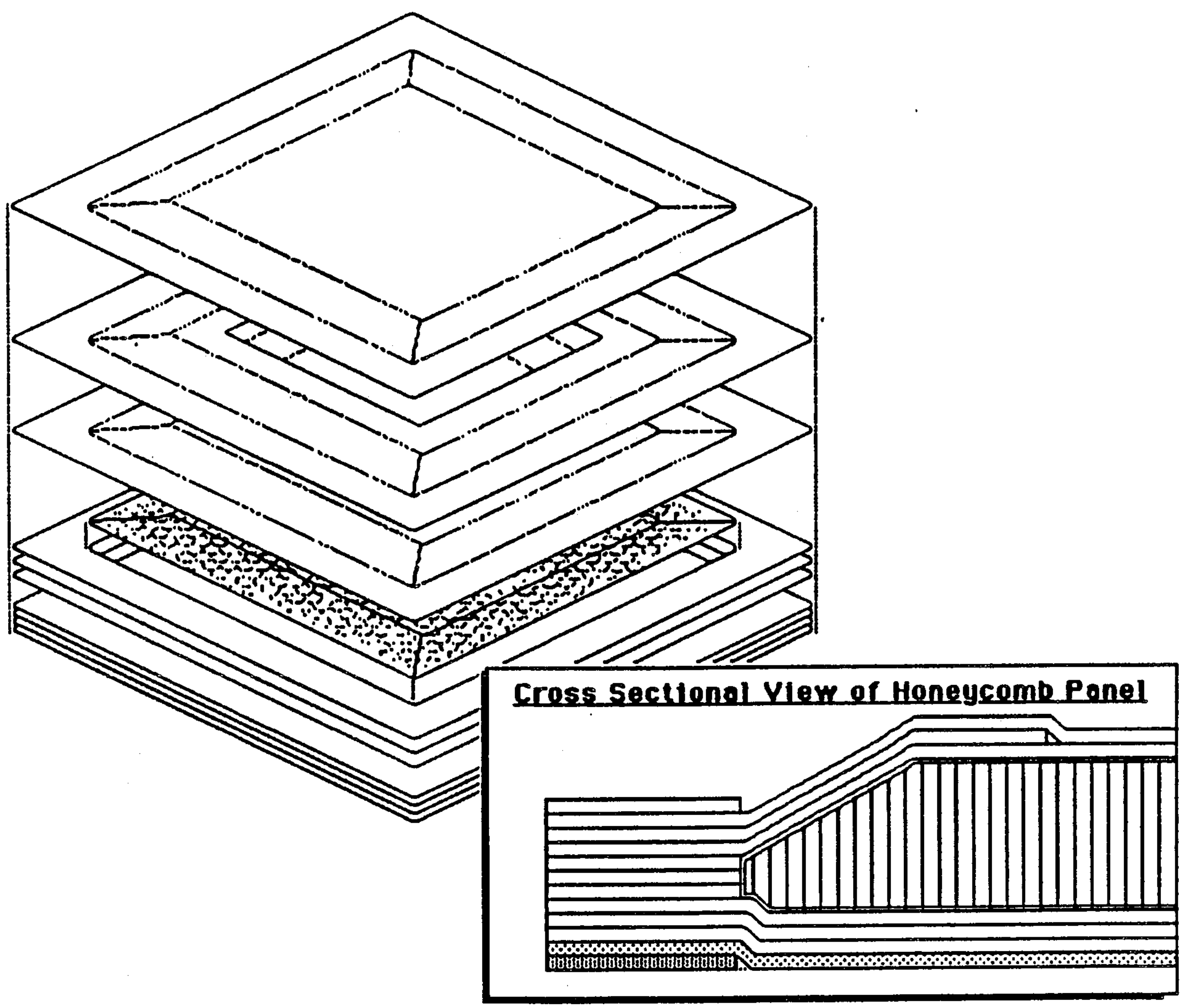
MOLDED SILICONE SHAPE—INFLATABLE
(FROM SHEET)

EXTRUDED SILICONE SHAPE—INFLATABLE



[25]

GENERIC CORE PANELS



[28]

MECHANICAL PROPERTIES OF STAMPED VS. COMPRESSION MOLDED PPS COMPOSITES

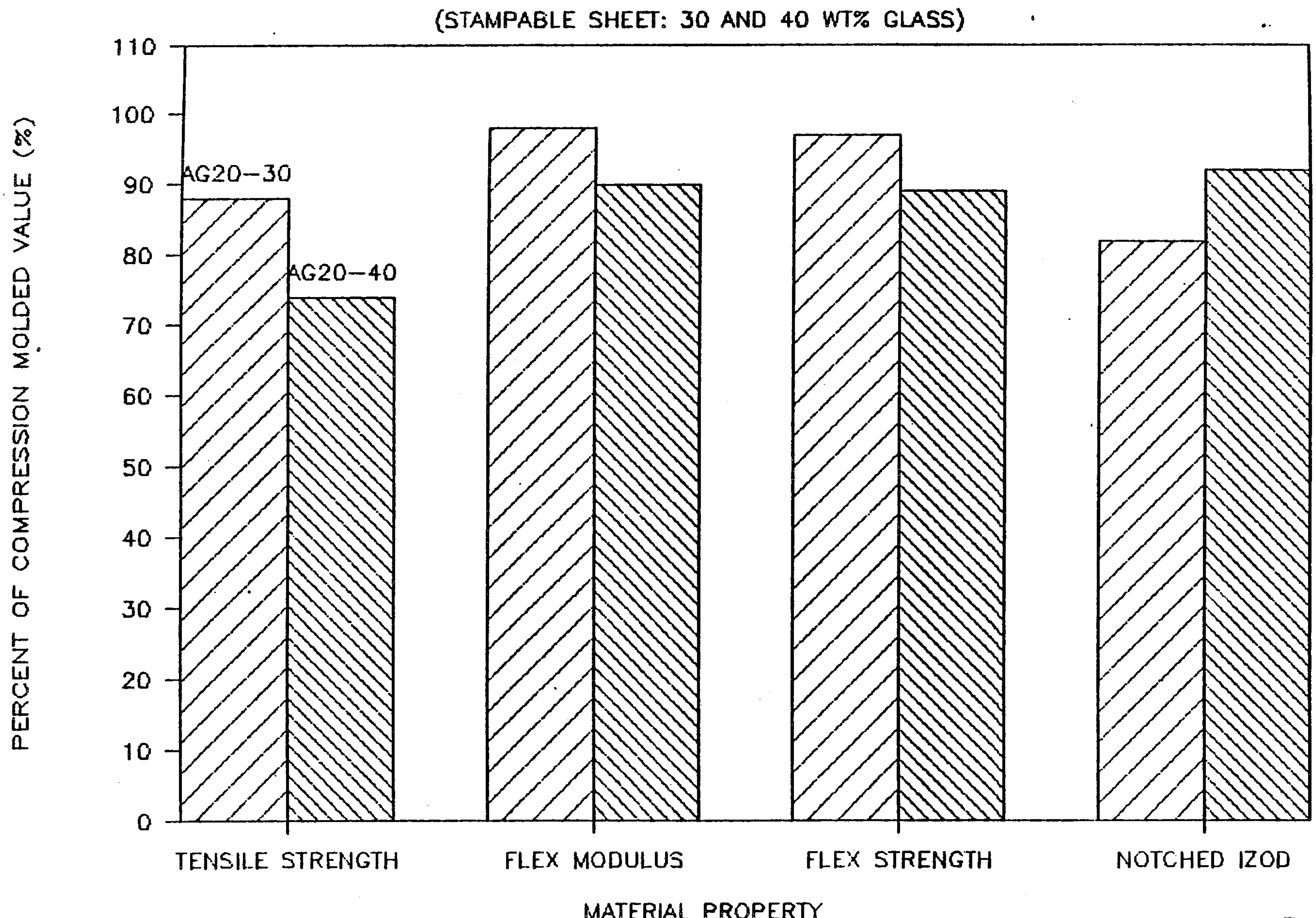
Property	AG20-30a	AG20-40a	AG20-30b	AG20-40b
Tensile Strength (ksi)	15.8	17.0	18.0	23.0
Flexural Modulus (msi)	1.6	1.6	1.6	1.8
Flexural Strength (ksi)	31.0	30.3	32.0	34.0
Izod Impact, Notched (ft-lbs/in)	9.8	12.9	12.0	14.0

a. From bottom of tray; stamped at 5000 PSI for approximately 2 minutes; material free to flow.

b. From plaque; molded at 75-100 PSI for 12 minutes; material flow was constrained.

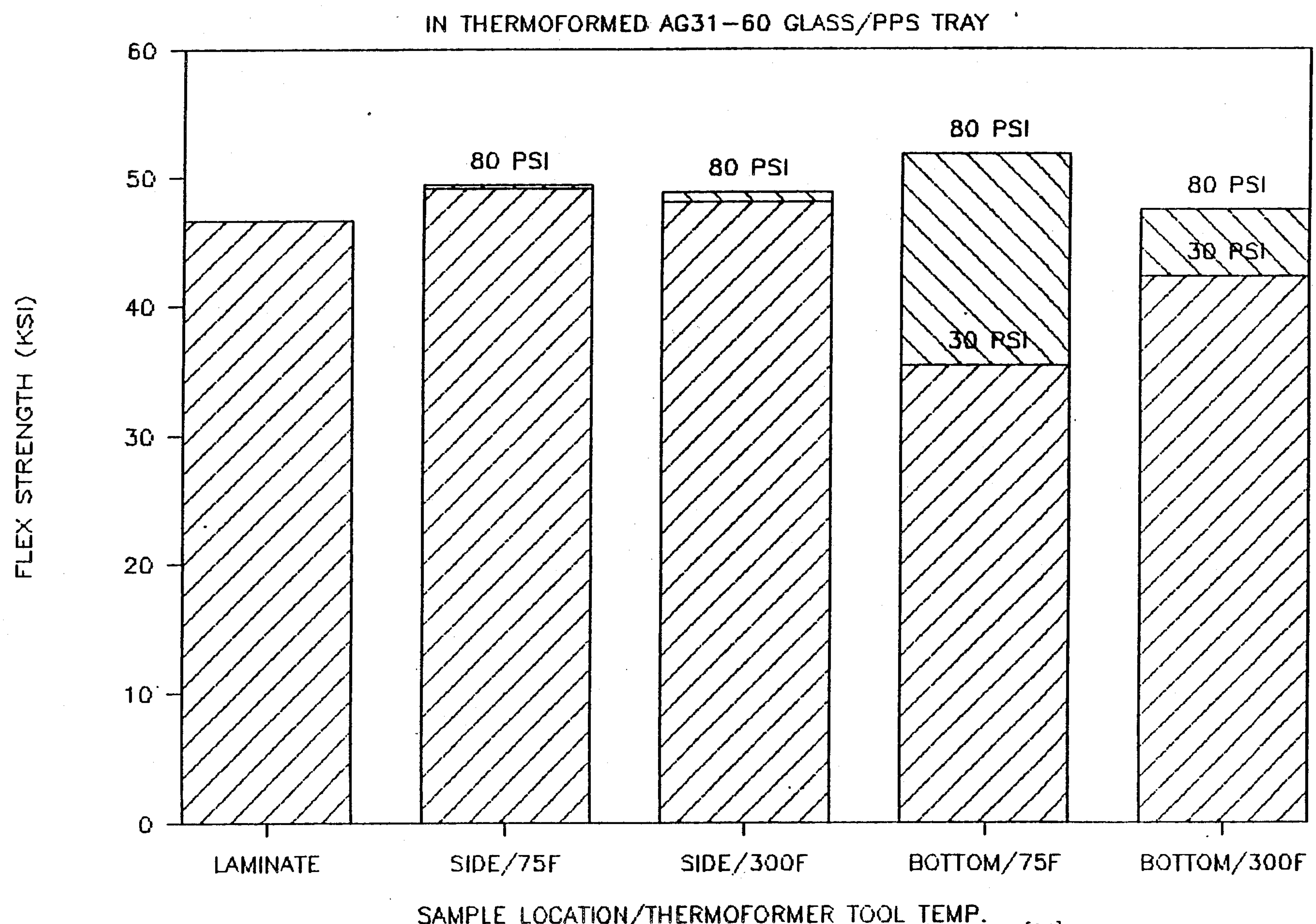
[31]

EFFECT OF MOLDING ON PROPERTY RETENTION

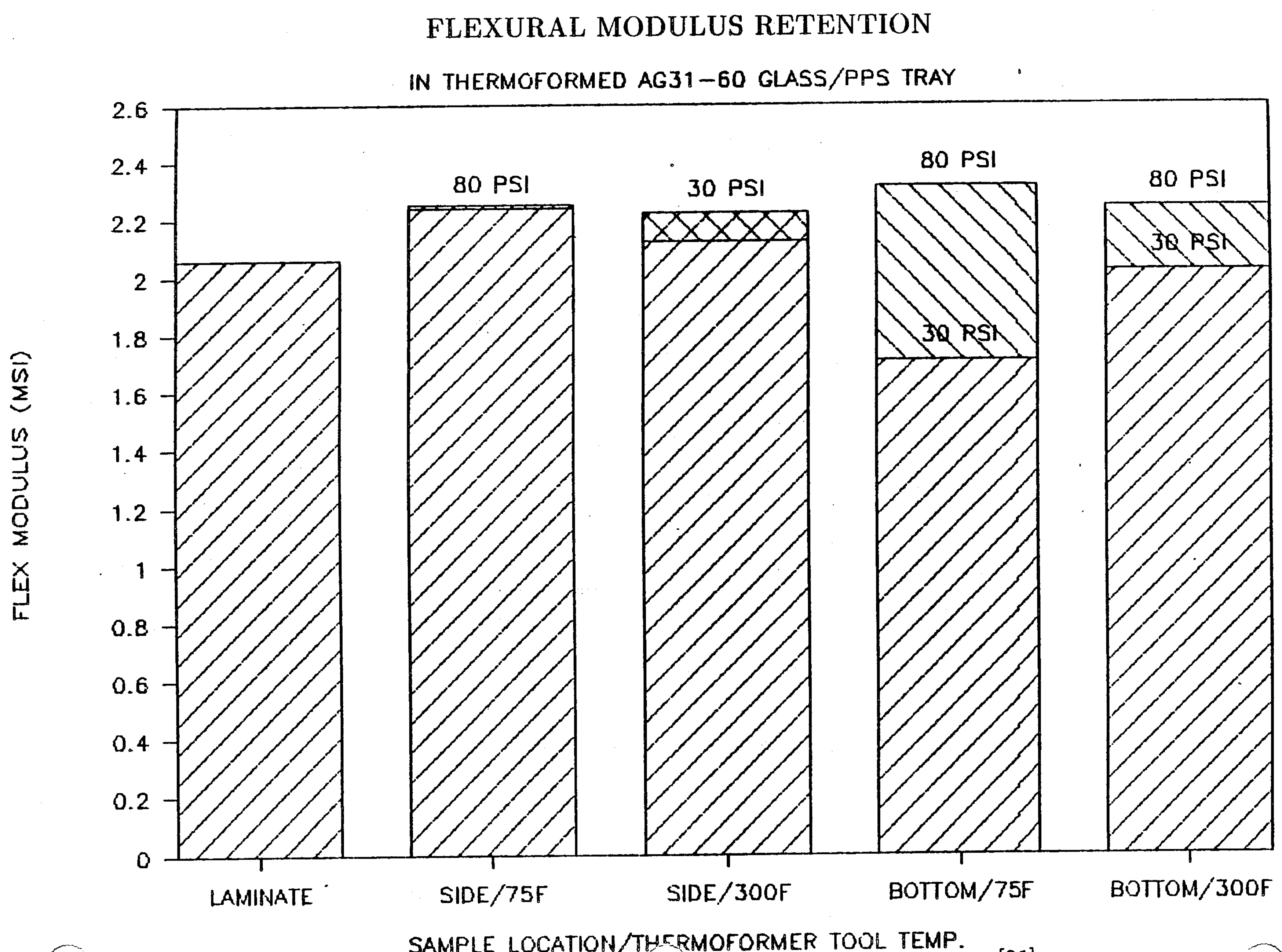


[31]

FLEXURAL STRENGTH RETENTION

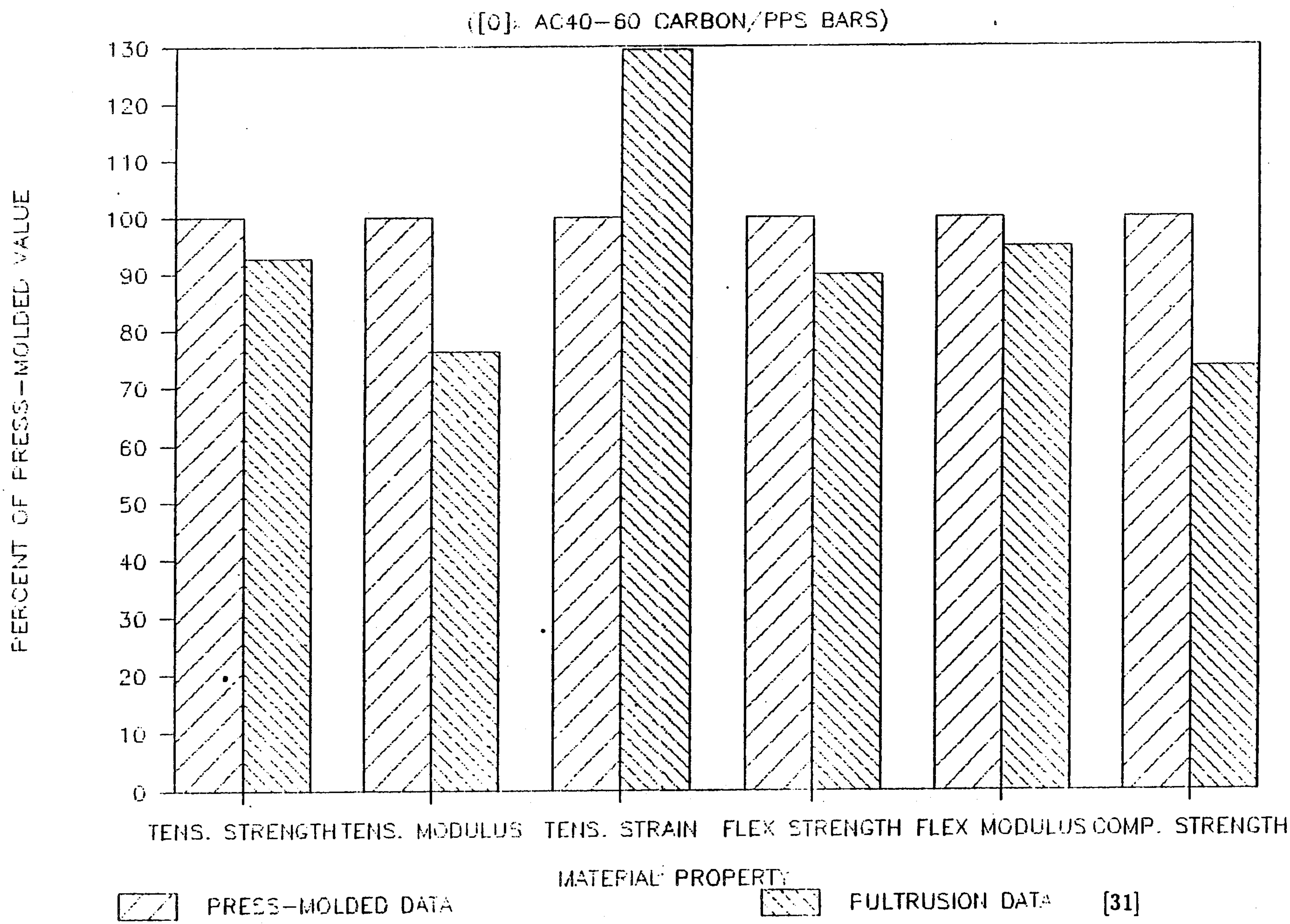


[31]


FLEXURAL MODULUS RETENTION
IN THERMOFORMED AG31-60 GLASS/PPS TRAY
FLEX MODULUS (MSI)
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
80 PSI
30 PSI
80 PSI
30 PSI
80 PSI
30 PSI
LAMINATE
SIDE/75F
SIDE/300F
BOTTOM/75F
BOTTOM/300F
SAMPLE LOCATION/THERMOFORMER TOOL TEMP.

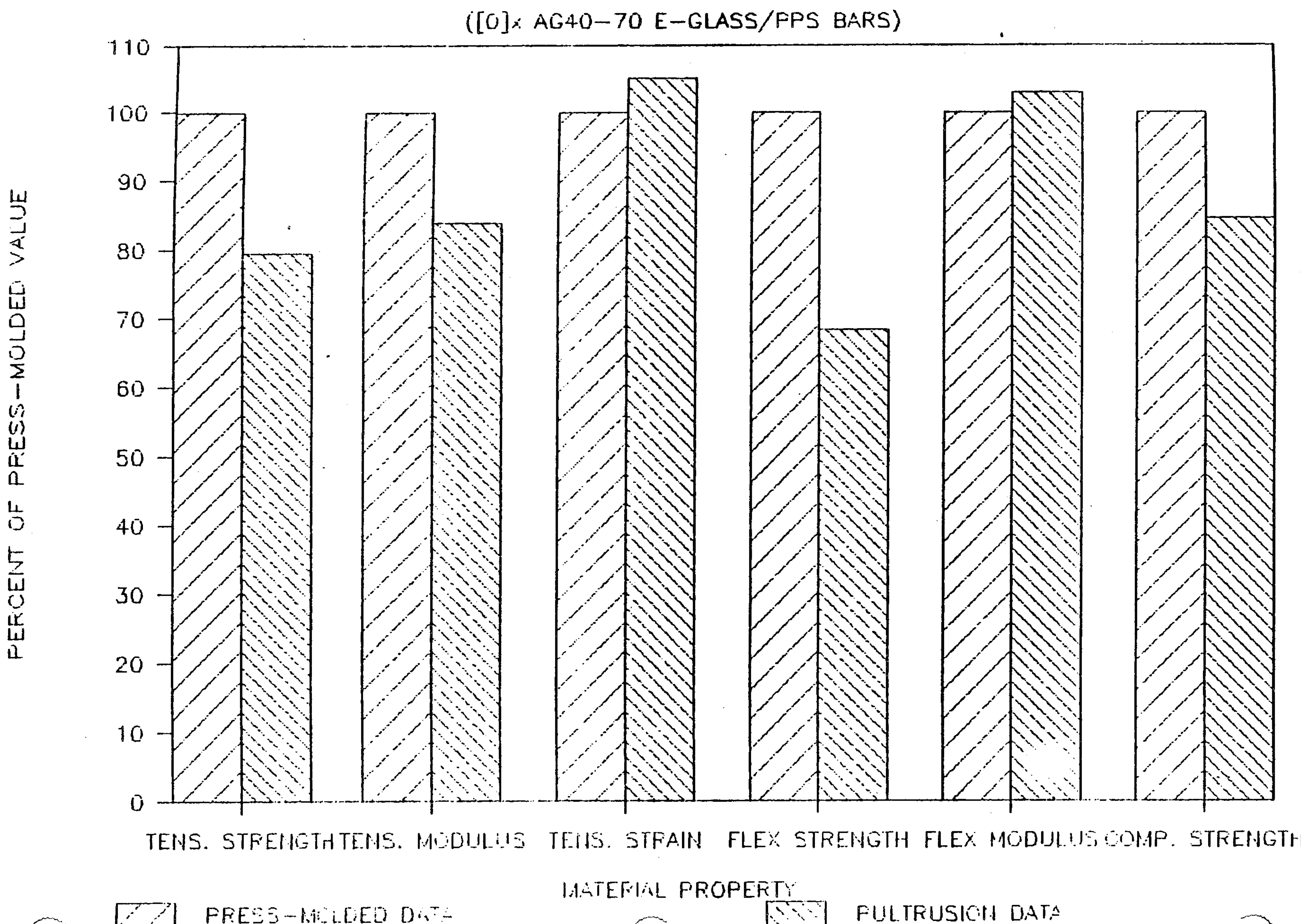
[31]

TYPICAL PULTRUSION PROPERTY COMPARISON



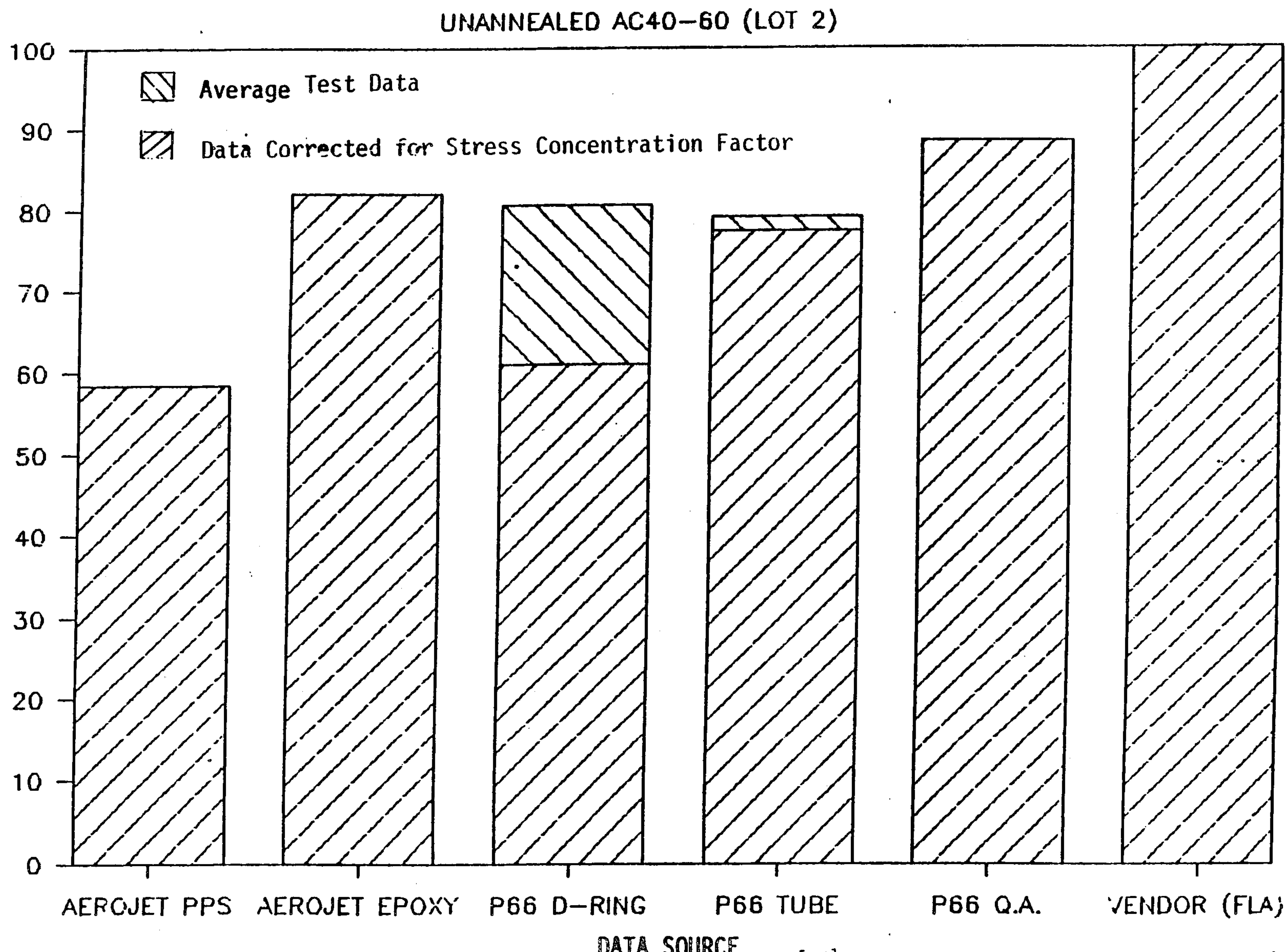
[31]

TYPICAL PULTRUSION PROPERTY COMPARISON



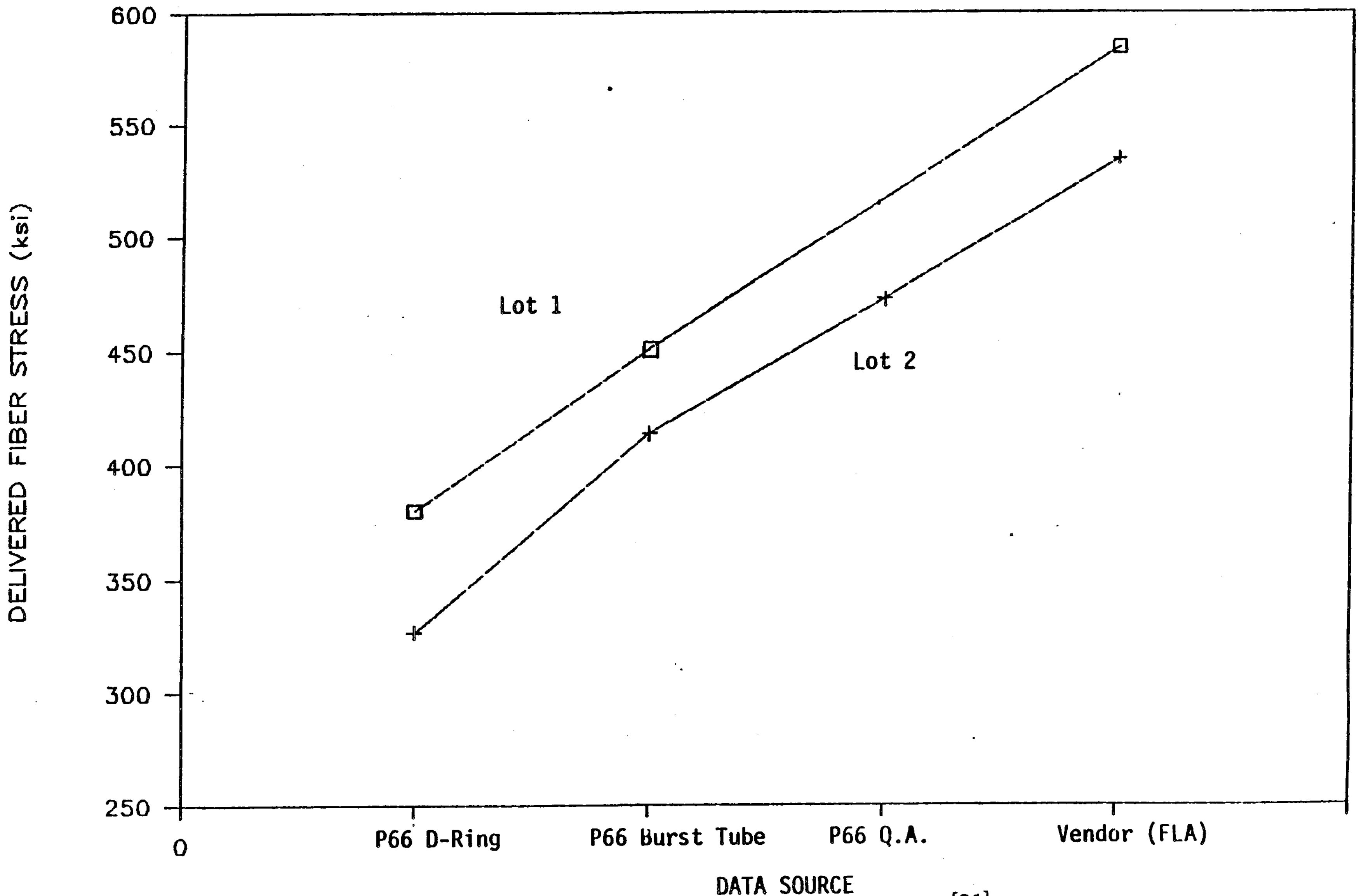
[31]

DELIVERED FIBER STRESS



[31]

AC40-60 DELIVERED FIBER STRESS



[31]

Aircraft Components

Primary Structure

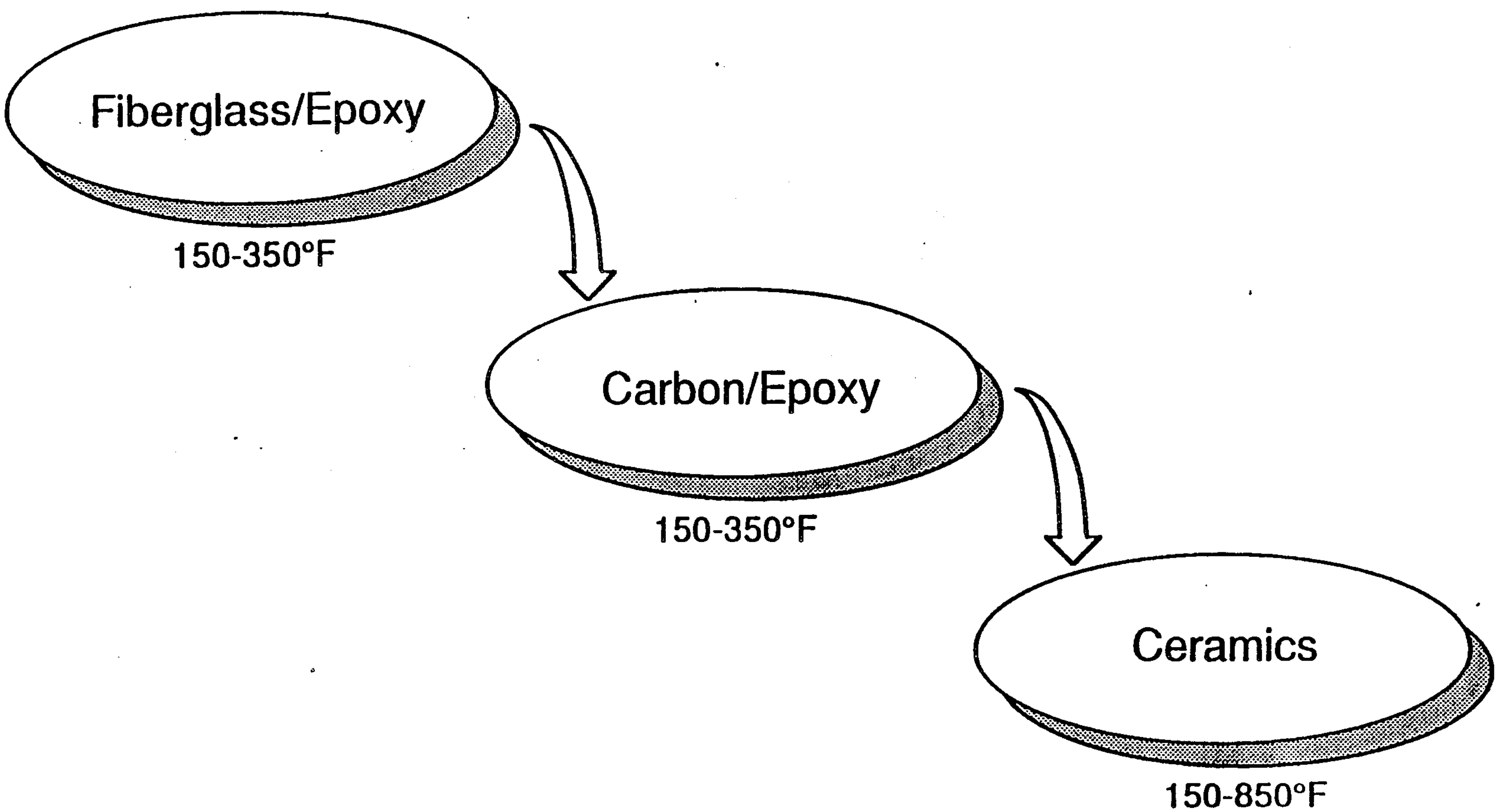
Secondary Structure

Covers & Fairings

Inlet Ducts

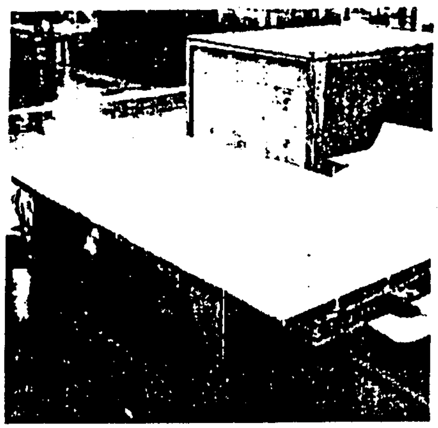
[32]

Non-Metallic Tooling Evolution

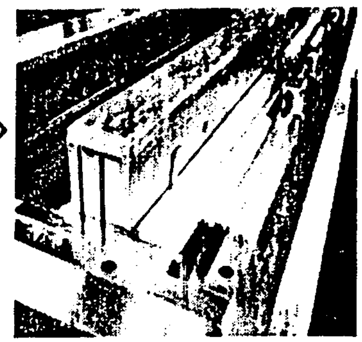


[32]

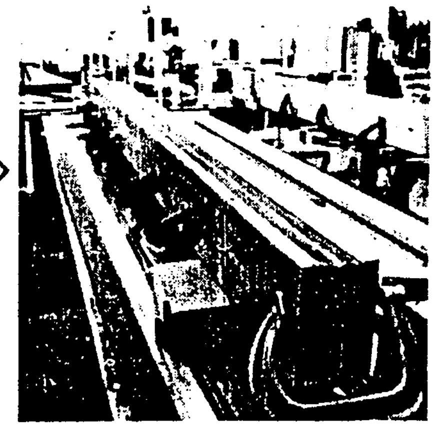
Full-Size Wingbox Fabrication



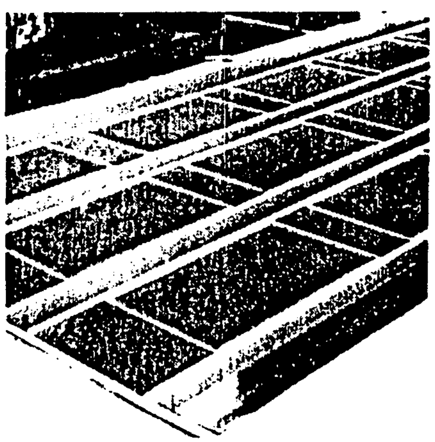
Lower Skin/Spar Tooling



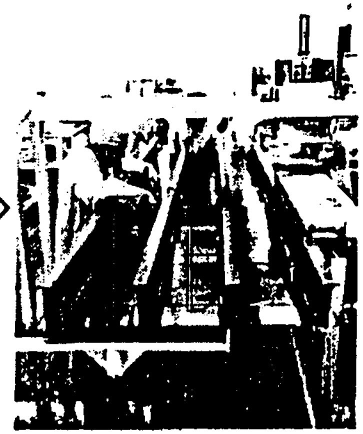
Spar Tooling



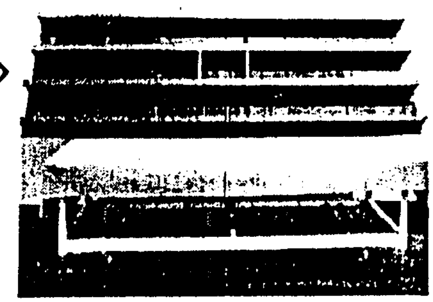
Spar Collation



Skin Collation



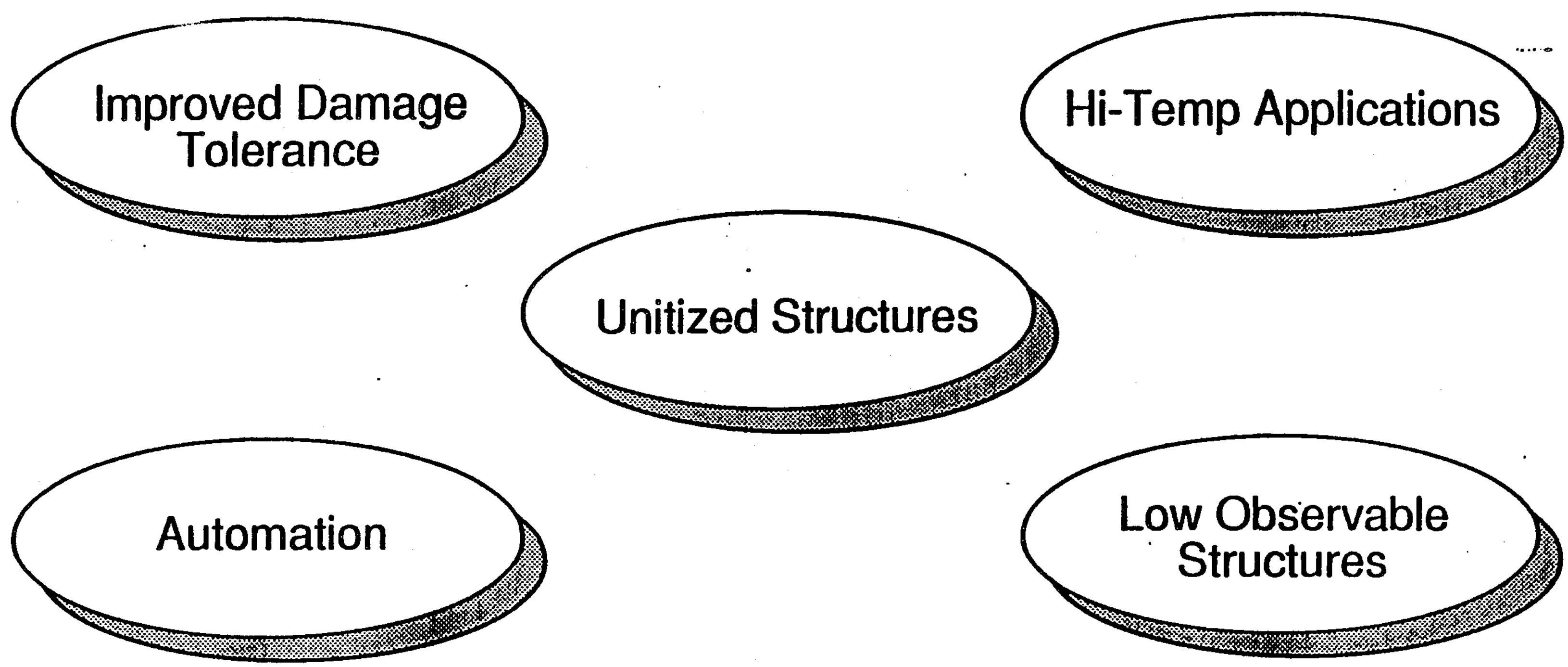
Stitching of Spars to Skins



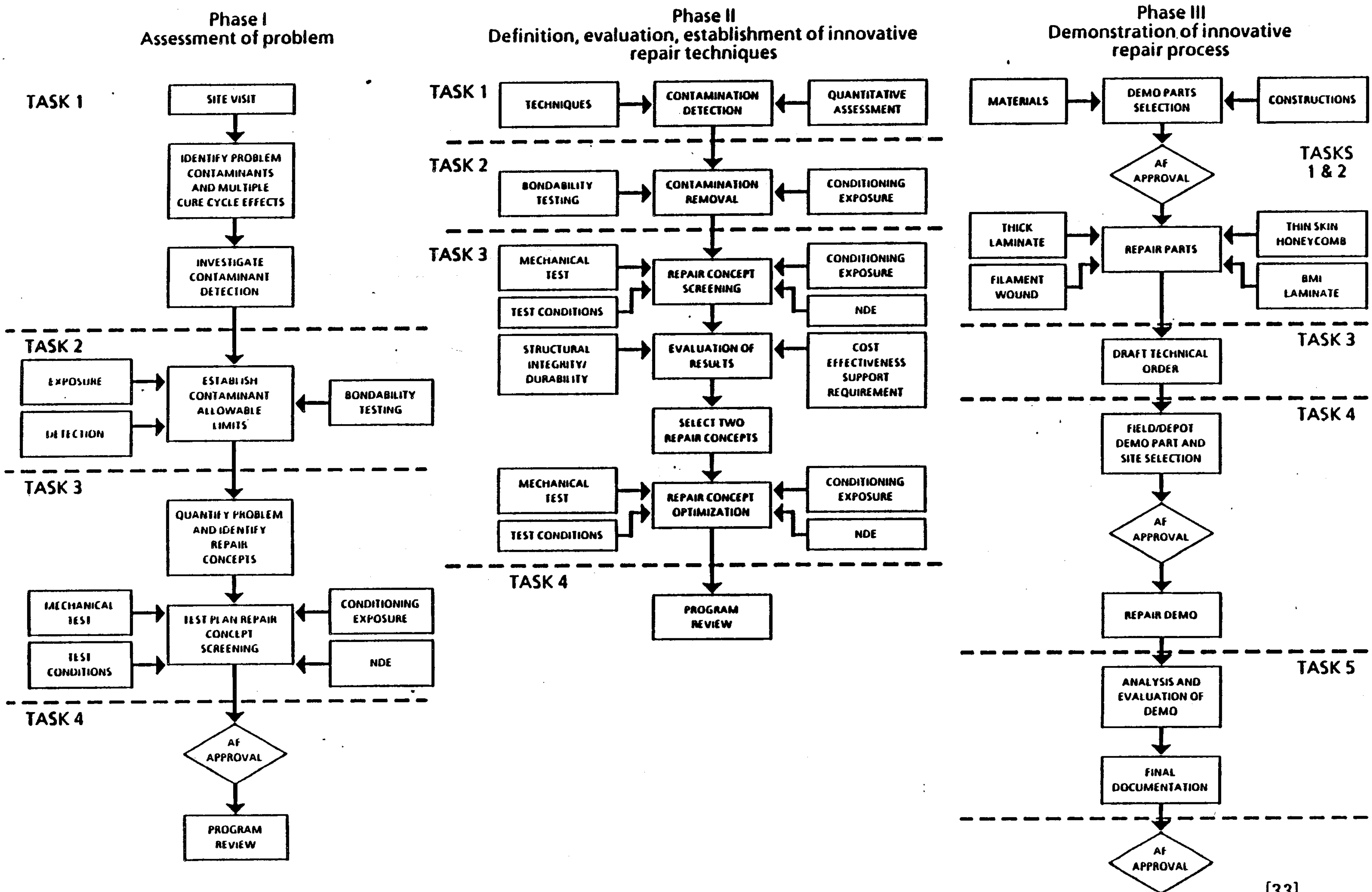
Lower Skin With Cocured Spars

[32]

Emerging Composites Manufacturing Challenges



[32]



Program Overview, Advanced Depot Repair Process

Wide Area Lapshear Test Results of Moisturized Graphite/Epoxy Laminates

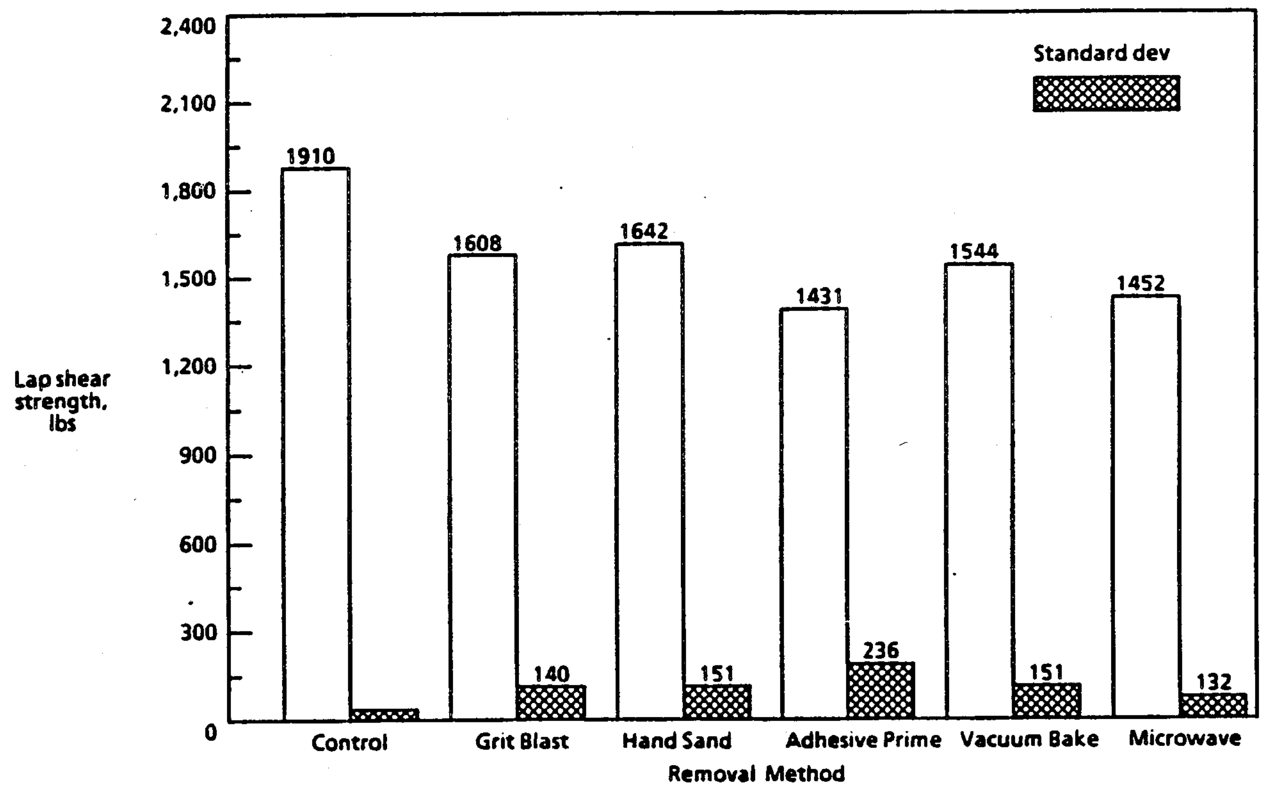
Percent moisture	Average lapshear, PSI
1.00	2642
0.50	3604
0.20	3582
0.10	3762
0.080	3742
0.05	3724
0.04	3622
0	4152

Hand abrade, MEK wipe, FM300 grade 05, vacuum bag cure @ 350° F, 2 hours.

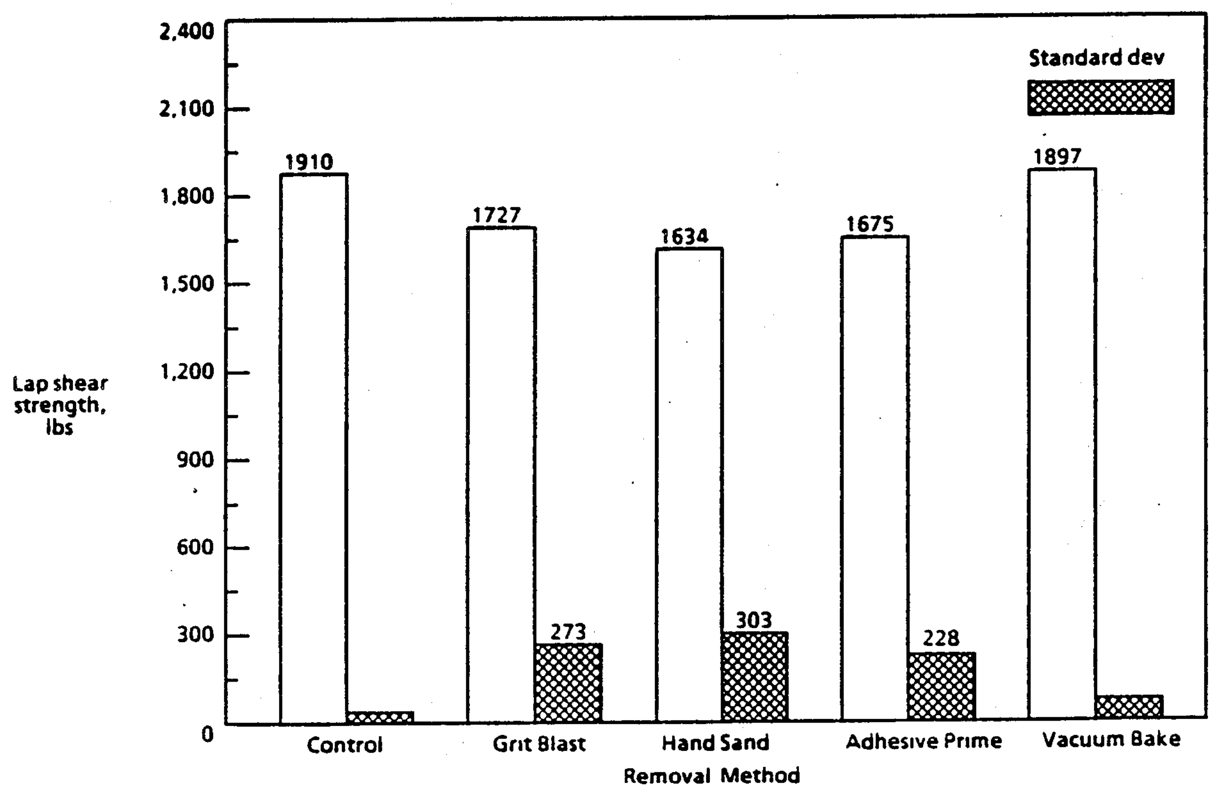
Moisture Allowable Limits for Graphite/Epoxy [33]

Identified in Phase I	Evaluated in Phase II
• Moisture	
• Mitsubishi moisture analyzer	X
• DuPont 902 moisture analyzer	
• Karl Fisher titration	
• Gas chromotography	
• Moisture/fuel/hydraulic fluid	
• Nuclear magnetic resonance	X
• Photoelectron emission (UV)	X
• Infrared	
– Photoacoustic spectroscopy	
– Thermography	
• Microwave spectroscopy	X
• Radiography	
– Neutron	X
– Computed tomography	
– Compton scatter imaging	X

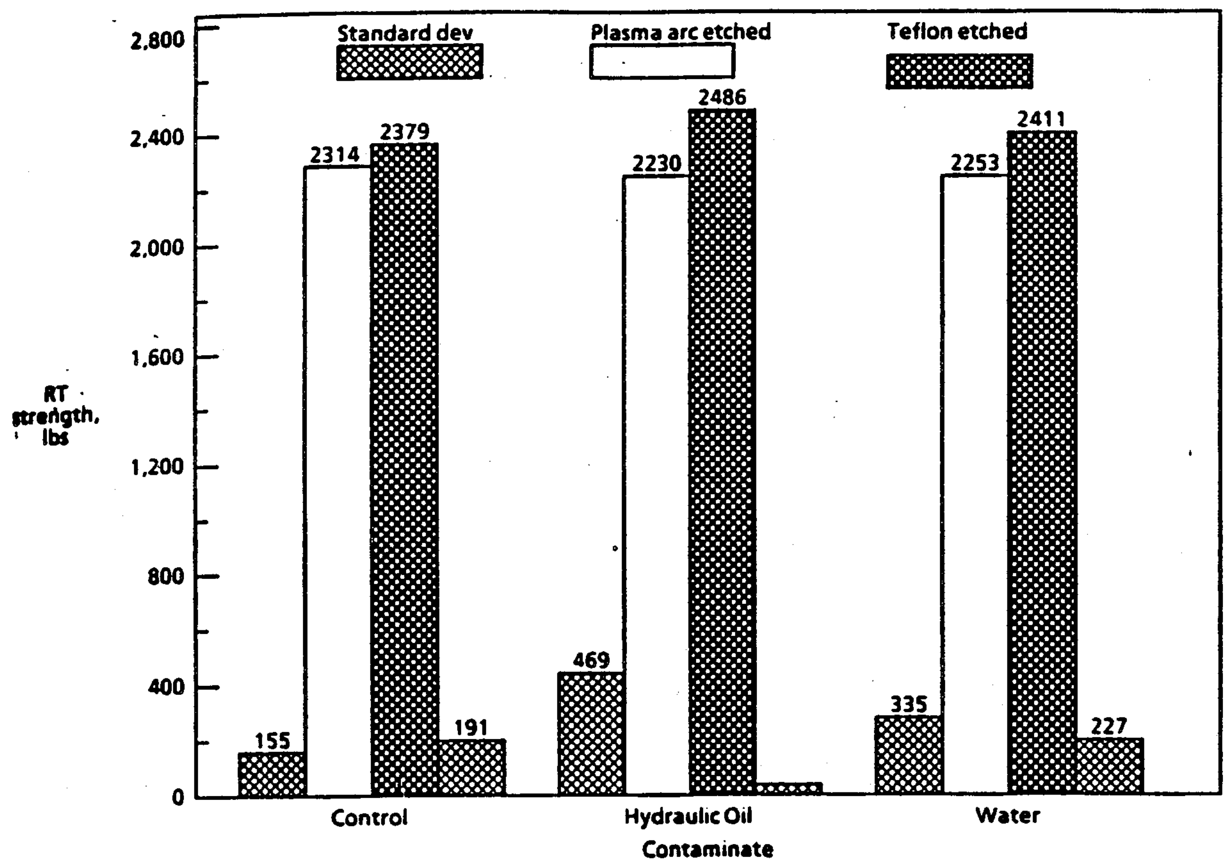
Contaminate Detection Techniques [33]



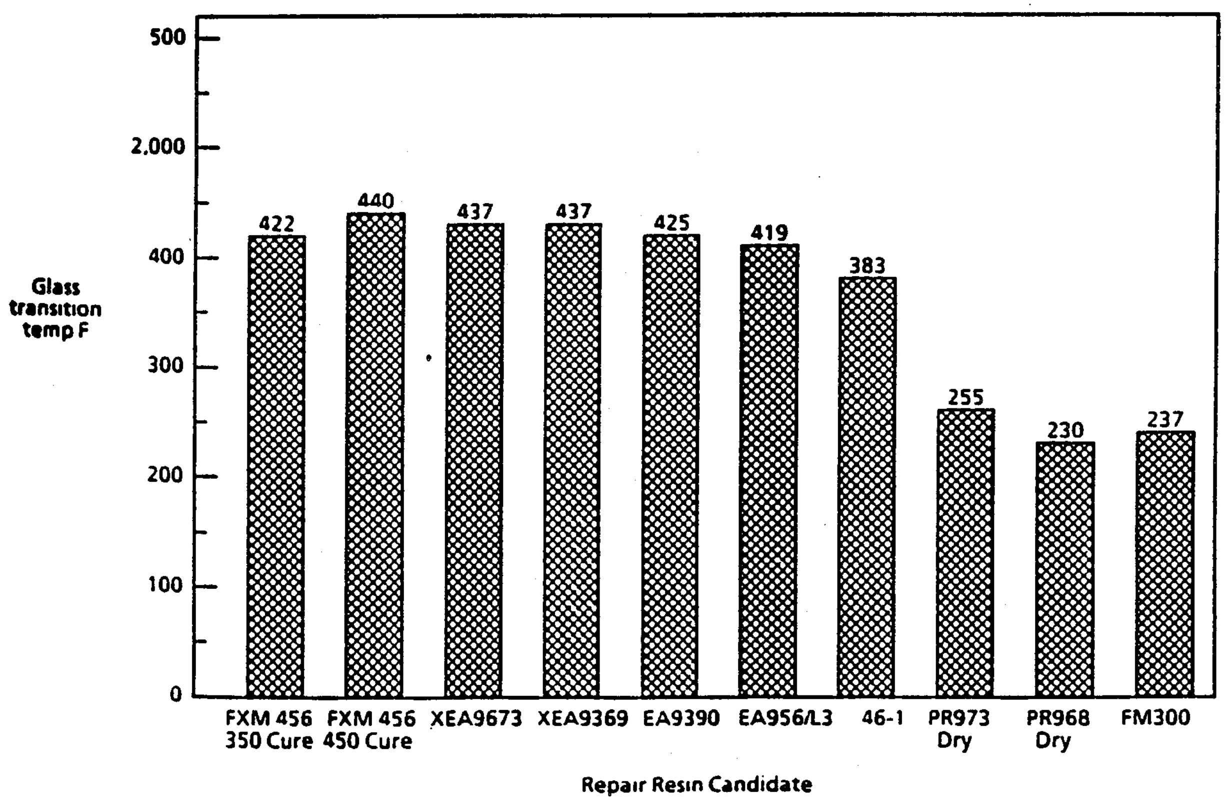
Contaminate Removal Methods for Water in Graphite/Epoxy [33]



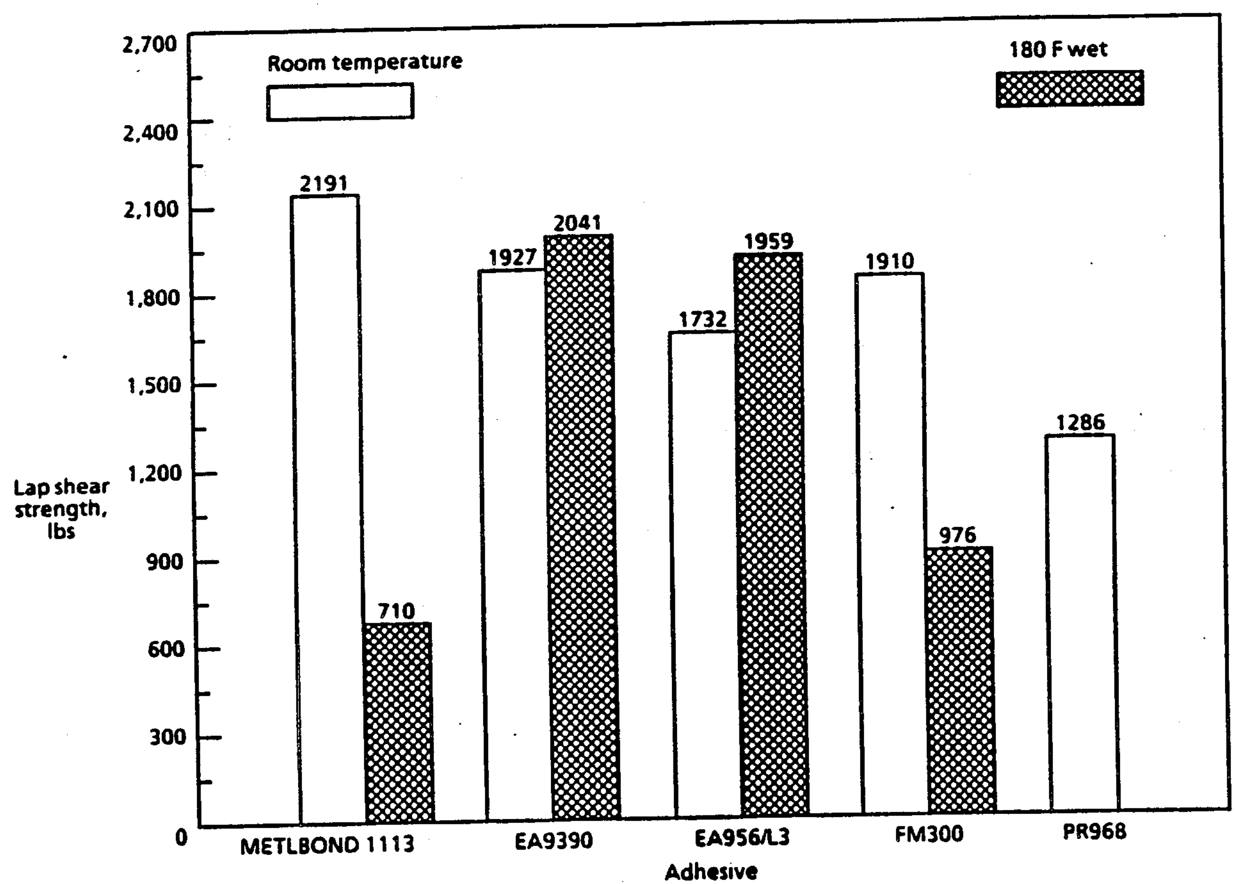
Contaminate Removal Methods for JP4 in Graphite/Epoxy [33]



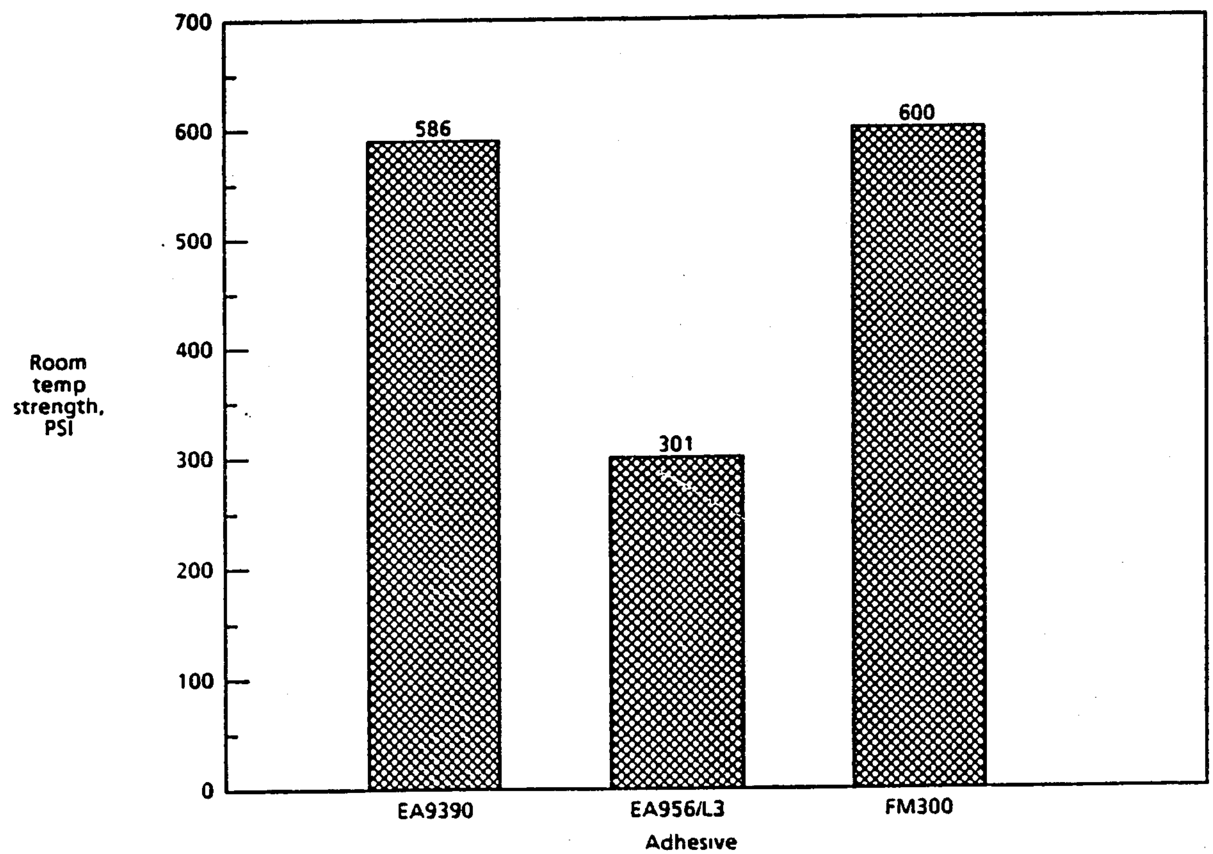
Contaminate Removal Methods for Graphite/PEEK [33]



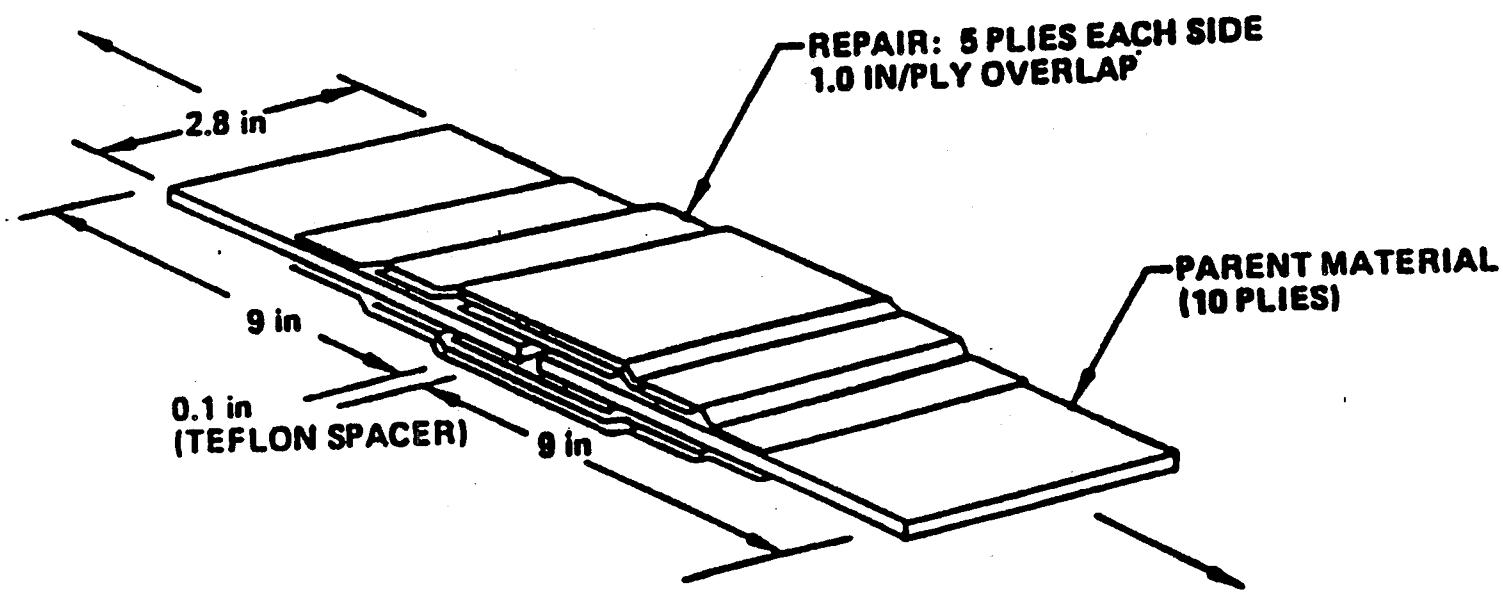
Wet Glass Transition Temperature of Candidate Repair Materials [33]



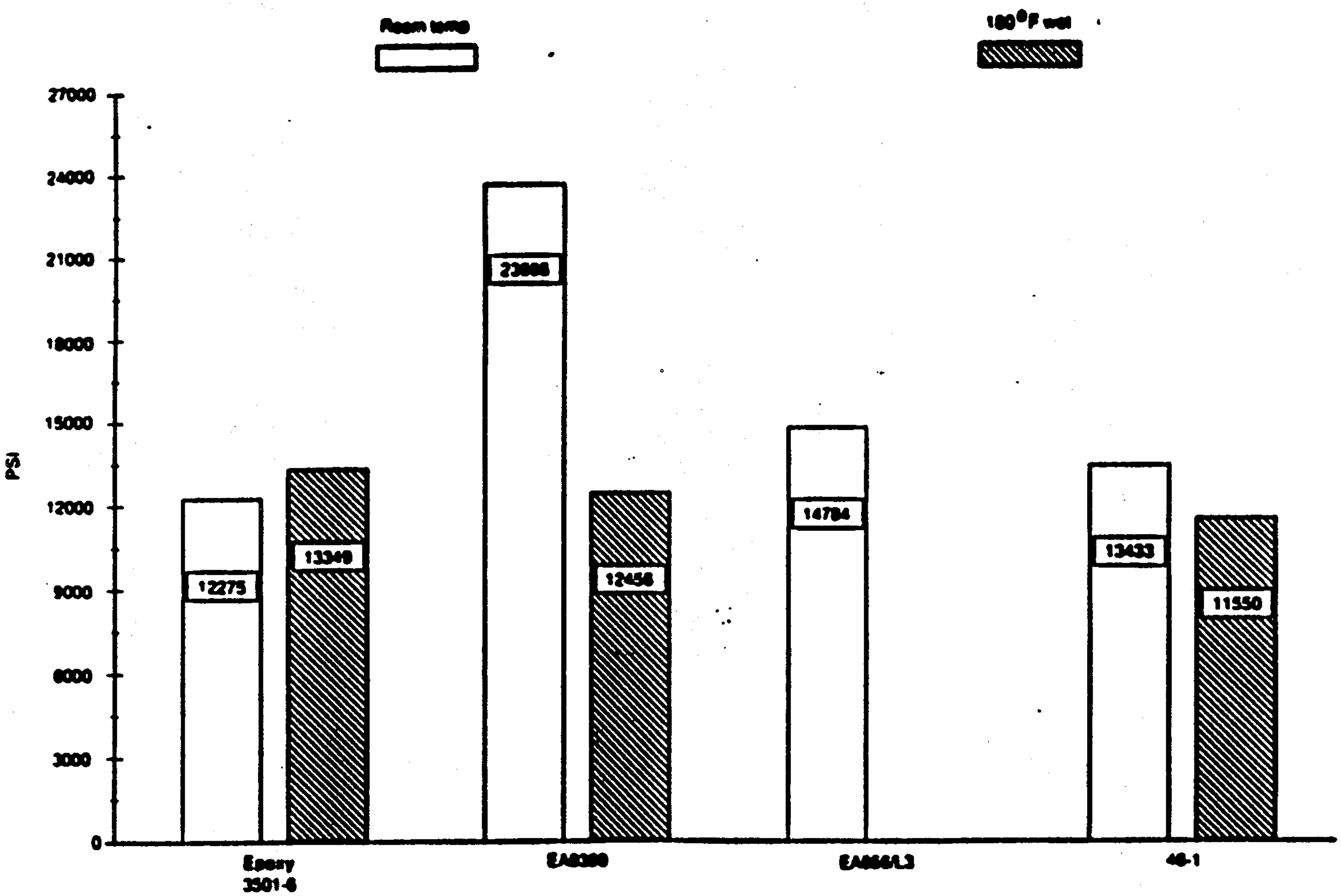
Lap Shear Strength of Candidate Adhesives [33]



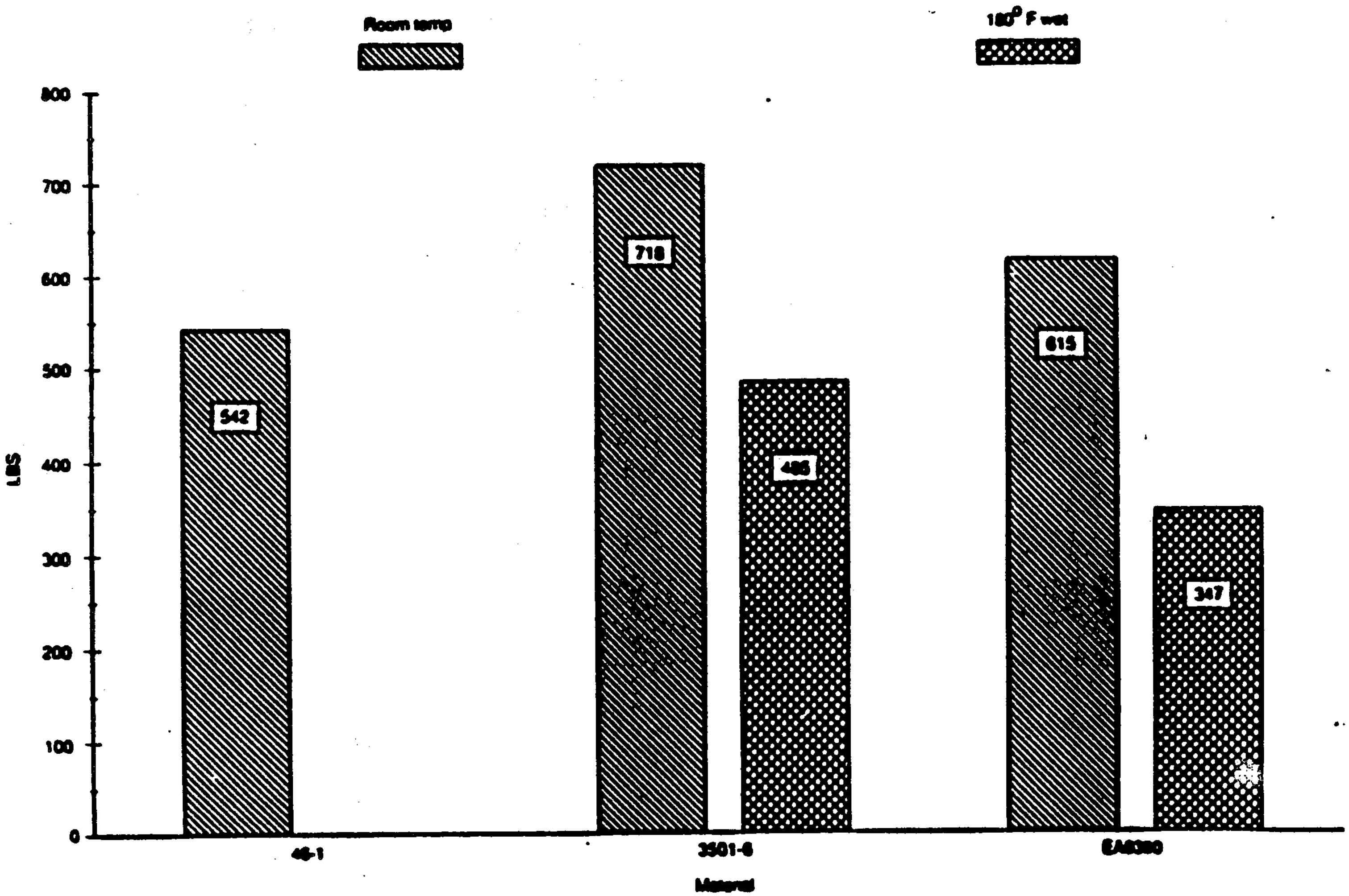
Flatwise Tensile Strength of Candidate Repair Adhesives [33]



Tension Overlap Splice Specimen Configuration [33]

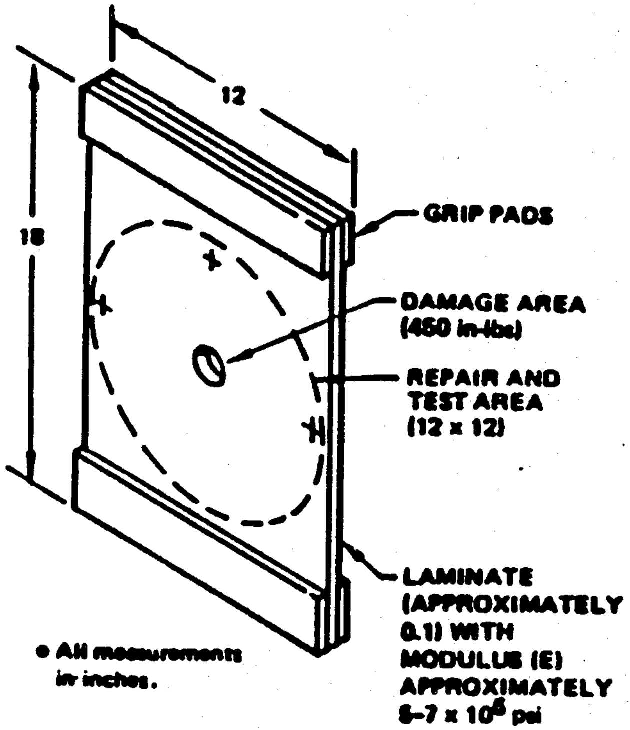


Tensile Splice Lap Test Results of Repair Candidate Materials [33]

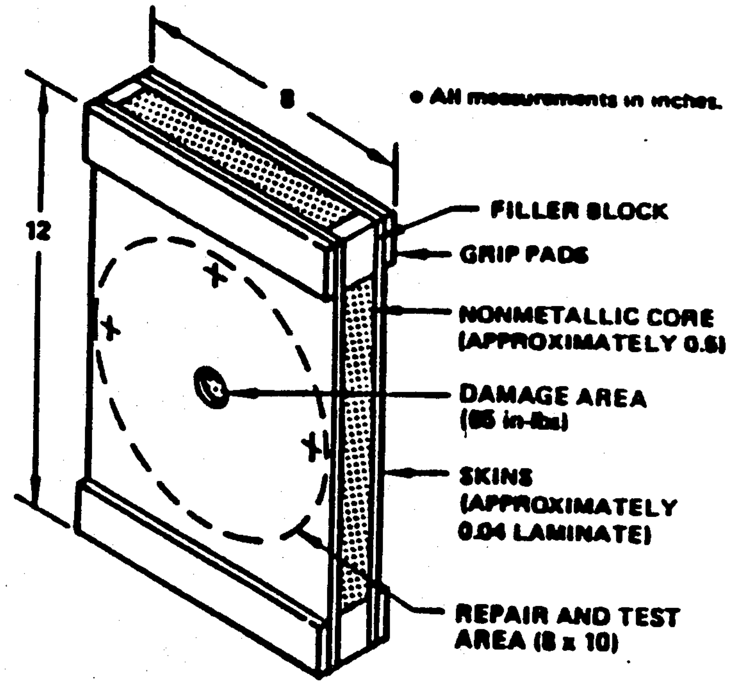


Longbeam Flexure Test Results [33]

more complicated
removes honeycomb as well as lamina

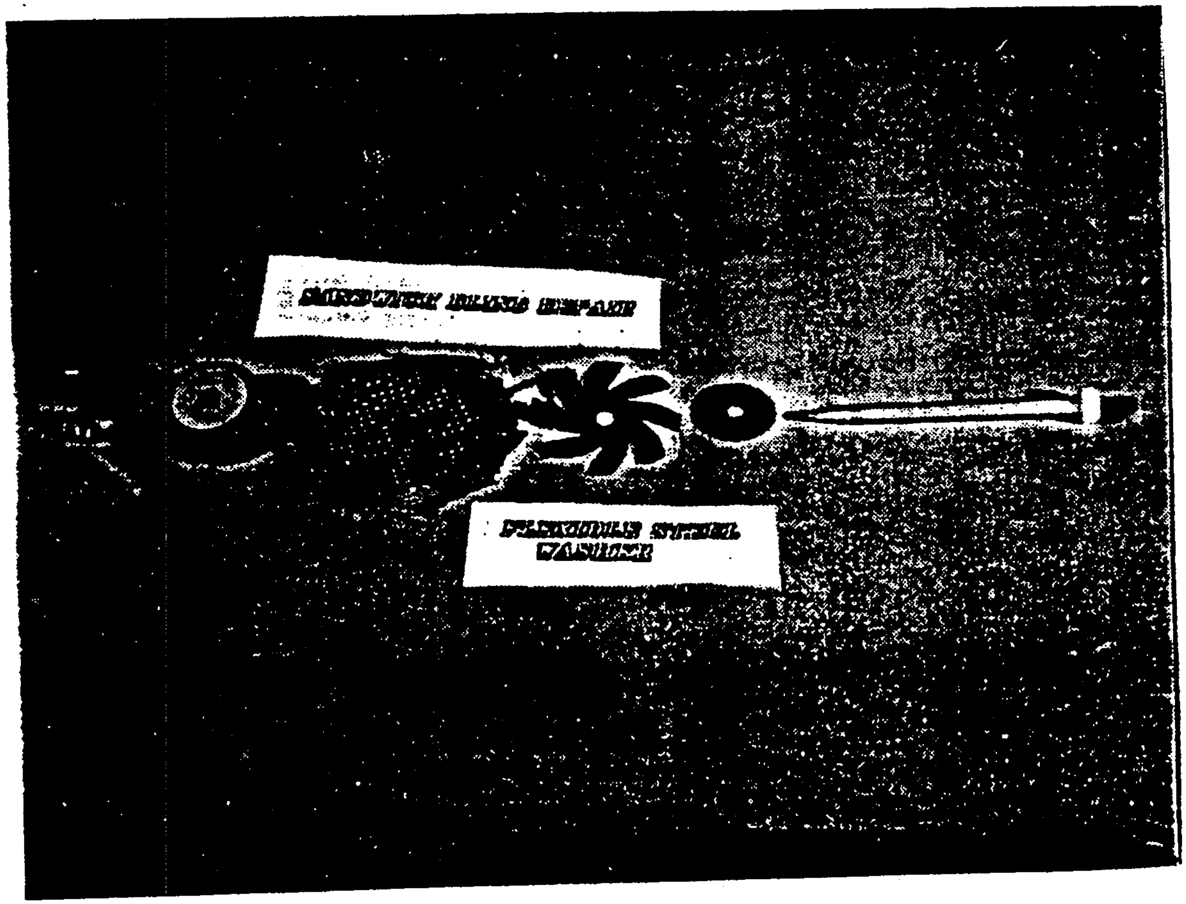


Laminate Test Coupon

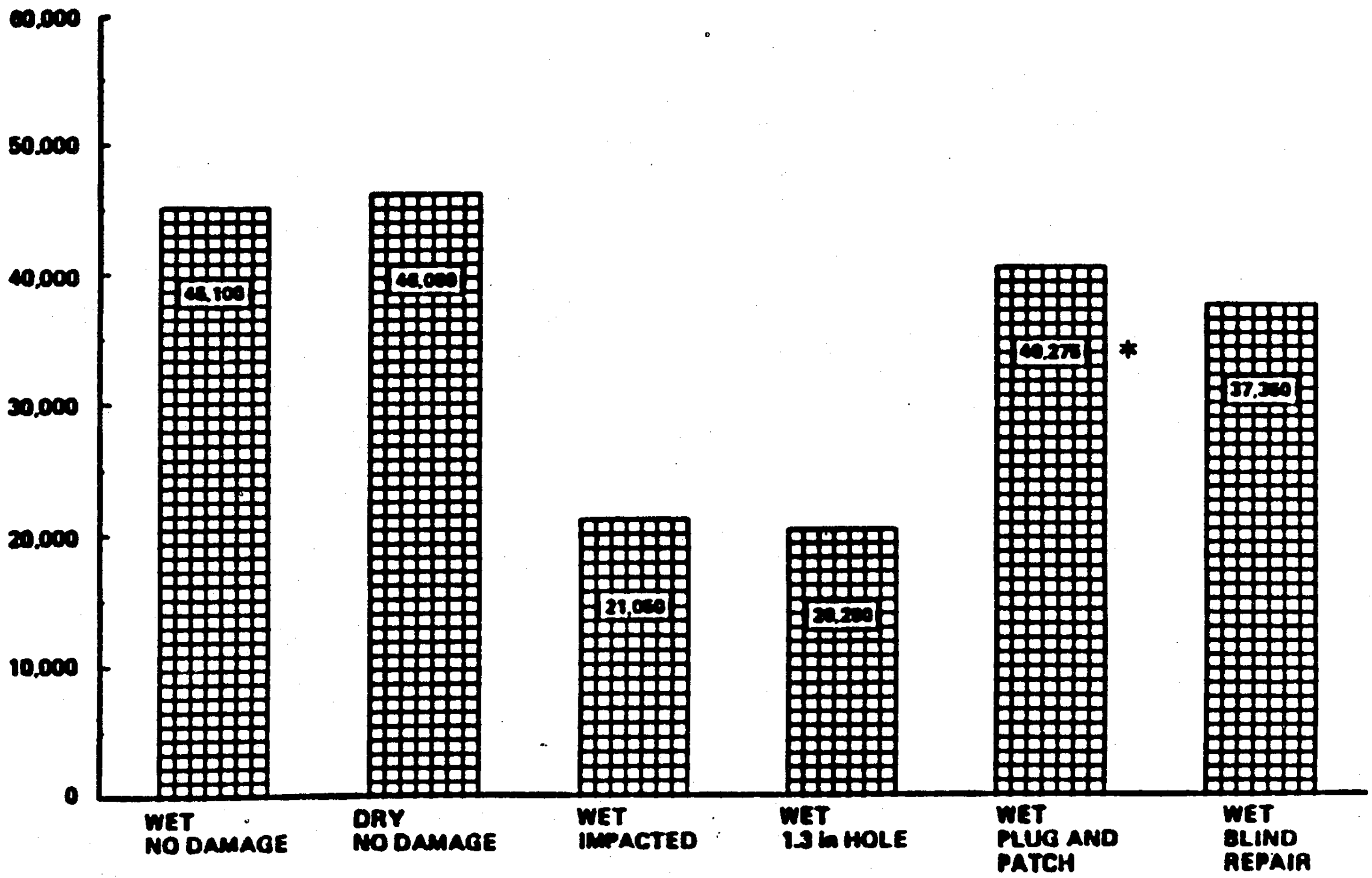


Sandwich Test Coupon

Repair Process Optimization Test Panel Configuration [33]

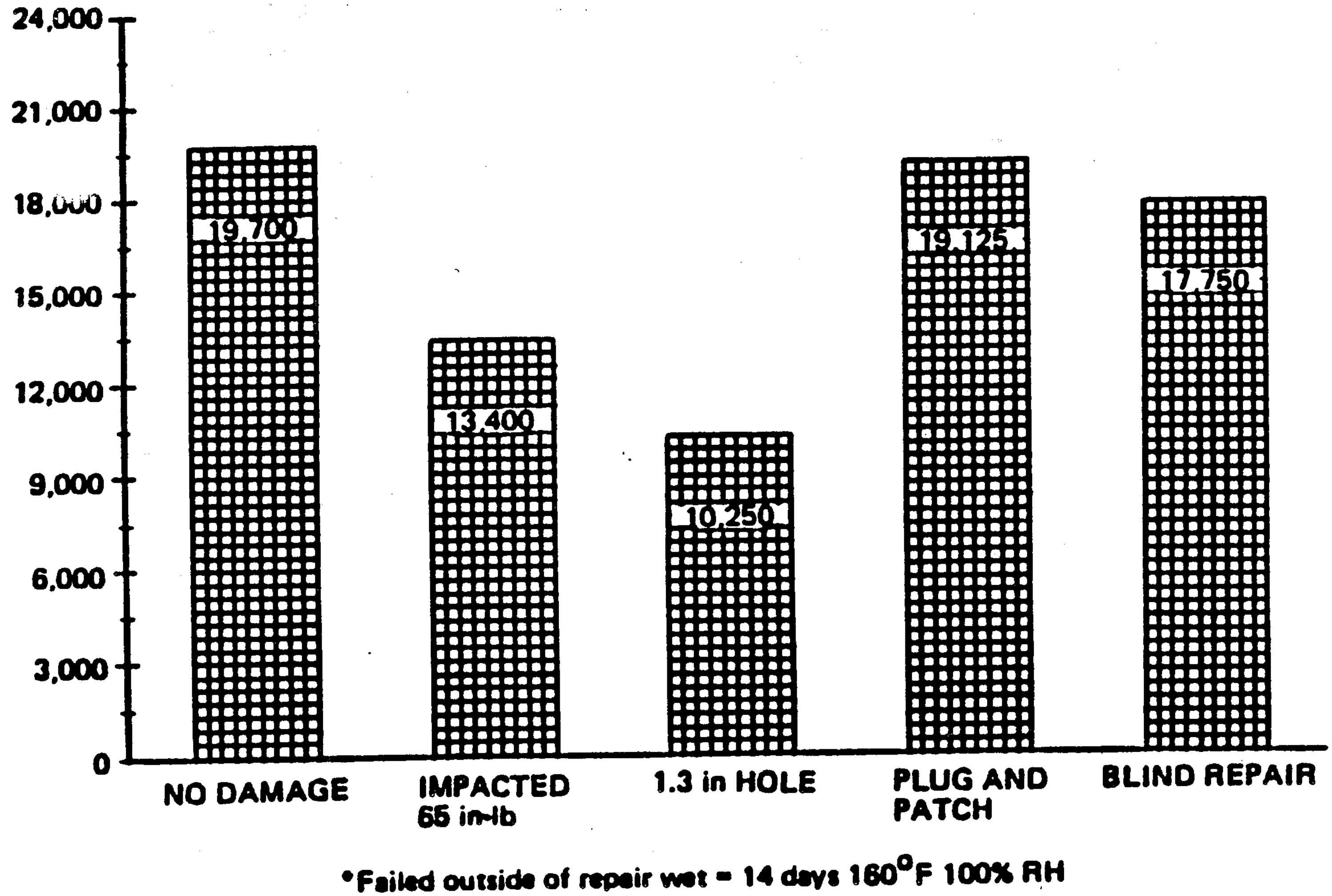


Components of the Sandwich Blindside Repair [33]

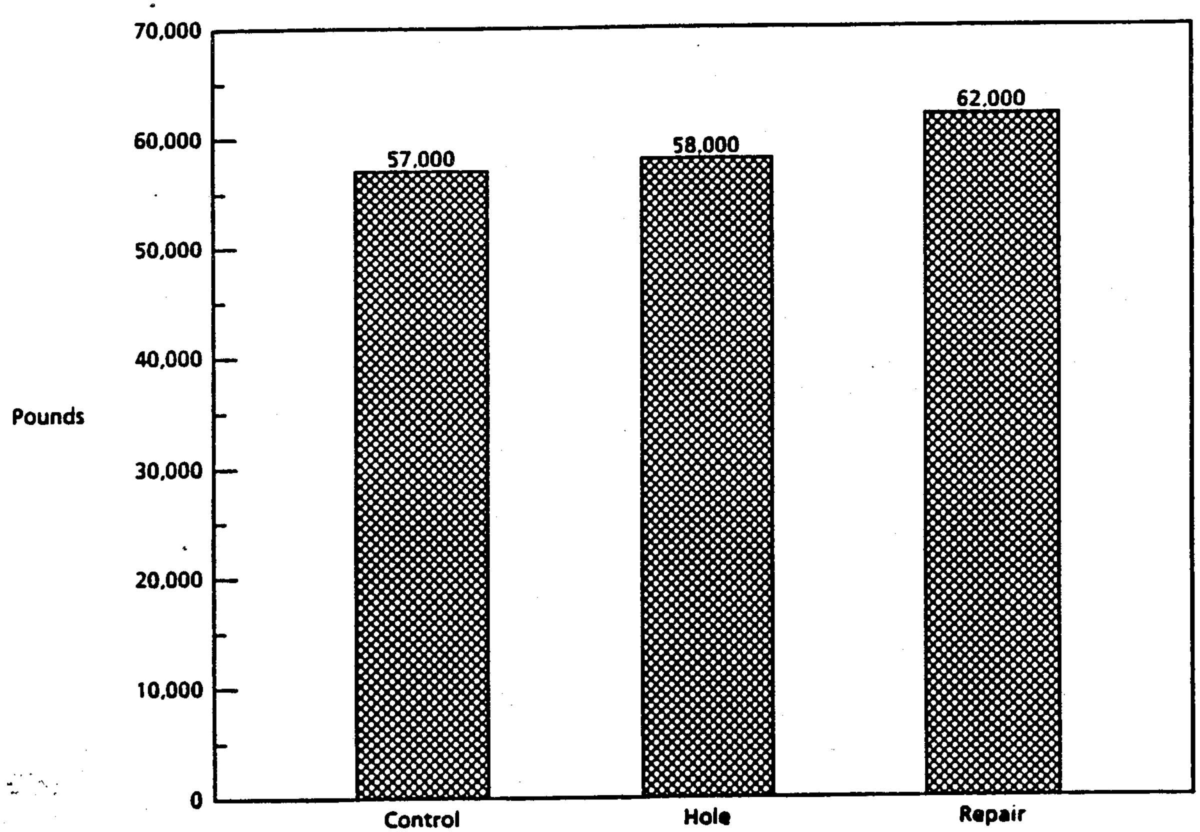


*Failed outside of repair, wet = 14 days 160°F 100% RH

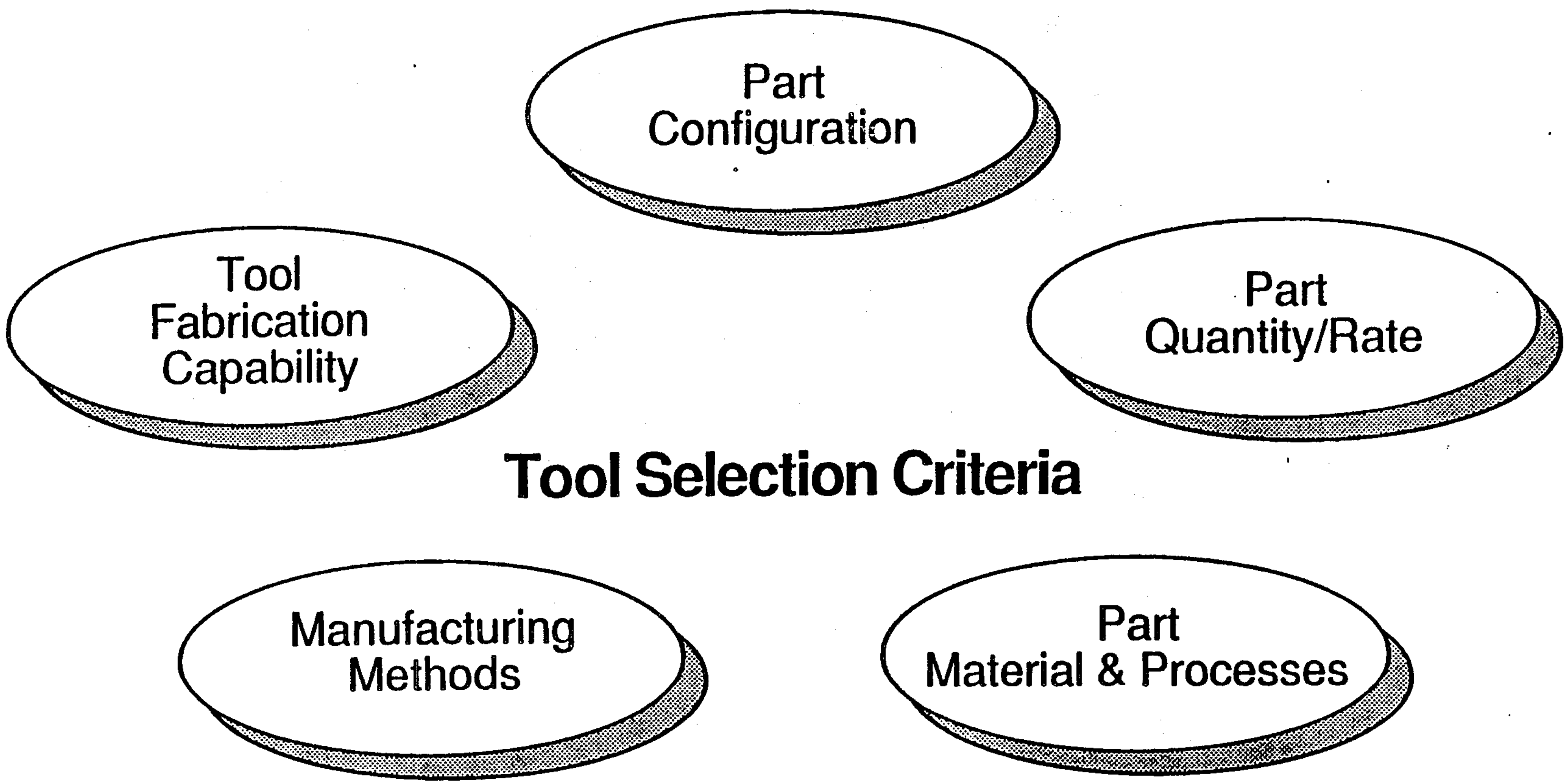
Sandwich Repair Coupon Room Temperature Compression Strength [33]



Sandwich Repair Coupons 250^oF Compression Tests [33]



Laminate Repair Coupon Compression Test Results [33]


Part
Configuration
Tool
Fabrication
Capability
Part
Quantity/Rate
Tool Selection Criteria
Manufacturing
Methods
Part
Material & Processes

[32]

References: 2, 5, 25, 28, 31, 32, 33

REFERENCES

1. Riggs, J.P., Emerging Non-metallic Structural Materials Used for Airframes and other Demanding Applications, Mater. Soc., 8:351 (1984)

2. Mallick, P.K., Fiber-Reinforced Composites, Marcel Dekker, Inc., New York, New York, 1988

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