APPLIED STRESS ANALYSIS

SECTION XI

Composite Materials (Analysis)

Instructor: Bob Matthews
Engineering Specialist
Structural Analysis

COMPOSITE MATERIALS
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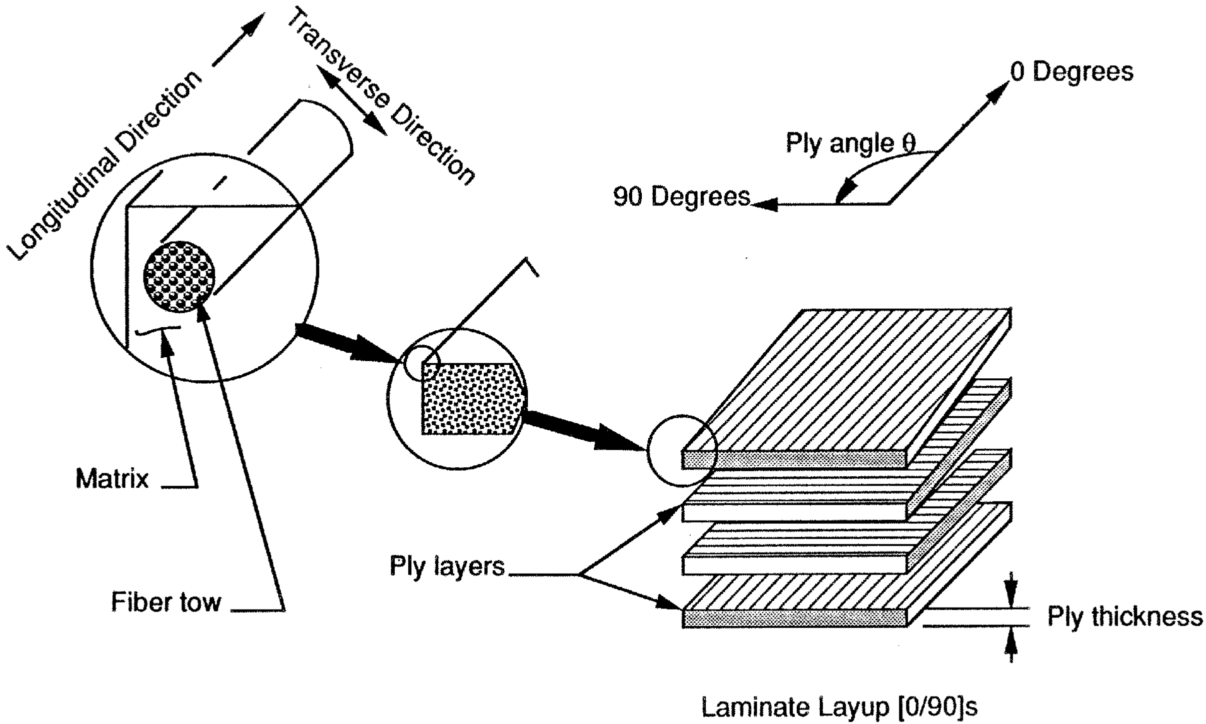
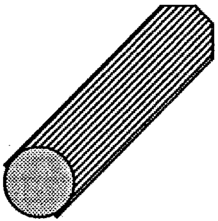
Chapter 1.0 Introduction

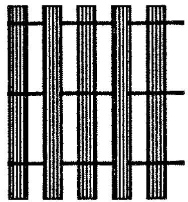
COMPOSITE MATERIALS
Composite Anatomy



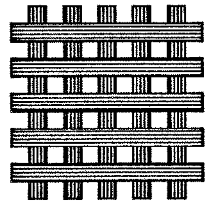
COMPOSITE MATERIALS
Material Forms



Fiber Tow
(12K, 6K, 3K)



Unidirectional Tape



Cloth
(Plain, 8HS weave)

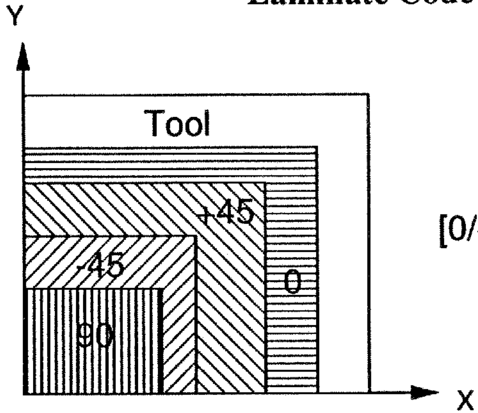
COMPOSITE MATERIALS
Laminate Code

- Three different laminate codes are used to define ply orientations of laminate

    1. (25/50/25) 25% 0's, 50% ±45's, 25% 90's
    2. (25/25/25/25) 25% 0's, 25% +45's, 25% -45's, 25% 90's
    3. [0/+45/-45/90] 1st ply is 0, 2nd ply is +45, 3rd ply is -45, 4th ply is 90

- The third code is the most descriptive and is used here at General Dynamics.

COMPOSITE MATERIALS
Laminate Code Examples



$[0/+45/-45/90]_T$ Laminate Layup

0
90
0
90

$[0/90]_2$

+45
-45
0
-45
+45

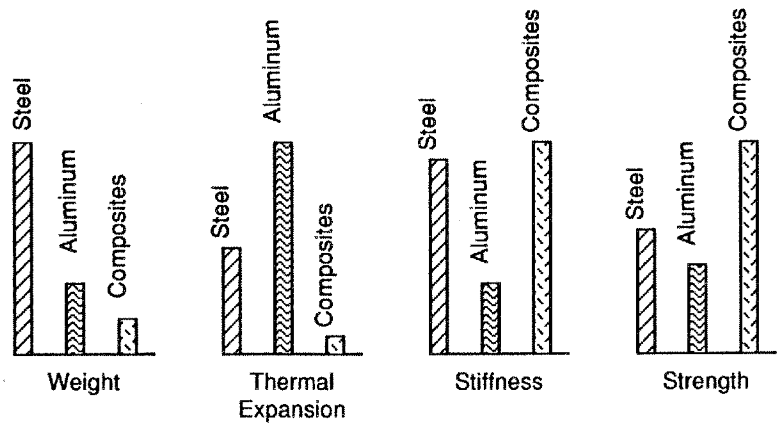
$[\pm 45/\bar{0}]_S$

0
+45
-45
90
90
-45
+45
0

$[0/\pm 45/90]_S$

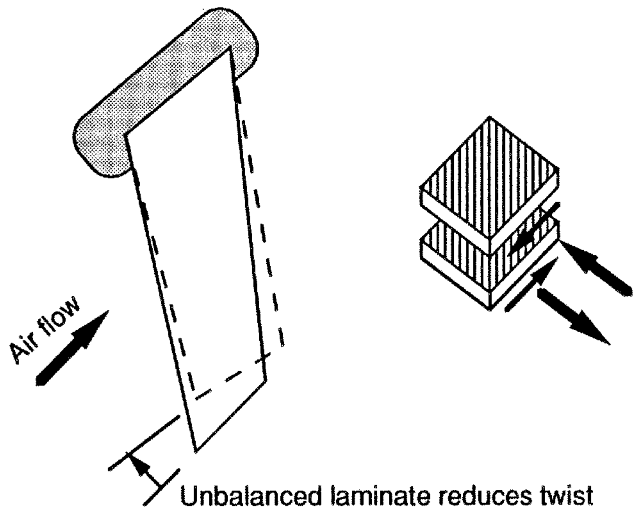
COMPOSITE MATERIALS
Why Composites?

- The demands on material performance are so great and diverse that no one material is able to satisfy them, e.g., lightweight yet strong and stiff structures.
- Composite material systems result in a performance unattainable by the individual constituents.
- Composite materials offer the advantage of a flexible design that can be tailored to the design requirements.



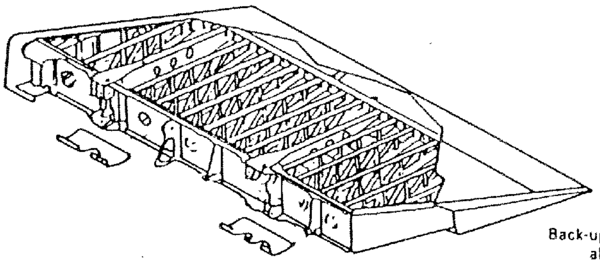
COMPOSITE MATERIALS
Advantages of Composites

- Dimensional stability (e.g., Space-based telescopes)
- Low dielectric
- Corrosion resistance
- Aeroelastic tailoring

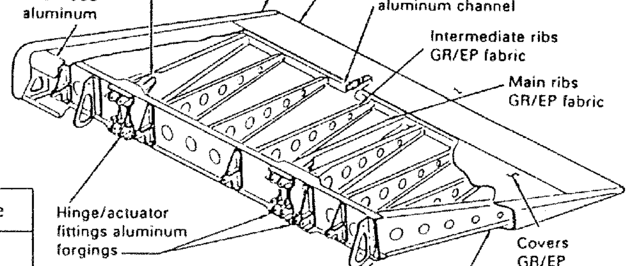


Unbalanced laminate reduces twist in forward-swept wing

COMPOSITE MATERIALS
Weight Savings



(a) Aluminum

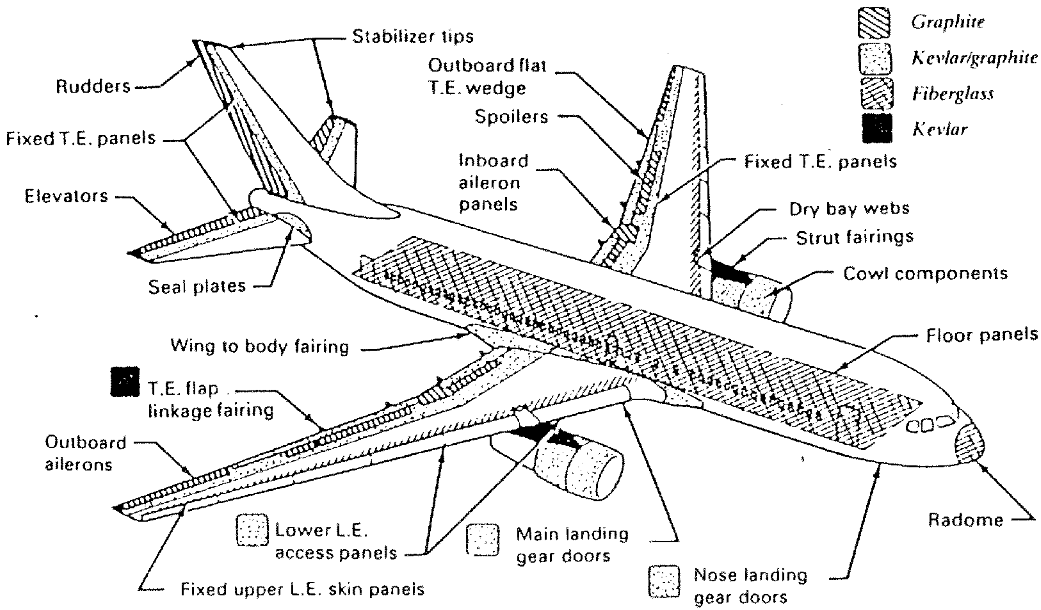


(b) Composite

	Aluminum	Composite
Weight (lb)	140.5	103.9
Weight saved (lb)	0	36.5 (26%)
No. of ribs	18	10
No. of parts	398	205
No. of fasteners	5253	2574

Fig. 14.1.1 Comparison of composite aileron to aluminum counterpart — L-1011.
(Courtesy of Lockheed Aeronautical Systems Co.)

COMPOSITE MATERIALS
Applications



(a) Boeing B767

COMPOSITE MATERIALS
Chapter 2.0 Laminated Plate Theory

COMPOSITE MATERIALS
Hooke's Law for Composites

- Hooke's Law for an isotropic material

$\sigma = E\varepsilon$

σ = stress
E = Young's modulus
ε = strain

- Hooke's Law for a composite material

$\sigma_m = C_{mn}\varepsilon_n$

C_{mn} = stiffness matrix

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ C_{21} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36} \\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} & C_{46} \\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} & C_{56} \\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & C_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \\ \varepsilon_5 \\ \varepsilon_6 \end{bmatrix}$$

COMPOSITE MATERIALS
Ply Stiffness Matrix

- A ply is the basic building block of a laminated composite
- A ply is a thin orthotropic material that can be fully characterized by 4 elastic constants

  E11, E22, G12, v12

  E11 = Longitudinal stiffness
  E22 = Transverse stiffness
  G12 = Shear stiffness
  v12 = Poisson's ratio

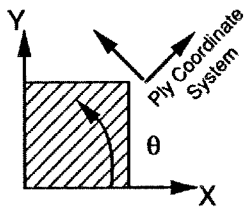
- Ply stiffness matrix:

$$\begin{bmatrix}\sigma_1\\ \sigma_2\\ \sigma_6\end{bmatrix} = \begin{bmatrix}Q_{11} & Q_{12} & 0\\ Q_{21} & Q_{22} & 0\\ 0 & 0 & Q_{66}\end{bmatrix}\begin{bmatrix}\varepsilon_1\\ \varepsilon_2\\ \varepsilon_6\end{bmatrix}$$

$$Q_{11} = E_{11} / (1 - \nu_{12}\nu_{21})$$
$$Q_{22} = E_{22} / (1 - \nu_{12}\nu_{21})$$
$$Q_{12} = \nu_{12}E_{22}$$
$$Q_{21} = Q_{12}$$
$$Q_{66} = G_{12}$$

COMPOSITE MATERIALS
Laminate Stiffness Matrices

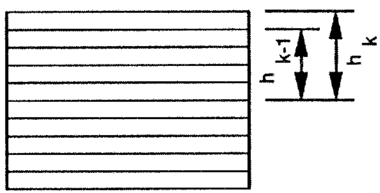
- The laminate stiffness matrices are built-up from the ply stiffness matrices
- The stiffness matrices of all the plies must be transformed to one direction



Laminate Coordinate System

$$\bar{Q}_{11} = Q_{11}m^4 + 2(Q_{12} + 2Q_{66})m^2n^2 + Q_{22}n^4$$
$$\bar{Q}_{12} = (Q_{11} + Q_{22} - 4Q_{66})m^2n^2 + Q_{12}(m^4 + n^4)$$
$$\bar{Q}_{22} = Q_{11}n^4 + 2(Q_{12} + 2Q_{66})m^2n^2 + Q_{22}m^4$$
$$\bar{Q}_{16} = (Q_{11} - Q_{12} - 2Q_{66})m^3n + (Q_{12} - Q_{22} + 2Q_{66})mn^3$$
$$\bar{Q}_{26} = (Q_{11} - Q_{12} - 2Q_{66})mn^3 + (Q_{12} - Q_{22} + 2Q_{66})m^3n$$
$$\bar{Q}_{66} = (Q_{11} + Q_{22} - 2Q_{12} - 2Q_{66})m^2n^2 + Q_{66}(m^4 + n^4)$$

- Laminate stiffness matrices:



[A] = extensional stiffness matrix

$$A_{ij} = \sum_{k=1}^{n} (\bar{Q}_{ij})_k (h_k - h_{k-1})$$

[B] = stretching-bending coupling matrix

$$B_{ij} = \frac{1}{2} \sum_{k=1}^{n} (\bar{Q}_{ij})_k (h_k^2 - h_{k-1}^2)$$

[D] = flexural stiffness matrix

$$D_{ij} = \frac{1}{3} \sum_{k=1}^{n} (\bar{Q}_{ij})_k (h_k^3 - h_{k-1}^3)$$

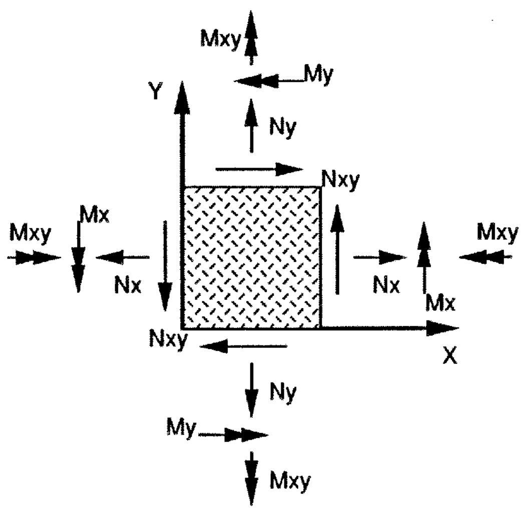
COMPOSITE MATERIALS
Constitutive Equation

- Laminate constitutive equation in compact matrix form

$$\left[\begin{array}{c} N \\ \hline M \end{array}\right] = \left[\begin{array}{c|c} A & B \\ \hline B & D \end{array}\right] \left[\begin{array}{c} \varepsilon^{0} \\ \hline K \end{array}\right]$$

[A] matrix, [B] matrix, [D] matrix

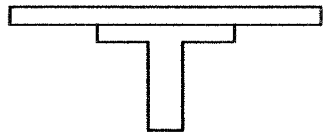
N = membrane loads
M = bending loads
ε = strain
K = curvature



COMPOSITE MATERIALS
Strength of Composite Materials

- Several failure criterion are available (e.g., Max. stress, max. strain, Tsai-Wu, Hoffman, etc.)
- General Dynamics / Convair uses max. stress and max. strain failure criterion
- Maximum stress criterion may be used at the laminate level

Example: Blade stiffened panel



Load: Bending moment M = 25000 in-lbs
Axial load P = 5000 lbs

$A = 1.0 \text{ in}^2 \quad I = 0.5 \text{ in}^4 \quad c = 0.75 \text{ in}$

Max. stress = Mc/I + P/A
25000(.75)/0.5 + 5000/1.0 = 42500 psi
Allowable stress = 50000 psi
M.S. = 50000 / 42500 - 1 = +0.18

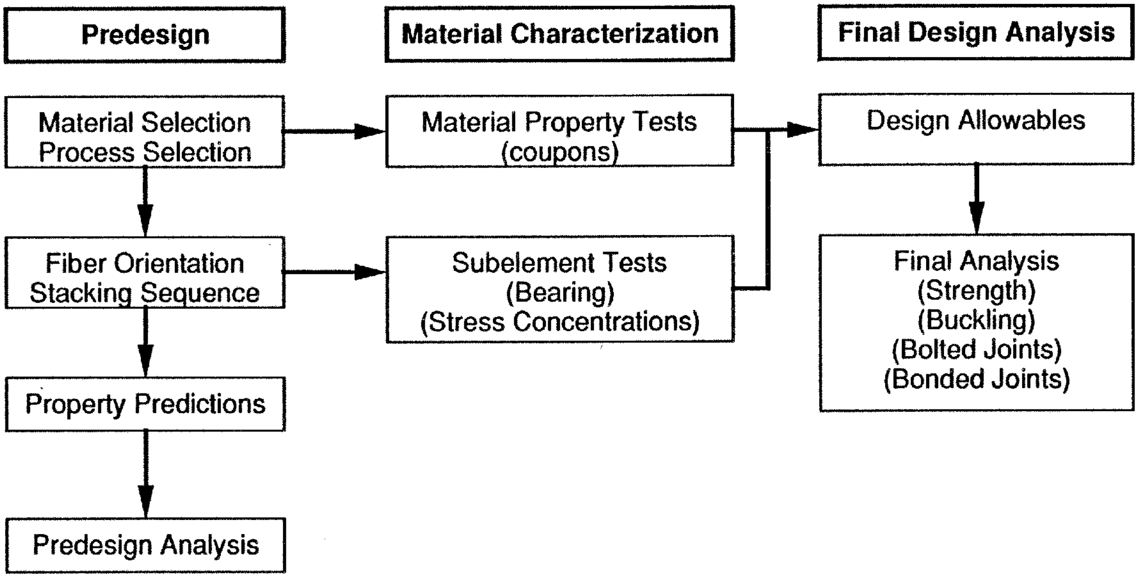
- Maximum strain criterion is used at the ply level and requires solution of constitutive equation

COMPOSITE MATERIALS
SQ5PJW Computer Code

- Computes laminate stiffness matrices from ply engineering constants
- Solves constitutive equation and computes ply stresses and strains
- Performs failure analysis based on maximum strain failure criterion and computes minimum margins of safety
- Generates NASTRAN MAT2 material property cards for finite element analysis
- Generates a plot file for interaction curves
- Performs interlaminar shear stress analysis
- Available on Cyber, VAX, Apollo, DECstation and Macintosh computers

COMPOSITE MATERIALS
Chapter 3.0 Predesign

COMPOSITE MATERIALS
Design Process



COMPOSITE MATERIALS
Design References

- General
  - DOD/NASA Advanced Composites Design Guide, July 1983
    - Volume I: Design
    - Volume II: Analysis
    - Volume III: Applications
    - Volume IV: Materials
  - MIL-HDBK-17B, "Polymer Matrix Composites, 29 February 1988
    - Volume I: Guidelines
    - Volume II: Material Properties (not released)
    - Volume III: Utilization of Data (not released)
- Material Properties
  - GD/C Specification PR-043 Rev. B, "Advanced Programs Strength Data Book", January 1990
- Buckling
  - AFWAL-TR-85-3069, "Buckling of Laminated Composite Plates and Shell Panels", June 1985
  - Lekhnitskii, "Anisotropic Plates", 1968
- Bolted Joints
  - AFWAL-TR-88-3035, "Design Guide for Bolted Joints in Composite Structures", March 1986
- Bonded Joints
  - NASACR112236, "Adhesive-Bonded Single-Lap Joints", January 1973
  - NASACR112237, "Adhesive-Bonded Scarf and Stepped-Lap Joints", January 1973

COMPOSITE MATERIALS
Material Selection

- The first step in predesign is to select the material (fiber, resin, etc.)
- Material selection is usually based on several requirements

  - Environment
  - Stiffness
  - Strength
  - Coefficient of Thermal Expansion
  - Weight
  - Cost
  - Machineability

COMPOSITE MATERIALS
Material Selection

Environment

- Temperature:

Material System	Maximum use temperature (Degrees F)
Epoxy	260
Bismaleimide	450
Polyimide	550
Experimental (PMR)	700
Aluminum matrix	500
Titanium matrix	1000
Silicon carbide matrix	2500
Coated carbon-carbon	3500

- Moisture: Organic matrix systems absorb some water and swell. Kevlar fiber absorbs water.

- Corrosion: Fiberglass acts as a corrosion barrier. Graphite reacts with aluminum and steel (okay for titanium)

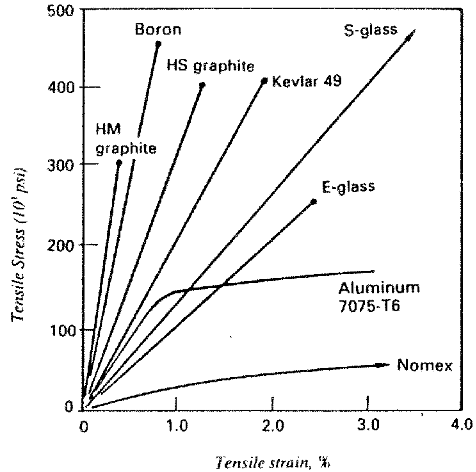
COMPOSITE MATERIALS
Material Selection

<u>Stiffness</u>

- Buckling or deflection-critical components

[1]Composite System	Long. Modulus E11 (Msi)
E-glass/epoxy	5.5
S2-glass/epoxy	7.1
Kevlar/epoxy	11.0
Graphite/epoxy	20.4
[2] HM graphite/epoxy	31.2
[3] UHM graphite/epoxy	45.0

Notes:
1. All systems are UD tape for comparison
2. High modulus
3. Ultra-high modulus



Stress and strain curves of various fibers/ epoxy.

COMPOSITE MATERIALS
Material Selection

Strength

Composite System	Ftu (ksi)	Fcu (ksi)	Fsu (ksi)
E-glass/epoxy	175	85	9
S2-glass/epoxy	221	124	12
Kevlar/epoxy	200	40	6
Graphite/epoxy	210	172	13

Note: All systems are UD tape for comparison

Coefficient of Thermal Expansion (CTE)

Composite System	Long. CTE (micro-in/in/F)
E-glass/epoxy	3.3
S2-glass/epoxy	2.2
Kevlar/epoxy	-2.2
Graphite/epoxy	-0.3

Note: All systems are UD tape for comparison

COMPOSITE MATERIALS
Material Selection

Weight

Composite System	Density (pci)
E-glass/epoxy	0.075
S2-glass/epoxy	0.072
Kevlar/epoxy	0.049
Graphite/epoxy	0.055

Cost

Composite System	Cost ($/lb)
E-glass/epoxy	9
S2-glass/epoxy	13
Kevlar/epoxy	27
Graphite/epoxy	30

Note: Cost numbers shown for fabric and epoxy with RTM process.

Machineability

Kevlar/epoxy leaves rough surface
Glass and graphite machine well

COMPOSITE MATERIALS
Process Selection

- Process selection is usually made on the basis of lowest cost which will produce the part to meet the specified requirements.

  - Production rate
  - Consistant quality

- The process selection will probably be based on part configuration.

  - Cylindrical shape → Filiment Winding
  - Beam shape → Pultrusion

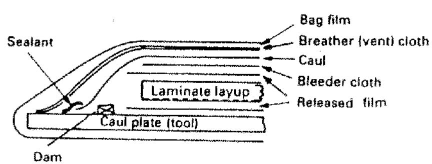
- Several processes are available.

  - Prepreg tape laying (hand or automated)
  - Filiment winding
  - Pultrusion
  - Resin transfer moulding (RTM)
  - Compression moulding
  - Thermoforming

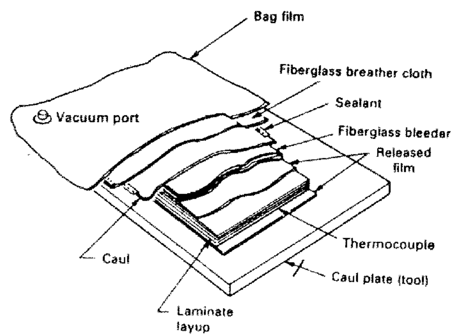
COMPOSITE MATERIALS
Process Selection

Prepreg Tape Laying

- Material layed up on mould
- Pressure and heat applied in autoclave
- Advantages: - Consistent material properties
  - High fiber volume
  - Flexibility in fiber orientation
- Disadvantages: - High labor cost unless automated



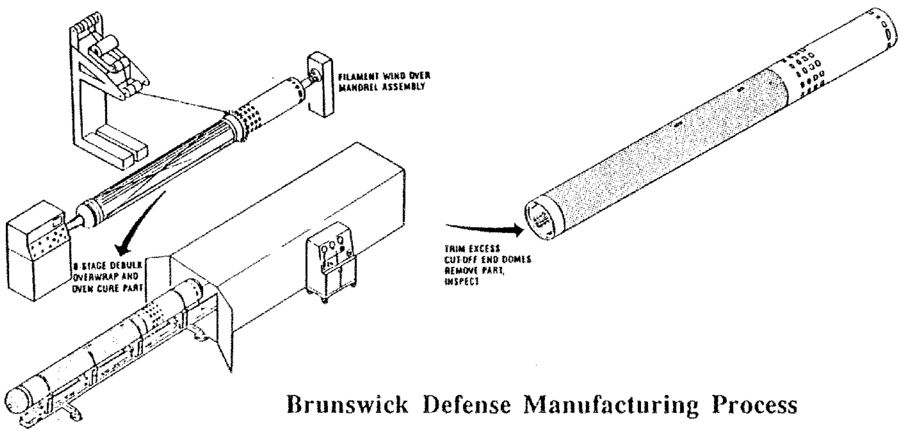
Typical composite layup and bagging.



COMPOSITE MATERIALS
Process Selection

Filiment Winding

- Fibers wetted in resin bath and wound on a mandrel (wet winding)
- Oven or autoclave curing
- Prepreg tape may also be wound
- Advantages:
  - Automated process
  - Low material cost for wet winding
- Disadvantages:
  - Geometry limited
  - Fiber orientation limited

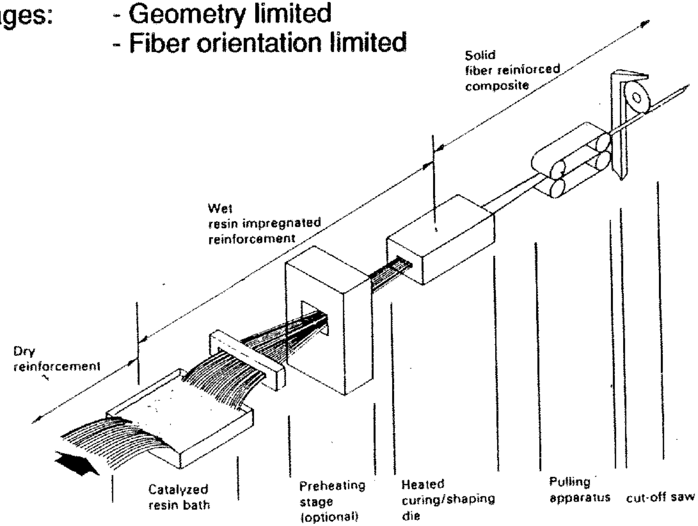


Brunswick Defense Manufacturing Process

COMPOSITE MATERIALS
Process Selection

Pultrusion

- Fibers or cloth wetted in resin bath and pulled through heated die
- Advantages: - High production rate
- Disadvantages: - Geometry limited
  - Fiber orientation limited

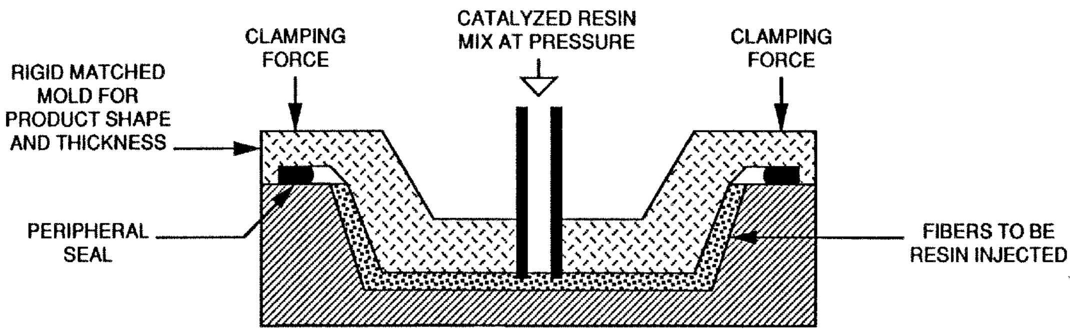


Pultrusion processing.
(Courtesy of Shell Chemical Co.)

COMPOSITE MATERIALS
Process Selection

Resin Transfer Moulding (RTM)

- Reinforcement placed between two parts of mould
- Resin injected in mould and heat applied
- Advantages:
  - Accurate moulded surfaces
  - Cocuring reduces part count
- Disadvantages:
  - Low fiber volume
  - Material property variability throughout part
  - High labor to assemble/disassemble preforms and tools

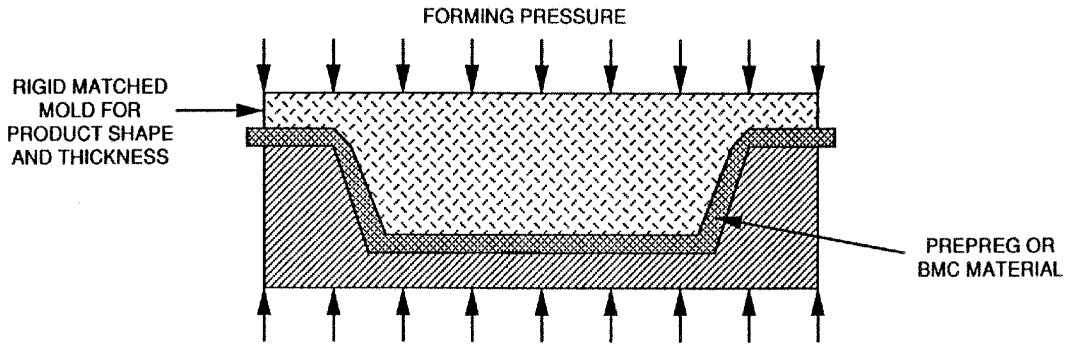


RTM Principle: pressure inject resin while fibers are held between mold faces

COMPOSITE MATERIALS
Process Selection

Compression Moulding

- Moulding compound placed in matched die moulding
- Pressure and heat applied by mould
- Advantages: - Increased production rate
- Disadvantages: - Expensive tooling



Compression moulding process

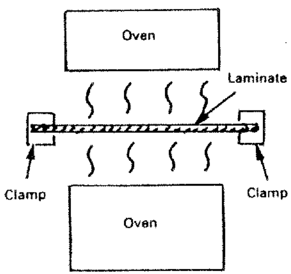
COMPOSITE MATERIALS
Process Selection

Thermoforming

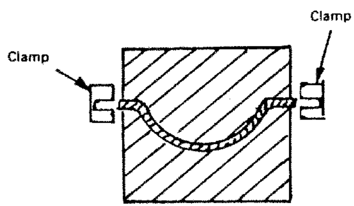
- Thermoplastic material placed in mould
- Material consolidated with heat and pressure

- Advantages:
  - Flexibility in fiber orientation
  - High fiber volume
  - Consistent material properties
  - Improved material toughness
  - Easily repairable

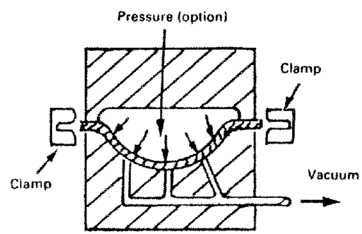
- Disadvantages:
  - High material cost
  - High processing temperature



(a) Heating unit



(b) Matched tools-laminate is unclamped during forming, so it can slip into the tool



(c) Vacuum forming–the laminate is free to slip into the tool, maintaining a gas seal may be difficult, unless a bladder or diaphgram is laid over the laminate

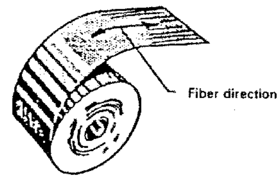
Thermoforming process.

COMPOSITE MATERIALS
Fiber Orientation

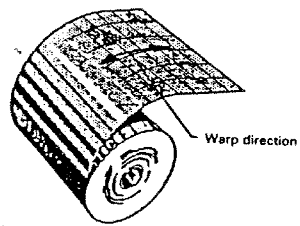
- Unidirectional (UD) tape vs. woven fabric

  UD Tape
  - Can be tailored more easily to match loads
  - Better surface finish
  - Less porous than fabric
  - Higher allowable strength and stiffness
  - Lower raw material cost

  Woven Fabric
  - Lower fabrication costs
  - Less material handling damage
  - Easier forming on contours and corners
  - More resistant to surface breakout and delamination



(a) Tape



(b) Woven fabric

- The fiber should be arranged to optimize resistance to loads
- Limit number of different angles to expedite manufacturing
- For filiment winding use hoop plies and 1(±) helical angle

COMPOSITE MATERIALS
Fiber Orientation

- Tailor fiber arrangement to optimize resistance to loads

  ±45 degree plies give buckling stability and carry shear
  0 degree plies give column stability and carry tension or compression
  90 degree plies carry transverse loads and reduce Poisson's effects

Configuration	Load	Percent Fiber 0 deg.	Percent Fiber ±45 deg.	Percent Fiber 90 deg.	Recommend
Rod	Axial	50-100	0-25	0-25	[0]n
Stiffener	Axial, V & M	25-50	25-50	0-25	[(0/0/0/0/45/-45/90/90)s]n
Cylinder	Int. Pressure	25-33	0-25	50-67	[(90/90/0)s]n
Cylinder	Ext. Pressure	25-33	0-50	25-67	[(0/45/-45/90)s]n
Cylinder	Torsion	0-25	50-100	0-25	[(45/-45)s]n
Plate	Tens. & M	25-50	0-50	0-25	[(0/0/0/0/45/-45/90/90)s]n
Plate	Shear	0-25	50-100	0-25	[(45/-45)s]n
Plate	Compression	25-50	25-50	0-25	[(0/45/-45/90)s]n
Plate	Bolted Joint	25-50	25-50	0-25	[(0/45/-45/90)s]n
Plate	General load	Orient % fibers relative to % load			

- Computer codes to optimize fiber arrangement

  - PANDA2 for stiffened shell panels
  - ASTROS for general geometry and membrane loads only
  - TM1 for curved panels

COMPOSITE MATERIALS
Stacking Sequence

- Balanced laminate - all angle plies (not 0's or 90's) must occur in pairs, though not necessarily adjacent.
- Symmetric laminate - stacking of plies is mirror image about the midplane
- Generally, the laminate should be balanced and symmetric
  - Unbalanced laminate induces shear/twist when applying axial load
  - Unsymmetric laminate induces bending when applying axial load
  - Part may warp during processing if not balanced and symmetric
- Some situations call for an unbalanced laminate (e.g., forward swept wing)
- Rules-of-thumb
  - For buckling the ±45 degree plies should be placed at the surfaces
  - For longitudinal bending the 0 degree plies should be placed at the surfaces
  - 0 and 90 degree UD-type plies should have an angle ply transition between them to avoid weak interlaminar shear strength (due to CTE diff. during processing)

COMPOSITE MATERIALS
Property Predictions

- Material property predictions are needed to size the components
- Some material systems are already characterized here at GD/Convair

  A. Prepreg (ACM Program)
  - T300/934 UD Tape, T300/934 Plain Weave Cloth, T300/5208 UD Tape Graphite/Epoxy
  - T300/V378A 8HS Weave Cloth Graphite/Bismaleimide
  - S2/E788 UD Tape, S2/E788 6581 Cloth, E/E788 120 Cloth,Quartz/E788 Cloth Glass/Epoxy
  - S2/V378A 6581 Cloth Glass/Bismaleimide

  B. Resin Transfer Moulded (Tomahawk Submunitions Module)
  - C3000/Tactix 123-H41 8HS Weave Cloth, C3000/Tactix 123-H31 8HS Weave Cloth Graphite/Epoxy
  - Kevlar 49/Tactix 123-H41 353 Cloth, Kevlar 49/Tactix 123-H31 353 Cloth Glass/Epoxy

  C. Filiment Wound (LTTL Capsule)
  - G30-500/(9405/9470) Graphite/Epoxy [90/20/-20/90] Laminate

  D. Compression Moulded (Tomahawk Submunitions Module)
  - T300/NB1102 Cloth Graphite/Epoxy

- SQ5 can be used to get laminate properties for characterized material system

COMPOSITE MATERIALS
Property Predictions

- Methods are available for uncharacterized material systems
- Micromechanics may be used to get rough estimates of ply properties
- Properties of plies are obtained from properties of constituents (matrix and fiber)
- Rule-of-Mixtures is the common micromechanics approach

e.g., Longitudinal Modulus E11 = Vf X Ef + Vm X Em

Vf = Fiber volume ratio
Ef = Fiber longitudinal modulus
Vm = Matrix volume ratio
Em = Matrix modulus

Example : Calculate longitudinal modulus for G30-500/(9405/9470) ply

- From Celion fiber data sheet; Ef = 34 Msi
- Neglect contribution of matrix
- Assume 60% fiber volume

E11 = 0.6 X 34 = 20.4 Msi

COMPOSITE MATERIALS
Property Predictions

- Better property estimates can be made by ratioing properties of similar materials

Example: Calculate properties of G30-500/(9405/9470) filiment wound graphite/epoxy laminate.

- T300 fiber has similar properties as G30-500 fiber
- T300/934 UD tape is fully characterized with 60% fiber volume
- Assume 55% filiment wound fiber volume
- Ratio fiber-dominated properties by 55/60
- Keep matrix-dominated properties the same

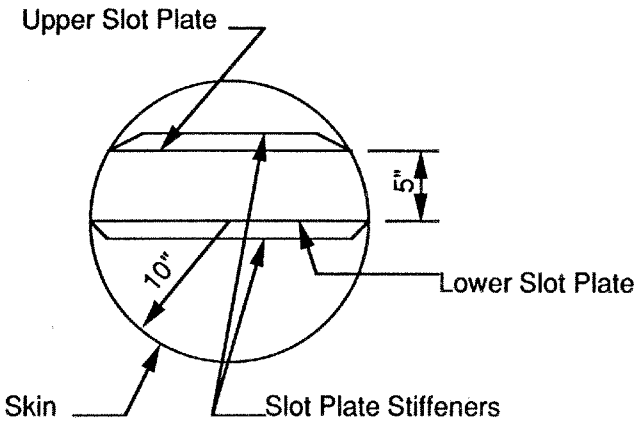
Property	T300/934	Ratio	G30-500/(9405/9470)
E11 (Msi)	21.7	55/60	19.9
E22 (Msi)	1.46	1	1.46
G12 (Msi)	0.83	1	0.83
v12	0.312	1	0.312
Ft1 (ksi)	210	55/60	192
Ft2 (ksi)	5.6	1	5.6
Fc1 (ksi)	172	55/60	158
Fc2 (ksi)	38.8	1	38.8
Fs (ksi)	13.3	1	13.3

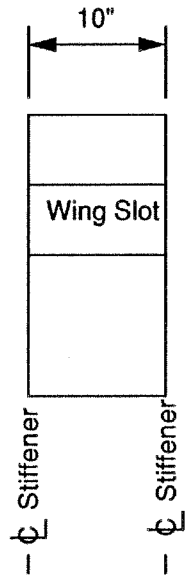
COMPOSITE MATERIALS
Predesign Analysis Methods

- Assume material is isotropic for preliminary sizing of components
- Calculate internal loads (Axial, Shear and Bending Moment) using methods outlined in previous sections
- Compute maximum stress in laminate and compare to allowable
- Predesign analysis methods are illustrated by the following example

COMPOSITE MATERIALS
Predesign Analysis Example

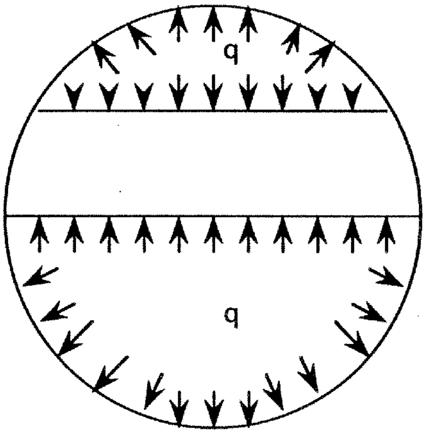
EXAMPLE: Size a Tomahawk midbody section using graphite/epoxy prepreg cloth



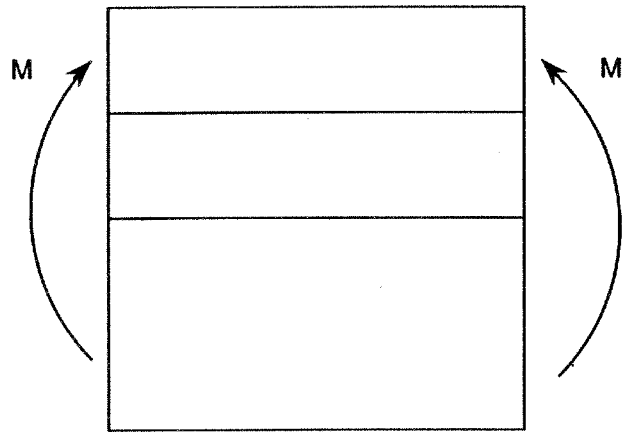


COMPOSITE MATERIALS
Predesign Analysis Example

<u>Design Loads</u>



Load Condition 1
Internal Fuel Pressure
q = 50 psi



Load Condition 2
Barge Shock Bending Moment
M = 1,000,000 in-lbs

COMPOSITE MATERIALS
Predesign Analysis Example

STEP 1: Assume quasi-isotropic layup [(0/±45/90)s]n and calculate properties using SQ5

a. Ply properties from Advanced Programs Strength Data Book

T300/934 Cloth
t = .0133 in/ply

E_{11} = 10.1 Msi	G_{12} = 0.83 Msi
E_{22} = 9.14 Msi	ν_{12} = 0.06
F_{t11} = 90.5 ksi	F_{c11} = 50.8 ksi
F_{t22} = 94.2 ksi	F_{c22} = 55.7 ksi
F_s = 18 ksi	

b. Laminate properties for [0/±45/90]s layup using SQ5

t = .106 in

E_x = 7.05 Msi	G_{xy} = 2.69 Msi
E_y = 7.05 Msi	ν_{12} = 0.309
F_{tx} = 62.8 ksi	F_{cx} = 35.3 ksi
F_{ty} = 62.8 ksi	F_{cy} = 35.3 ksi
F_s = 27.0 ksi	

COMPOSITE MATERIALS
Predesign Analysis Example

STEP 2: Calculate required thickness of slot plate for internal pressure load

Pressure q = 50 X 1.5 = 75 psi (ultimate)

Analyze as flat plate simply supported at the outboard edges and fixed at the stiffeners
Refer to the Structural Analysis Manual pg. 6.4.30 (or Roark)

a = 20", b = 10", $\alpha = b/a = 10/20 = 0.5$

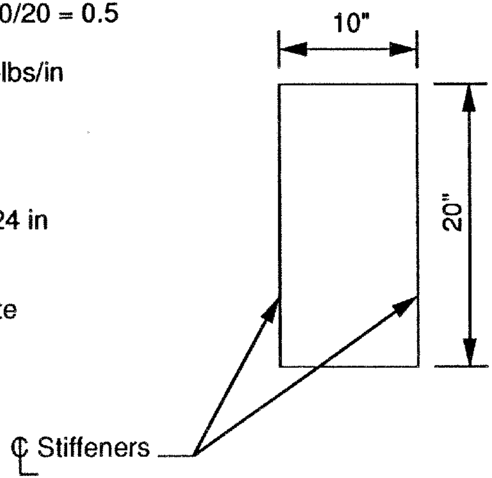
$$M = \frac{q \times b^2}{12(1 + 0.2\alpha^4)} = 617 \text{ in-lbs/in}$$

$$fb = 6 \times M / t^2 = 35300 \text{ psi}$$

$$t = (6 \times 617 / 35300)^{1/2} = 0.324 \text{ in}$$

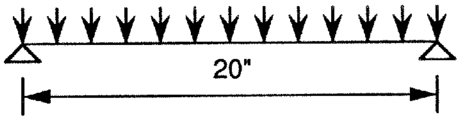
Use next highest thickness
that has quasi-iso sublaminate

t = 4 X .1064 = 0.426 in



COMPOSITE MATERIALS
Predesign Analysis Example

STEP 3: Determine size of slot plate stiffener for internal pressure load



$M = w \times l^2 / 8 = 750 \times (20)^2 / 8 = 37500$ in-lbs

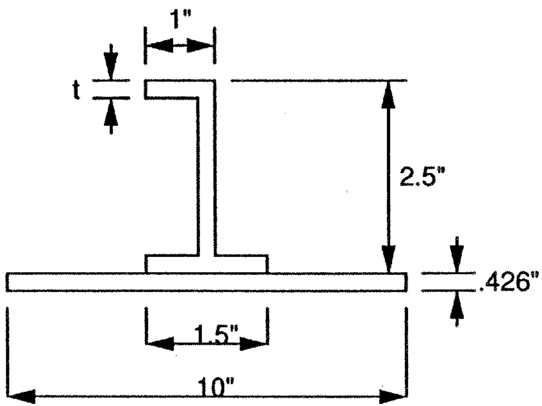
$fb = Mc/I = 35300$ psi

$I/c = M/fb = 37500 / 35300 = 1.06$ in ^{4}

COMPOSITE MATERIALS
Predesign Analysis Example

STEP 3: (Continued)

Calculate section properties of several thicknesses of J-Stiffener until I/c = 1.06



t	I	c	I/c
.213"	2.32	2.47	0.94
.319"	3.04	2.39	1.27
.426"	3.59	2.33	1.54

Use t = 0.319 in.

COMPOSITE MATERIALS
Predesign Analysis Example

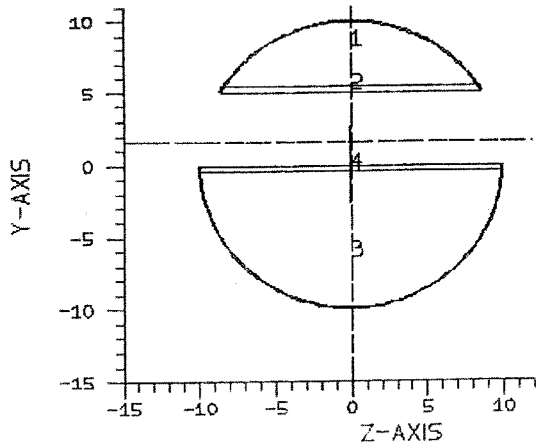
STEP 4: Calculate properties of missile section

- Assume skin t = .106 in [0/±45/90]s laminate
- Section property program used

Top Section
$A = 9.5\ in^2$
$I = 21.04\ in^4$
$c = 4.07\ in$

Bottom Section
$A = 11.74\ in^2$
$I = 120.22\ in^4$
$c = 8.06\ in$

Combined Section
$A = 21.26\ in^2$
$I = 466.22\ in^4$
$c = 11.58\ in$



COMPOSITE MATERIALS
Predesign Analysis Example

STEP 5: Calculate skin thickness for barge shock loading

- Calculate running loads in skin

  M = 1,000,000 in-lbs

  w = Mc/I X t = [1,000,000 X 11.58 / 466.22] X 0.106 = 2633 lbs/in

- Calculate required skin thickness

  fa = w / t = 35300 psi

  t = w / 35300 = 2633 / 35300 = 0.07 in

  use 0.106 inch skin thickness

COMPOSITE MATERIALS
Chapter 4.0 Material Characterization

COMPOSITE MATERIALS
Introduction

- Material characterization is needed to support the design and analysis
- Material properties are a function of the fiber, resin and process
- Material characterization must be performed for each new material system (e.g. different fiber/resin combination or different process)
- MIL-HNBK-17B will have some characterized composite material properties in the future
- The material characterization will answer the questions on how the material will behave under the design load and environmental conditions.
- The material behavior must be predictable and repeatable

COMPOSITE MATERIALS
Material Property Tests

- Material may be characterized at the ply level or laminate level depending on the application
- The laminate level characterization should only be used if you are certain that there is only one layup to be used in the design
- For most applications, material characterization is performed at the ply level
- General rules of characterization

Process	Material Form	Char. Level
Prepreg tape laying	Prepreg	Ply
Resin transfer moulding	Woven cloth	Ply
Compression moulding	Prepreg	Ply
Thermoforming	Prepreg	Ply
Filiment winding	Fiber & resin	Laminate
Pultrusion	Fiber or woven cloth and resin	Laminate

COMPOSITE MATERIALS
Material Property Tests

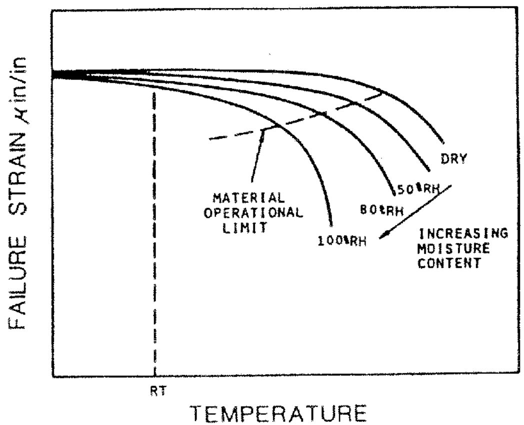
- MIL-HNBK-17B recommends characterizing filiment wound materials at the ply level (see Table 6.6.9 below)
- The lamination theory (SQ5) has not been verified for filiment winding and our experience on LTTL Capsule shows that the laminate properties cannot be predicted accurately from ply properties
- We recommend that you do a limited amount of ply level testing to support predesign of the laminate layup and characterize at the laminate level.

TABLE 6.6.9 JANNAF interim standard test methods.

0° Tension:	Pressurized NOL Ring, Pressurized Tube (90° Wind)	E_{11}, ν_{12}, σ_{11}, ϵ_{11}
90° Tension:	Tube (90° Wind)	E_{22}, ν_{21}, σ_{22}, ϵ_{22}
0° Compression:	Flat Laminate (0°)	E_{11}, ν_{12}, σ_{11}, ϵ_{11}
90° Compression:	Tube (90° Wind)	E_{22}, ν_{21}, σ_{22}, ϵ_{22}
In-Plane Shear:	Torsion Tube (90° Wind)	G_{12}, τ_{12}, γ_{12}
Transverse Shear	Iosipescu	G_{23}, τ_{23}, γ_{23}

COMPOSITE MATERIALS
Material Property Tests

- Environmental effects must be considered in the material characterization.
- Material Operating Limit (MOL) - The temperature level at which a drastic reduction in properties occurs. MOL is a function of moisture.
- Testing should be done at the highest temperature and moisture level (Hot/Wet) that the material will see in service.



Influence of temperature and moisture on matrix dependent failure strain.

COMPOSITE MATERIALS
Material Property Tests

- The material property tests should be done on different material batches and panels to be representative
- MIL-HNBK-17B suggests (for prepreg) five prepreg batches made with five different fiber lots impregnated with five different resin batches
- The key is to get agreement from the certifying agency on what is representative

COMPOSITE MATERIALS
Material Property Tests

- Basic physical property tests

    1. Specific gravity (ASTM D792)
    2. Resin content and fiber volume (ASTM D3172 or GDC Spec. 0-75224)
    3. Glass transition temperature (ASTM D3418)
    4. Measure per ply thickness

- Basic mechanical property tests to support Structural Analysis

    1. Tension (ASTM D3039)
    2. Compression (ASTM D3410)
    3. In-plane shear (Iosipescu)

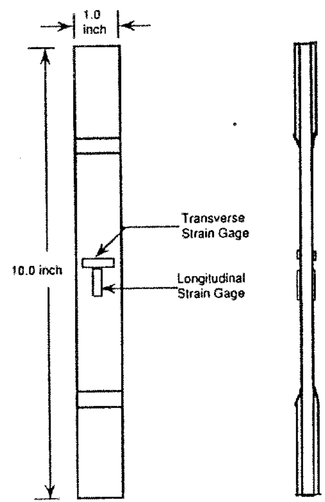
    Optional Tests
    4. Interlaminar shear (ASTM-D2344)
    5. Coefficient of thermal expansion (ASTM E831)
    6. Interlaminar tension

- Basic thermophysical property tests to support Thermal Analysis

    1. Thermal conductivity
    2. Specific heat

COMPOSITE MATERIALS
Ply Level Material Characterization
Tension Tests

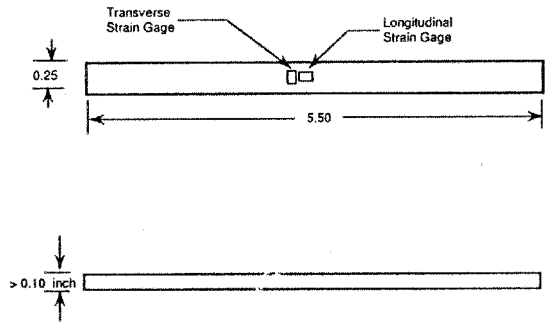
- Specimens tested in both longitudinal (warp) and transverse (fill) directions
- Tested per ASTM D3039 - Standard Test Method for Tensile Properties of Fiber-Resin Composites
- Properties to be derived:
    1. Longitudinal tensile modulus
    2. Longitudinal tensile strength
    3. Poisson's ratio
    4. Transverse tensile modulus
    5. Transverse tensile strength



Tensile Specimen

COMPOSITE MATERIALS
Ply Level Material Characterization
Compression Tests

- Specimens tested in both longitudinal (warp) and transverse (fill) directions
- Tested per ASTM D3410 - Standard Test Method for Compressive Properties of Unidirectional or Crossply Fiber-Resin Composites
- Properties to be derived:
  1. Longitudinal compressive modulus
  2. Longitudinal compressive strength
  3. Transverse compressive modulus
  4. Transverse compressive strength

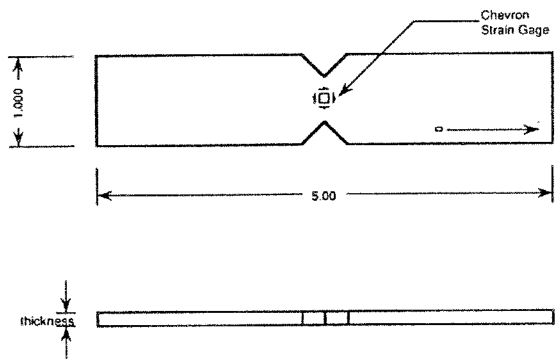


Compression Specimen

COMPOSITE MATERIALS
Ply Level Material Characterization
In-Plane Shear Tests

- Specimens tested in longitudinal direction
- No standard method - Iosipescu shear specimen recommended
- Properties to be derived:

  1. Shear modulus
  2. Shear strength



Iosipescu shear specimen

COMPOSITE MATERIALS
Laminate Level Material Characterization

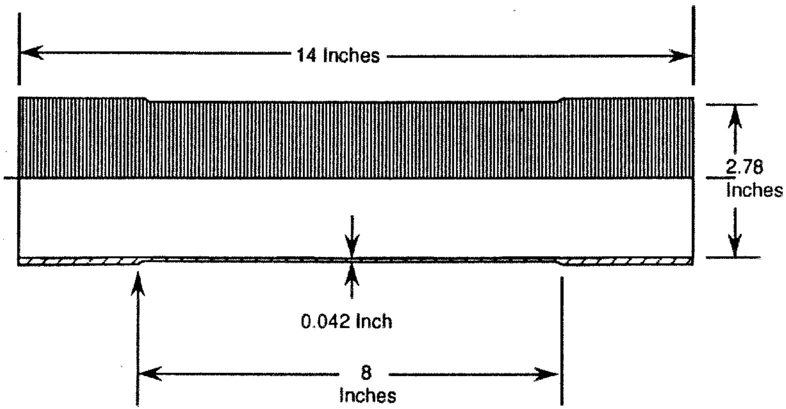
- Laminate level characterization is usually not done because it limits you to one design layup

- Laminate level testing for pultrusion process may use coupon samples similar to those described for ply level testing (pultrude a panel)

- Laminate level testing for filament wound process should use special cylindrical coupons for most of the tests
    - Axial Tension
    - Hoop Tension
    - Axial Compression
    - Torsional Shear

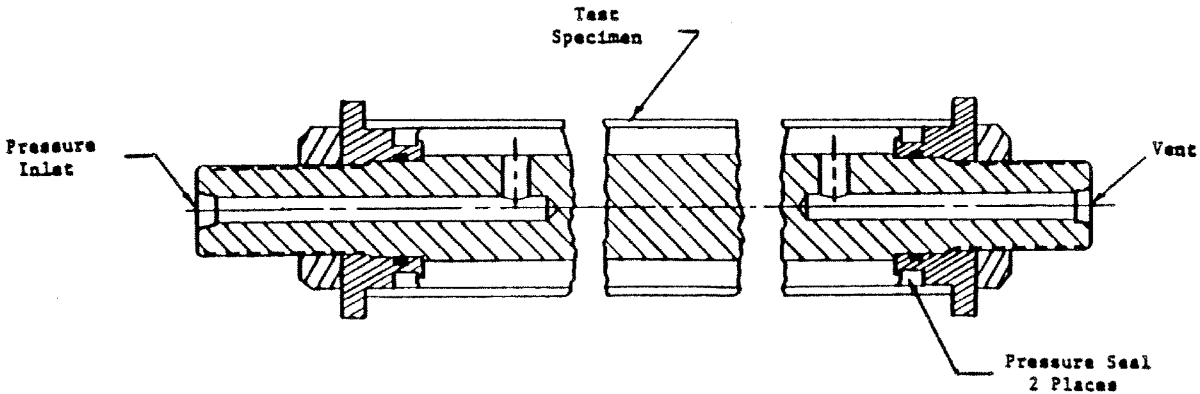
COMPOSITE MATERIALS
Filament Wound Material Characterization
Axial Tension Test

- Cylindrical specimens wound with either full laminate or repeating sublaminate layup
- Expanding grip test fixture used to apply tensile loading
- Properties to be derived:
    1. Axial tensile modulus
    2. Axial tensile strength
    3. Poisson's ratio



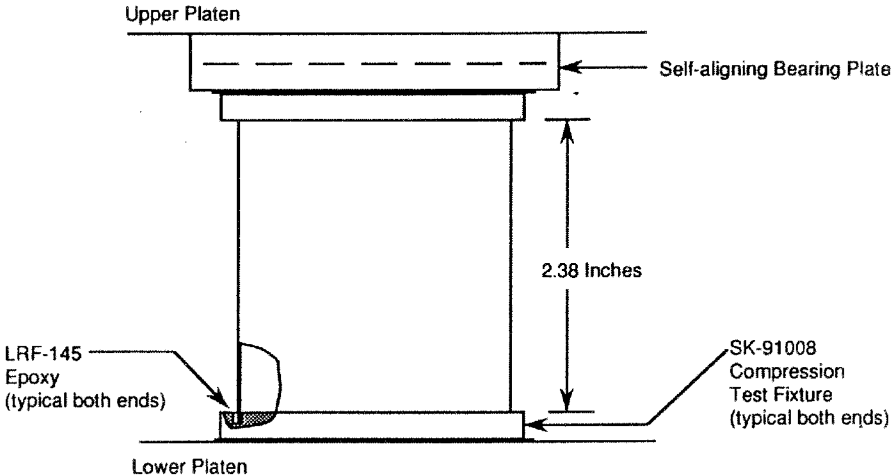
COMPOSITE MATERIALS
Filament Wound Material Characterization
Hoop Tension Test

- Cylindrical specimens wound with either full laminate or repeating sublaminate layup
- Pressure test fixture used to apply burst pressure load
- Properties to be derived:
    1. Hoop tensile modulus
    2. Hoop tensile strength



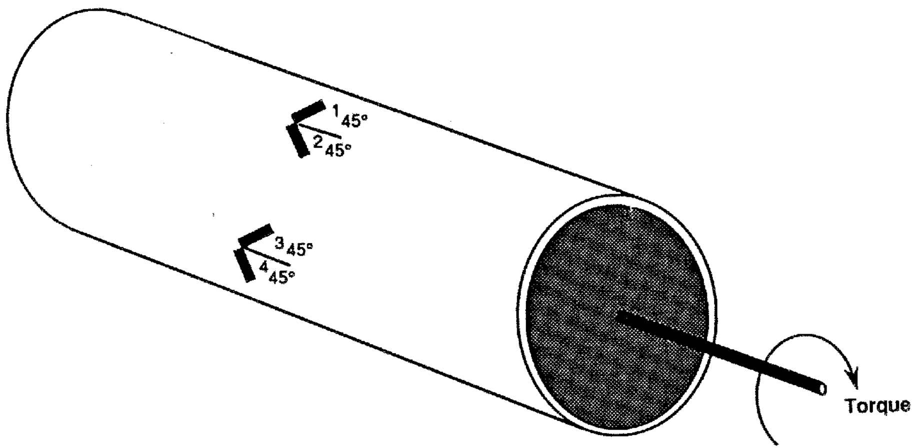
COMPOSITE MATERIALS
Filament Wound Material Characterization
Axial Compression Test

- Cylindrical specimens wound with either full laminate or repeating sublaminate layup
- Self-aligning test fixture used to apply compressive loading
- Properties to be derived:
    1. Axial compressive modulus
    2. Axial compressive strength



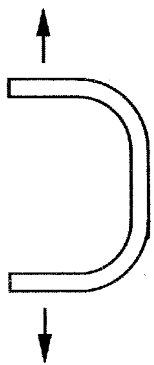
COMPOSITE MATERIALS
Filament Wound Material Characterization
Torsional Shear Test

- Cylindrical specimens wound with either full laminate or repeating sublaminate layup
- Geared test fixture used to apply pure torsional loading
- Properties to be derived:
    1. Shear modulus
    2. Torsional shear strength (Note that this value may be different from the in-plane shear strength if the specimen does not fail in pure shear)

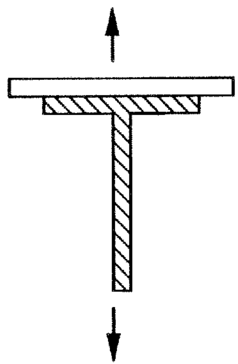


COMPOSITE MATERIALS
Subelement Tests

- Subelement tests required to evaluate strength of special features
  - Open hole tension
  - Bolt bearing
  - Bonded joint
- Additional subelement tests may be required to evaluate areas which are difficult to analyze



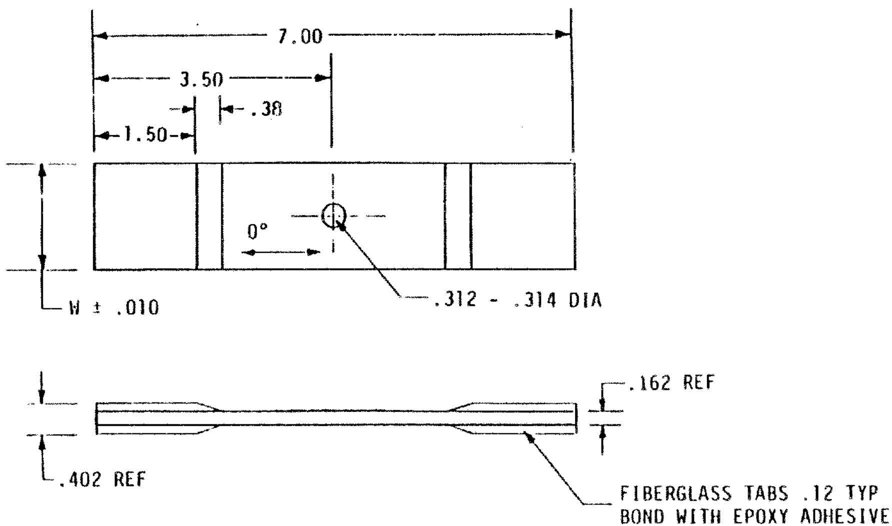
Corner bending



Stiffener pulloff

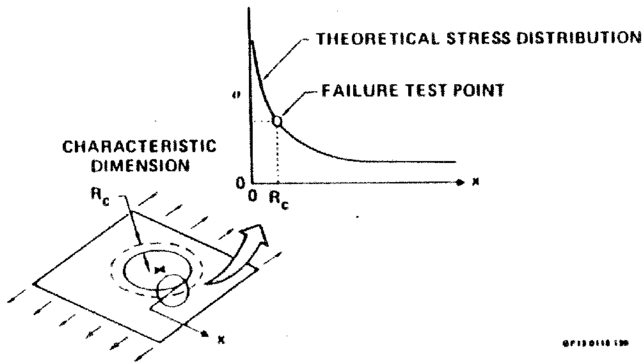
COMPOSITE MATERIALS
Open Hole Tension Test

- Used to evaluate stress concentrations by determining characteristic dimension
- Characteristic dimension used in bolted joint codes (SASCJ and BJSFM)
- Test 3 hole sizes with same e/D ratios to determine characteristic dimension



COMPOSITE MATERIALS
Open Hole Tension Test

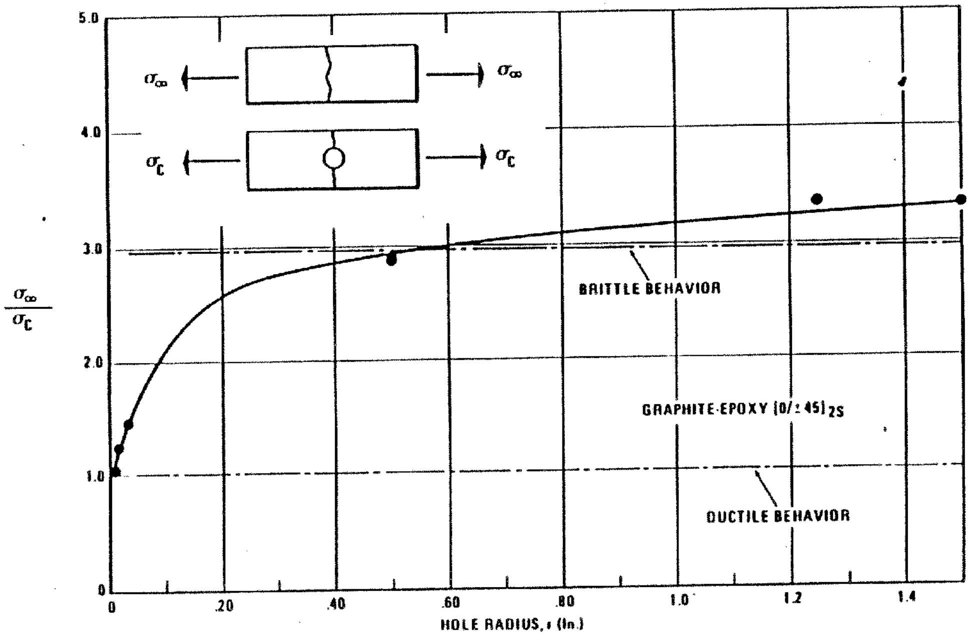
- Characteristic dimension failure hypothesis used with polymer matrix composites



Characteristic Dimension Failure Hypothesis

COMPOSITE MATERIALS
Open Hole Tension Test

- Stress concentration at a hole in polymer matrix composite is a function of hole size



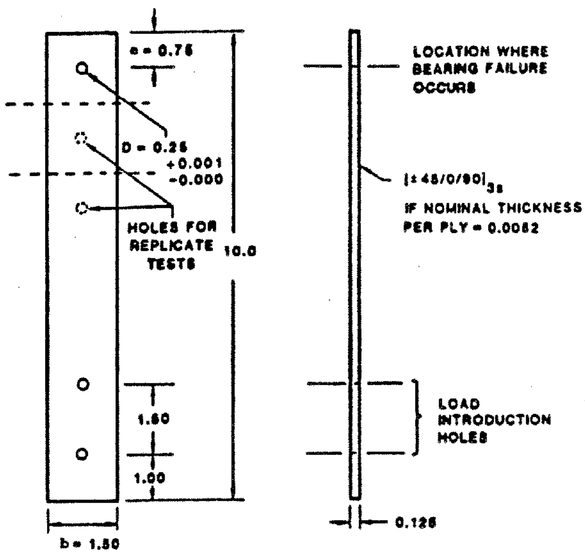
COMPOSITE MATERIALS
Bolt Bearing Test

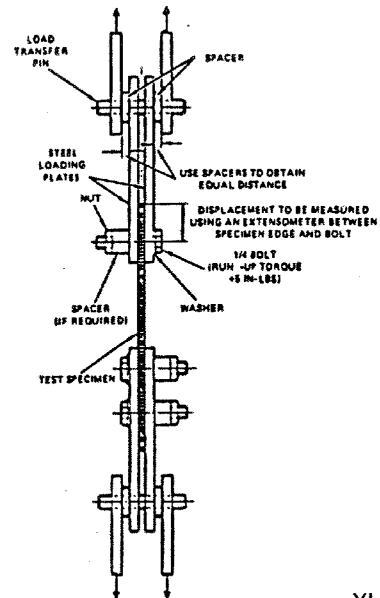
- Used to determine strength of bolted joints and verify analysis codes
- Double shear test
- Vary bolt diameters and e/D ratios as needed to support design
- Analysis codes (SASCJ) will calculate the effect of a single shear joint
- Specimen configurations

    - MIL-HNBK-17B recommendation
    - GDC specimen

COMPOSITE MATERIALS
Bolt Bearing Test

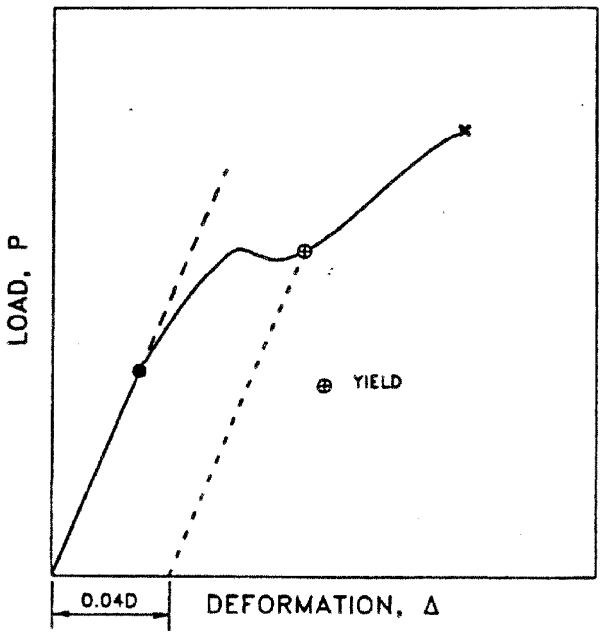
- MIL-HNBK-17B recommended bolt bearing test specimen configuration





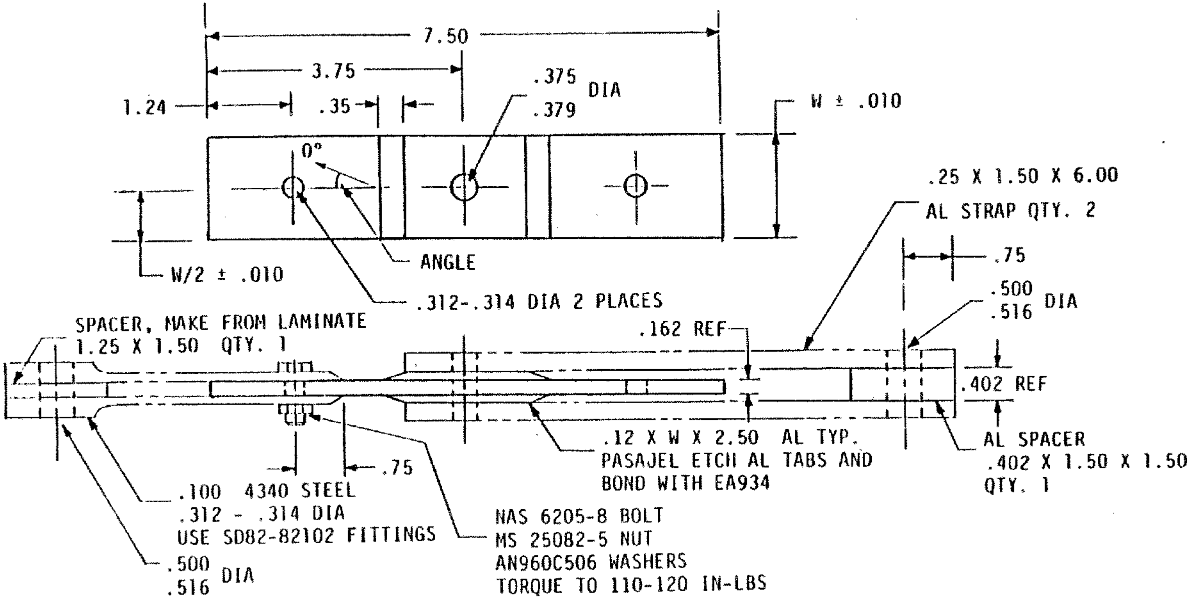
COMPOSITE MATERIALS
Bolt Bearing Test

- Typical Load-Deformation curve for bolt bearing test
- Bearing strength = P / (D X t)
- MIL-HNBK-17B recommends using load at 0.04D



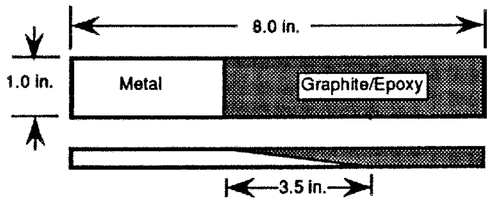
COMPOSITE MATERIALS
Bolt Bearing Test

- GDC bolt bearing specimen configuration (used on ACM Program)

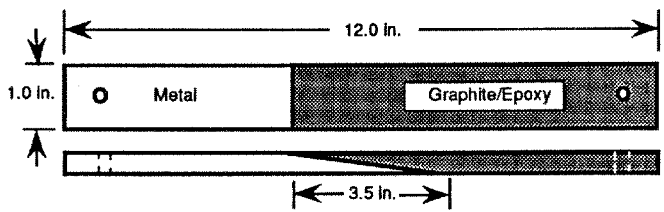


COMPOSITE MATERIALS
Bonded Joint Test

- Used to determine strength of bonded joints and verify analysis codes
- Standard test machine grips used to load specimens



Joint Compression Test Specimen



Joint Tensile Test Specimen

COMPOSITE MATERIALS
Chapter 5.0 Design Analysis

COMPOSITE MATERIALS
Design Allowables

- Material characterization test values used to develop design allowables
- Design allowable basis
  - Typical basis: Property is the sample mean
  - B basis: Property above which at least 90% of the population is expected to fall with a confidence of 95%
  - A basis: Property above which at least 99% of the population is expected to fall with a confidence of 95%
- Composite materials use B-basis design allowables for strength

COMPOSITE MATERIALS
B-Basis Design Allowable

- STEP 1: Calculate the sample mean (average) $\overline{X} = \Sigma X_i / n$
  X_i = test value
  n = number of samples
- STEP 2: Calculate the standard deviation $S = (\Sigma(X_i - \overline{X})^2 / (n - 1))^{1/2}$
- STEP 3: Obtain the one-sided tolerance limit factor (K_B) from Table 8.8.1 in MIL-HNBK-17B (Note that K_B is a function of the number of samples)
- STEP 4: Calculate design allowable $B = \overline{X} - K_B S$

- Notice that the more samples you test the higher your design allowable will be

COMPOSITE MATERIALS
B-Basis Design Allowable

TABLE 8.8.1 One-sided tolerance limit factors, k_B, for the normal distribution, 0.95 confidence.

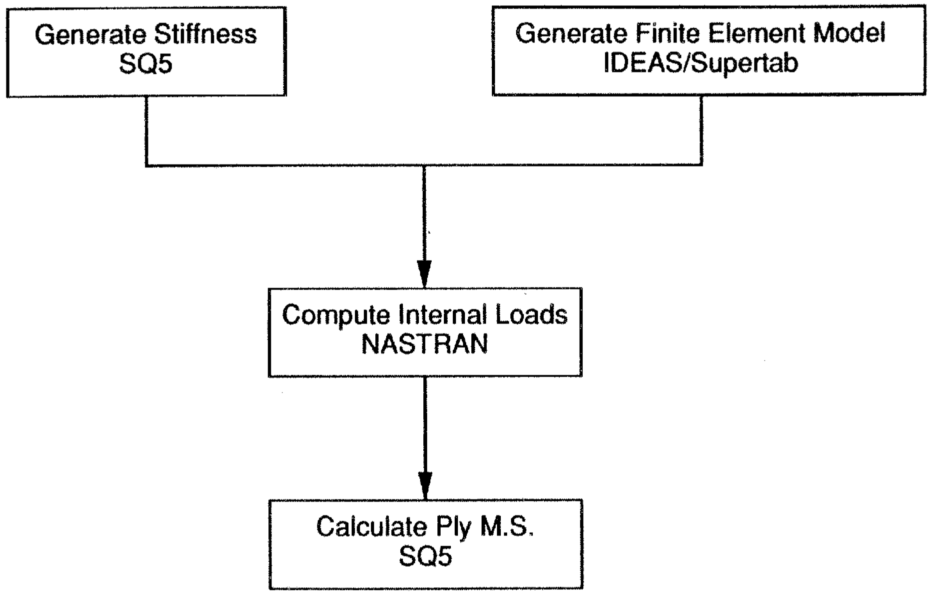
n = 2 - 136

n	k_B	n	k_B	n	k_B
2	20.581	47	1.660	92	1.539
3	6.157	48	1.655	93	1.537
4	4.163	49	1.650	94	1.536
5	3.408	50	1.646	95	1.534
6	3.007	51	1.642	96	1.533
7	2.756	52	1.638	97	1.531
8	2.583	53	1.634	98	1.530
9	2.454	54	1.630	99	1.529
10	2.355	55	1.626	100	1.527
11	2.276	56	1.623	101	1.526
12	2.211	57	1.619	102	1.525
13	2.156	58	1.616	103	1.523
14	2.109	59	1.613	104	1.522
15	2.069	60	1.609	105	1.521
16	2.034	61	1.606	106	1.519
17	2.002	62	1.603	107	1.518
18	1.974	63	1.600	108	1.517
19	1.949	64	1.597	109	1.516
20	1.927	65	1.595	110	1.515
21	1.906	66	1.592	111	1.513
22	1.887	67	1.589	112	1.512
23	1.870	68	1.587	113	1.511
24	1.854	69	1.584	114	1.510
25	1.839	70	1.582	115	1.509
26	1.825	71	1.579	116	1.508
27	1.812	72	1.577	117	1.507
28	1.800	73	1.575	118	1.506
29	1.789	74	1.572	119	1.505
30	1.778	75	1.570	120	1.504
31	1.768	76	1.568	121	1.503
32	1.758	77	1.566	122	1.502
33	1.749	78	1.564	123	1.501
34	1.741	79	1.562	124	1.500
35	1.733	80	1.560	125	1.499
36	1.725	81	1.558	126	1.498
37	1.718	82	1.556	127	1.497
38	1.711	83	1.554	128	1.496
39	1.704	84	1.552	129	1.495
40	1.698	85	1.551	130	1.494
41	1.692	86	1.549	131	1.493
42	1.686	87	1.547	132	1.492
43	1.680	88	1.545	133	1.492
44	1.675	89	1.544	134	1.491
45	1.669	90	1.542	135	1.490
46	1.664	91	1.540	136	1.489

COMPOSITE MATERIALS
Strength Analysis

- Simple (non-redundant) structure
  - Calculate internal loads directly (e.g. bending moment in beam)
  - Input internal loads in SQ5 to obtain minimum margins of safety
- Complex (redundant) structure
  - Generate laminate stiffness (NASTRAN MAT2 card) using SQ5
  - Generate finite element model using I-DEAS/Supertab
  - Perform finite element analysis using NASTRAN to determine internal loads
  - Input internal loads to SQ5 to obtain minimum margins of safety

COMPOSITE MATERIALS
Strength Analysis Process



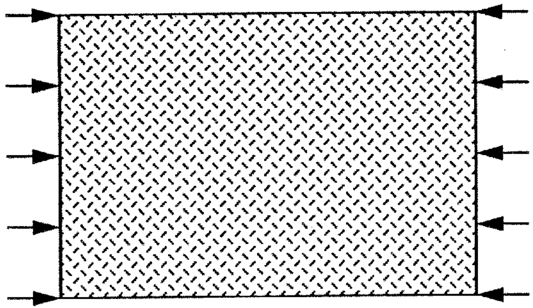
COMPOSITE MATERIALS
Buckling Analysis

- Complex differential equation governs buckling of anisotropic plates

$$D_{11}\frac{\partial^4 w}{\partial x^4} + 4D_{16}\frac{\partial^4 w}{\partial x^3 \partial y} + 2(D_{12}+2D_{66})\frac{\partial^4 w}{\partial x^2 \partial y} + 4D_{26}\frac{\partial^4 w}{\partial x \partial y^3} + D_{22}\frac{\partial^4 w}{\partial y^4}$$

$$= h\left(\sigma_x \frac{\partial^2 w}{\partial x^2} + 2\tau_{xy}\frac{\partial^2 w}{\partial x \partial y} + \sigma_y \frac{\partial^2 w}{\partial y^2}\right)$$

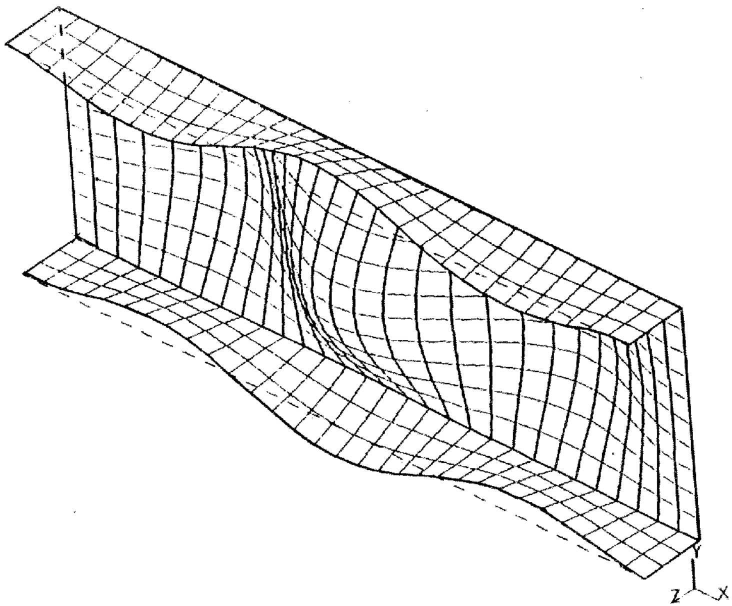
- Classical solutions are available for rectangular orthotropic plates
- Even classical solutions require solving tedious formulas



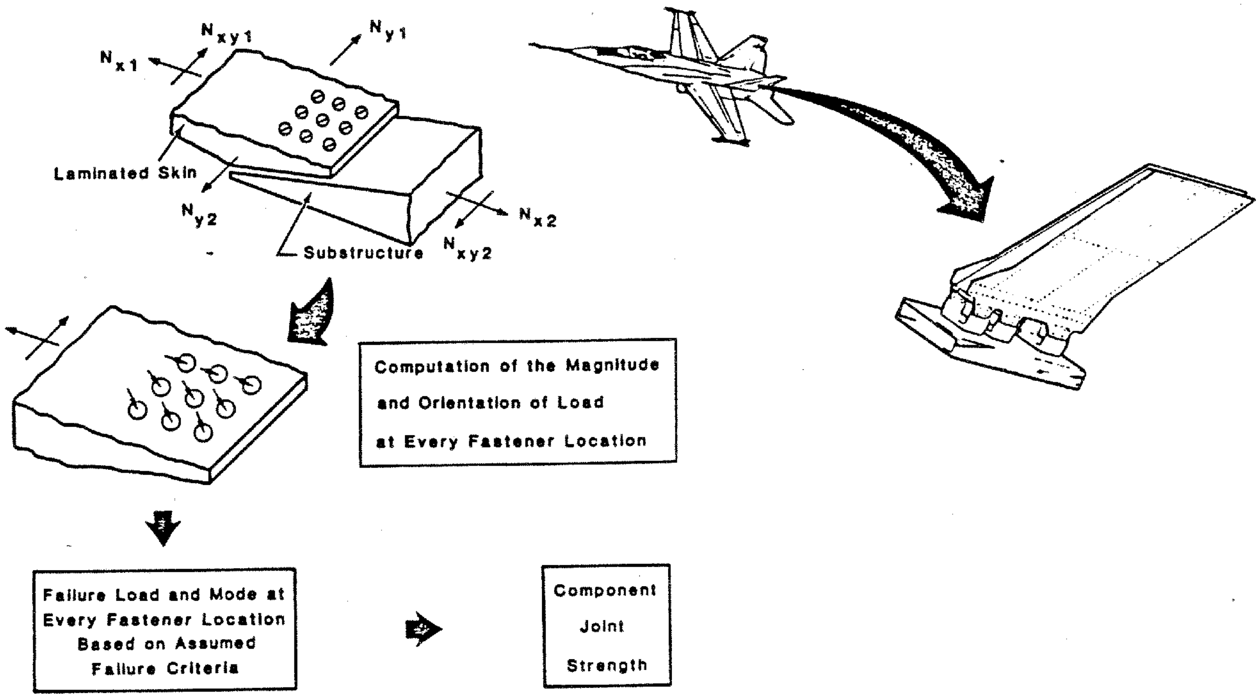
COMPOSITE MATERIALS
Buckling Analysis

- Computer methods available
- BUCKLE contains classical rectangular orthotropic plate solutions
- TM1 is used for curved orthotropic plates
- SO0 is used for stiffened or unstiffened trapezoidal anisotropic plates
- PANDA2/BOSOR4 are used for stiffened flat panels or shells of revolution
- NASTRAN is used for complex structures

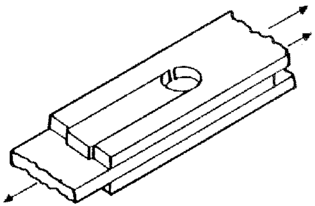
COMPOSITE MATERIALS
Buckling Analysis with NASTRAN



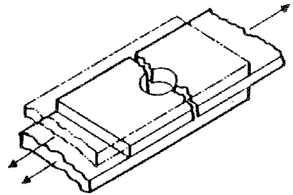
COMPOSITE MATERIALS
Bolted Joint Analysis Procedure



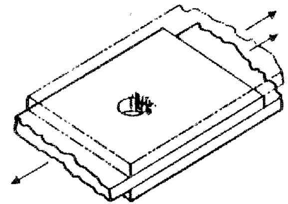
COMPOSITE MATERIALS
Bolted Joint Failure Modes



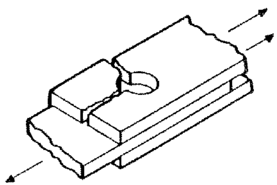
(a) Shearout failure



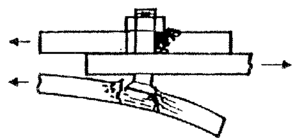
(b) Tension failure



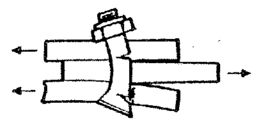
(c) Bearing failure



(d) Cleavage — tension failure



(e) Bolt pulling through laminate



(f) Bolt failure

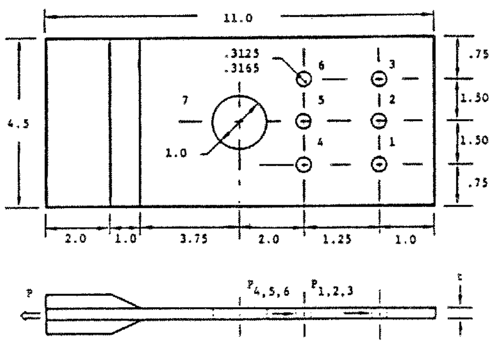
COMPOSITE MATERIALS
Bolted Joint Analysis Methods

- SAMCJ - Strength Analysis of Multifastener Composite Joints
- SASCJ - Strength Analysis of Single-fastener Composite Joints
- BJSFM - Bolted Joint Stress Field Model
- IBOLT - GD/Ft. Worth code

COMPOSITE MATERIALS
SAMCJ Code

- Computes load distribution and joint failure in one step
- Code is limited to rectangular geometry and axial loads
- Shows good correlation with test data

*Test Case 246, Static Tension, Single-Lap
40-Ply, 70/20/10 Laminate, t=0.236 in., t_{AL}=0.50 in.
D=5/16 in., B_D=1 in., $S_L/D=S_T/D=4$, W/D=14.4, E/D=3.2

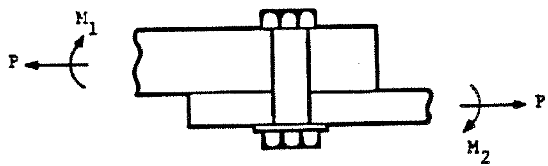


	SAMCJ PREDICTION	TEST RESULTS (Ref. 2)
P_1/P	0.164	0.158
P_2/P	0.186	0.165
P_3/P	0.163	0.199
P_4/P	0.156	0.172
P_5/P	0.177	0.166
P_6/P	0.154	0.140
$P_{failure}$ (kips)	37.8 (38.8)*	42.9
FAILURE LOCATION	5 (7)	1 to 6
FAILURE MODE(S)	SHEAR-OUT (NET SECTION)	SHEAR-OUT, DELAMINATION

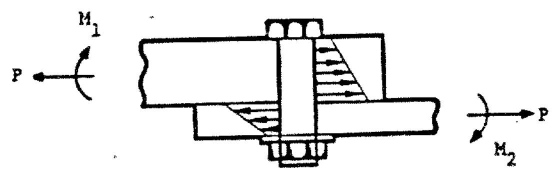
*Next possible failure mode and location at a higher load level

COMPOSITE MATERIALS
SASCJ Code

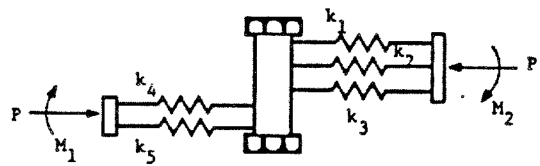
- Single fastener analysis
- Includes through-the-thickness effects such as load eccentricity and fastener flexibility
- Strength based on progressive ply failure prediction (last ply failure)



(a) Single Lap Bolted Joint



(b) Typical Fastener/Plate Displacement Variation



(c) Mathematical Representation

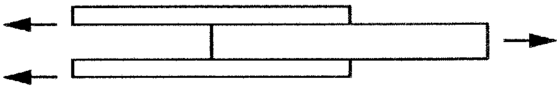
COMPOSITE MATERIALS
Bolted Joint Design Guidelines

- Corrosion barriers needed in graphite/epoxy to metal joints
- Design joint to fail in bearing to avoid catastrophic failures
- Tension head fasteners are preferred over shear head fasteners
- Titanium fasteners are preferred with graphite-reinforced composites
- The fastener diameter should be larger than the thickness of the plate
- Fastener torque-up increases strength of bolted joint

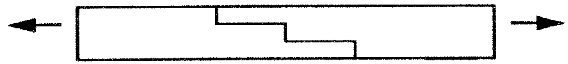
COMPOSITE MATERIALS
Bolted Joint Design Guidelines

- Bearing strength maximized when layup contains less than 40% of each of 0,±45 and 90 degree plies
- Groups of identical plies should not exceed .02 inch in thickness to avoid delamination-induced strength reductions
- E/D ratio should be greater than or equal to 3.0
- S/D ratio should be greater than or equal to 4.0

COMPOSITE MATERIALS
Types of Bonded Joints

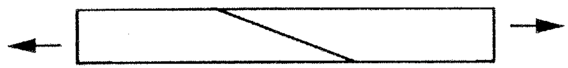


Double Lap



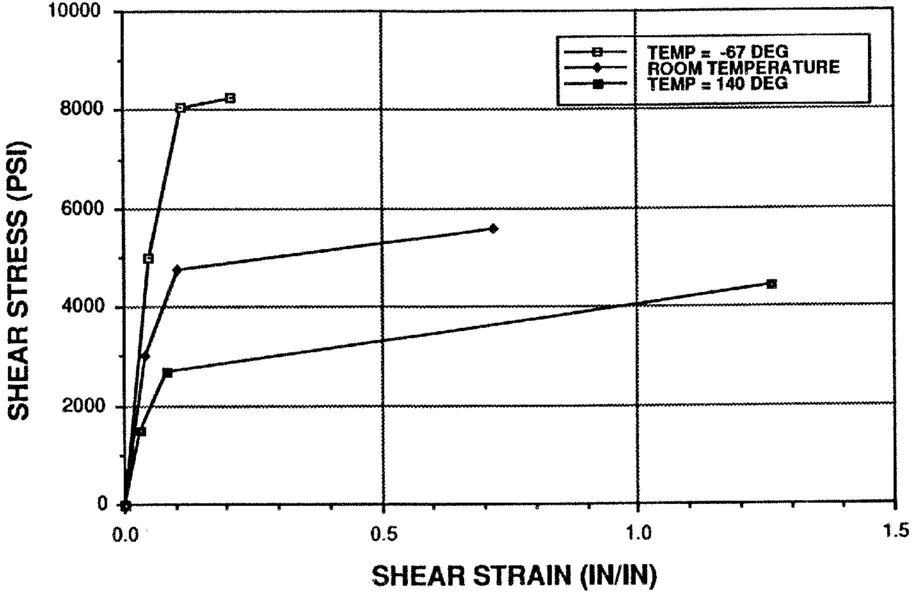
Stepped Lap

Single Lap

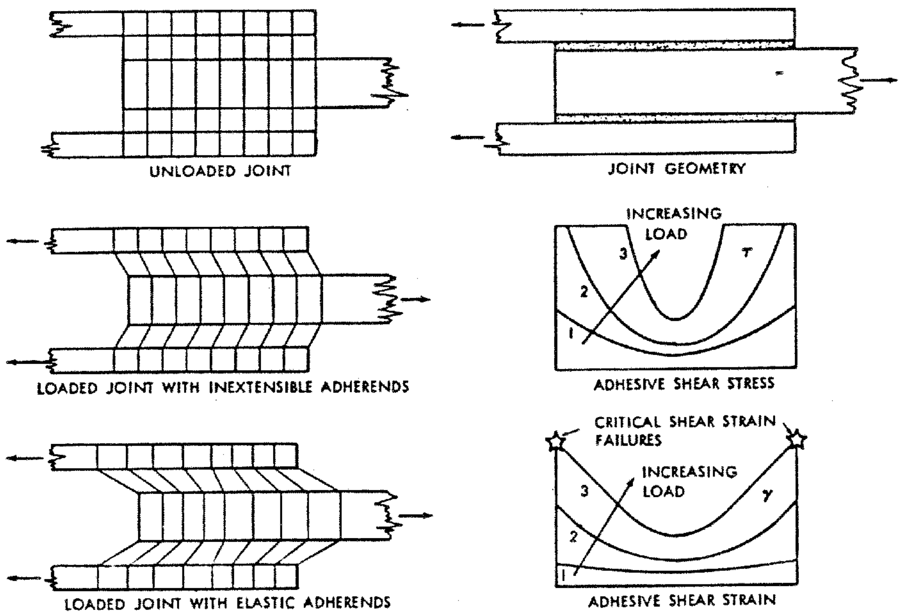


Scarf

COMPOSITE MATERIALS
Adhesive Stress-Strain Diagram



COMPOSITE MATERIALS
Shearing in Adhesive



COMPOSITE MATERIALS
Bonded Joint Analysis Methods

- A4EI (Hart-Smith Code)
  - One dimensional analysis good for trade studies and flat coupon test correlation
  - Nonlinear adhesive properties
- NASTRAN Shell/Spring Elements
  - Three dimensional analysis good for non-axisymmetric geometry and loads
  - Linear adhesive properties
- NASTRAN Solid Elements
  - Three dimensional analysis good for flat panel or axisymmetric geometry and loads
  - Linear or nonlinear properties
  - Local thickness effects included
- PROBE 2D (Cross-Section Analysis)
  - Two dimensional analysis good for axisymmetric geometry and loads
  - Linear adhesive properties
  - Can use high aspect ratio for elements