M2794.007700 Smart Materials and Design

Hygrothermal effects, Manufacturing and Joining

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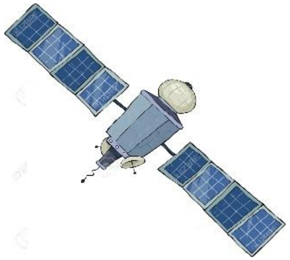
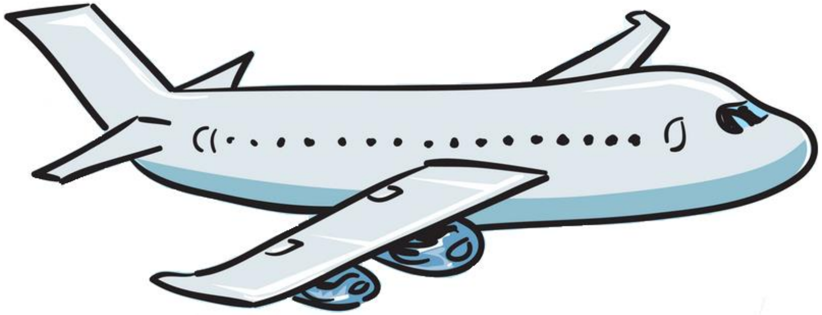
Outline

Hygrothermal effect
Sandwich structure
Joint & Repair





Hygrothermal effect

- **Hygrothermal efffects**
  - Hygro (Moisture) + thermal (Temperature) effects
  - Matrix dominated properties
  - transverse tensile, transverse compressive and shear

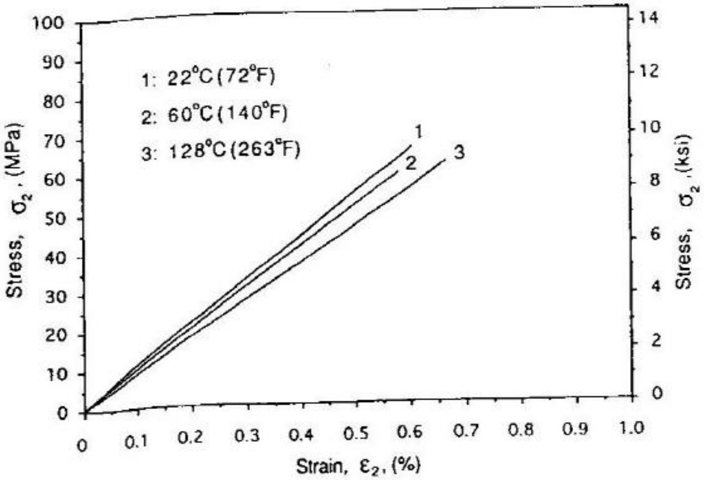


Fig. 6.1 Transverse tensile stress-strain curves for dry AS4/3501-6 carbon/epoxy composite at various temperatures.[2]

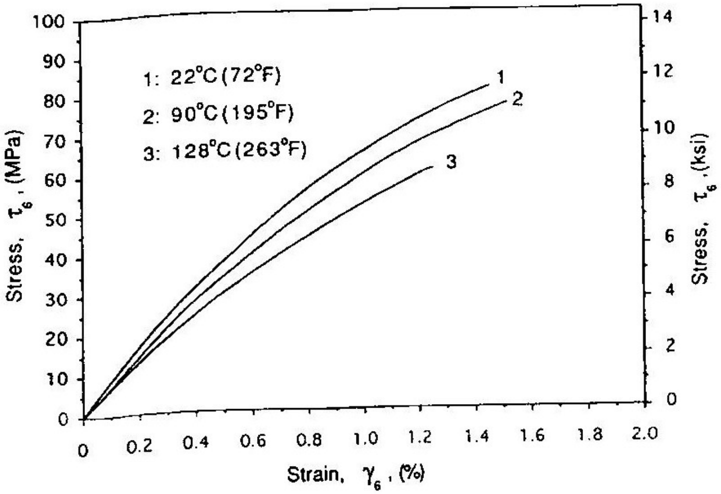


Fig. 6.2 In-plane shear stress–strain curves for unidirectional AS4/3501-6 carbon/epoxy composite at various temperatures.[2]

Hygrothermal effect

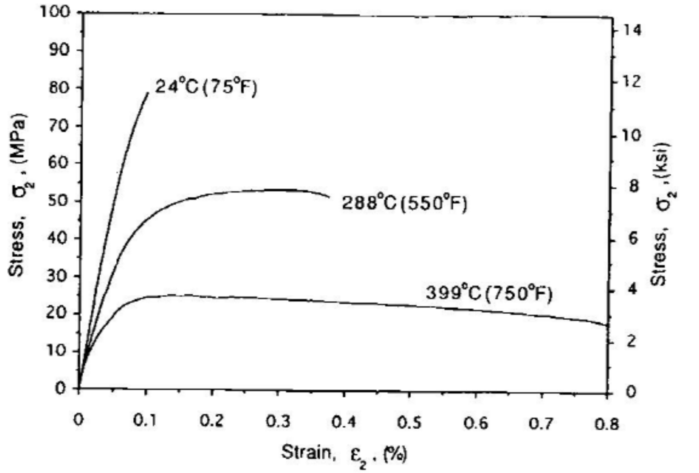


Fig. 6.3 Transverse tensile stress–strain curves for unidirectional silicon carbide/aluminum (SCS-2/6061Al) composite at various temperatures.

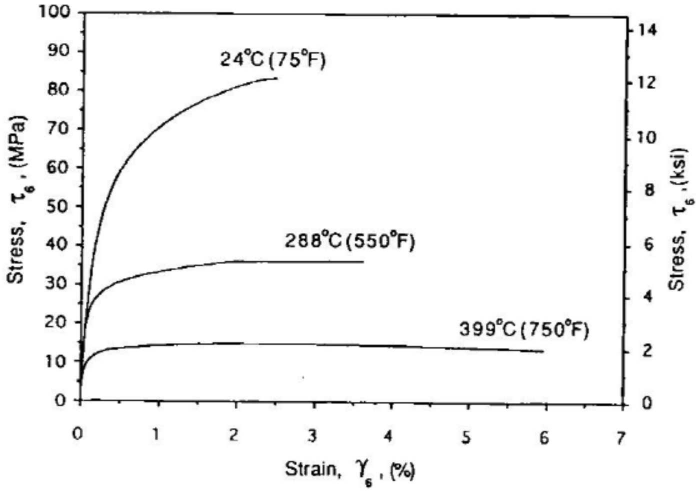


Fig. 6.4 In-plane shear stress–strain curves for unidirectional silicon carbide/aluminum (SCS-2/6061Al) composite at various temperatures.

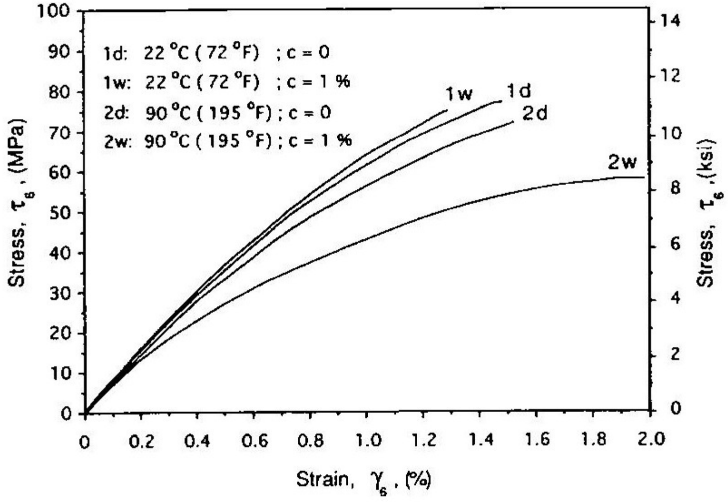


Fig. 6.5 In-plane shear stress–strain curves for unidirectional AS4/3501-6 carbon/epoxy composite illustrating effects of temperature and moisture concentration.

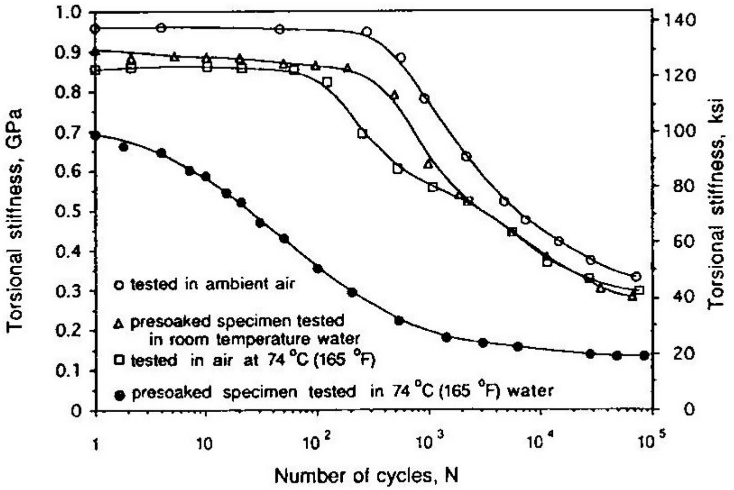
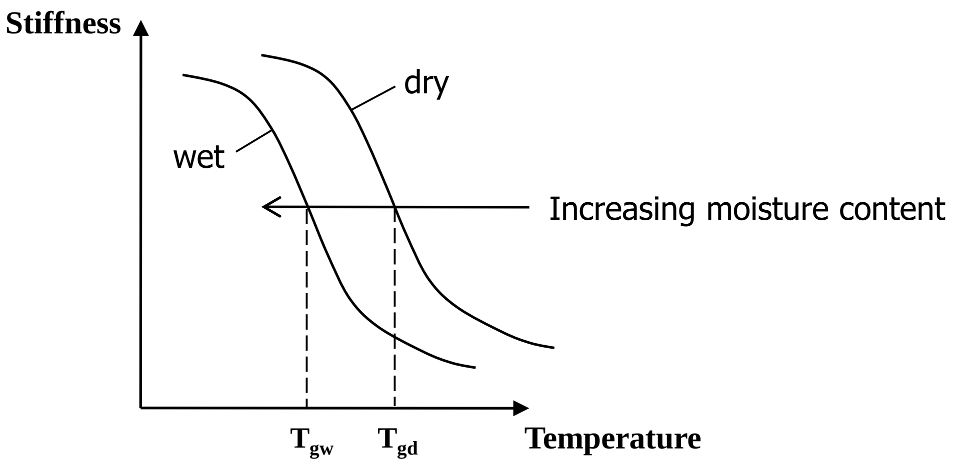
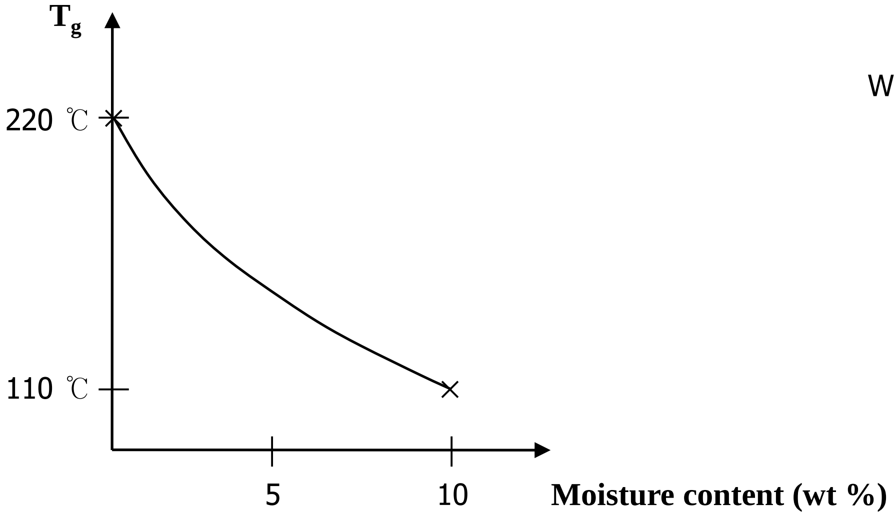
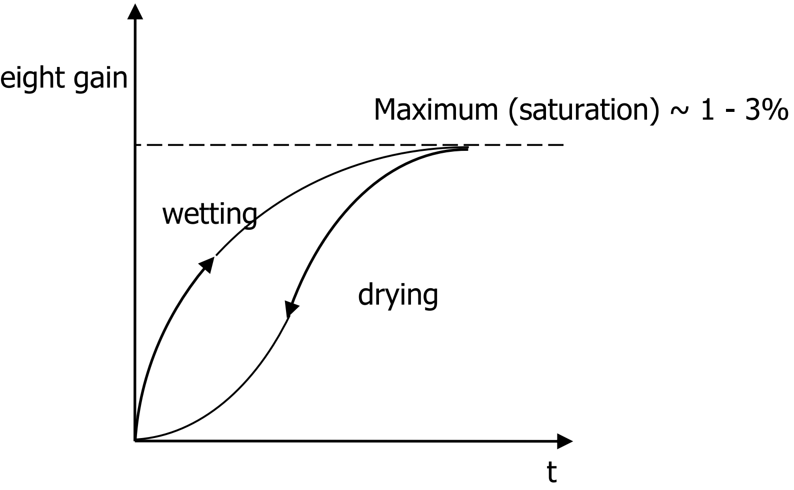


Fig. 6.6 Torsional stiffness degradation of carbon/epoxy composite under cyclic loading under various hygrothermal conditions.

Moisture effect on typical polymer

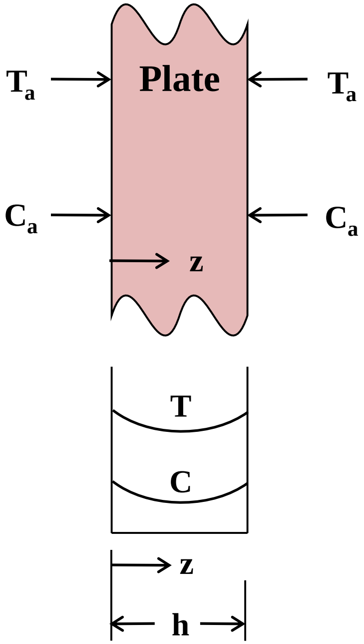






Moisture effect on typical polymer

- **Governing equation**



  - Temperature (Fourier heat conduction)

$$\rho C \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} K_z \frac{\partial T}{\partial z}$$

  - Moisture (Fick's 2nd law)

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial z} D_z \frac{\partial c}{\partial z}$$

    - Cf) Fick's 1st law $J\ [\text{flux}] = -D\frac{dc}{dz}$

Ambient temperature T_a
Ambient moisture concentration C_a

  - Where,

ρ = Density of material
C = Specific heat of material
K_z = Thermal conductivity of material along the z-direction
D_z = Mass diffusivity along the z-direction
t = Time
c = Moisture concentration

- Temperature reaches equilibrium about one million times faster than the moisture concentration → T assumed to be the same as T_a

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Moisture weight gain

$$G = \frac{M - M_i}{M_m - M_i} = 1 - \frac{8}{\pi^2} \sum_{j=1}^{\infty} \frac{\exp[-(2j+1)^2 \pi^2 (D_z t / h^2)]}{(2j+1)^2}$$

Where,

M_i : Initial weight percent of moisture

M_m : Fully saturated weight percent of moisture

- Measured value: composite 0~2 %

Moisture weight gain

- **Example**

Epoxy sample with h = 5 mm, D (diffusivity) = 3×10^{-8} mm^2/s.
Determine the moisture absorption of an initially dry sample after a period t = 100 days.

$$\frac{\pi^2 D t}{h^2} = 0.102$$

$M_i = 0$ for initially dry sample

$$\frac{M}{M_m} = 1 - \frac{8}{\pi^2}\left[\exp(-0.102) + \frac{\exp(-9(0.102))}{9} + \cdots\right]$$

→ one term will be sufficient.

$$\sim 0.23$$

Degradation of composite properties

- $$F_m = \frac{P}{P_0} = \left(\frac{T_{gw} - T}{T_{go} - T_o}\right)^{\frac{1}{2}}$$

F_m = Matrix mechanical property retention ratio
P = Strength of matrix after degradation
P_o = Net strength of matrix after degradation
T_{go} = Glass transition temperature (dry)
T_{gw} = Glass transition temperature (wet)
T_o = Temperature at F_0 was measured

} [°F]

- Chamis (1982) suggested an empirical eq. for T_{gw} of aerospace epoxy resins.

$$T_{gw} = (0.005M_r{}^2 - 0.10M_r{}^2 + 1.0)\,T_{go}$$

- Degraded material properties (longitudinal modulus)

$$E_1 = E_{f_1} v_f + F_m E_{mo} v_m$$

Degradation of composite properties

- **Example**

At a "hot-wet" condition, T = 200 °F, M_r = 3 %.

T_{go} = 350 °F

$E_m = 0.5 \times 10^6$ psi

$E_f = 32 \times 10^6$ psi

$v_f = 0.510$

$v_m = 0.49$

$T_{gw} = (0.005(3)^2 - 0.10(3) + 1.0)\,350 = 261$ °F

E of matrix,

$$E_m' = \left(\frac{261-200}{350-70}\right)^{\frac{1}{2}} (0.5 \times 10^6 \text{ psi}) = 0.23 \times 10^6 \text{ psi}$$

Longitudinal modulus

$$E_1' = (32 \times 10^6)(0.51) + (0.23 \times 10^6)(0.49) = 16 \times 10^6 \text{ psi}$$

Cf. $E_1 = 16.4 \times 10^6$ psi

→ 99 %

Transverse modulus

$$E_2' = 0.434 \times 10^6 \text{ psi} \qquad E_2 = 0.82 \times 10^6 \text{ psi}$$

→ Only 53 %

Hygrothermal strains in lamina

- **Uncoupled deformation from the thermal & moisture**
- **Hygrothermal strains**

$$e_1 = \alpha_1 \Delta T + \beta_1 \Delta C$$

$$e_2 = \alpha_2 \Delta T + \beta_2 \Delta C$$

$$e_6 = 0$$

α: Coefficient of thermal expansion

β: Coefficient of moisture expansion

Note
Carbon/epoxy – 0.9 × 10^{-6}
Carbon/polyimde – 0.4 × 10^{-6}
Kevlar/epoxy – 4 × 10^{-6}
have negative α_1.

- **Transformation**

$$e_x = e_1 m^2 + e_2 n^2$$

$$e_y = e_1 n^2 + e_2 m^2$$

$$e_s = 2(e_1 - e_2)mn$$

$$m = \cos\theta$$

$$n = \sin\theta$$

Hygrothermal strains in lamina

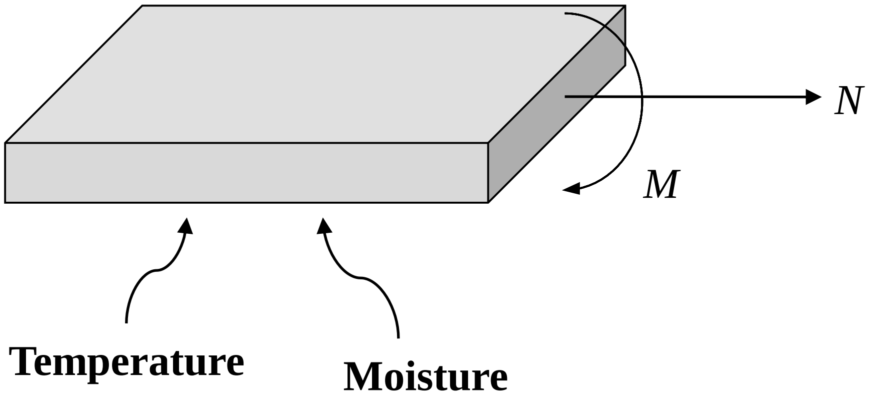
- **Using above equations,**

$$e_x = \alpha_x \Delta T + \beta_x \Delta C$$
$$e_y = \alpha_y \Delta T + \beta_y \Delta C$$
$$e_s = \alpha_s \Delta T + \beta_s \Delta C$$

with (Eq. 6.6)

$$\alpha_x = \alpha_1 m^2 + \alpha_2 n^2$$
$$\alpha_y = \alpha_1 n^2 + \alpha_2 m^2$$
$$\alpha_s = 2(\alpha_1 - \alpha_2)mn$$

σ-ε with hygrothermal effects



$$\begin{pmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_s \end{pmatrix} = \underbrace{\begin{bmatrix} S_{xx} & S_{xy} & S_{xs} \\ S_{ys} & S_{ss} & S_{ys} \\ S_{sx} & S_{sy} & S_{ss} \end{bmatrix}_k \begin{pmatrix} \sigma_x \\ \sigma_y \\ \tau_s \end{pmatrix}_k}_{\text{Strains from mechanical loading}} + \underset{\underset{\text{Hygrothermal strain}}{\uparrow}}{\begin{pmatrix} e_x \\ e_y \\ e_s \end{pmatrix}_k}$$

σ-ε with hygrothermal effects

- **Inverting,**

$$\begin{pmatrix} \sigma_x \\ \sigma_y \\ \sigma_s \end{pmatrix} = \begin{bmatrix} Q_{xx} & Q_{xy} & Q_{xs} \\ Q_{ys} & Q_{ss} & Q_{ys} \\ Q_{sx} & Q_{sy} & Q_{ss} \end{bmatrix}_k \begin{pmatrix} \varepsilon_x - e_x \\ \varepsilon_y - e_y \\ \gamma_s - e_s \end{pmatrix}_k$$

$$= \begin{bmatrix} Q_{xx} & Q_{xy} & Q_{xs} \\ Q_{ys} & Q_{ss} & Q_{ys} \\ Q_{sx} & Q_{sy} & Q_{ss} \end{bmatrix}_k \begin{pmatrix} \varepsilon_x{}^o + z\kappa_x - e_x \\ \varepsilon_y{}^o + z\kappa_y - e_y \\ \gamma_s{}^o + z\kappa_s - e_s \end{pmatrix}_k$$

- **For a laminate,**

$$\begin{pmatrix} N_x \\ N_y \\ N_s \end{pmatrix} = \sum_{k=1}^{n} \int_{h_{k-1}}^{h_k} \begin{bmatrix} Q_{xx} & Q_{xy} & Q_{xs} \\ Q_{ys} & Q_{ss} & Q_{ys} \\ Q_{sx} & Q_{sy} & Q_{ss} \end{bmatrix}_k \left\{ \begin{pmatrix} \varepsilon_x{}^o \\ \varepsilon_y{}^o \\ \gamma_s{}^o \end{pmatrix} + z \begin{pmatrix} \kappa_x \\ \kappa_y \\ \kappa_s \end{pmatrix} - \begin{pmatrix} e_x \\ e_y \\ e_s \end{pmatrix} \right\}_k dz$$

σ-ε with hygrothermal effects

- **In terms of [*A*] and [*B*]**

$$\begin{pmatrix} N_x \\ N_y \\ N_s \end{pmatrix} = \begin{bmatrix} A_{xx} & A_{xy} & A_{xs} \\ A_{yx} & A_{yy} & A_{ys} \\ A_{sx} & A_{sy} & A_{ss} \end{bmatrix} \begin{pmatrix} \varepsilon_x{}^o \\ \varepsilon_y{}^o \\ \gamma_s{}^o \end{pmatrix} + \begin{bmatrix} B_{xx} & B_{xy} & B_{xs} \\ B_{yx} & B_{yy} & B_{ys} \\ B_{sx} & B_{sy} & B_{ss} \end{bmatrix} \begin{pmatrix} \kappa_s \\ \kappa_y \\ \kappa_s \end{pmatrix} - \underbrace{\sum_{k=1}^{n} \begin{bmatrix} Q_{xx} & Q_{xy} & Q_{xs} \\ Q_{yx} & Q_{yy} & Q_{ys} \\ Q_{sx} & Q_{sy} & Q_{ss} \end{bmatrix} \begin{pmatrix} e_x \\ e_y \\ e_s \end{pmatrix}_k}_{\begin{pmatrix} N_x{}^{HT} \\ N_y{}^{HT} \\ N_s{}^{HT} \end{pmatrix}} t_k$$

- **Similarly,**

$$[M]_{x,y} = \sum_{k=1}^{n} \int_{h_{k-1}}^{h_k} \left[Q^k{}_{x,y}\right] \left\{ [\varepsilon^o]_{x,y} + z[\kappa]_{x,y} - [e]^k{}_{x,y} \right\} z\, dz$$

$$\begin{pmatrix} M_x \\ M_y \\ M_s \end{pmatrix} = \begin{bmatrix} B_{xx} & B_{xy} & B_{xs} \\ B_{yx} & B_{yy} & B_{ys} \\ B_{sx} & B_{sy} & B_{ss} \end{bmatrix} \begin{pmatrix} \varepsilon_x{}^o \\ \varepsilon_y{}^o \\ \gamma_s{}^o \end{pmatrix} + \begin{bmatrix} D_{xx} & D_{xy} & D_{xs} \\ D_{yx} & D_{yy} & D_{ys} \\ D_{sx} & D_{sy} & D_{ss} \end{bmatrix} \begin{pmatrix} \kappa_s \\ \kappa_y \\ \kappa_s \end{pmatrix} - \underbrace{\sum_{k=1}^{n} \begin{bmatrix} Q_{xx} & Q_{xy} & Q_{xs} \\ Q_{yx} & Q_{yy} & Q_{ys} \\ Q_{sx} & Q_{sy} & Q_{ss} \end{bmatrix} \begin{pmatrix} e_x \\ e_y \\ e_s \end{pmatrix}_k}_{\begin{pmatrix} M_x{}^{HT} \\ M_y{}^{HT} \\ M_s{}^{HT} \end{pmatrix}} Z_k t$$

$$Z_k = \frac{h_k - h_{k-1}}{2}$$

σ-ε with hygrothermal effects

- **Let $[\overline{N}]$ & $[\overline{M}]$ be the total force & moment resultant**

$$[\overline{N}]_{x,y} = [N]_{x,y} + [N^{HT}]_{x,y} = [A][\varepsilon^o]_{x,y} + [B][\kappa]_{x,y}$$

$$[\overline{M}]_{x,y} = [M]_{x,y} + [M^{HT}]_{x,y} = [B][\varepsilon^o]_{x,y} + [D][\kappa]_{x,y}$$

As before,

$$\begin{pmatrix} \overline{N} \\ \overline{M} \end{pmatrix} = \begin{pmatrix} A & B \\ B & D \end{pmatrix} \begin{pmatrix} \varepsilon^o \\ \kappa \end{pmatrix}$$

Also inverting,

$$\begin{pmatrix} \varepsilon^o \\ \kappa \end{pmatrix} = \begin{pmatrix} a & b \\ b & d \end{pmatrix} \begin{pmatrix} \overline{N} \\ \overline{M} \end{pmatrix}$$

σ-ε with hygrothermal effects

- **Example**

  [-45/45/-45/45], 0.25 mm thick unidirectional (t : total thickness)
  laminate heated from 20 ℃ to 100 ℃.
  Determine the hygrothermal stresses.

CTEs $\alpha_1 = 0.88 \times 10^{-6}$ /℃

$\alpha_2 = 31 \times 10^{-6}$ /℃

CTE at +45° & -45° :

$$\begin{Bmatrix} \alpha_x \\ \alpha_y \\ \alpha_{xy/2} \end{Bmatrix}_{45^\circ} = [T^{-1}]_{45^\circ} \begin{Bmatrix} \alpha_1 \\ \alpha_2 \\ 0 \end{Bmatrix} = \begin{Bmatrix} 15.94 \\ 15.94 \\ -15.06 \end{Bmatrix} \times 10^{-6} \ {}^\circ C \qquad \begin{Bmatrix} \alpha_x \\ \alpha_y \\ \alpha_{xy/2} \end{Bmatrix}_{-45^\circ} = [T^{-1}]_{-45^\circ} \begin{Bmatrix} 0.88 \\ 31.0 \\ 0 \end{Bmatrix} = \begin{Bmatrix} 15.94 \\ 15.94 \\ -15.06 \end{Bmatrix} \times 10^{-6} \ {}^\circ C$$

From equation ①, [N] = 0, and [M] = 0

σ-ε with hygrothermal effects

- **Example**

  From equation ①, $[N] = 0$, and $[M] = 0$

$$[N^T] = \left\{ [Q]_{45}\{\alpha\}_{45} + [Q]_{-45}\{\alpha\}_{-45} \right\} (2)\,(\Delta T)(t/4)$$

Thermal load

2 plies

$$\begin{Bmatrix} N_x{}^T \\ N_y{}^T \\ N_s{}^T \end{Bmatrix} = \left[Q_{xy} \right]_{45^\circ} \begin{Bmatrix} 15.94 \\ 15.94 \\ -30.12 \end{Bmatrix} \times 10^{-6}\ (2)\,(80\ ^\circ C)\,(0.25)\ + \left[Q_{xy} \right]_{-45^\circ} \begin{Bmatrix} 15.94 \\ 15.94 \\ 30.12 \end{Bmatrix} \times 10^{-6}\ (2)\,(80\ ^\circ C)\,(0.25)$$

$$= \begin{Bmatrix} 1.95 \\ 1.95 \\ 0 \end{Bmatrix} \times 10^{-2}\ GPa \cdot mm$$

σ-ε with hygrothermal effects

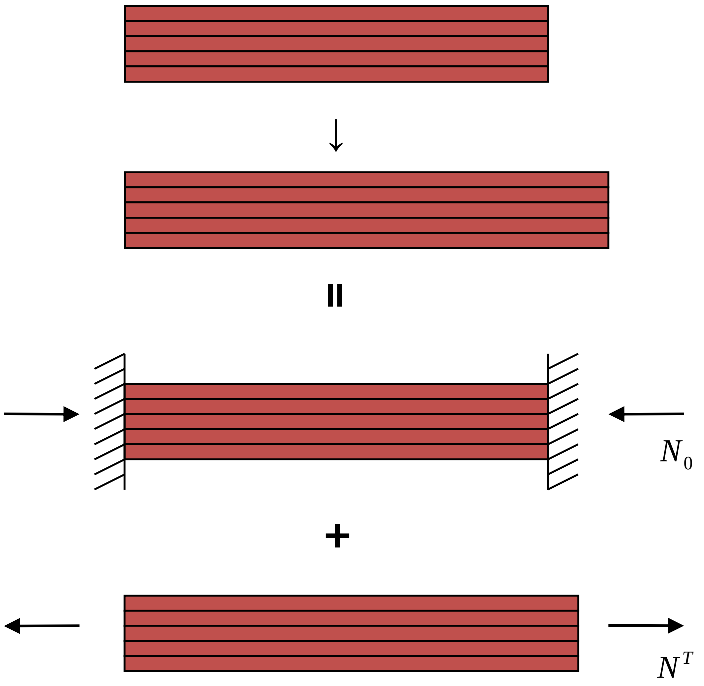
- **Example**

  Similarly for moment

$$[M^T] = \Big([Q]_{-45}\{\alpha\}_{-45}({z_1}^2 - {z_0}^2) + [Q]_{45}\{\alpha\}_{45}({z_2}^2 - {z_1}^2) + [Q]_{-45}\{\alpha\}_{-45}({z_3}^2 - {z_2}^2) + [Q]_{45}\{\alpha\}_{45}({z_4}^2 - {z_3}^2)\Big)\frac{\Delta T}{2}$$

$$= \begin{Bmatrix} 0 \\ 0 \\ -3.81 \end{Bmatrix} \times 10^{-4}\ GPa \cdot mm^2$$

Physical significance



$$\Delta T = 0$$
$$N = 0$$
$$\varepsilon = 0$$

$$\Delta T = \Delta T_0$$
$$N = 0$$
$$\varepsilon = \varepsilon_0$$

$$\Delta T = \Delta T_0$$
$$N = -N_0 = -\sum_{k=1}^{n} Q^k e^k t_k$$
$$\varepsilon = 0$$

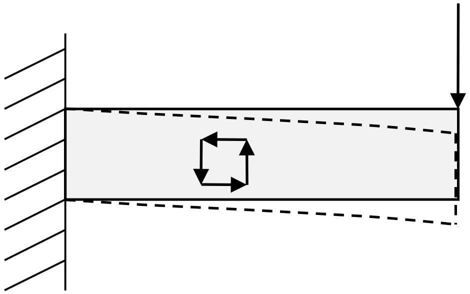
$$\left([\varepsilon] = 0\right)$$

$$\Delta T = 0$$
$$N = N^T = N_0$$
$$\varepsilon = \varepsilon_0$$

- Thermal loading N^T is equal to the reaction N_0 of the fixed-end beam under thermal loading. The mechanical force necessary to produce a strain is equal to the purely thermal strain of the laminate.

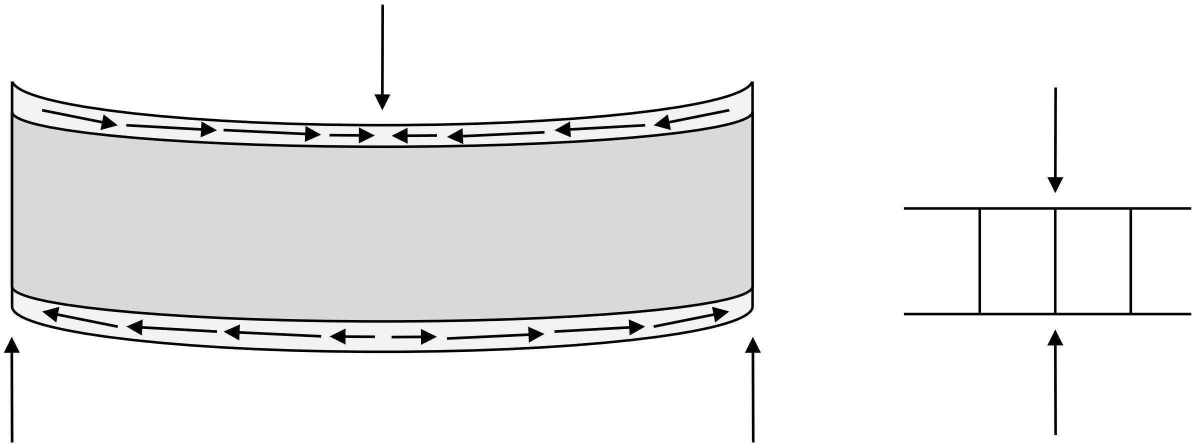
Sandwich structure

- **Sandwich – face sheets & core**
- **Analysis**
  - Modified classical laminate theory accommodating shear flexibility of the core
  - Material behavior
    - The core material is orthotropic and linear elastic.
    - The face sheet material is orthotropic and linear elastic.
  - Stresses
    - Core sustains only transverse shear stresses; the in-plane stresses in the core are negligible.
    - Face sheets sustain only in-plane loads; the transverse shear stresses in the face sheets are negligible.



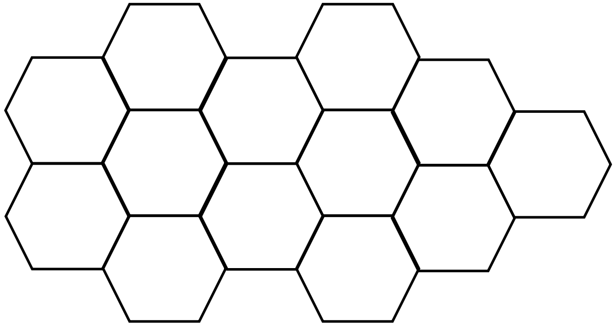
Sandwich structure

- Strain
  - The transverse strain is negligible.



Core material

- **Honeycomb**
  - Aluminum $\rho \sim \begin{pmatrix} 2-10\,lb/ft^3 \\ 0.0126-0.63\,kg/m^3 \end{pmatrix}$
  - Phenolic (1/100 CTE of Al) (Porous wall – air connection, in space structure escape)



- **Synthetic core**
  - Glass microballons with matrix (resin)
  - $\rho \sim \left(2-10\,lb/ft^3\right) \sim 2.51\,kg/m^3$

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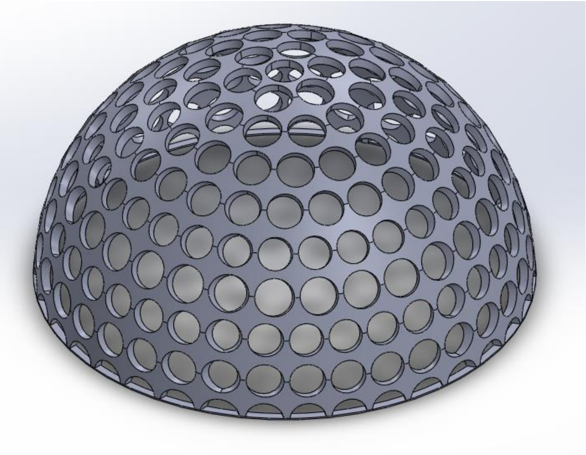
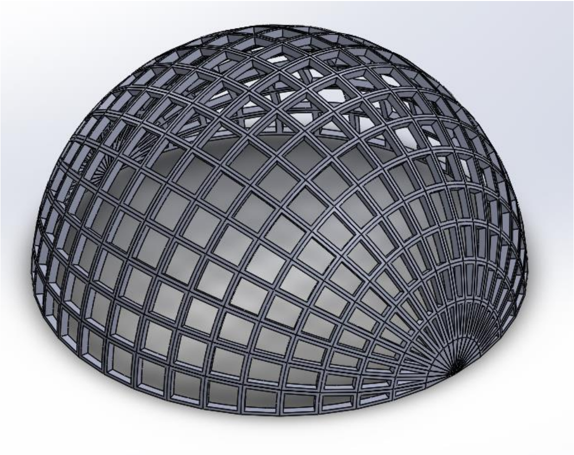
Core material

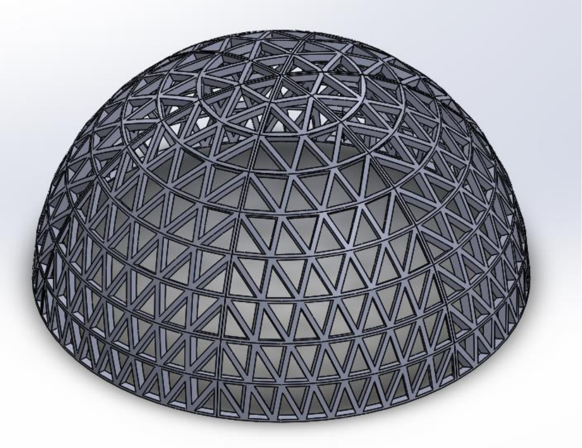
- **Honeycomb**



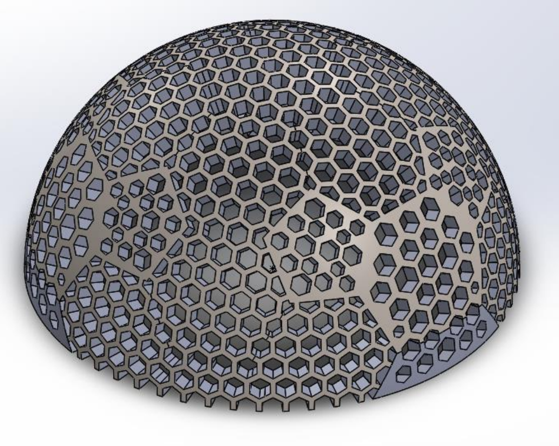
Circular Cell



Rectangular Cell



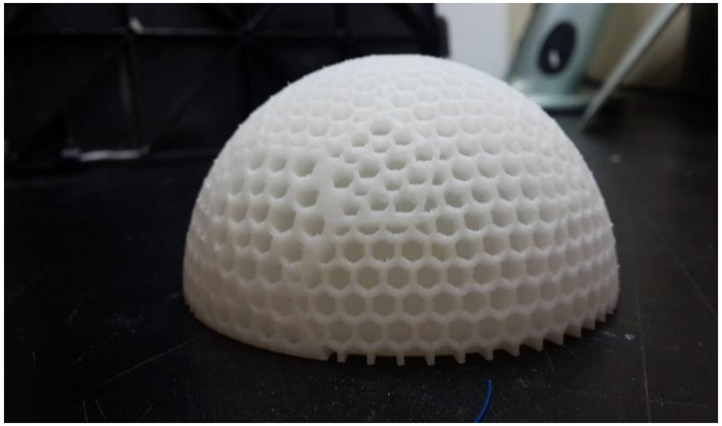
Triangular Cell



Hexagonal Cell

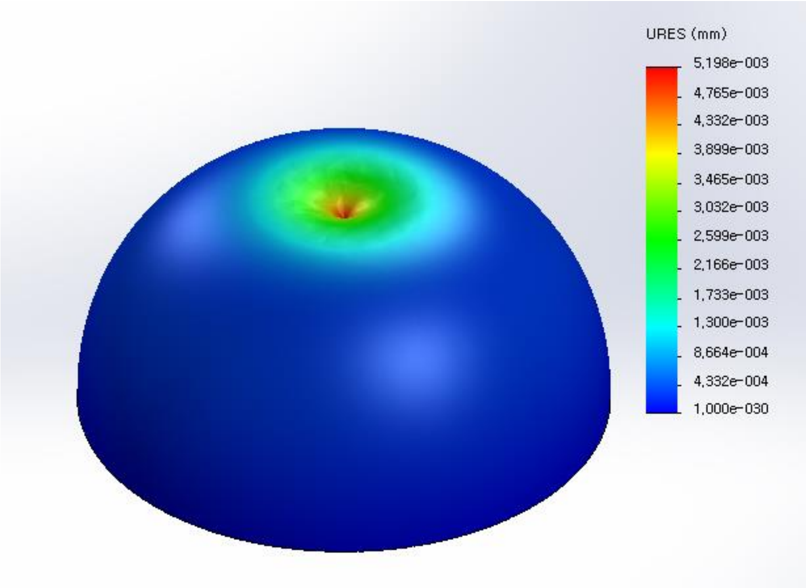
Core material

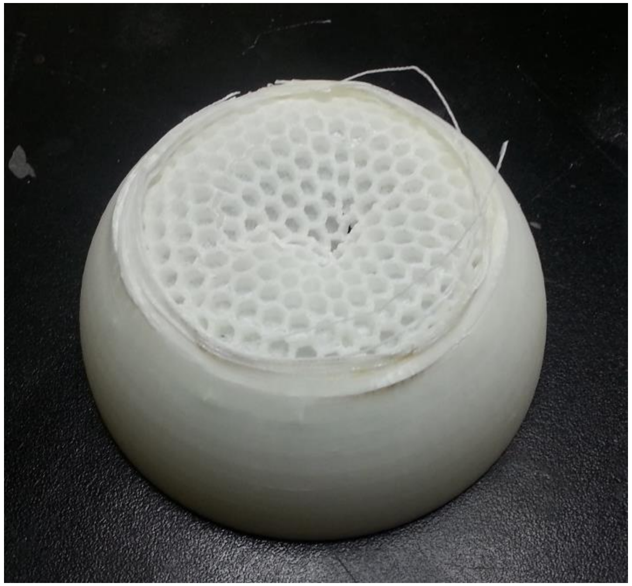
- **Honeycomb**



Core material

- **Honeycomb**
  - **Compare Theoretical Result to Experimental Result**

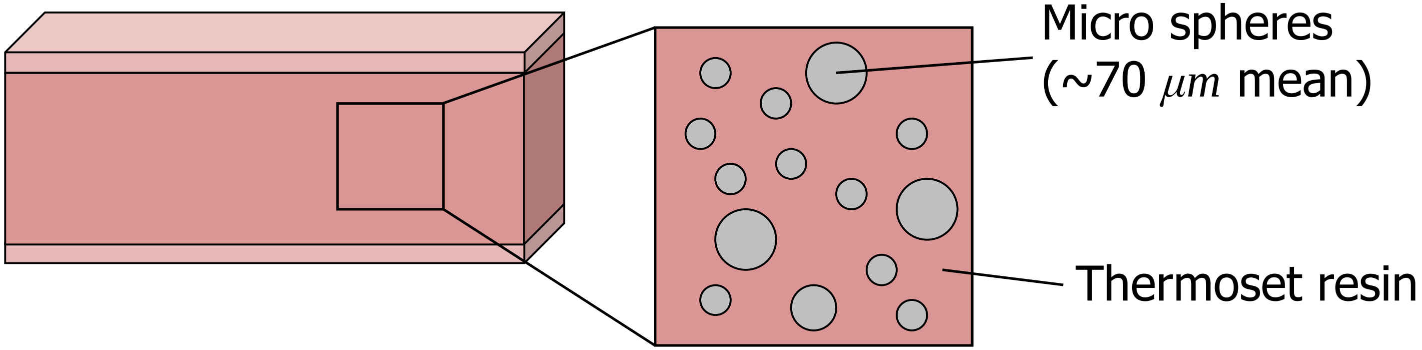




Simulation result VS Actual Test

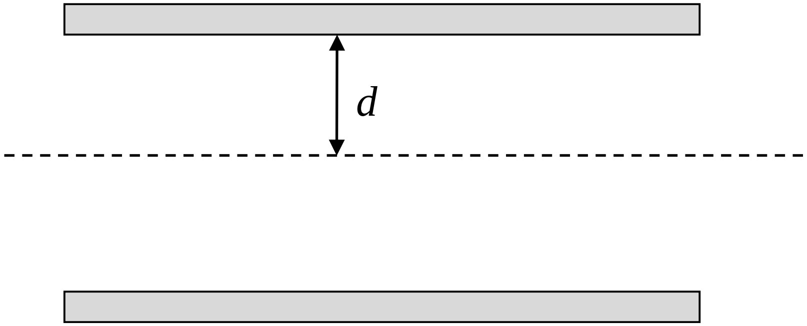
Core material

- Advantages
  - Continuous support to the face sheet
  - No moisture ingress problems
  - High compressive, transverse tensile & lateral strength



- Foam
  - Sponge-like material – resin
  - $\rho \sim (2 - 10\, lb/ft^3) \sim 2.51\, kg/m^3$

Benefit of core



$$A_{ij}' = A_{ij}$$

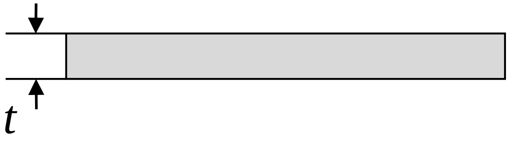
$$B_{ij}' = B_{ij} + d\,A_{ij}$$

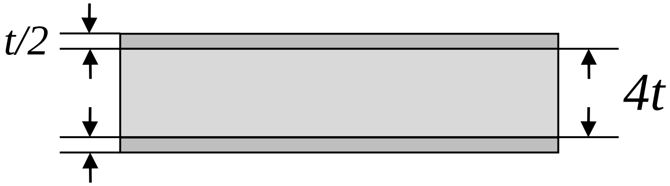
$$D_{ij}' = D_{ij} + 2d\,B_{ij} + d^2 A_{ij}$$

→ Increased bending stiffness

$$N_i' = N_i$$

$$M_i' = M_i + d\,N_i$$

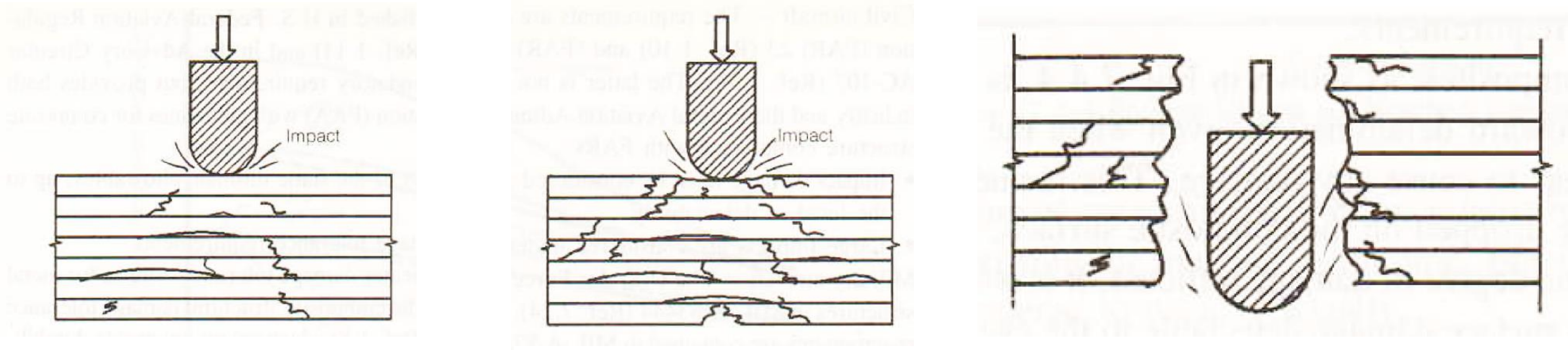




	Solid	Sandwich
Stiffness	1	37
Strength	1	9
Weight	1	1.06

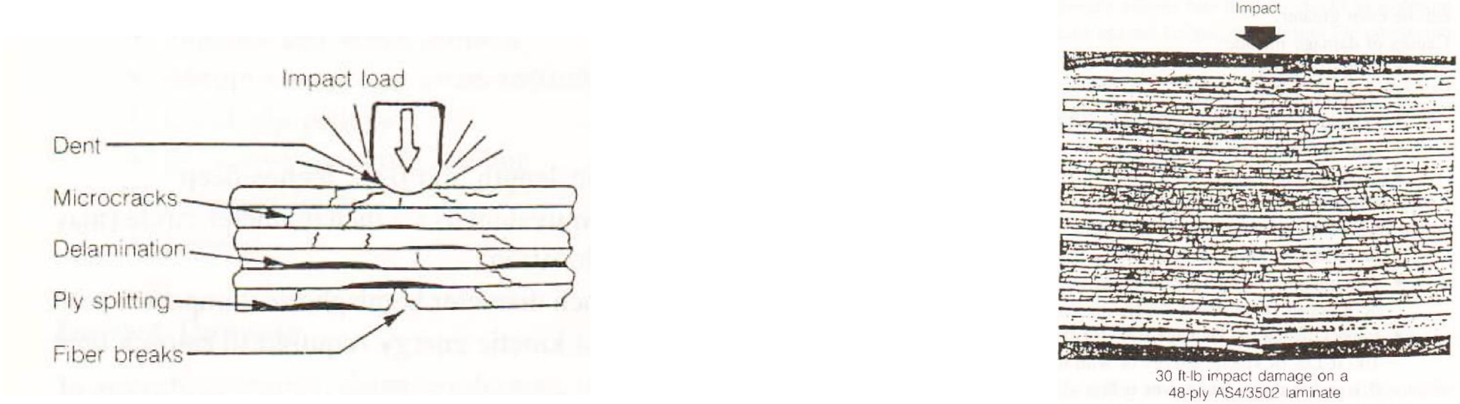
Damage type

- **Types of damage**



(a) Undetectable damage (b) Detectable damage (c) Penetration damage

- **Delamination after impact**

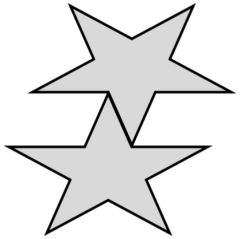


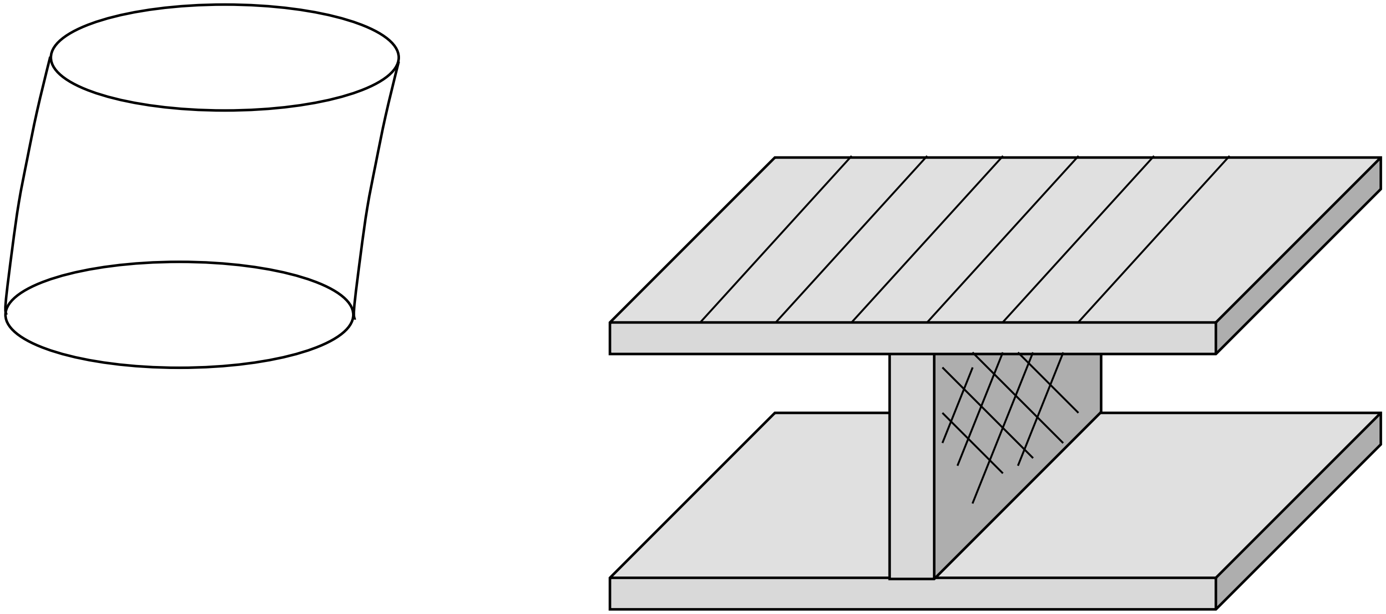
(a) Delamination and microcracks under dent

(b) Enlarged view

Issues

- **Water ingression**
- **Directional properties of cone → Starcell plate bending**
- **Space craft - perforated**





Joint

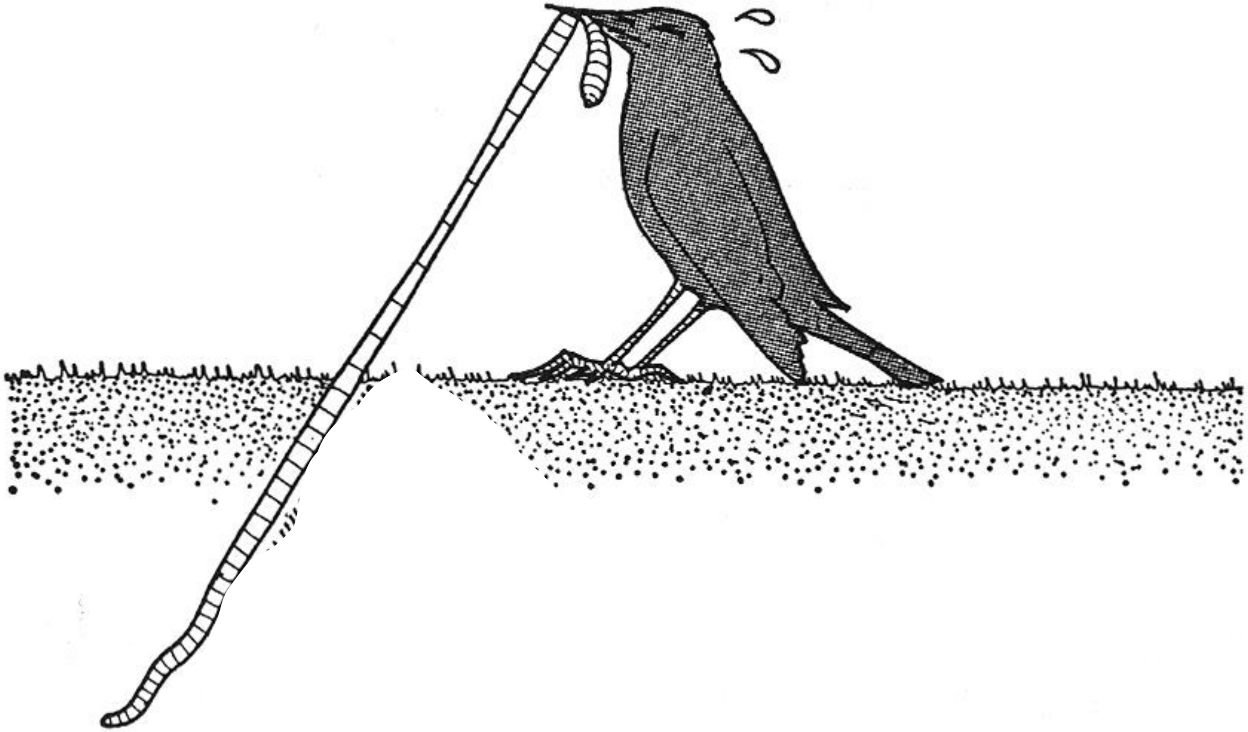
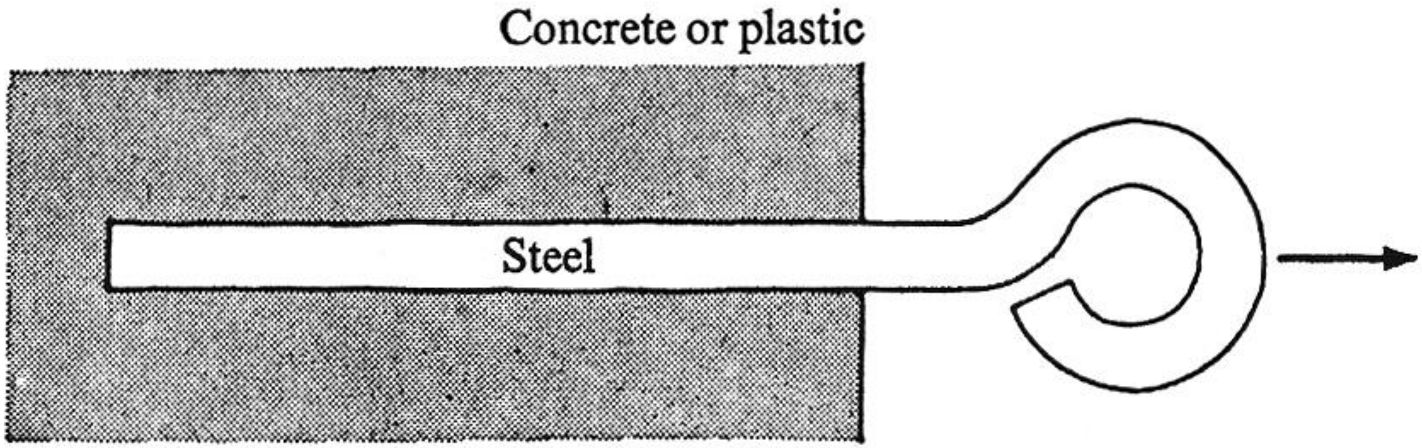


Figure 6.

Joint



Joint

- **Mechanical joint**
  - Bearing
    Shear out
    Tension
    - Reduced load carrying material
    - Stress concentration
  - Strength of joint → 20-50 % of laminate strength
  - Near optimum layup: $[0/\pm45/0]_s$ or $[0/45/90/-45]_s$

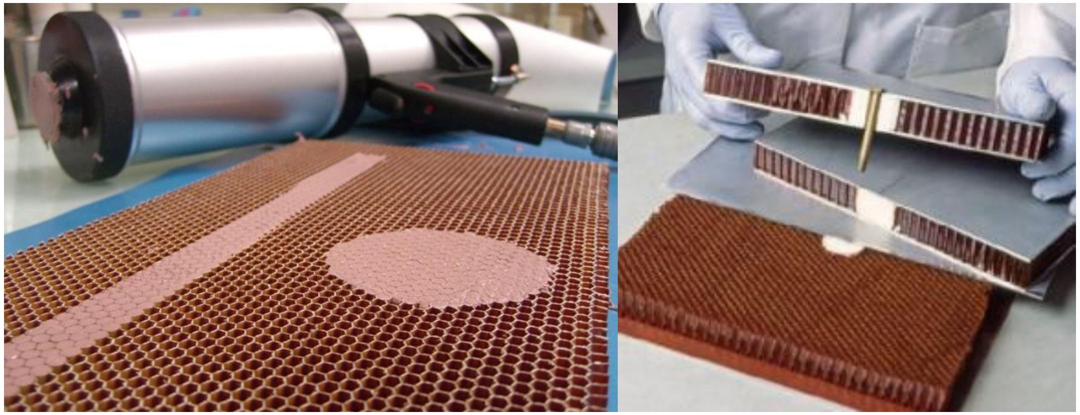
Joint

- **Adhesive bonded joint**
  - Analysis
    - Volkersen (1938)
    - Hart-Smith (1970's)

  - Load transfer by shear
  - Minimize stress concentration – scartf, and stepped joint
  - Surface treatment
  - Do not use 90 ° plies on the outer surface → use ±45 °
  - Better fatigue performance

- **Review paper by Gleich *et al.***
  - Comparison of mechanical & adhesive joints
  - *Cf.* bonded and fastened

Structural joint of Composite/Metal



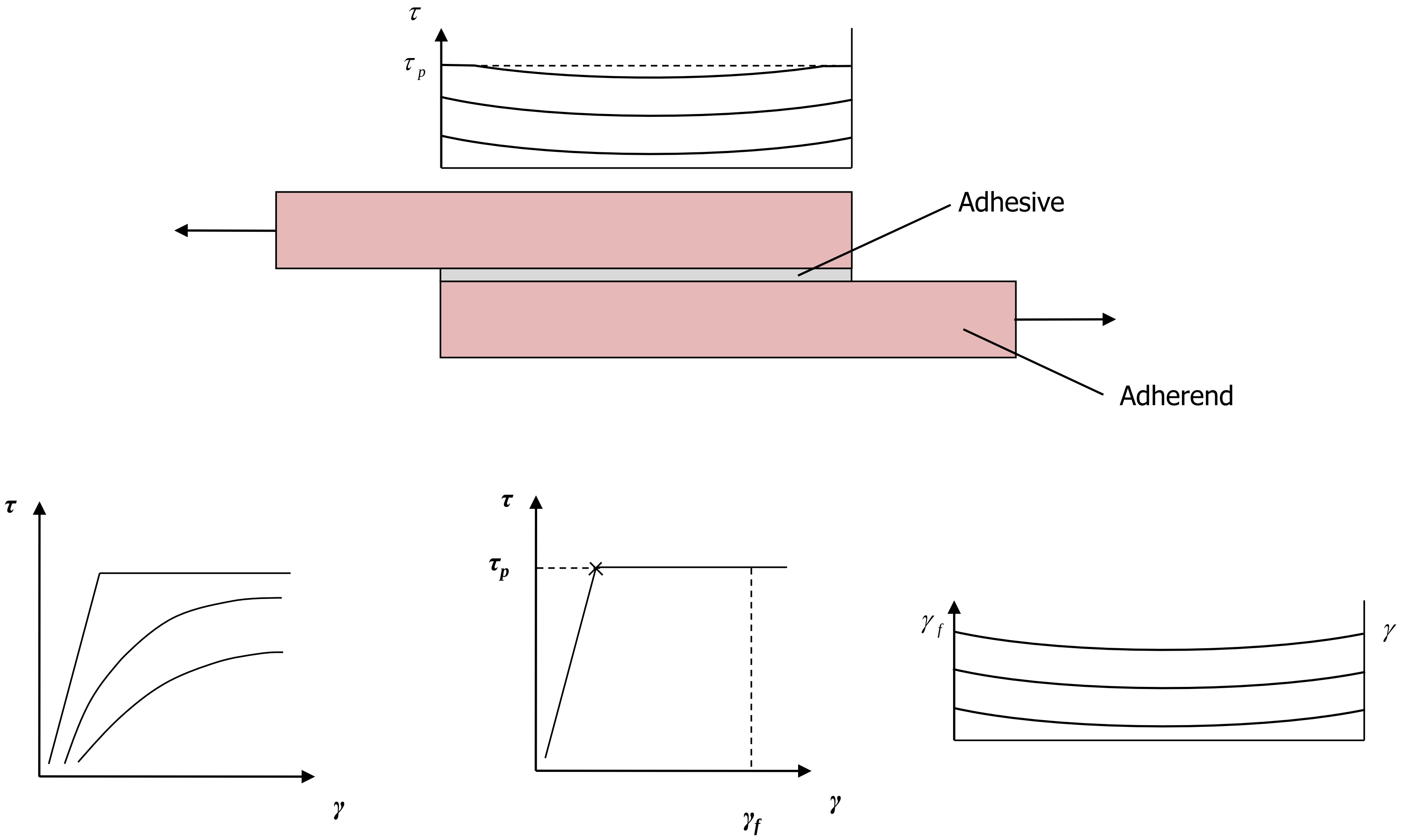
Bonding of honeycomb reinforcement

Bolt joint of metal to CFRP

Bonding different materials Al/SAF/CFRP

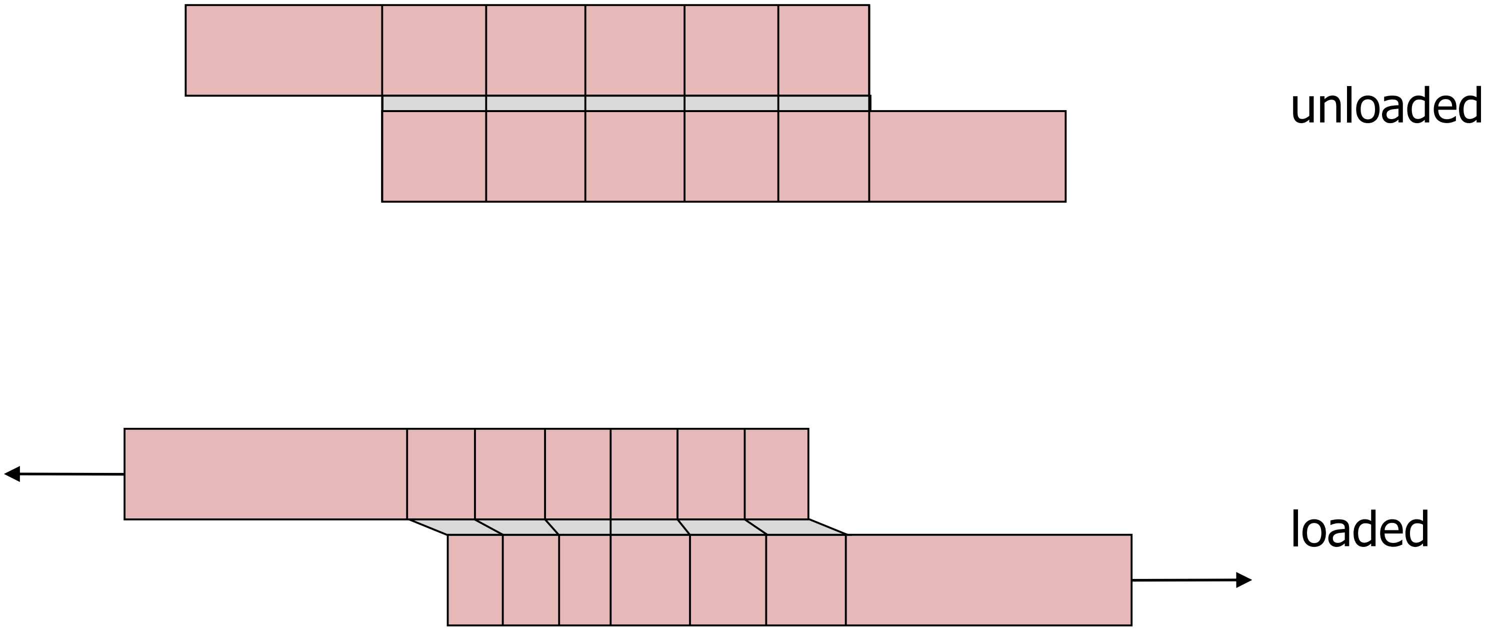
Bonding different materials
CFRP/SAF/Al honeycomb/SAF/CFRP

Stress analysis of bonded joint

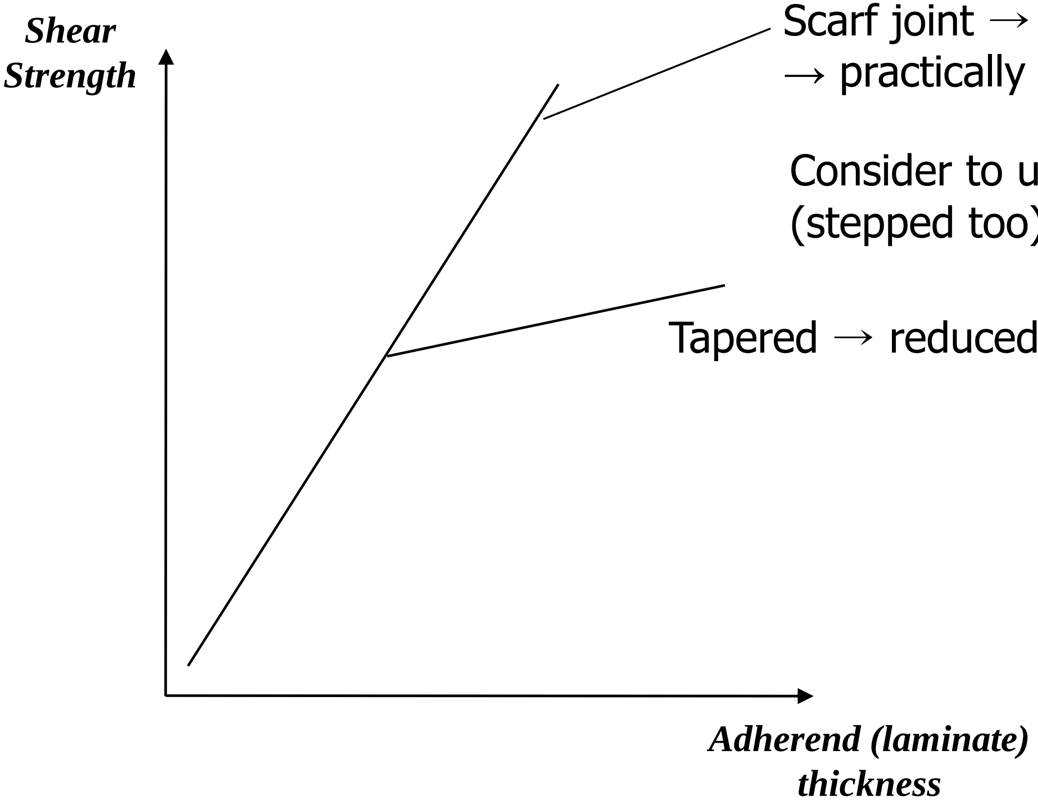


Stress analysis of bonded joint

- **In terms of displacement**



Failure modes

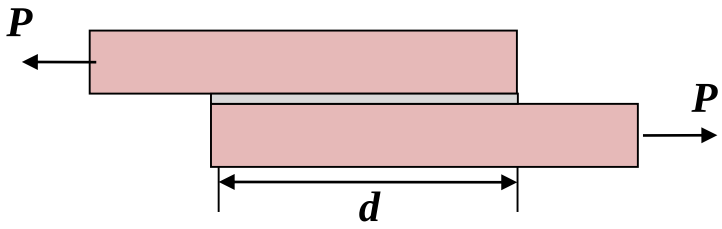


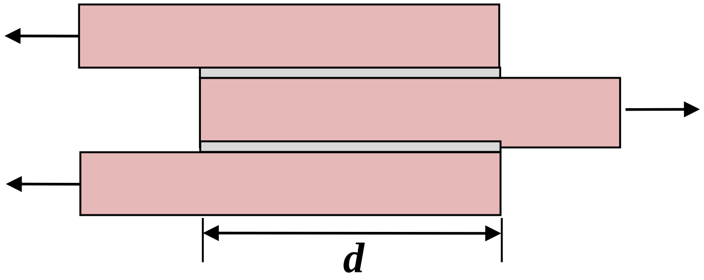
Scarf joint → could be as strong as the adherend
→ practically note

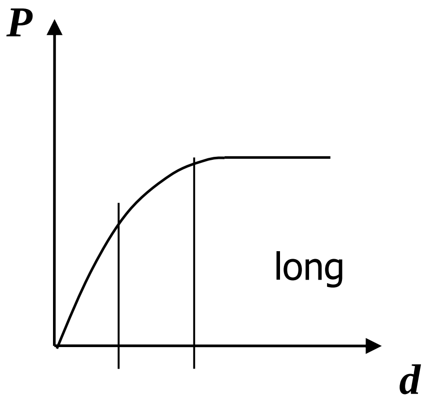
Consider to use when ***t*** > 6.35 mm
(stepped too)

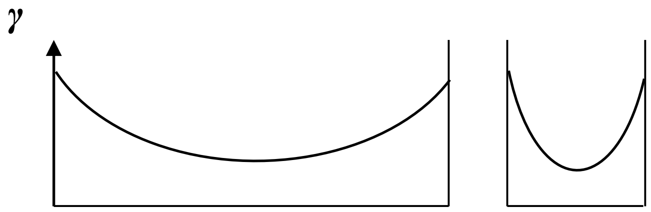
Tapered → reduced stress concentration

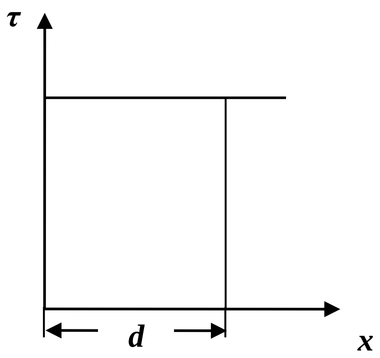
Effect of length of joint



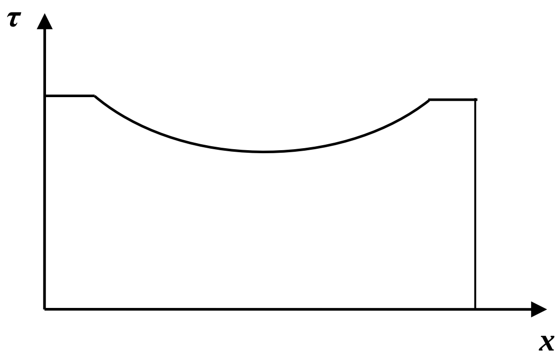








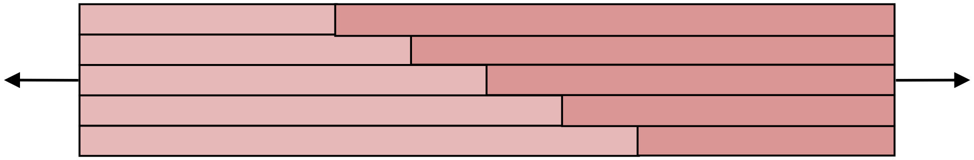
Short joint

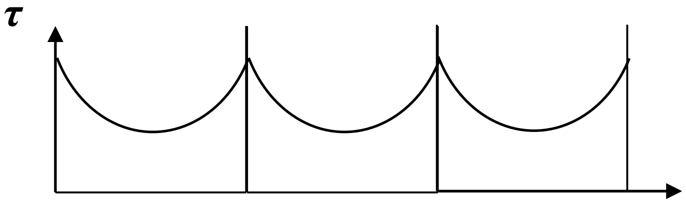


Long joint

Stepped lap joint

- **Extensively used to join CFRP & titanium**

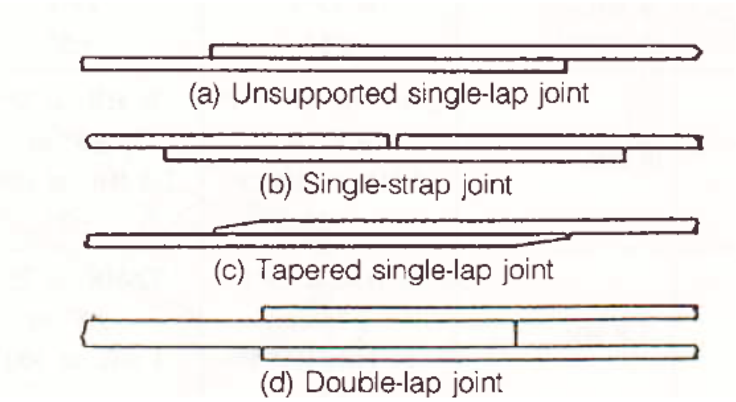




← Composite affects
stress profile

Joint and Repair

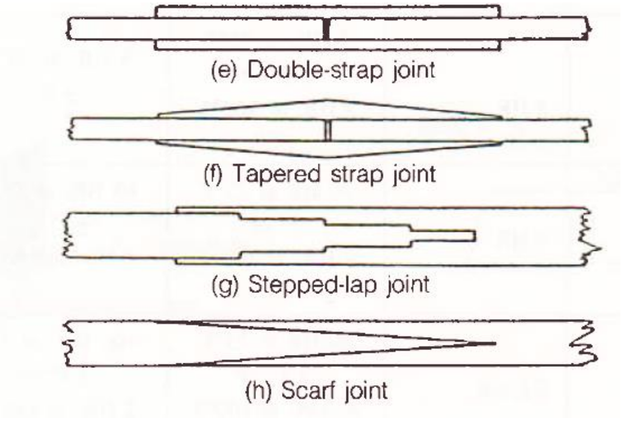
- **Joint type**


(a) Unsupported single-lap joint

(b) Single-strap joint

(c) Tapered single-lap joint

(d) Double-lap joint

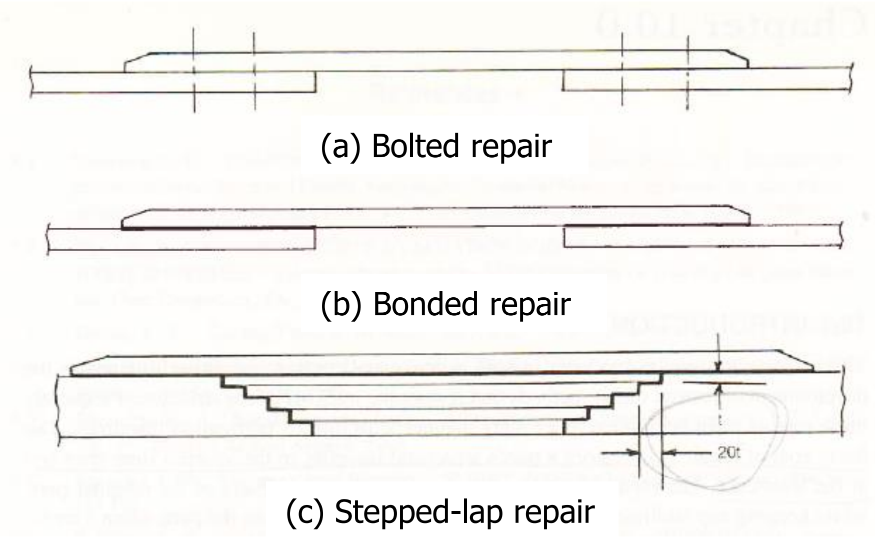

(e) Double-strap joint

(f) Tapered strap joint

(g) Stepped-lap joint

(h) Scarf joint

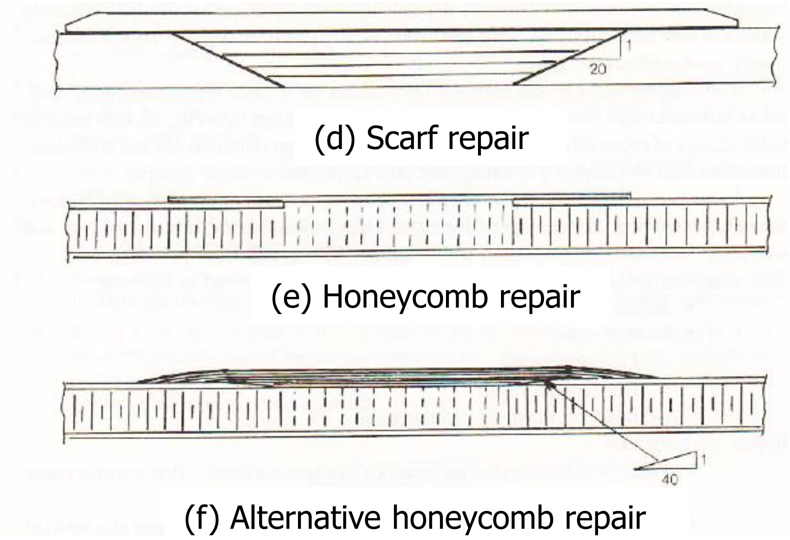
- **Repair type**



(a) Bolted repair

(b) Bonded repair

(c) Stepped-lap repair



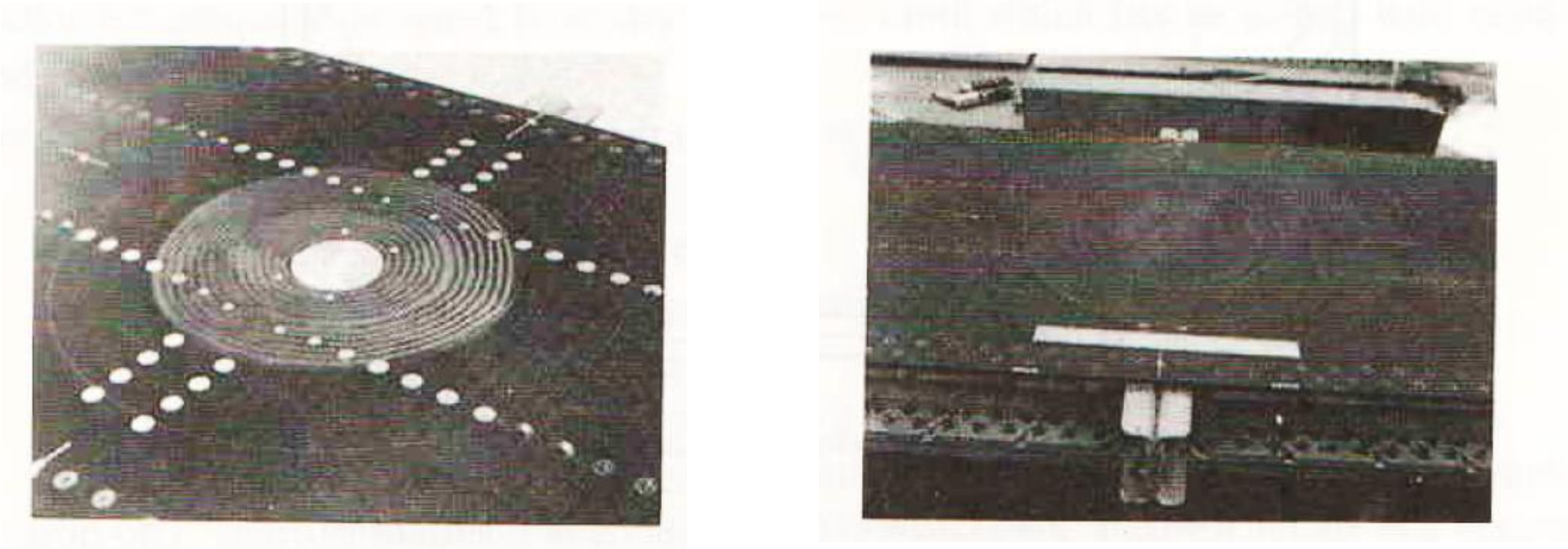
(d) Scarf repair

(e) Honeycomb repair

(f) Alternative honeycomb repair

Joint and Repair

- **Flush repair**



(a) Remove damaged material

(b) Flush repaired panel

Typical flush repair (Scarf)

Reaction-injection molding / Blow molding

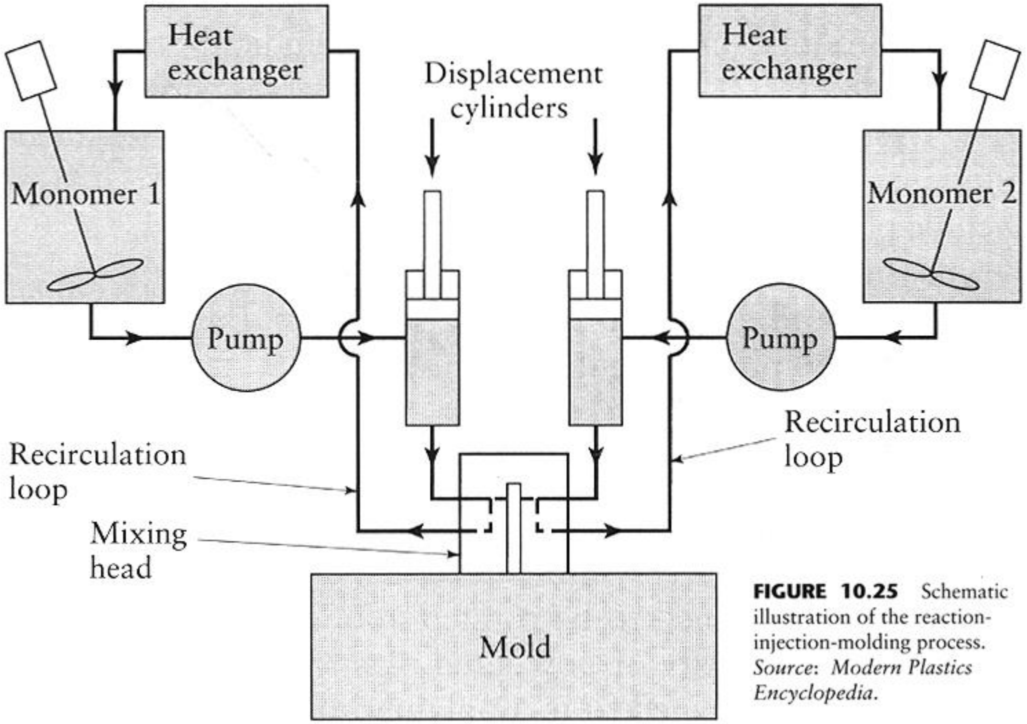
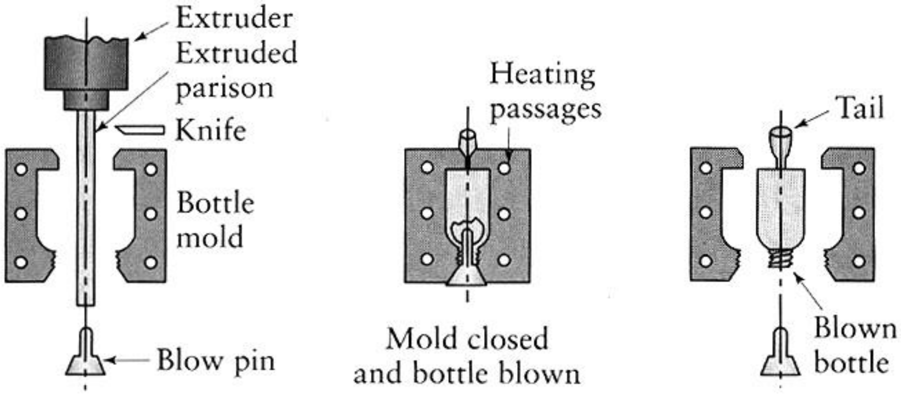


FIGURE 10.25 Schematic illustration of the reaction-injection-molding process. *Source: Modern Plastics Encyclopedia.*



Thermoforming / Compression molding

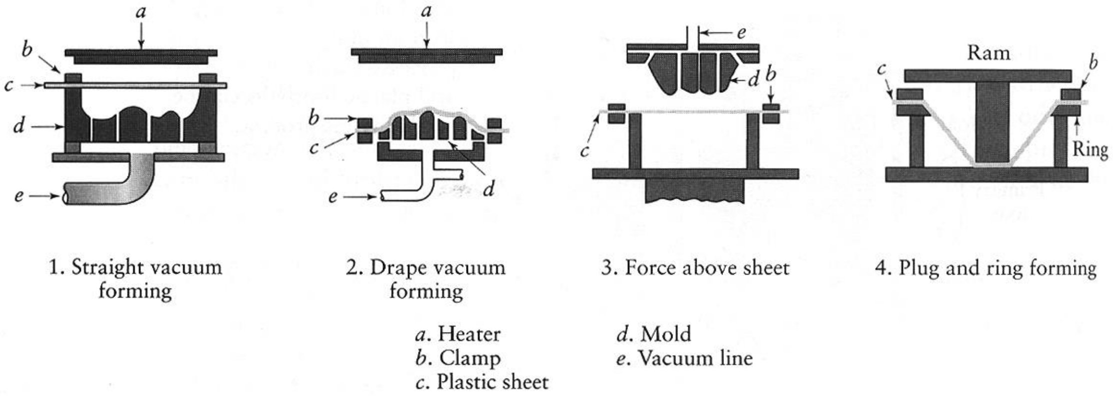


FIGURE 10.28 Various thermoforming processes for thermoplastic sheet. These processes are commonly used in making advertising signs, cookie and candy trays, panels for shower stalls, and packaging.

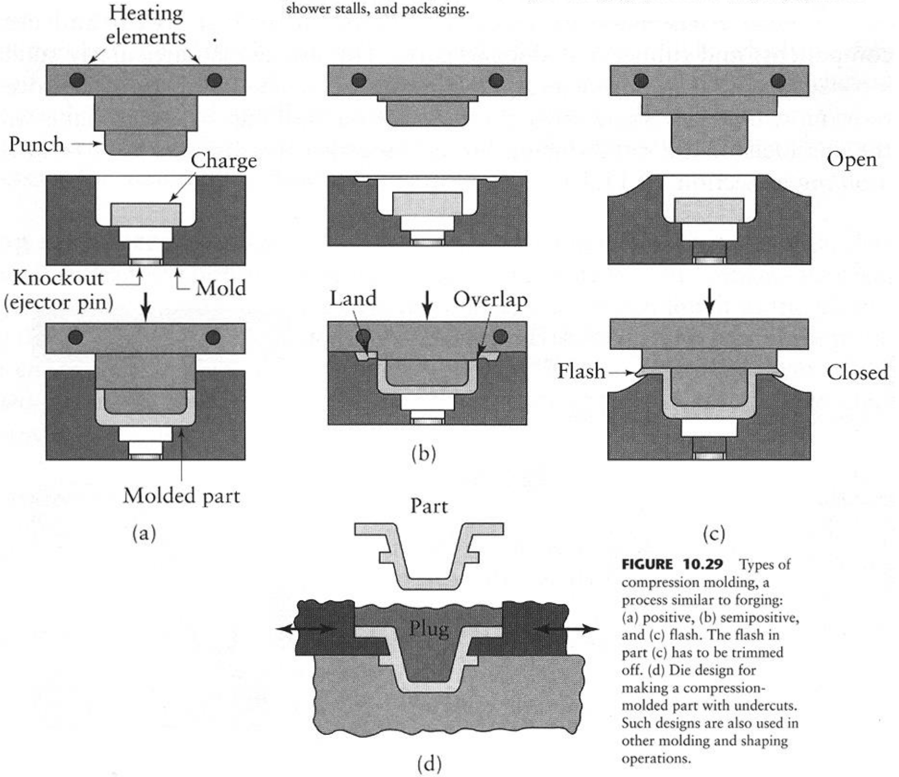


FIGURE 10.29 Types of compression molding, a process similar to forging: (a) positive, (b) semipositive, and (c) flash. The flash in part (c) has to be trimmed off. (d) Die design for making a compression-molded part with undercuts. Such designs are also used in other molding and shaping operations.

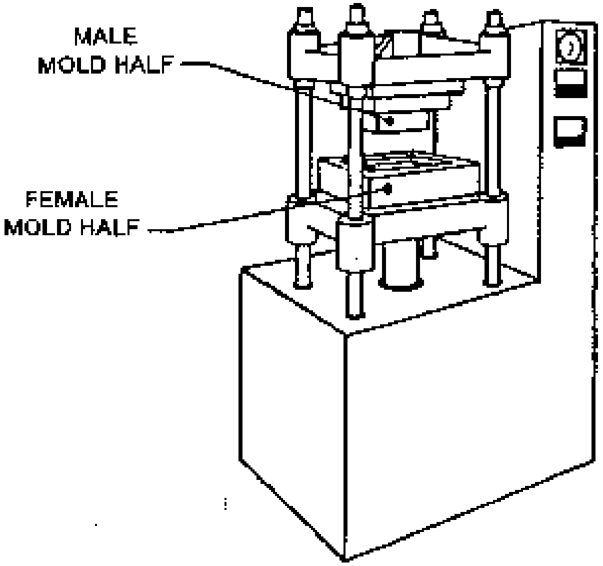


FIGURE 11 Matched-die (compression) molding.

Transfer molding / Casting

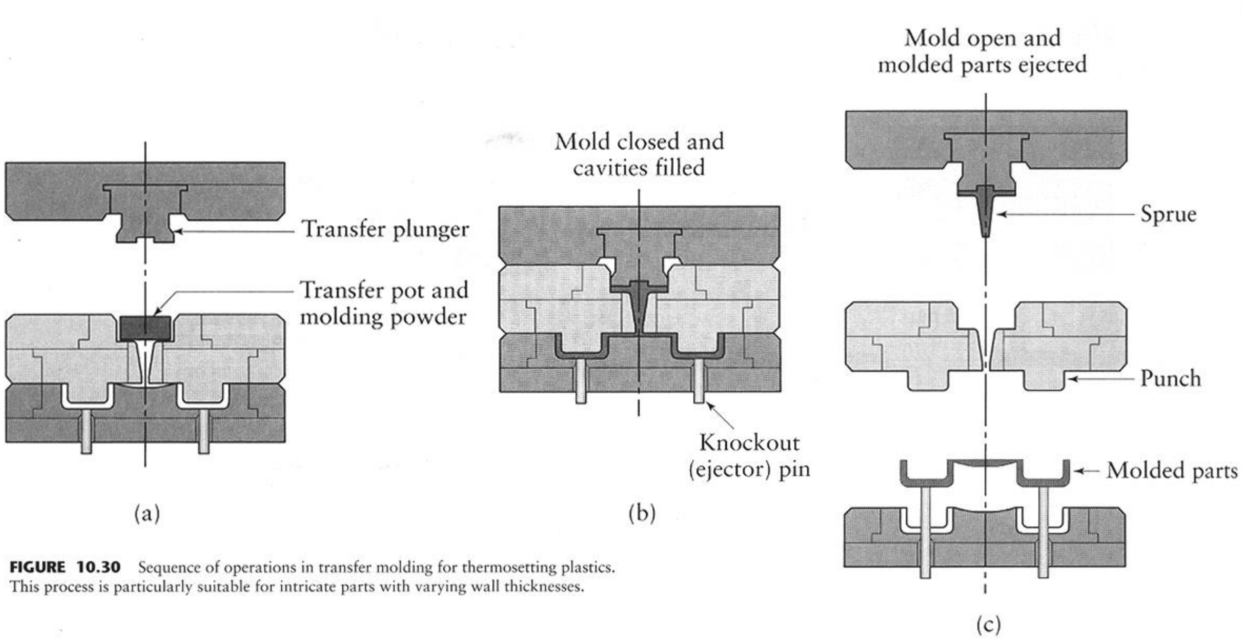


FIGURE 10.30 Sequence of operations in transfer molding for thermosetting plastics. This process is particularly suitable for intricate parts with varying wall thicknesses.

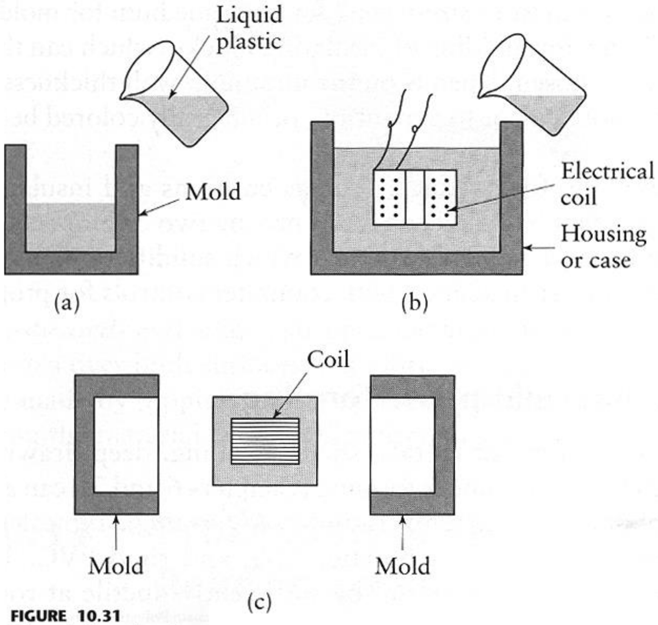
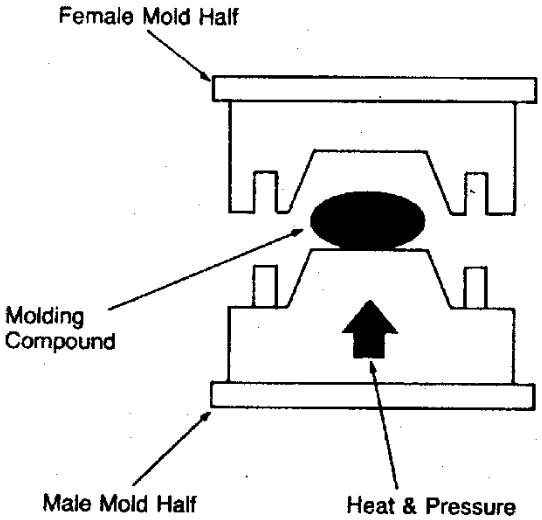


FIGURE 10.31 Schematic illustration of (a) casting, (b) potting, and (c) encapsulation of plastics.

Polymer matrix reinforced plastics

- **Prepregs**
- **Sheet-molding compound (SMC)**
- **Bulk-molding compound (BMC)**
- **Thick molding compound (TMC)**



BMC

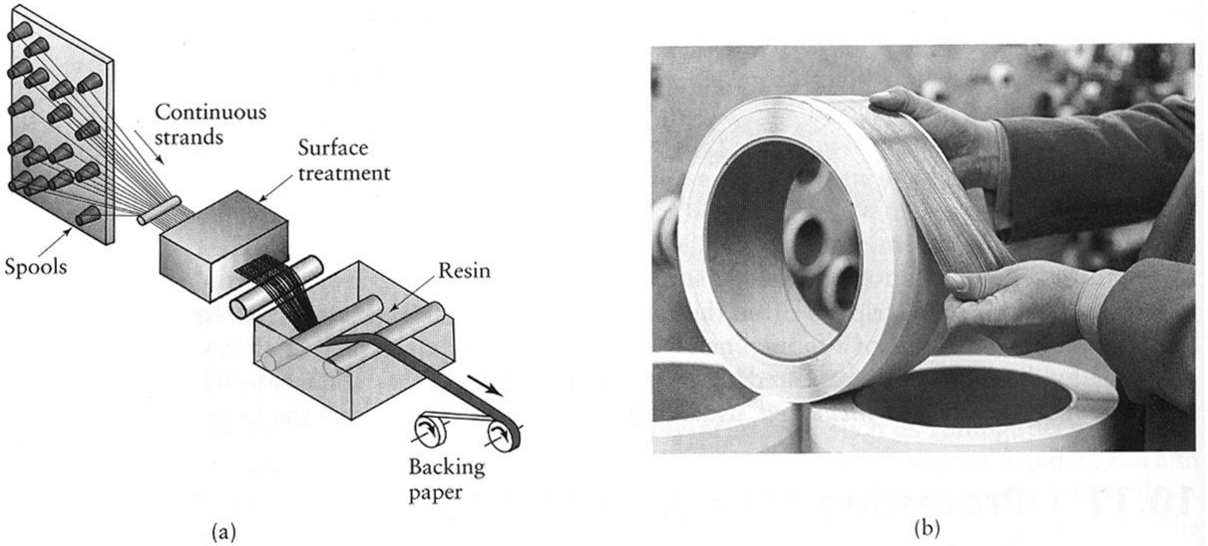


FIGURE 10.34 (a) Manufacturing process for polymer-matrix composite. *Source:* T.-W. Chou, R. L. McCullough, and R. B. Pipes. (b) Boron–epoxy prepreg tape. *Source:* Textron Systems.

Manufacturing of polymer matrix reinforced plastics

- **Molding**
  - Compression molding
  - Vacuum-bag molding
    - Autoclave
  - Contact molding
    - Hand lay-up
  - Resin transfer molding
  - Injection molding
- **Filament winding**
- **Pultrusion**

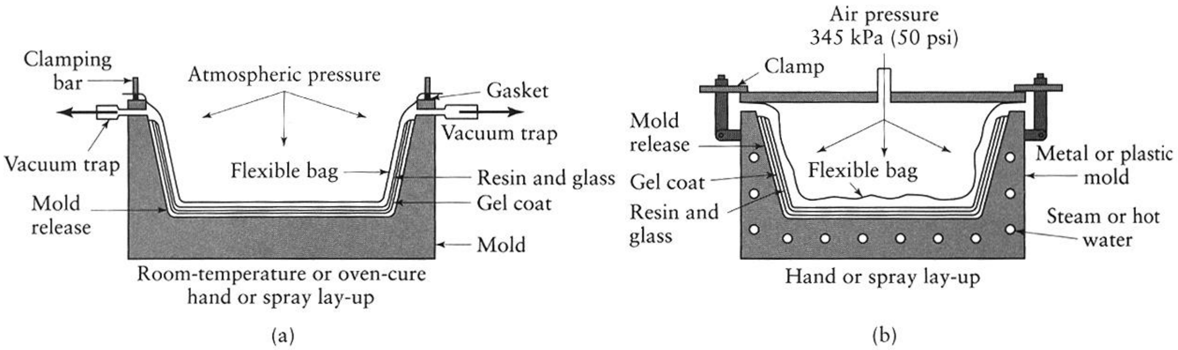
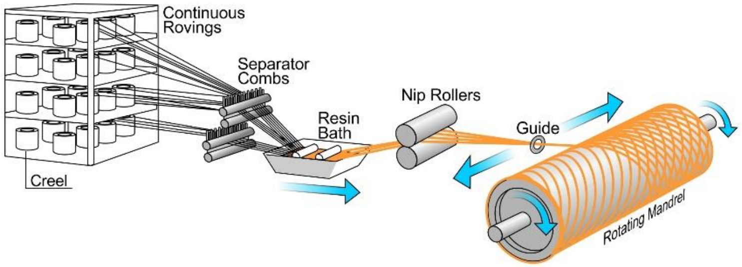
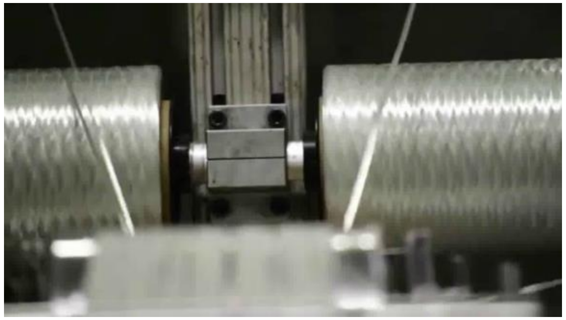
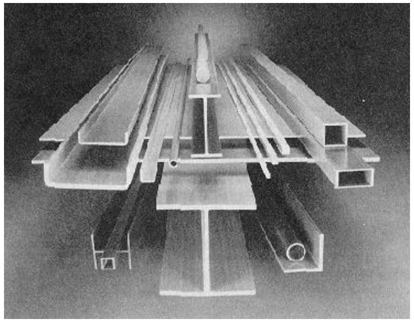


FIGURE 10.36 (a) Vacuum-bag forming. (b) Pressure-bag forming. *Source:* T. H. Meister.





Advanced Composites Inc.



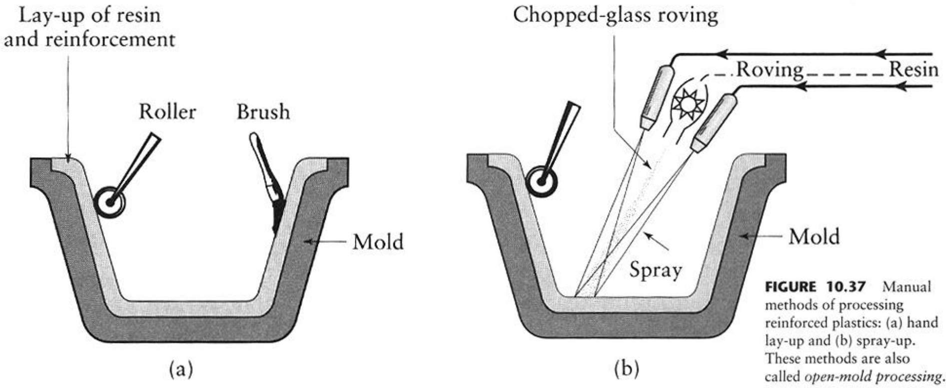
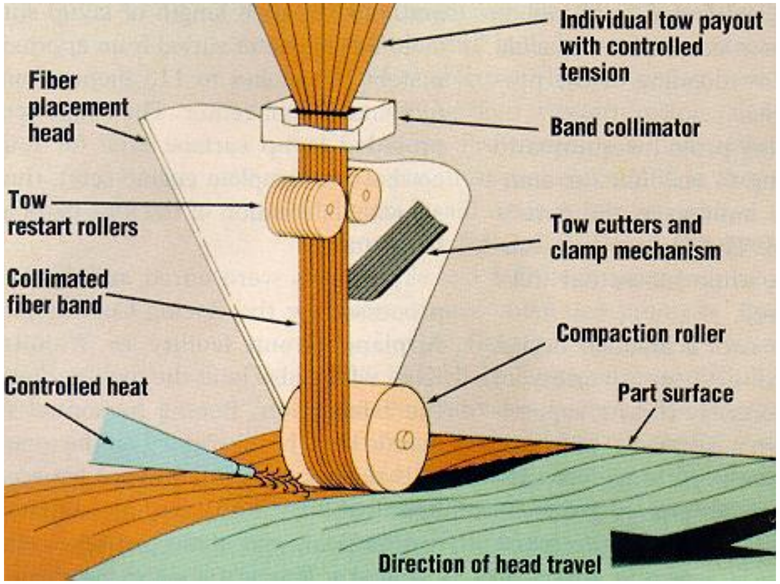
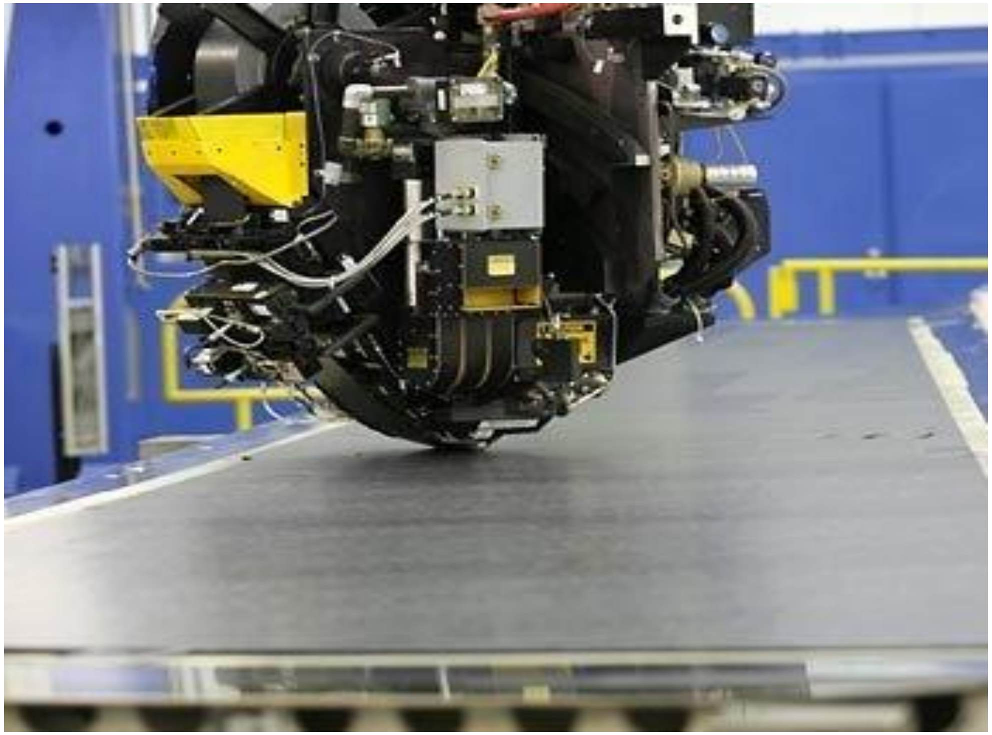


FIGURE 10.37 Manual methods of processing reinforced plastics: (a) hand lay-up and (b) spray-up. These methods are also called *open-mold processing*.

Automatic tape lay-up





Automated Composite Layup & Spray Up
https://www.youtube.com/watch?v=Dl2xVPVif0w

Vacuum bag molding / Autoclave

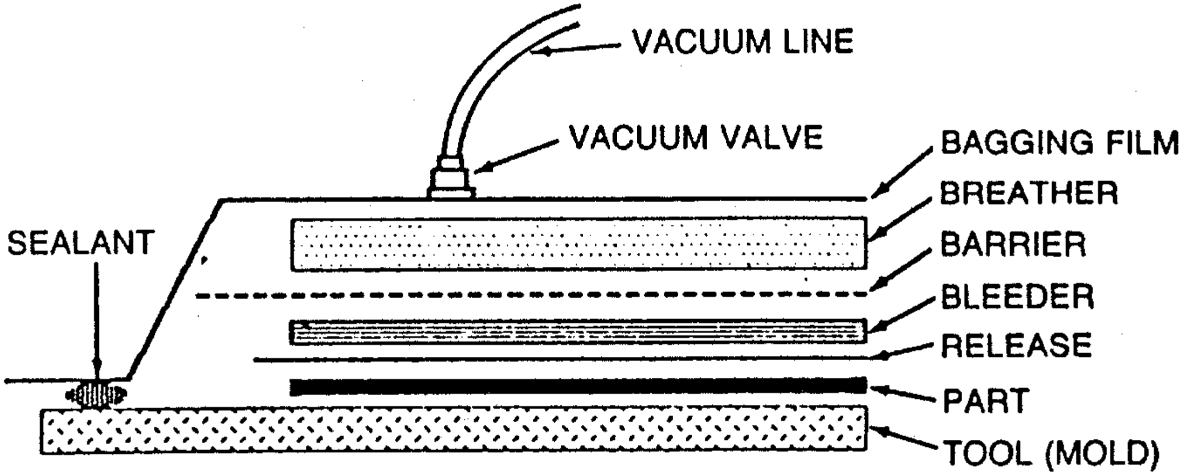
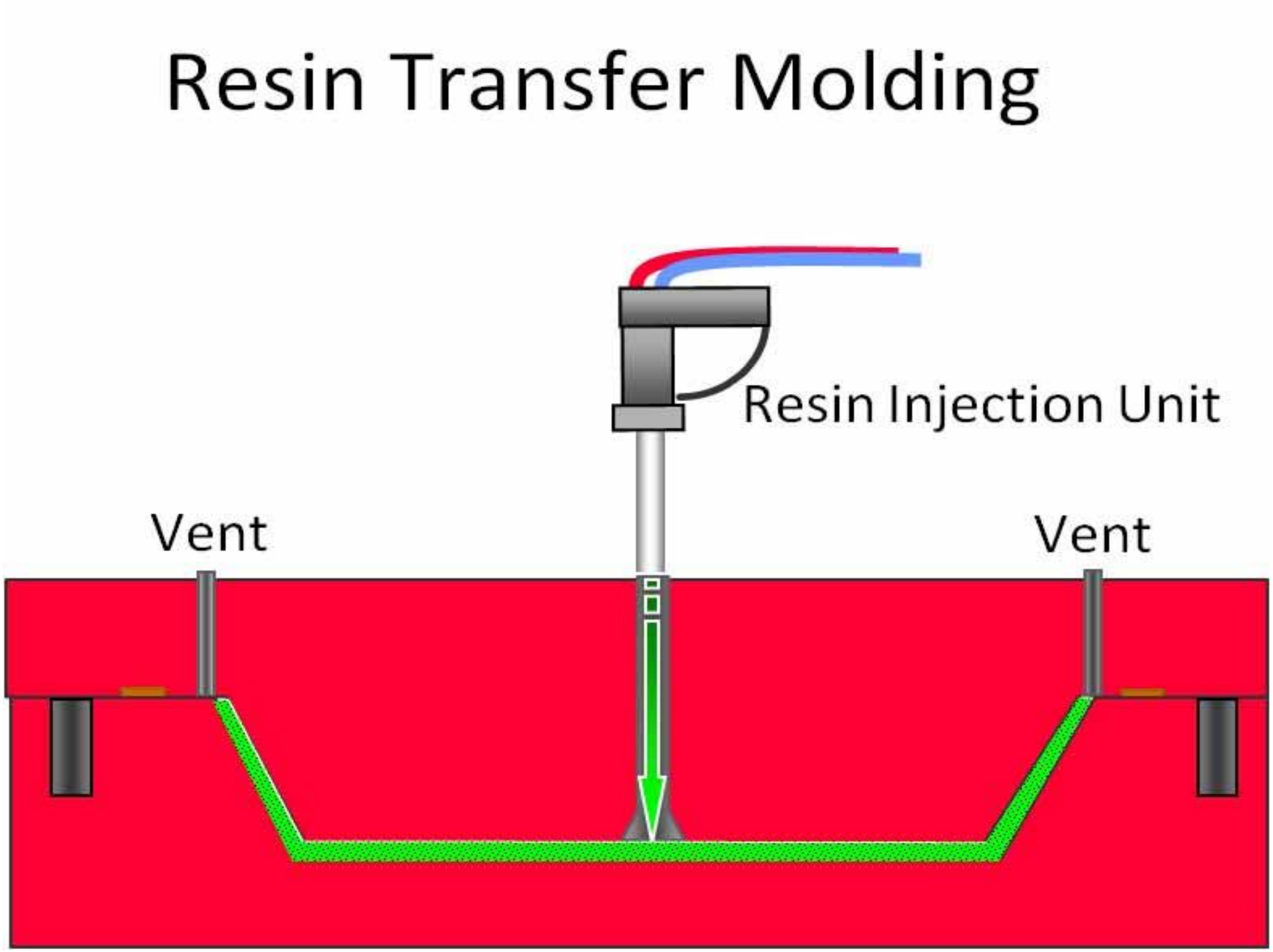


FIGURE 5 Vacuum bag assembly.

Resin transfer molding (RTM) manufacturing



Resin Transfer Moulding
https://www.youtube.com/watch?v=1u-2GvhghQA

3D-Printed electric production car

Plastic / Carbon Fiber pellets used to print 3-D Car, *Local Motors*

Roughly **75 percent** of the LM3D Swim will be 3D printed, including the body panels and chassis, using some sort of composite ABS plastic/carbon fiber material that’s yet to be finalized. Eventually, Local Motors hopes to be printing as much as 90 percent of the car.