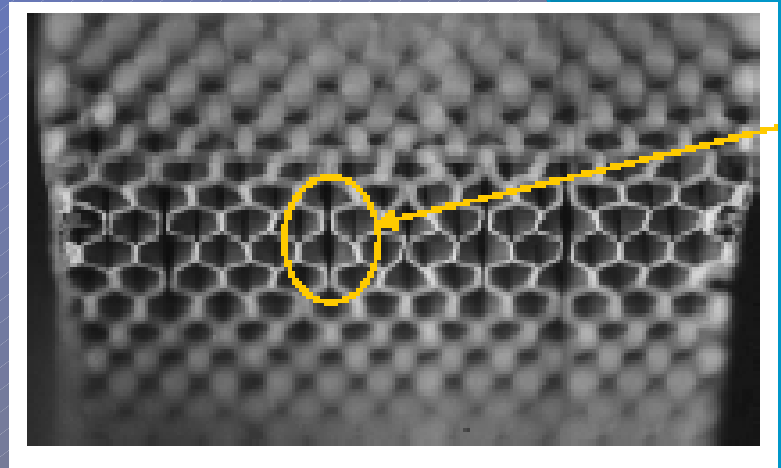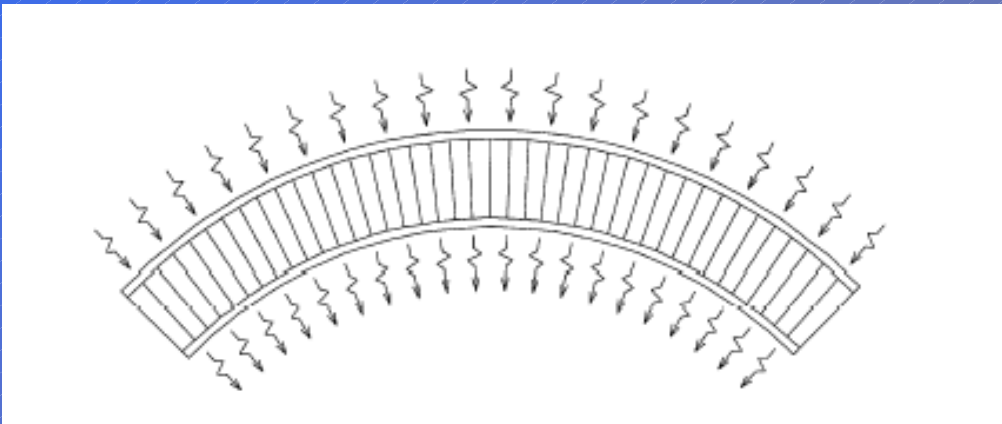# Sandwich Structures

➢ Virtually every aircraft has some sandwich structure

➢ Replaces skin stiffeners with lightweight, honeycomb core and fasteners with adhesive bonding.

➢ Permits the use of very thin airframe skin operating at high stress levels without buckling

Sandwich Structures

➢ First honeycomb core patent (Budwig Patent) ~ 1905, Germany

➢ First aircraft sandwich panel, thin mahogany facings bonded to an end-grain balsa wood core (1919)

➢ Widely adapted for primary structure in Italain seaplanes between WWI and WWII.

➢ Late 1930s hardwood facings bonded to relatively thick slice of paper honeycomb used in manufacture of furniture, Lincoln Industries, Marion, VA.

➢ 1938 plywood–cork sandwich wing monoplane was displayed at the French Salon d'Aeronautique

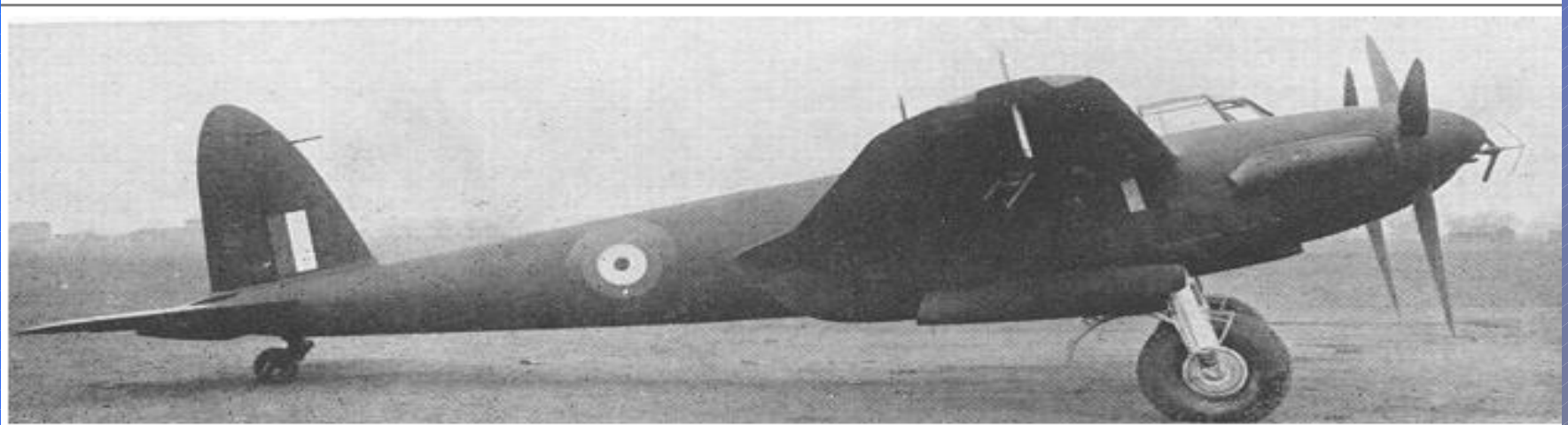➢ Similarly, de Haviiland introduces sandwich structure on the Albatross(commercial airliner.)

Sandwich Structure

De Havilland Albatross (1938) built as a commercial airliner

- ➤ plywood-balsa sandwich
- ➤ Used as a transport in the South Pacific theater WWII
  - ➤ Tropical organisms and humidity were said to have done more damage than the Japanese

De Havilland Mosquito

1938 de Havilland Mosquito bomber

  ➢ Bonded wood sandwich structure for wing panels

   ➢ Shortage of wood in prewar England

  ➢ Fuselage - sandwich of spruce veneer on balsa core with solid spruce core at attachments

  ➢ Success led to the wide acceptance, esp. in England of sandwich structure in the post war aerospace industry.

[4]Coleman, T., *Jack Northrop and The Flying Wing: The Story Behind the Stealth Bomber*, Paragon House, New York, 1988, p. 16.

Sandwich Structures

➤ Paper honeycomb used in radomes by Glen L. Martin Co. at the outbreak of WWII
  ➤ Quite successful, paper core picked up moisture
  ➤ Martin developed cores of cotton fabric, glass fabric, Al foil

➤ 1945 first all-aluminum sandwich panel was produced, made possible by the development of superior adhesives

➤ 1968 C-5 contains 35,000 ft^2 of bonded sandwich

B-36 "Peacemaker"

➢ Development begun in 1941 with the objective of bombing European targets from the Western Hemisphere.

➢ First flight, 1946

➢ Never dropped a bomb in combat

➢ Replaced by the more modern B-52 in 1958.

➢ First application of fiberglass honeycomb (Hexcel) on fuel cell support panels.

Sandwich Structure

Although described as being "robust to battle damage*,"
maintenance problems have arisen

- GD B-58 (broke 12 world speed records)
  - 'Bonded bomber' - extensively used bonded aluminum sandwich.
  - Aluminum sandwich panels - 90% wings & 80% airframe.
  - If the **B-58** had not been retired early, "it is fair to conjecture that the extreme maintenance problems with honeycomb sandwich could well have become the limiting life factor."
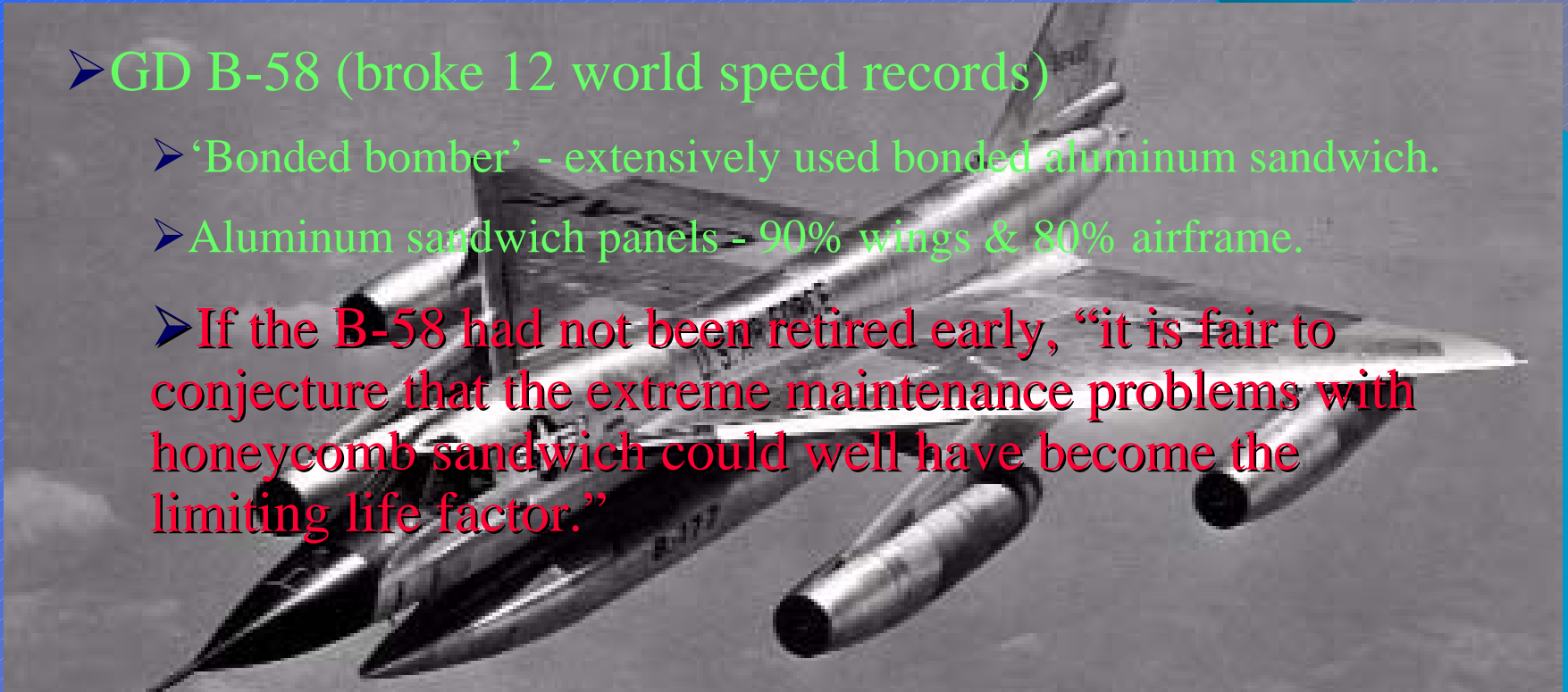
B-58 "the bonded bomber"
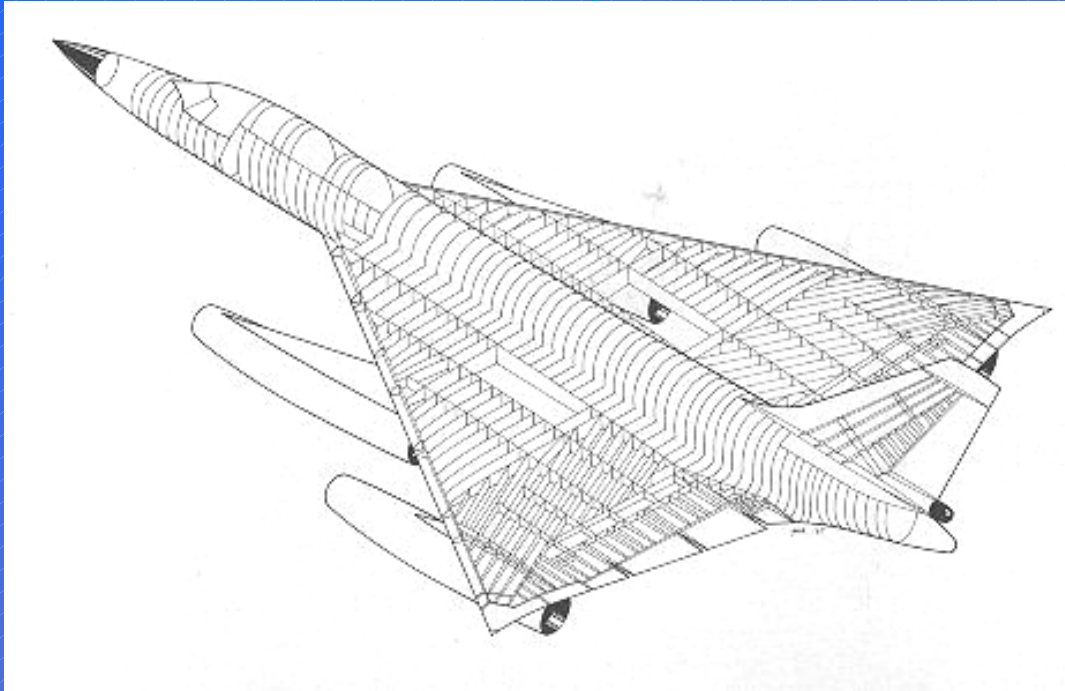
Internally, the B-58 is framed like a Navy destroyer, with transverse duralumin spars, corrugated for strength, spaced only 11 to 15 inches apart running from one wing margin through the fuselage to the opposite wing. There are no chordwise ribs, only chordwise members or bulkheads to serve as attachments for elevons, engine nacelles and landing gear. For covering the wing, Convair evolved a new material--at once stiff, strong, light, relatively easy to replace, and with good thermal-insulating qualities--the so-called bonded sandwich panel. The top and bottom of the sandwich are sheets of duralumin alloy about 1 mm. thick; the half-inch-thick filling consists of tiny honeycombs of either phenolic resin-fiberglass cloth, or less commonly, of very light gauge duralumin. The core is bonded to the duralumin outer layers with phenolic adhesives and cured at a pressure of 175 p.s.i. at 350 degrees F. for two hours. Absolute cleanliness is essential for solid bonding, and the department of the Convair plant where this was done was known as the "hospital section." The panel is then attached to the wing structure with titanium screws. Because it is absolutely impossible to bend or deform a cured sandwich panel, those with curved surfaces have to be set up in a jig before bonding. Fuselage structure panels are reinforced with beaded inner skins bonded to the outer skins. In a few areas exposed to high temperatures, such as the after portion of jet engine nacelles and the elevons which dip into the blast of the inboard jet units, panels of brazed stainless steel sandwich replace the duralumin and fiberglass ones.

B-70 Valkyrie

➢ Fabricated using titanium and brazed stainless steel "honeycomb" materials to withstand the heating during the sustained high Mach number portions of the flights

➢ The technology that made Mach 3 possible yielded an airframe with a large RCS that added to the effectiveness of SAMs against the XB-70

➢ Two XB-70 prototypes were built, with the first flight in 1964, the program terminated in 1969.

➢ The XB-70 had speed, range, and adequate payload, but it was expensive, not suited to low level penetration, and thus did not compete with ICBMs for strategic funds.
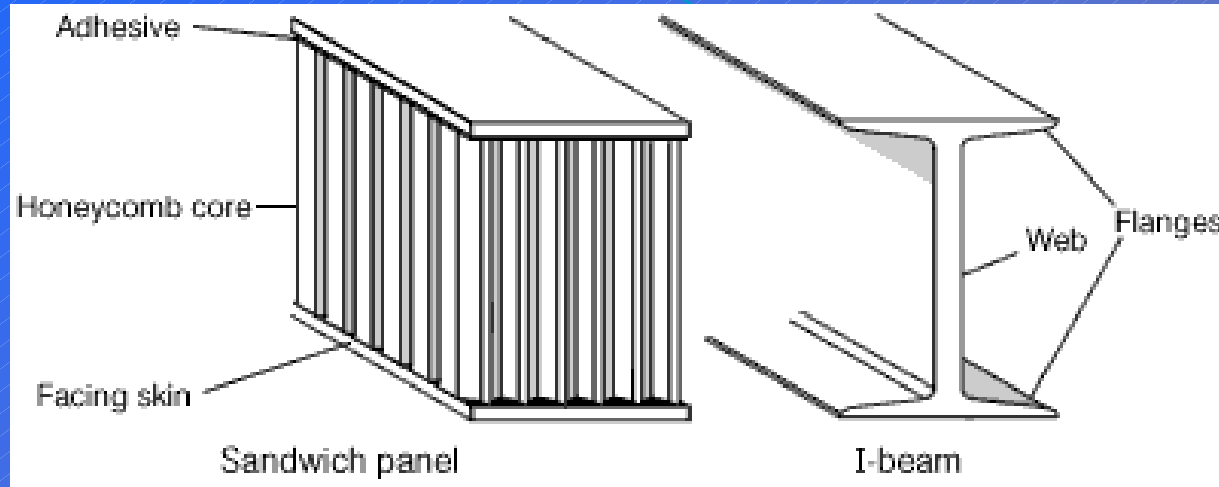
C-5 Galaxy
(1970)

➢ The C-5 Galaxy contains 35,000 ft^2 of bonded sandwich materials.

Sandwich Construction

- The **facing skins** of a sandwich panel can be compared to the **flanges** of an I-beam, as **they carry the bending stresses** to which the beam is subjected. With only one facing skin in compression, the other is in tension.

- Similarly the honeycomb **core** corresponds to the **web** of the I-beam. The core resists the **shear loads**, **increases the stiffness** of the structure by holding the facing skins apart, and improving the I-beam, it **gives continuous support** to the flanges or facing skins to produce a uniformly stiffened panel.

- The core-skin adhesive rigidly joins the sandwich components and allows them to act as one unit with a high torsional and bending rigidity.
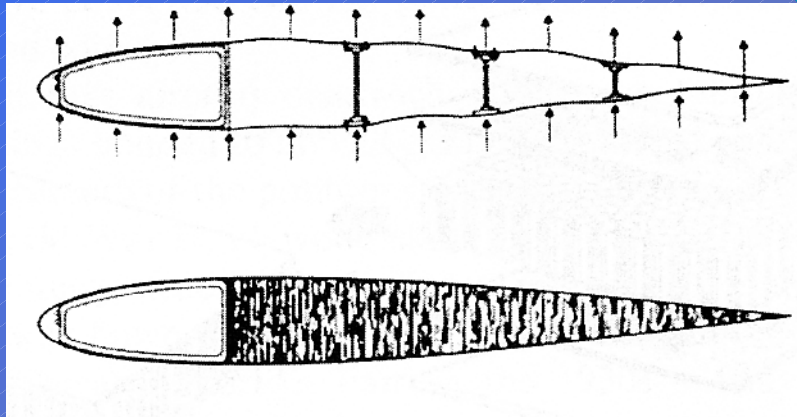
Why Sandwich Structure?

➤ To save weight

| | | t | | $2t$ | | $4t$ | |

Solid material   Core thickness = t Core thickness = $3t$
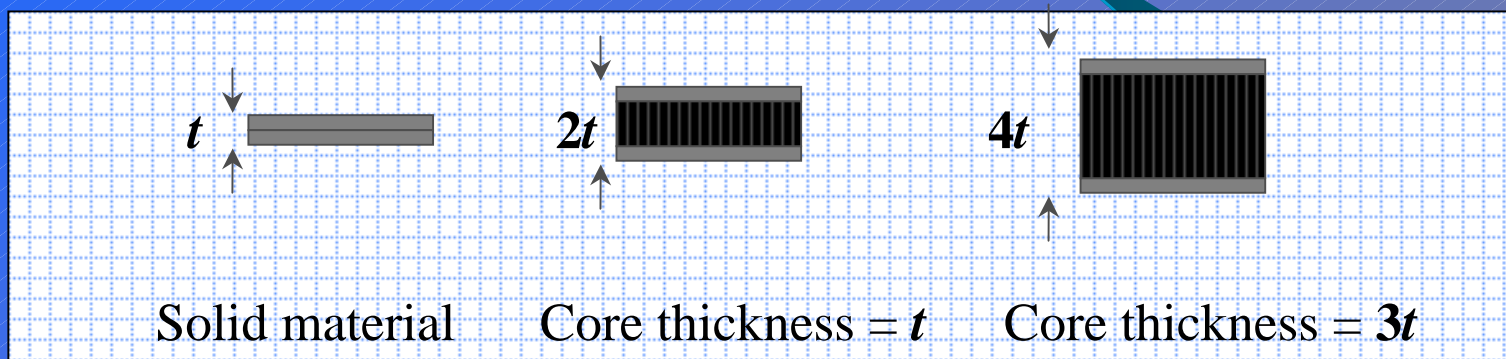
Stiffness	1.0	7.0	37.0
Flexural Strength	1.0	3.5	9.2
Weight	1.0	1.03	1.06

Why Sandwich Construction?

➢ Smooth skins (even under applied load)

➢ Excellent fatigue resistance ~ four orders of magnitude, depending on frequency

   ➢ No rivets (stress risers)

   ➢ The most critical part of a sandwich structure in regard to its fatigue characteristics is at its attachment points (usu. fail at these points.)

Face sheets (skins)

➢ Can be laminated <u>composites</u>, <u>metallic</u>, even <u>wood veneer</u>

➢ Responsible for load carrying capability

 ➢ Facings (or skins) take all the bending stresses

Core materials

➤ Core carries the shear load

➤ Foam core

  ➤ Polystyrene (styrofoam) ~ 2 pcf (also 4 pcf)

    ➤ Soluble in styrene monomer (found in polyester and vinylester resins)

    ➤ Badly softened by gasoline

  ➤ Polyurethane (Last-A-Foam) ~ 2.5-20 pcf

    ➤ All PU foams very flammable, except Last-A-Foam

    ➤ PU foams extremely fragile and somewhat unreliable @ densities < 4 pcf
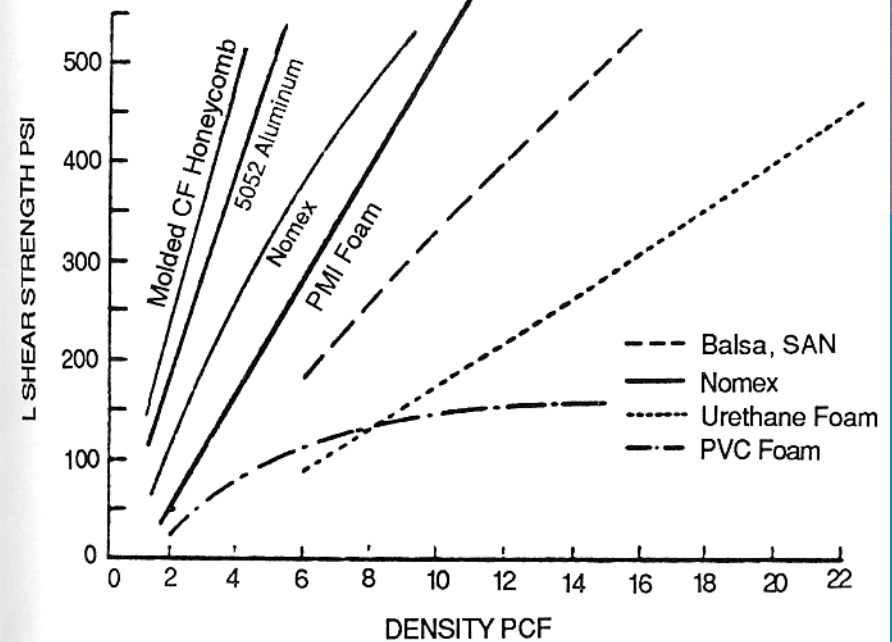
Core materials

- Foam core (cont.)
  - PVC
    - Klegecell (Italy)
    - Divinylcell (Sweden by way of Germany, even Texas)
    - Airex (Switzerland), esp. popular in boat hull applications
    - Less solvent resistance than PU foams
    - Surprisingly good strength down to 2.5 pcf
      - Better than PU for $\rho < 6$ pcf
      - PU better for $\rho > 6$ pcf
  - Polymethacrylimide (Rohacell) ~ available down to 1.9 pcf
    - Mechanical properties >> PU and PVC
    - Resistant to nearly all solvents and chemicals
    - Retains structural properties up to 250°F
    - Cost is higher than other foam core materials
    - Only foam core material at all competitive w/ Nomex honeycomb in commercial aircraft applications
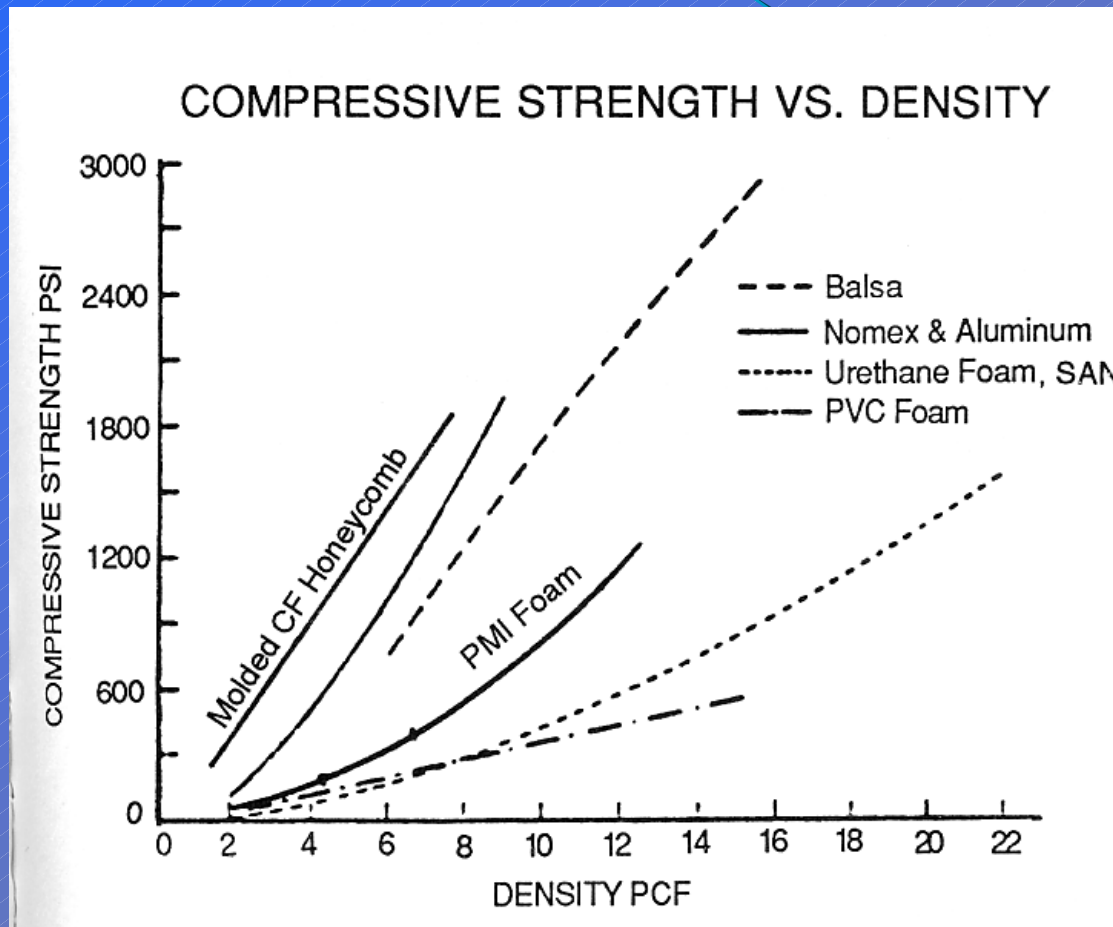
Core materials

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Core materials

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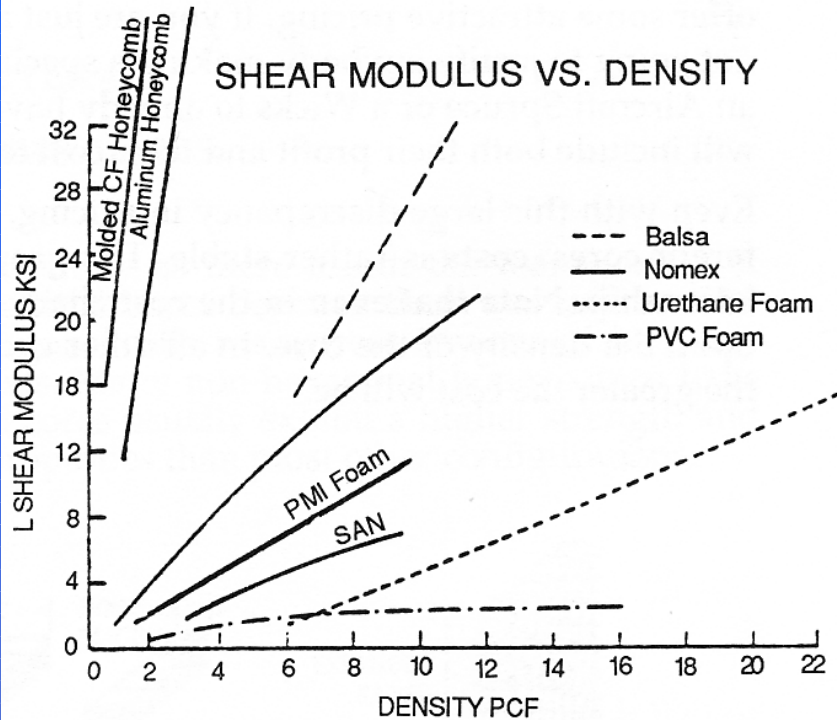
Core materials

- Metallic cores fail by shear buckling and diagonal tension cracking of the cell walls
  - Brittle foils tend to fail by cracking (poor in fatigue)
  - Perforations tend to promote fatigue cracks and premature failure
- Non-metallic cores may fail by spalling of resin from the web material, leaving web material unsupported, or may fail in normal shear buckling mode.

Core materials

➢Decrease cell size ➔ increase fatigue strength

➢Decrease core density ➔ decrease fatigue strength

➢Core thickness > 1 in. ➔ fatigue strength decreases slightly

Core materials
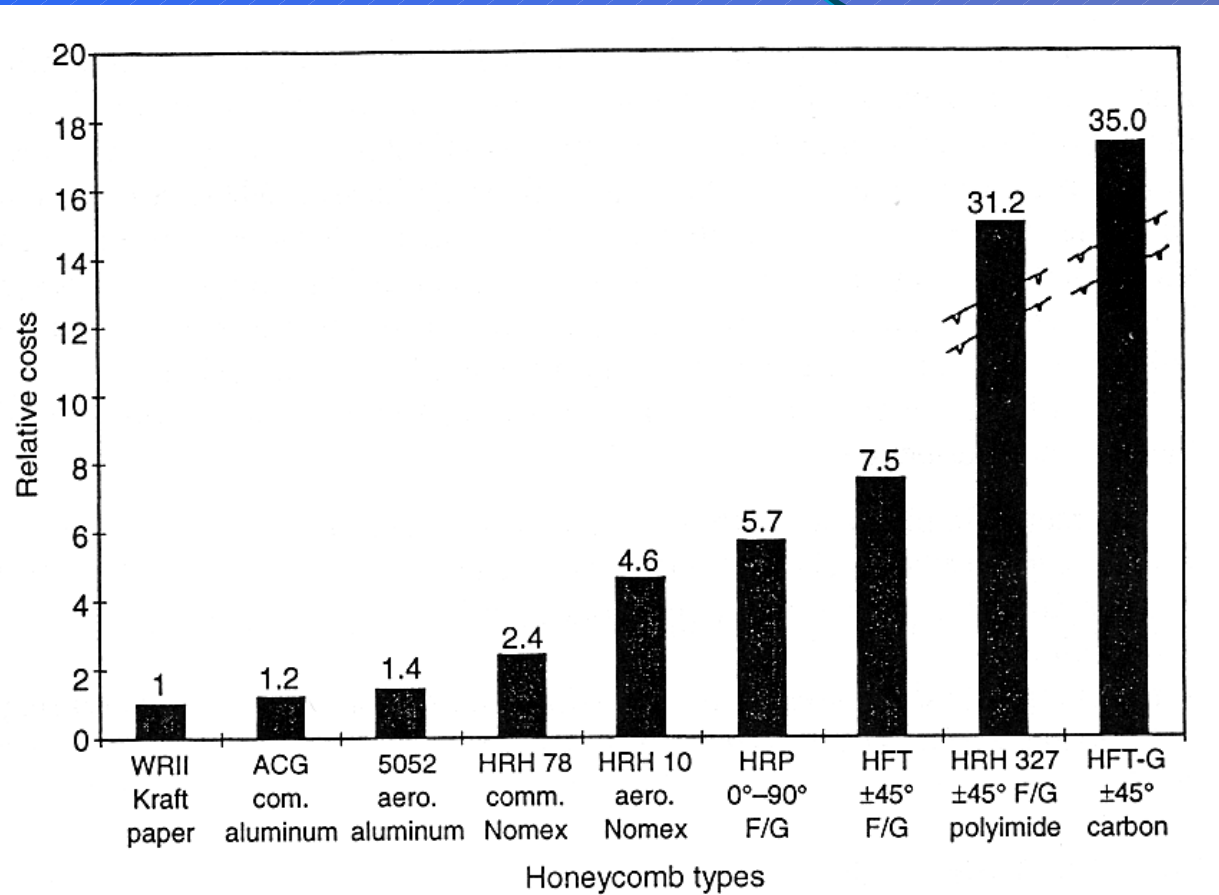
Hexcel CR-PAA

CR-PAA is a <u>phosphoric acid anodized aluminum</u> honeycomb designed for <u>aircraft structures</u> that are exposed to demanding environmental conditions.

➢ CR-PAA delivers:
- Superior corrosion protection compared to standard aluminum cores
- Enhanced bond strength and durability
- Improved bonded-assembly part life—and, therefore, lower life cycle costs

➢ CR-PAA has superior corrosion protection over standard aluminum cores and outperforms standard MIL-C-7438 core in tests, including:
- Acidified salt spray testing
- Wedge crack propagation testing
- Bond strength peel testing

➢ CR-PAA's superior long-term bonding in hot/wet environments is due to the exceptional quality of the bond between the face sheets that carry bending loads and the honeycomb that carries the shear loads.

Materials Selection

- Structural Considerations
    - **Strength:** Honeycomb cores and some facing materials are directional with regard to mechanical properties and care must be taken to ensure that the materials are oriented in the panel to take the best advantage of this attribute.
    - **Stiffness:** Sandwich structures are frequently used to maximize stiffness at very low weights. Because of the relatively low shear modulus of most core materials, however, the deflection calculations must allow for shear deflection of the structure in addition to the bending deflections usually considered.
    - Adhesive Performance: The adhesive must rigidly attach the facings to the core material in order for loads to be transmitted from one facing to the other. Suitable adhesives include high modulus, high strength materials available as liquids, pastes or dry films. As a general rule, a low peel-strength, or relatively brittle adhesive should never be used with very light sandwich structures which may be subjected to abuse or damage in storage, handling or service.

Material Selection

- Environmental Considerations
  - **Temperature:** As in any materials system the thermal environment will play an important role in the selection of materials.
    - All systems are basically operational at Room Temperature and materials are readily available to give performance up to 170°C.
    - Material selection should also take account of available manufacturing facilities, especially cure temperature capability.
  - **Flammability:** Materials used in bonded sandwich construction are usually classified into three categories:
    1. Non-burning - which means that the product will not burn.
    2. Self-extinguishing - which means that the material will burn while held in a flame but will extinguish when the flame is removed.
    3. Flammable. Flammable materials are sometimes further defined by determining the flame spread rate under specified conditions.
  - **Moisture/Humidity:** Some core and facing materials offer excellent resistance to degradation due to moisture and humidity.

Material Selection

➢ Other Considerations

 ➢ **Heat Transfer:** The transfer of heat through a sandwich panel is dependent upon the basic principles of convection, conduction and radiation. Metallic cores with metallic facings maximize heat flow characteristics.

 ➢ **Acoustics:** Bonded honeycomb sandwich structures can be used as part of an acoustic absorption system. By perforating one skin, the sandwich is used as a sound attenuation box.

 ➢ **Adhesive Solvents and Outgassing:** Some adhesives give off gases or solvent vapors during cure which can interact with resin systems in some non-metallic cores, or with the node adhesive in some metallic honeycombs. The entire bonding process must be checked to ensure that no reduction in mechanical properties has occurred due to incompatibility of the materials or process actually used.

Physical Characteristics

➢ **Cell Size**

 ➢ A large cell size is the lower cost option, but in combination with thin skins may result in telegraphing, i.e. a dimpled outer surface of the sandwich.

 ➢ A small cell size will give an improved surface appearance, and provides a greater bonding area, but at higher cost.

Physical Characteristics

➢ **Cell Shape**

    ➢ Normally supplied with hexagonal cell shapes

        ➢ give minimum density for a given amount of material

    ➢ A few honeycomb types can be supplied with rectangular cell shapes (W:L approximately 2:1), and designated OX

        ➢ give easier forming in the W direction (with less anticlastic curvature than is exhibited by hexagonal cell honeycomb).

Ribbon or 'L' dimension — 'W' dimension — thickness 'T' — node bonds — cell size

L — W

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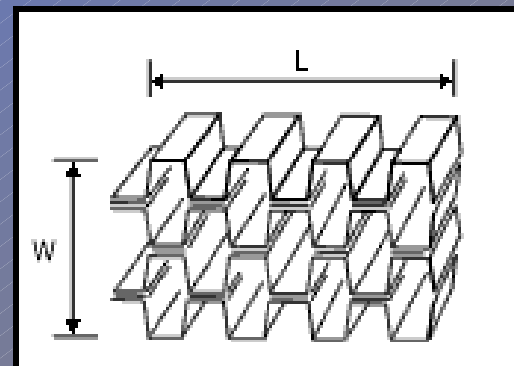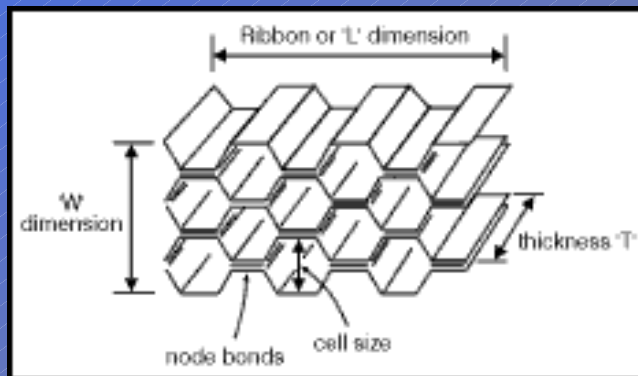
Adhesive Materials

For honeycomb sandwich bonding, the following criteria are important:

> ➢ 1. Fillet Forming - To achieve a good attachment to an open cell core such as honeycomb, the adhesive should flow sufficiently to form a fillet without running away from the skin to core joint.

> ➢ 2. Bond Line Control

>> ➢ Every endeavor should be made to ensure intimate contact between the parts during bonding, as the adhesive needs to fill any gaps between the bonding surfaces.

>> ➢ Adhesives are often supplied supported by a carrier cloth, for the purpose of helping them to remain in place where the parts are squeezed particularly tightly together.

How a Sandwich Beam Works

Loads

Consider a cantilever beam with a load applied at the free end. The applied load creates a bending moment which is a maximum at the fixed end, and a shear force along the length of the beam.
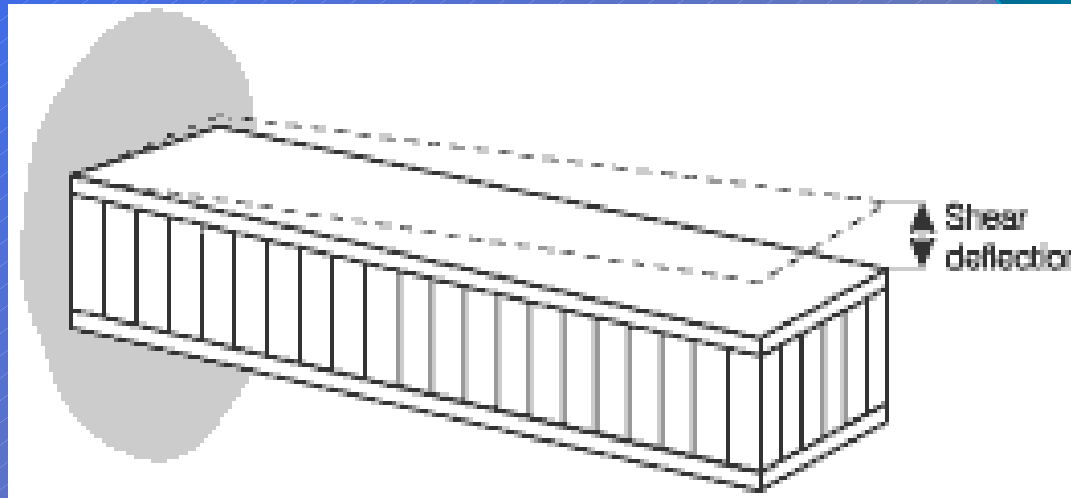
In a sandwich panel these forces create tension in the upper skin and compression in the lower skin. The core spaces the facing skins and transfers shear between them to make the composite panel work as a homogeneous structure.

Skin in tension

Core in shear

Skin in compression
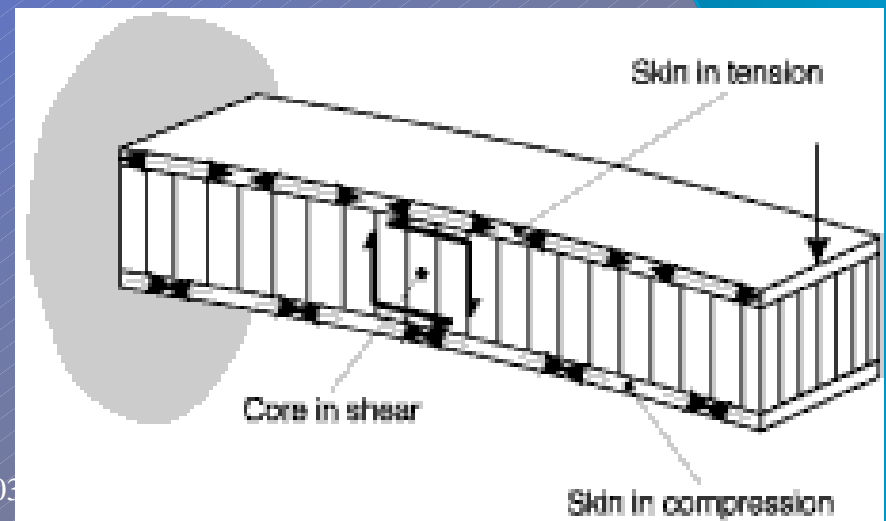
How a Sandwich Beam Works

Deflections

The deflection of a sandwich panel is made up from bending and shear components.

The bending deflection is dependent on the relative tensile and compressive moduli of the skin materials.

**Total Deflection = Bending Deflection + Shear Deflection.**

Sandwich Beam Failure Modes

1. Strength - The skin and core materials should be able to withstand the tensile, compressive and shear stresses induced by the design load. The skin to core adhesive must be capable of transferring the shear stresses between skin and core.
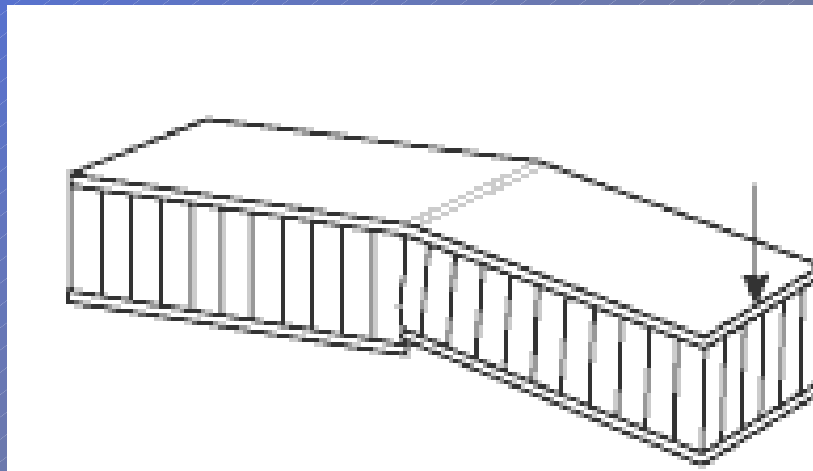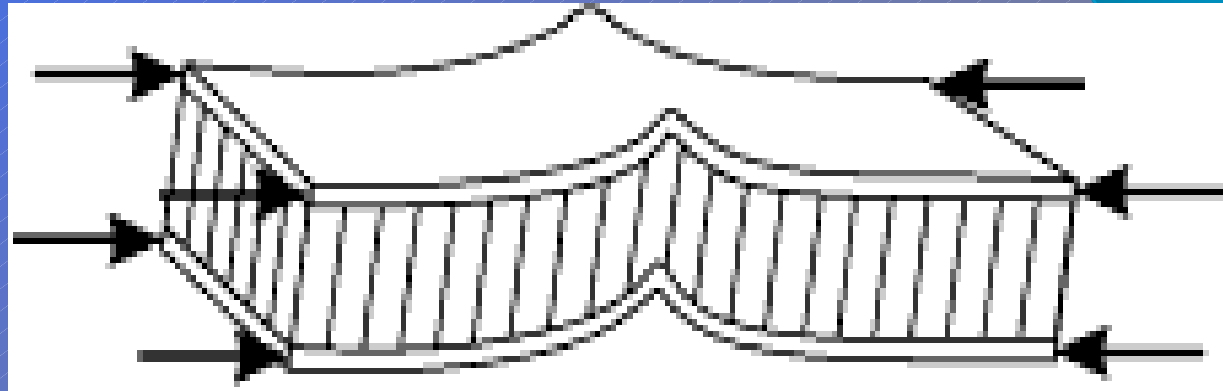
Sandwich Beam Failure Modes

2. Stiffness - The sandwich panel should have sufficient bending and shear stiffness to prevent excessive deflection.
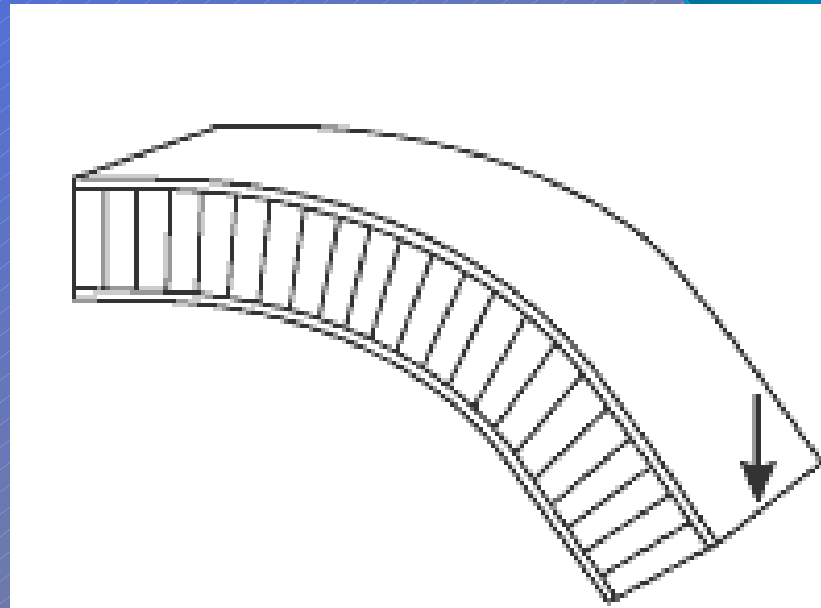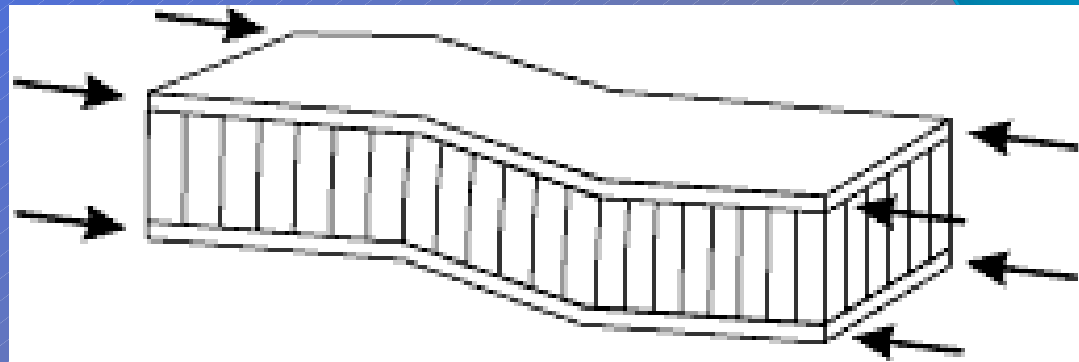
Sandwich Beam Failure Modes

3. Panel buckling - The core thickness and shear modulus must be adequate to prevent the panel from buckling under end compression loads.
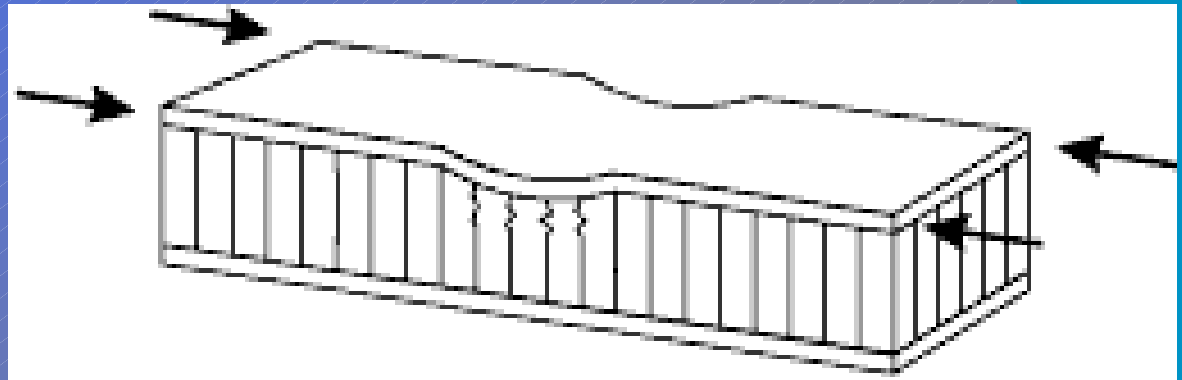
Sandwich Beam Failure Modes

4. Shear crimping - The core thickness and shear modulus must be adequate to prevent the core from prematurely failing in shear under end compression loads.
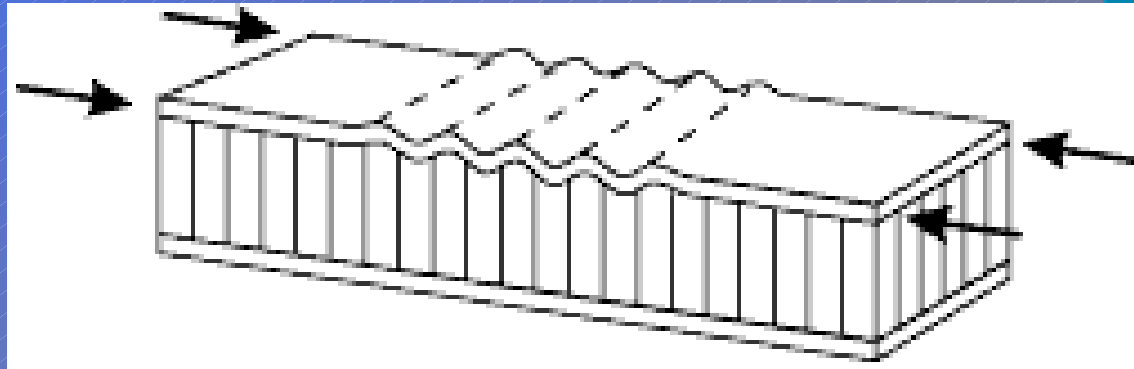
Sandwich Beam Failure Modes

5. Skin wrinkling - The compressive modulus of the facing skin and the core compression strength must both be high enough to prevent a skin wrinkling failure.
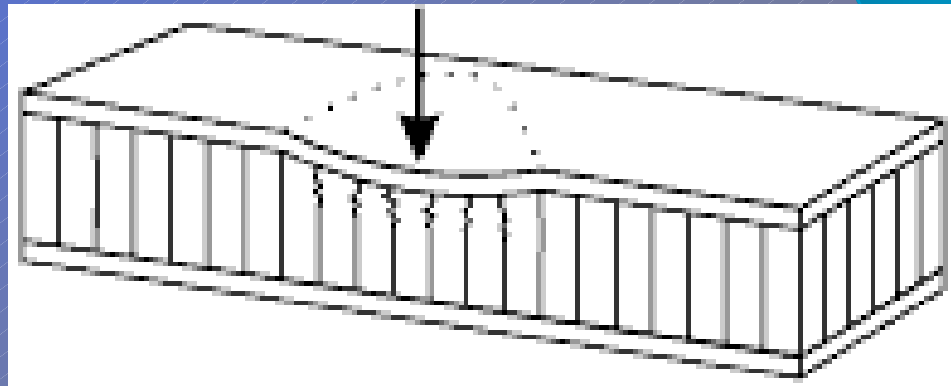
Sandwich Beam Failure Modes

6. Intra cell buckling - For a given skin material, the core cell size must be small enough to prevent intra cell buckling.

Sandwich Beam Failure Modes

7. Local compression - The core compressive strength must be adequate to resist local loads on the panel surface.

Design Guidelines

➢ Define loading conditions

➢ Define panel type (boundary conditions)

  ➢ Cantilever

  ➢ Simply supported

➢ Define physical/space constraints

  ➢ deflection limit

  ➢ thickness limit

  ➢ weight limit

  ➢ factor of safety

➢ *Can now begin to make preliminary material selections. . .*

Preliminary calculations

➢ Make an assumption about skin material, skin thickness and panel thickness. Ignore the core material at this stage.

    ➢ Calculate stiffness.

    ➢ Calculate deflection (ignoring shear deflection).

    ➢ Calculate facing skin stress.

    ➢ Calculate core shear stress.

Design Optimization

➢ Modify skin thickness, skin material and panel thickness to achieve acceptable performance.

➢ Select suitable core to withstand shear stress.

Design Review

➤ Detailed calculations
- ➤ Calculate stiffness.
- ➤ Calculate deflection, including shear deflection.
- ➤ Calculate facing skin stress.
- ➤ Calculate core shear stress.
- ➤ Check for panel buckling - where applicable
- ➤ Check for shear crimping.
- ➤ Check for skin wrinkling.
- ➤ Check for intra-cell buckling.
- ➤ Check for local compression loads on core.

Mechanics of Materials (Review)

➤ Shear Force and Bending Moment
  ➤ Determine maximum shear force
  ➤ Determine maximum bending moment
➤ Beam Deflections and Slopes
  ➤ Determine equation of the elastic curve
  ➤ Or at least the value of the maximum deflection

Summary of Formulae

➢ Beams

Bending Stiffness	$D = \dfrac{E_f t_f h^2 b}{2}$
Shear Stiffness	$S = bhG_c$
Deflection	$\delta = k_b Pl^3 / D \text{ (bending)} + k_s Pl/S \text{ (shear)}$
Facing Stress	$\sigma_f = \dfrac{M}{ht_f b}$
Core Stress	$\tau_c = \dfrac{F}{hb}$

Summary of Formulae

> Plates

Deflection	$\delta = \dfrac{2K_1qb^4\lambda}{E_f t_f h^2}$
Facing Stress	$\sigma_f = \dfrac{K_2qb^2}{ht}$
Core Shear	$\tau_c = K_3qb/h$
Local Compression	$\sigma_c = \dfrac{P}{A} = \dfrac{qA}{A}$

Summary of Formulae

➢ End Loading

Facing Stress	$\sigma_f = \dfrac{P}{2t_f b}$
Panel Buckling	$P_b = \dfrac{\pi^2 D}{l^2 + (\pi^2 D / G_c hb)}$
Shear Crimping	$P_b = t_c G_c b$
Skin Wrinkling	$\sigma_{CR} = 0.5[G_c E_c E_f]^{\frac{1}{3}}$
Intra-cell Buckling	$\sigma_{CR} = 2E_f [t_f / s]^2$

Nomenclature

a = Panel length

A = Area of applied load

b = Beam width

D = Panel bending stiffness

E_c = Compression modulus of core

E_f = Modulus of elasticity of facing skin

F = Maximum shear force

G_c = Core shear modulus - in direction of applied load

G_L = Core shear modulus - Ribbon direction

G_W = Core shear modulus - Transverse direction

h = Distance between facing skin centers

k_b = Beam - bending deflection coefficient

k_S = Beam - shear deflection coefficient

K_1 = Panel parameter (used for simply supported plate)

K_2 = Panel parameter (used for simply supported plate)

K_3 = Panel parameter (used for simply supported plate)

L = Beam span

M = Maximum bending moment

P = Applied load

P_b = Critical buckling load

q = Uniformly distributed load

R = Ratio G_L/G_W

s = Cell size

S = Panel shear stiffness

t_c = Thickness of core

t_f = Thickness of facing skin

V = Panel parameter (used for simply supported plate)

δ = Calculated deflection

σ_c = Core compressive stress

σ_{CR} = Critical facing skin stress

σ_f = Calculated facing skin stress

τ_c = Shear stress in core

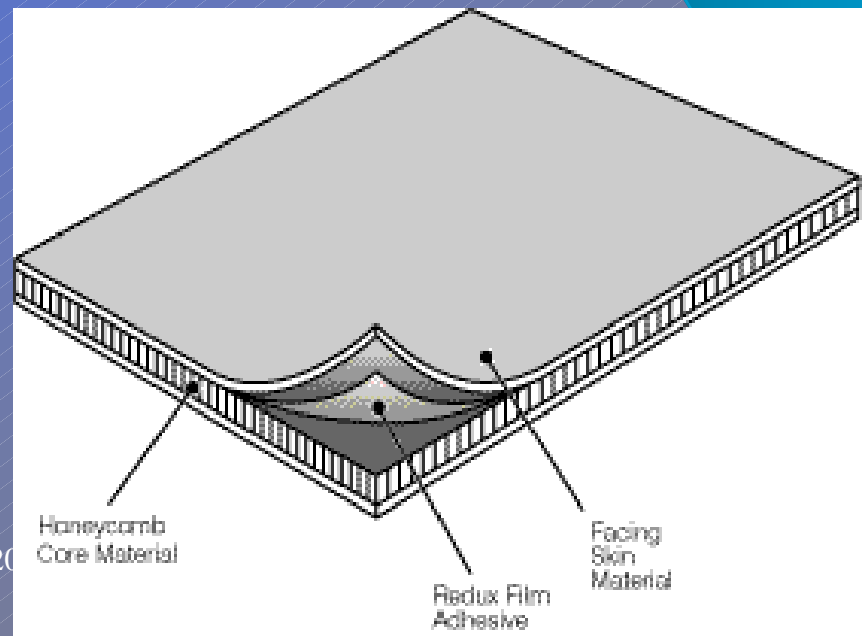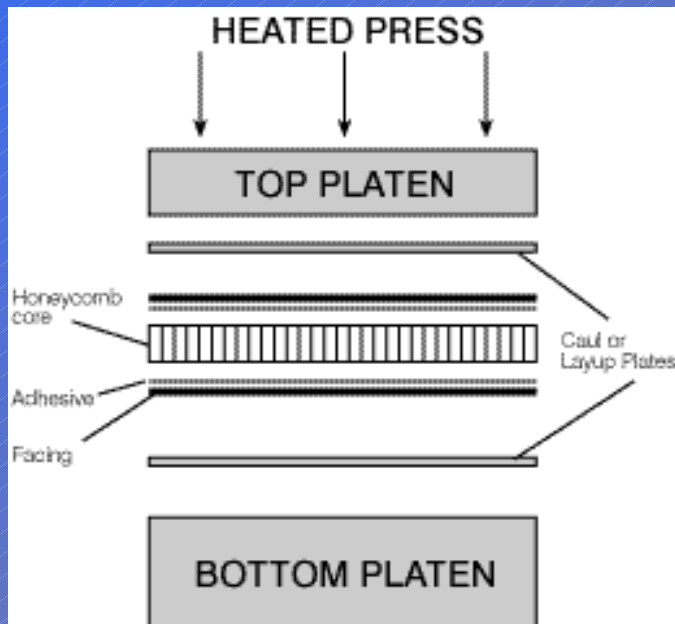ν = Poisson's Ratio of face material

$\textit{l}$ = Bending correction factor for Poisson's Ratio effect

Basic Honeycomb Sandwich Production Methods

➢ Honeycomb sandwich components may be produced using any number of well-established methods:-

  ➢ Heated Press, generally used for the production of flat board or simple preformed panels.

  ➢ Vacuum Bag Processing, used for curved and complex form panels.

  ➢ Matched Mold Processing, used generally for batch production of finished panels.

Heated Press

➢ Ideally the panels should be assembled ready for curing as a single shot process. This method is suitable for metallic and prepreg (pre-impregnated) facing skins.

➢ Alternatively prepreg facing skin materials may be pre-cured by using a press, and subsequently bonding with a film adhesive layer.

➢ Integrally bonded items such as extruded bar sections and inserts may be included and located by the honeycomb core or with simple tooling.

HEATED PRESS

TOP PLATEN

Honeycomb core

Caul or Layup Plates

Adhesive

Facing

BOTTOM PLATEN

Honeycomb Core Material

Redux Film Adhesive

Facing Skin Material
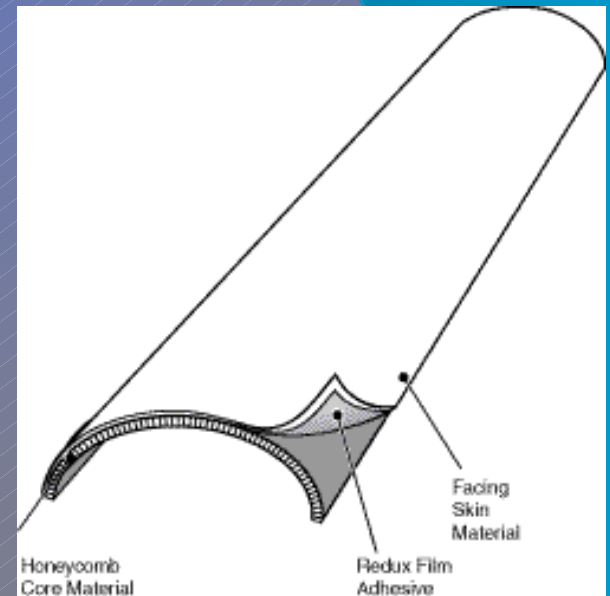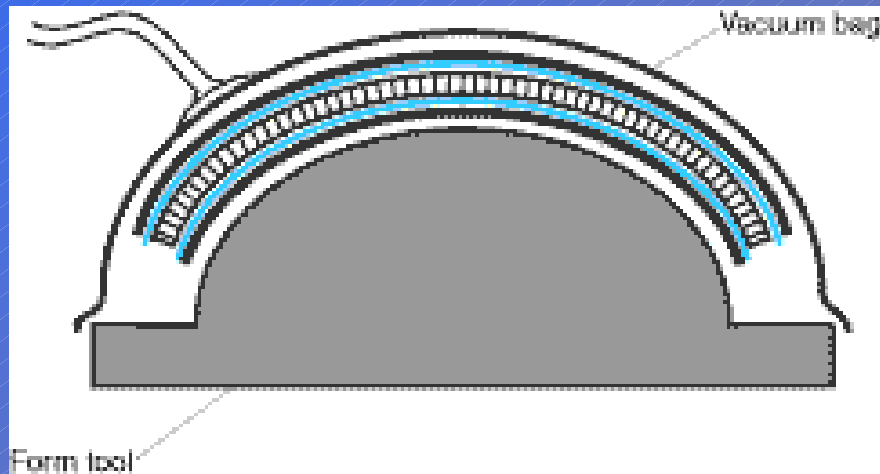
Tooling for Sandwich Construction

➢ Aluminum platens most often used for flat panels

   ➢ Low cost "tooling plate" flat within 0.005"/ft

   ➢ Cast jig plate close to perfect

   ➢ Stability/durability (long term aging occurs after 100 hrs at 350°F)

   ➢ Flexible caul sheet used to distribute pressure

   ➢ Rails needed to prevent collapsing edge of honeycomb

   ➢ Sometimes integrally heated to avoid warping thin F/S panels from ΔT
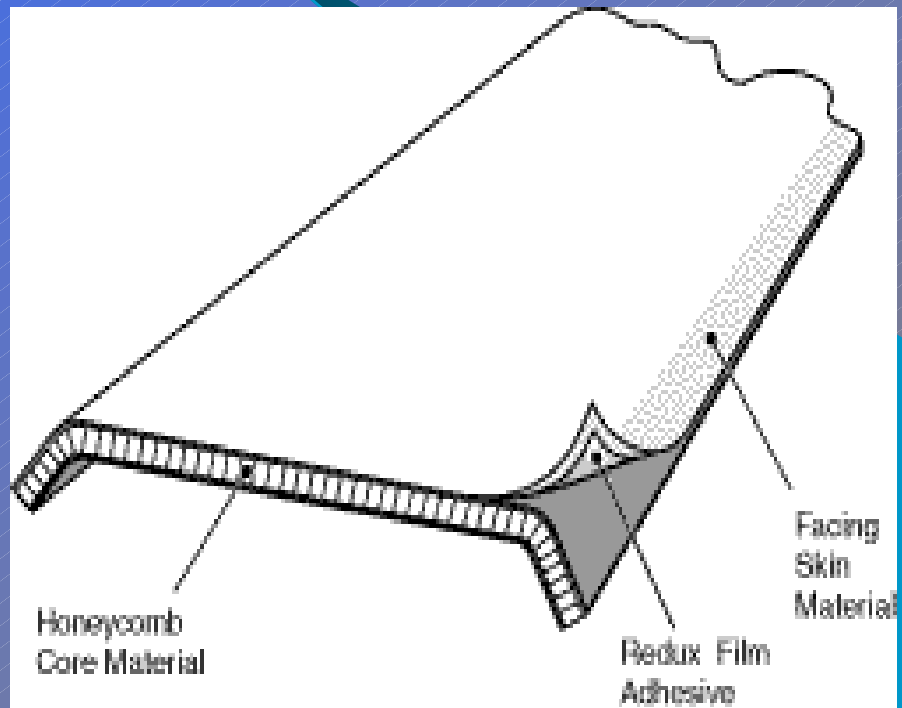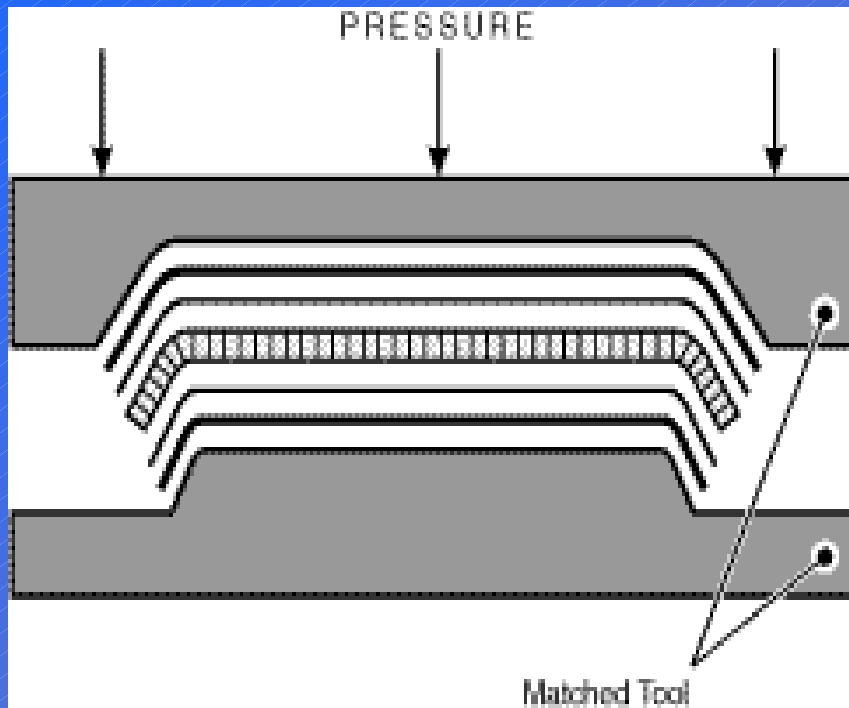
Tooling for Sandwich Construction

➢ Steel mandrels often used for tubes
  ➢ Stiffer to avoid sag, relatively low cost & very machinable
  ➢ Rubber caul sheet

➢ Composite tooling typically used for complex contours and large parts
  ➢ Carbon or glass prepreg cured on machined master mold (120-180°F cure)
  ➢ Composite slip sheets also used on Al platens to avoid CTE mismatch

➢ Cast Invar or monolithic graphite used for highest precision shapes

➢ Zerodur (cast glass) used as mold for composite space mirrors (extreme case)

Vacuum Bag Processing

➢ The component should be assembled for cure as a single shot process, the necessary consolidation is obtained using a vacuum. This can be cured in an oven, and additional pressure can be applied if an autoclave is used.

➢ This method is suitable for items with prepreg or preformed composite or metallic facing skins.

➢ When flexible or formed honeycomb core and film adhesives are used complex items may be produced.

Vacuum bag

Form tool

Honeycomb Core Material

Redux Film Adhesive

Facing Skin Material

Matched Mold Processing

PRESSURE

Matched Tool

Honeycomb Core Material

Redux Film Adhesive

Facing Skin Material

Matched Mold Processing

This method is most suited to the single shot cure process where a key objective is to achieve production items with high levels of tolerance and surface finish.

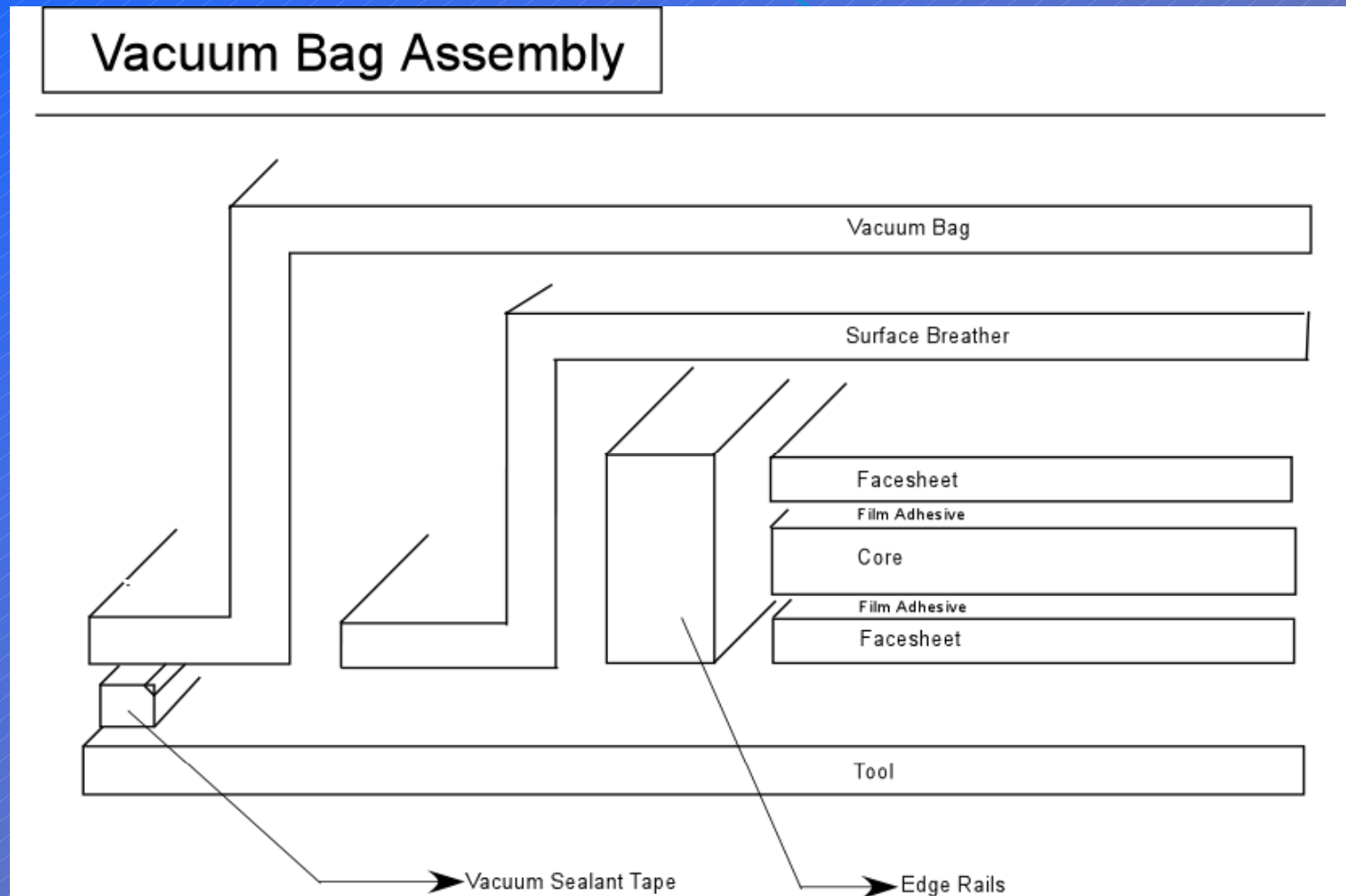The heat and pressure cure cycle in this case is applied using a variety of methods.

Typical methods are the use of heated tools with external mechanical pressure or non heated tools placed in a press or oven to achieve the full cycle.

Using a room temperature curing adhesive cold bonding may be considered if the sandwich construction is too large to be processed using the above methods, or if heating equipment is unavailable.

Other Processing Considerations

➢ Debulking should be used to minimize dimpling or wrinkling "knockdown factor"

  ➢ The larger the cell size – the more critical

➢ There are 3 levels of debulking:

  ➢ RT/vacuum bag only removes layup air only

  ➢ Oven/vac-bag consolidation removes some volatiles also

  ➢ Autoclave prebleed (eg. 20 min. @ 200°F & 100 psi is best but costly)

➢ Net resin prepreg systems are preferred. If bleeding is required, it must be done as a pre-bleed prior to core assembly with facesheets. Trying to bleed during cure produces wrinkles.

➢ Automated ply cutters and/or laser placement can be used if production rate and geometry warrant.

Secondary Bonding of Facesheets

Vacuum Bag Assembly

- Vacuum Bag
- Surface Breather
- Facesheet
- Film Adhesive
- Core
- Film Adhesive
- Facesheet
- Tool
- Vacuum Sealant Tape
- Edge Rails

Process Summary

| Pressure	Cure Temp	Features
Weights or Clamps	Room Temp (Oven Cure)	Lowest cost comercial approach for "non-structural" panels
Vacuum bag assembly	RT Oven Cure (180°F, 250°, 350°)	Vacuum bag significantly improves facesheet to core contact and therefore bonding
Composite co-cure	180-350°F	Consolidation/cure of facesheet & bond to core in one cycle saves time ($)
Autoclave (15-50 psi)	180-350+°F	Positive pressure used to improve facesheet to core bond. Used with mismatched core segments, multiple inserts, or complex shapes, corners, etc.
Heated Press (15-50 psi)	RT to 250°F	Lower cost than vac-bag or autoclave but has size limitations. Requires flexible caul sheet.
RTM	RT-350°F	Developmental – best with foam or Balsa core.

Sandwich Panel Edge Closure

➢ When designing of sandwich panels it may be necessary to consider methods of closing or sealing the edges. Exposed edge areas are a potential weakness in the design as they may be susceptible to local impact or environmental damage.

➢ Edge closures may also provide local reinforcements, attachment points, or simply meet aesthetic requirements.

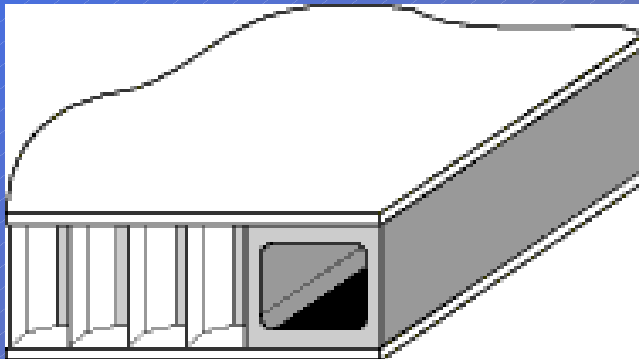➢ Illustrated are a number of methods commonly used to close sandwich boards:
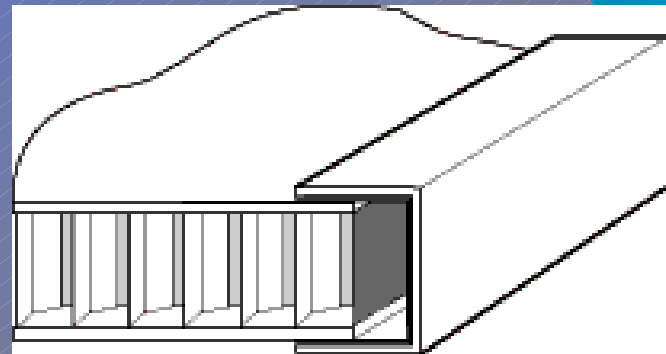
Edge Closure
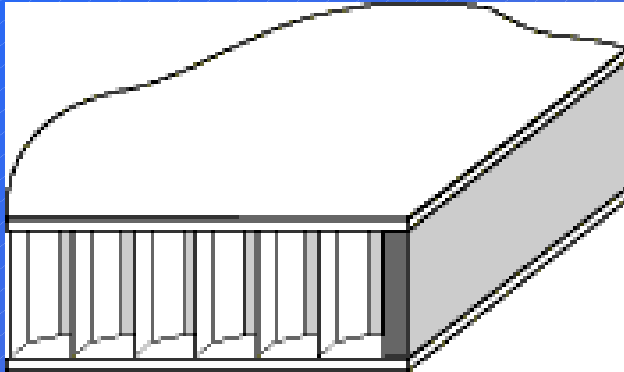
Edge filler
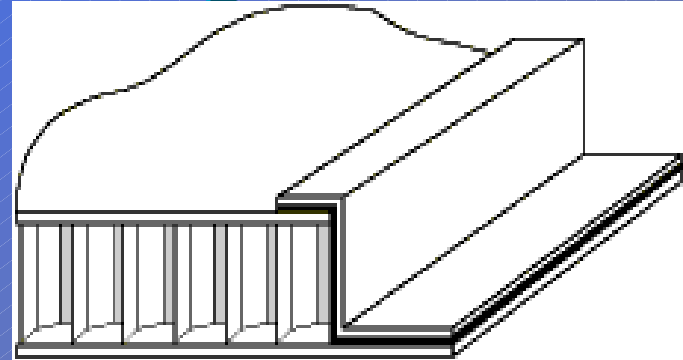
Bonded Z section

Box extrusion

Bonded U section

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