# 4

# SANDWICH STRUCTURES

Sandwich structures occupy a large proportion of composite materials design. They appear in almost all applications. Historically they were the first light and high-performance structures.[1] In the majority of cases, one has to design them for a specific purpose. Sandwich structures usually appear in industry as semi-finished products. In this chapter we will discuss the principal properties of sandwich structures.

## 4.1 WHAT IS A SANDWICH STRUCTURE?

A sandwich structure results from the assembly by bonding—or welding—of two thin facings or skins on a lighter core that is used to keep the two skins separated (see Figure 4.1).

Their properties are astonishing. They have

- **Very light weight.** As a comparison, the mass per unit area of the dome of the Saint Peter's Basilica in Rome (45 meter diameter) is 2,600 kg/m$^2$, whereas the mass per surface area of the same dome made of steel/polyurethane foam sandwich (Hanover) is only 33 kg/m$^2$.
- **Very high flexural rigidity.** Separation of the surface skins increases flexural rigidity.
- **Excellent thermal insulation characteristics.**

However, be careful:

- Sandwich materials are not dampening (no acoustic insulation).
- Fire resistance is not good for certain core types.
- The risk of **buckling** is greater than for classical structures.

The facing materials are diverse, and the core materials are as light as possible. One can denote couples of compatible materials to form the sandwich (see Figure 4.2).

Be careful: Polyester resins attack polystyrene foams.

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[1] See Section 7.1.

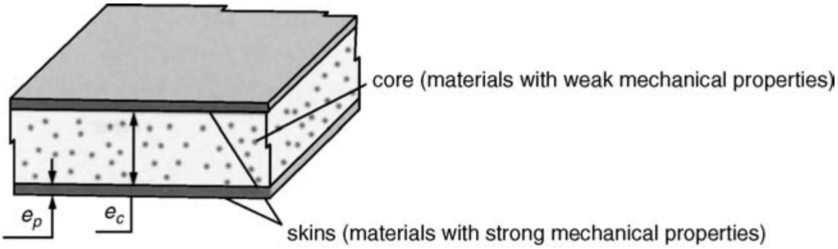
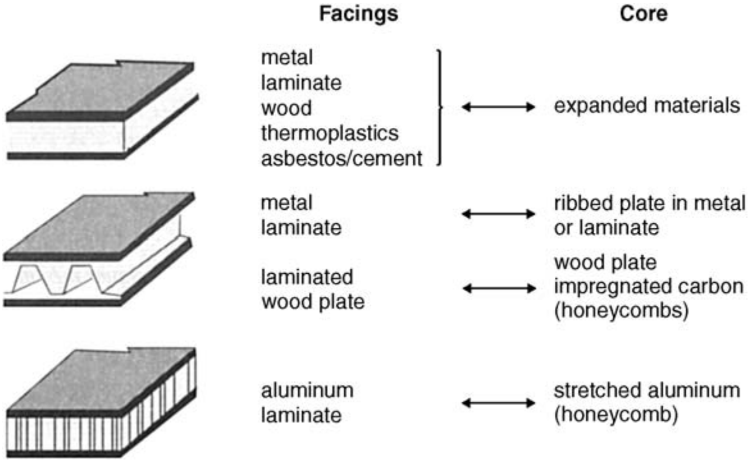


Figure 4.1 Sandwich Structure ($10 \le E_c/E_p \le 100$)



| Facings | | Core |
|---|---|---|
| metal<br>laminate<br>wood<br>thermoplastics<br>asbestos/cement | ↔ | expanded materials |
| metal<br>laminate | ↔ | ribbed plate in metal<br>or laminate |
| laminated<br>wood plate | ↔ | wood plate<br>impregnated carbon<br>(honeycombs) |
| aluminum<br>laminate | ↔ | stretched aluminum<br>(honeycomb) |

Figure 4.2 Constituents of Sandwich Materials

The **assembly** of the facings to the core is carried out using bonding adhesives. In some exceptional cases, the facings are welded to the core. The quality of the bond is fundamental for the performance and life duration of the piece. In practice we have

$$\boxed{0.025 \text{ mm} \le \text{adhesive thickness} \le 0.2 \text{ mm}}$$

## 4.2 SIMPLIFIED FLEXURE

### 4.2.1 Stresses

Figure 4.3 shows in a simple manner the main stresses that arise due to the application of bending on a sandwich beam.[2] The beam is clamped at its left end, and a force $T$ is applied at its right end. Isolating and magnifying one elementary segment of the beam, on a cross section, one can observe the **shear stress resultant** $\boldsymbol{T}$ and the **moment resultant** $\boldsymbol{M}$. The shear stress resultant $T$ causes shear stresses $\tau$ and the moment resultant causes normal stresses $\sigma$.

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[2] For more details on these stresses, see Chapters 15 and 17, and also Applications 18.3.5 and 18.3.8.

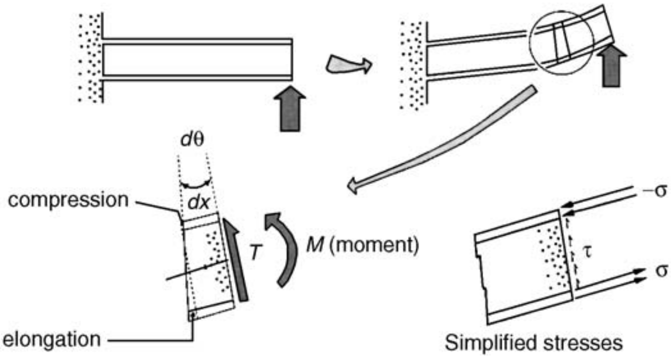

**Figure 4.3 Bending Representation**

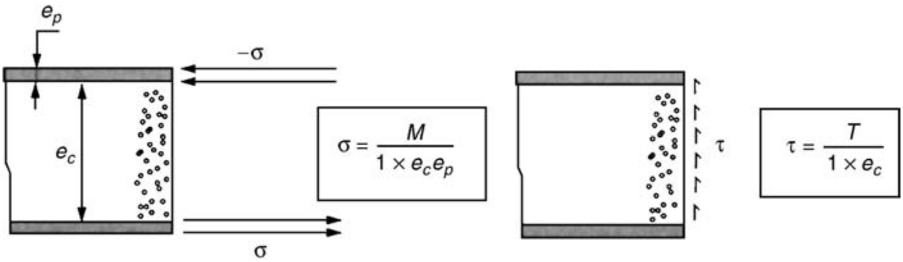

**Figure 4.4 Stresses in Sandwich Structure**

To evaluate $\tau$ and $\sigma$, one makes the following simplifications:

- The normal stresses are assumed to occur in the facings only, and they are uniform across the thickness of the facings.
- The shear stresses are assumed to occur in the core only, and they are uniform in the core.[3]

One then obtains immediately the expressions for $\tau$ and $\sigma$ for a beam of **unit width** and thin facings shown in Figure 4.4.

### 4.2.2 Displacements

In the following example, the displacement $\Delta$ is determined for a sandwich beam subjected to bending as a consequence of

- Deformation due to normal stresses $\sigma$ and
- Deformation created by shear stresses $\tau$ (see Figure 4.5).

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[3] See Section 17.7.2 and the Applications 18.2.1 and 18.3.5 for a better approach.

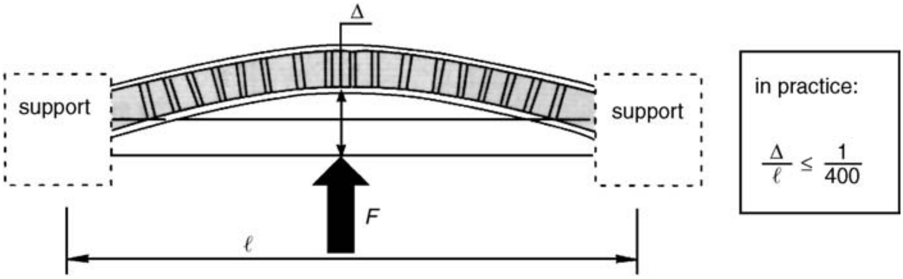

**Figure 4.5 Bending Deflection**

To evaluate Δ, one can, among other methods,[4] use the Castigliano theorem

$$\underbrace{W}_{\text{elastic energy}} = \underbrace{\frac{1}{2}\int\frac{M^2}{\langle EI\rangle}dx}_{\text{contribution from bending}} + \underbrace{\frac{1}{2}\int\frac{k}{\langle GS\rangle}T^2dx}_{\text{contribution from shear}}$$

$$\Downarrow$$

$$\underbrace{\Delta}_{\text{deflection}} = \frac{\partial W}{\partial F}\begin{matrix}\text{energy}\\ \text{load}\end{matrix}$$

where the following notations[5] are used for a beam of unit width:

$M$ = Moment resultant
$T$ = Shear stress resultant
$E_p$ = Modulus of elasticity of the material of the facings
$G_c$ = Shear modulus of the core material

$$\langle EI\rangle \# E_p e_p \times 1 \times \frac{(e_c + e_p)^2}{2}; \qquad k/\langle GS\rangle = 1/G_c(e_c + 2e_p) \times 1.$$

**Example:** A cantilever sandwich structure treated as a sandwich beam (see Figure 4.6).

Elastic energy is shown by

$$W = \frac{1}{2}\int_0^\ell \frac{F^2(\ell - x)^2}{\langle EI\rangle}dx + \frac{1}{2}\int_0^\ell \frac{k}{\langle GS\rangle}F^2dx$$

$$W = \frac{F^2}{2}\left(\frac{\ell^3}{3\langle EI\rangle} + \frac{k}{\langle GS\rangle}\ell\right)$$

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[4] See Equation 15.16 that allows one to treat this sandwich beam like a homogeneous beam. One can also use the classical strength of materials approach.

[5] See Application 18.2.1 or Chapter 15.

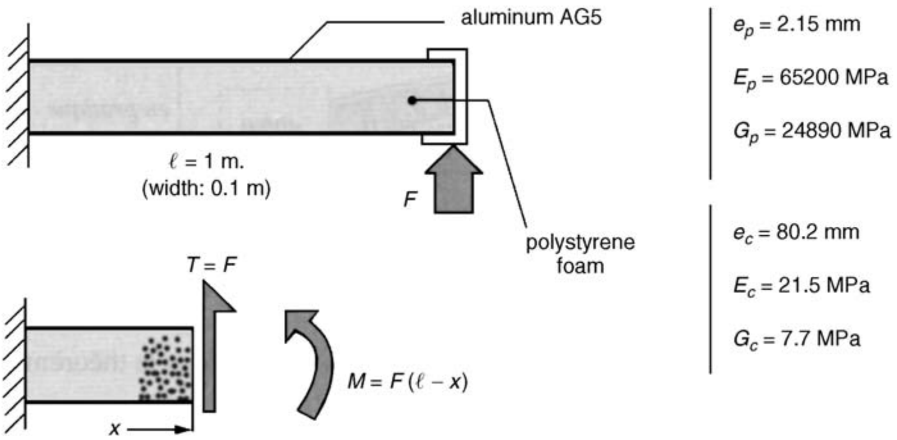


**Figure 4.6 Cantilever Beam**

where

$$\langle EI \rangle = 475 \times 10^2; \quad \frac{\langle GS \rangle}{k} = 650 \times 10^2$$

The end displacement Δ can be written as

$$\Delta = \frac{\partial W}{\partial F}$$

Then for an applied load of 1 Newton

$$\Delta = \underbrace{0.7 \times 10^{-2} \text{ mm/N}}_{\text{Flexure}} + \underbrace{1.54 \times 10^{-2} \text{ mm/N}}_{\text{Shear}}$$

**Remark:** Part of the displacement Δ due to shear appears to be higher than that due to bending, whereas in the case of classical homogeneous beams, the shear displacement is very small and usually neglected. Thus, this is a specific property of sandwich structures that strongly influences the estimation of the bending displacements.

## 4.3 A FEW SPECIAL ASPECTS

### 4.3.1 Comparison of Mass Based on Equivalent Flexural Rigidity (EI)

Figure 4.7 allows the comparison of different sandwich structures having the same flexural rigidity ⟨*EI*⟩. Following the discussion in the previous section, this accounts for only a part of the total flexural deformation.

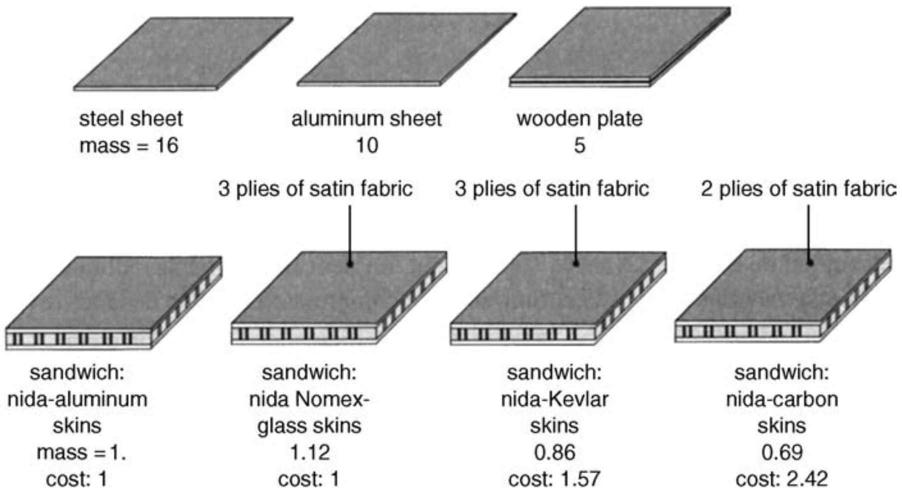


**Figure 4.7** Comparison of Plates Having Similar Flexural Rigidity *EI*

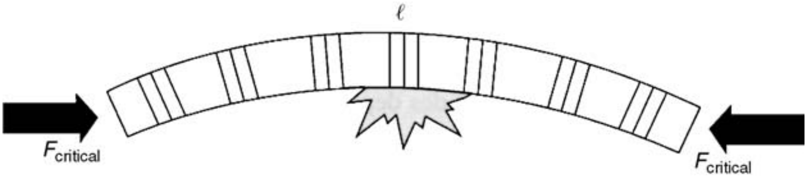


**Figure 4.8** Buckling of Sandwich Structure

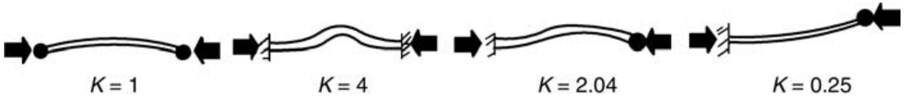
## 4.3.2 Buckling of Sandwich Structures

The compression resistance of all or part of a sandwich structure is limited by the so-called **critical values** of the applied load, above which the deformations become large and uncontrollable. This phenomenon is called **buckling** of the structure (see Figure 4.8). Depending on the type of loading, one can distinguish different types of buckling which can be global or local.

### 4.3.2.1 *Global Buckling*

Depending on the supports, the critical buckling load $F_c$ is given[6] by

$$\boxed{F_{cr} = K\frac{\pi^2\langle EI\rangle}{\ell^2 + \pi^2\dfrac{\langle EI\rangle}{\langle GS\rangle}kK}}$$



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[6] See Application 18.3.4.

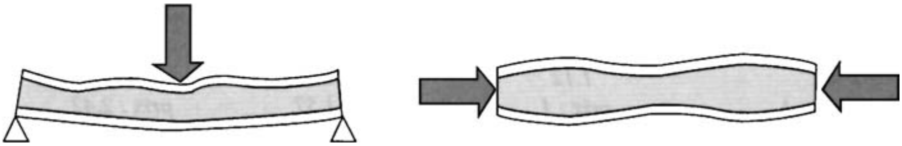


Figure 4.9 Local Buckling of Facings

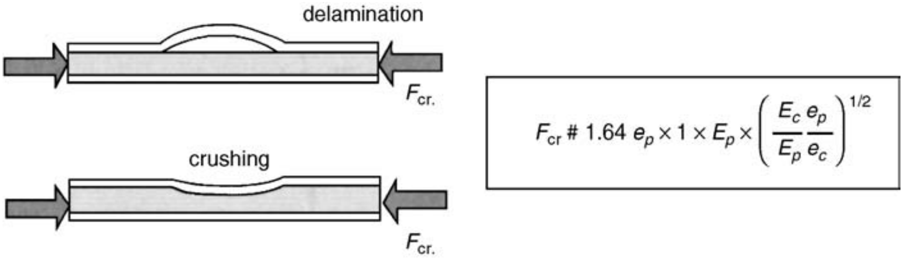


Figure 4.10 Damage by Local Buckling

### 4.3.2.2 *Local Buckling of the Facings*

The facings are subject to buckling due to the low stiffness of the core. Depending on the type of loading, one can find the modes of deformation as shown in Figure 4.9.

The critical compression stress is given in the equation below where $\nu_c$ is the Poisson coefficient of the core.

$$\sigma_{cr} = a \times (E_p \times E_c^2)^{1/3}$$

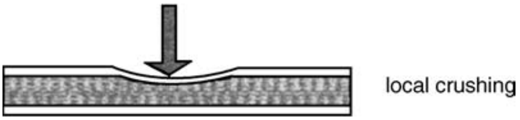
with

$$a = 3\{12(3 - \upsilon_c)^2(1 + \upsilon_c)^2\}^{-1/3}$$

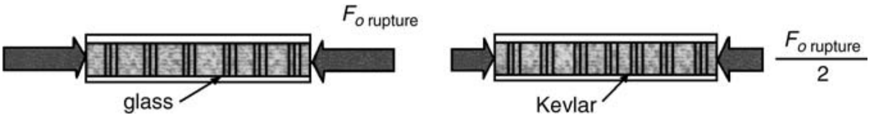
The critical load to cause local damage by local buckling of a facing and the types of damage are shown in Figure 4.10.

## 4.3.3 Other Types of Damage

Local crushing: This is the crushing of the core material at the location of the load application (see figure below).



Compression rupture: In this case (see figure below), note that the weak compression resistance of Kevlar fibers[7] leads to a compression strength about two times less than for sandwich panels made using glass fibers.



## 4.4 FABRICATION AND DESIGN PROBLEMS

### 4.4.1 Honeycomb: An Example of Core Material

These well-known materials are made of hexagonal cells that are regularly spaced. Such geometry can be obtained using a technique that is relatively simple. Many thin sheets are partially bonded. Starting from stacked bonded sheets, they are expanded as shown in Figure 4.11.

The honeycomb material can be metal (light alloy, steel) or nonmetal (carton impregnated with phenolic resin, polyamide sheets, or impregnated glass fabrics).

Metallic honeycombs are less expensive and more resistant. Nonmetallic honeycombs are not sensitive to corrosion and are good thermal insulators. The following table shows the mechanical and geometric characteristics of a few current honeycombs, using the notations of Figure 4.11.

**Table 4.1 Properties of Some Honeycomb**

| | *Bonded Sheets of Polyamide: Nomex*[a] | *Light Alloy AG3* | *Light Alloy 2024* |
|---|---|---|---|
| Dia. (D): inscribed circle (mm) | 6; 8; 12 | 4 | 6 |
| Thickness e (mm) | | 0.05 | 0.04 |
| Specific mass (kg/m$^3$) | 64 | 80 | 46 |
| Shear strength $\tau_{xz\ \mathrm{rup}}$ (MPa) | 1.7 | 3.2 | 1.5 |
| Shear modulus: $G_{xz}$ (MPa) # 1.5 $G_{\mathrm{mat}}(e/D)$ | 58 | 520 | 280 |
| Shear strength $\tau_{yz\ \mathrm{rup}}$ (MPa) | 0.85 | 2 | 0.9 |
| Shear modulus: $G_{yz}$ (MPa) | 24 | 250 | 140 |
| Compression strength: $\sigma_{z\ \mathrm{rup}}$ (MPa) | 2.8 | 4.4 | 2 |

[a] Nomex® is a product of Du Pont de Nemours.

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[7] See Section 3.3.3.

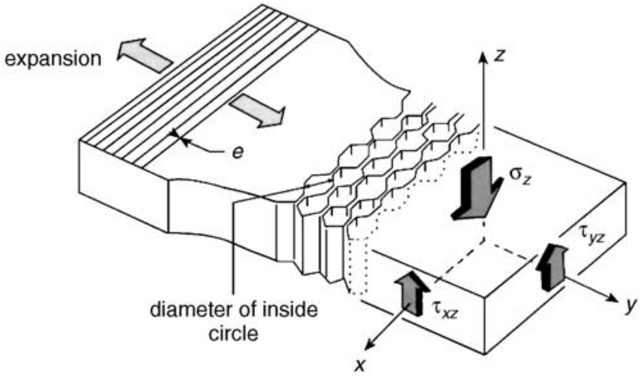

**Figure 4.11 Honeycomb**

**Figure 4.12 Processing of Honeycomb**

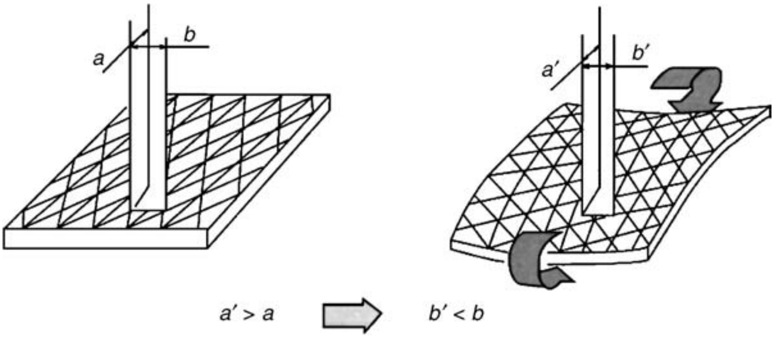

**Figure 4.13 Deformation of Honeycomb**

### 4.4.2 Processing Aspects

The processing of the honeycomb is done with a diamond disk (peripheral speed in the order of 30 m/s). The honeycomb is kept on the table of the machine by an aluminum sheet to which it is bonded. Below the aluminum sheet, a depression anchors it to the table (see Figure 4.12).

One can also **deform** the honeycomb. It is important to constrain it carefully, because the deformation behavior is complex. For example, a piece of honeycomb under cylindrical bending shows two curvatures as illustrated in Figure 4.13.[8]

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[8] This phenomenon is due to the Poisson effect, particularly sensitive here (see Section 12.1.4).

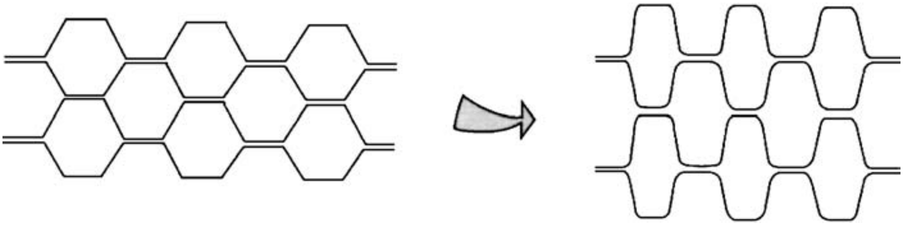

**Figure 4.14 Over-Expansion of Honeycomb**

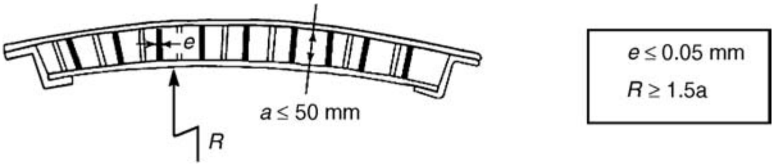

**Figure 4.15 Curvature of Honeycomb**

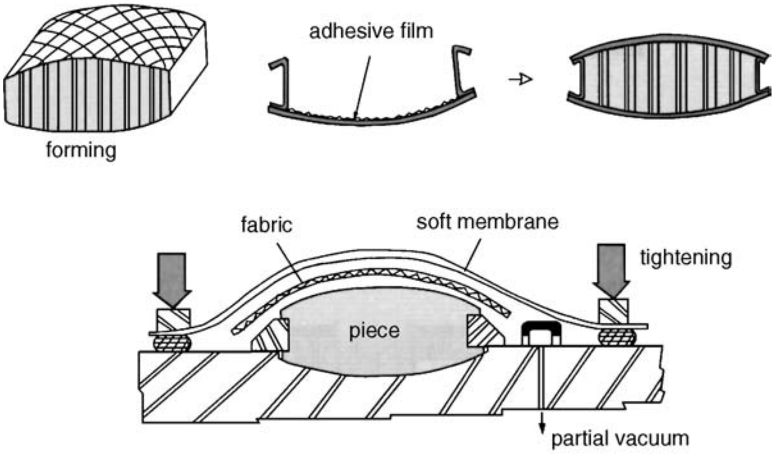

**Figure 4.16 Processing of a Sandwich Piece of a Structural Part**

The processing can be facilitated using the method of **overexpansion** which modifies the configuration of the cells as shown in Figure 4.14.

At limit of **curvature**, *R* is the radius of the contour, and *e* is the thickness of the sheets which consitute the honeycombs (see Figure 4.15). **Nomex** honeycombs (sheets of bonded polyamide) must be processed at high temperature. The **schematic** for the processing of a structural part of sandwich honeycomb is as in Figure 4.16. For **moderate loadings** (for example, bulkheads), it is possible to fold a sandwich panel following the schematic in Figure 4.17.

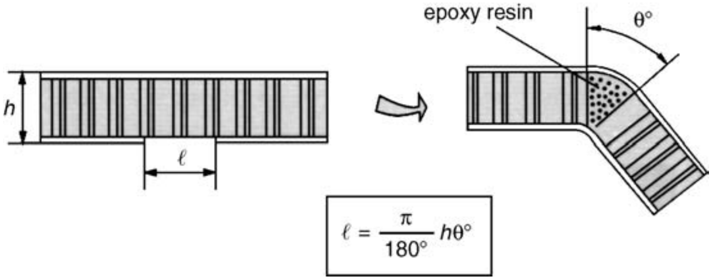

Figure 4.17 Folding of Honeycomb

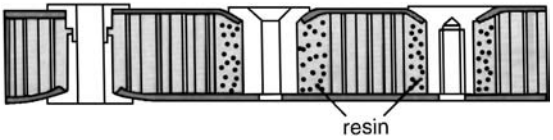

Figure 4.18 Incorporation of Inserts

### 4.4.3 Insertion of Attachment Pieces

When it is necessary to transmit local loadings, depending on the intensity of these loads, it is convenient to distribute these over one or many **inserts,** as indicated in Figure 4.18.[9] The filling resin of epoxy type, shown in Figure 4.18, can be lightened by incorporation of phenolic microspheres with resulting density for the lightened resin of 700 to 900 $kg/m^3$ and crush strength # 35 MPa (see Figure 4.19).

### 4.4.4 Repair of Laminated Facings

For sandwich materials of the type "honeycombs/laminates," the repair of local damage is relatively easy. It consists of **patching** the plies of the laminate. The configuration of the repair zone appears as in Figure 4.20.

## 4.5 NONDESTRUCTIVE QUALITY CONTROL

Apart from using the classical methods for controlling the surface defects, which allows the repair of external delaminations of laminated facings, using the following techniques allows the identification and repair of internal defects due to fabrication or due to damages in service. These defects can entail imperfect bonding, delaminations, and inclusions. Principal nondestructive detection methods are illustrated in Figure 4.21.

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[9] See Sections 6.2.4 and 6.3.

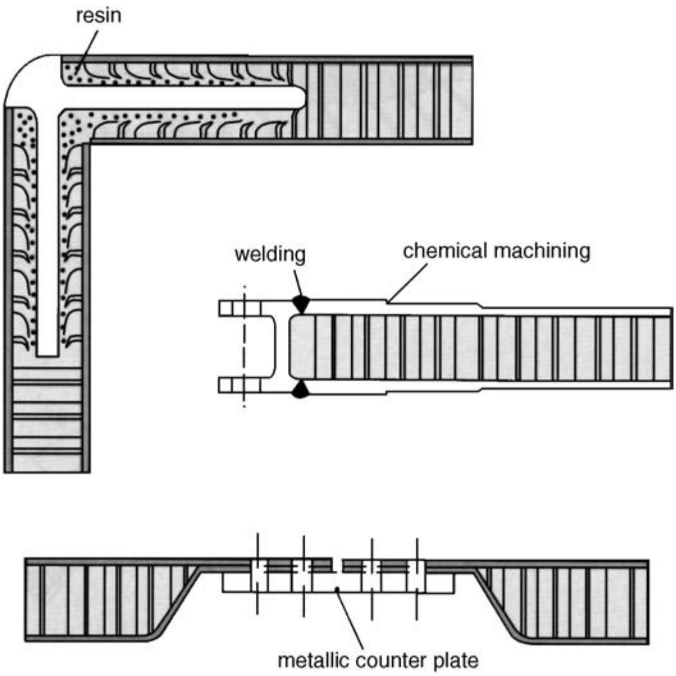


**Figure 4.19 Some Links for Sandwich Structures**

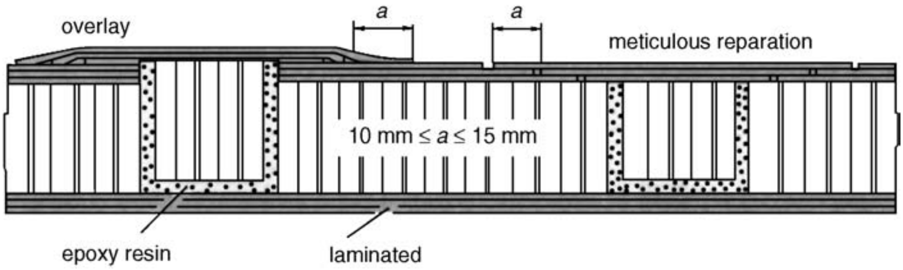


**Figure 4.20 Honeycomb Repair**

When a composite structure (for example, a reservoir under pressure) is subjected to loading, many microcracks can occur within the piece. Microcracking in the resin, fiber fracture, and disbond between fiber and matrix can exist even within the admissible loading range. These ruptures create acoustic waves that propagate to the surface of the piece. They can be detected and analyzed using **acoustic emission** sensors (see Figure 4.22).

The number of peaks as well as the duration and the amplitude of the signal can be used to indicate the integrity of the piece. In addition, the accumulated number of peaks may be used to predict the fracture of the piece (i.e., the change of slope of the curve in Figure 4.23).

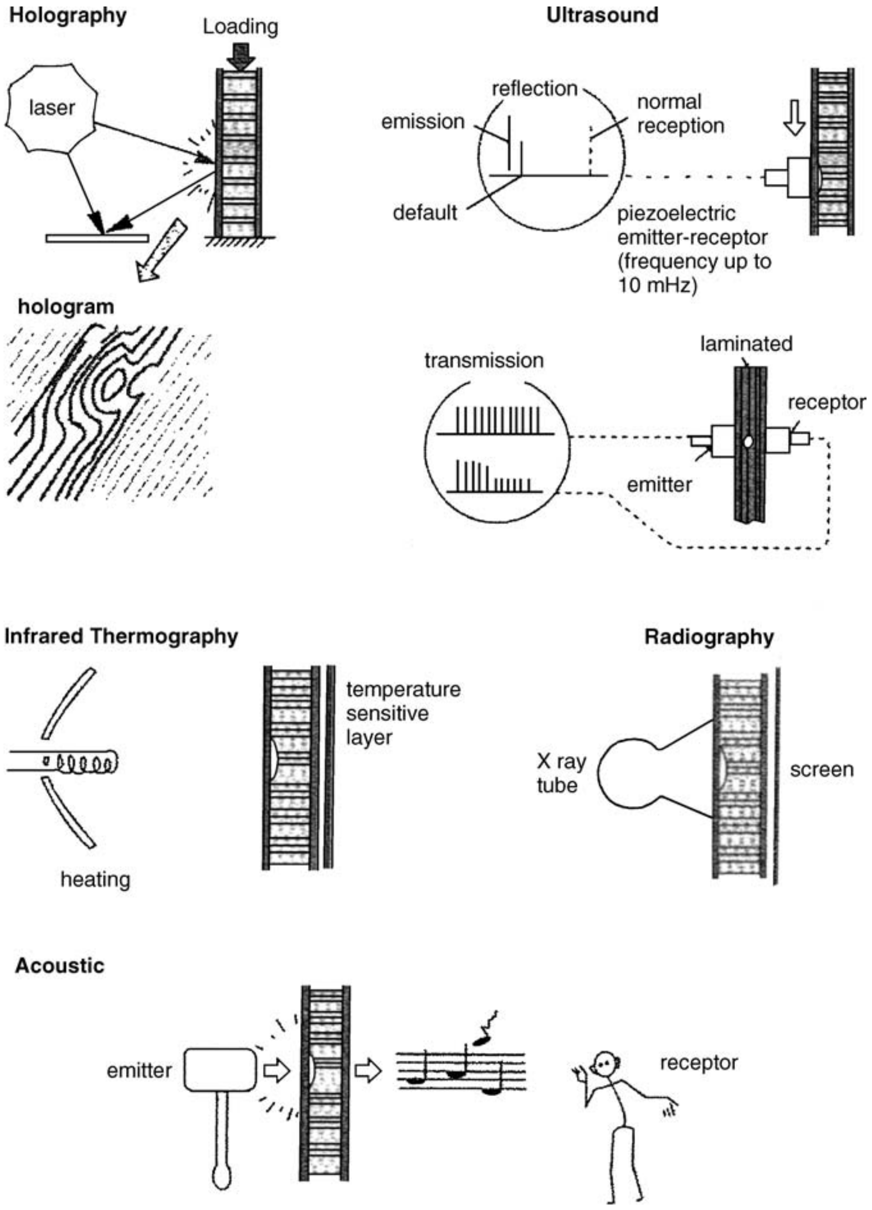
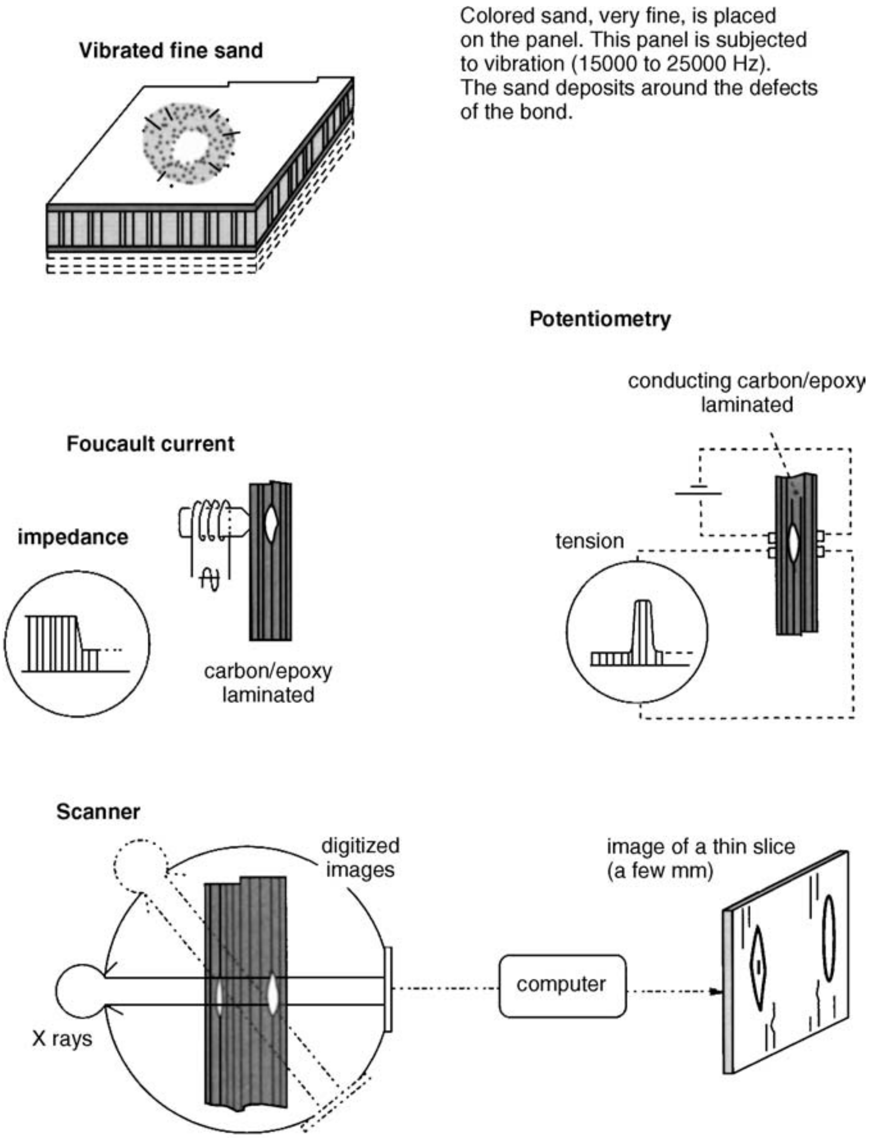


**Figure 4.21 Principal Nondestructive Testing Methods**



Colored sand, very fine, is placed on the panel. This panel is subjected to vibration (15000 to 25000 Hz). The sand deposits around the defects of the bond.

Figure 4.21 (Continued).

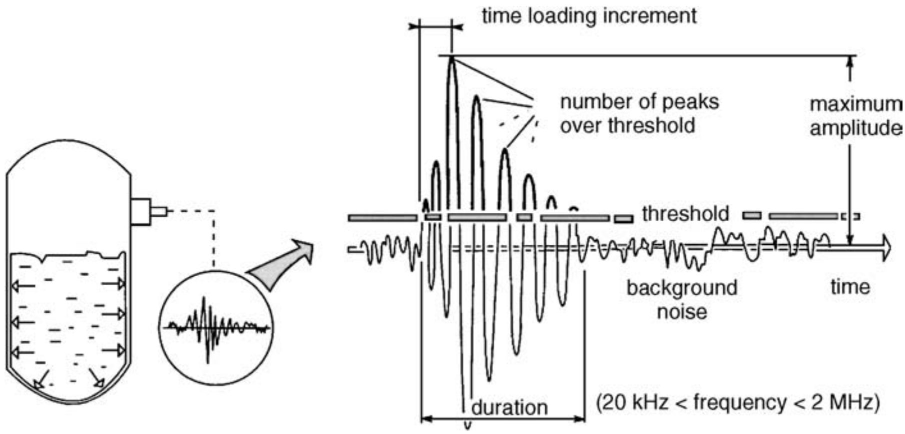


**Figure 4.22 Acoustic Emission Technique**

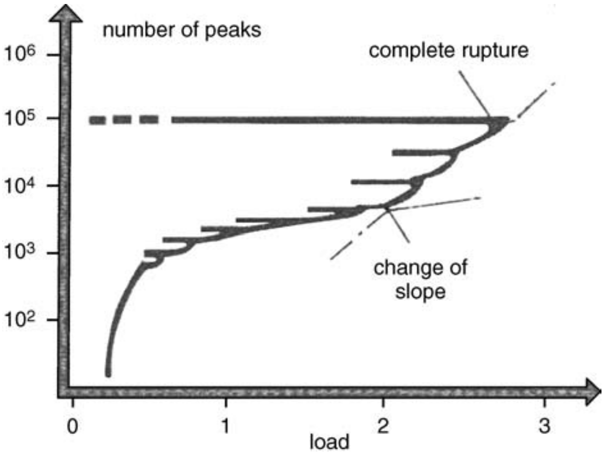


**Figure 4.23 Plotting of AE Events**