Chapter 1
Introduction

A structural sandwich typically consists of two thin "face sheets" made from stiff and strong relatively dense material such as metal or fiber composite bonded to a thick lightweight material called "core". This concept mimics an I-beam, but in two dimensions, where the face sheets support bending loads and the core transfers shear force between the faces in a sandwich panel under load. Figure 1.1 illustrates flat and curved elements from a sandwich structure.

Sandwich structures allow optimization of structures that are weight-critical such as parts of airplanes, space structures, sporting goods, naval structures, and blades for wind-power generation (see Figure 1.2).

In addition to providing a very efficient load-carrying structure, the sandwich concept enables design of multi-functional structures. Figure 1.3 shows an example of the enclosed mast of USS Radford, where stealth properties, i.e., invisibility to radar, is accomplished by embedding radar absorbing materials in the core.

In addition to advanced structural applications, the sandwich concept has long been utilized in packaging materials, such as corrugated paper board (Figure 1.4), and in natural materials and structures such as human and animal bones and skulls and wings of birds (see Gibson and Ashby, 1997).

Core materials are classified within two broad categories, i.e., "cellular" and "structural". Cellular implies that the material consists of "cells" containing open space enclosed by walls in a repetitive manner so that space-filling is achieved (see Figure 1.5). Cellular foams, e.g. polymer or metal foams, honeycomb core, and balsa wood, are very common in structural applications. Web core is a structural core that consists of a continuous web made from a solid material formed in such a way that it separates the faces and becomes effective in transferring shear forces.

L.A. Carlsson and G.A. Kardomateas, *Structural and Failure Mechanics of Sandwich Composites*, Solid Mechanics and its Applications 121, DOI 10.1007/978-1-4020-3225-7_1,

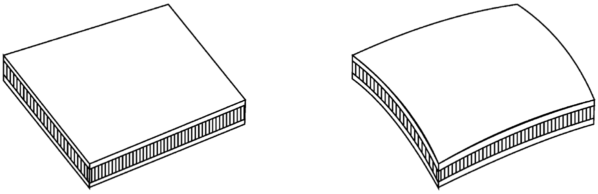

Figure 1.1 Flat and curved elements of a sandwich structure.

Because core materials are lightweight and stiffness and strength of materials scale with density (Gibson and Ashby, 1997), the core is commonly the weak constituent of a sandwich. In some instances, the bond between face and core may be critical for the integrity of the sandwich.

Proper selection of face and core materials requires understanding of the mechanics of sandwich structures. In this introductory chapter, we will examine some basic loading cases and failure modes of sandwich structures. Understanding of the contribution from the faces and core to important structural stiffnesses and strengths of a sandwich panel will guide the designer towards selection of appropriate materials and enable him or her to design a weight efficient and reliable structure. With almost no exceptions, sandwich structures utilize flat or curved panels (Figure 1.1). Still, much can be learned by consideration of a simpler sandwich structure, viz. a beam. This chapter will emphasize beams. Panels made from sandwich are examined in some detail in later chapters.

1.1 Bending Stiffness of a Sandwich Beam

The overall bending stiffness $E_x I$ of a sandwich beam is readily obtained from the parallel axis theorem (PAT) (Gere, 2004), which provides $E_x I$ in terms of the moduli and thicknesses of the constituents. For a symmetrical cross-section shown in Figure 1.6, PAT yields

$$E_x I = E_x^c I_c + 2E_x^f I_f, \tag{1.1}$$

where I_c and I_f are the moments of inertia of the core and each face sheet with respect to the neutral axis (y axis).

$$I_c = \frac{bh_c^3}{12}, \tag{1.2a}$$

Figure 1.2 Examples of sandwich structures.

$$I_f = \frac{bh_f^3}{12} + \frac{bh_f d^2}{4}. \tag{1.2b}$$

Hence, the bending stiffness per unit width of the sandwich beam becomes

$$\frac{E_x I}{b} = \frac{E_x^c h_c^3}{12} + E_x^f \left(\frac{h_f^3}{6} + \frac{h_f d^2}{2} \right). \tag{1.3}$$

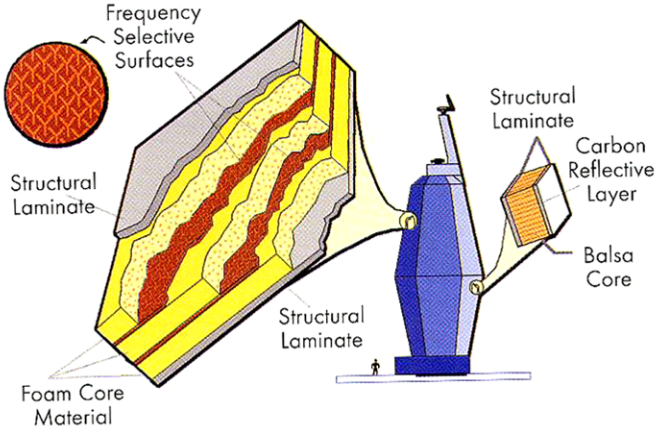

Figure 1.3 Cross-section of sandwich used to enclose the USS Radford mast.

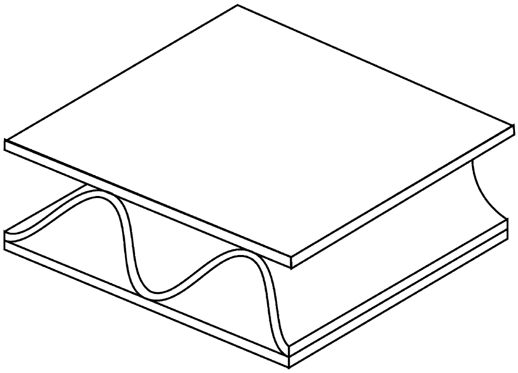

Figure 1.4 Corrugated core sandwich used in packaging boxes.

The quantity $E_x I/b$ is commonly referred to as "bending stiffness", D_x. Simplification of Equation (1.3) yields

$$D_x = E_x^f h_f d^2 \left[\frac{h_c^3}{12 h_f d^2} \left(\frac{E_x^c}{E_x^f} \right) + \frac{1}{6} \left(\frac{h_f}{d} \right)^2 + \frac{1}{2} \right]. \tag{1.4}$$

Sandwich structures are requested to be lightweight. Determination of optimal stiffness requires consideration of the density. The weight, W, of the sandwich beam, normalized by the beam width and length, is given by

$$\frac{W}{bl} = 2 h_f \rho_f + h_c \rho_c, \tag{1.5}$$

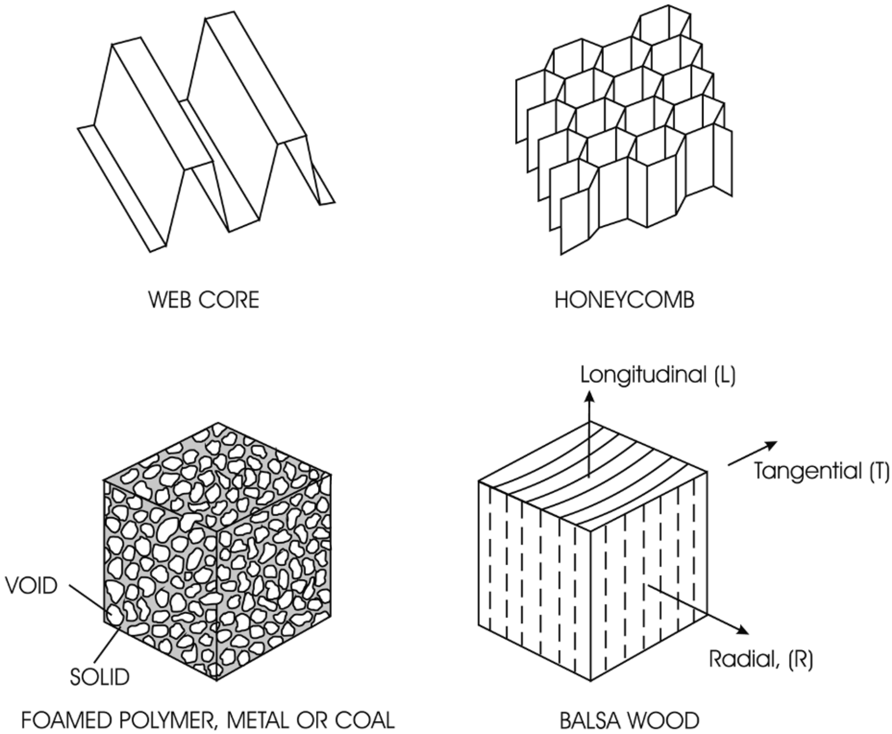

Figure 1.5 Core concepts utilized in sandwich structures.

where ρ_f and ρ_c are the densities (mass/unit volume) of the faces and core. The average (effective) density of the sandwich, ρ^*, becomes

$$\rho^* = 2\frac{h_f}{h}\rho_f + \frac{h_c}{h}\rho_c, \tag{1.6}$$

where h is the total thickness of the sandwich ($h = 2h_f + h_c$). Figure 1.7 shows D_x normalized by $E_x^f h_f d^2$, and ρ^* normalized by ρ_f, plotted vs. the core/face thickness ratio (h_c/h_f), for a typical sandwich consisting of aluminum face sheets and a H100 PVC foam core with: $E_x^f = 70$ GPa, $E_x^c = 0.1$ GPa, $\rho_f = 2.7$ g/cm^3, and $\rho_c = 0.1$ g/cm^3. Properties of typical face and core materials are provided in Tables 1.1 through 1.4. Inspection of the results in Figure 1.7 reveals that both the bending stiffness and density decrease with an increasing core-to-face thickness ratio. The normalized bending stiffness decreases rapidly at small thickness ratios and approaches 1/2 asymptotically, while the normalized density shows a continuous decrease with h_f/h_c.

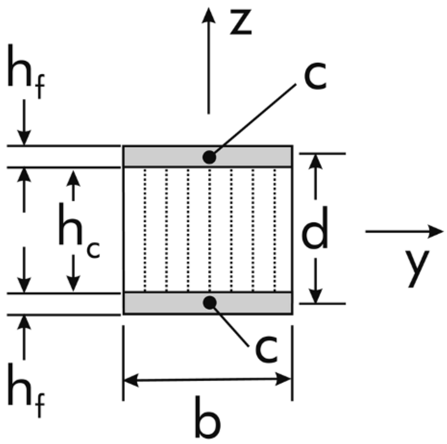

Figure 1.6 Cross-sectional view of a symmetric sandwich beam. "C" represents the centroid location for each of the face sheets, and y the neutral axis of the beam.

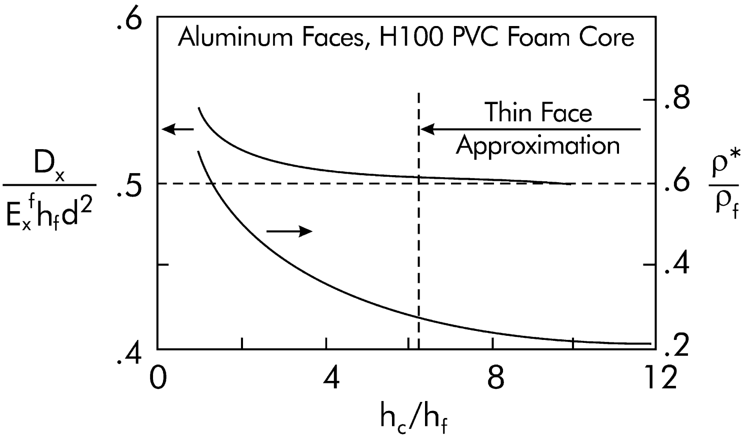

Figure 1.7 Bending stiffness and density of a sandwich beam vs. core-to-face thickness ratio. Face sheets are aluminum and the core is a H100 PVC foam.

The first term within the brackets of Equation (1.4) represents the bending stiffness contribution from the core, which is small by virtue of the small core-to-face modulus ratio (0.00143) for this combination and remains small for most other combinations of face and core materials, see Tables 1.1 through 1.4. The second term within the brackets in Equation (1.4) makes a significant contribution only for very thick faces (see Figure 1.7). Most practically used sandwich structures utilize thin face sheets, and the strictly geometry-dependent second term can be neglected in comparison to the third

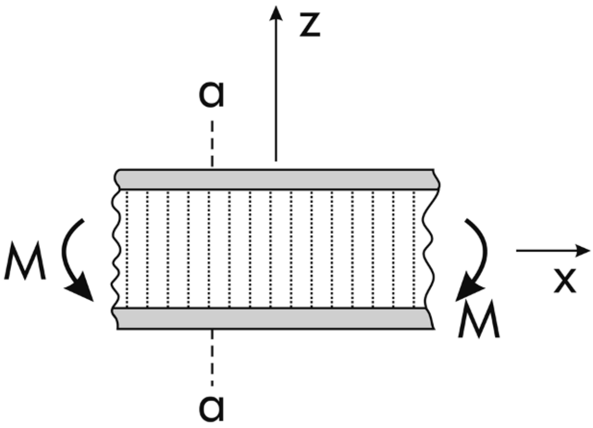

Figure 1.8 Sandwich element under pure bending.

term (1/2). We may at this point establish a limit on core/face thickness ratio above which the contribution from the second term to the bending stiffness is below 1%. Equation (1.4) yields

$$h_c/h_f \geq 5.35. \tag{1.7}$$

If this inequality is satisfied, the faces may be considered "thin", and the bending stiffness becomes

$$D_x = \frac{E_x^f h_f d^2}{2}. \tag{1.8}$$

This equation identifies the two most important factors for achieving high bending stiffness, i.e., high face sheet modulus, E_x^f, and a large distance, d, between the face sheet's centroids. A large value of the face sheet thickness, h_f, however, seemingly beneficial, will not be favorable from a weight point of view, see Figure 1.7. Consequently, from a bending stiffness and weight point of view, the most favorable sandwich design utilizes thin, high-modulus face sheets over a low-density core.

1.2 Stresses in the Face Sheets and Core

Consider the element of a sandwich under pure bending loads in Figure 1.8. Most core materials are compliant and do not significantly contribute to the bending rigidity. For such a case, and if the faces are thin compared to the

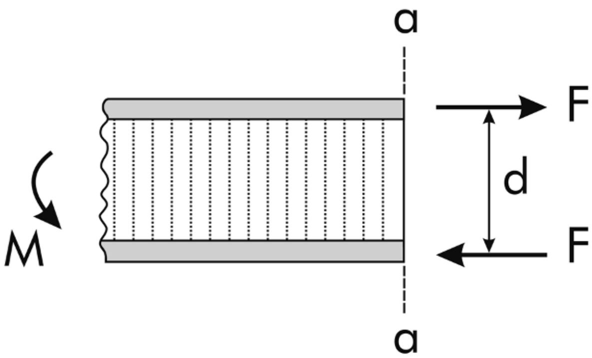

Figure 1.9 Free body diagram illustrating internal forces in the face sheets.

core, it is recognized that the bending moment, M, is equilibrated by internal tension and compression forces of equal magnitude acting at the centroids of the face sheets ("a couple"), as illustrated in the free body diagram in Figure 1.9.

If the bending stresses in the core are neglected, equilibrium of the element in Figure 1.9 yields an average bending stress in the face sheets

$$\sigma = \frac{M}{bdh_f}, \tag{1.9}$$

where d is the distance between the centroids of the faces, $d = h_c + h_f$, where h_c and h_f are the core and face thicknesses, respectively, and b is the width of the element (Figure 1.6). Notice that σ is tensile (positive) in the top face and compressive (negative) in the bottom face for the loading considered. Consequently, the face sheets need to be strong in tension and compression to be able to support the bending load.

If a sandwich beam is loaded by a bending moment that varies along the length of the beam, equilibrium analysis (Gere, 2004) shows that there will be a shear force, V, acting transversely to the beam axis (Figure 1.10).

$$V = \frac{dM}{dx}. \tag{1.10}$$

The shear stress, τ_{xz}, acting on the core, is obtained from equilibrium consideration of the element mm_1ab shown in the lower part of Figure 1.11. The horizontal (x axis) force due to the stress, σ, acting on the left side of the element is

$$F_1 = \sigma b h_f = \frac{M}{d}. \tag{1.11}$$

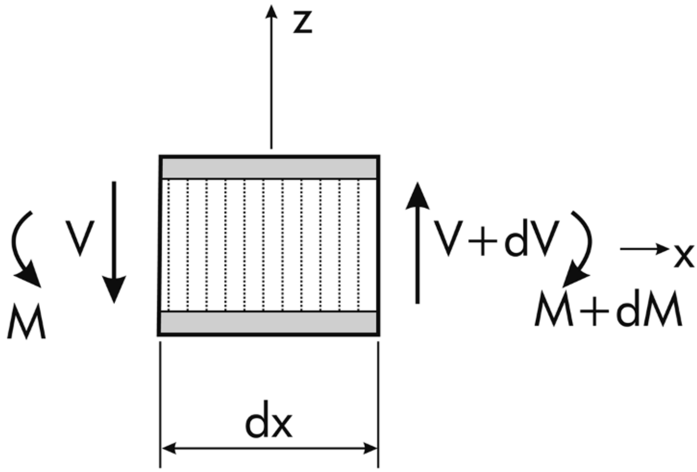

Figure 1.10 Element of a sandwich beam under variable bending moment.

The corresponding horizontal force acting on the right side of the element is

$$F_2 = \frac{M + dM}{d}. \tag{1.12}$$

The horizontal force due to the shear stress acting on the core surface at section *ab* is

$$F_3 = \tau_{xz}\, bdx. \tag{1.13}$$

Notice that the top surface (mm_1) is free from shear stress. Equilibrium yields

$$\tau_{xz} = \frac{dM}{dx}\frac{1}{bd} = \frac{V}{bd}. \tag{1.14}$$

This equation shows that the shear stress in the core, calculated based on the thin face/compliant core assumptions, is uniform (independent of the z coordinate). Exact analysis (Zenkert, 1997) reveals that the shear stress decreases almost linearly from the value, $V/(bd)$, at the face/core interfaces, to zero at the outer face surfaces. Equation (1.14) highlights the need for selecting a core material that is strong in shear. Further, as will be discussed later, for low modulus core material (Tables 1.2–1.4), shear deformation in the core may be excessive and may govern the overall deformation of the sandwich. Therefore, to avoid extensive shear deformation in sandwich structures, a core material with sufficiently high shear modulus must be used.

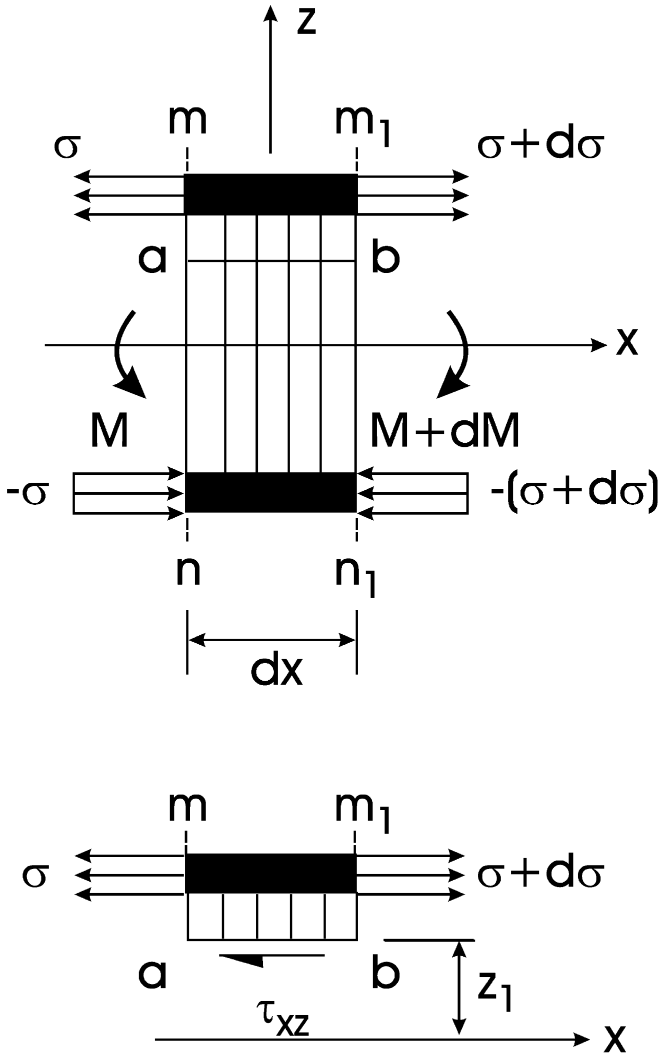

Figure 1.11 Sandwich elements considered in the calculations of core shear stress.

1.3 Local Failures

In addition to face failure in tension or compression, and core failure in shear, sandwich panels may fail locally through a host of failure modes to be discussed in detail in subsequent chapters. One such failure mode is "face wrinkling", sketched in Figure 1.12. Such a failure mode may occur in sand-

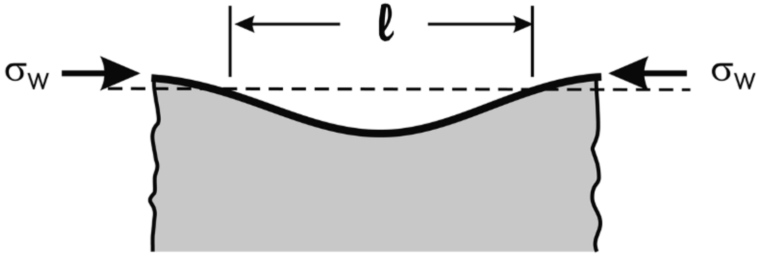

Figure 1.12 Wrinkling of the face sheets in compression loaded sandwich elements.

wich beams and panels with a soft homogeneous core (e.g. polymer foam or balsa wood core) under in-plane uniaxial compression loading. Wrinkling may also occur on the compression side of a sandwich panel or beam under bending. It manifests itself as a short wave-length buckling (local buckling) instability of the faces.

The wrinkling failure mode has been the subject of much research, as will be further discussed in Chapter 7. Such analysis shows that a high core stiffness will prevent such failures, in particular the out-of-plane extensional and shear stiffness.

For honeycomb-cored sandwich panels with thin faces, it is possible that the face sheets buckle between the supporting cells, as illustrated for square cells in Figure 1.13. Such a failure mode is called "intracell buckling" or "face dimpling" and this will be discussed later in this text. For the purpose of this chapter it is noticed that the local face buckling stress is proportional to the product of face modulus and face thickness squared ($E_f h_f^2$).

Sandwich panels with a web core (Figure 1.5) loaded in compression perpendicular to the corrugations (see Figure 1.14), may fail by local buckling of unsupported segments of both face and web core (Plantema, 1966).

Figure 1.15 shows that local buckling of a web-cored sandwich is a possible failure mode also when the panel is loaded in compression parallel to the corrugations.

The critical load for buckling of the face or web is proportional to the product of modulus and the ratio of thickness to unsupported length squared, i.e. $E(h_f/\lambda)^2$ for face buckling of the sandwich loaded perpendicular to the corrugations (Figure 1.14).

Sandwich panels with honeycomb or web-cores may also buckle locally when the sandwich is loaded in shear. As a guideline, such failures are cir-

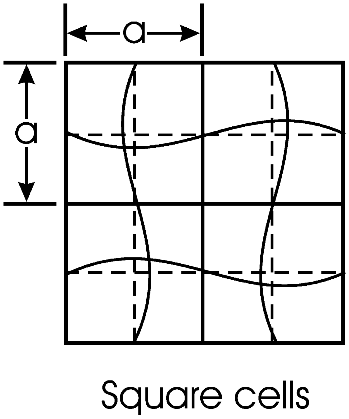

Figure 1.13 Local face buckling in a honeycomb-cored sandwich.

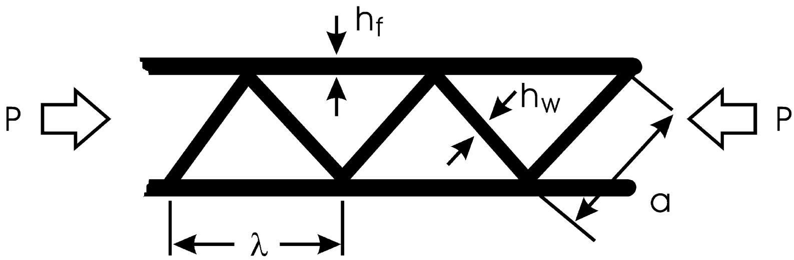

Figure 1.14 Web-cored sandwich loaded perpendicular to the corrugations.

cumvented by using short segments of high local bending stiffness (Eh^3) where h is the wall thickness of the honeycomb or web core.

Sandwich structures may suffer from failure due to concentrated loads acting normal to the plane of the sandwich panel, see Figure 1.16. Localized loads may occur due to hard object impact loading (dropped tools or hull/log collision for example), and at fittings and joints between panel sections.

Failure of sandwich beams due to localized loads have been analyzed by, e.g., Thomsen (1977), Ashby et al. (2000), and Steeves and Fleck (2004). Concentrated loads acting transverse to the plane of the sandwich may produce substantial local deformations of the faces and core, and induce a complex state of stress in the affected regions of the face and core. For the purposes of this chapter, it suffices to mention that the analysis of Ashby et al. (2000), provides an expression where the indentation load is directly proportional to the out-of-plane compression strength of the core. Consequently,

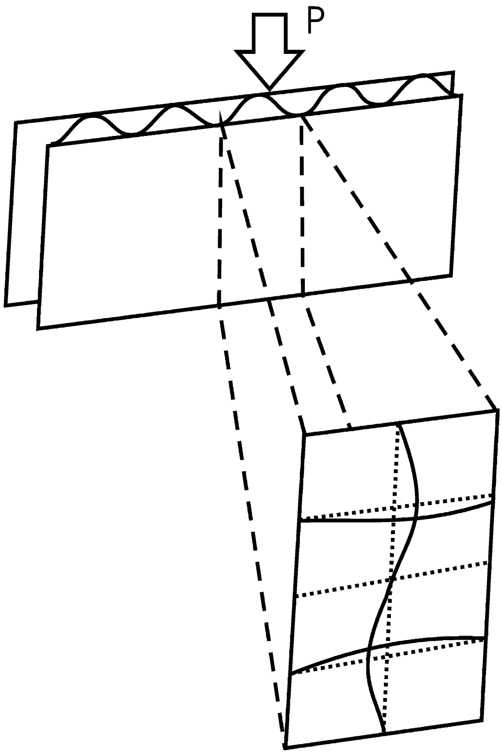

Figure 1.15 Local face buckling in corrugated core sandwich loaded parallel to the corrugations.

the out-of-plane compression stiffnes and strength of the core are important for the ability of the sandwich to resist localized loads.

1.4 Face and Core Materials

The preceding analysis of the stiffness and strength of sandwich has identified several important properties of the face sheets and core. The face sheets need to be stiff and strong in tension and compression to resist the bending and wrinkling loads. The core needs to be stiff and strong under shear and extension in the thickness direction to provide resistance to wrinkling and local indentation failure. At the same time, the core should be of low density in order to minimize the structural weight. Such demands are conflicting since, in general, low density materials are less stiff and strong than materi-

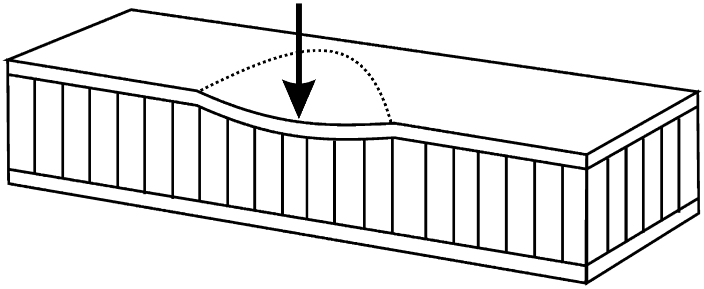

Figure 1.16 Local indentation failure due to concentrated load acting on a sandwich panel.

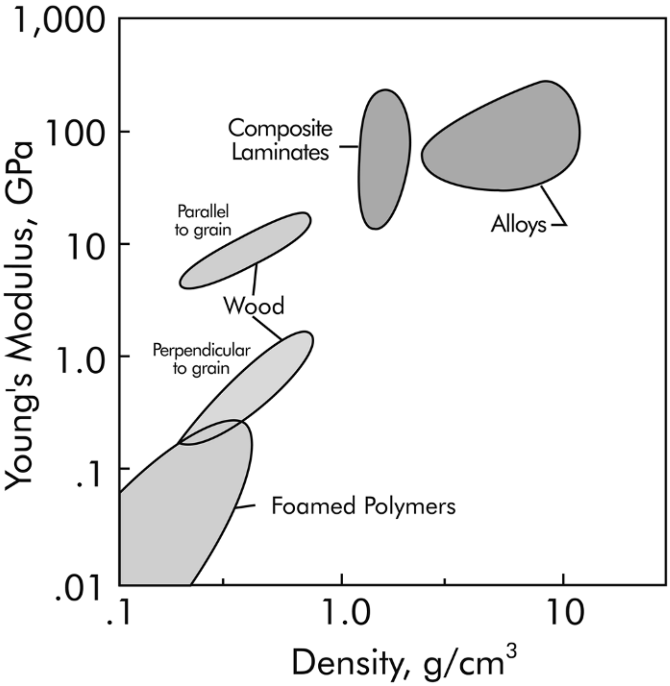

Figure 1.17 Modulus-density chart for various classes of materials. After Ashby (1999).

als of higher density. The selection of face and core materials may be guided by Ashby's materials property charts (Ashby, 1999). An example of such a chart is shown in Figure 1.17.

According to the guidelines outlined above, the face sheets should be made from high modulus materials, i.e., composite laminates or light-weight alloys (see Figure 1.17). The core should be of low density. Consequently, foamed polymers or balsa wood are common selections. In addition to the modulus-density chart shown above, Ashby (1999) presents material property charts for several other important mechanical as well as thermal insulation properties. Such graphs are extremely useful procedures for the proper selection of materials for given structural and thermal requirements.

Some typical mechanical properties of face and core materials will be provided. The mechanical properties of heterogeneous materials such as honeycomb core, foams, and wood are average properties, representative for a large volume of material, being part of a sandwich structure. The face materials may be made from isotropic metals or anisotropic composite laminates. Typically, however, the laminates are symmetric and balanced (same number of plies at positive and negative angles), which simplifies their mechanical description. It must be recognized that the mechanical properties of face laminates vary depending on type of fiber, ply orientation, and volume fractions of fiber and matrix. The type of matrix material will also influence the mechanical properties of the composite. In most applications of sandwich structures, however, the matrix is a thermoset resin such as epoxy, polyester, or vinylester, with much less stiffness and strength than the fibers. Consequently, for fiber-dominated lay-ups, the influence of matrix on the static, short-term mechanical properties is quite small.

Table 1.1 lists density and mechanical properties of some typical face materials. The properties represent short-term, room temperature values, as determined by standard test methods. It must be pointed out that such properties should not be used for actual design purposes since the properties may vary depending on temperature and humidity, and several other controlled and uncontrolled factors. The metal properties were obtained from Daniel and Ishai (2006) and Gere (2004). The S-glass/EP properties were determined by Aviles (2005), while the E-glass/EP and AS4-Carbon/EP properties were determined by Alif and Carlsson (1997).

Cores for sandwich panels are grouped in web core, honeycomb core, foams, and end-grain balsa wood (see Figure 1.5). It should again be pointed out that the most important core properties are the out-of-plane extensional and shear stiffnesses and strengths. It is not always possible or meaningful to test the core isolated without the presence of the faces since the faces tend to stabilize the core, especially for web and honeycomb cores. Furthermore, the mechanical stiffnesses of web cores are highly dependent on the geometry and the material of the web and, for these reasons, it is very difficult to list properties for such cores. For honeycomb cores, the most common materials are Nomex, which is an aramid fiber paper impregnated with a

Table 1.1 Mechanical properties of face materials. ρ = density, E = Young's modulus, G = shear modulus, ν = Poisson's ratio, X = strength, T = tension, C = compression.

Material	ρ g/cm^3	E GPa	G GPa	ν	X_T MPa	X_c MPa
Aluminum (2024-T3)	2.80	73	27.4	0.33	414	414
Steel (AISI 1025)	7.80	207	80.0	0.30	394	394
Titanium	4.40	108	42.4	0.30	550	475
S-Glass/EP[1]	1.73	20.6	3.10	0.12	261	177
E-Glass/EP[1]	2.00	26.6	4.63	0.144	422	410
AS4-Carbon/EP[1]	1.63	59.5	4.96	0.047	584	491

[1]The composites consist of woven 0 and 90°fibers in an epoxy (EP) matrix.

Table 1.2 Mechanical properties of honeycomb core. ρ = density, G = shear modulus, S = shear strength, W = width direction, L = length direction. From Zenkert (1997).

Material	ρ g/cm^3	G_L MPa	G_W MPa	S_L MPa	S_W MPa
Paper	0.056	141	38	1.3	0.48
Aluminum	0.070	460	200	2.2	1.50
Nomex	0.080	69	44	2.2	1.00
Nomex	0.129	112	64	3.2	1.70

polymer resin, usually phenolic, or aluminum alloy. The method of manufacturing of honeycomb core provides a structure with double walls in one direction and single walls in the other. As a result, the mechanical properties are different in the two in-plane principal directions (width W and length L). Mechanical properties of honeycomb cores are considered in great detail by Gibson and Ashby (1997). Product literature sometimes reports on modulus and strength in compression and shear, see, e.g., Hexcel product information www.hexcel.com), while other sources of data, e.g., Vinson (1999), reports only shear moduli. It is not practical to reproduce the very large amount of data on honeycomb cores available in a publication of this nature. Here we will only reproduce some typical data provided by Zenkert (1997), see Table 1.2.

Foams are very common core materials. Most commercial foams are made from polymers, although there is much interest in metallic foams (Ashby et al., 2000), and more recently carbon foams (Sihn and Rice, 2002). The

Table 1.3 Mechanical properties of various polymer foams. ρ = density, G = shear modulus, S = shear strength. Data obtained from Zenkert (1997), DIAB* and Rohacell**.

Material	ρ g/cm^3	G MPa	S MPa
Polyurethane	0.04	4	0.25
PVC H100	0.10	40	1.40
PVC HD130	0.13	40	1.50
PMI 110IG	0.11	50	2.40

*www.diabgroup.com; **www.roehm.com

Table 1.4 Mechanical properties of balsa wood core. ρ = density, G = shear modulus (out-of-plane), S = shear strength (out-of-plane). From www.alcanairex.com.

Product Designation	ρ g/cm^3	G MPa	S MPa
SB50	0.100	110	1.91
SB100	0.151	157	2.94
SB150	0.244	302	4.85

most common polymers used are polyurethane, polyvinylchloride (PVC), and polymethacrylimide (PMI). Such foams are closed-cell structures, making them isotropic and resistant to water penetration.

Balsa wood core is used as the core in structural sandwich panels because of its low density combined with good mechanical properties and a closed-cell structure. As a result of the unidirectional orientation of the fibers along the longitudinal direction of the wood (Figure 1.5), balsa wood is highly anisotropic, with much higher stiffness and strength in the longitudinal (along the grain) than in the radial and tangential directions. Balsa wood utilized as the core in a sandwich structure, is delivered in the desired thickness in the form of small square blocks with the L-direction (fiber direction) in the through-thickness direction, assembled in a panel held together with a scrim cloth on the top and bottom. The blocks are randomly oriented in the plane of the sandwich making the effective properties of the core in-plane isotropic. End-grain balsa wood core is available over a range of densities between about 0.1 to 0.3 g/cm^3. Typical mechanical properties of end grain balsa wood, obtained from Baltek (www.alcanairex.com or www.alcanbaltek.com) are provided in Table 1.4.