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# Preface

This report is a part of the R&D project "The use of stainless steel sandwich panels in transport vehicles" implemented in collaboration between Helsinki University of Technology and VTT Manufacturing Technology. The project is financed by Technology Development Centre of Finland (TEKES) and Finnish industry. Types of sandwich structures, manufacturing technology and applications of sandwich structures are presented in this report.

Espoo, 12 April, 1999

Authors

# Abstract

The aim of this report is to review types of sandwich structures, manufacturing technology and applications of sandwich structures as presented in literature.

Structural design engineer in all sectors of the transport vehicle industry is faced with the challenge to strive lighter and more efficient structures. A proven and well-established solution is the use of composite materials and sandwich structures.

Aluminium honeycomb and sandwich structures are well known in large transportation systems such as aircrafts, ships and railway vehicles. The use of sandwich panels made of steel in heavily loaded structures has been quite unknown.

There is a very wide range of forming and joining techniques available for manufacturing of sandwich structures. The sandwich structures have the potential to offer a wide range of attractive design solutions. In addition to weight savings, these can include space savings, fire resistance, noise control and improved heating and cooling performance.

# Contents

# 1 Introduction

Properties of engineering materials have characteristic ranges of values. In engineering design the performance of the structure is maximized and, e.g., in a load-bearing component this means maximum stiffness/strength for a given weight. The performance of a structure depends on the mode of loading (tension, compression, bending, torsion or a combination of them), on the shape of the section (solid, tubular, I-section and so on) as well as on the properties of a material (modulus, strength, toughness, cost, etc.). Ashby (1989, 1991) has proposed a materials selection method and a technique by which from a large group of materials and section shapes available a combination which maximises the performance can be made. Firstly, the weight-saving potential of the canditate materials can be evaluated by a graphical method from a double logarithmic plot of Young's modulus/strength against density, Figs 1 and 2.

By considering a number of idealized design cases, it is possible to show that the weight of the structural component is proportional to one of the following material parameters (performance or merit indices): $E/\rho$ $(\sigma_f/\rho)$ (tie), $E^{1/2}/\rho$ $(\sigma_f^{2/3}/\rho)$ (column), or $E^{1/3}/\zeta$ $(\sigma_f^{1/2}/\rho)$ (plate). For any given value of each of these parameters a straight line representing these parameters can be drawn on the diagram. This is giving the properties of a solid section. However, many materials are available also as very efficient structure such as thin-walled tube, honeycomb, sandwich structures and the like. What is then the best material-and-shape combination?

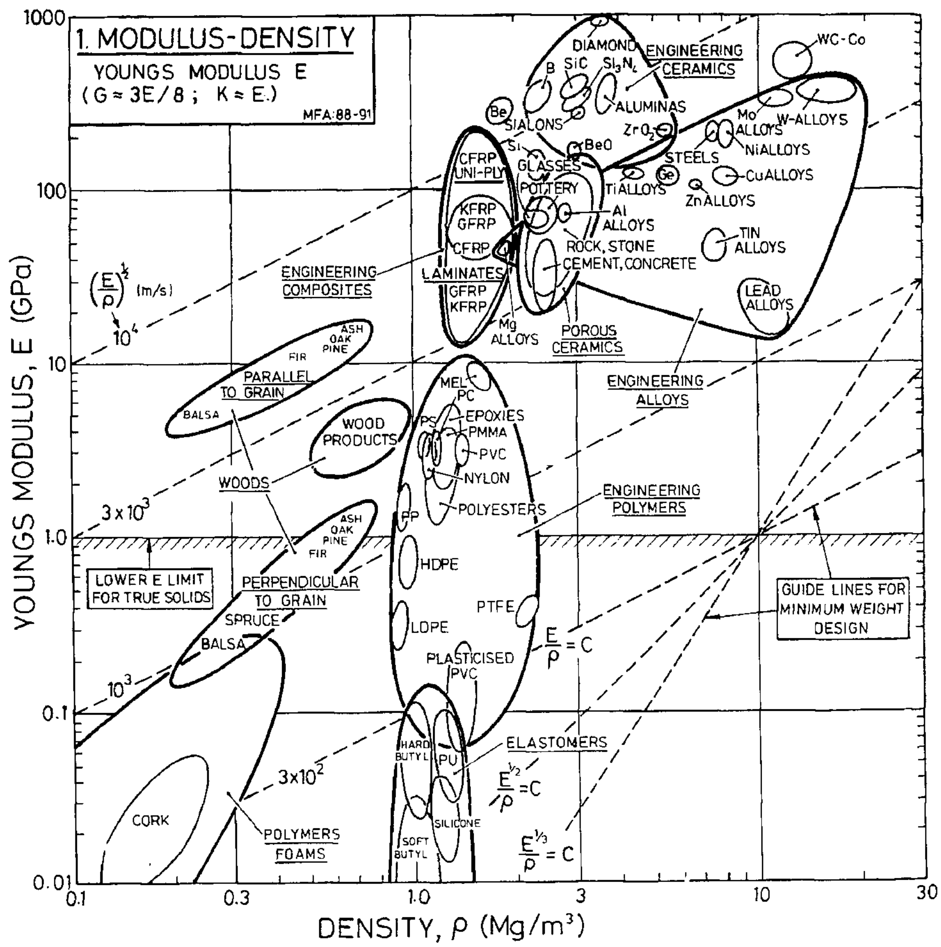



Fig. 1. Young's modulus, E, plotted against density, ρ. The heavy envelopes enclose data for a given class of material. The guide lines of constant E/ρ, $E^{1/2}/\rho$ and $E^{1/3}/\rho$ allow selection of materials for minimum weight, deflection-limited design (Ashby 1992).

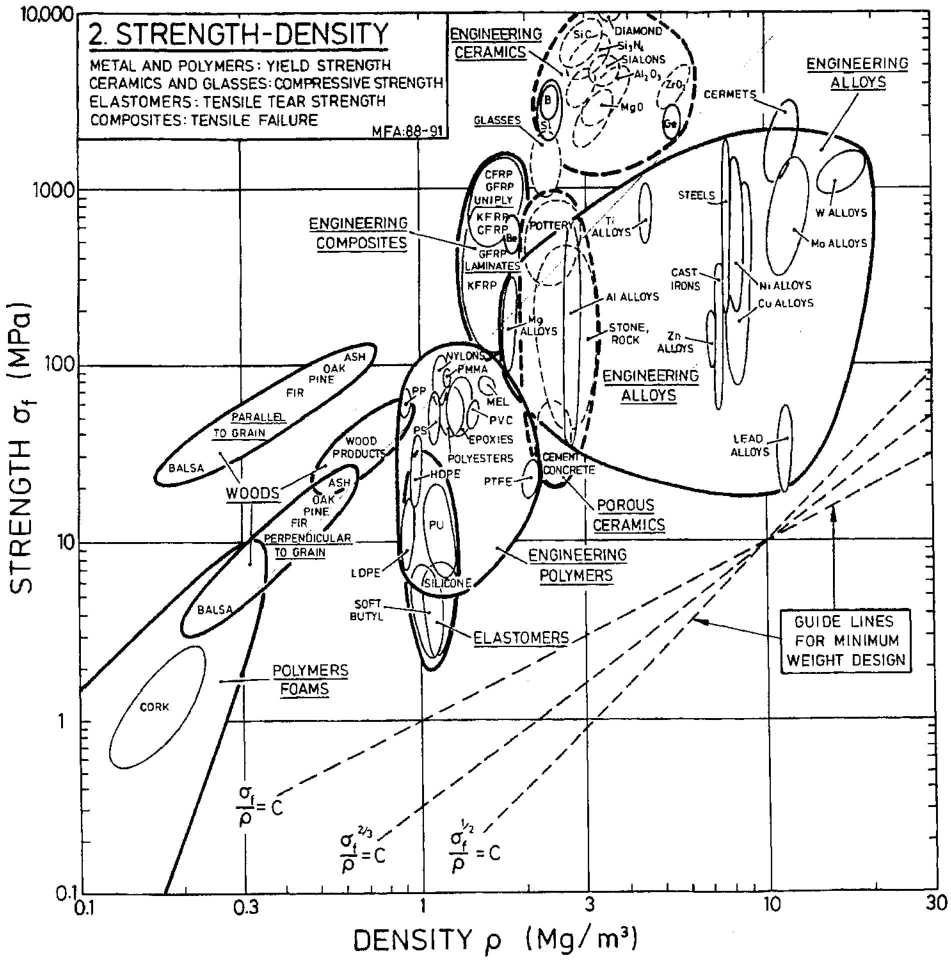


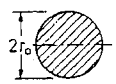
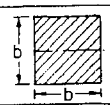
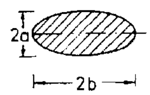
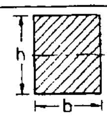
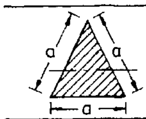
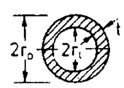
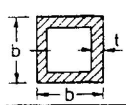
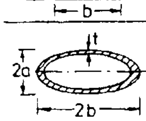
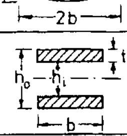
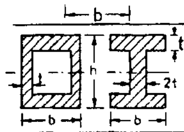
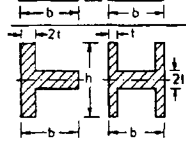
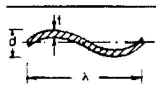

Fig. 2. Strength $\sigma_f$, (yield strength for metals and polymers, compressive strength for ceramics, tear strength for elastomers and tensile strength for composites), plotted against density, $\rho$. The guide lines of constant $\sigma_f/\rho$, $\sigma_f^{2/3}/\rho$ and $\sigma_f^{1/2}/\rho$ are used in minimum weight, yield-limited design (Ashby 1992).

Almost always one mode of loading dominates in loading (axial tension or compression, bending, and torsion), Fig. 3, and the best material-and-shape combination depends on the mode of loading. In axial loading, the area of the cross-section is important but its shape is not: all sections of the same area will carry the same load. In bending and torsion the shape is very important: beams of hollow or I-sections are better than solid sections and circular tubes are better than either solid sections or I-sections, respectively. Ashby (1991) has defined a shape factor ($\phi$) for each section shape and each mode of loading, respectively, which is a dimensionless number depending on shape but not on scale, thus, characterizing the efficiency of a shape. The shape factors are tabulated for a number of common sections by Ashby (1992). The shape factor of a solid bar with a circular cross-section is one (1). Shape factors for more efficient shapes are given in Table 1 for elastic and failure loading. It can be seen that if the sections are elongated, hollow, or corrugated, the shape factor increases and can be for a slender thin-walled steel tube of 30 or more. With this kind of shapes with less material (and weight) same bending stiffness or strength can be achieved. Failure in bending and torsion through plasticity starts when the yield stress is reached and fracture occurs when the stress exceeds somewhere the ultimate tensile strength.

The shape factors achievable are limited by manufacturing constraints or by local buckling, which sets practical upper limits to the shape factors. For example, the optimal choice of shape factors for tubular columns can be determined to be for aluminum between 20...30 (Ashby 1991). In principle, similar approaches can also be applied for bending beams and sandwich panels, even though the problem of identifying of optimal value of shape factor is much more complex (Huang and Gibson 1995; Wegner and Gibson 1995). For example, bracing or foam support can suppress local buckling as a failure mode. This allows a further increase of shape factor until failure by new localized buckling mode appears or manufacturing constraints limit the design.

Table 1. Shape factors (Ashby 1992).

## SHAPE FACTORS

| SECTION SHAPE | STIFFNESS $\Phi_B^e$ | STIFFNESS $\Phi_T^e$ | STRENGTH $\Phi_B^f$ | STRENGTH $\Phi_T^f$ |
|---|---|---|---|---|
|  | 1 | 1 | 1 | 1 |
|  | $\frac{\pi}{3} = 1.05$ | 0.88 | $\frac{4\pi}{9} = 1.40$ | 0.55 |
|  | $\frac{a}{b}$ | $\frac{2ab}{(a^2+b^2)}$ | $\frac{a}{b}$ | $\frac{a}{b}$ $(a<b)$ |
|  | $\frac{\pi}{3}\frac{h}{b}$ | $\frac{2\pi}{3}\frac{b}{h}(1-0.58\frac{h}{b})$ $(h>b)$ | $\frac{4\pi}{9}\frac{h}{b}$ | $\frac{4\pi}{9}\frac{(b/h)}{(1+0.6b/h)^2}$ $(h>b)$ |
|  | $\frac{2\pi}{3\sqrt{3}} = 1.21$ | $\frac{2\pi}{5\sqrt{3}} = 0.73$ | $\frac{\pi}{3\sqrt{3}} = 0.60$ | 0.39 |
|  | $\frac{r}{t}$ | $\frac{r}{t}$ | $\frac{2r}{t}$ | $\frac{2r}{t}$ |
|  | $\frac{\pi}{6}\frac{b}{t}$ | $\frac{\pi}{8}\frac{b}{t}(1-\frac{t}{b})^4$ | $\frac{4\pi}{9}\frac{b}{t}$ | $\frac{\pi}{4}\frac{b}{t}(1-\frac{t}{b})^4$ |
|  | $\frac{a}{t}\frac{(1+3b/a)}{(1+b/a)^2}$ | $\frac{8(ab)^{5/2}}{t(a^2+b^2)(a+b)^2}$ | $\frac{a}{t}\frac{(1+3b/a)^2}{(1+b/a)^3}$ | $\frac{16a}{t(1+a/b)^3}$ |
|  | $\frac{\pi}{2}\frac{h^2}{bt}$ | — | $2\pi\frac{h^2}{bt}$ | — |
|  | $\frac{\pi}{6}\frac{h}{t}\frac{(1+3b/h)}{(1+b/h)^2}$ | I: $\frac{\pi b^2h^2}{t(h+b)^3}$; □: $\frac{\pi}{3}\frac{t}{b}\frac{(1+4h/b)}{(1+h/b)^2}$ | $\frac{2\pi}{9}\frac{h}{t}\frac{(1+3b/h)^2}{(1+b/h)^3}$ | I: $\frac{2\pi h^2}{bt(1+h/b)^3}$; □: $\frac{2\pi}{9}\frac{t}{b}\frac{(1+4h/b)^2}{(1+h/b)^3}$ |
|  | $\frac{\pi}{6}\frac{h}{t}\frac{(1+4bt^2/h^3)}{(1+b/h)^2}$ | H: $\frac{\pi}{6}\frac{t}{h}\frac{(1+8b/h)}{(1+b/h)^2}$; ⊢: $\frac{\pi}{3}\frac{t}{h}\frac{(1+4b/h)}{(1+b/h)^2}$ | $\frac{\pi}{4}\frac{h}{t}\frac{(1+4bt^2/h^3)^2}{(1+b/h)^3}$ | H: $\frac{\pi}{18}\frac{t}{h}\frac{(1+8b/h)^2}{(1+b/h)^3}$; ⊢: $\frac{2\pi}{9}\frac{t}{h}\frac{(1+4b/h)^2}{(1+b/h)^3}$ |
|  | $\frac{\pi}{2}\frac{d^2}{t\lambda}$ | — | $\pi\frac{d^2}{t\lambda}$ | — |

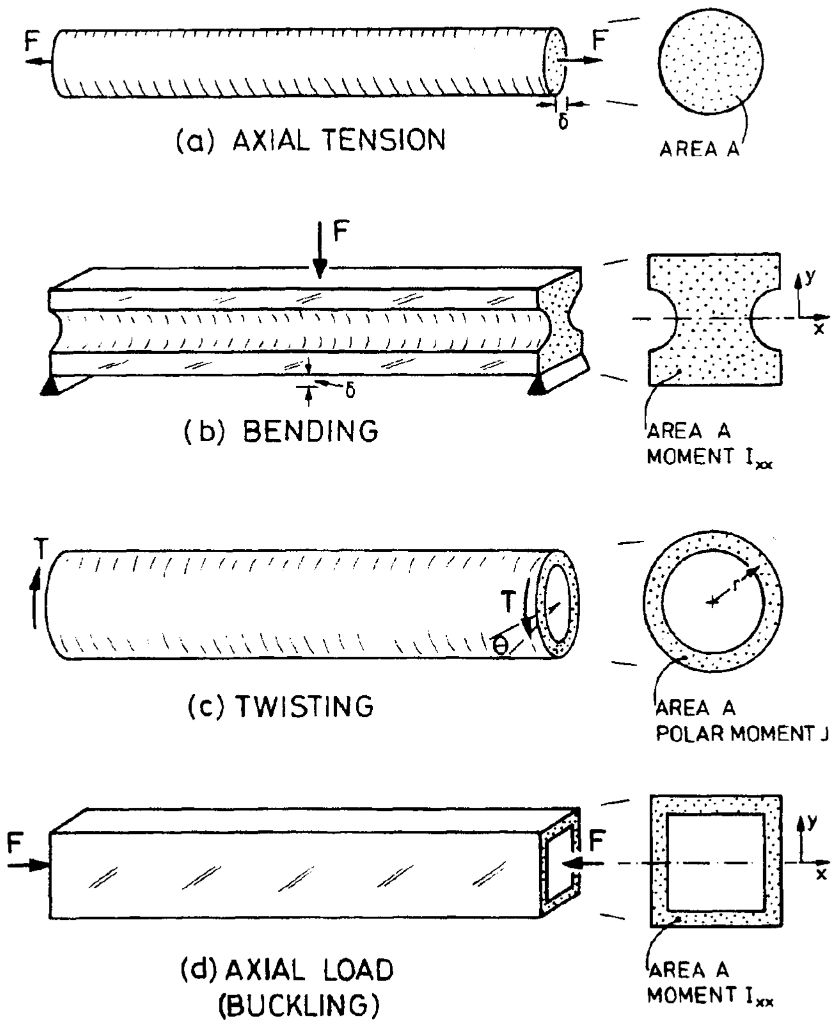



Fig. 3. Common modes of loading: (a) axial tension, (b) bending, (c) torsion and (d) axial compression, which can lead to buckling (Ashby 1992).

The mechanical efficiency is not only obtained by combining material properties with macroscopic shape. Efficiency can also be obtained in another way: through internal shape or on a small scale through microscopic or microstructural shape, Figs 4 and 5. Wood is an excellent example of this consisting of a solid component of cellulose as prismatic cells and lignin and other polymers. The added microstructural efficiency through dispersion of the solid as compared to the axis of bending and torsion is characterised by a microscopic shape factor, $\psi$. Characteristic for the microscopic shape is that it repeats itself extensively. Many natural materials have microscopic shape such as wood, bone, stalk and cuttle having high stiffness at low weight. Figure 6 shows in a) wood-like structure, in b) palm tree structure, in c) a structure typical for stem of some plants and in d) a multiple sandwich panel structure common for the shell of some fish. The microscopic shape factor, $\psi$, is defined in the same way as the macroscopic one. For example, the microscopic shape factor for wood (prismatic cells with prism axis normal to the axis of bending) is $\zeta_s / \zeta^*$ , where $\zeta^*$ is the overall density of the structure and $\zeta_s$ is that of the solid. The overall shape factor is the product of the macroscopic and microscopic shape factors as shown in Fig. 7. The microstructured material having microscopic shape can be thought as new material having density, strength, thermal conductivity and so on of its own, if the section is large enough as compared to the cell size, when properties are not size dependent any more. The best material-and-shape combination is that with the greatest value of the performance/merit index.

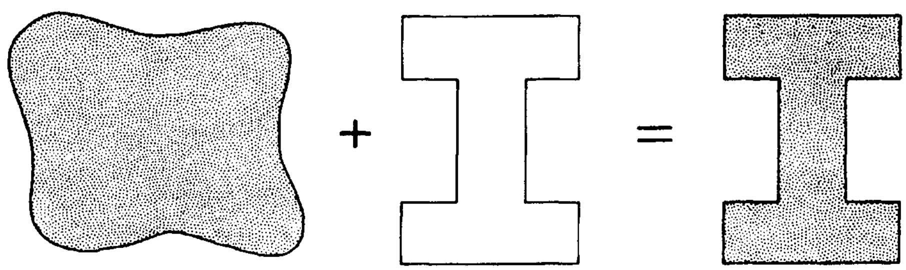


Fig. 4. Mechanical efficiency is obtained by combining material with macroscopic shape. The shape is characterised by a dimensionless shape factor, $\phi$ (Ashby 1992).

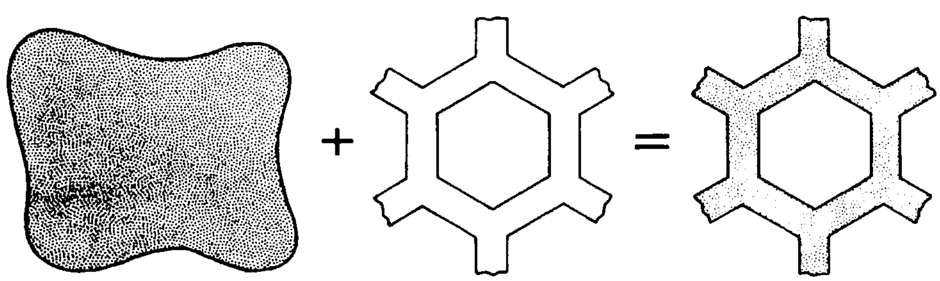


Fig. 5. Mechanical efficiency can be obtained by combining material with microscopic, or internal shape, which repeats itself to give an extensive

structure. The shape is characterised by microscopic shape factor, $\psi$ (Ashby 1992).

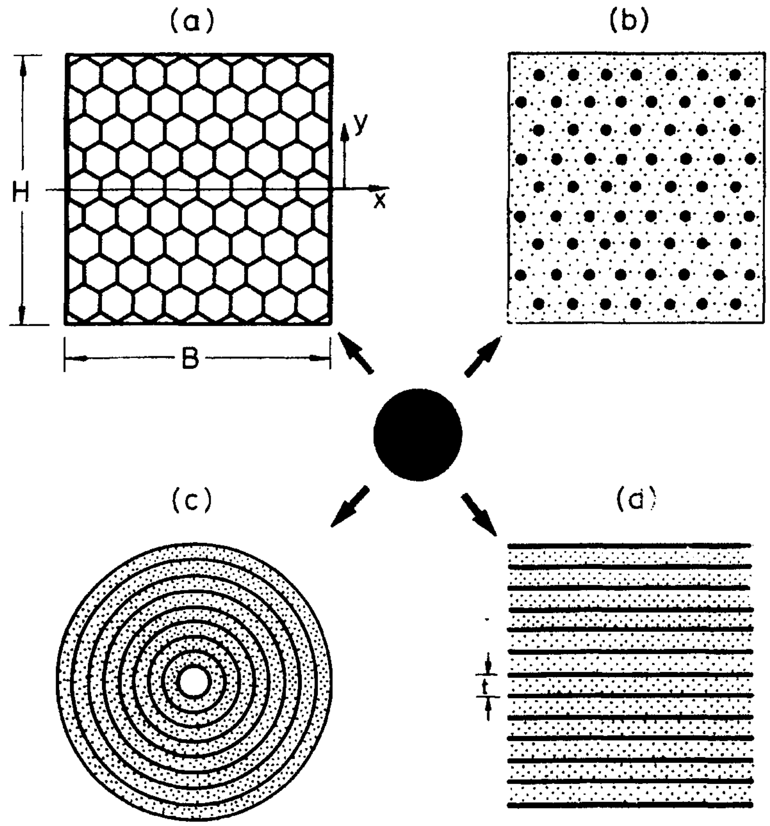



Fig. 6. Four extensive microstructured materials which are mechanically efficient: (a) prismatic cells, (b) fibres embedded in a foamed matrix, (c) concentric cylindrical shells with foam between and (d) parallel plates separated by foamed spacers (Ashby 1992).

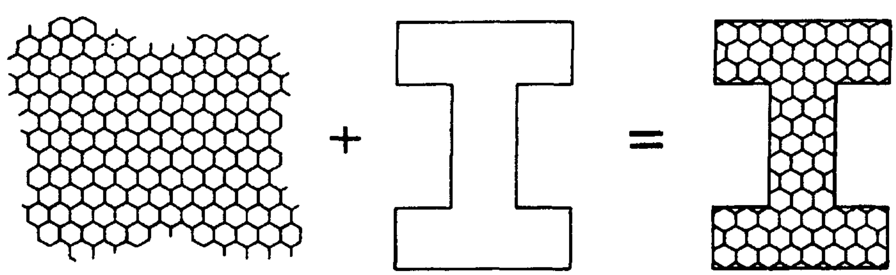



Fig. 7. Microstructural shape can be combined with macrostructural shape to give efficient structures. The overall shape factor is a product of the microscopic and macroscopic shape factors (Ashby 1992).

There are limits to the shape factors which depend mainly on the material properties, i.e., they are limited either by local buckling or by manufacturing constraints. If manufacturing is possible the structures can be further optimized by suppressing local buckling by adding ribs and stringers thereby allowing higher shape factors. Also even better combination of microscopic and macroscopic shape can result in efficiently microstructured materials where the small scale is causing again manufacturing constraints. However, it has also to be remembered that these materials/structures are anisotropic, which is very important in multiaxial loading. Also other performance criteria as minimizing weight are present, such as minimizing volume of the structure or, for example, maximizing energy storage or damping capacity, etc.

However, the design of large transportation systems such as busses, ships, railway vehicles and aircrafts is always determined by considerations of weight. A proven and well-established solution is the use of composite materials and sandwich structures. In this way high strength/weight ratio and minimum weight can be obtained. The right choice of sandwich materials and competitive manufacturing method for the components are the keys to successful overall concept. The sandwich structures have the potential to offer a wide range of attractive design solutions. In addition to weight savings, these can include space savings, fire resistance, noise control and improved heating and cooling performance.

## 2 Sandwich structures

The most simple type of sandwich structure consists of two thin, stiff and strong sheets of dense material separated by a low density material which may be less stiff and strong (Figs. 8 and 9). As a crude guide to the proportions, an efficient sandwich is obtained when the weight of the core is roughly equal to the combined weight of the faces. Obviously the bending stiffness of this arrangement is very much greater than that of a single solid plate of the same total weight made of the same material as the faces (Allen 1969, Zenkert 1997).

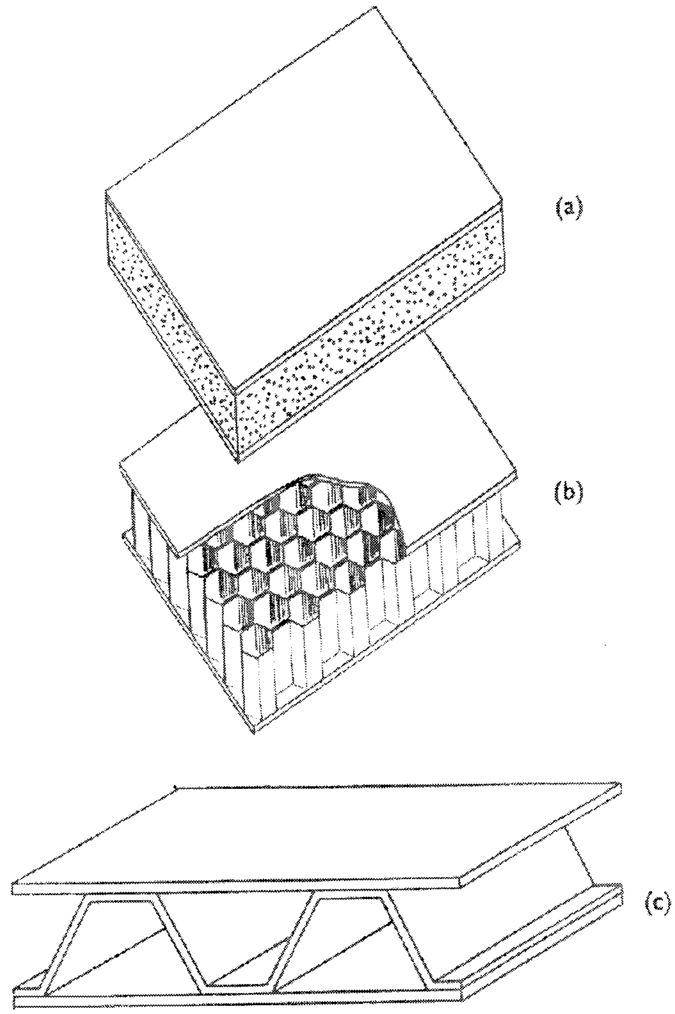



Fig. 8. Sandwich panels with a) expanded plastic core, b) honeycomb core and c) corrugated core (Allen 1969).

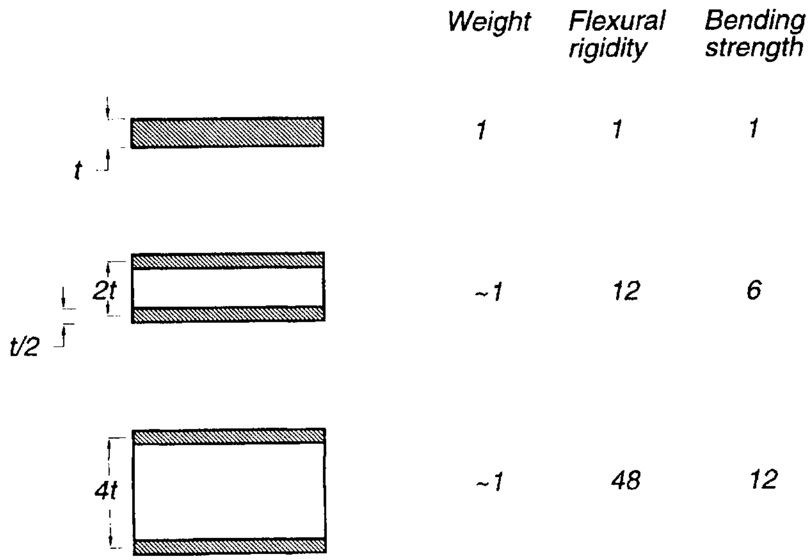



Fig. 9. Comparison between homogeneous and sandwich cross-sections (Zenkert 1997).

## 2.1 *Types of sandwich structures*

The core has several important functions. It must be stiff enough in the direction perpendicular to the faces to ensure that they remain at the correct distance apart. It must be stiff enough in shear to ensure that when the panel is bent the faces do not slide over each other. If this last condition is not fulfilled the faces behave only as two independent beams or panels and the sandwich effect is lost. The core must also be stiff enough to keep the faces nearly flat. Otherwise it is possible for a face to buckle locally under an influence of compressive stress in its own plane. The core must satisfy all these requirements and it is also important that the adhesive (if used) should not be flexible to permit substantial relative movements of the faces and the core. If the core is stiff enough it may make a useful contribution to the bending stiffness of the panel as a whole (Allen 1969, Vinson 1999).

Variations of the sandwich structure are shown in Figs. 10. The simple parallel-strip arrangement of Fig. 10a is sometimes stiffened by the addition of expanded plastics to fill the voids. The tubular core of Fig. 10b and the double truss-core of Fig. 10c are rather rare. The dimpled core shown in Fig. 10d is similar in appearance to the pulpboard commonly used for packing eggs.

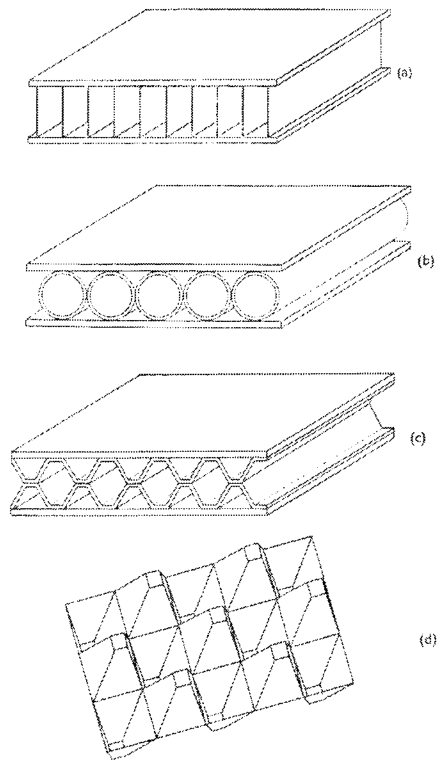



Fig. 10. Variations of the sandwich structure (Allen 1969).

### 2.1.1 *Solid-core sandwich*

In this case the core is of very low density. The core fills the whole space between the faces. Originally, sandwiches with plywood and hardwood faces were used for lightly loaded applications. Nowadays, solid-core sandwiches are used extensively in wall and roof constructions. The faces are usually made of steel, aluminium, fibre-reinforced plastic material etc. The core may be made of cork, rubber, solid plastic material, rigid foam material (polystyrene and polyurethane) (Norris 1987).

### 2.1.2 *Honeycomb-core sandwich*

The honeycomb core is made of very thin ribbons of material, shaped and bonded together at intervals. Often both the faces and the core are made of aluminium alloy. The heavier aluminium honeycomb cores are made by forming aluminium ribbons into a corrugated shape and then bonding them together. However, especially for lighter applications, flat ribbons of aluminium are usually bonded together at intervals and then expanded by pulling apart. Metal honeycomb sandwiches are light, strong and stiff and have found a wide application as load-carrying components in aircrafts, trains, ships and rockets (Siebert 1987). There are several variations of the honeycomb core. The deformed honeycomb and multiwave core which is made of wrinkled metal foil, are both more easily bent than the simple honeycomb and are used primarily in curved sandwich panels (Norris 1987).

### 2.1.3 *Ribbed-core sandwich*

Ribbed-core sandwiches are often used as internal partitions in buildings and are usually made with plasterboard faces and with resin-ribbed cores. Doors are commonly made with hardboard faces and resin-paper ribbed cores. In these applications a two-way ribbed core is used, which can only be made easily by making slots in the ribs. However, one-way ribbed cores are much easier to fabricate, but these are obviously very weak in one direction and thus are not often used, although a type with resin-paper ribs and with the voids filled with expanded polystyrene has been tried (Norris 1987).

### *2.1.4 Corrugated-core sandwich*

A corrugated core consists of a single sheet of material, deformed in various ways. The basic corrugated core sandwich is fabricated from three metal sheets, using adhesives, rivets or welds. A variation is the double-layer core which is similar in some ways to the tubular core. All these corrugated core sandwiches are stiff in the direction of the corrugations, but less stiff at right angle to the corrugation direction. If identical properties are required in the principal directions, it is necessary to use the "egg-box" core.

The hat types corrugated core sandwich is a periodic structure. The basic cells of these structures have an important number of design parameters (Fig. 11). These parameters are (Barre et al. 1987):

- the thickness of face plates
- the period of the basic cell
- the thickness of the structure
- the angle of the corrugation
- the sequence and thickness of the corrugation
- the core material between the corrugation.

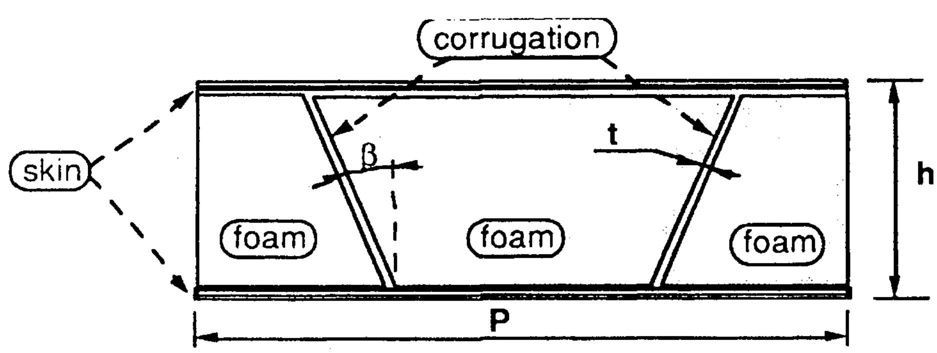



Fig. 11. Basic cell of corrugated sandwich structure (Barre et al. 1987).

Aluminium honeycomb and sandwich structures are well known in large transportation systems such as aircrafts, ships and railway vehicles (Siebert 1987). Corrugated core sandwich panels have long been used in lightweight structures, predominantly lightly loaded aircraft parts. The use of such panels made of steel in heavily loaded structures has been quite unknown. The production difficulties have prevented the wide spread use of the steel corrugated core sandwich panels (Kattan 1987). A new-type honeycomb structure, which is called as "all-laser-welded honeycomb structure" has been developed in Japan. This panel is made of high corrosion resistance stainless steel, and is produced by laser welding for the joining of the core, face sheets and flanges (Oikawa et al. 1993). The aerospace industry also uses a superplastic forming/diffusion bonding technique to form lightweight structures. This requires a superplastic forming material which are currently aluminium and titanium alloys (Ayres & Riches 1996, Impiö 1998).

# 3 Mechanical properties

The correct design of the details of sandwich constructions is at least as important as the analysis of deflections, stresses and buckling loads. These details include nature of the edge members, splices and joints in the cores and faces, stiffeners and inserts to distribute concentrated loads, type of adhesive and method of fabrication (Allen 1969).

Sandwich panels can fail in several ways, each one of these failure modes giving one constraint on the load bearing capacity of the sandwich. The most common failure modes are schematically illustrated in Fig. 12.

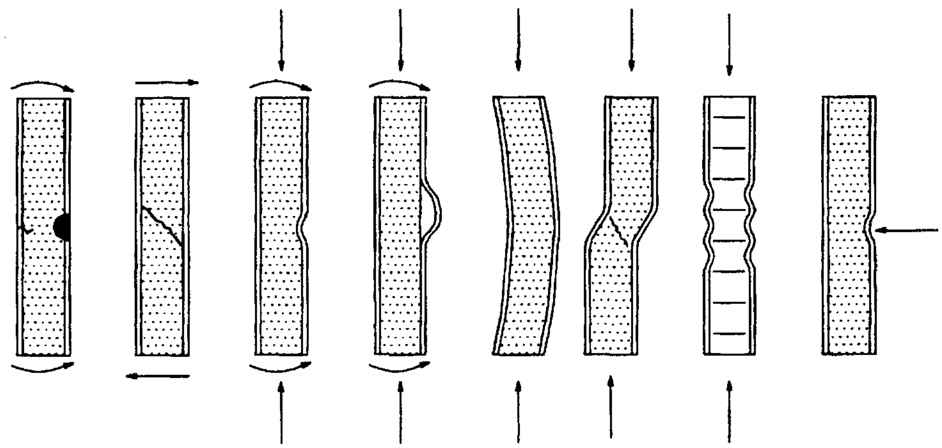



Fig. 12. Failure modes in sandwich beams. a) Face yielding/fracture, b) core shear failure, c) and d) face wrinkling, e) general buckling, f) shear crimping, g) face dimpling and h) local indentation (Zenkert 1997).

The bending stiffness of the board is generally much larger in the MD-direction than in the CD-direction, while the reverse is true for transverse shear stiffness, see Fig. 13. This means that the direction of the large bending stiffness (MD) coincides with the direction of low transverse shear stiffness. Sufficient magnitudes of the shear stiffness are required in order to achieve sufficient strength and stability of sandwich structures. For corrugated core plate this means that the overall structural stiffness and stability may suffer because of low shear stiffness in the MD-direction (Nordstrand & Carlsson 1987).

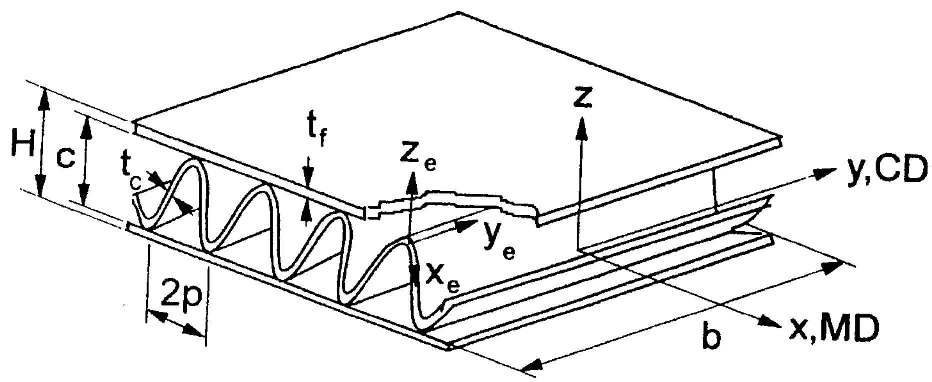



Fig. 13. A sandwich with a corrugated core (Nordstrand & Carlsson 1987).

The failure criteria of corrugated core sandwich panels are not as well established as the linear stress analysis methods. As these structures are constructed from thin plates, local instabilities of a face of core plates must be considered as possible failure modes. Under bending one of the face plates and part of the corrugated core are under compression and can buckle (Kujala 1987).

Any new form of sandwich construction should be subjected to tests to verify the applicability of the formulae for wrinkling, tensile bond failure or intercellular buckling of the faces. Such tests are easily carried out by subjecting a short sample of a complete sandwich to a compressive load. It is often desired to determine the flexural and shear stiffnesses of a particular sample of sandwich construction and the three-point load test is commonly used for this purpose (Allen 1969).

Roberts (1983) and Roberts and Newark (1997) have developed simple solutions for predicting ultimate loads for girders under patch loading. The solution for web buckling is based on the formation of plastic yield lines in the web plate and plastic hinges in the flange (Fig. 14).

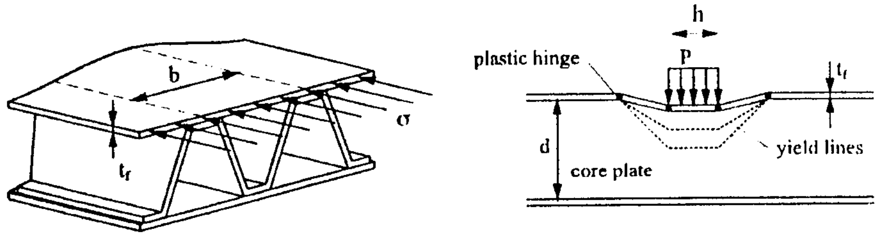



Fig. 14. Collapse mechanism of a web of corrugated-core sandwich (Roberts 1983).

Roberts (1983) has given two equations for the ultimate load. The basic forms of the equations are based on the analysis of the solution and thereafter some complex parametres are adjusted using observations of numerous tests on slender plate girders. The web buckling can be assumed to be similar for sandwich panels and in the following these equations are used for comparison purposes so that the load is multiplied by 2 to take into account that there are 2 web plates on the corrugated core under the local load. The equations for the ultimate load $P_u$ get the form (Roberts 1983, Roberts and Newark 1997):

$$P_u = t^2 c \left\{ E\sigma_{yc} \frac{t_f}{t_c} \right\}^{0.5} \left\{ 1 + \frac{3h}{d} \left( \frac{t_c}{t_f} \right)^{1.5} \right\} \left\{ 1 - \left( \frac{\sigma_b}{\sigma_{yc}} \right)^2 \right\}^{0.5} \quad (1)$$

$$P_u = \frac{2}{F} \left[ 1{,}1 t^2 c \left( E\sigma_{yc} \right)^{0.5} \left( \frac{t_f}{t_c} \right)^{0.25} \left( 1 + \frac{ht_c}{dt_f} \right) \right] \left\{ 1 - \left( \frac{\sigma_b}{\sigma_{yc}} \right)^2 \right\}^{0.5} \quad (2)$$

Where d is the height of the beam, h is load height, E is elastic modulus, t is plate thickness and $\sigma_y$ is yield stress with subscripts c and f referring to core and face plate and $\sigma_b$ is the stress due to the global bending of the panel under consideration. On equation (2) F is a safety factor, which is recommended to be taken as 1,45.

B6 is a Finnish building rule for thin steel plate constructions. The rule gives an empirical equation, which is intended to estimate the strength of corrugated plates under point loading.

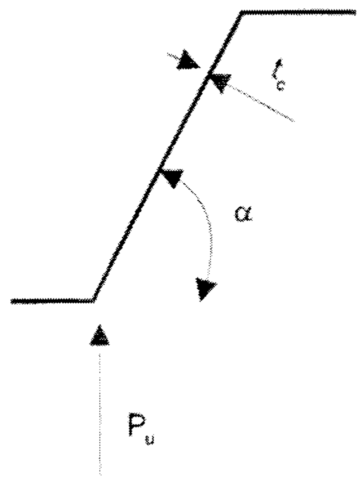



Fig. 15. Definitions for corrugated core according to B6 rule (Anon. 1989).

For the detail shown in Fig.15, the resistance to point load can be calculated from the equation (3) (Anon. 1989):

$$P_u = 2\left(1 + 0{,}01\frac{h}{t_c}\right)\sigma_{yc}t^2c\left(4{,}3 - 765\frac{\sigma_{yc}}{E}\right)\left(2{,}4 + \left(\frac{\alpha}{90}\right)^2\right) \qquad (3)$$

Here also the load is multiplied by 2 to take into account that in the sandwich structure shown in Fig. 14, there are 2 web plates under the load.

The airborne sound transmission losses of the conventional steel grillage and Lascor panels have been tested at the Turku Regional Institute of Occupational Health (Kujala 1995). Three tests were conducted with the Lascor panel: 1) Lascor with no insulation, 2) Lascor with 1,5 mm thick rubber layer on the upper surface and 3) Lascor with 55 mm mineral wool inside and 1,5 mm thick rubber layer. The Lascor panel has better sound absorption characteristics than the conventional panel with frequencies higher than 1600 Hz but with lower frequencies the conventional panel is somewhat better. The higher mass of the conventional panel is the main reason for the higher sound transmission loss with lower frequencies.

# 4 Manufacturing technology

There is a very wide range of forming and joining techniques available for manufacturing of sandwich structures. These techniques are well known and understood for traditional "monolithic" construction. However, there are a number of special considerations when a sandwich design is proposed.

## *4.1 Laser welding of stainless steel*

This is a high-speed, low-distortion welding process which can be used for attaching the skins to a corrugated core. A continuous "stake-weld" is produced which penetrates through the face plate and into the core. Since the process does not require access from both sides of the joint it is possible to attach both skins by this method. A disadvantage of the process is the high capital cost of the equipment and surface damage to the skins (Koli 1998).

Austenitic stainless steel is ideally suited for laser welding. Austenitic stainless steel has a thermal conductivity of one third of carbon steel and is good absorber of laser light. One of the reasons why austenitic stainless steel is ideally suited for laser welding is because the low heat input and high welding speeds do not allow metallurgical damage to occur which can impair the corrosion resistance of the weld metal. Another advantage of using laser to weld austenitic stainless steels is the small weld distortion produced by the low heat input and the laser weld shape.

### 4.2 *Resistance spot welding of stainless steel*

This technique is widely applied in the manufacture of automotive bodies and domestic appliances. Although it may appear attractive for the assembly of sandwich panels employing a corrugated steel core, the technique does have some disadvantages. Firstly, since access from both sides is required it is usually only possible to attach one of the face plates to the core by this method (see Chapter 11). Secondly, the face plate may be very sensitive to local buckling between the individual spot welds, and this tendency is aggravated by the initial out-of-plane displacements resulting from the inevitable welding distortion. Thirdly, the external face will be cosmetically damaged by the weldspots and the distortion (Davies 1987).

Resistance spot welding joins metals and metal alloys by applying pressure to and passing high-density current through the joint area for a length of time. The process uses no flux or filler metals. The process generates heat and energy rapidly in the weld zone. To form a spot weld, the most common type of resistance weld, workpieces overlap and current passes among stationary electrodes through a localized contact area. Electrodes apply force to the workpieces to develop good electrical contact and to contain the molten weld metal (Brosilow 1994, Talonen 1997).

The process can be found in numerous industries joining a range of products from 0,02 mm diameter wires to sheets and plates with joint thickness of 25 mm or more. The most obvious application is automobile manufactures where resistance welding is used to build bodies, frames, housings, levers, wheels and seats. The process is ideal for high-speed joining of small accessories such as braces and brackets (Brosilow 1994).

Spot welding of stainless steel is commercially used. Among the high-alloy steels, the stainless steels are the most commonly welded. The domestic appliance industry presents numerous examples of spot welding stainless steel. Sensitization is not usually a concern during resistance welding, where heating cycle is short (Bernabai et al. 1997).

Procedures for spot welding of the stainless steels are similar to those for low carbon steel. Current levels are 20 to 50 % lower, since electrical resistance of the material is higher. Welding time is less, since thermal conductivity is low. Force is higher since the stainless steel retains its strength at elevated temperatures. These differences result in greater control over the welding cycle, since reduced time and current magnify the variations in these parameters. With its higher coefficient of thermal expansion, stainless steel is more susceptible to distortion than low carbon steel (Brosilow 1994, Talonen 1997).

## 4.3 *Adhesive bonding of stainless steel*

This technique has a number of advantages, and in the case of low-density foam cores, it may be the only practical method of attaching the skins. The technique produces little or no distortion, provides continuous attachment of the skin to the core, and gives a smooth, stain-free external surface. From the performance point of view, panels fabricated in this way usually have limited resistance to elevated temperatures (such as in a fire), and may be subjected to long-term degradation in service. From the production point of view, the curing times for the adhesives may be inconveniently long, and fabrication procedures need to be closely controlled to avoid defective joints. Although stress distributions in adhesively bonded joints have been a subject of much study, many engineers remain sceptical concerning the design of such joints for structural connections; however, since sandwich construction is mainly attractive for long-span panels, and since a large width is normally available for bonding, and since optimum panels tend to have thin skins, it is usually found that average shear stresses in the bonds are quite modest. The limitations of adhesive bonding may be overcome to a great extent by using adhesives as part of a hybrid joining method (see Chapter 4.8) (Davies 1987).

Stainless steel alloys have often proved to be difficult to bond, because of their inherently passive, non-interacting surfaces, which characterise these alloys. As a consequence of this, mechanical and/or chemical pre-treatments are often used to modify the surface of stainless steel adherends, in order to improve joint performance. The development of the toughened adhesives has helped to relieve the problem: toughened acrylic and single-part epoxy types will bond these alloys well, giving high initial joint strengths. Abrasion followed by a solvent wipe may be sufficient for low load applications, although chemical treatments will almost invariably be necessary when good durability in demanding environments is a requirement (Boyes 1995).

# 5 Adhesives

The most commonly used chemically reactive structural adhesives are epoxies, polyurethanes, modified acrylics, cyanoacrylates and anaerobics. Epoxies provide strong joints and their excellent creep properties make them ideal for structural applications, but unmodified epoxies have only moderate peel strength and low impact toughness. The advantages and limitations of the five most popular structural adhesives are summarized in Table 2 (Boyes 1995).

Adhesive selection is influenced by many factors which include: the materials to be bonded (compatibility of adherends and adhesives), the surface preparation requirements, the desired joint design, the assembly, processing and storage requirements, the desired properties and service requirements, and the cost.

The strength of an adhesive joint depends not only on the cohesive strength of the adhesive, but also on the bond strength at the adherend/adhesive interface. Adhesion at the interface occurs within a layer of molecular dimensions. The presence of surface contaminations, which are themselves weakly adherent and which prevent contact between the adhesive and the adherend, can reduce the bond strength considerably. Certain adhesives are available, which can tolerate contaminants such as light-machine or protective oils, but the type of contaminants needs to be carefully matched with the adhesive type and its thickness has to be controlled to enable the adhesive to dissolve and displace the contaminant adequately (Boyes 1995).

Table 2. The advantages and limitations of the five most popular structural adhesives (Brinson 1990).

| EPOXY | POLYURETHANE | MODIFIED ACRYLIC | CYANOACRYLATE | ANAEROBIC |
|---|---|---|---|---|
| **Advantages** | | | | |
| High strength<br>Good solvent resistance<br>Good gap-filling capabilities<br>Good elevated-temperature resistance<br>Wide range of formulations<br>Relatively low cost | Varying cure times<br>Tough<br>Excellent flexibility even at low temperatures<br>One- or two-component, room- or elevated-temperature cure<br>Moderate cost | Good flexibility<br>Good peel and shear strengths<br>No mixing required<br>Will bond dirty surfaces<br>Room-temperature cure<br>Moderate cost | Rapid room-temperature cure<br>One component<br>High tensile strengths<br>Long pot life<br>Good adhesion to metal<br>Dispenses easily from package | Rapid room-temperature cure<br>Good solvent resistance<br>Good elevated-temperature resistance<br>No mixing<br>Indefinite pot life<br>Nontoxic<br>High strength on some substrates<br>Moderate cost |
| **Limitations** | | | | |
| Exothermic reaction<br>Exact proportions needed for optimum properties<br>Two-component formulations require exact measuring and mixing<br>One-component formulations often require refrigerated storage and an elevated-temperature cure<br>Short pot life | Both un-cured and cured are moisture sensitive<br>Poor elevated-temperature resistance<br>May revert with heat and moisture<br>Short pot life<br>Special mixing and dispensing equipment required | Low high-temperature strength<br>Slower cure than with anaerobics or cyanoacrylates<br>Toxic<br>Flammable<br>Odor<br>Limited open time<br>Dispensing equipment required | High cost<br>Poor durability on some surfaces<br>Limited solvent resistance<br>Limited elevated-temperature resistance<br>Bonds skin | Not recommended for permeable surfaces<br>Will not cure in air as a wet fillet<br>Limited gap cure |

Adhesive bonding may be combined with other joining methods. In weldbonding, spot welds are made through uncured adhesive, which is displaced from the immediate nearness of the weld. This process has been extensively studied by the automotive industry (Irving 1994). It is also possible to drive mechanical fasteners through a joint containing cured or uncured adhesive. Several benefits arise from the use of such techniques. Firstly, production is eased since the spot welds/fasteners locate the components, whilst the adhesive is curing, eliminating the need to hold the panels in assembly jigs for extended periods. Secondly, the spot welds/fasteners help the bonded joint to withstand secondary peel forces during service; this may be particularly important in cases of impact loading, where the supplementary joints enable the assembly to collapse progressively in an energy absorbing manner. Thirdly, the supplementary joints enable the panel to retain integrity in the event of total failure of the adhesive bond (for example, in a fire) (Davies 1987).

Weldbonding was developed in the early 1950s as a result of problems with spot welded joints of aluminium in aircrafts: poor fatigue resistance of overlap joints was noted at sonic speeds, combined with corrosion problems at the inner surface of the overlap. Inclusion of an adhesive in a spot weld produced a remarkably stronger joint with outstanding fatigue characteristics and this led to a renewed interest in weldbonding as a primary joining method (Jones 1978).

The normal procedure is to apply an adhesive paste to the parts being joined, close the joint and resistance spot weld the component. The sequence is shown schematically in Fig. 16. During welding, electrode pressure displaces locally the adhesive from between the sheets being joined, electrical contact is achieved and a weld is made in the normal way. After welding, the adhesive is cured. Although the metal is fused at the point of weld, there occurs relatively little degradation of the adhesive (Westgate 1987).

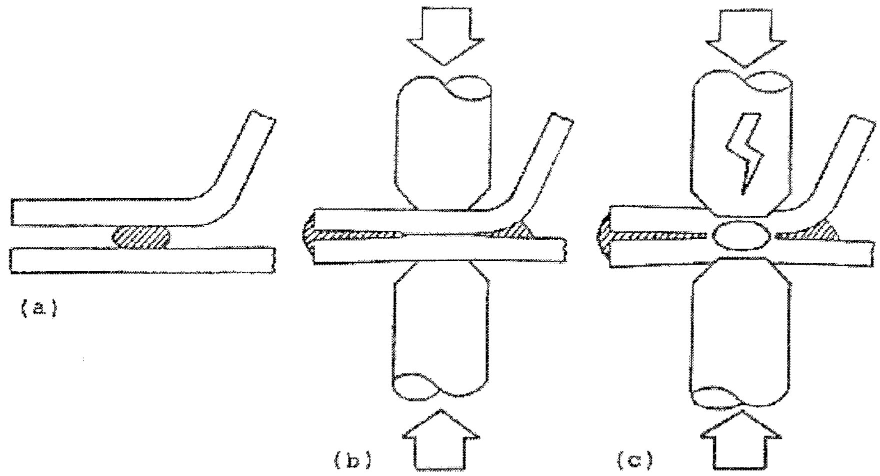



Fig. 16. Schematic presentation of the weldbonding process: a) bead of paste adhesive applied and joint closed, b) electrode force applied, which displaces adhesive locally enabling electrical contact, c) welding current passed, weld made and subsequently allowed to cool under pressure (Westgate 1987).

The advantages offered by the adhesive are increased stiffness and more even load distribution, improved fatigue performance, providing joint sealing and avoidance of surface markings. Conversely, resistance spot welding provides a rapid assembly method and overcomes the need for complex jigging which otherwise may be required during the adhesive cure. Furthermore, the presence of welds at strategic points in a structure can act as "peel stoppers", preventing undesirable peel or split loads being applied to the adhesive bond (Westgate 1987).

Single-part, heat-curing paste adhesives are ideal for weldbonding as the viscosity of adhesives does not change with time during assembly welding. Delays are also permitted between lay-up of adhesive and welding. A room temperature curing with limited pot life can adversely affect weldability if viscosity became too high, before welding was completed (Westgate 1987).

Certain adhesives have also been developed in weld-through-tape form with a release liner. These are either viscous or conductive partially-cured films. Whilst such films can allow more accurate application to the joint, gap-filling capacity can be limited. An alternative approach reported by Russian workers involves infiltration of the crevice in a spot welded structure with a low viscosity adhesive by capillary action. However, the technique is limited by the type of adhesive available, the variations in size of gap to be filled and the consequent risk of incomplete joint filling (Westgate 1987).

Weldbonding methods are not a common technique for joining of stainless steel sheets. A majority of research reports deal with aluminium for weldbonding. Weldbonding of stainless steels has been researched in Sweden during last few years (Ring Groth 1998).

## 7 Surface preparation

Removal of surface contamination is advantageous for both spot welding and adhesive bonding, but it is the latter which imposes higher demands. For the production of good spot welds, the prime consideration is a uniform surface resistance. In some cases, traces of rust protectant oil on steel sheets would have little influence on weld quality and it is quite sufficient to remove coarser contaminants such as local rust. In contrast, slight contamination of the surface by oil, grease, dust, moisture or oxide layers adversely influences the adhesion and careful surface preparation is recommended (Jones 1978).

A chemical or mechanical pretreatment offers the additional advantage of improved joint durability. However, this extra preparation stage is usually difficult to justify because of the extra time and cost involved. Also, benefits are frequently small. After surface preparation, the components must be processed as soon as possible, or must be stored in a clean room. If the storage period is lengthy, surfaces can be chemically treated or primed with a weldable primer. Selection of the adhesive is usually based on the static or dynamic requirements which the components must withstand, as well as on the service temperature and corrosion environment. The adhesive should interfere as little as possible with the flow of current between the welding electrodes (Jones 1978, Boyes 1995).

Mechanical treatments involve the abrasive action of wire brushes, abrasive pads, sand and emery papers, or shot/grit blasting techniques to remove weak surface layers which complicate the bonding operation. In addition to cleaning the substrates and removing weak oxide layers, abrasion techniques create a macroscopically rough surface that increases the surface area available for bonding. Mechanical roughening also increases the activity of the surface, which enhances the bonding mechanism. The techniques of grit or shot blasting are preferred in industry, because they give the most reproducible results compared with other abrasion methods. Generally, however, abrasion methods are less uniform and more difficult to control than chemical treatments, and they may produce a roughened surface which is susceptible to penetration by liquids and corrosion media (Boyes 1995).

Chemical and electrochemical treatments are employed to chemically modify the surfaces of adherends in order to improve initial joint strength and enhance durability. In addition to the cleaning action, chemical treatments can be used to increase the microscopical roughness of substrates, and may be employed to produce a strong, chemically resistant surface layer that, for example, may improve bond strength retention in service. The treatments involve immersing the substrates in reagents (which range from dilute or concentrated acids to alkaline solutions) at room or elevated temperatures. The acids and caustics attack metal oxides preferentially to the base metal and remove the potential mechanically-weak layers. The ultimate performance of adhesive-bonded stainless steel joints is observed when the substrates are chemically pretreated. A typical pretreatment consists of degreasing and water rinsing, followed by etching in sulphuric acid (60 °C), water rinsing, desmutting in chromic acid (60 °C), water rinsing and drying (Boyes 1995).

## 8 Brazing and Soldering

In the brazing process, the steel surfaces are first cleaned and a flux and a brazing alloy are placed in the joint. The assembled panel is then heated in a furnace under a clamping load. The joint can be considered in some ways to be analogous to an adhesively bonded joint, using a metallic rather than a polymeric adhesive: the skin and the core are connected over the entire bond area by a physically distinct layer of material. Brazed joints offer better high temperature performance than most adhesively bonded joints. The process is not tolerant for gaps, and it is normally necessary to ensure that the bondline thickness is less than 0,13 mm. In order to avoid corrosion problems in service it is necessary to remove all traces of flux from the joint. Where this is not feasible (e.g., due to difficulty of access to the joint after brazing) it is necessary to use a flux-free process, which generally involves the use of a vacuum furnace (Davies 1987, Vikström 1998).

## 9 Mechanical fastening

This term embraces a number of techniques, including threaded fasteners, various types of rivets, and several types of press-joints (in which one sheet partially penetrates and interlocks with a second sheet). Although these techniques do not suffer from process-induced distortion, they share the disadvantage with spot welding of local skin buckling between attachment points, and some of the techniques also require access from both sides of the joint (Davies 1987).

## 10 Attachment of structures

Besides the structural design criteria, special considerations are required for the design of all joints between the sandwich structures and other structural components. Since the assembling costs influence crucially the overall cost of the structure, considerable effort has to be made in the design of the joints.

The attachment of sandwich panel to other sandwich panels or to other structures is one of the key elements in the practical application of these structures. Joints in this context include joining panels to each other, or sandwich panels to single skin composite laminates or metal structures. This is done by intergrating some kind of end-close to the panel in which a connection element is included.

### *10.1 End-closures*

A free end of a sandwich panel is very difficult to attach to anything due to its sensitivity to peel stresses and impact loads in the plane of the panel. The end-closure of the panel is not only sealing for the free edge but a connection element by which one may attach the panel to the surrounding structures or to another panel. Below follows some illustrations of end-closures arranged in pre-fabricated and post-fabricated groups.

The problem of connecting two sandwich panels to each other is one of never ending problems. The are two basic problems to be addressed: the connection of two panels edge-to-edge and the connection of two panels at a corner. In Figs. 17 and 18 some examples of end-closures are shown. In Fig. 19 some examples of corner design are shown. In Figs. 20, 21 and 22 some examples of joint design are shown for sandwich structures.

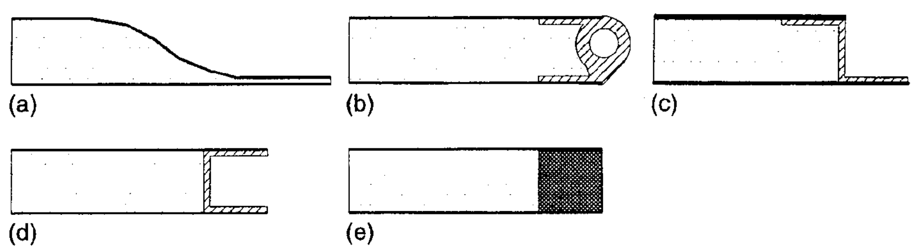



Fig. 17. Examples of pre-fabricated end-closures: a) tapered end-closure, b) example of special metal insert, c) Z-section beam, d) channel section, e) solid, wood or high density foam insert bonded to panel (Zenkert 1997).

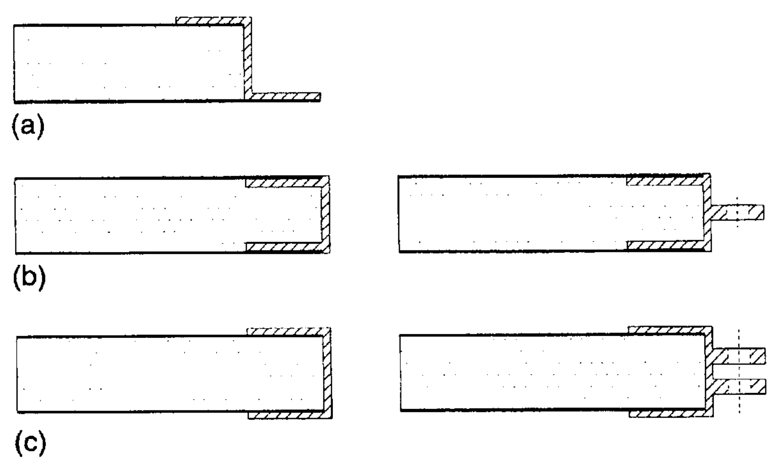



Fig. 18. Examples of post-fabricated end-closures: a) bonded Z-section to panel edge, simple channel bonded to the edge, c) metal insert (Zenkert 1997).

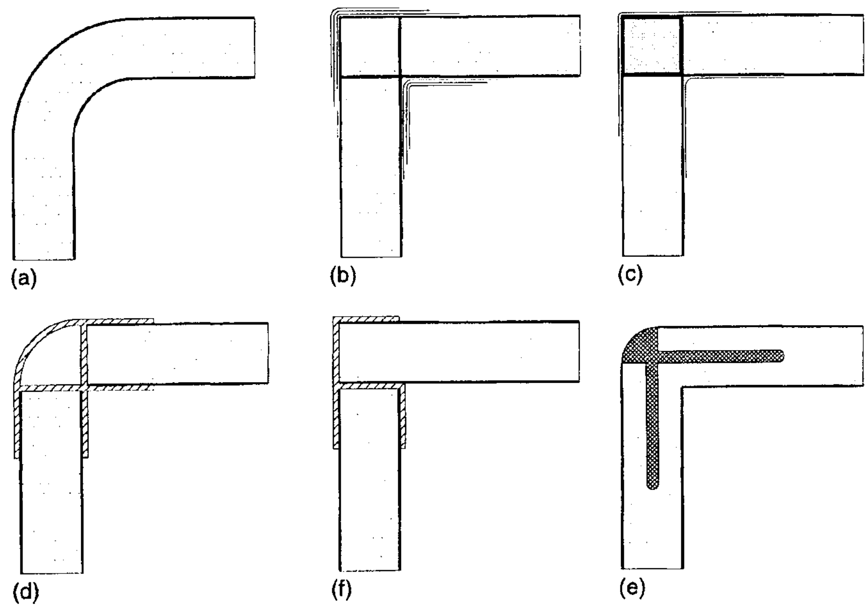



Fig. 19. Examples of corners in sandwich panels: a) rounded corner in sandwich construction, b) laminated corner, c) higher density core material in the corner section, d) channel section bonded and /or mechanically joined connection, e) channel section bonded/or mechanically joined connection, f) metal insert design (Zenkert 1997).

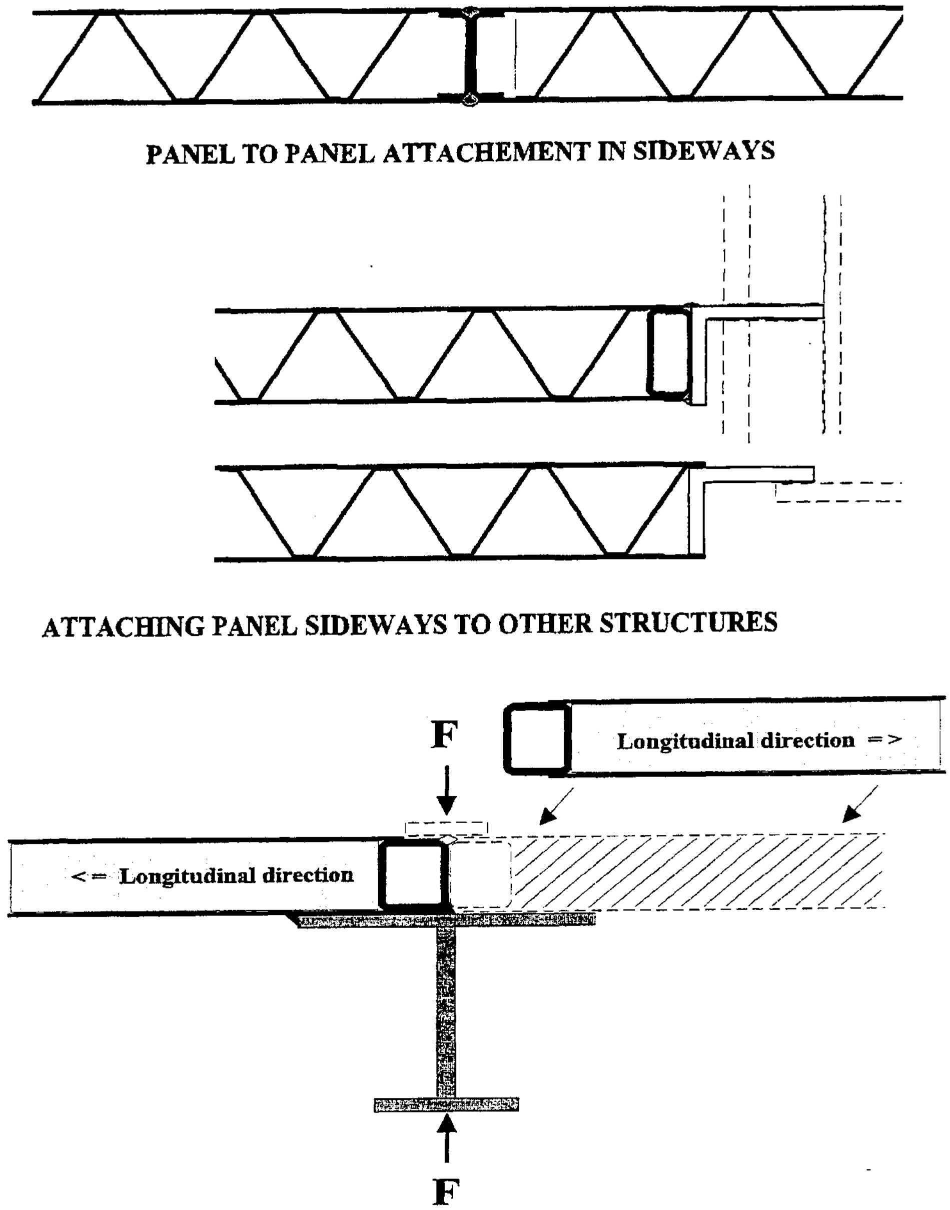



Fig. 20. Transverse and longitudinal joints of sandwich panels (Kujala et al. 1995).

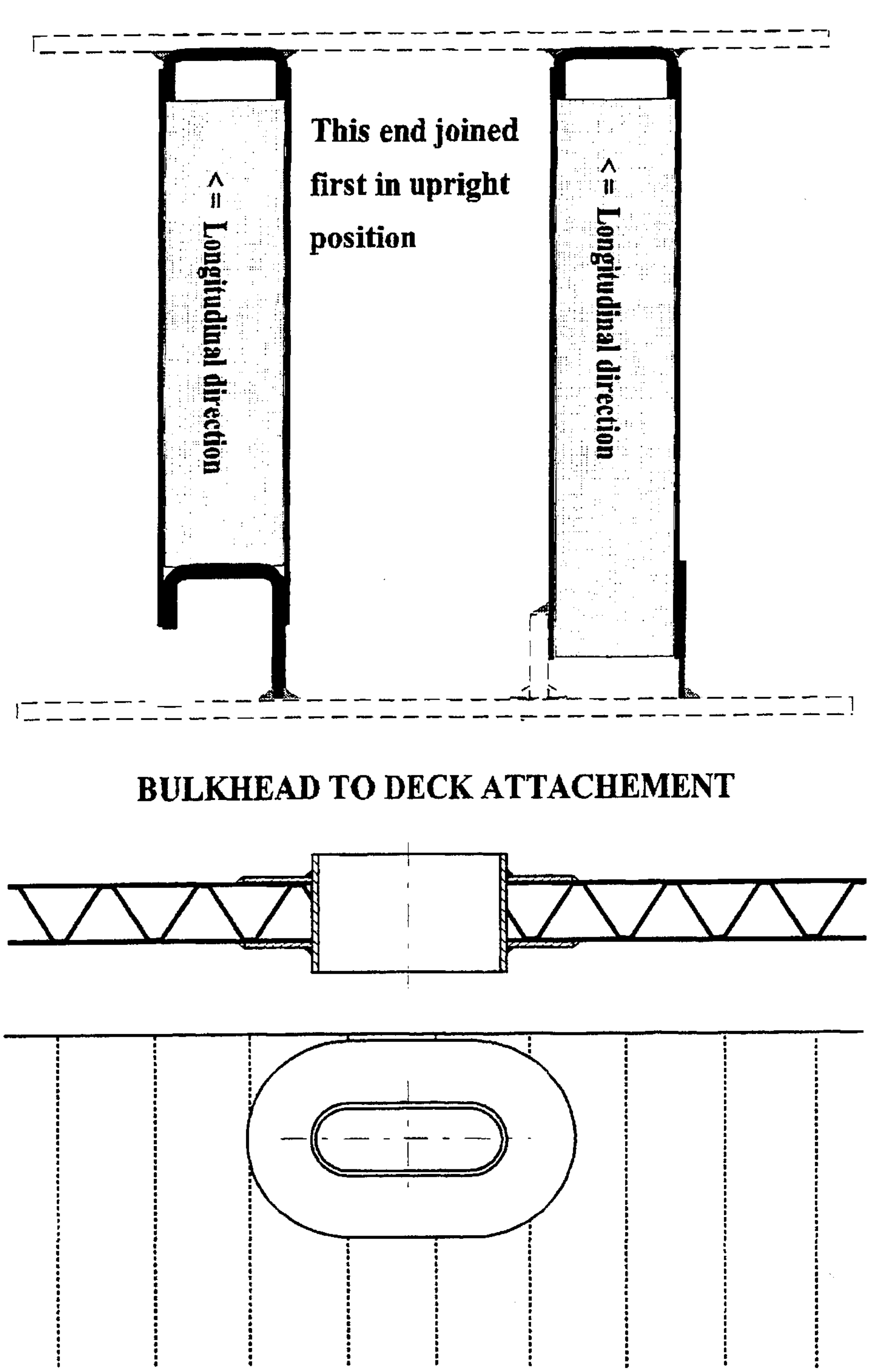



Fig. 21. Bulkheads and penetration through panels (Kujala et al. 1995).

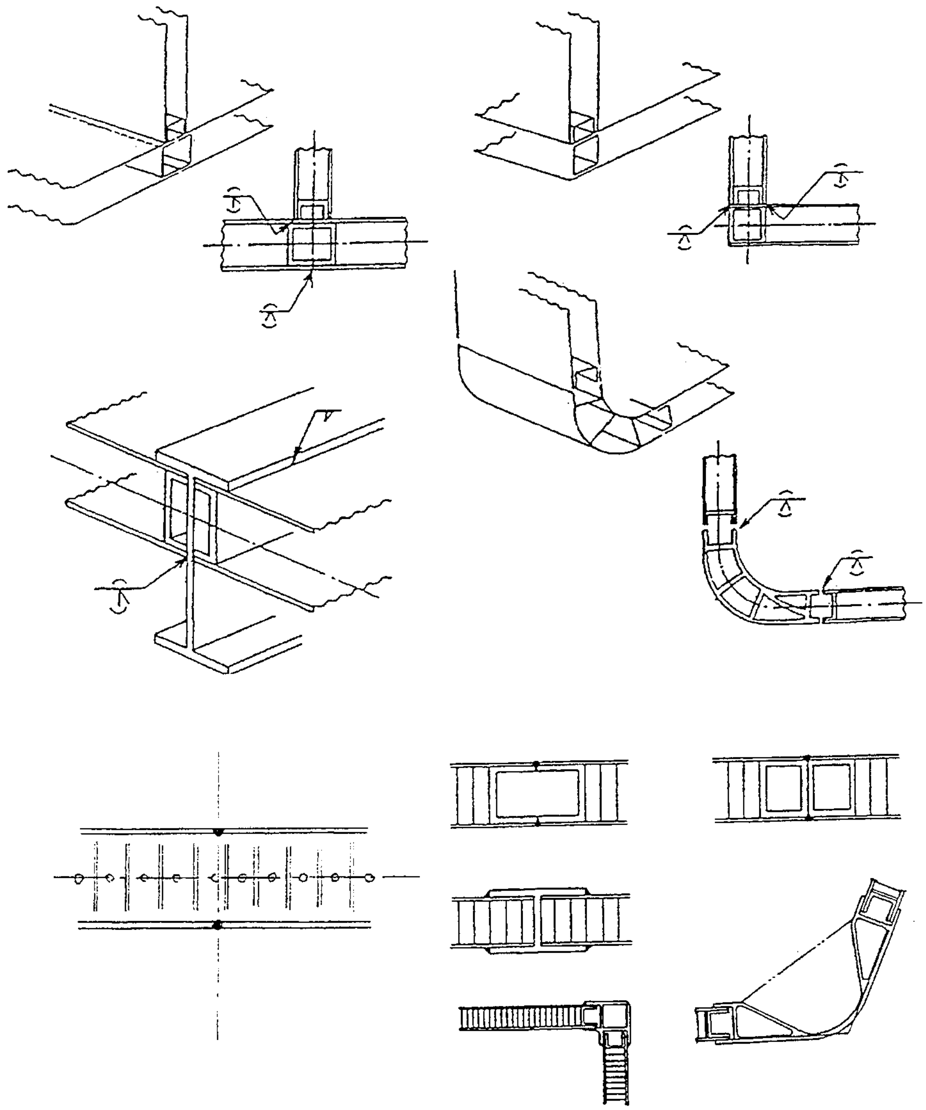


Fig. 22. Examples of joint design for ABH-panels (Okuto & Namba 1995).

Since early 1980s the U.S. Navy in conjunction with industry, has continued to develop and to test lightweight structures with the purpose of seeking an alternative replacement for conventional aluminium and steel plate structures. These applications cover bulkheads and decks on accommodation areas, deckhouses, deck edge elevator doors and hangar by division doors, see Figs. 23 to 26 (Wiernicki 1991, Furio 1997).

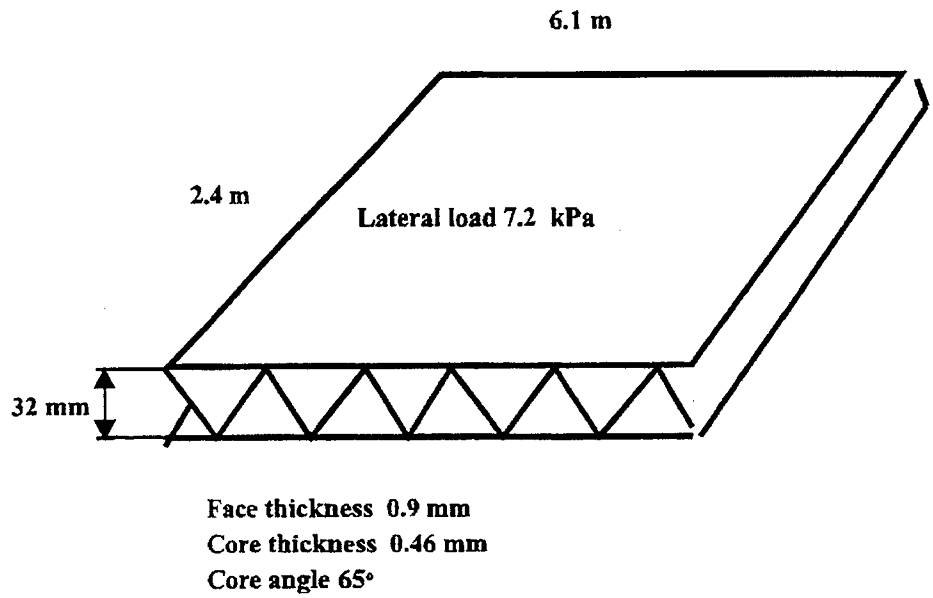



Fig. 23. Deck structure, HSLA 80 steel (Sikora 1990).

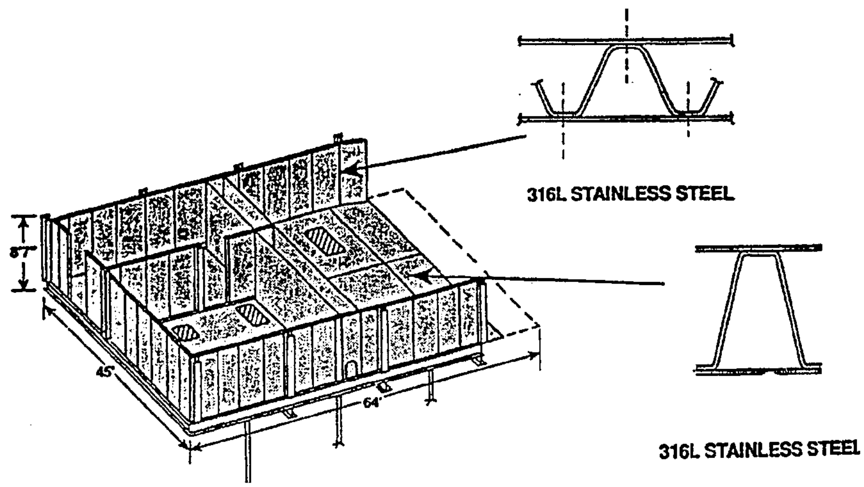



Fig. 24. Lascor structure to form an avionics facility module (Kujala et al. 1995).

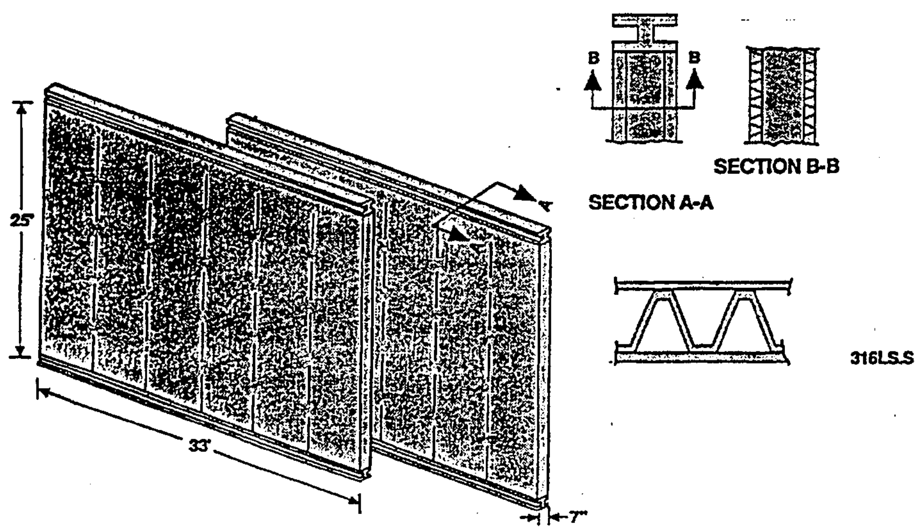



Fig. 25. Lascor structure as deck edge elevator door (Kujala et al. 1995).

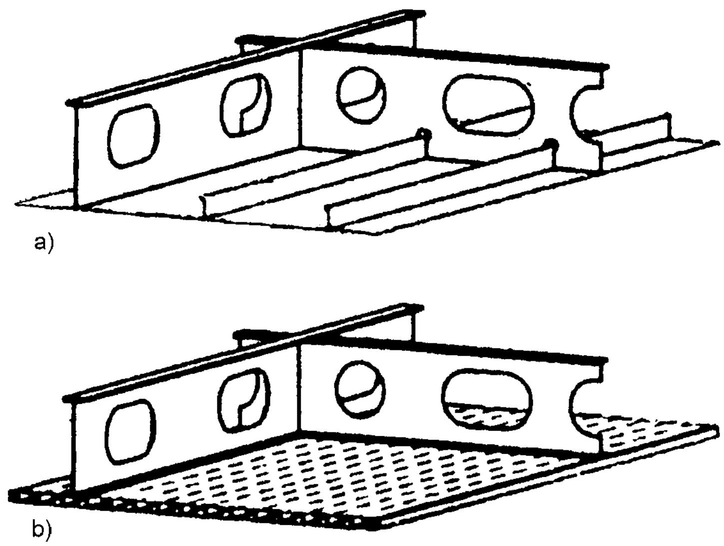



Fig. 26. Conventional (a) and sandwich (b) ship deck structure (Lassila 1998).

In Japan all-laser-welded sandwich panels have been developed for high speed civil transport. These sandwich structures consist of two-face sheet, corrugated core and special flanges at each panel side. In Figs. 27 and 28 the schematic structures are shown of this honeycomb panel.

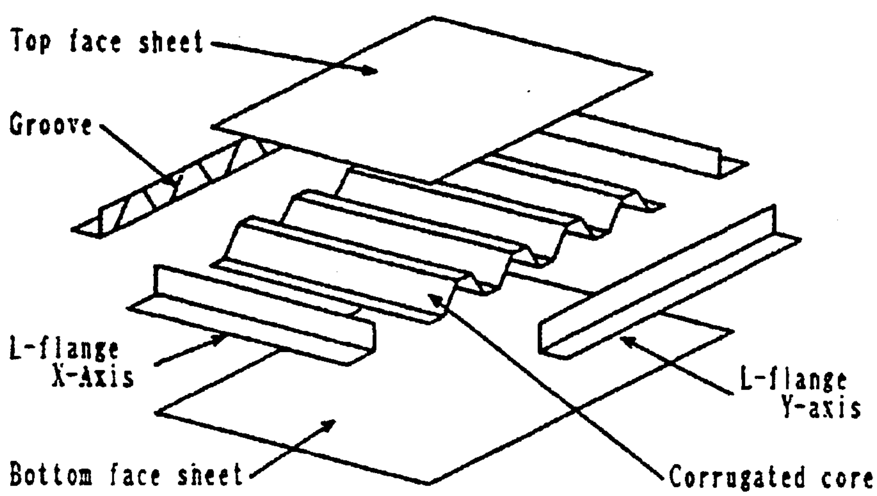



Fig. 27. Schematic construction of an all-laser-welded honeycomb structure (Oikawa et al. 1993).

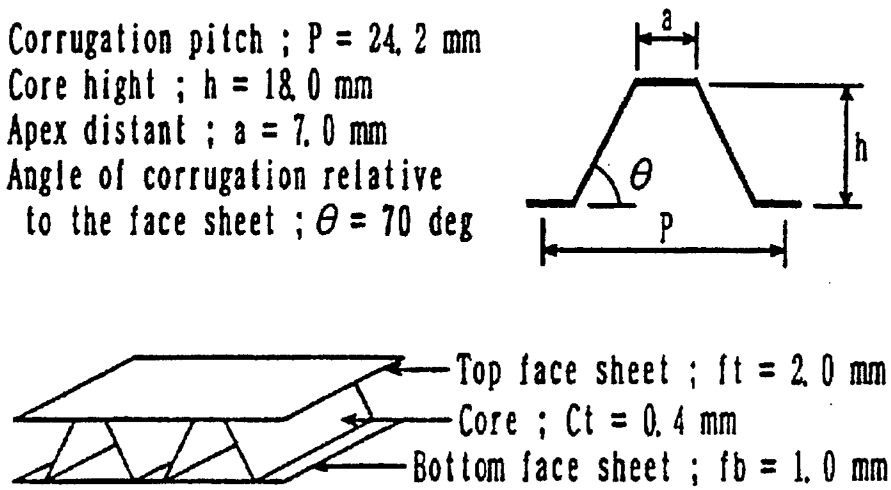



Fig. 28. Structural dimensions of structure shown in Fig. 27. (Oikawa et al. 1993).

The main characteristics of the new panels are the side flanges which improve the mechanical properties of the panels and allow easy joining of the panels and easy production of curved surfaces for structures. It is difficult to weld the side flanges with the corrugated core sheet. To avoid the dropping out or lack of fusion, a Nd:YAG laser and a paste including metal powder and organic solution are used (Oikawa et al. 1993).

Stainless steel sandwich panels are used in a ship bottom structures of Techno-Super Liner Model, laser welded by Nippon Steel (Kujala 1997). Theoretical and experimental studies on the strength of steel sandwiches have also been carried out at the University of Manchester for offshore deck structures and at the Helsinki University of Technology for a shell structure of an icebreaker. The offshore deck structures were found to be 20 to 40 % lighter than the conventional steel grillages (Kujala & Tuhkuri 1987).

Spot welded sandwich structures are shown in Fig. 29i. It combines a thin steel folded or corrugated core with flat steel face plates to act as flanges. The geometry is not, in itself, remarkable, but it has an interesting feature in the use of one-sided spot welding to connect the corrugated core to the face. This facilitates a relatively cheap and quick fabrication process which can be automated. The welds can be applied by one or two procedures. First, the face plates are connected to the core by applying the welding gun to the outside of each plate. This leaves a series of welds on both surfaces of the finished panel, as shown in Fig. 29ii. Alternatively, the first face plate can be connected by welding from the inside of the core. This leaves the plate with an outside surface entirely free of welds. The second plate is then attached by welding from the outside as in the first method. It has been found that the panels can be fabricated with acceptable small distortions by the spot welding. Variations on the theme of Fig. 29i are illustrated in Fig. 29iii, which shows top-hat stiffeners and Fig. 29iv is a sinusoidal core (Montague & Norris 1987).

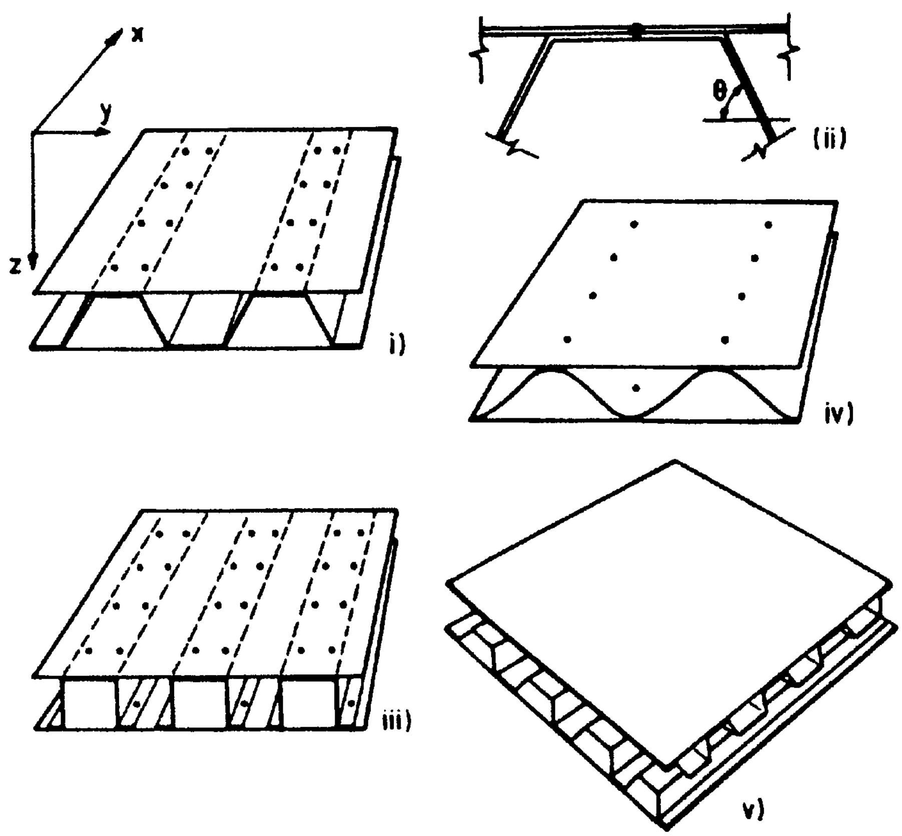



Fig. 29. Spot welded sandwich structures (Montague & Norris 1987).

# 12 Conclusions

The design of large transportation systems such as busses, ships, railway vehicles and aircrafts is always determined by considerations of weight. The use of sandwich structures in transport industry has been an increasing interest among the manufacturers and users of e.g., buses, trains, ships and aircrafts. By using sandwich structures, it is possible to obtain high strength/weight ratio and minimum weight, e.g., the sandwich offshore deck structures were found to be 20 to 40 % lighter than the conventional steel grillages. The right choice of sandwich structures and competitive manufacturing method for the components are the keys to successful overall concept.

The sandwich structures have the potential to offer a wide range of attractive design solutions. The correct design of the details of sandwich constructions is at least as important as the analysis of deflections, stresses and buckling loads. The attachment of sandwich panel to other sandwich panels or to other structures is the one of the key elements in the practical application of these structures.

Aluminium honeycomb and sandwich structures are well known. The production difficulties have prevented the wide spread use of the steel sandwich structures. Stainless steel sandwich structures are quite unknown. The development of laser welding, resistance spot welding, adhesive bonding and weldbonding processes offers efficient techniques for the manufacture of sandwich structures of stainless steels in the future.

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