Structural Sandwich Components in Building

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STRUCTURAL SANDWICH COMPONENTS IN BUILDING

by R. E. Platts

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SOMMAIRE

Les éléments de construction stratifiés peuvent donner le maximum de résistance et constituer la plus grande paroi avec le minimum de matériaux. Etant donné l'intérêt que l'on attache actuellement à la mise au point de matériaux en feuilles ne nécessitant qu'un faible entretien et d'ensembles préfinis de grands panneaux de construction, à l'excellence de l'isolement thermique, à la vitesse d'érection des bâtiments, à l'utilisation maximale de l'espace et à la productivité générale, le concept d'élément stratifié prend de l'importance. L'auteur examine les bases technologiques de la construction avec les éléments stratifiés et les besoins de développement technique, particulièrement en fonction de la nature des matériaux canadiens et de la situation de l'industrie. Il étudie les limitations naturelles et souvent décisives des éléments stratifiés, et particulièrement leur perte de résistance aux hautes températures et à l'incendie: cette faiblesse constitue une gêne évidente pour leur emploi comme éléments porteurs. On peut calculer et généralement obvier au cambrement dû à des différences de température ou d'humidification des lamelles constituantes. Les caractéristiques d'impédance acoustique des ensembles stratifiés [illegible] lier, ont mauvaises. Le concept de l'élément de constr[illegible] met en lumière nombre de nouveaux matériaux en feuilles [illegible]aniques et plastiques, suscitant des questions au sujet de leur rés[illegible]ance [illegible] et de leur fluage. L'auteur rassemble un amas cr[illegible] es d'essais de fluage sur de nombreux m[illegible]ériaux st[illegible] s matériaux médians de stratifi[illegible]tion. Il [illegible] cepts de réalisation des joints entre [illegible] et [illegible] possibles des matériaux stratifiés.

NATIONAL RESEARCH COUNCIL OF CANADA

DIVISION OF BUILDING RESEARCH

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PART I - PAST AND PRESENT

Structural sandwich construction can give maximum structure with minimum material. Thin sheet materials are bonded as strong "skins" on a light "core" material, which is thus sandwiched between them. Stressed-skin structure is achieved. The skins take the direct stresses as the component is loaded as column, beam or diaphragm; the core positions the skins away from the neutral axis to provide over-all rigidity, stabilizes them against local buckling, takes the shear stresses between them, and often provides thermal insulation as needed.

With today's emphasis on development of low-maintenance sheet materials, on prefinished large-panel building systems, on better thermal control, speed of erection, utilization of space and over-all productivity, the sandwich idea is attractive to many. An increasing number of inquiries and a significant number of requests for assistance with feasibility studies have been received by the Division of Building Research, indicating a rapidly growing interest. This paper reviews the engineering basis of sandwich construction and its development needs, relating particularly to Canadian materials and conditions.

Questions are just as important as the promises of the structural sandwich concept. The inherent limitations are those of skin structures generally. With the structural elements - the skins - positioned at the surfaces, sensitivity to high temperatures and especially to fire is an obvious drawback where load-bearing uses are involved. Deeply-shaped forms can improve the fire safety performance in such uses. Temperature or moisture differentials between the skins can cause smooth bowing of sandwich panels, but this effect is readily calculable and need not be critical. Resistance to sound transmission is an inherent limitation of sandwich space separations: weight, complete separation of layers, and pliability are all important in reducing sound transmission, whereas the sandwich strives for minimum material and weight, complete bonding together of elements, and high stiffness.

Other limitations are not inherent but are brought to the fore by the capabilities of the structural sandwich. Several thin sheet materials appear promising as sandwich skins, materials rarely considered before in structural terms. What is the long-term sustained strength of hardboards and particleboards? Can creep deflection be kept within acceptable limits with such skins; with paper-plastics or glass fibre reinforced plastics; with plastic foams or deformed or extruded particleboards as cores? How can the durability of a new adhesive be assessed without waiting ten years? Must new systems be restricted or modified to meet traditional building rules that evolved around older structural shapes? These and other questions are considered in this paper insofar as present knowledge permits.

Basic design concepts are followed far enough to be usable in feasibility studies, or even to the point of prototype designs with some materials. The rigorous mathematical treatments of complex sandwich design (developed so thoroughly by or for the aerospace interests since the early 1940's) are neglected, except in referencing the literature for those who want to go further. An attempt will be made to define sandwich design and example capabilities within present knowledge of materials in order to allow consideration of the development areas of apparent promise.

1.2 HISTORY

The rigorous engineering design required of sandwich composites had scarcely developed before 1940. As its use before and since has been primarily in aircraft, it could be argued that efforts to trace the progress of sandwich design are worthless in terms of present building interests. Relevant lessons may be found, however, and perhaps they will be better applied in time. In any case the story is fascinating. It is built on the contributions of many of the great figures of elastic stability theory; their findings have made possible all modern aircraft, and may affect ground environment more than can be predicted.

Structural sandwich history can properly be traced only in the context of general stressed skin developments. The terminology should be noted briefly:
Stressed skin is the family term for all structures where thin sheet

coverings are major contributors to structural performance. Other members are used to transfer stresses and stabilize the compression portions of the skins. The term has come into particular use for components such as flat panels where stabilizing and shear-resisting members are spaced some distance apart.

Monocoque is more or less the same thing. It may refer to stressed skin enclosures where the side walls themselves are arranged as the sole shear webs, as in aircraft fuselages, but the term is equally applicable to aircraft wings where some shear webs are enclosed.

Structural sandwich refers to thin skin laminates where the shear and stabilizing functions are given to a continuous or near-continuous "core" bonded to the entire area of both skins.

The term quasi-stressed skin is used in these discussions to denote structures where the skins add to the beam strength of the whole, but where longitudinal framing still plays a large part, or is thought to do so.

The theory began long before the terms were coined, and remarkable applications antedated the more complete design science by some ninety years. It began with the bridge builders, even before Whipple published apparently the first treatise on stress analysis of simple bridge frames in 1847. With wrought iron plate just recently competing with cast iron in bridge building, Robert Stephenson toyed with ideas to stress such plate to achieve the high-clearance, stiff, long span needed for the first railroad bridge across the Menai Straits in Wales. Apparently it was he who first conceived of a "through-tubular" structure: twin rectangular tubes of 15-ft width, 27-ft depth, and 1,511-ft length, the central span 460 ft, with the train deck (lower deck), sides and top "skins" all sharing in the deep beam action (1). This is the Britannia Bridge, built between 1845 and 1850 and still in use (Figure 1).

William Fairbairn, whose shops had recently pioneered wrought iron plate manufacture and use in small girder bridges and large ship hulls (which thus became and have remained quasi-stressed skin structures) shares credit for the Britannia design. Fairbairn conducted and assessed extensive model tests, stiffener refinements, and even full-scale testing for Stephenson, while Professor Hodgkinson, a mathematician, helped deduce empirical formulae from the tests. Fairbairn secured patents on the tubular girder and published his noted engineering milestone "An Account of the Construction of the Britannia and Conway Tubular Bridges," London, 1849 (2).

Fairbairn was remarkable. Gough (3) attributes the first sandwich-like thinking to him, noting that in one of his tests on arrangements for the Britannia he used wood backing planks to stabilize the wrought iron plates. The temptation to dwell on the Britannia Bridge and all its supporting tests and works is strong indeed. In this one triumph civil engineering can perhaps claim the first true stressed skin or monocoque design, although it has scarcely used it again as a complete structure in the intervening century. Plate girders and even tubular columns can also be dated from this one program, and these have been engineering tools ever since.

Perhaps the first truly successful - if empirical - sandwich sheet material came a little later, with the advent of corrugated cardboard in the 1870's. The further development of new sheet materials and man's efforts to fly worked together to push the evolution of stressed skin. The most important of these materials was plywood, in which the ability to turn wood into large dimensionally-controlled sheets opened the door to easy exploitation of stressed skin applications. The thickness of plywood gives very high bending stiffness compared to metals of similar weight, so that high stressing of compression skins is readily achieved.

One early reviewer (4) implies that reliable water-resistant plywoods were first in use in Russia "many years" before 1900. Russian aircraft began to use it in a quasi-stressed skin sense in the early 1900's, with Steglau in 1912 building the first completely plywood aircraft, including the wing covering. In the same year Bechereau in France used plywood in the first true "monocoque" fuselage. The Germans made extensive use of glued-on plywood as "an integral part of the structure" in their World War I aircraft (4). Older ideas were still in advance of practice: the first U.S. patent on plywood, No. 51734, in 1865, is credited to John K. Mayo of Maine; in a re-issue of 1868 the inventor includes drawings of large tubular bridges of both circular and rectangular cross-section (5).

The drive for "cleaner," fast aircraft led Professor Hugo Junkers to develop the first cantilever wings, in which he utilized metal sheet stressed skin action, laboriously stabilizing flat steel sheet by welding corrugated steel sheet behind it. His small Junkers J-1 used the idea successfully in 1916, and led to quite large multi-engine machines (6). The approach was tedious and somewhat heavy, and the British and others preferred to direct all efforts to developing the necessary forms with light alloy spars and ribs with fabric covers, or unstressed metal sheet covers, paralleling the traditional wood craft. In the meantime, Fokker used thick cantilever wings of quasi-stressed skin plywood construction through the 1920's. Plywood stressed skin panels later went into building through the design and test work of the U.S. Forest Products in the mid-1930's, and they have remained a sound (if conservative) design choice in small buildings since that time.

The plastics were allowing new choices of formable, high-strength sheet materials by the early 1900's. In 1918 Westinghouse obtained British Patent 120701 on high-pressure paper-plastic and other fibre-plastic laminates, with drawings showing one-piece monocoque fuselage construction. It is remarkable that in 1886 Jules Verne visualized the mythical Albatross giant aircraft, describing its construction as entirely of high-pressure paper-plastic laminates, with remarkable properties indeed, all in his novel The Clipper of the Clouds.

The paper-plastic laminates apparently excited much thought, and were much in mind in what may have been the first engineering conception of the true structural sandwich. Long interested in full sheet stabilization for optimum strength-to-weight for aircraft, von Karman described his structural sandwich "for light structures" in Germany in 1924 (British Patent 235883, 1925). Von Karman suggested kraft paper and other fibre-plastic skins bonded to both sides of cork or balsa wood cores, and included stiffened joint details connected by the glue-lapped laminate skins. All this antedated the first noted use of sandwich aircraft by over ten years, while forecasting its design almost exactly.

A breakthrough in single-skin monocoque design satisfied the needs of low-speed aircraft for several years, and ideas of sandwich construction were set aside. In 1930 the U.S. National

Bureau of Standards conducted extensive tests of edge compression of thin sheets with their unloaded edges stiffened or restrained to various degrees (2). This work changed the implications of elastic theory of thin plate quite radically: long after the centre area of the sheet has buckled, the restrained edge areas remain stable and readily support loads of many times the initial buckling load. The action is consistent, reversible and sound, and following von Karman's resolution of the basic equation in 1932, the post-buckling-stressed "thin wall monocoque" became the basis for all the large transport aircraft of the 1930's and 1940's, and for the normal speed ones of today. Yet all such post-buckling capabilities remain unused in ground-based construction engineering.

The structural sandwich was next forced from theory into practice to provide the smoothness and strength required in high-performance aircraft. At deHavilland in England, A. E. Hagg's design group built the radical and successful Albatross mail-carrier in 1937 (7), following von Karman's 1924 propositions quite closely. Thin cedar plywood was bonded to both surfaces of a balsa wood core to form a complete sandwich monocoque fuselage, a beautifully curved smooth tube. The wings used stressed skins of spruce planking. The craft flew fast and regular courier runs, cruising at over 200 mph with a range of 3,000 miles. Then in 1943 the remarkable deHavilland Mosquito bomber (7) brought decisive attention to sandwich construction. Designed by R. E. Bishop and built largely in Canada, it used thin birch plywood skins on balsa core and flew 380 mph, 425 mph in later models, taking it far ahead of its competitors (Figure 2).

The incentives of war and the consequent need for fast flight quickly directed many resources to work on sandwich theory and development - far more than are usually focussed on civil projects. Speeds near and beyond the supersonic require very thin laminar-flow wings with highly stressed skins free from protruding rivets or any rippling effects. By the late 1940's engineering theory and practice moved beyond the basic stages of relevance to most building development, now or in the near future. While missing many important contributors, a few will be noted: at Cambridge University in 1939, Gough, Elam and de Bruyne pioneered the theory of edge compression and local buckling of sandwich laminates, checking by rigorous testing programs that became the rule in all following work (3). They began from the over-all stability theory of Timoshenko (1913) and Biot, Reissner and others (2). Such buckling was reduced to formulae within useful engineering limits by Hoff and Mautner, while Williams, Leggett and Hopkins developed sandwich beam theory and noted the function of shear deformations. Other notable work of the pioneering 1940's was carried out under March, Ericksen, Libove, Batdorf, Van de Neut, Cox, Bijlaard, Goodier, Stein and Mayers. Habip (8) has recently surveyed the thread of the mathematics of sandwich analysis in the form of a concise review and bibliography.

1.3 IMPLICATIONS IN BUILDING

Perhaps the more notable institutions in early sandwich design work were the Royal Aircraft Establishment in the U.K., and the U.S. Forest Products Laboratory in Madison, Wisconsin. The latter group had been intensively involved in the engineering analysis and test development of plywoods, and their resulting competence in orthotropic structure analysis and adhesives technology was well adapted to "sandwich thinking" and, later, the engineering development of glass-fibre-reinforced plastics. Although aircraft-inspired sandwich engineering soon progressed beyond the requirements of building, the work of such groups in material developments has remained relevant indeed. Reliable plywoods, paper-plastics (countertops and surfacings), reinforced plastics, wood adhesives and especially metal adhesives, honeycomb and plastic foam cores and insulations, elastomer sealants for curtain walls and sealed double windows, plastic skylights, all are to some extent by-products of aircraft development and its demand for ideal sandwich structure.

Performance criteria and attitudes in the aircraft and other young industries should have even more relevance to hopes for a viable building production industry, as it strains to keep abreast of mounting needs. Technical performance codes, prepared solely by and for technical people, are the rule in governing the evolution of aircraft, and requirements are seldom irrational.

Structural sandwich developments have made progress in building applications. The Jicwood House in Great Britain followed on the heels of the Mosquito bomber in 1944 with plywood-honeycomb sandwich design. The U.S. Forest Products Laboratory erected a plywood-honeycomb sandwich house in 1947 that is still performing well, and their concurrent work on hollow-core flush doors resulted in the only true sandwich "commodity" in the building field (9). Koch and Bemis' notable Acorn plywood-honeycomb sandwich house of 1948 (10) was far more advanced as a folding, lightweight unit than the folding military houses of today. In Canada, stressed-skin plywood and later sandwich units have satisfied much of our Far North housing needs since the late 1940's, but their costs scarcely compete with the fast-produced wood frame housing in the populated areas (11). Curtain-wall developments have been fairly steady, with some difficulties.

There are real limitations on the use of sandwich in total structure, as will be discussed, but the critically expanding needs for housing and building production demand a rational system approach (12), and in this the structural sandwich will probably play a larger role. While stretching the use of material to the ultimate, the sandwich concept is also amenable to optimum machine production that may become critically important (11). Its real limitations represent a challenge; imposed limitations on building uses must be accorded much more basic thought in terms of the whole building job.

PART II - ENGINEERING DESIGN

When structural sandwich theory takes account of plate action, corner effects, skin stability, shear deformations, directional rigidity variations and combined load conditions, it becomes unusually complex. Using strain-energy relations made solvable only by assumptions of edge conditions and elastic actions, solutions have been derived that correlate reasonably well with load tests. Given the variations between assumed and actual conditions, as well as those in the normal properties of materials, even rigorous mathematical analyses do not predict performance much more accurately than do simple approximate methods.

This paper confines itself to engineering approximations, which can be more than adequate for feasibility studies where a proponent requires a "first look" at where a sandwich composite might be used, for example, finding the spans for given loads and deflections. Approximations can be adequate for prototype designs that are to be fabricated for proof-testing or development-testing, and such testing is desirable even if onerous design methods have been followed. Simple load and environmental testing is almost always of value in such development work. Overdesign can be reduced, load-factors derived more closely, and the usual "unexpected" stress or other weakness corrected. The "on paper" design should not be considered fully adequate without such supporting evidence.

Design and test properties are determinable, but in building construction the performance criteria are often ill-defined in theory and practice. These are discussed for certain applications in Part IV.

The notation used is as follows, except where otherwise noted:

ℓ = span
w = distributed load per unit area
W = total distributed load
P = total concentrated load at a point or along a line
M = bending moment
V = shear load
E = Young's modulus of elasticity of the skin material in the span direction
I = moment of inertia
G = shear modulus of rigidity of core relating to span direction
σ = stress, usually in skin in span direction
ϵ = strain in axial extension or compression
δ = deflection
τ = shear stress
ν = Poisson's ratio

A = cross-section area as designated
b = sandwich width
h = full thickness
t = skin thickness
c = core thickness
d = distance between centroids of skins
NA = neutral axis

2.2 BENDING

A structural sandwich is, in effect, an I-beam and can be designed as such: the skins are the flanges and the core the web. Figure 3 shows the strain and stress action through a symmetrical sandwich spanning the page under bending load. Symmetrical here means that the skins are equal in E as well as in thickness. The first assumption with such bonded composites is that transverse sections plane before bending remain plane after bending, and that all materials are elastic under normal conditions; hence the straight-line strain diagram. The stresses are then $\sigma = \epsilon E$ at any point.

The unscaled stress diagram of Figure 3 suggests that in this case the E of the core is about one-sixth the E of the skin, so that the core is stressed only one-sixth as much as the skins and contributes little to the bending resistance of the whole. In practice the core material usually has less than one-hundredth the E of the skin, so that the "approximate stress" diagram shown is very close to the actual one. Thus the bending stiffness of the core can be neglected in most cases. Further, the separate bending resistances of the thin skins are usually small and can be neglected, so that their axial forces produce the only resisting couple or moment that need be considered. That is

$$M = \text{skin force} \times d = \sigma t b d \qquad (1)$$

(as determined for either of two identical skins).

The shear forces in a thin-skin sandwich are carried almost entirely by the core, giving fairly uniform stress intensity throughout, so that

$$\tau = \frac{V}{A} = \frac{V}{bc} \qquad (2)$$

Thicker skins pick up more of the shear load so that the core shear stress may be better approximated as

$$\tau = \frac{V}{b\,(c + t)}$$

which is sometimes expressed for convenience as

$$\tau = \frac{2V}{b\,(h + c)} \qquad (3)$$

This sums up normal bending strength considerations for present purposes. In building applications deflections rather than strength usually rule sandwich design or use. Unfortunately, bending stiffness is more difficult to calculate even in simplified form.

The stiffness factor EI is again determined from the skins alone. The general expression $I = \Sigma(I_o + Ak^2)$ readily gives the moment of inertia of this simplified section, where I_o is the moment of inertia of each skin about its own axis, A the area of each skin, and k (its distance from the neutral axis of the section) equals d/2 for a symmetrical sandwich. With thin skins the I_o can be neglected so that $I = \Sigma A\,(\frac{d}{2})^2$. Summed for the two skins this becomes

$$I = \frac{Ad^2}{2} = \frac{btd^2}{2} \qquad (4)$$

and

$$EI = \frac{Ebtd^2}{2} \qquad (5)$$

for a symmetrical sandwich strip with thin skins.

Where the skins have appreciable thickness the EI may be made to include the I_o for each skin by the more exact expression

$$I = \frac{b\,(h^3 - c^3)}{12} \qquad (6)$$

Hence

$$EI = \frac{Eb\,(h^3 - c^3)}{12} \qquad (7)$$

for a symmetrical sandwich strip with thick skins.

Where a sandwich or any laminate includes skins differing in thickness and/or E, or the core itself has appreciable bending stiffness (e.g., a solid plywood core with thin metal skins), or when any number of layers are involved, the method of "transformed section" is useful. As shown for a simple case in Figure 4, the elements are transformed into an equivalent homogeneous cross-section of the same E throughout. It is most convenient to conceive of this adjustment as affecting the widths, b, of the elements of the cross-section only, these being made in proportion to the ratio of the E for the element to the reference E selected. It is further convenient to select the E for one of the elements as the reference E, e.g. E in Figure 2. The width of this element then remains as before, but the other element widths must be transformed to $\frac{E_2}{E_1} b$, $\frac{E_3}{E_1} b$ as shown. All other dimensions such as t, c, h and d, and thus the centroidal distances between elements, remain as before.

Calculation of I and EI may now be made for the transformed section, using the reference E (E_1 in Figure 4). The value of EI so obtained will apply directly to the original section without further adjustment.

The transformed section technique is also applicable and useful for calculations of stresses and strains in such unbalanced sections. When carried out as described above the I for the transformed section may be calculated and used in calculating strains at various points in the section under a given applied bending moment M. These will also be the strains in the corresponding parts of the real section, the neutral axis being in the same relative position for both cases. The stresses in the real section may be found from the strains by using the real E for the material at the point in question. Thus the stresses at any point in the original section will be related to those calculated for the transformed section in the ratio of the real E to the reference E for the material at that point.

When using the transformed section approach for the calculation of EI, and recalling that the contributions of the individual elements to I are given approximately by Ak^2 in each case, it can be reasoned that the respective areas of elements only need to be transformed, by multiplying the real element area in each case by its E rather than by a ratio of E. Thus when the determination is carried out by summing the values of Ak^2 for each element the result obtained yields EI since the transformation has already introduced E.

In the normal sandwich the core stiffness does not contribute appreciably and the above procedure yields

$$EI = \frac{b\,(E_1\,t_1\,E_2\,t_2)d^2}{E_1\,t_1 + E_2\,t_2} \qquad (8)$$

for an asymmetrical sandwich strip with thin skins.

Again, where the skins have appreciable thickness, their contribution amounts to $\frac{b(E_1\,t_1 + E_2\,t_2{}^3)}{12}$ (9)
and can be added directly to equation (8) to obtain the full EI.

In many beams the sole property governing deflection under load is the EI value. Unfortunately this is the case in sandwich composites only when the span is very long in relation to the thickness, or when the modulus of rigidity G of the core is quite high. For many building applications and many core materials the shear deflection becomes significant and must be considered in addition to the usual bending deflection, which relates only to the extension and compression of the skins. The shear stiffness = bcG (for thin skins). The approximate relations for maximum deflection for a simply supported beam then become

$$\delta = \frac{5W\ell^3}{384\ EI} + \frac{W\ell}{8\ bcG} \qquad (10)$$

for a sandwich strip under uniform loads and

$$\delta = \frac{P\ell^3}{48\,EI} + \frac{P\ell}{4\,bcG} \qquad (11)$$

for centre-point load.

These apply particularly for thin-skin sandwich strips, but the approximations are rough so that further adjustments for normal skins are seldom warranted. Typical effects of shear stiffness will be shown later.

The foregoing stiffness relations all refer, as noted, to sandwich "strips," denoting narrow beams. The width of most sandwich panels introduces "plate action" to the bending stiffness portion of the total deflection. This is the stiffening due to restraint against widening and narrowing of the compression and tension skins, respectively. The tendency to extend or contract laterally with stress is the Poisson effect, and the restraint forces in turn set up counteracting stresses in accordance with Poisson's ratio, ν. The result is that the skin will deform only $(1 - \nu^2)$ as much as it would in a narrow strip under equal axial stress. The bending stiffness EI of a sandwich panel is thus more accurately stated as

$$EI\,(\text{plate}) = EI\,(\text{strip})/(1 - \nu^2) \qquad (12)$$

and equations (5), (7), (8), (9) could be so modified to represent more accurately a panel in simple bending or in column loading, as will be noted.

As ν for most isotropic materials is in the order of 0.3, $(1 - \nu^2)$ becomes about 0.9. Thus the bending stiffness of a sandwich panel will be about 10 per cent greater than that calculated for a strip beam. This applies only to the pure bending portion of sandwich deflections (the first parts of equations (10) and (11)), not to the shear portion, so that the final effect will be something less than 10 per cent in most cases. Such plate action of panels is often neglected in the usual approximate calculations.

When a sandwich panel or any plate is supported on all edges the added bending strength and stiffness is marked. To date derived solutions for sandwich plates are complex and still approximate. Very roughly, the deflection of such a plate may be about 50 per cent of the deflection calculated for a narrow strip running the short way, when the panel is nearly square. As the geometry changes so that the length approaches twice the width, this factor increases to about 90 per cent, becoming the same as if only two sides were supported. Such simple factors are not reliable and are useful only for preliminary feasibility studies.

The above completes the approximate assessment of sandwich bending stiffness and strength, except for the often-important aspect of ripple-instability of the compression skin. This is introduced more readily in the discussion of sandwich columns.

2.3 IMPACT

The impact resistance in bending of a sandwich panel can be approximated by assuming that the deflection at failure under static load equals the deflection at failure under dynamic impact load, and that the materials behave elastically to failure under such fast loading. For simplicity it is also assumed that a given width of panel acts fully in resisting the point load. With the ultimate bending resistance M calculated as in equation (1), the ultimate point load is calculated to produce M at the point in question. Considering both normal bending and shear, the ultimate deflection is then calculated elastically as in equation (11). The work done is, then, in the order of

$$\text{work-to-failure} = \tfrac{1}{2} P\delta = \text{impact resistance} \qquad (13)$$

in load x distance units.

Again, testing is necessary where impact resistance is important in a particular application. The lower the bending stiffness the higher the impact strength; the structural sandwich often exhibits remarkable impact properties because of its high strength and thickness ratio and its low shear modulus.

2.4 COLUMN LOADING

The structural sandwich is seldom used as yet for load-bearing walls in buildings, the few exceptions being in low houses where almost any sandwich configuration is excessively strong in column action. Again, the exhaustive mathematical derivations are onerous and still approximate in relation to practical conditions. Given that the usual situation is one of over-design, and that a simple load test would be done in any case, the following approximations should be adequate. Plate action effects are operative as in bending, but their inclusion is scarcely warranted unless vertical edge stiffeners are included in the panel system.

Where the skins are sufficiently stabilized by the core (discussed a little later) a flat sandwich panel column may fail in over-all buckling of the Euler type. If the column length-to-thickness ratio is very high (perhaps about 70 or more) the classic Euler equation holds:

$$Pe = \frac{\pi^2 EI}{L^{12}} \qquad (14)$$

for slender columns. Pe = Euler load - ultimate (buckling) load; L^1 = effective vertical length of the panel column = full height where the top and bottom edges are free to rotate.

For the less slender panels normally encountered in building the buckling load is influenced by the low shear modulus of sandwich cores in something like the following manner:

$$Pes = \frac{Pe\,Gbc}{Pe + Gbc} \qquad (15)$$

for stubby columns with thin skins. Pes = ultimate (buckling) load = Euler load modified for shear; Pe = Euler load as before. This equation gives only a rough idea of the order of Pes where the skins have appreciable thickness.

Local buckling (rippling) of the skins may occur at less load than over-all or Euler buckling if the core is too low in stiffness. Fortunately, Hoff and Mautner's conservative approximation for most sandwich constructions is simple:

$$\sigma_{cr} = \tfrac{1}{2} \sqrt[3]{E_s E_c G_c} \tag{16}$$

σ_{cr} is the critical stress in the skin and E_s, E_c, G_c refer to skin and core properties as indicated.

Note the independence of such rippling from skin or core thicknesses. Wave-stability mathematics finally resolved that only the elastic properties of the materials are operative, and that both the theoretical work and supporting test programs were remarkable indeed. The critical stress σ_{cr} also applies without change as the ultimate stress in the compression skin of a sandwich in bending. This is especially important in assessing a sandwich beam strength under point load.

2.5 CONCENTRATED LOAD

The buffeting of supersonic airstreams may be the prime factor in aircraft, demanding cores with high strength and stiffness perpendicular to the skins. Buildings are free of such unusual problems, but the simple question of denting abuse can demand similar core properties. Whether the expected load ranges from a bicycle leaning against a wall to a stiletto heel placed on a floor, the support of thin skins (e.g., metal) against permanent denting is often the sole reason for using a hard core rather than a soft one. With such skins, a reasonable first assumption may be that the resistance to visible denting under concentrated load testing (tested with a 1-in. diameter disc) is about twice the flat compressive strength of the usual core material or greater. This should be checked by actual test wherever dent resistance is important. The plate action effect of even thin skins on an elastic support can be substantial in local load resistance. Where the skins are thicker (e.g., hardboard, plywood) the dent and puncture resistances increase sharply and soft cores are often adequate - except sometimes in shipping where puncture loads may be very high indeed.

2.6 RACKING OR DIAPHRAGM ACTION

Sandwich panel house structures often use the panels as the sole means of resisting wind racking forces. Racking stresses are rarely analysed for the actual design or construction. The stresses are low in relation to the racking stiffness and strength of almost any sheet material used in building. Nevertheless the racking question is usually raised for new systems. The forces on fasteners do deserve thought, but even these are usually small because of the large size of most panels and their corresponding "leverage." These forces can be conservatively assessed for panel wall, roof or floor diaphragms by considering the panels as unyielding rectangles of fixed geometry that rack by rotation only. Successive groups of fasteners may be eliminated to allow determinant moment couples, or the load sharing between all fasteners may be assumed to be proportional to the relative movement at each point with an increment of rotation.

Such assessments should be adequate for most low buildings, even industrial buildings where a long roof diaphragm must carry cross-wind loads to short end walls. Since the early attempts at "engineering analysis" of small house structures in the U.S.A. in the 1930's, authorities have continued to require a traditional racking test of an 8- by 8-ft wall section for acceptance of new constructions. This may have been useful for an understanding of the limits of traditional walls with horizontal boards, but it usually has little relevance to rigid sheet and panel walls. Its size and tie-down method allow no measure of fastener performance, and almost any sandwich or other stabilized sheet construction will pass this test with ease.

Although these sections are intended to deal with design methods rather than application questions, it is awkward to discuss racking analysis without noting that it is often unwarranted. Where the racking efficiency of the structural sandwich may be of importance, as in use for high buildings, the rigorous mathematical solutions referenced in Section 2.9 would be useful.

2.7 BOWING

As the skins and cores of sandwich laminates have little bending resistance, taken separately, any dimensional change of one skin only forces an over-all curvature from the plane. If the change occurs in both directions in the plane, the curvature is compound. The bowing is essentially a geometrical effect inversely proportional to the thickness, and may be calculated approximately as

$$\delta = \frac{k\ell^2}{800h} \qquad (17)$$

where k = percentage change of one skin compared to the other

and δ = max. (centre) deflection from the plane.

An initially warped core cannot bow a panel originally fabricated flat; only changes in the strong faces can do so. If the panel is fabricated with both skins at equal temperature and moisture content, bowing will only result from different environments on either side, as will be discussed. The bowing is smooth and not severe if the thickness is reasonable and the edges free to allow planar expansion. It has been reported that rigidly restrained dimensions have caused panel skins to tear the core apart, in extreme conditions, when the core tensile strength normal to the faces was low.

2.8 TESTS

Considerable effort has been expended in preparing standard test methods for sandwich constructions and building components, and some relevant ones may be noted briefly. The test procedures may often be simplified considerably for particular cases, especially when used for successive developmental purposes. Important core properties include flat compression strength and modulus, ASTM C365-57, which relates to denting abuse and skin stabilizing. Flat tension, ASTM C297-61, also relates to the latter. Shear strength and shear modulus are key properties, and ASTM C273-61 compression method is straightforward and useful.

Concerning the performance of the whole panel, ASTM C480-62 gives a stable set-up to measure long-term creep, which will be discussed in detail in Part III. General durability is always difficult to assess; the exposure cycles of ASTM C481-62 may be as good as any, but the effect of edge closures of a panel can make such short-term exposures of questionable meaning. Some such exposures, correlated with expected environmental extremes, should always be tried when dimensional changes or forces might occur in the core materials, e.g., urethane foams and wood fibre cores. ASTM E72-61, strength tests of panels for building construction, can be applied as relevant to desired uses of sandwich panels. Simplification can often be effected responsibly. The ubiquitous racking test is there. It and the rather difficult axial load (column) test for load-bearing walls often may be unnecessary because of the intrinsic overdesign of any stiff sandwich in such loading and the ability to check by calculation the order of performance. Thermal transmission and condensation control can be calculated or tested as for any panel; the latter is noted in Part III. Fire properties receive considerable attention in Part IV.

2.9 ADVANCED SANDWICH THEORY AND OPTIMUM DESIGN

A brief note with references may be useful where engineering interests warrant fuller understanding of sandwich theory. Habip's review and bibliography (8) should again be cited, particularly in tracing original work. The notable work of the U.S. Forest Products Laboratory for military sponsors has always attempted to expedite solutions. Such work by Raville defines the bending of sandwich plates (13). Norris, March, Ericksen, Kuenzi, Zahn and Kommers developed and tested expressions for edge compression, edge shear (racking), cylinders under axial load, etc., that are concisely stated in a flight vehicle handbook (14). Such work has been extended and further refinements made in the last few years. Again, these rigorous derivations may often show little improvement over approximate methods for practical building conditions.

Physical expressions have been used further to establish optimum design rules based on minimizing either material (weight) or cost. Kuenzi (15) derives simple minimum weight relations for bending stiffness and strength, edge compression (column loading), etc., assuming that core properties are a consistent function of density. Darvas (16) similarly derives minimum cost design for bending stiffness and strength, resulting again in simple relations:

$$u = \frac{4}{r} - 3 \quad \text{for optimum stiffness and}$$

$$u = \frac{2}{r} - 2 \quad \text{for optimum strength in bending,}$$

where u = ratio of core thickness to skin thickness, and

r = ratio of price per unit volume of core to price per unit volume of skin.

These and other investigators have noted that such optimum approaches cannot be followed very often in practice. In building, the core thickness may be dictated by insulation requirements, bowing, the size of electrical boxes, or simply the need to "look solid." The skin thickness may be controlled by denting considerations, or quite often the available sheet stock may be much thicker than is structurally necessary.

PART III - MATERIAL PROPERTIES AND EFFECTS

Sandwich skins are, essentially, axially loaded elements. The significance of axial property levels is a familiar part of engineering principle. The significance of core and adhesive actions and some other effects, on the other hand, should be introduced by quantitative examples to allow more meaningful discussion of sandwich materials. Then the relevant properties of the more promising materials may be described, allowing the capabilities of various structural sandwich composites to be demonstrated and problems and potentials discussed.

3.2 DESIGN EXAMPLES: THE EFFECTS OF CORE PROPERTIES

Consider a structural sandwich strip with 28-gauge (0.0149-in.) sheet steel skins bonded to a 2-in. core, in the first instance eliminating any core effects by assuming a very high G value. This is a rather stiff sandwich, but it would be comparable to one using 3/8-in. fir plywood, certain $\frac{1}{4}$-in. asbestos board, or 3/16-in. glass-fibre-reinforced plastic on the same core. From equation (5), Part II:

$$\text{EI 12-in. strip} \approx \frac{29 \times 10^6 \times 12 \times 0.015 \times 2^2}{2} = 10.4 \times 10^6$$

A residential floor load of 40 psf with a live load deflection requirement of 1/360 span (Residential Standards, Canada 1965) can be carried over a considerable span. From the first or pure bending portion of equation (10)

$$\frac{5w\ell^4}{384\ EI} = \frac{\ell}{360} \quad ; \quad = \sqrt[3]{\frac{384\ EI}{(5w)\ 360}}$$

w = 40 psf = 40 lb/lin. ft (plf) on 12-in. strip = 3.33 lb/lin. in. (pli)

$\ell = \sqrt[3]{0.064\ EI}$ = 87 in., allowable span

$\delta_b = \frac{86}{360}$ = 0.24-in. = pure bending deflection

Substituting a core of, say, 2 pcf polyurethane foam of G = 400 psi, the shear deflection of this floor panel is approximated by the second portion of equation (10):

$$\delta_s = \frac{w\ell^2}{8bcG} = \frac{3.33 \times 87^2}{8 \times 12 \times 2 \times 400} = 0.33 \text{ in.}$$

The total deflection δ_T is thus about 0.57-in. or 2.4 times the pure bending δ_b. The new allowable span should be close to $\sqrt[3]{\frac{1}{2.4}}$ times the old span, or about 65 in. (Such a relation cannot be extended to wide variations of span because the δ_s portion does not vary as the cube of the span.) Table I shows the effects of a normal range of shear stiffnesses for this "stubby" example. As normal plate action will render the panels some 10 per cent stiffer than shown in these narrow strip calculations, the shear effect may be considered negligible when the calculated δ_T/δ_b becomes as low as, say, 1.09. This happens with this stubby example, with the core G approaching 8000 psi.

Similarly, Table I shows these effects for a longer span use of the same panel, as in curtain wall or some roof uses. Now the shear effect may be considered negligible when G = 3000 or more. When the EI value is less at a given thickness, as is the case for most sandwich skins, then δ_s is decreased in relation to δ_b, and the need for high G values is reduced.

3.3 CORE SHEAR, EXTENSIBILITY AND STABILIZING EFFECTS

The preceding examples allow the normal range of shear stresses to be demonstrated. These are surprisingly low because the shear "web" of the sandwich "I-beam" covers the entire area. The stubby floor panel yields the most severe shear:

$$\tau_{max} = \frac{V}{bc} = \frac{w\ell}{2bc} = 6 \text{ psi}$$

The longer curtain wall example yields a core shear of 4.4 psi. These are typical core shear stresses, although thinner panels under heavy floor loads on shorter spans can approach 15 psi core shear. The shear stresses on the adhesive between core and skin are practically identical to the core shear. Even very low density cores and inexpensive adhesives can take such stresses for dynamic or short term loads, but if they are sustained indefinitely there may be a creep problem, as will be discussed.

No matter what its strength, the core material cannot allow full development of sandwich capacity unless it can "give" enough to follow the strain in the skins. A few materials of otherwise excellent properties are either too brittle or friable to suit sandwich composites. The working range of compressibility and extensibility of the skin materials can be determined well enough by dividing the relevant yield stress by E. Thus steel will be strained about 0.13 per cent to be fully worked in tension or compression, aluminum about 0.17 per cent, wood perhaps about 0.25 per cent, hardboards 0.5 per cent or so, and both paper-plastic and glass fibre plastic laminates 1 to 1.5 per cent, representing the high extreme. Most core materials can follow such skin strains without rupture.

Finally, the compression skin in a panel in bending or column loading will fail in local rippling at less than yield stress if the core provides inadequate stabilization. Equation (16) of Section 2.4 may be rewritten:

$$E_c G_c = \frac{8\sigma_{cr}^3}{E_s} .$$

But

$$G_c = \text{about } \tfrac{1}{2} E_c \text{ for isotropic core materials,}$$

so that

$$E_c = \frac{16\sigma_{cr}^3}{E_s} \text{ for isotropic cores.}$$

Using the yield or ultimate stress of a skin material and its axial modulus E_s, the minimum compression modulus E_c of the core perpendicular to the skin can thus be determined to prevent skin rippling. As examples, carbon steel skins would demand a core of E_c = 4500 psi or more if the use required the full yield stress of the steel. Similarly, utility aluminum sheet would require a core E_c of about 2800 psi, and fir plywood one of about 1800 psi. Generally, the core materials with better G properties will also have E values more than adequate for normal skin stabilization.

3.4 THERMAL AND MOISTURE EFFECTS

Bowing and internal condensation can be particular, if unrelated, problems of sandwich constructions wherever differential temperature or moisture regimes exist across the panel thickness. The environmental ranges and effects should be briefly sketched before discussing material properties. In cold countries the outer skin of an insulated panel (wall or roof) can be at -30°F while the inner skin is near 70°F, giving a 100 F deg differential. Similarly, in summer the outer skin can reach 170°F for brief periods, or even higher with dark colours (17), while the inner skin is at say 70°F, again a 100°F differential. The amount of bowing will be the same in either case, inward in the first and outward in the second, as determined by equation (17), Section 2.7. With temperature sensitive materials such as metals and plastics the 100°F differential may be used to assess the dimensional responses, at least for cold countries.

Hygroscopic materials such as wood and wood-fibre products generally move more with moisture content than with temperature; this is important in Canada where relative humidity differentials are severe. The indoor relative humidity in the heating season may be 20 per cent, while that outdoors may be 80 per cent, with both extremes sustained for several weeks. Thus hygroscopic skins of enclosure panels may approach full equilibrium with these relative humidity (RH) conditions even when protected by coatings, so that again their dimensional response should be noted over this range for such design purposes. Similarly, indoor panels will be subjected to as low as 20 per cent RH in the winter and 80 per cent RH in the summer, and their response should be so noted. Bowing will not occur in this latter case if both skins are of the same material, but the range of expected movement in the panel plane must be considered in the system design.

The winter differential in moisture and temperature conditions can cause an insulated construction to trap condensation if the inner skin allows passage of air or water vapour. The time-honoured way of preventing or controlling this is to ensure that the outer layers are some five times more permeable than the inner layers or vapour barrier, or that the internal space is vented to the outside air. This approach has been advocated for sandwich constructions (18), but it can complicate sandwich manufacture and choice of materials, perhaps quite needlessly. Based on general observations that it is mass air leakage rather than vapour diffusion that causes condensation troubles, on long-term experience in the Far North (19), and on testing under extreme conditions (20), it may be concluded that a closed sandwich construction should remain trouble-free with neither vents nor permeable outer skins. This applies to normal cycling conditions where a summer drying condition follows the winter condensation period. The inner skin should be of low permeance (less than one perm, say), in any case equal to or less than the outer skin. No air path should exist between the indoor environment and the core space, unless the core itself is a closed-cell material with permeance not more than 3 perm-inches, say. All this assumes that the chosen materials can tolerate the expected small amount of condensate each winter.

3.5 CREEP AND STRESS-RUPTURE

More than any other construction, the sandwich concept encourages the structural use of many materials that have little history of performance under sustained load. Long-term creep and stress-rupture safety is not amenable to quick study. Even creep-prone traditional materials such as wood have been widely used without serious investigation until recent years, but today's emphasis on more efficient structure and closer regulation of use means that newer materials must prove their way from the first. Some exemplary creep studies of the past decade now allow useful discussion of promising sandwich materials in terms of empirical performance and criteria.

Rational criteria for acceptable creep are difficult to establish. Building loads and durations are not well known, allowable deflections are arbitrary, and creep itself is not closely predictable in the real environment. Perhaps the only approach at present is to forego attempts at precise derivations and fall back on traditional lessons: relate creep criteria to the fully acceptable performance of wood. If a material demonstrates equal or less creep than wood, it should be usable in like places and like manner. At proper stress levels it should be adequate even for floors in residential and light constructions, for example, with no allowance for further deflection. For larger buildings and uses where deflection limits are important, initial deflections may be restricted, as with wood, to allow for creep deflection.

A fuller discussion of the rheology of wood is not warranted here, but wood creep under sustained load may be described within broad limits. Two rheological models are shown in Figure (5). Both suggest that a stiff viscous drag within the material takes up much of the load at first, but this component of resistance slowly gives with time and the basic elastic structure must finally take up all the load. The first model denotes this "visco-elastic" action and suggests that the material will stop deforming and slowly return to original dimensions once load is removed, as the "spring" overcomes the "dashpot." The second model denotes "visco-elastic-plastic" action: the final very stiff dashpot infers that some plastic flow occurs at any load over any time, and this flow remains as the permanent set after removal of load. Review of several intensive studies suggests that a modification of the first model may give a more correct picture for wood and probably other high polymers such as many plastics, and possibly other materials too. The modification would be difficult to show in diagram form, but is is simple enough: the main spring or elastic structure can behave elastically up to a certain strain, after which it yields and allows plastic flow.

Tottenham (21) deduces that such a critical maximum strain must exist for wood, and suggests that once it occurs failure must eventually follow at that load. King (22) shows that this limit or "threshold of set" is about 0.4 per cent strain for many or all woods in pure tension, but concludes that this is below a threshold of eventual failure. (Note that a stress of 6800 psi would cause such a strain immediately in Douglas fir, while half that stress might cause such a strain in a lifetime with no implications of eventual failure.) L. W. Wood (23) derived regression curves showing that stress-rupture times of beyond 27 years should be attained by wood at 56 per cent of its immediate ultimate bending stress (Figure 6). This fraction would be about 6200 psi for clear Douglas fir. Clouser (24) worked with data from 10-year creep testing of wood at stresses over 60 per cent of immediate ultimate in bending to derive creep and point-of-inflection expressions. He and others conclude that the result fits a straight-line plot on a log-log chart that can be empirically fitted to the equation $\epsilon = \epsilon o + at^m$, as found for many other materials. The constant ϵo is close to the initial strain or deflection, "a" and "m" are also constants at the stress level in question, but "a" shows a sharp trend downwards with decreasing stress, while the power "m" seems somewhat independent of stress and has a value of about 1/3, also common for other materials. Unfortunately the terms cannot be extrapolated down to normal stress levels with any confidence: the work was aimed at stress-rupture study rather than normal long-term deflections.

Armstrong and Kingston (25) and Christensen (26) summarize the following for beams large and small at 25 per cent of ultimate stress (not greatly over normal design stresses) and any constant moisture content: relative creep about 5 per cent in 2 hours, 12 per cent in 24 hours, 20 per cent in 4 days, 30 per cent in 20 days, after which it reaches equilibrium or nearly so. (The useful concept "relative creep" is the amount of strain or deflection beyond the initial amount under load expressed as a percentage of the initial amount.) These results follow the expression $\epsilon = \epsilon o + at^m$, and "m" is still 1/3 even at this low stress (the slope is one log cycle in three), but only for a short period. Creep then stops or slows sharply, but the authors show that severe changes in moisture content can accelerate early creep most drastically. Installing wood in the green state, placing the design loads, and letting it dry in place would allow 200 per cent relative creep in 9 days, with total deflection three times that "allowable." Yet such practice occurs in housing, with no inadequacies in relation to real use and real requirements. The severe moisture cycling in these studies caused drastic creep increases at first, but the rate settled down to normal, indicating that the viscous drag portion of internal structure, not the elastic structure, is affected. The broad wood band of Figure 7 may allow for normal moisture changes with seasoned wood. Finally, several authorities report that long-term experience with wood in normal use shows deflections of $1\frac{1}{2}$ to 2 times the initial deflection (27), and this concludes the wood curve of Figure 5. This offers a criterion for floors or other uses where design loads can occur for long periods. Roofs might better relate to other accepted materials, as will be noted in Section 3.7.1.

3.6 SKIN MATERIALS

Table II lists typical approximate properties of some sheet materials. The notes to the table explain the terms and parameters. The following sections discuss relevant attributes for these and related materials of apparent promise, dwelling particularly on the newer ones with little engineering history.

Material ranges in composition, performance and environmental effects are noted insofar as present knowledge permits, and references are given. It is the intention in Table II to indicate performance ranges and limitations, not to list final or precise properties; it should not be used without reference to the text.

3.6.1 STEEL

Perhaps the key property of steel for sandwich constructions is its very high stiffness, E. This permits longer spans that meet the usual arbitrary deflection requirements, while its high strength σw will seldom be used to the full. Dimensional stability is better than that of other materials. The advent of continuous strip coating plants in Canada and other countries allows production of plastic coated steels with high consistency and reliability at quite moderate prices. On galvanized sheet, vinyl, acrylic, silicone and other coatings can perform quite well as exterior finishes. Such thin organic coatings cannot be expected to maintain a satisfactory appearance for very many years, but they can provide a good base for on-site recoatings of substantial durability. The costlier "Tedlar" polyvinyl fluoride films can provide indefinite life on metals, fibre-reinforced-plastics and other base materials. Expensive and permanent exterior choices are available in ceramic-coated or stainless steels. For interior uses, even lower cost plastic coatings can be consistent, tough, and durable enough, and galvanizing may be omitted if storage and handling methods are given some thought.

3.6.2 ALUMINUM

The preceding comments apply also to plastic-coated aluminum sheet. Accidental scratches cannot cause stains, as they can with coated steel, even when galvanized. One wonders whether the limited range of colours created through chemical treatment of aluminum would not be pleasing and acceptable "basics" for wide use. It does seem questionable to cover a durable metal with a limited-life coating, although plastic coatings are now quite remarkable in their own right. Aluminum panels may require somewhat harder cores than steels to provide dent resistance (both metals are often backed by hardboards over a soft core, but this demands extra operations and two more adhesive layers). The lower E value gives lower span capability than does steel, at least where deflections are limited. Dimensional changes due to temperature are appreciably higher than for steel.

3.6.3 GLASS-FIBRE-REINFORCED PLASTIC (FRP)

This development of World War II may finally be coming of age in the building field, as it has in other fields. Costs continue to decrease while those of other materials increase steadily. FRP is still expensive in comparison with basic residential materials, but not with low-maintenance materials, particularly for larger buildings. This is especially true where formed or sculptured shapes are desired for facade effects; here the FRP's can be much less expensive than stamped, coated metals, at least within the quantity of production usually associated with building. Some European developments in such sandwich curtain walls are receiving great attention. In turn, certain rigid but readily-formed thermoplastics are challenging the FRP's in such applications.

Despite their youth, the FRP's can be used with perhaps greater engineering efficiency and confidence than can wood, even under long-term load. Durability of appearance and strength in exterior use demands that the glass fibre structure be protected with surface coatings (28, 29). These are built up in greater thicknesses than on coated metals, and the base is sufficiently durable if properly impregnated and pigmented that perhaps longer life can be assured before recoating. Continued immersion in water reduces their stress-rupture life, but otherwise it is similar to that of wood (30, 31), assuming continuous surface protection (Figure 6). Relative creep is less than that of wood if glass fibres are placed parallel to the stress plane (32) (Figure 7), and well-made FRP's should be suitable for sustained-load applications.

It is not difficult, indeed, to manufacture FRP skins with none of the above qualities; and authorative sources should be consulted on actual design, materials and manufacture. Properties are highly directional, depending on the orientation of the glass fibres. The E values are low, as noted in Table II, so that spans are limited if deflections are important. Flame spread can be high, but recent formulations are achieving low values while retaining very good weathering qualities, aimed at significant curtain wall developments (33).

3.6.4 PAPER-PLASTICS

These high-pressure laminates can no longer be considered young (see Part I) or untested. Their low cost constituents, usually kraft papers and phenolic resins, and remarkable properties seem to make them at least as promising as FRP's for large building components. Nevertheless, their production still requires discrete and tedious lay-up and final batch pressing at high temperatures and pressures, keeping the basic costs high. If recent plastic resins can allow continuous production of such laminates, their role may yet approach Jules Verne's dreams (Part I).

Present uses in building are limited mainly to the very successful melamine plastic-surfaced laminates for counter-tops, furniture and wall surfacings. Roof and curtain wall products are used in the United Kingdom. The present and potential major implications of these and other plastics have been reviewed (34).

Kraft-phenolics can be very brittle, and cracks propagate readily from any sharp-cornered opening or notch. Toughness can be adequate for sandwich constructions where the core shear modulus can add to impact resistance. Strength is high, but the modulus E is low. Shrinkage problems are encountered in some instances. As the material is a well-bonded laminate of wood fibres, one would expect its relative creep to be similar to that of wood. This is the case, as shown by a plot derived from Findley's singular creep studies (35) (Figure 7). Sustained-load uses should be appropriate. Thin sheets of a single ply of heavy kraft paper saturated with phenolic can be produced at moderate cost as satisfactory skins for partition panels.

3.6.5 PLYWOOD

The properties of this well-known and proved product are essentially those of solid wood, except that the cross-plies greatly increase strength and stability in the cross-grain direction at the expense of some reduction in the grain direction. Its performance history in load bearing uses is long and quite trouble-free, including stressed-skin and sandwich constructions. The common exterior form uses Douglas fir veneers with phenolic adhesives. The modulus E is low, but thicknesses are substantial at moderate cost and weight, so that resulting sandwich stiffness and span capacity are high. For sandwich uses greater strength and stiffness bias in the span direction would be desirable, but available 3-ply products feature a thick cross-veneer for better flatness stability in single sheet uses. A variation with a better bias is called "kraft-veneer;" a thick veneer is both distended and bonded to a kraft paper to form a stable sheet that could be singularly promising for sandwich panels. This is an old form well worth further thought.

Coatings have always been a problem. Plywood can be an even more troublesome paint base than solid wood. Dark pigment oil stains on rough-cut plywoods can perform quite well. Kraft-phenolic overlays are well proved and now widely used on plywood as a paint base. Again, the kraft-veneer variation suggests itself. Although the flame spread of bare plywood may be considered moderately high for widespread interior use, the usual use of common paints and overlays can reduce it to 100 or less. Some shellacs and lacquers can increase it drastically. (As noted in Table II, flame spread values are derived from Galbreath's review (36). Implications are discussed in Part IV.)

3.6.6 HARDBOARD

Despite some recent work, it remains difficult to consider even treated hardboards as engineering materials - much more so than with some plastics that are younger. One would hope that well-bonded hardboards could show about the same relative creep as wood. Unfortunately, the limited and short-term work that has been located for this review (37, 38) considers only bending of thin sheets. This shows considerable relative creep in dry conditions, and higher moisture contents cause sharp increases in creep rates and decreases in the initial E and strength properties in bending. A notable study of paper rheology (39) suggests that such sharp breaks in E are due to bond slip and progressive bond rupture. As interfibre bond is improved, the break disappears and performance is dictated by the wood fibres. Thin sheet bending does exaggerate the effects of bond stresses, slippage and twisting between fibres. The implications may be unduly severe for sandwich constructions where skin stresses are axial and run from fibre to fibre through multiple contact and overlap points. Some general experience suggests that hardboards creep very little in axial tension. Where lines of stress must cut through fibres, as in paper in edgewise shear (e.g. honeycomb cores), creep performance is quite good. It is thought that some early stressed skin huts used hardboard skins on floor panels and performed satisfactorily, but no corroboration has been found. In any case, it is apparent that axial creep should be studied further, and that any hardboards in stressed applications should be well overlaid or coated. Weathering durability of painted hardboards is very good. Dimensional stability is poor.

3.6.7 PARTICLEBOARD

The long-range implications of expanding populations and needs increase the need to utilize more and more of every tree and should make particleboard materials the dominant forest product for all board uses. Intensive development and testing programs should be fully warranted. Although one would expect rigid and stable bond netting in these products, using such proved thermo-setting adhesives as ureas and phenolics, the comments of Section 3.6.6 on creep and moisture effects apply here also. Again, all the investigation seems to have been in bending. Relative creep in dry versus moisture cycling conditions for boards is plotted in Figure 7 from Bryan and Schniewind's study (40). Again, one would hope for wood-like axial creep performance but further testing is necessary. Supporting this assumption, Bryan has shown that the stress-rupture time characteristics of particleboards, dry, are essentially the same as for wood, (41) (Figure 6). The rapid levelling-off of moisture effects on creep (Figure 7) compares well with the weathering effects on stiffness and strength, which are severe at first but then approach an equilibrium. Hann and Black (42) and others suggest this is due to "springback" as the wood particles relieve their residual stresses from the high-pressure forming process, resuming their natural densities and shapes. This apparently results in rapid rupture of bond points which stops in the relaxed state. Perhaps "springback" accounts for the similar effects in hardboards too. It has been noted that well-painted particleboards show little springback effect, at least visually (42). Perhaps the long flake/phenolic boards could offer sustained performance as sandwich skins if overlaid or coated. It would be very desirable to bias the flake orientation to achieve higher E's in the long direction.

A variation should be worth consideration as both structural skin and final surface for floor planks or panels in sandwich forms. This development applies the older "compreg" idea to particleboards, wherein flakes are fully impregnated with phenolics and pressed at very high pressures and temperatures. Specific gravity may be 1.4, E over 2×10^6 psi, and axial ultimate stress over 14,000 psi (43).

3.6.8 ASBESTOS-CEMENT

These materials have long been noted for general durability and fire resistance when properly manufactured, but it is surprisingly difficult to locate any information, testing or research reports, that would support engineering uses. Dimensional stability is good, E value fair, and tensile strength and toughness generally poor. Stress-rupture characteristics could not be located, but Findley's creep studies (35) on well-bonded asbestos fibre-phenolic laminates indicated consistent but high relative creep (Figure 7), which must reflect on the asbestos fibre itself. The asbestos-cements should have good intermittent-load applications in sandwich constructions such as roofs, but there is a real need for wider dissemination of any existing information, and for further basic and applied study.

3.6.9 RIGID POLYVINYL CHLORIDES

The long and notable development of plastic piping has become the key to other load-bearing uses of thermoplastics, perhaps most notably the rigid vinyls. Modulus E and dimensional stability are poor, but formability is excellent. This suggests that optimum applications could take the form of deeply curved sandwich shapes, as, say, curtain walls or load-bearing vaulted or folded roofs (see also Part IV). Among several intensive programs the work of Niklas and Eifflaender in Germany (44) showed stress-rupture curves quite similar to those for wood (Figure 4). Relative creep at allowable sustained stresses can be less than that of wood (45) (Figure 7). Formulations must be chosen to avoid brittleness in cold weather. Temperatures above 140°F can increase the creep rates and reduce even short-term properties quite severely, so that light colours are preferred outdoors. Roofs may expect sustained loads in the winter only, when temperatures are low and creep is minimized. Flame spread can be quite low. Other rigid thermoplastics may offer similar surprising promise for large building components both for interior and exterior use.

3.7 CORE MATERIALS

3.7.1 SOME EARLIER CORES AND PRESENT POSITIONS

Balsa wood was probably the first satisfactory structural sandwich core material and is still used for certain high-strength applications. A recent example is a Formula One racing car with aluminum skin on balsa core. In such uses balsa is sliced across the grain and placed with the grain running perpendicular to the skin. This provides high strength and E in that direction, and can stabilize metal skins at full yield stress; it does not increase the shear strength or G, as is sometimes assumed. It is one of the few cores that can support metal against denting without the use of a backup sheet. All relevant properties are very high, but cost and supply are troublesome. Developing from its use during World War II was a dense and fairly rigid foamed synthetic rubber that provided very strong, tough sandwich composites. An interesting recent variation is a one-piece, self-skinning, foam-centre ABS rubber with intriguing possibilities for car bodies, boats, and any panels that must withstand abuse.

Among the earlier plastic foams, phenolics seemed to show promise, and this still describes their position. If they could be "foamed" uniformly without cell wall disruptions, and perhaps with a modified polymer for better extensibility, they should yield very desirable qualities. Such production has been difficult to achieve, although there are recent indications of success. In the meantime, cells are open, uniformity is poor, strength and stiffness are low, and water vapour transmission is high; dimensional stability, temperature resistance, and resistance to ignition are good. For various reasons, often including cost, other plastic foams such as acrylics, cellulose acetates, ureas and polyesters have been replaced by the few plastics described in the following sections.

Wood fibreboard and similar board of sugar cane fibre, etc., should be mentioned if only to amplify the creep criteria discussion in Section 3.5. They were used for decades in empirically-designed sandwich boards, usually for non-load-bearing wall applications. On the flat, they allow severe shear creep even when kept dry. A strong and stable variation is made by cutting the board into narrow strips that are then placed on edge and glued together parallel to the span to form a core with no plane of weakness; shear forces must cut through the fibres. Good creep resistance is reported in general terms, supporting the discussion of Section 3.6.6. Further, the normal flat board is commonly used as a structural roof deck (usually non-sandwich) despite its substantial creep (46) as plotted in Figure 7. It is widely used with apparent satisfaction, with designs controlled to avoid exceeding an arbitrary l/180 deflection limit under one year of test loading at design load (46). This and other roof experience strongly suggests that a creep rate much higher than that of wood can be tolerated for roof uses. High loads are seldom imposed and are not long sustained, thus allowing prolonged recovery periods.

3.7.2 HONEYCOMB CORES

High temperature and stresses in aircraft forced the changeover from paper to aluminum foil to FRP and even stainless steel for honeycomb constructions. Only the paper types are appropriate in price and properties for most building uses. Table III shows properties of one grade (47), but these versatile materials can be obtained in many densities and grades with good and well-tested properties. Treatment of the kraft paper with phenolic resin assures adequate durability (48) if the panels are made and assembled in place to remain dry, or at least drain freely at edges and joints. Adhesives should be chosen to "wet" the honeycomb and skin to form a fillet to distribute the shear stresses on the thin paper edges. Creep experience has apparently been quite satisfactory. Metal skins can be fully stabilized by the high strength of these hexagonal paper structures, but the open cells provide little dent resistance. Thermal insulation is intrinsically poor in Canadian terms, and the addition of inexpensive insulants in the cells complicates the application of adhesives. For many uses paper-phenolic honeycomb remains the standard for structural cores.

3.7.3 EXTRUDED PARTICLEBOARD

This German development possesses singular advantages for sandwich building components, as well as some adverse qualities that should be considered in most designs. As is shown in Figure 8, a tubular board can be extruded on a continuous basis and the whole tree can be well used. The particles tend to pile up in planes transverse to the extrusion direction and to the surface, which gives very good stability, strength, and E values in thickness, i.e. perpendicular to the surface. Thus the board allows loading to the full strength of thin metal skins, and supports them against denting without the use of backup boards.

At the same time, this "extruded wood" behaves the same along its length as does wood across the grain - essentially what it is in this direction. Its lengthwise strength and dimensional stability are both very poor. Thus a sustained exposure to 20 per cent RH in the winter, followed by 75 per cent RH through a summer could cause the free board to expand about 2 per cent in length. Its corresponding modulus E may be about 9,400 psi at this higher humidity, so that the board could develop a stress of about 190 psi through its cross-section if it were restrained by skins.

In practice, the first such humidity cycle can allow a "springback" (Section 3.6.7) of about 1 per cent, which would add to the internal stress unless the board were relaxed before sandwich fabrication by aging or wetting and drying. The presence of skins and end closures of the tubes would reduce the board response to such humidity environments. In European practice, sandwich panels using treated hardboard skins on extruded wood have been used for some years as exterior walls and doors, with no reported problems of core expansion.

The lower the "X-ratio" the lower the shear stress the core can exert on the adhesive layers and skins under the above conditions and the less the material weight and cost. This term is convenient to designate the ratio of solid material to the whole cross-section, a basic factor in the design of extruded tubular and other deformed core shapes. In Table III the term $\frac{1}{2}$X refers to a hypothetical core with an X-ratio of $\frac{1}{2}$. Given the characteristics of the ram extruder with circular tubes, this might be about the lowest ratio obtainable with thinner cores; 3-in. thick or less oval or rounded rectangular tubes could allow a lower ratio. The approximate values in the table were estimated for this ratio. For solid stock, the actual density would be twice that given, the G and E perhaps 1/3 more, and so on. The G and other values could be increased markedly by more complete bonding in making the material, if so desired, or the density and bonding could be further reduced for light uses such as in partitions.

In the present example the tubes run parallel to the span. The properties across the board, across the tubular or machine direction, are about the same as the high properties perpendicular to the surface. Thus sandwich components are sometimes made with single wood veneers as skins, their fibres running in the tube direction. The veneers make a strong sandwich and restrain the core in the tube direction; and the core itself provides good strength and stability in the cross-direction. Most of these comments and those properties shown in Table III are derived from preliminary testing on early runs of spruce-chip extruded wood manufactured in Canada, using about 7 per cent urea resin solids. They are indicative only and are not intended as conclusive in any respect. Private work is well under way with various skins on these promising core materials (49).

3.7.4 DEFORMED PARTICLEBOARD AND HARDBOARD

This concept, again, should allow conversion of the whole tree to structural components. It is difficult to mould long wood fibres into deeply-formed shapes because of limited flow characteristics, but in recent years several processes have been developed. Insofar as is known generally, no shapes have been produced for sandwich core purposes. The core type sketched in Figure 9 (a) probably could be produced in deformed pressed materials that are essentially hardboards. Table III lists values deduced roughly for a hypothetical shape of hardboard similar to Figure 9(a), with an X-ratio of 1/10. Deformed particleboard processes can produce core shapes of somewhat thicker section, say a minimum X-ratio of 3/10, giving an over-all core specific gravity of about 0.15. These could at least equal the above properties, and could also be shaped as in Figure 9 (b) to support the skins for full stability and dent resistance (50). A substantial proportion of fibres run in the long direction (span direction), so that such board can be a complete structural panel in itself without separate skins.

3.7.5 EXTRUDED "FOAM" POLYSTYRENE

This proprietary product of the Dow Chemical Company is the strongest of the polystyrene foams and has long been a leading core material. (Most of these and the following plastic "foams" are not true foams, but the term is useful and descriptive enough.) The properties in Table III are derived largely from a recent company report on sandwich engineering (51) and are self-explanatory. Note the good insulation value and the high water vapour resistance that can ensure freedom from condensation in building panel uses (19). Temperature softening can be troublesome with dark-coloured skins in outdoor exposures, particularly in roofs. The modulus G is low so that panel bending becomes a limitation in many spanning uses, but this helps achieve remarkable toughness and impact resistance with this and other foam plastics. In the light of the creep criteria of Section 3.5 and creep experience with the bead foam polystyrenes next discussed, the manufacturer's suggested values for sustained shear stress might well be conservative. In any case such cores are better suited to intermittent-load uses, such as in walls and roofs, rather than to floors. Metal skins may require a back-up material such as hardboard to provide dent resistance and stability against buckling.

3.7.6 BEAD FOAM POLYSTYRENE

These materials are somewhat similar to the extruded polystyrenes, except that most values are lower, including costs. They can be foamed-in-place by heat fusion methods, and their low cost and amenability to fast production has made them popular for lightly-loaded panel applications. The properties indicated in Table III are derived from the work of Hughes and Wajda (52). Hummel (53) showed creep in bending shear as plotted in Figure 5, and Brown (54) comments on compression limits in shear that suggest that sustained load properties might be within useful limits. Solar temperatures even on light coloured metal surfaces reduce the strength of these cores and can cause drastic increases in creep rates.

3.7.7 FOAMED RIGID POLYVINYL CHLORIDE

This is one of the strongest thermoplastics and its foam properties are high. Other sources suggest that the G in particular can be double the values shown in Table III, which are also taken from Hughes and Wajda (52). These foams have not been widely used in North America, but European developments have placed them in rigorous structural sandwich applications. Taal and Algra (55) report on their toughness and closed-cell advantages in Dutch boat hull work. Their creep plots can be interpolated for relative creep at 25 per cent of ultimate stress and are found to fit Findley's measurements (45) on solid PVC creep with precision (Figure 5). Other authors suggest that safe sustained shear stresses may be about one-fifth the ultimate shear for this foam; this again agrees with experience with solid PVC. Some PVC foams are claimed to be partially thermosetting, and general temperature resistance is apparently better than with polystyrenes. Costs can be high.

3.7.8 FOAMED POLYURETHANE

Three aspects have made these materials the centre of attention as sandwich cores: they can be foamed in place between skins; their insulation "k" value can be extremely good; and they can provide their own fully durable bond to many skin materials. On the other hand, their strength properties are very low for sandwich spanning purposes (the values in Table III are from Stengard (56)). The unusually low "k" value is due to the entrapping of inert gases and can be permanent in fully closed sandwich uses. Temperature resistance can be good, but dimensional expansion and collapse problems can be severe unless formulations are well designed and controlled (56, 34). The creep plot on Figure 7 for urethane core sandwich panels in bending shows that it stays close to the wood band, at 3 psi shear; further testing of other samples of 2 pcf indicates that this continues at a much flatter slope for another year to the end of the test. Perhaps uses in floor panels should be carefully considered, but roof or wall uses are fully appropriate.

3.7.9 INORGANIC CORE MATERIALS

In building construction as against aircraft technology, the incentives are to save materials, labour, and space rather than weight alone. Hence the long interest in utilizing low-cost inorganic materials as sandwich cores despite the penalty in weight. Combustibility and resistance to high temperature are strong incentives in this direction. Normally the organic adhesives would form the weakest link in limiting fire resistance of a load-bearing sandwich. Possibly an inorganic bonding with mechanical keying could overcome this deficiency, as will be discussed briefly in Part IV. In any case, there are no successful inorganic cores for true structural sandwich composites, insofar as is known generally. Extensibility is the problem. As noted in Section 3.3, an extensibility of about 0.25 per cent would suit most skin materials, but this is about three times the range of most inorganic materials. This may no longer be a critical limitation; latex polymer additions are used now to toughen some inorganic materials for certain uses, i.e., latex-cements. The usage is crude as yet and no one knows the range of modification of properties that could be obtained through simple mixing methods, let alone through linking at the molecular level. Research efforts should be well justified. In Table III calcium hydrosilicate is given to show the properties that could be modified and utilized if extensibility could be improved.

3.8 ADHESIVES

This is a complex area of rapid development. It is generally agreed that the older methods of accelerated testing, developed by and for the wood interests (ASTM C481-62 CycleA), may have little correlation with expected use of various materials in sandwich form. As has been seen, the sandwich arrangement imposes extremely low stresses on the core and adhesive. General experience suggests that several adhesives, old and new, that cannot pass the above or other "boiling" tests, have performed well for decades in outdoor stressed skin and sandwich composites. They can often be formulated to pass such tests, but costs may increase, perhaps quite needlessly. Where skins and/or cores are wood or wood-products, the recent cross-linking polyvinyl co-polymers can meet such tests and should be fully satisfactory, allowing faster and more tolerant fabrication than the older, proven phenolics and resorcinols.

Caseins and ureas are adequate for all interior work and have proved satisfactory for well-made exposed panels (57). The rubber-resin contact adhesives may still be troublesome with wood products unless heat-reactivated and well rolled. They are perhaps the most versatile and satisfactory adhesives for all metal skins, allowing fast nip-roll lamination. Solar surface temperatures in exterior uses must be carefully considered (58). The cross-linking polyvinyl co-polymers are good with galvanized steels, and for all metals if heat-cured and used on porous cores (59). All the above adhesives are creep free within the low stress ranges of normal sandwich action. Adhesive choice and usage is one area where it is especially important to check with the manufacturer.

3.9 SPANS

With a wide choice of materials of a controllable range of properties, structural sandwich design can involve a bewildering range of possibilities. A simple stiffness-span chart forms a useful tool for purposes of quick feasibility studies for one or many combinations of materials. Figure 10 is such a chart. The higher curves can suggest partition or curtain wall possibilities; the middle ones, roofs; and the lower ones, floors. The EI-span relations are precise, but the sandwich constructions are intended only as typical examples derived from the approximate E values of Table II, not as final or precise examples. Note that for thin-skin examples EI varies directly as the skin thickness. For example, if one wishes to check the capacity of a steel skin sandwich with double the gauge shown, the EI is read at the desired thickness and the new spans are determined using the doubled EI value. Pure bending alone is considered in these curves. This is valid enough if the core G ranges from 3000 psi for long spans to 8000 psi for short spans, or corrections can be calculated as discussed.

PART IV: SYSTEMS, LIMITATIONS, POTENTIALS

Engineering design of a component is one thing, final development and acceptance of an effective system is another. This is especially so in building. The performance requirements may be severe but arbitrarily defined, if at all. The market is scattered. The distribution is in many hands at several levels, and no one group has a major stake in the final product on a volume production basis. Other "major appliances" have evolved free of such a fragmentation of control and interest. Much of this is beyond the scope of the present discussion, but an attempt will be made to consider the effects and trends of some larger factors in building use.

4.2 FIRE

Proponents of structural sandwich building systems must concern themselves with what constitutes responsible thinking on fire safety and how such thinking may develop. This is difficult. This discussion will rely primarily on the National Building Code of Canada, 1965, and on the opinions of those most involved with fire technology and the evolution of the Code. The National Building Code of Canada is an advisory document, produced by an Associate Committee of the National Research Council made up of leading individuals from private industry, industry associations, research groups, and others. It is widely recognized as a leading, continually evolving model code and has been adopted in whole or in part by communities that include about three quarters of the country's population. As such, it has encouraged a trend throughout Canada toward uniform acceptance attitudes on an engineering performance basis, although such attitudes and abilities still differ among municipalities.

Fire safety involves the following properties: flame spread, smoke emission, and fuel load within an area; fire resistance of components that separate occupancies or buildings from each other; and structural integrity or resistance to collapse. In sandwich constructions, flame spread is largely a function of the skins alone. The problem is seldom critical. Table II lists typical flame spread indices. The National Building Code of Canada, 1965, establishes maxima of 150 for all walls and ceilings of assembly halls, institutional and residential buildings, or any exit or corridor leading to an exit. In addition, the latter exits or corridors must have 90 per cent of the walls limited to 75, or 90 per cent of the upper half of the walls limited to 25. Sprinkler installations allow considerable relaxation of these requirements. Flame spread is receiving more emphasis, and restrictions may become more rigid and universal, applying even to furnishings.

Smoke emission is recognized as a hazard under some conditions, but its definition and correlation with safety have not yet been possible. Obscurity of exits and corridors is obviously undesirable, but dark smoke also serves as a warning of fire and of toxic gases that may be invisible in themselves. Smoke emission and colour will be given much more attention in the near future, especially for high buildings. In some cases at present, the more the skins or flame-resistant treatments inhibit combustion, the more and blacker the smoke emitted. Organic material industries are now sponsoring more intensive studies on this and other fire aspects and on their real meaning in terms of building safety.

Fire load is a vital factor in fire safety that is receiving new attention in building design and regulation, and must continue to do so. The term is defined as the amount of fuel contained in the structure, expressed in equivalent weight of wood fuel per square foot of floor area. The fire load obviously influences the fire intensity and duration, and earlier editions of the National Building Code state empirical relationships between fire resistance and fire load (one-hour building structure can safely contain 10 psf fire load, two-hour, 20 psf, and so on). Although no longer stated in the Code, such relations are said to have influenced the present requirements and will come to be expressed better and correlated with building safety. It is difficult indeed to reduce these factors to a scientific basis, especially for high buildings, but it may be stated that the past insistence of the "purists" on "non-combustible or nothing" is giving way to consideration of limiting the amount of combustible material (fire load) or its rate of release of energy, or both.

The structural sandwich usually entails a low fire load. As examples, the National Building Code names wood frame partitions as acceptable within floor tenancies of residential and commercial buildings within a wide range of parameters. Most foam plastic and honeycomb core sandwich partitions would constitute a fire load of only a small fraction of that in such wood frame partitions. Extruded or deformed wood fibre cores would be comparable to wood frame. Where fire resistance is relevant in such non-load-bearing partitions, the sandwich construction can again be compared with wood frame. As the fire temperatures can quickly destroy the bond between the core and some skins, particularly metals, it is important to provide strong ties across the top of the panels or to the top joint detail so that the skins continue to hang in place.

If temperature rise on the unexposed face is considered meaningful, then cores of wood fibre, honeycomb or thermosetting plastics are preferred to thermoplastics because the former can remain in place as insulants, despite deep charring. There are no concealed air spaces running along most sandwich constructions, and fire cannot spread within the panel from ignition points on the skins. Generally, the use of flame-retardant or "self-extinguishing" core materials would seem of little advantage. These comments on partitions should apply equally to curtain walls, again assuming that each skin is firmly hung from a durable top connection.

Where sandwich floors, roofs or walls assume important load-bearing functions, fire resistance becomes critical, especially for high buildings. As test experience indicates that a fast-developing fire can fill a house with lethal concentrations of toxic gases within minutes (60), it has been suggested that a structural fire resistance criterion for low houses be just this: that the structure should retain its shape and allow egress for at least 10 minutes in a fully developed fire. Although all fire-resistance comments here relate to the standard ASTM time-temperature curve, it has been suggested that this curve presents an abnormal rate of fire development and this is under international study. In any case, a sandwich with insulating or heat-dissipating skins with stability at high temperatures (plywood, asbestos-cement, or gypsum board) and using thermosetting adhesives and cores could sustain loads well enough in a fire to meet such a residential criterion and more.

If metal skins are used, other approaches will be necessary. Protected auxiliary framing could be arranged to retain integrity under normal dead loads. Alternatively, the outer or unexposed skin could be deeply corrugated to carry such dead loads in bending or in column action after the inner skin or adhesive had failed. Alternatively, the whole sandwich system could be arranged in folded plate, barrel vault, or other deep shapes, so designed that the outer skin and core alone could carry dead loads for sufficient periods of time. Such an approach could allow long-span roofs for low buildings such as supermarkets. Finally, it may be that resilient inorganic core materials can be developed, and bonded and keyed to metal or other non-combustible skins using stamped or brazed keys or mesh to retain good bond. Such a sandwich could perform well in a fire. Only developments of this type could allow economic sandwich composites to perform prime load-bearing functions in multi-storey buildings.

4.3 SOUND

The light weight, high stiffness and integral construction of sandwich components all work against their use as sound barriers. The increasing requirements for movable partition systems for offices, schools and other uses form a natural area for sandwich systems, but sound control can be a real problem. Perhaps the current trend among architects to demand specific values of sound insulation - 45 dB and up - is unrealistic in terms of normal daytime user's habits and wants. For example, office doors and areas are left open so that the extra cost of high-rated partitions can be a waste. Further, as is so often emphasized, false ceiling space, air ducts, door gaps and general "leaks" in the jointing assemblies can pass so much sound that an expensive panel may have little effect on the final environment. In any case, when light weight partitions must provide substantial sound privacy it is better to twin the sandwich panel assembly.

A "heavy" single-sandwich partition of good mechanical quality (stiffness) and superficial density of 4 psf may yield a Sound Transmission Class rating (STC) of 25 dB. This is considerably less than the Mass Law would suggest, the reduction being caused by the "coincidence dip." This phenomenon occurs at higher frequencies where the wave length of sound in air coincides with the bending wave length in the partition, reinforcing the transfer of energy. If the panel is very flexible this coincidence dip can be moved beyond the test frequency so that it no longer reduces the performance rating. Berry's most useful paper on partitions of such weight for sound barrier uses (61) shows that such flexibility must be in the order of 2- to 5-in. sag for an 8-ft long panel under its own weight (held horizontally). If the sandwich example above were weakened grossly to be as flexible, its STC would be about 30 or higher (i.e., twice as much sound would be stopped). Such flexibility would be undesirable in terms of traditionally accepted stiffnesses.

Most comments here are based on Berry's paper, adapted from the British sound measuring system to the North American STC as relevant.

If the weakened or thinner panel were then twinned to create a double wall system, the sound resistance could rise well above the Mass Law if certain relations were followed. The air gap between the leaves must have a minimum thickness to avoid resonant vibration of the leaves on this elastic air column. Such resonance encourages high transmissions at the lower frequencies. To reduce such weaknesses or their effects on the STC system, the air gap between the independent leaves should be about 4 in. thick if each panel weighs 2 psf, about 3 in. if 3 psf, 2.5 in. if 4 psf and so on.

Where space is important, as it usually is, the use of a sound-absorbing material in the cavity can allow the cavity thickness to be halved, within limits. Although it should be very soft, such a material can allow a surprising transfer of load or bending movement from one leaf to the other, so that mechanical stiffness of the assembly can be increased considerably. Flexible panels can be more firmly braced by incorporating separate framing in each plane, or by placing the framing in the cavity while using felts or other buffers to avoid excessive transfer of energy (see also Section 4.4). Berry suggests that such approaches can allow a 5 psf (total weight) double sandwich partition to achieve 40 dB sound insulation or about 10 dB over the Mass Law. A total weight of 10 psf could be arranged similarly to yield 45-47 dB. The STC ratings would be somewhat higher than these British ratings. The latter double sandwich could form a very good party wall and, if non-load bearing, its fire resistance also could be ample.

4.4 JOINTS

Designers of sandwich panel curtain walls often strive for two goals that needlessly complicate the attainment of adequate performance. The one is the attempt to seal the outer surface like a boat hull, the other to achieve structural continuity from panel to panel. Concerning the latter, seldom is there anything to gain from full structural joints. The panels can readily span from spandrel to spandrel, in one- or two-storey jumps, or partial panels, mullions or supporting grids can support the infill windows. All vertical joints need provide transverse alignment only, to retain surfaces and edges in the plane.

Rigid fixing to the prime structure should be avoided. For example, since the spandrel beam and floor assemblies of concrete may yield substantially in creep deflection, straining and warping of curtain wall assemblies have been observed due to their rigid tying to the spandrels.

It is a simple matter to avoid this by assembling the light sandwich panel walls so that they span as deep beams across the full bay modules, vertically supported at their ends only by cross walls or columns. The spandrel or grid back-up can provide transverse support along the top and bottom edges of this long assembly, all the supports allowing movement in the plane of the panels. The joints must accept the transient or long term movements while maintaining weather tightness between the panels and the spandrel structure, but this may be easier to effect than is commonly supposed.

Such deep-beam arrangements of panels can be brought about in a direct and calculable manner. A dowel or dowels can be set into the vertical joints to act as a shear key while providing transverse alignment too. Horizontal ties are let into the top and bottom edges of the assembled panels to pull them together and to act as the "flanges" of the deep beam. The same approach has been found simple and effective for small northern buildings where it is desirable to use the panels as the sole structure, i.e., to form a sandwich monocoque unit. Unusual edge locks and other expensive details may not be warranted. Wind racking loads are very small, but the deep-beam approach can take the heavier spanning loads caused by shifting foundations of such northern building units (20).

All too often a sandwich approach is chosen to ensure flatness only, while the supporting structures are arranged as before, making no use of the panel's ability to do the entire job itself. Partition systems are common examples. Often the vertical joints are effected in the form of separate rigid posts which are themselves distinct and costly "small panels," which can be far less stiff than the panels they "support." Perhaps something like the extruded vinyl shapes of Figure 11 can be adequate for pencil-line joining of such partitions, or for double partitions for sound control purposes.

The sandwich concept encourages the use of thin panels as the entire wall in one, from interior to exterior finish. The shallow joint space becomes a problem in detailing for weather proofing, a problem that is receiving much attention. The traditional efforts to provide all sealing of such curtain walls at or near the outer surface have always incurred costly difficulties despite the development of some remarkable elastomer sealants. Accordingly, some curtain wall manufacturers have promoted a double-seal, internal draining approach for some time. The Norwegians, especially, have taken this approach one good step further, developing, testing and using their "open rain screen" approach in the most severe areas of wind driven rain.

As applied to through-joints between one-layer wall components, the concept involves the placing of a loose shield over the exterior face of the joint, with the joint gap having free venting to the outside, followed finally by an air-seal placed near the indoor side. Under uniform wind pressure no pressure difference can exist across the wetted portion of the joint: the venting maintains the joint gap pressure equal to the outside pressure. The shedding of water or snow by the rain screen is thus greatly simplified. The full wind pressure is exerted on the air-seal but it operates under dry conditions.

A program of exploratory, qualitative testing of many shapes of joints following this concept was carried out at the Division of Building Research to facilitate the development of a stressed skin northern house (20). Recently-built wind-rain simulation apparatus was used to provide severe but uniform air pressures, and then severe non-uniform pressures. Even the simplest plain-gap joints similar to those illustrated in Figure 12 (a) admitted no water under uniform air pressures. When the "wind" was of non-uniform pressure along the joint, or struck the surface at a slant, or if the air seal was opened to form a large leak, such simple joints admitted some water through to the gasket, and a little through such a leak. Such conditions cause air currents to blow in, along, and out of the joint gap in the windward side, or through-currents are set up in the last instance. Provision of a distinct enlargement or "air chamber" as in Figure 12 (b) can serve to channel such currents along the outer portion of the joint, and to act as a "setting basin" to allow any water to drop out. Such joints proved trouble free in all laboratory tests and in limited field trials of the northern prototype.

The implications of such an approach for low buildings are simple. The detail may be varied widely in design and manufacture, and assembly tolerances are generous. The air seal itself can be a low-cost limp plastic filler exerting the very low pressure required to stop even severe winds, and accommodating movement through multi-layer slip rather than material distortion. In the above laboratory and field trials, the gasket was formed from 4 mil (0.1 mm) polyethylene folded into six layers. It withstood repeated and exaggerated movements laterally and transversely without water leaks.

Higher buildings may justify more precautions in such open rain screen arrangements. Thick water films can build up and travel horizontally or upwards as well as downwards. Surface dams are often recommended to break such flows and keep the vents open, as in Figure 13 (a). Slanting winds create pressure differences parallel to the wall surface acting across such protruding battens as those shown in Figure 11 (a), but a chambered "leg," as shown, should settle out any water that is pushed in from the side. The size and geometry of such dams, vents and air chambers should be studied or checked for high building uses. Isaksen (62) recommends that the vertical air chambers or drains should lead to the outfall portion of horizontal joints. The detail of Figure 13 (b) is adapted from his discussion and sketches of horizontal joints for concrete panel systems.

4.5 POTENTIALS

Consider such studied estimates as that recently attributed to Weissman of the United Nations Centre for Housing, Building and Planning; within 35 years the construction rate must be increased some 40 times to house the world's urban growth; by the year 2,000 some 4,000,000,000 people may be living in cities and towns, an eightfold growth over the 1950's. Then consider the continuous-belt production of complete sandwich sections that is feasible now with urethane foam technology; wall, partition and roof sections could be produced at speeds in the order of one hundred feet per minute. If one such machine were turned on full time it could form all the new housing supply in

Canada. The extruded wood or other core material processes also could be linked to continuous composite lines with startling implications. Indigenous materials such as all fibrous materials could be developed to fit such idealized production concepts as both cores and skins. Perhaps the inorganic expanded clays, concretes or other lightweight cores could be extruded or shaped on a continuous basis, and made in tough self-skinning sandwich form; this may not be very far beyond present technology.

The connotations need not be structural. Perhaps one of the big needs at present, considering the popularity of large window areas and the attendant costs of heating and cooling, is to develop a screen of light, overlapping suspended shields for large buildings. These could be created in varying translucencies with, say vinyl or acrylic thermoformed skins on thin foam cores, easily replaceable and involving little fire load. They could be arranged in vented "shingle" fashion to act as open rain screens, as well as solar screens, for the prime walls and structure, and they could use very little material since they would not be subjected to wind loads except at corners and discontinuities.

Heavy construction potentials should not be neglected. The recent "orthotropic" bridges are, of course, stressed skin structures that are promising, although perhaps not as advanced yet as Stephenson and Fairbairn's tubular bridge of 1849 (Part I). Complete sandwich bridge spans are feasible, varying in section depth, using steel skins bonded to cores of inorganic materials or treated wood particle composites. Much of the above is oversimplified, as indicated in the previous discussions, but the potentials are great and developmental programs are well warranted.

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TABLE I

EFFECTS OF CORE SHEAR MODULUS

Example: 28 GA (0.149") Steel Skins on 2" Core

G psi	Bending δ_b in.	Shear δ_s	Total δ_T	δ_T/δ_b	ℓ in. Approx.	Some Example Cores
Short Span: 40 psf L L at $\delta_T = 1/360\ \ell$						
∞	0.24	0	0.24	1	87	Aluminum Honeycomb in Effect
400	0.24	.33	.57	2.4	65	2 pcf Urethane
1000	0.24	.13	.37	1.54	75	2 pcf Styrene
3000	0.24	.044	.28	1.2	83	Light Paper Honeycomb
8000	0.24	.0165	.26	1.07	85	Heavy Paper Honeycomb
Long Span: 20 p s f L L at $\delta_T = 1/240\ \ell$						
∞	0.53	0	0.53	1	126	Balsa in Effect
400	0.53	.35	.88	1.66	106	
1000	0.53	.14	.67	1.27	117	
3000	0.53	.046	.576	1.09	123	
8000	0.53	.017	.547	1.03	125	

TABLE II

SOME SANDWICH SKIN PROPERTIES

MATERIALS	APPROX. PROPERTIES IN SPAN DIRECTION (a)							REMARKS
SHEET	S.G.	E, Axial Span	σ_y, ULT Yield or ULT	σ_w Working (b)	Dimension Response (c)	Flame Spread (d)	Other	
STEEL ASTM A 446	7.85	29 x 10^6	37000 y	>22000	.065% (T)	0		
ALUMINUM 3S $\frac{1}{2}$H	2.7	10	19000 y	11500	.13% (T)	0		
FIBRE GLASS-PLASTIC	1.4 1.7	1 2.3	8500 ULT 41000 ULT	<2100 <10000	.12% (T) .09% (T)	<60- >240	Wet degrades Wet degrades	Polyest. 67%; Mat Polyest. 43%; 181 Fabric
PAPER-PLASTIC	1.4	1.1	>16000 ULT	Assumed 4000	.13% (T)	100	Wet degrades	Kraft-Phenolic
PLYWOOD	0.56	3-ply effective-axial 1.2	4800 y	1600	<.10% (R.H.)	115		Strength props. avg. for full thickness of 3 ply
HARDBOARD	1	0.7	4600 ULT	Assumed <1000	.25% (R.H.)	100	Wet degrades	1/8-in. "tempered"
PARTICLEBOARD	0.6	0.6	2500 ULT	<600	.10% (R.H.)	100	Wet degrades	Long flakes
ASBESTOS-CEMENT BD.	2	2	3000 ULT	Assumed <900	<.08% (R.H.)	0		Not authoritative. Compressive props. are greater
RIGID POLYVINYL-CHLORIDE	1.35	.35	7000 y	2000	.25% (T)	25	>150°F May soften	Comp. props. are greater

(a) The typical strength and elasticity properties as listed relate to the strong direction only for all fibrous reinforced materials. Only the metals and rigid P.V.C. have properties essentially equal in all directions.

(b) Where stress-rupture plots are available (Fig. 4) the sustained working stress σ_w is suggested here, for comparative purposes, as one half the rupture stress at about 27 years, as with wood. This results in suggested approximations of about one-quarter ultimate for well known materials and perhaps one-fifth ultimate for lesser known or water-sensitive materials. The metals are listed with commonly used working stresses.

(c) The bracketted T in the dimensional response column denotes a temperature range of 100°F; R.H. denotes a relative humidity change from 20% R.H. to 80% R.H., each sustained until the material reaches equilibrium.

(d) Flame spread values are taken or averaged from Galbreath's review (36). Common paints or coatings increase the values for metals and asbestos-cement board slightly, and reduce them for all the wood-base products.

TABLE III

SOME SANDWICH CORE PROPERTIES

MATERIALS	S.G.	G psi	τ Short Term psi	τ Long Term psi	E psi	σ Short Term psi	k	Water Vapour Transfer	OTHER	REMARKS
		Relating to Span Direction				⊥ to Surface				
PAPER HONEYCOMB	.027 (1.7 pcf)	>9000	>50	Assumed >12	21000	90	>.40	Direct Air	Poor Dent Resistance	Many wgts/ strength choices; high G in one direction.
EXTRUDED PARTICLEBOARD	.26 (½X)	3800	80	15	120000	500 yield	Air or Fill	High	Very Good Dent	Rough or estimated props. Consider length expansion forces at high M. C.
POTENTIAL DEFORMED PARTICLEBOARD OR HARDBOARD	.1 (1/10X)	12000	80	15	25000	100	Air or Fill	Direct Air	Very Poor Dent	Rough estimate of props. to show potential.
EXTRUDED FOAM POLYSTYRENE	.032 (2 pcf)	1100	35 yield	2-4	2200	30	0.24	<1.5	Fair Dent Temp. Soft	Dow Chemical, Midland, Mich. U.S.A.
BEAD FOAM POLYSTYRENE	(1 pcf) .016 .032	300 550	14 ULT 36 ULT	<2 >2	600 1200	14 yield 27 yield	0.25 0.25	2.5 <2	Poor Dent Temp. Soft	Requires good fusion to ensure props.
FOAM P. V. C.	.032 .064	500 1300	50 ULT 160 ULT	<10 <30	1600 7500	35 yield 145 yield	0.19	.022 <.022	Fair Dent Temp. Soft	
FOAM POLY-URETHANE	.032 .064	350 700	30 ULT 60 ULT	Assumed 3 6	700 2000	30 at 10% 90 at 10%	0.12 0.12	3 2	Self-bond to skins	Thickness and other dimension control can be poor.
CALCIUM HYDROSILICATE	.185	9000	Circa 80 ?		Circa 20000 ?	150 ULT	0.41	High	Brittle and Friable	Perhaps latex-modification could toughen

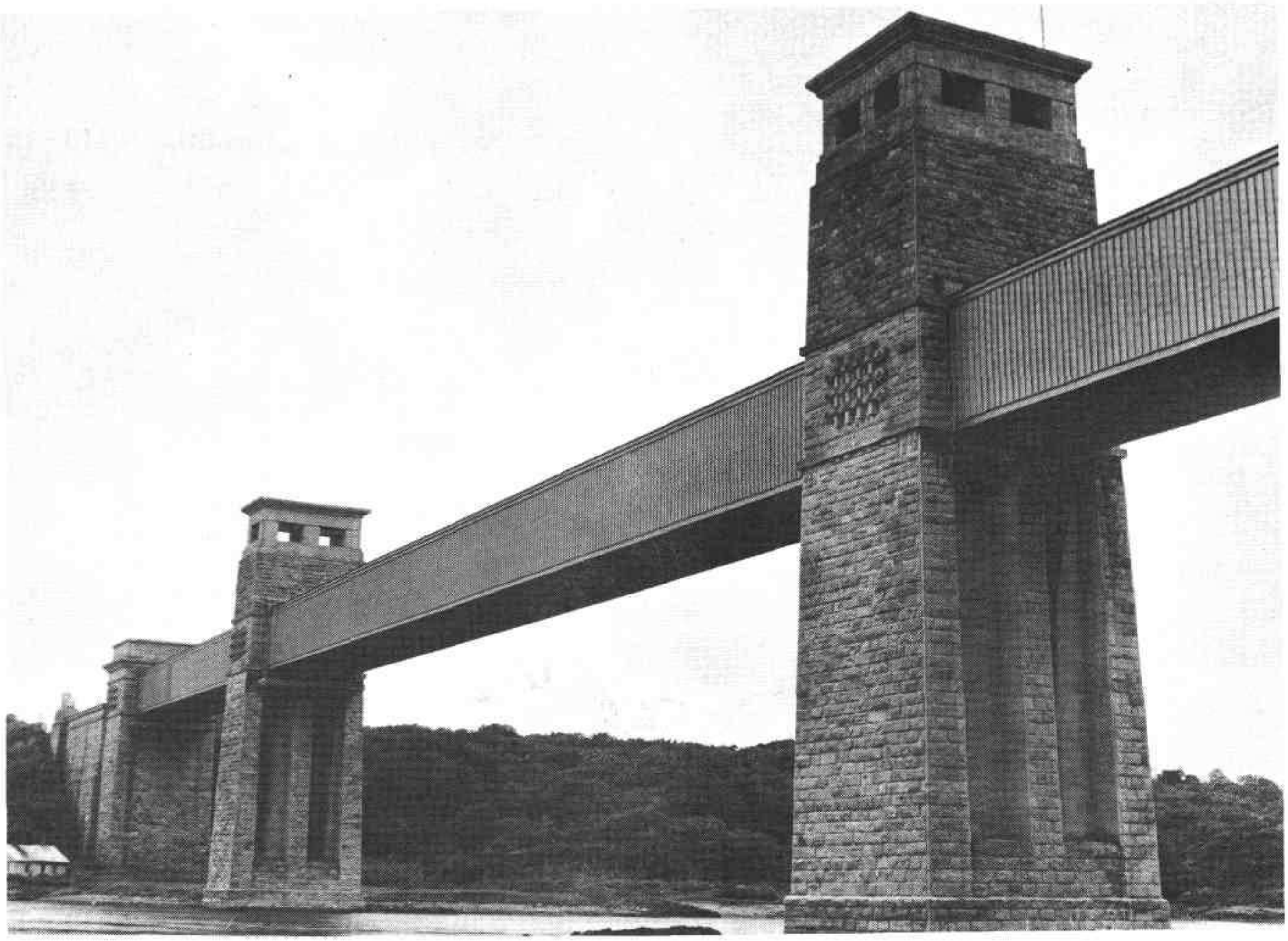


FIGURE 1: The Britannia Bridge of Stephenson and Fairbairn, 1849, perhaps the first large stressed skin structure (courtesy London Midland Region, British Railway).

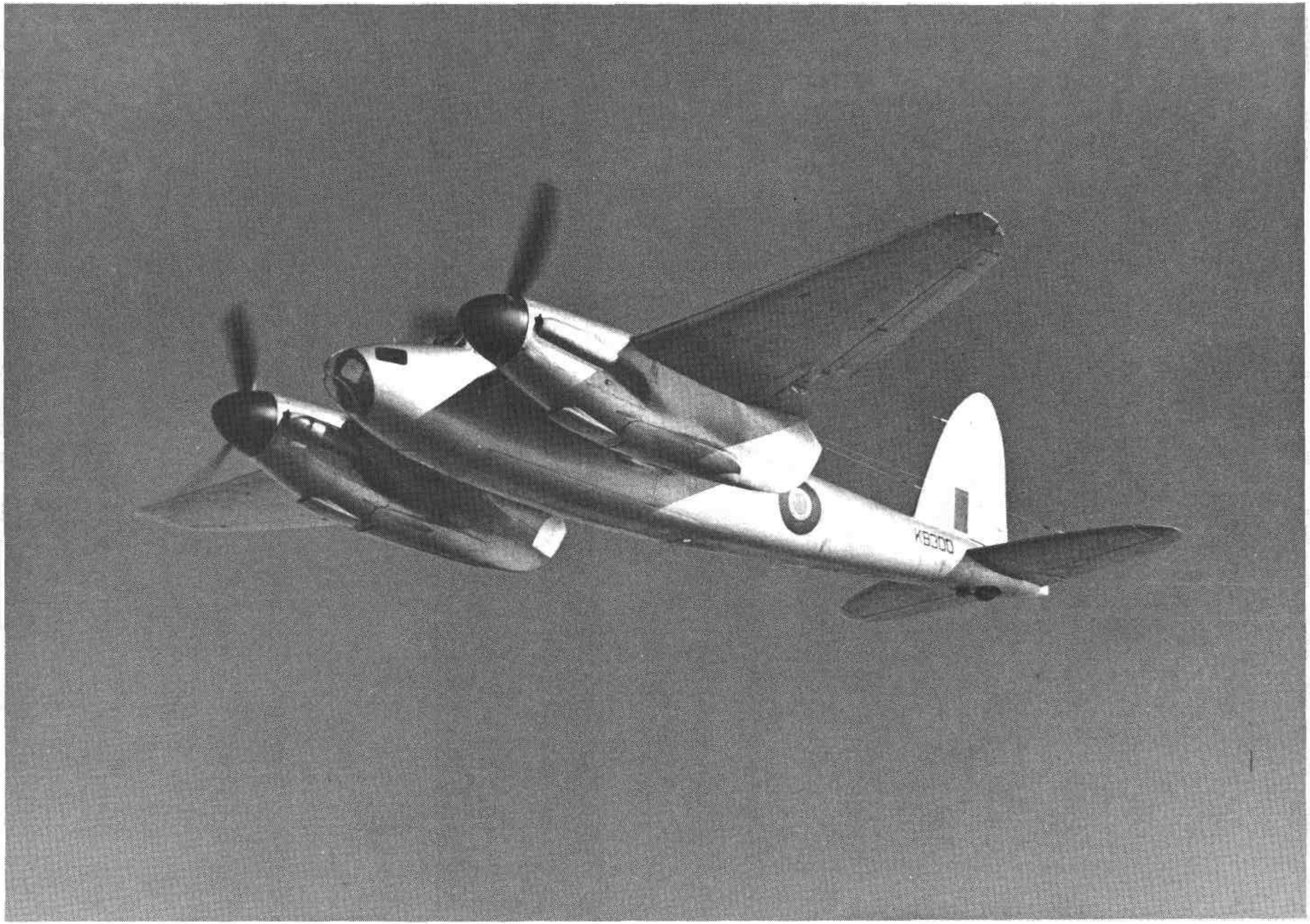


FIGURE 2: The Mosquito Bomber, 1943

(courtesy RCAF)

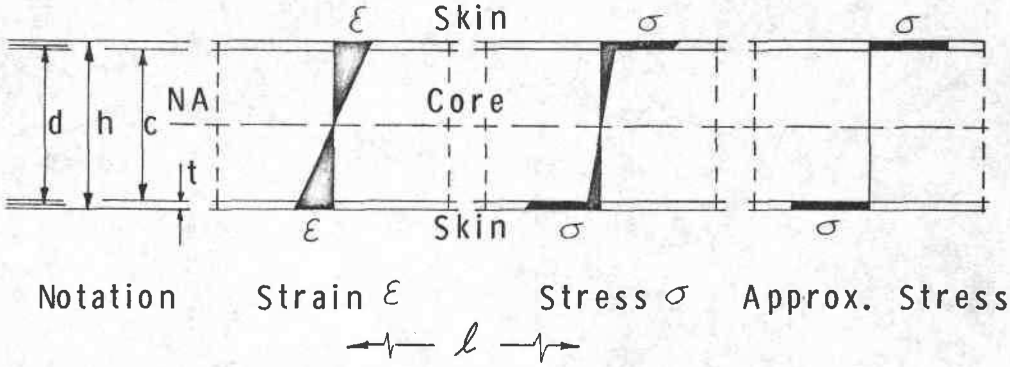


FIGURE 3

STRESS & STRAIN DIAGRAMS

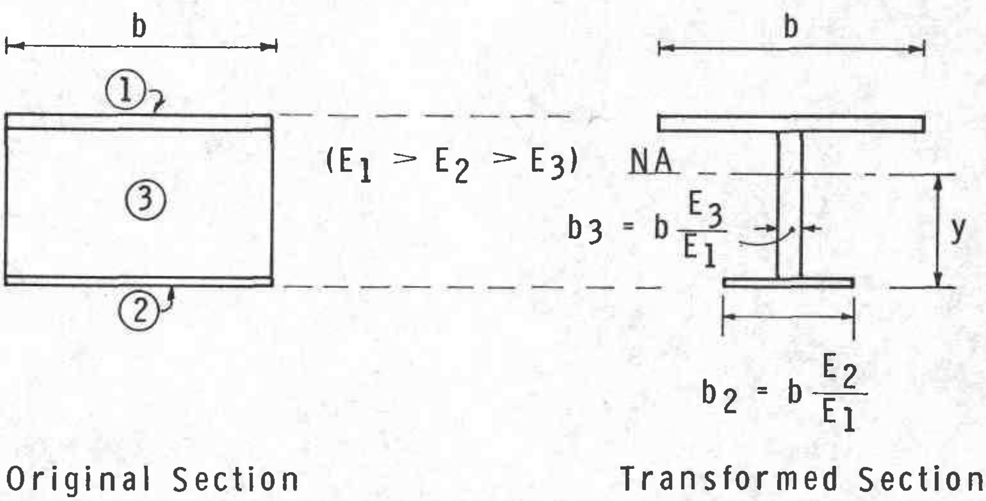
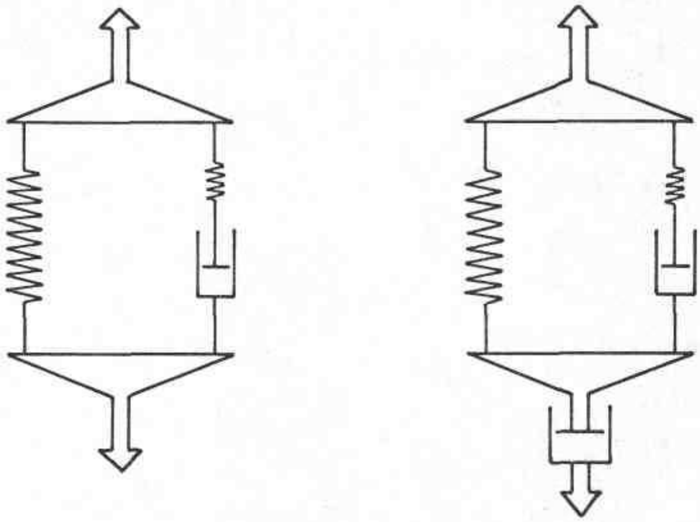


FIGURE 4

METHOD OF TRANSFORMED SECTIONS

8R4104-1



(a) Visco-elastic (b) Visco-elastic-plastic

FIGURE 5 RHEOLOGICAL MODELS

8R4104-2

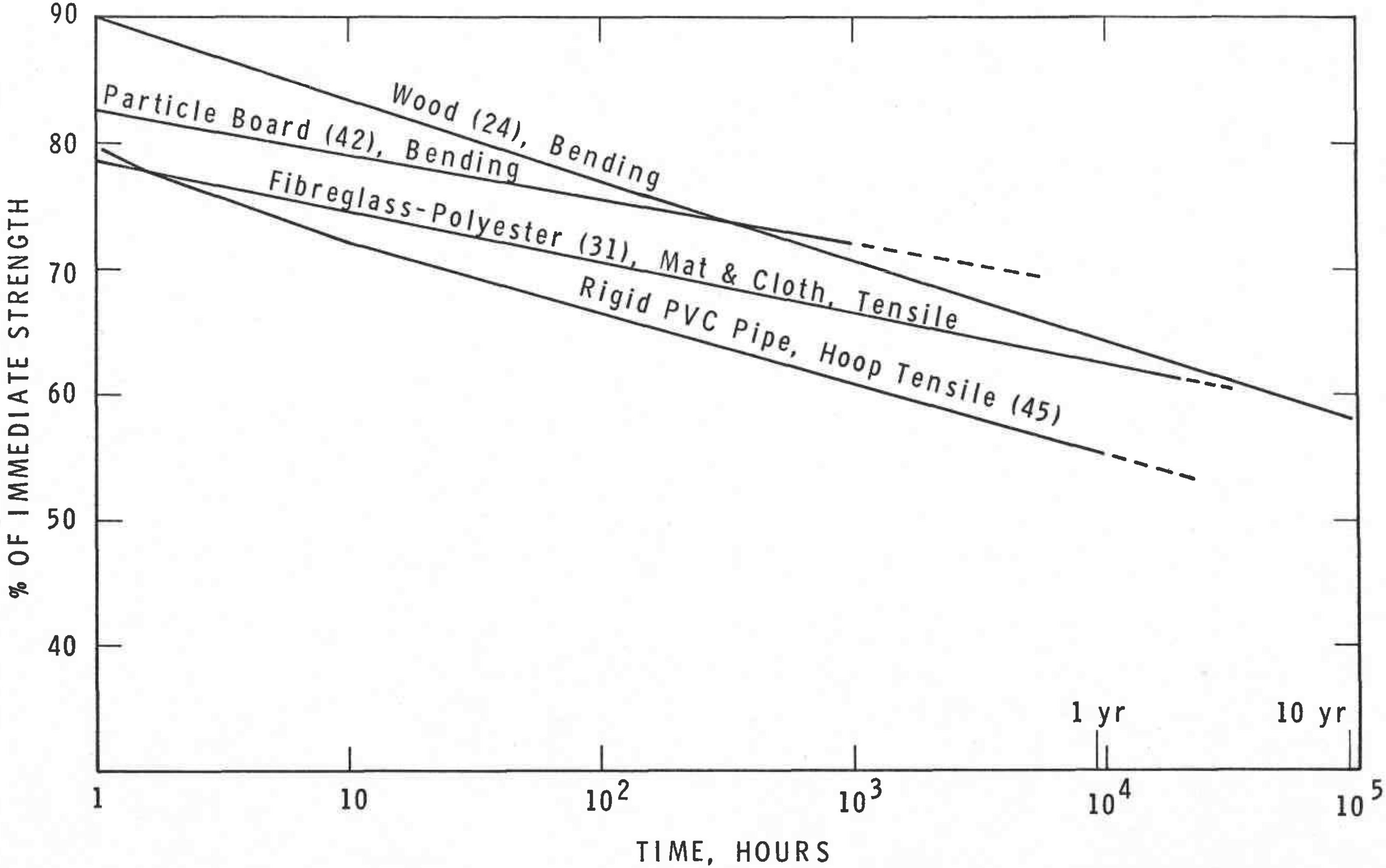


FIGURE 6

STRESS RUPTURE REGRESSION PLOTS FOR SOME MATERIALS
(REFERENCE NOS. IN BRACKETS)

BR 4104-3

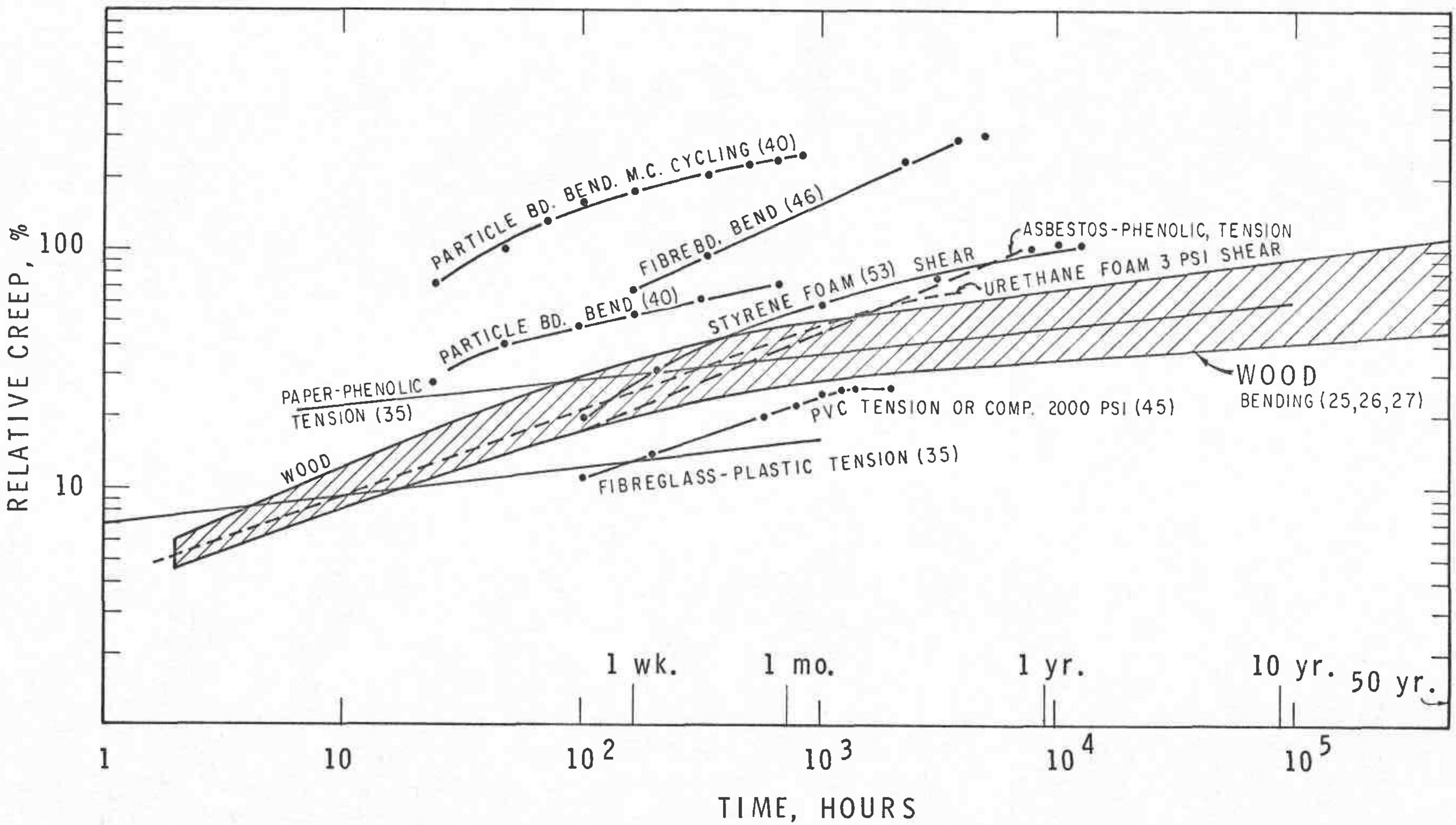


FIGURE 7

RELATIVE CREEP OF MATERIALS AT ABOUT 25% ULT. STRESS
(REFERENCE NOS. IN BRACKETS)

BR 4104-4

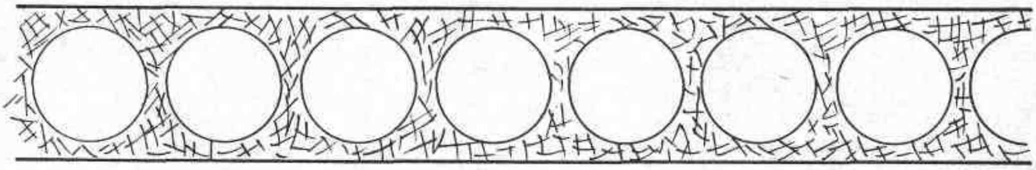
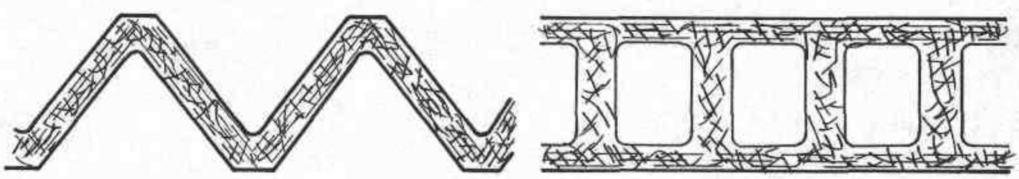


FIGURE 8

SECTION OF EXTRUDED TUBULAR PARTICLE BOARD



(a) Corrugated Core (b) Two-piece Panel

FIGURE 9

DEFORMED PRESSED PARTICLEBOARD OR HARDBOARD CORE AND PANEL

BR 4104-5

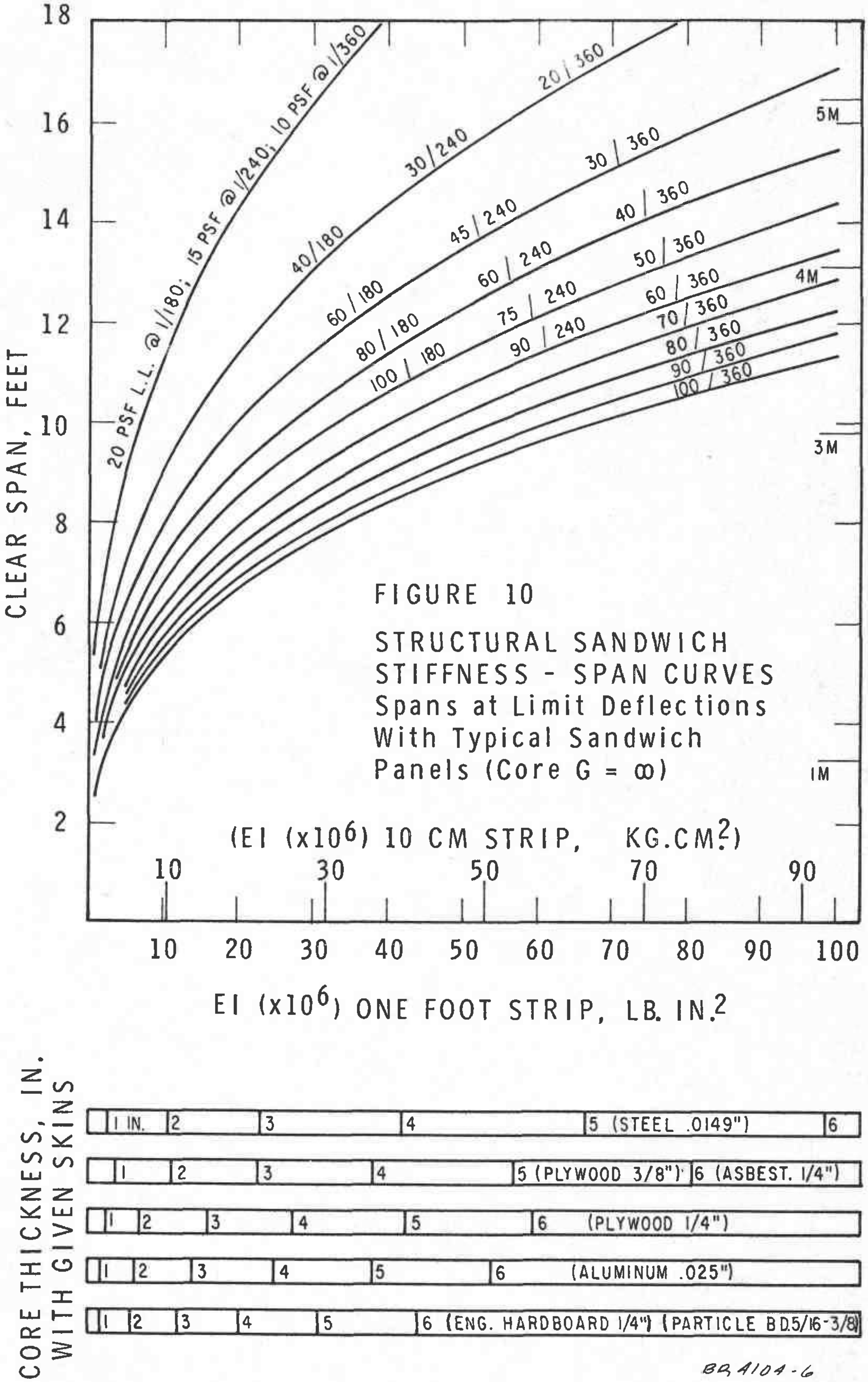
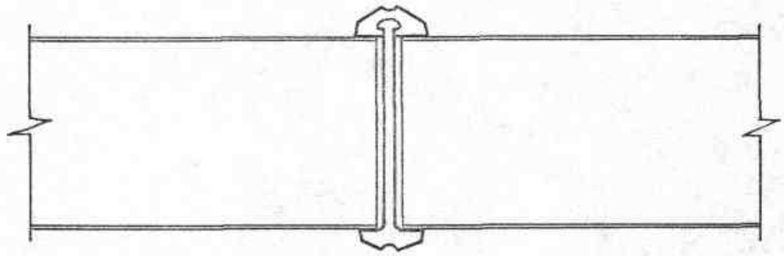


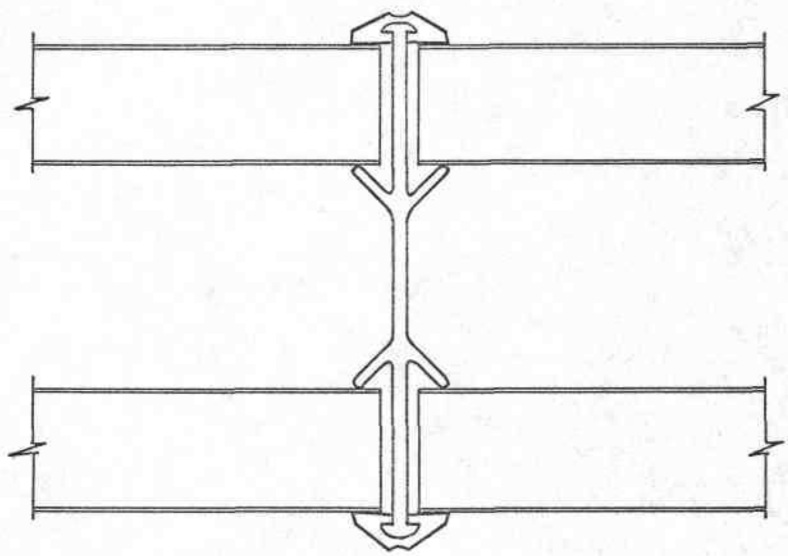
FIGURE 10

STRUCTURAL SANDWICH STIFFNESS - SPAN CURVES
Spans at Limit Deflections With Typical Sandwich Panels (Core G = ∞)

BQ A104-6



(a) Single-partition Joint

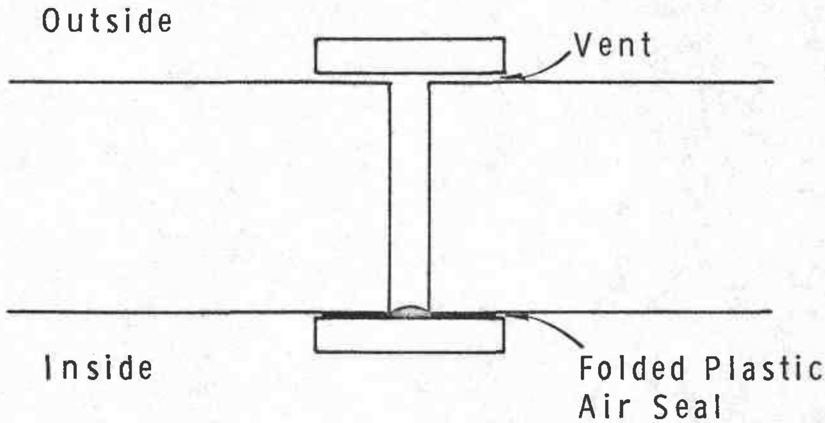


(b) Double-partition Joint

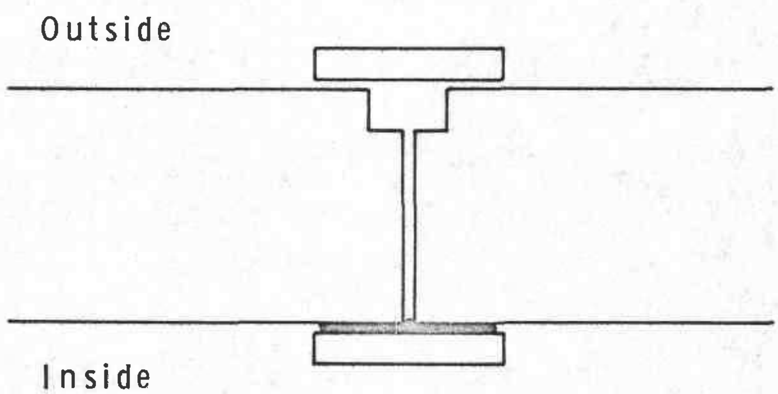
FIGURE 11

EXTRUDED PLASTIC JOINTS FOR PARTITIONS

BR 4104-7



(a) Simple Rain Screen Joint
- No rain penetration under uniform wind pressure
- Water dispersed throughout gap with non-uniform or slanting winds

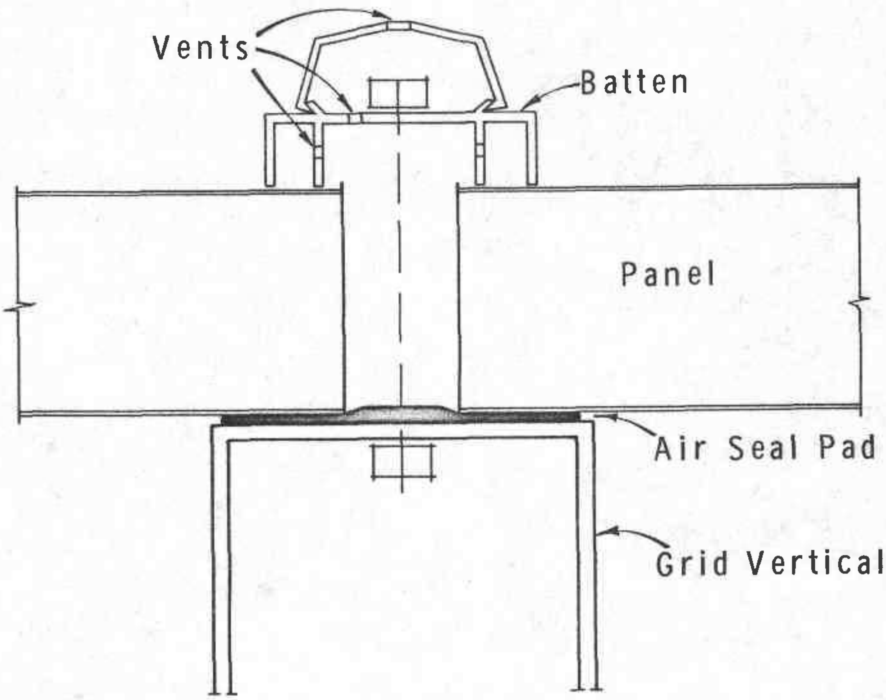


(b) Chambered Rain Screen Joint
- No water passed outer air chamber in limited laboratory and field trials
- Concept apparently quite adequate for low bldgs.

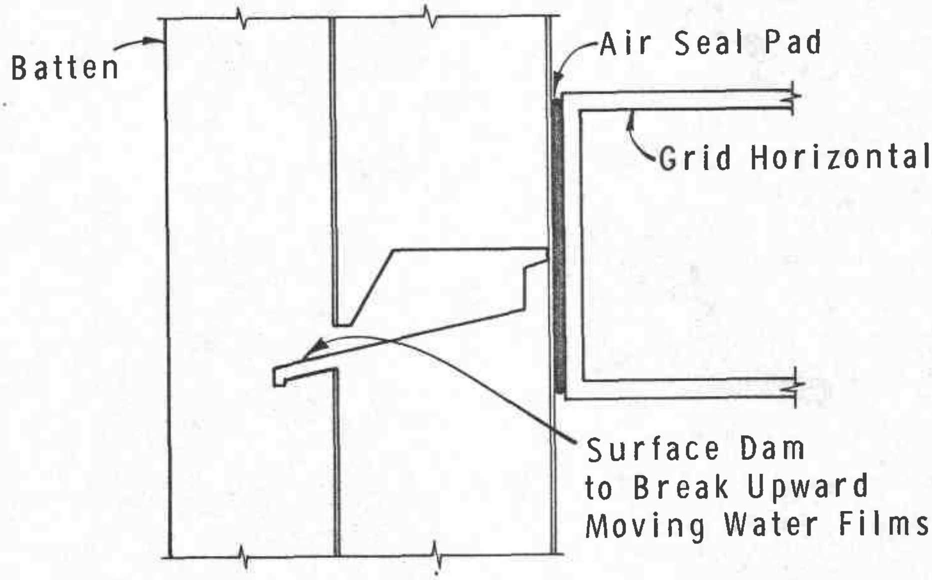
FIGURE 12

BASIC RAIN SCREEN APPROACH FOR THROUGH-WALL JOINTS

BR 4104-8



(a) Plan Section of Vertical Joint



(b) Elevation Section of Horizontal Joint

FIGURE 13

AN OPEN RAIN SCREEN JOINT APPROACH FOR HIGH BUILDINGS

BR 4104-9