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BUILDING WITH PLASTIC STRUCTURAL SANDWICH PANELS

PREFACE

The purpose of this study has been to explore the architectural potentialities of an engineering concept that is relatively new to building construction — the structural sandwich panel. Looking ahead five or ten years into the future of the building industry has prompted us to pay special attention to the use of structural plastics in sandwich panel construction. Still new and unfamiliar as building materials, the plastics promise to open up valuable and exciting paths in design in the years to come.

When the study began, in June, 1956, there was very little information available on the sandwich panels that were undergoing development or being produced at that time. We made inquiries to all persons we could discover who had an interest in sandwich panel construction.* The correspondence which followed made it clear that while there was widespread interest in this new form of construction, most producers were limiting their activities to experimentation and custom fabrication. The majority appeared to be waiting for the role of the structural sandwich in the building industry to become better established before they made a major commitment.

On the basis of this knowledge of the current situation, it was felt that this report

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*Our correspondents are listed in the Appendix.

might make a contribution by trying to predict a design approach for the plastic structural sandwich panel that could allow it to be used to greatest advantage by the building industry. In making this prediction, the period considered was not the immediate future.

History shows us that virtually all new building materials were initially thought of and used as substitutes for conventional materials. Only in the second phase of their development were the inherent advantages of materials like cast iron or plywood utilized and thereby allowed to influence the forms and methods of building. It is with this second phase in the development of sandwich panels, which will come in the not too immediate future, that we are concerned here.

Our work is not concluded with the publication of this report. Members of the staff are continuing with a more detailed analysis and design of one versatile new system of construction with plastic structural sandwich panels which is founded on the approach outlined in these pages.

We owe a great deal to the help that was given to us by our correspondents, who supplied essential background information in the letters and literature they sent to us, and who in many cases made personal visits for consultation with the project staff.

We wish to express our appreciation for the help and cooperation of the Monsanto Chemical Company, and in particular that of Ralph F. Hansen, Robert P. Whittier, Luigi A. Contini, the Structural Plastics Engineering Group, and the Market Development Department.

In addition, we would like to thank the members of our Advisory Committee, under the direction of Professor Lawrence B. Anderson, Head of the Department of Architecture at M.I.T., for their able guidance and active interest in this work.

Special mention should be made of the vital role played by Richard W. Hamilton, Research Associate in Architecture, in setting up this study. His recent illness has deprived us of a great deal of experienced and well-informed leadership.

Bernard P. Spring, *editor*
for the staff
October, 1958

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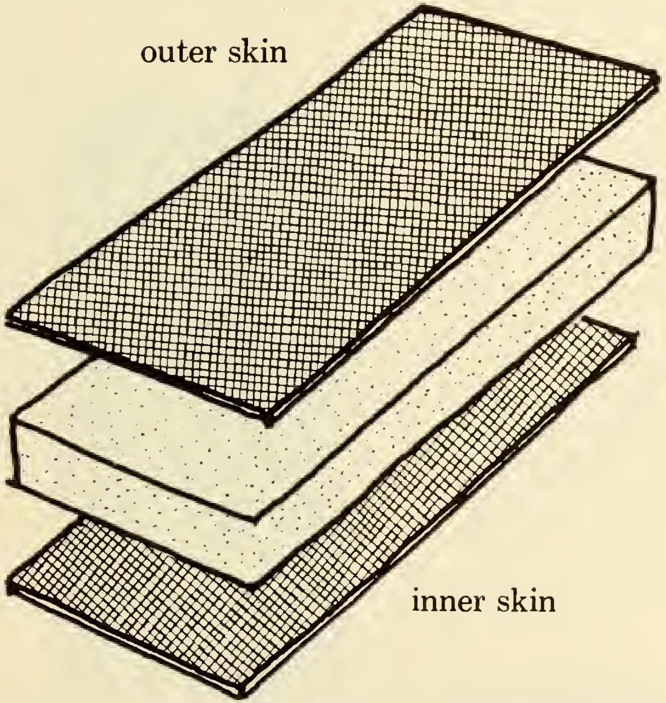
DEFINITIONS



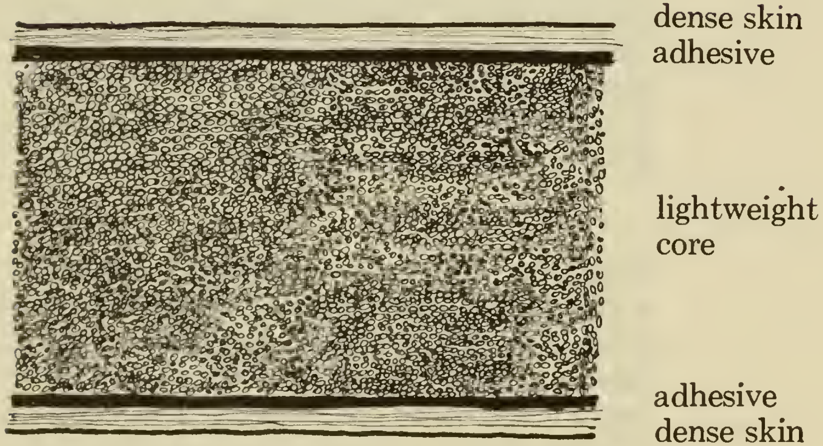
Exploded view of a laminated sandwich panel.

The structural sandwich panel consists of three or more layers of material bonded together so that they act as a unit. The thin outer layers, or *skins*, are of dense, strong material and bear most of the load imposed on the panel. The thicker central layer (or layers), or *core*, is of softer, lighter and weaker material. Its primary function is to stabilize the outer skins, preventing them from buckling when stressed. The core also serves to resist shearing stresses and may often be used as thermal insulation.

The structural sandwich is a type of *stressed skin* structure which owes its great potential economy to the fact that a very minimum of expensive, strong material need be used in the thin skins. What distinguishes the structural sandwich construction from stressed skin structures in general is that the sandwich contains a core composed of a homogeneous and continuous mass of material.

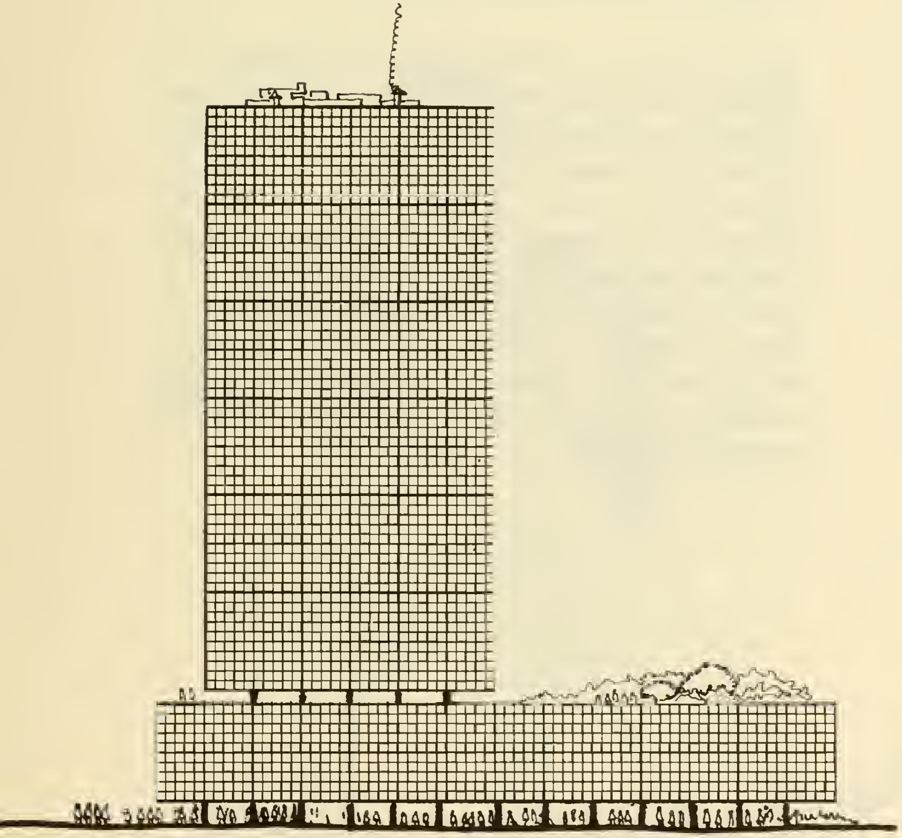
This study has focused its attention on sandwich panels which are bonded together with adhesives, the so-called *laminated* panels. Mechanically fastened or bonded panels were not studied, as the discontinuous interaction of skins and core in such constructions makes them less likely contenders in the development of a lightweight panel capable of taking major building loads.

Because our concern is with future uses of the sandwich panel in the building industry, we have chosen to study only panels which use their great inherent strength to resist both *primary* building loads — such as the weight of the building itself, its contents, occupants, and snow load — in addition to the *secondary* loads, such as those imposed by wind or by expansion and contraction.



Full size section of a laminated sandwich panel.

INTRODUCTION



In The Present: Curtain walls.

Up to the present time, the principal use of sandwich panels by the building industry has been as an infilling for curtain wall construction. The use of the curtain wall as a building skin has increased enormously in the last decade because it can reduce dead weight, save space, and be rapidly and easily installed.

As used in the curtain wall, the laminated sandwich panel has been able to offer some advantages over the mechanically fastened type in resisting such secondary loads as wind force and thermal expansion. As a structural form, the laminated sandwich panel has enormous potential strength and could be made to support substantial primary building loads as well.

How to design the sandwich so that it can use its inherent capacity to form not only the skin but also the muscle and bone of a building is the problem faced by this study. It was found that looking to any single factor in design — whether structural analysis, aesthetics, or any other — was not the way to bring the special advantages of this new material into play. The design of a plastic structural sandwich panel that would encompass its fullest potentialities involves a balanced consideration of at least eleven factors:

1. Planning for use
2. Visual quality
3. Structural analysis
4. Materials technology
5. Fabrication process
6. Handling operations
7. Erection process
8. Environmental controls
9. Distribution
10. Financing
11. Legal controls.

Effective use of the sandwich panel design in its broad new role will bring significant changes to the familiar scene. The form of buildings, the basic method of their production, and the traditional role of the designer are all likely to change. Behind all these changes is the growing, inevitable shift from hand-craft methods of building at the site to factory-based, mechanically aided production of building components. It is not simply through mechanization of today's manual work that this oncoming industrialization can increase efficiency in building. New means of production will present opportunities for the design of an entirely new kind of complex, multifunction building product.

This shift to an industrialized building industry will add new responsibilities to the traditional role of the designer. Along with the entrepreneur, the economist, and the engineer, the designer will have an important part to play on the teams which create our new building systems. As professional adviser to the purchaser of a component system, the designer will also have to see that components are assembled into buildings that best suit the client, the building site, the climate and, not least of all, the aesthetic demands of the neighborhood.

In order to see what kind of building the plastic structural sandwich panel might yield in the years ahead, the project staff has tried, by every means at its disposal, to put itself in the place of this designer of the future. The designs that have resulted from this conjecture are *not* presented here as a goal that must necessarily be reached someday. At best, it is hoped they are examples of what may result from a fresh attitude about building and a new, more comprehensive approach to design.

HISTORY

Egyptian laminating, c. 1500 B.C.

The structural sandwich panel could not be called a new invention. Although it has only recently appeared on the building scene, it is a reapplication of two concepts that have been used for many years in plywood and in the I-beam.

Engineering knowledge which led to the removal of material doing the least work from a structural section was developed in the early nineteenth century. The flanges of the I-beam shape that resulted from this development correspond in their structural role to the skins of a sandwich panel. The web of an I-beam, which resists shearing stresses and prevents buckling of the flanges, works in the same way as the core of a sandwich panel.

Stressed skin structures which replaced the flanges of a series of beams with a continuous sheet were used as early as the mid-nineteenth century. The British engineer, Isambard Kingdom Brunel (1806-1859), who used stressed skin construction in building railroad bridges and in the renowned ship "Great Eastern," was perhaps the first to make extensive use of this idea.

The idea of slicing wood into thin sheets and reconstituting it with glue to give it superior characteristics was known to the ancient Egyptians. The idea of the laminated structural sandwich panel results from the same basic thinking. An Egyptian mural dated about 1500 B.C. shows in detail the process of making plywood. Through the centuries, experienced cabinet makers used the technique of gluing thin sheets of wood together with the grain of each layer turned at right angles to the grain of the preceding layer in order to minimize expansion and contraction.

Plywood as we know it today originated about 1890 with the advent of the rotary peeling of logs. Douglas fir plywood, the first that could perform major structural tasks, was produced commercially from about 1920. This material opened such attractive possibilities for building use that it was often asked to perform beyond its ability.

Such demands led to great efforts to perfect stronger glues and waterproof glues. The synthetic resins, or plastics, which were developed to fill new needs — phenol-formaldehyde and urea-formaldehyde — were used in plywood starting in about 1935. Without this improvement in adhesives called forth by the plywood industry, the laminated structural sandwich could not have followed. In addition, structural plywood itself became an ideal material for the high-density, high-strength skins needed for structural sandwiches.

Another antecedent of the sandwich panel is the familiar corrugated cardboard used to make most of our strong, light, shipping cases. The material was first patented in this country in 1871 with the idea that its resiliency would make it an ideal wrapping for glass and other fragile materials. It was not long before manufacturers realized the tremendous strength and rigidity which they could give to paper with this sandwich construction and began to use it in place of the wooden crate.

The first actual laminated sandwich panel used by the building industry was the Cemesto board, first produced in 1930 by the Celotex Corporation. Today, Cemesto and a number of other proprietary sandwiches made with cement-asbestos skins bonded to a fiberboard core are very widely used.

The first building to employ Cemesto panels was a custom-built house designed by Holden, McLaughlin, Architects and Engineers, and built in Oyster Bay, Long Island, in 1933. The John B. Pierce Foundation then developed the so-called Cemesto House in answer to the need for low-cost housing. This house was widely publicized, and many were built. The material gained steadily in popularity during the thirties, being used principally for industrial and commercial construction.

The idea of laminating other materials into structural panels was considered by many in the years immediately preceding World War II. At that time the cost of manufacturing sandwich panels, with the exception of the Cemesto type, was clearly too high in relation to conventional building methods to encourage experimentation.

The advent of the second World War greatly accelerated the development of the sandwich panel. Because it contained a minimum of critical materials, the cement-asbestos and fiberboard sandwich was used on a tremendous scale during the war years. And once builders became familiar with it, it became a firmly established material in the building industry.

It was in the aircraft industry that the materials and techniques that form the basis for our present-day structural sandwiches were created. A sandwich of high-strength plywood skin and end grain balsa wood core was used by the British de Havilland Aircraft Company for their "Albatross" in 1940. Their famous "Mosquito" bomber, built with the same construction, followed shortly after.

In the United States, the Glenn L. Martin Company and United States Plywood Company made the first use of the now familiar honeycomb core early in the war. The strength, lightness, and ease of fabrication of sandwich construction prompted its adoption for parts of a number of wartime aircraft, as for example the wing tank of the Lockheed P-38. Chance-Vought and Boeing were other early users of sandwich construction in their planes.

We emerged from the war with a well-developed knowledge of sandwich fabrication. In 1945, when there was both an excess capacity in the aircraft industry and a serious shortage of housing, many people naturally sought to solve the housing problem with aircraft production techniques. There was a great surge of development work on houses to be prefabricated with sandwich panels.

The Forest Products Laboratory made the pioneering efforts in the theoretical and testing work on house panels with plywood and aluminum faces and four types of phenolic resin impregnated cores. A test house using some of these panels was built in 1947 under the sponsorship of the Housing and Home Finance Agency. Burnham Kelly, in *The Prefabrication of Houses*, mentions the fact that in this same period thirty-two companies were at work on the development of stressed skin panels for housing. At least seven of these were interested in using a laminated structural sandwich panel.

In 1947 the architects Dreyfus and Barnes designed a house with aluminum skins bonded to honeycomb core, under the sponsorship of the Consolidated Vultee Aircraft Corporation. In 1948 Carl Koch, John Bemis and Associates built the foldable Acorn

House with striated plywood skin and impregnated paper core sandwich panels. Lincoln Houses, Southern California Homes, the Chrysler Corporation, and Douglas Aircraft were among the others who experimented with similar systems.

Not primarily due to design or fabrication problems but more because of difficulties with financing and distribution, these, as well as the more conventional systems of prefabrication, failed to solve the post-war housing problem. The development of laminated sandwich panels for building subsided for a number of years.

Between the end of the war and about 1950, the curtain wall idea gradually gained importance among designers and manufacturers. This trend was not simply the result of the structural and design advantages of the new system. The proportion of labor costs to material costs had, in general, been rising during this period. Materials and assemblies like the curtain wall, though more costly than their forerunners, became economically feasible when their use could substantially reduce the man-hours required for installation and maintenance.

In the widespread use of the curtain wall since 1950, the laminated panel has played a relatively minor role compared to the independently framed, thin skin panel and the mechanically fastened panel. Where laminated panels have been used, the motivation was usually a desire for flatness rather than for their inherent strength.

Plastics have played a central role in the development of the laminated sandwich panel. As pointed out earlier, synthetic resin adhesives (actually plastics) are essential to the strong waterproof bond which allows a sandwich to be used structurally. They also make possible a plywood strong enough to be used as an effective sandwich skin. And the widely used paper honeycomb core will not stand up as a structural material unless it is impregnated with a plastic.

There are other tasks best performed by plastics that have recently helped broaden the applications of the sandwich panel.

Adhesives far superior to any we have known are coming on the scene as the result of new plastics technology. Plastic foams are being developed for core materials that promise to have the ideal characteristics of strength, density, and impermeability.

A major development now in progress is that of the foamed-in-place plastic core, which permits extremely complex sandwich shapes to be more easily fabricated.

A number of companies have begun to produce all-plastic panels with glass fiber reinforced polyester skins, which have unusual possibilities as an integrally finished wearing surface. Two manufacturers presently feature translucent structural panels — an idea which might radically transform architectural design.

Other unique plastic sandwich panels of compound curvature are appearing, as those used for the primary structural unit of the Monsanto House of the Future built in Anaheim, California, in 1957.

DESIGN

GENERAL PRINCIPLES

The designer must bring about a creative synthesis of all the factors of the building process. His goals in making this synthesis are to plan a building which will have the optimum usefulness for its owner, provide a rewarding visual experience, and be durable and safe in its construction.

PLANNING FOR USE

The complexity of these goals has increased almost out of hand since Sir Henry Wotton summed them up in 1624 as "Commodity, Firmness, and Delight." The requirements of a modern building are not only complex but they are constantly changing. Few activity patterns are so firmly established today that we can safely freeze them with the fixed building forms and immovable walls which Sir Henry proposed in his *Elements of Architecture.*

But a new kind of simplicity is possible in the face of the complex and changing demands made on a building plan. A system of building which emphasizes flexibility, rather than one which suits the initial needs of the owner as a glove fits the hand, could be the answer to both the present-day complexity and the need for further industrialization of the building industry.

A building system is most flexible if, first of all, it can suit a great variety of activities.

Perhaps it can accommodate a school, a small hospital, or a light industrial plant with equal ease. Secondly, a flexible system should be capable of being altered easily to meet the changing needs of the occupant. The system should be able to expand or contract, with the size and relationship of interior spaces easily shifted. Finally, the system should be able to fit itself comfortably into a wide variety of site conditions. It must be adaptable to different kinds of topography and climate and fit well into neighborhoods of varying character. While it is unlikely that any system can be devised at the moment that will fulfill all of these requirements, our improving building technology makes it possible to approach such goals ever more closely.

VISUAL QUALITY

Perhaps the most essential part of the design synthesis is the creation of a visual experience of high quality. For centuries, writers on aesthetics have examined at great length the meaning of "quality of experience."

In this study we have held to three general criteria for visual quality. These three are: suitability of forms and their relationships, suitability of scale, and suitability of the expression of materials.

We have no adequate words to describe what constitutes "suitable form," probably because visual experience speaks so directly to our minds without need of literal translation. However, words such as unity and variety, balance, proportion, rhythm, incident, and play of light and shade are often used to characterize satisfying formal experience.

The suitability of scale, equally difficult to put into words, may be said to be that quality of a building which allows a person to relate himself in a meaningful way to the building and its surroundings. A person may sense a domestic or human scale when he sees a small house nestled close to the ground, a monumental scale when he looks at the Capitol or the Lincoln Memorial in Washington, a super-human scale where the towers of Wall Street frame the Statue of Liberty.

While scale is usually related to size, it cannot be explained in terms of size alone, for we often see a small house which is monumental in scale or a large apartment house with human scale. More likely, it is the relationship of the sizes of the parts of a building to the functions of these parts which gives us the sense of scale.

As the building systems we will propose and criticize herein have all been thought of as utilizing plastic materials new to the building industry, expression of the quality of these materials has been of great concern.

It has been assumed that the most satisfying visual experience results when the unique and inherent physical characteristics of a material are brought out by the way the material is used.

There is probably no other class of materials that can be made with the enormous range of physical characteristics possible with plastics. We have tried to single out the characteristics which send an immediate visual message which unmistakably identifies the material and the unique tasks it can be made to perform.

These salient characteristics are, first of all, the ease with which plastics can be formed into complex surfaces of double curvature. Both ease of fabrication and the behavior of the material under stress are enhanced if the material is not forced into abrupt angular changes of shape but is allowed to flow in smooth curves.

Secondly, the ability of some plastic materials to perform major structural jobs and yet remain transparent or translucent is shared by no other class of materials. The ability to provide interior illumination not only through the traditional window openings but also through the structural parts of the building opens up a whole new approach to design. The glow of artificial illumination emanating from a building of translucent panels could also change our experience of architecture at night.

A durable wearing surface and integral color can be built right into the plastic component. With present-day structural materials, on the other hand, there is a relatively limited range of colors available. Also, these materials often require a protective coating which has to be regularly maintained. A new freedom of choice will be available to designers, for the future will undoubtedly provide plastics with an infinite variety of integral colors.

Plastics are often thought of as having uniformly smooth, even, slick textures. While texture cannot usually be obtained from porosity, as it is in conventional building materials, there are two ways in which integral texture of sympathetic quality can be obtained in plastics. The reinforcing needed for structural plastics usually consists of layers of cloth or mat. Varying the arrangement of this reinforcement will produce as wide a range of textures as we have in textiles. The texture alone or the combined texture and color of the reinforcing cloth or filler materials can reveal themselves in the surface of a structural plastic sandwich panel. In addition, almost any form of textural patterning can be impressed in the surface of a plastic structure simply by texturing the mold which forms the parts.

The strength-to-weight ratio of plastic structural sandwich panels, as compared with conventional structural materials, is high. The panels, being at once structure, wearing surfaces, and insulation, also eliminate the need for piling up several separate layers of material to do these three jobs. Taken together, these characteristics produce a finished structure which is usually much thinner than we are used to seeing. This gives the plastic structure an air of lightness and effortlessness in supporting loads. Lightness, then, is another unique visual quality the designer can make use of when building with plastics.

DETAIL DESIGN

Whether he uses conventional materials or new ones like the plastics, the designer must understand in detail how his materials respond to the natural and man-made forces that will act on them during the fabrication and erection process and that will act on the completed building during the entire course of its life. The detailed behavior of building materials will determine how they must be joined together; this, in turn, will have a major influence on the appearance and durability of the structure.

Through the years, direct and relatively trouble-free methods for joining the more conventional materials have evolved. These generally accepted details are the result of untold hours of study and analysis, trial and error. With the use of plastics — newcomers to the field of building construction — there are a number of traditional problems which are more easily solved. At the same time, new problems are generated which have yet to find a solution.

Some of the detailed conditions to which the designer of a plastic structural sandwich panel will have to give careful consideration will be briefly pointed out.

The machines which can produce large structural parts, such as sandwich panels, with a reasonable degree of economy are not very precise. (Anyone can verify this by watching the assembly of an automobile body.) The design of a sandwich panel system should take into account the large dimensional tolerances that will have to be allowed if the factory-made system is to compete with handcrafted site construction. Joints will have to be detailed to overcome the awkward situation that results when one panel does not exactly match or meet its neighbors. Each joint will have to accomodate the thickest or thinnest, widest or most narrow panel which the machines turn out.

Joints which transfer bending moments from one panel to the next are a particular problem, since they are most easily made by fitting the panels snugly together. When this is done, however, all the variations from the nominal dimension of the panel add up over the length of the building. If there is a preponderance of either plus or minus tolerances in a series of panels with snug fitting, moment-resisting joints, there will be an overlap or open gap somewhere in the structure.

Flawless surfaces are equally expensive to fabricate. Any method of making large parts from plastic is likely to produce finished surfaces with some irregularities. Rather than rejecting such imperfect-appearing but structurally sound parts, the design could call for a built-in irregularity in the form of a surface that is textured in such a way that flaws would not attract attention.

The size and even the shape, of building materials exposed to temperature changes are constantly changing. This is particularly true of plastics materials, which have a coefficient of thermal expansion on the order of three times that of steel. If the parts are not allowed to move freely with changes in temperature, stresses may build up in the material which can exceed those inflicted by primary loads and cause buckling of the materials, destruction of joint seals, and even failure of the structure.

When one part of a sandwich panel is subjected to very high temperature, as from the radiant heating of the sun, and another part of the panel is subjected to very low temperatures, as it might be if shaded and cooled by snow, large internal stresses will again be created. It may be that this detailed action of the material, rather than the major building loads, will determine the size and strength of the panel. Panels incorporating materials with different rates of thermal expansion will curl with great changes in temperature. This is not only unsightly but can also prompt the sandwich to buckle and collapse under load or break the adhesive bond.

Water in the form of rain or snow, a vapor or condensate, makes one of the most serious attacks on building materials. It is easily pulled into a structure through capillary cracks. It penetrates absorbent material, causing it to expand and contract and perhaps to lose some of its strength. With many materials it forms chemical corrosion products which can exert enormous pressures when they are confined. The freezing of condensate within a structure can also exert destructive forces. The presence of water promotes biological growth which can weaken or destroy many materials.

Plastic-skinned sandwich panels with monocellular foam cores have the distinct advantage of being impervious to moisture penetration in the panel itself. However, joints remain vulnerable to attack. Here, the new plastic gaskets and sealants do a more satisfactory job than was possible with conventional sealing materials. They can absorb a great deal of movement without opening up a passage to water, and they maintain this ability for an estimated 25 to 50 years.

Although plastic joint seals can absorb a great deal of punishment from the elements, it only takes one microscopic flaw somewhere in the hundreds of lineal feet of joint which a building will normally have to initiate serious structural damage. Unless the designer makes certain that the joint is detailed so that the installation of the sealing materials is not only easy but absolutely foolproof, trouble spots are bound to appear. No workman, even the most highly skilled, is likely to be able to make the sustained and concentrated effort needed to insure one hundred per cent effective sealing of joints if the details are in any way complex.

Sandwich structures exposed to the activity of people or vehicles may be accidentally punctured. Because they have thin skins, they may be opened up almost as easily as a tin can by anyone trying to break into the building. Such things may not happen too often, but they must be taken into account. A skin which is thicker than required for structural purposes and which is reinforced with tough, impact-resistant material or backed with a special layer designed to resist impact will probably have to be used.

Next to the present high cost, the two major drawbacks to immediate widespread use of plastic sandwich panels are the uncertainties about durability and fire resistance. The plastics industry is making an all-out effort to bring more light on these two questions.

The ultra-violet rays of the sun have a negative effect on both the physical characteristics and appearance of most plastics. There are ways of treating the material with ultraviolet light absorbers which will prolong its life. At the present, however, this treatment reduces the possibility of using a wide range of color or translucency as an aid to design.

Special additives are also needed to reduce the flammability of most plastics. For public buildings where high fire resistance is required by law, plastics are not presently recognized as an acceptable structural material. Technology is finding ways to make the material more fire resistant, and this will do a great deal to bring it into greater use in the building industry.

If acoustical isolation is needed in a building of plastic structural sandwich panels, this will have a major influence on the details of construction. The rigidity and light weight which make the sandwich panel so structurally advantageous also allow easy transfer of sound. Making the panels massive by filling them with a heavy material such as sand, or making them limp so that they will not have sympathetic vibrations in the voice range can solve the acoustical problem. But this is done only by sacrificing the qualities that make the sandwich such an attractive building method.

The solution of all the detailing problems that are still faced by the plastic structural sandwich will require imaginative research and testing. Very likely, the answers found will have a significant effect on the appearance of these plastic structures. In fact, it would seem that for the plastic structural sandwich panel, the solution of secondary stress and detailing problems has a greater influence on how such structures look than has ever been the case with conventional materials.

Many building systems based on the plastic structural sandwich panel were considered by the project staff. We did not find that any of the systems could be singled out as best in all respects. Each was promising in some way. None was entirely free of flaws.

The sketches that follow are illustrations of the basic kinds of structural sandwich systems which deserve further study. Included are flat panels, folded structures, singly curved, and doubly curved structures.

The specific buildings shown are intended only as vehicles with which to demonstrate different systems of construction. Each building represents only one of the many ways in which any one system could be used and is not a fully worked out solution to any specific problem.

With each sketch we present a brief description of the system and our evaluation of its strengths and weaknesses.

PROPOSALS

THIN FLAT SANDWICH PANEL

The thin flat sandwich panel is perhaps the simplest and most immediately applicable form of this new structural type. A fair number of buildings using such sandwiches are in actual service today. The house used to illustrate the system here features a central garden court illuminated from above by translucent sandwich roof panels.

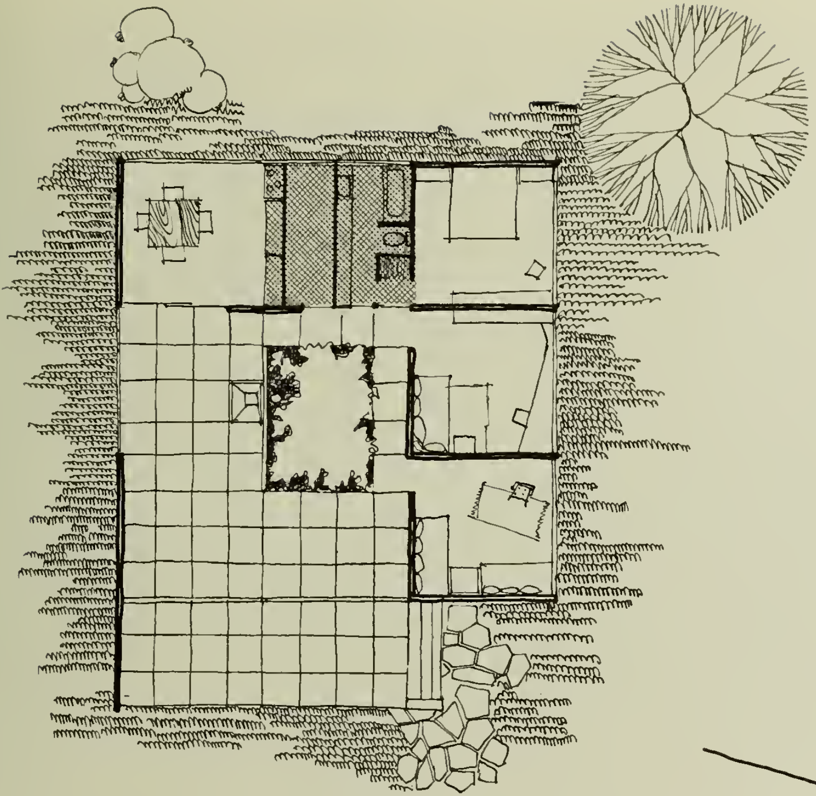
Use of the flat sandwich panel for roof and bearing walls makes this the system which most closely resembles conventional building systems in its planning. Unless columns and beams are introduced, the plan is strongly dependent on regular spacing of bearing walls. The building shape can be easily altered to fit site conditions, limited only by the dimension chosen for the width of the wall panels.

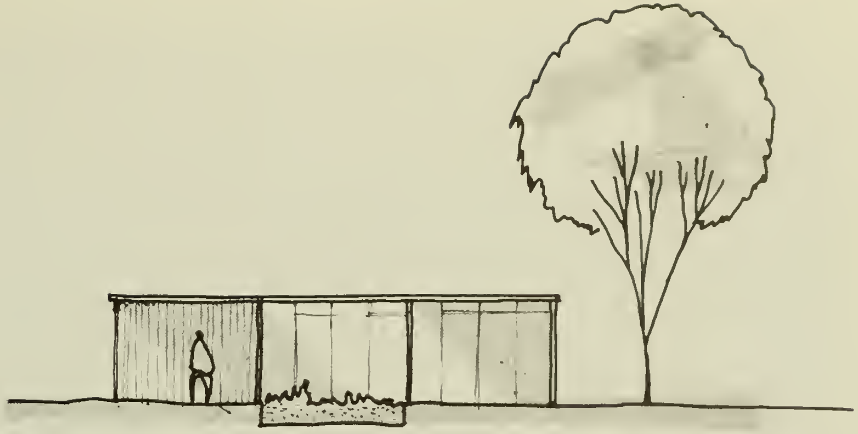
Interior spaces which can be created with this structural system are necessarily small. Consequently, the scale of buildings using it will tend to be domestic. Flat panels of this type can have skins of any strong sheet material. The quality of plastics will be expressed through translucent panels and through colors and textures not possible with other materials.

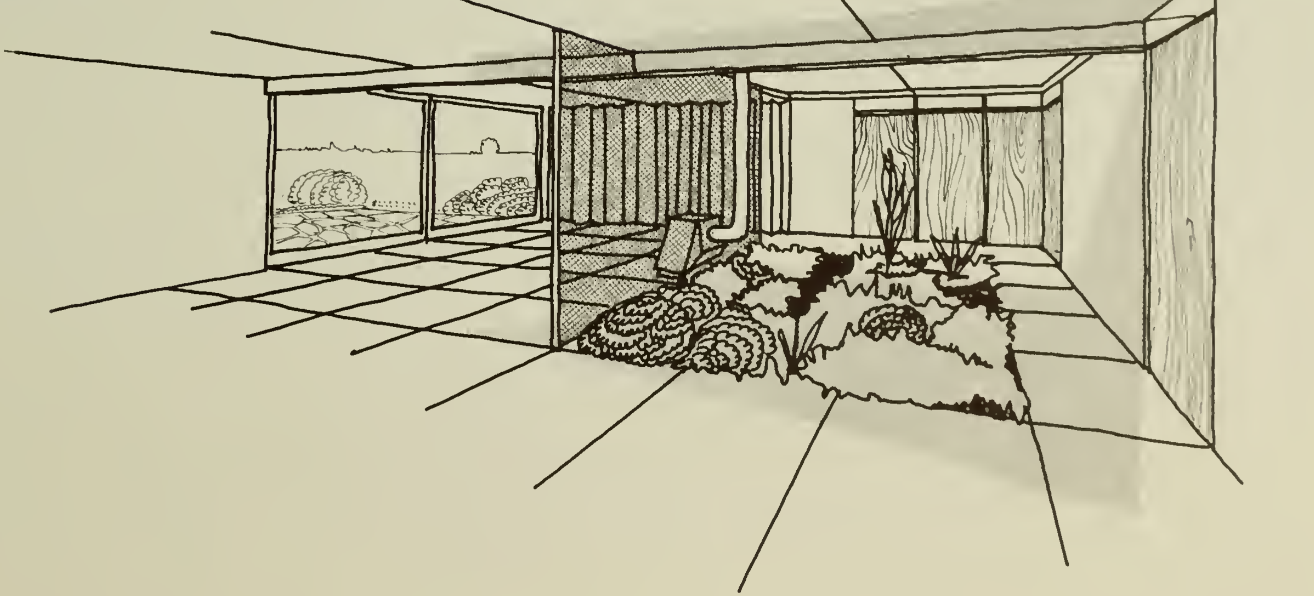
Flat and corrugated reinforced polyester sheet is already widely used in the building industry. It could be adapted for flat sandwich skins. The phenolic-impregnated honeycomb paper core and some plastic foam cores can be economically used today. A greater variety of foam core materials is on the horizon.

Fabrication and handling of flat panels would create no special problems for equipment presently in use. Six-by-twelve-foot roof panels and six-by-eight-foot wall panels are illustrated here. Weighing approximately 300 pounds each, they would be easily handled by four men. A simple gin pole rig could be used to place the roof panels. Fastening is simplified by the fact that joints do not have to resist bending moments. Mechanical services cannot easily be threaded through such thin panels, and central mechanical cores will probably have to be provided.

This system would cause the least disturbance to existing marketing channels. Panels could be easily stocked and sold by lumber yards and other building materials dealers. One-story buildings with relatively small interior spaces, particularly housing, would be the most likely use for this system.







GIANT FLAT SANDWICH PANEL

A variation of the flat sandwich, with very different characteristics from the thin panel system described on the preceding pages, is the giant sandwich. As shown here, it forms a rather long-span roof structure for a school building. The roof, in this case, is thought of as performing many more tasks than simply keeping the weather out. Mechanical equipment, acoustical treatment, and natural and artificial lighting are integrated within the structure itself.

A giant sandwich panel on the order of two or three feet in thickness might be made to span as many as fifty feet. Flexibility of planning between such widely spaced supports is greatly increased. As it can be used to form multistory structures, a new dimension of flexibility is added. Of course, the large structural bays of such a system make it more difficult to fit a building to irregular site conditions.

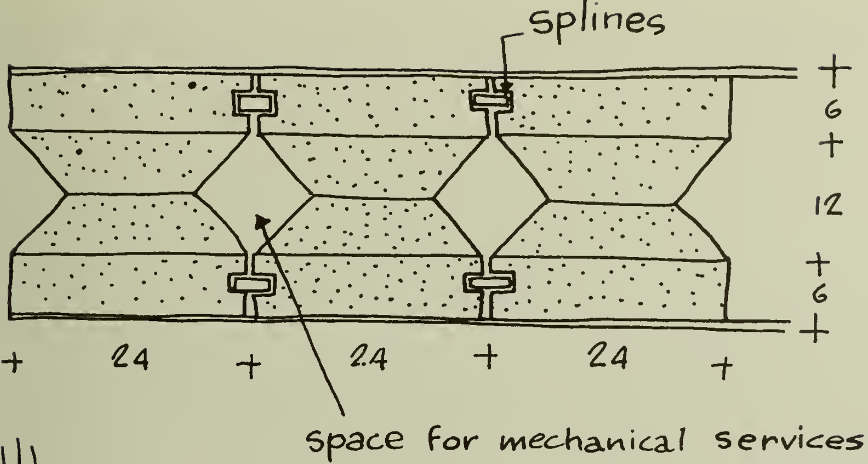
Because of the great size of all its elements, the giant sandwich would go beyond the domestic scale unless great care were exercised in detailing. For example, the scale of the example shown is humanized by the expression of each individual core unit along the edge of the roof. In this design, the formability of the plastic material is revealed only in the shaped core units.

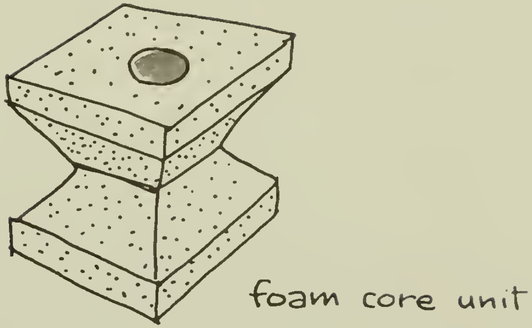
Transparency is exploited in the central lantern of the cores through which daylight may penetrate into the building. By varying the color and tonal value of each core unit and using a translucent inner skin, the ceiling design can be articulated. A large-scale texture is produced by the repetition of the central lanterns and the closely spaced joints.

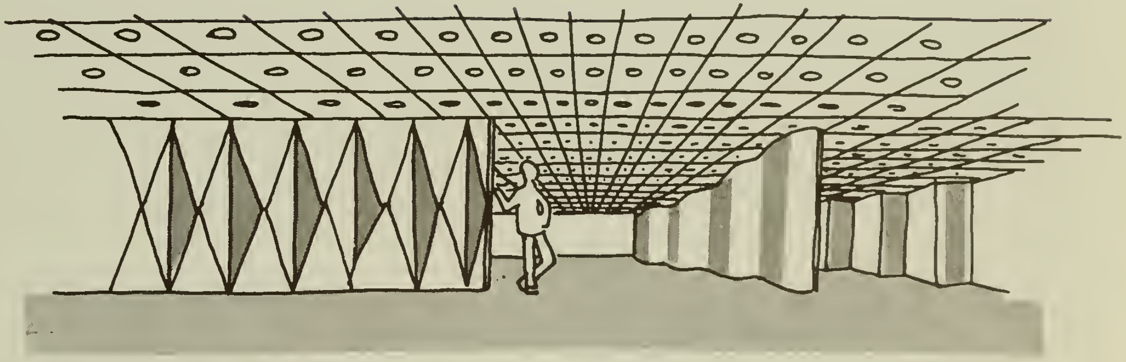
This system can also be thought of as being largely site-fabricated. The skins might come to the site in great rolls. The cores would be foamed in a mold, probably somewhere on the building site, as they would be bulky and easily damaged if transported. With such site work, problems of control of the physical properties of the foam would undoubtedly arise.

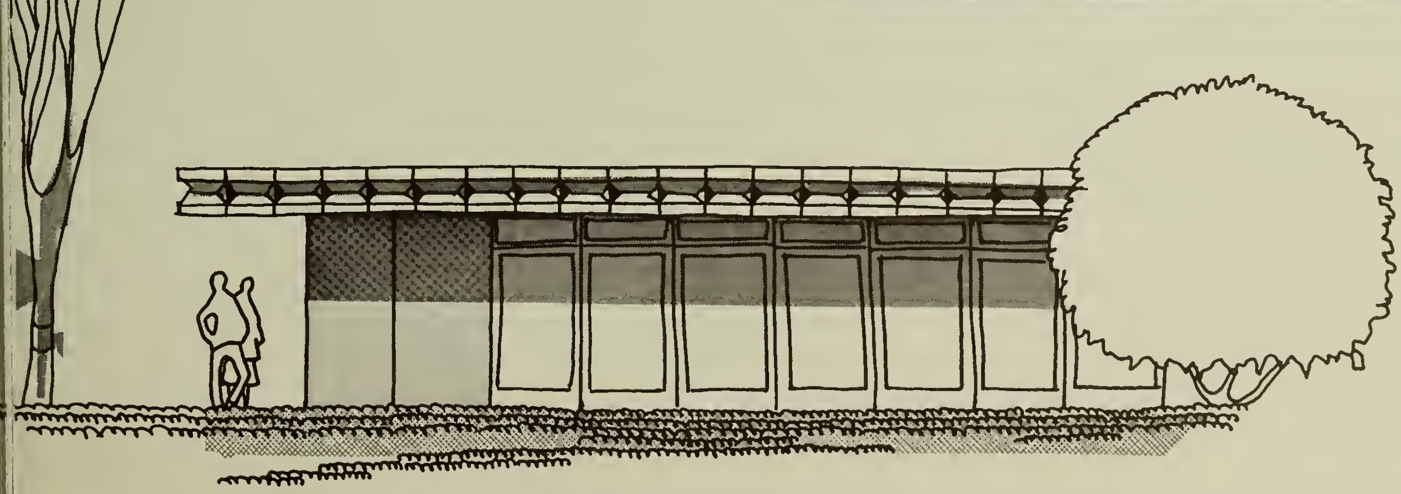
The giant sandwich would be well suited to the integration of mechanical equipment in the open spaces between the core units.

The giant sandwich structure forms a general space enclosure of one or many stories and would be adaptable to a wide range of building types. Excessive deflections over long spans would probably preclude activities which involve heavy live loads.


splines
6
12
6
24
24
24
space for mechanical services


foam core unit





FOLDED C-COLUMN

This system is a variation on the familiar post and beam construction. Here, however, the posts are made up of a sandwich construction that serves as a shear wall resisting lateral loads. The units may also form a storage space or utility core. The roof panels of the house illustrated here are thin flat sandwich panels.

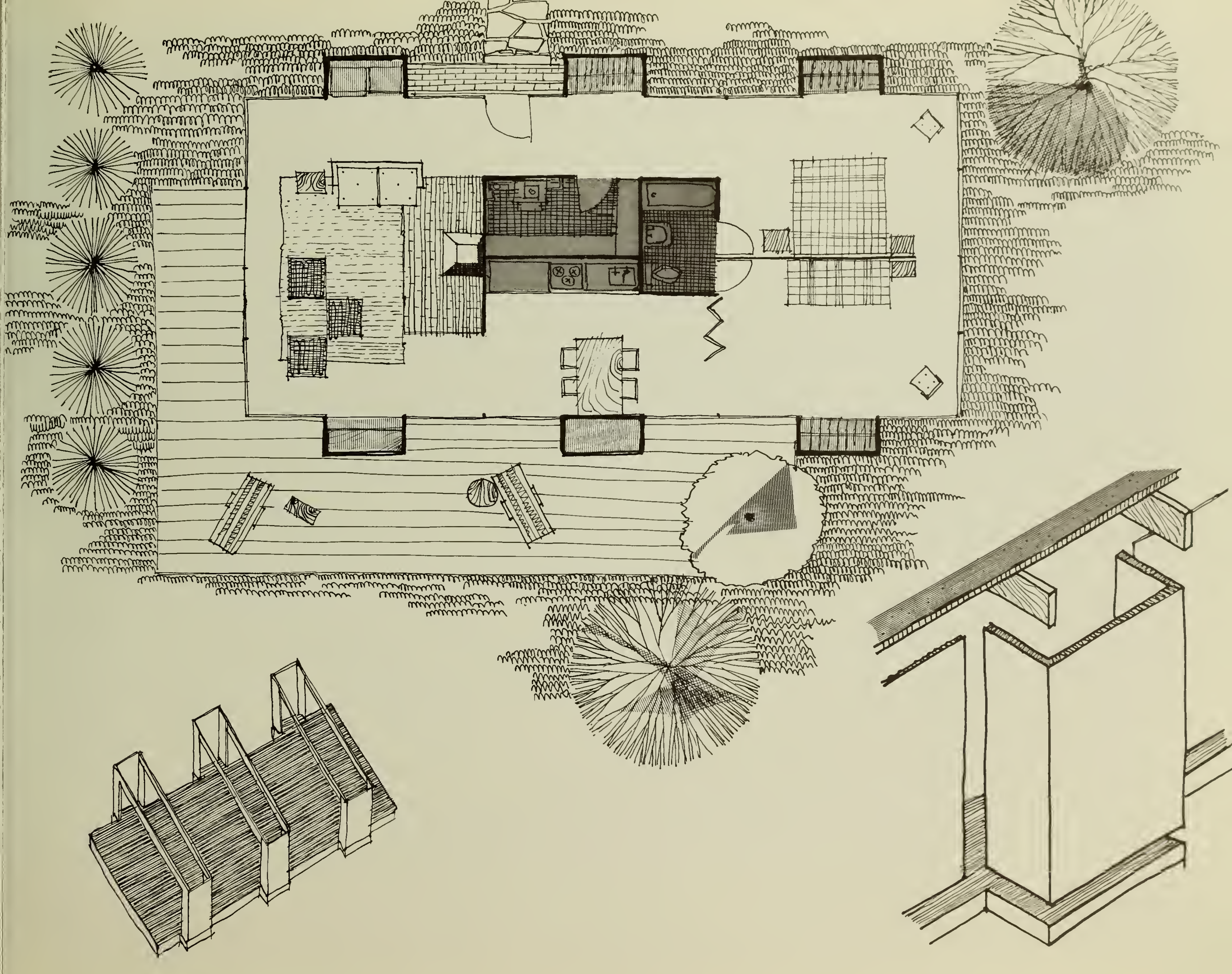
With such a system, flexibility of planning is seriously limited by the need for a substantial solid unit placed at regular intervals. The bay size chosen is the limiting factor in adapting to the site. A clear rhythm of solid and void is the dominant visual characteristic. The form is not characteristic of plastic alone but could be achieved as well with a variety of materials. Color and texture would be used to express the use of plastics.

The C-shape provides an excellent distribution of material for column action. The oversized dimensions of the columns would allow them to resist all the lateral forces imposed on the structure and eliminate the need for further bracing.

These column units could be fabricated with presently available materials and techniques. If the sides of the "C" were not at right angles to the back wall, as shown here, but instead had a draft, they could be stacked for storage and shipment. Although rather bulky, the units would be light enough to be handled by four men or a small machine during the erection process. The parts and connection details might easily be simplified so that no specially skilled labor would be required for site assembly.

One of the principal advantages of the C-column is that it could house mechanical control equipment. This would be helpful in conjunction with thin panels which cannot accommodate the usual piping and wiring.

Marketing of support systems of this kind could be handled almost in the same way as the distribution of appliances. The method of fastening the unit to the adjoining structure would have to be standardized to accommodate a variety of systems and loading conditions. A variation of this system could be applied to any building type which can make good use of regularly spaced storage or service units.



FOLDED PLATE

Flat sandwich panels which are folded into a system of corrugations gain in strength and rigidity, without the use of additional material. The motel shown here has structural bays of about fifteen by forty feet, each of which covers one room unit and its porch.

When strengthening corrugations are introduced, longer spans and greater freedom in planning become possible. The bays tend to be long and narrow, limiting physically and spatially the kind of activity that can be arranged within them. Expansion in units of one bay is most easily accomplished. Interior partitions are best placed directly under the roof valley folds. They would be more difficult to install at right angles to the folds.

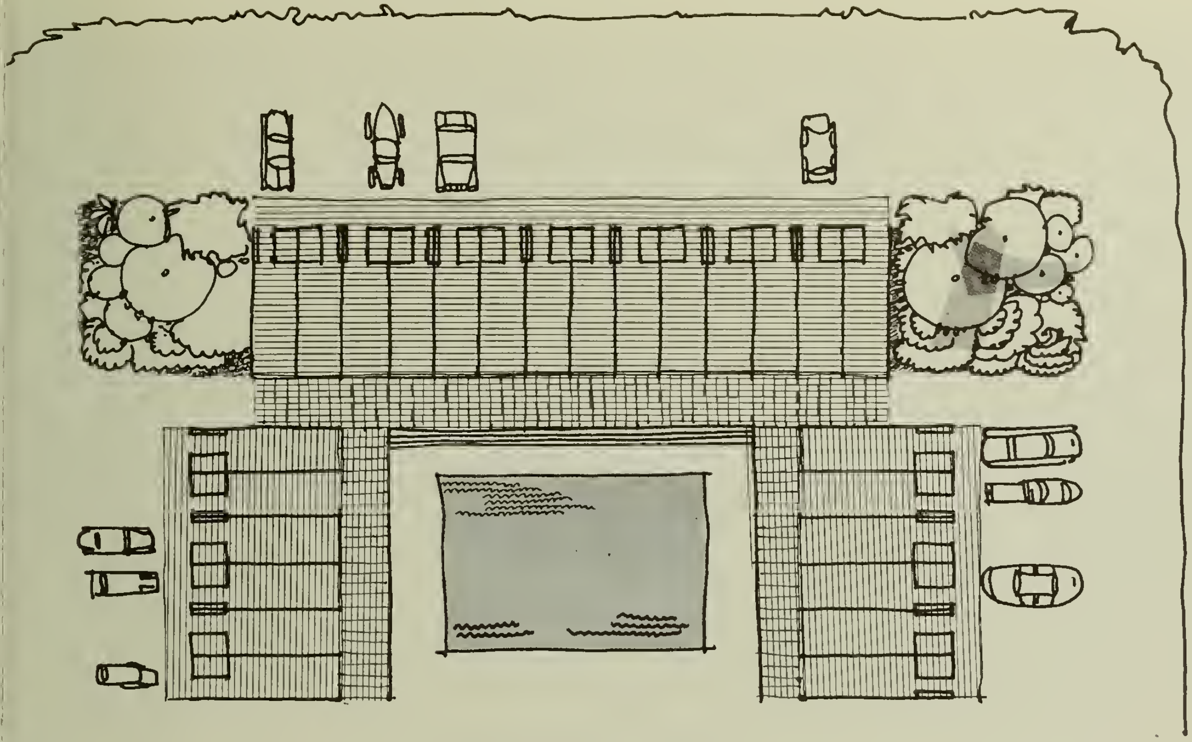
The scale of a folded plate system will depend on the size chosen for the individual bay. This might be determined by a planning module based on the need for regularly spaced interior partitions. The flat panels used for the folded plate do not take advantage of the formability of plastics. To gain the advantages of simplicity of fabrication, this system sacrifices the chance to conform more closely to the stress patterns, as would curved panels.

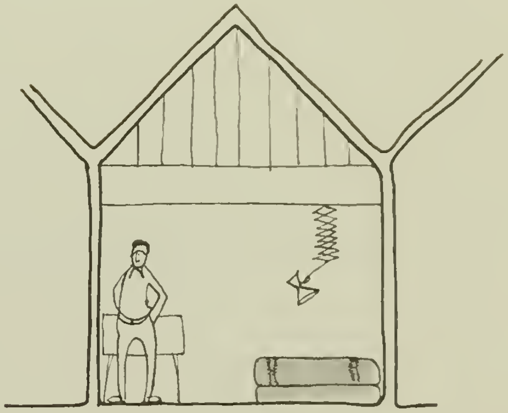
A procedure similar to that used in the analysis of concrete folded plate structures is used to design this plastic sandwich system. Moment-resisting joints may be avoided at the folds but will probably be necessary in the length of each panel to break it up into more easily handled sections.

While no unusual demands are made on the material of the panel itself, the joints of a folded plate structure require an extremely versatile method for gasketing and sealing. The tendency of the structure to open up at the joints because of the thermal expansion and contraction and longitudinal shear forces will be great.

If the panels are to be transported by any of the conventional carriers, their width cannot exceed eight feet. This places a severe limitation on the width of the structural bay, which could be no greater than sixteen feet multiplied by the cosine of the angle of roof pitch.

If an easy way could be found to adjust the joints along the folds so that they suit the angle of the roof, sandwich panels for folded plates could be stocked and sold in the same way as flat panels.





FOLDED RECTANGULAR PYRAMID

Another way of strengthening flat panels against bending is to fold them into rectangular pyramids. The small bus terminal illustrated is made up of nine such pyramids, with apexes alternately up and down. The whole structure would be bounded by a deep edge beam.

Column supports occur at the low points and are shown here twenty-four feet apart. With the supports placed in this way, all the panels and joints will be largely in compression. The interior arcade is lighted from above by means of translucent panels.

Square bays necessitate equal spacing of supports in two directions, which might limit planning. In the example shown, for instance, the column that would be necessary at the center of the crossing of the two arcades could be awkward. The system can easily be added to and can expand in any direction. The method of support would make it easy to adapt it to irregular topography if the roof line were broken between units. Such breaks could allow clerestory lighting.

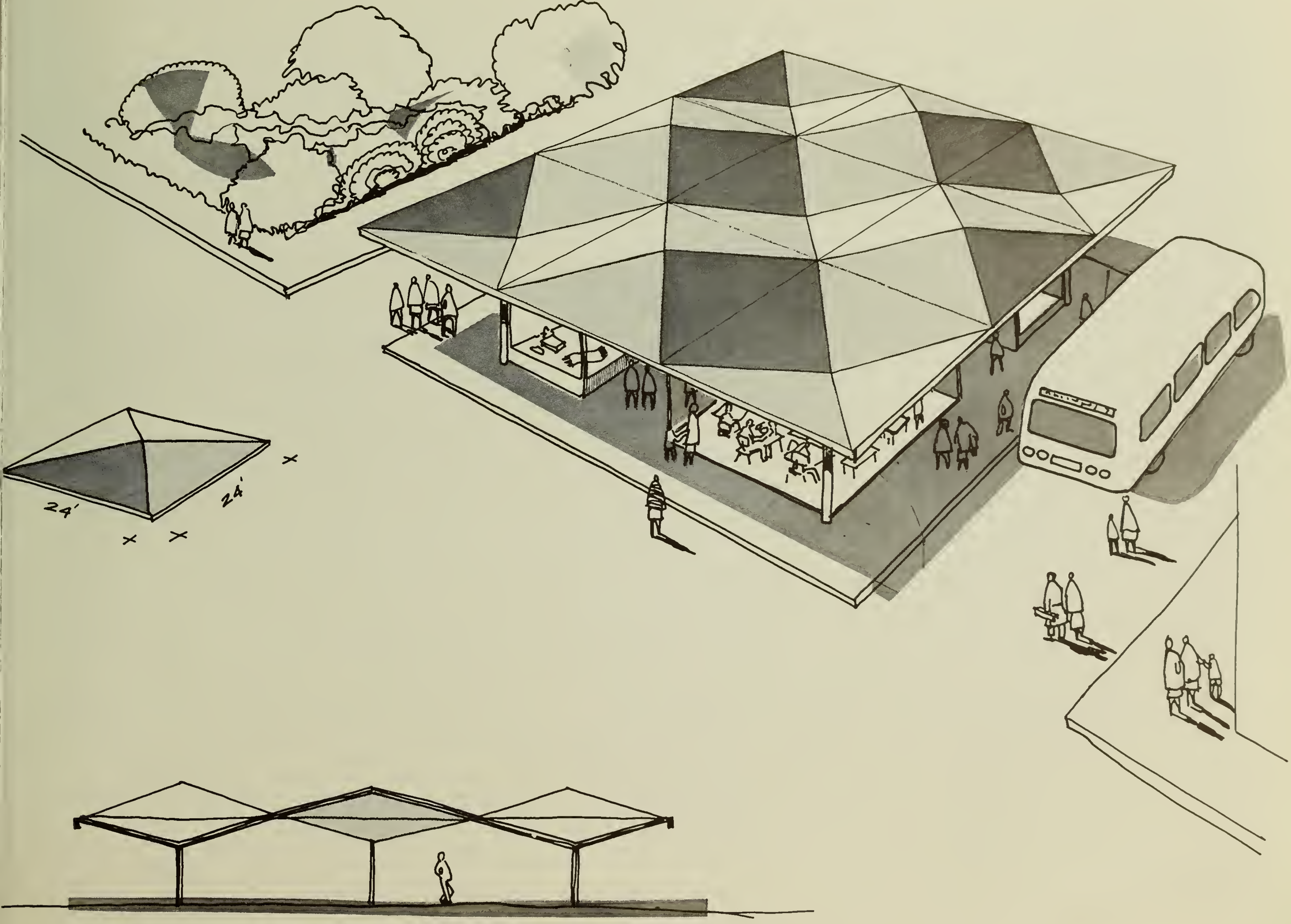
The scale of even a large building made up of these pyramids would be reduced by the strong expression of the individual units. The roof has a crystalline quality which would create an ever-changing play of light and shade.

The advantage of the form in adding strength would make this system another relatively economical way to use flat sandwiches. However, a rather substantial edge beam would be required to resist bending and shearing forces from the roof planes. The structure has no inherent resistance to lateral forces unless the columns are designed to cantilever from massive foundations. Loading on these cantilevered columns in the building shown would, in addition, be eccentric, and the columns would have to be quite heavy.

The panels of the twenty-four-foot-long bay system which is illustrated would be too large for present-day production or transportation facilities. With some difficulty, they could be made up of smaller units and site-connected with moment-resisting joints.

If the large parts are light enough, the development of new kinds of cargo carriers could solve the transportation problem.

By hollowing out the core of the necessarily thick columns, space would be provided for mechanical services that cannot easily be integrated in the thin roof panels. The system is suitable for large, one-story space enclosures for activities not hampered by closely spaced columns.


24'
24'

FOLDED HEXAGONAL PYRAMID

The distribution of stresses in this hexagonal folded structure would approximate that of a shallow dome. The illustration shows a school which uses the hexagonal form to roof the free-standing classroom units in a so-called "cluster plan." At the center of the main wing, another roof unit — in this case translucent — covers a multipurpose room.

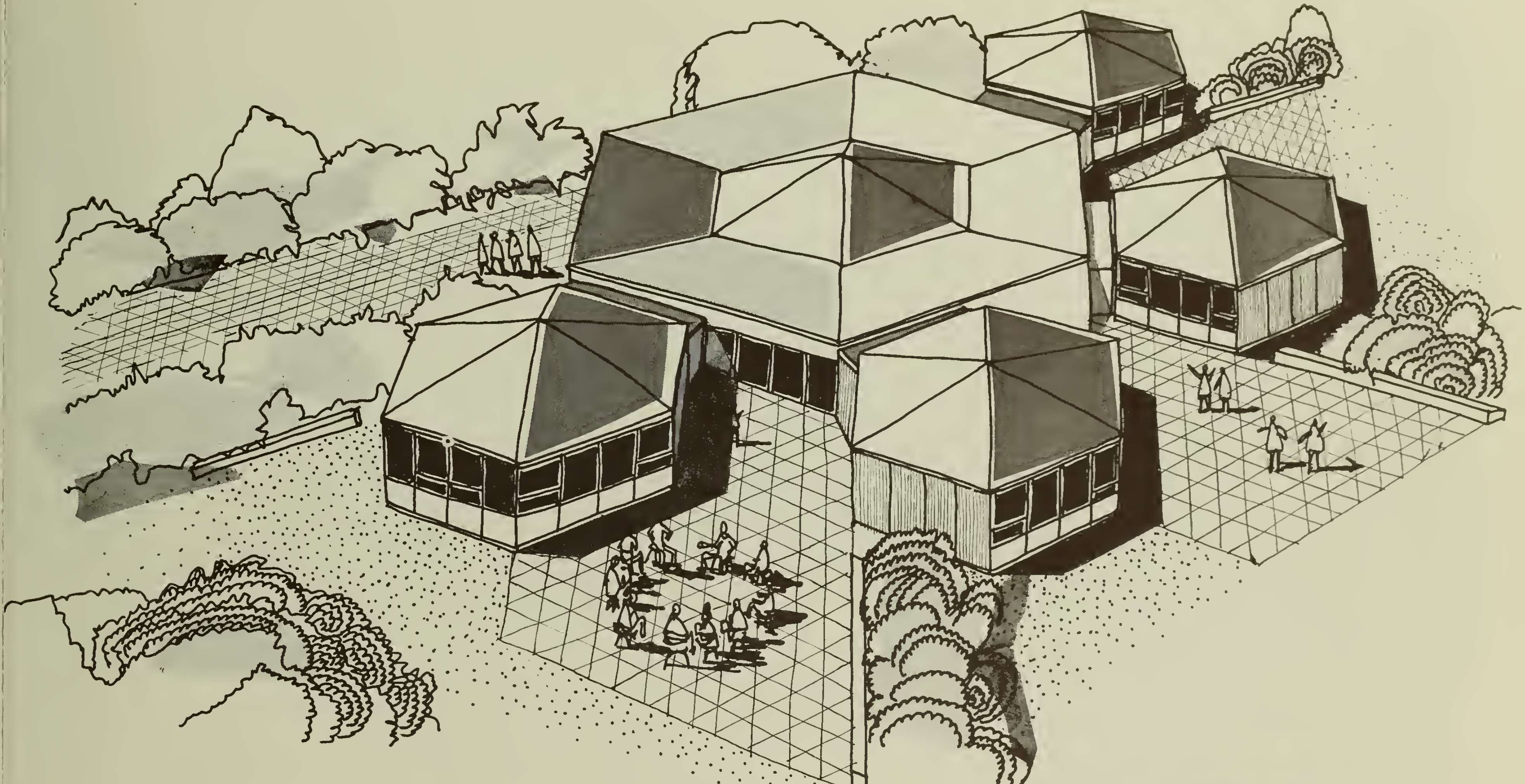
The structure must be supported along its entire perimeter by either a beam or bearing wall. The size and shape of the space created is fixed by this, and only a limited range of activities can be housed. Expansion can be accommodated only by adding new units to the cluster. By taking up irregularities of the site in the linking corridors, this system can be adapted to irregular terrain.

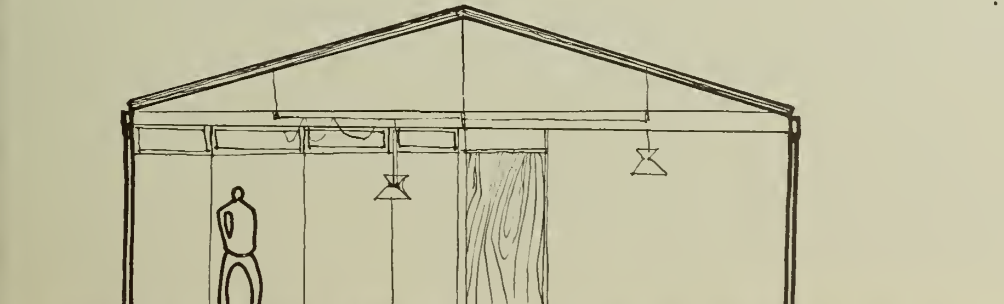
Small self-contained units roofed with the hexagonal pyramid would have an intimate human scale. When used in the cluster plan, as shown, the exterior spaces around the building are strongly defined by adjoining units. Like the other folded structures shown on the preceding pages, the form of this type could result from the use of any number of strong sheet materials. The nature of the plastic material used might be revealed by the use of translucent, specially textured, or colored panels.

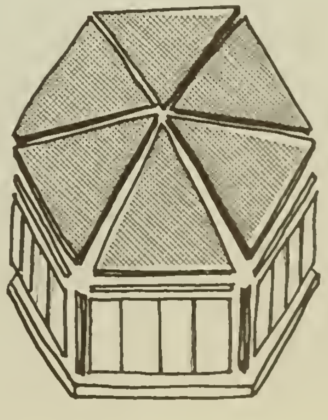
The form of this kind of structure would follow stress patterns fairly closely, and thus the panels would be largely in compression. A tension ring would be required at the base to provide a horizontal reaction. As the perimeter of the form must be continuously supported, an edge beam is needed to span openings in the bearing walls.

Again, flat panels would be joined together to create this structural form. The factors influencing fabrication, handling, erection, environmental controls, and marketing would be the same as they were for the rectangular pyramid and folded plate.

Certainly this type would be suitable for small houses, schools of a certain type, or demountable buildings.







CYLINDRICAL SHELL

Although it resembles an arched vault, this structure is actually a long beam which is curved to give it greater structural efficiency. Shown here, it roofs the classroom wings of a small school. Supports are needed only at the ends of the long, narrow bays.

The planning potentialities and scale of the curved beam system are in no significant way different from those of the folded plate. As a structure, however, it has some distinct advantages. Being curved rather than peaked, it follows stress patterns more smoothly and avoids concentrations of stress that occur with sharp changes in direction. A very vulnerable joint at the ridge may also be eliminated by the continuous curve from valley to valley.

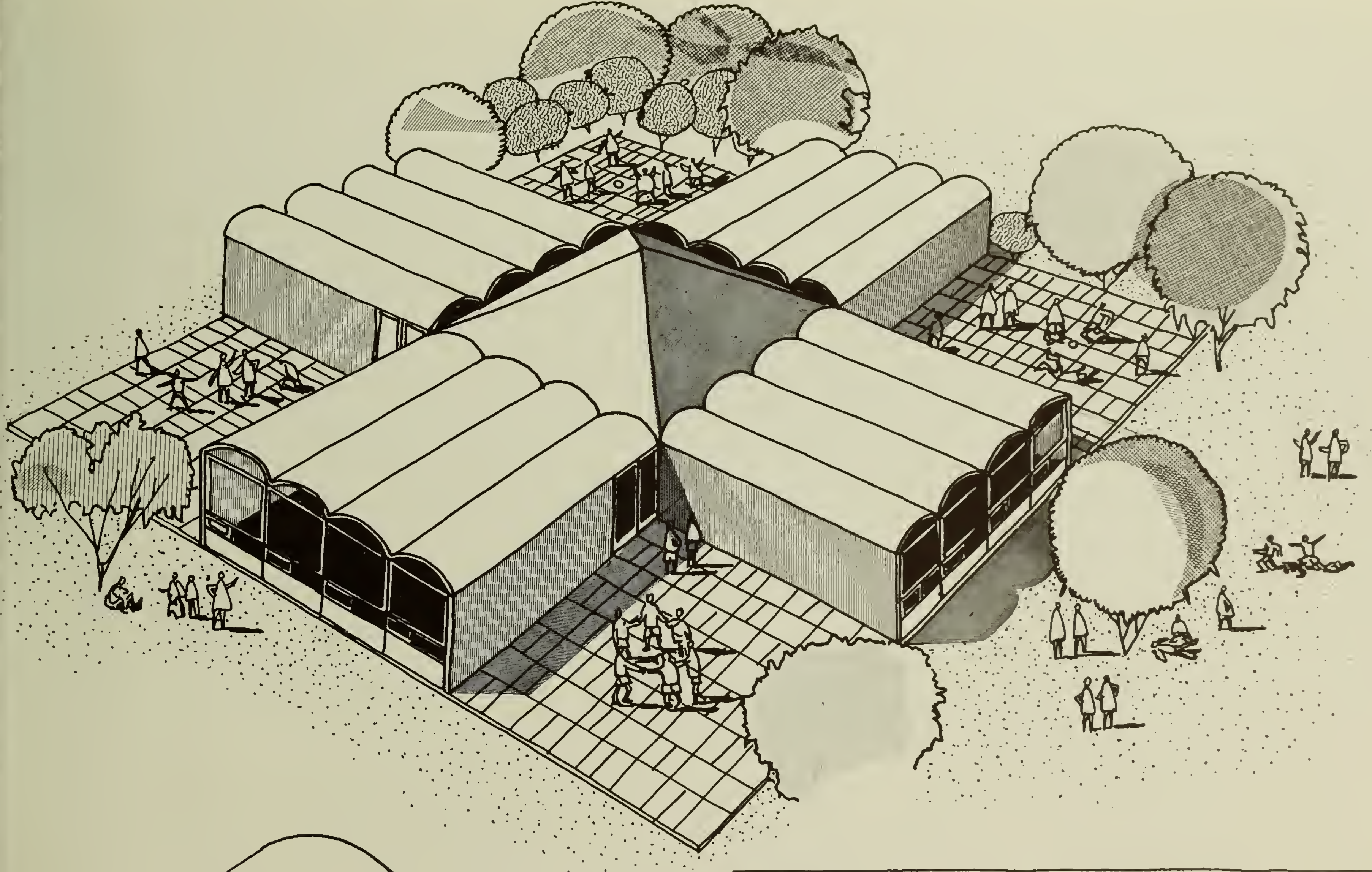
Here, too, we see that use is made of the formability of plastics. A foamed-in-place or honeycomb core can be made to follow the simple single curvature. Machinery that is not now commonly in use would be required to produce this type of unit in quantity.

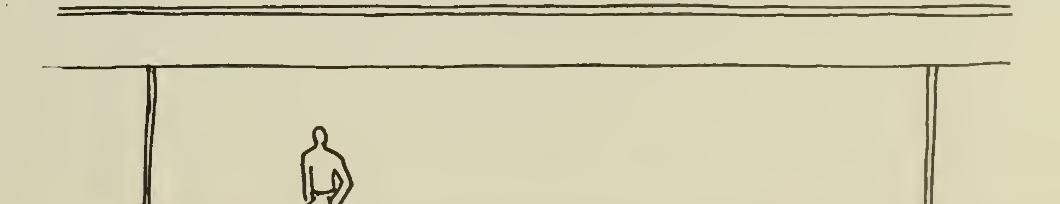
Bay widths would be limited to only eight feet if conventional transportation systems are used. In addition, the beams would probably be too long to ship in one piece. Dividing them into sections for shipment would necessitate making strong, moment-resisting joints in the field. Being curved, these joints would demand extremely careful detailing and workmanship. For shipment and storage, the curved shapes could be nested in one another.

Mechanical services could be most easily provided for if a flat ceiling were used. This would also preclude any difficulty with acoustics that might result from focusing of sound by concave interior surfaces. Partitioning would also be simplified. But once inside the building, any realization of the strong structural form would be lost.

Drainage problems must be carefully considered with any system which, like this one, has an abundance of roof valleys. The pocket created between the central rectangular pyramid and the clerestory windows would, for example, be complicated to drain.

The curved beam system would be adaptable to one-story light industrial and commercial buildings, schools, housing, or small office buildings.





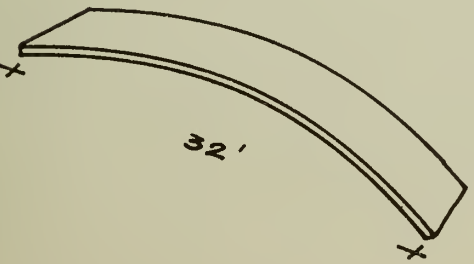
ARCHED PANEL

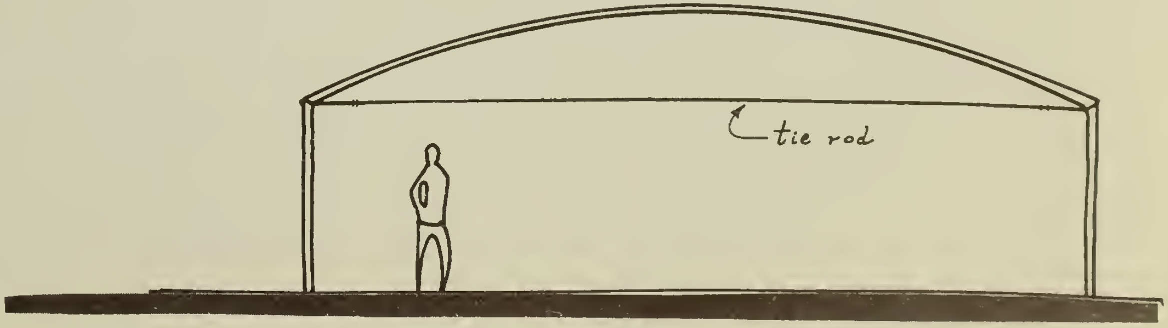
The arch, a time honored method of making materials span great distances, is applied here to the sandwich panel. Part of a school which has classrooms roofed with four structural units is shown here. Continuous supporting walls or beams, as well as tie rods, are necessary to this construction.

By increasing the thickness of the sandwich, considerable spans would be possible with the arch. The form of the roof seems to indicate a strong division of interior spaces at the springing of the arches. In the other direction, clear spaces as long as required can be easily provided. Expansion is thus facilitated in only one direction. If planning required spaces of widely varying sizes, more than one size of arch would be useful. Partitioning within any one bay can create extremely awkward room shapes.

Long, simple curvatures like this can give some sense of the formability of plastics but could be achieved as well with other sheet materials, such as plywood or aluminum. A sense of scale might be reinforced if arches of different span and curvature were used to cover and express the different activities housed in various room sizes. The basic form could work equally well over a small office and a large gymnasium.

Such arches could be plant-fabricated over simple male molds and shipped nested to the site. By using a hinged arch, the unit may be conveniently broken down for shipment. With the use of hinges, moment-resisting joints will not be needed when the parts are reassembled at the site.


32'


tie rod

MATTRESS BEAM

This system consists of a series of deep beams formed between two bowed skins. It is a type of construction familiar to the aircraft industry. Shown here as a roof for a filling station, the structure is supported on folded C-column sandwiches.

The simple curvatures might be obtained by arching two flat sheets and foaming a core between them or by bonding them to a preformed core. Relatively long spans are possible, and there would be few supports to interfere with planning flexibility.

The double convex curvature forms a handsome structure, but it is one which does not result in the most efficient use of materials. The area around the joints would be rather weak compared to the deeper center part of the beam. Another difficulty would arise in attaching the curved bottom of the beam to a supporting wall or girder.

For an umbrella-type roof like the one shown here, the use of a core which is insulating is perhaps wasteful. A system of ribs could be substituted. This would have an advantage in that some mechanical services could be worked into the structure. If it were desirable to have a translucent panel, this would be more easily accomplished with a rib system than with the solid core.

SHALLOW DOME

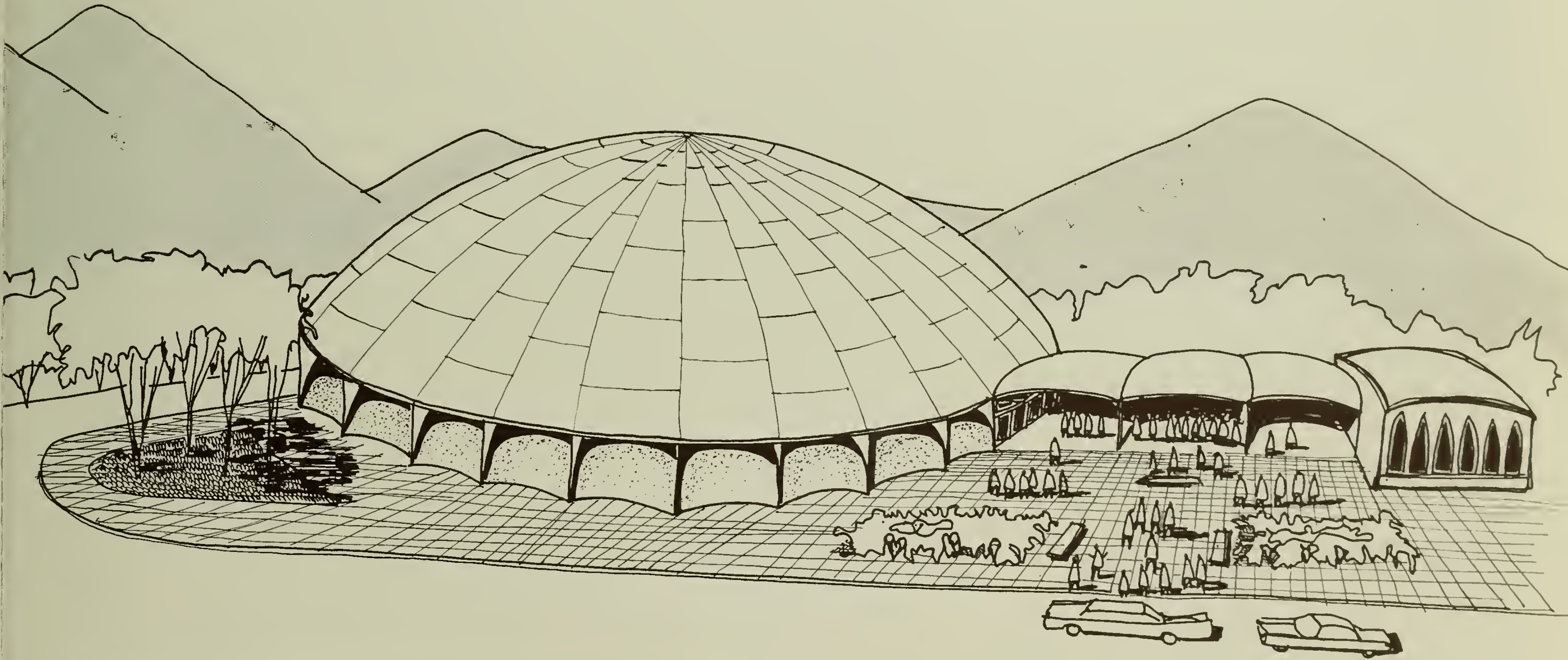
The inherent strength of the dome shape is very great. Plastic structural sandwiches formed in this way can enclose great spaces. Shown here is a civic center which has a large, multipurpose hall covered with a shallow dome.

A level site and firm supporting soil are needed for a structure of this kind. A very well-defined space is covered at one time, and expansion of the enclosed area is difficult. A compromise most usually has to be made between the structural advantages of a high dome and the saving of building cubage possible with a shallow one. The uncompromising completeness of the shape makes it difficult to attach ancillary structures gracefully. The scale of such a building is difficult to establish, as its bulk gives no hint of the variety of activities that may go on within.

The dome form most easily translates imposed loads into direct shell stresses and can probably enclose a greater number of cubic feet per pound of material than any other form. However, the shape precludes the active use of much of the volume, and this can vitiate the economy.

The most exacting hand methods are used today to create large structures of compound curvature. A considerable amount of development work that would open up the possibility of assembly line production of parts is yet to be done. Field erection could be accomplished with a central mast, the panels being attached in self-supporting concentric rings.

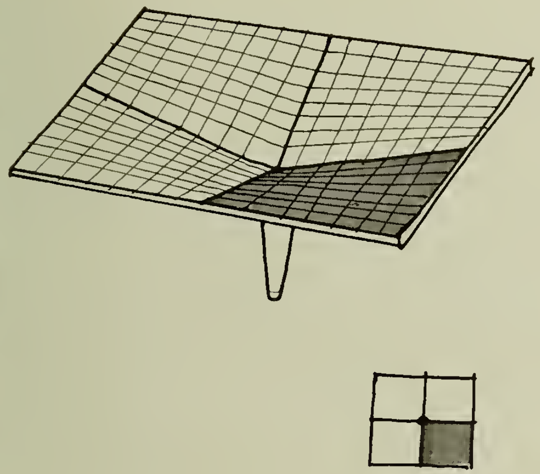
The dome shape often has acoustical problems, such as “focusing” and “creep.” In order to preserve the efficiency of the thin shell, mechanical services will have to be kept out of the sandwich structure itself.

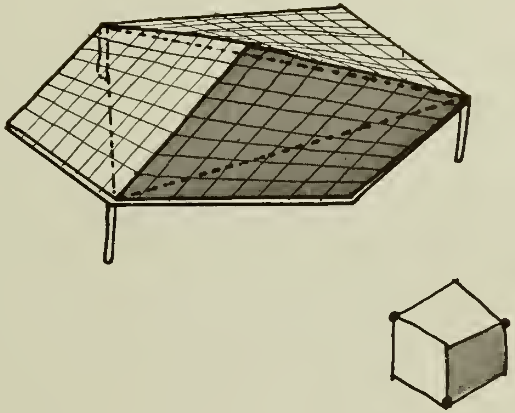


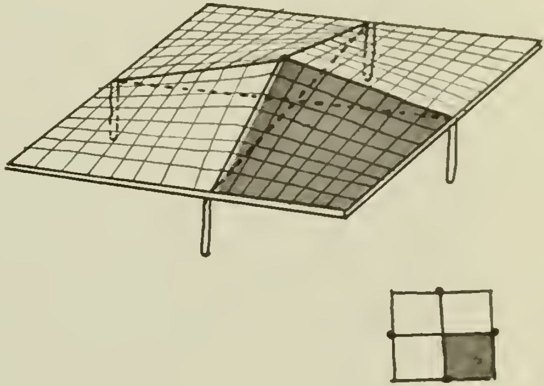
HYPERBOLIC PARABOLOID

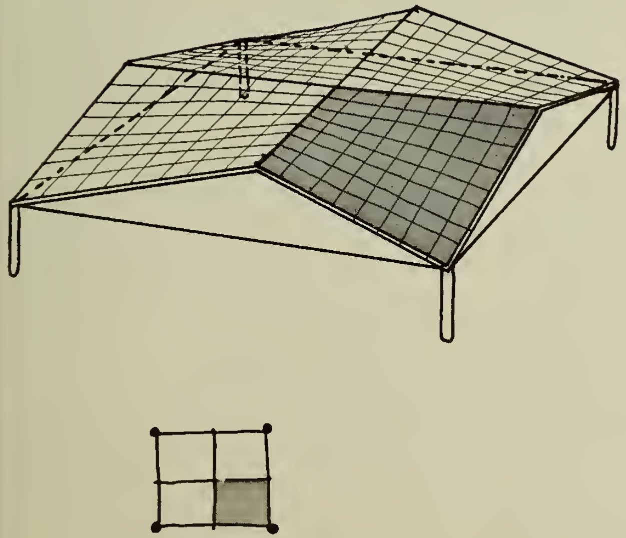
One of the most simply generated and easily varied doubly curved forms is the hyperbolic paraboloid. Its surface can be formed by a series of straight members. Six of the countless combinations in which this kind of structure can be used to roof a space are illustrated here. The scale of the individual units can be varied from a few feet to a hundred. The shape of the space, too, can be varied from a roof with an almost flat surface to one which has a steep slope.

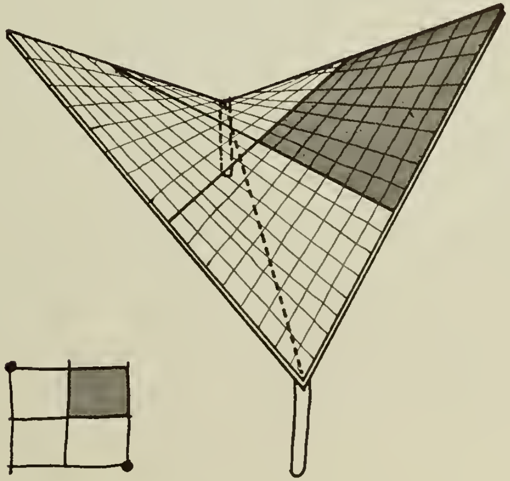
If it is to be put together in the field, the framework required is less complex to construct than for any other doubly curved surface. If it is to be plant fabricated, it may be broken up into similar units which are smaller hyperbolic paraboloids. In order to fit together, each of the subunits would have to be slightly different from the others unless a slightly flexible sandwich construction is used. If the small sections are flexible enough to bend slightly so they may fit in place in the erection process, they may all be struck from the same mould. A simple and inexpensive method of making curved, moment-resisting joints will have to be evolved before shape fabrication and easy field erection can become common practice.

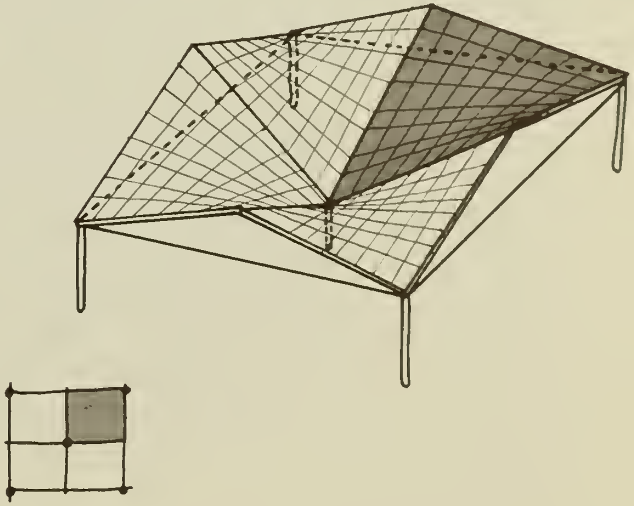












ELLIPTICAL PARABOLOID

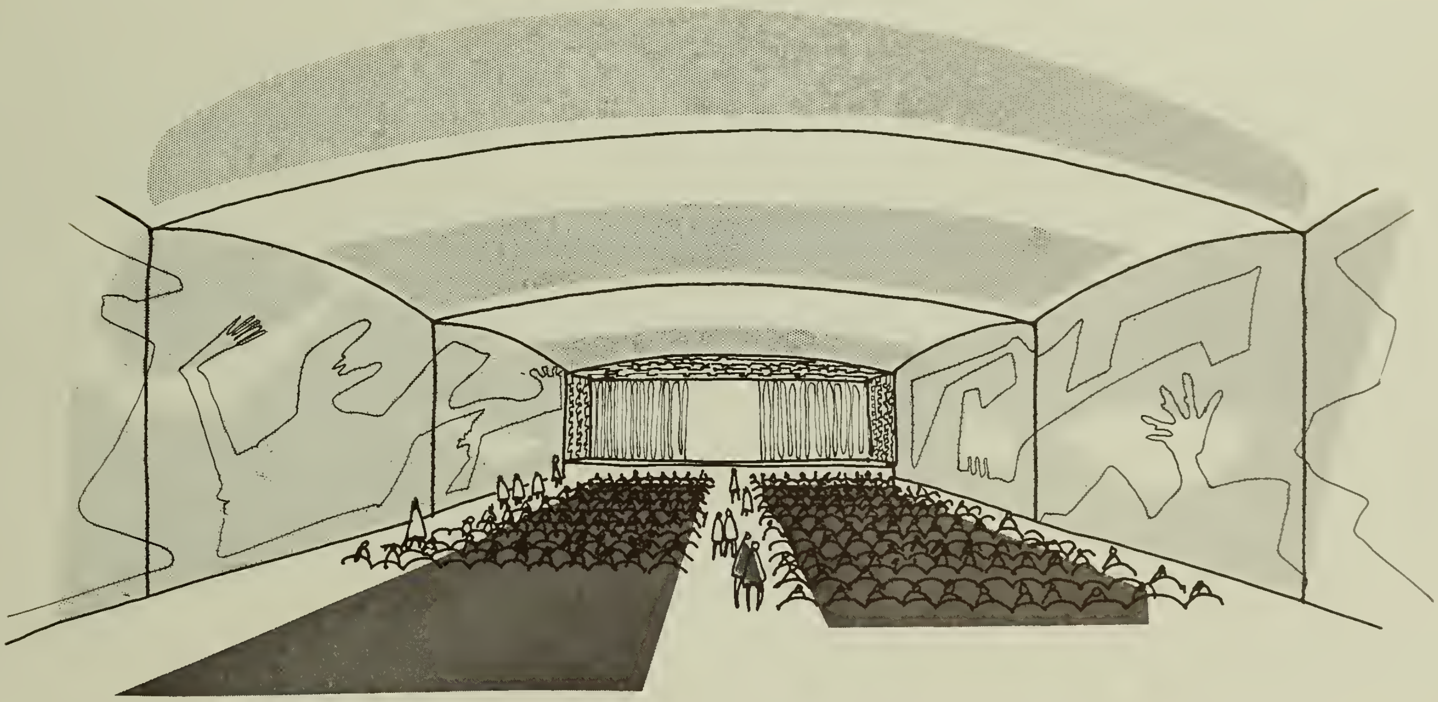
The illustration shows a theater roofed with long-span plastic sandwiches of double curvature. The elliptical paraboloid shape is generated by moving two parabolas at right angles to one another. This subtle and rather gentle curvature can impart enough strength to the structural sandwich to make it a device for spanning major spaces.

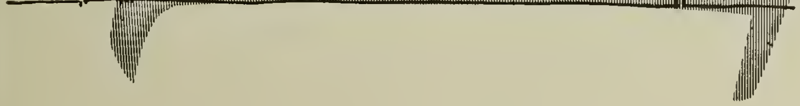
Structures of this magnitude are more likely to be used for special-purpose buildings which cannot be easily remodeled for new or changing activities. Rather, new uses are likely to adapt themselves to the structure. The site would also be modified to accommodate a large-span structure of this kind. The formability of plastics is fully used here, as is the flexibility of color application in the suggested mural integral with the sandwich skin.

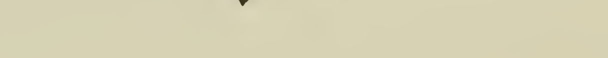
The large bay units shown would have to be fabricated in small sections. There would be a good number of individual forms used to build up the large shape. Then an equally great number of difficult, curved, moment-resisting joints would be required to piece the whole form together again. Unless many similar buildings were contemplated, it would probably be more advantageous to form the structure in the field than to build it up of factory-made parts. Storage and erection would have to be carefully organized to get the parts to their proper place in the proper order and at the proper time.

Great difficulties could be expected in finding a place for the enormous amount of mechanical control equipment required for special-purpose buildings like this theater, if thin sandwiches are used. Special space for equipment would probably have to be worked into the basic design. Point loads that would be created by suspending lights, bridges, and the like from the shell would probably make added reinforcing necessary.

Any number of building types requiring fairly large spans might use this structural system. Its size and form could not be easily varied, as a complex set of molds would be required for each condition. However, a standard size of great versatility might be found for a large enough number of buildings to make factory production feasible.







BOX SHELL

A hull-like box shell which derives great strength and rigidity from its compound curvatures was used for the Monsanto House of the Future. The building of this full-scale experimental house yielded much detailed information on the behavior of large, complex plastic sandwich panels under service conditions.

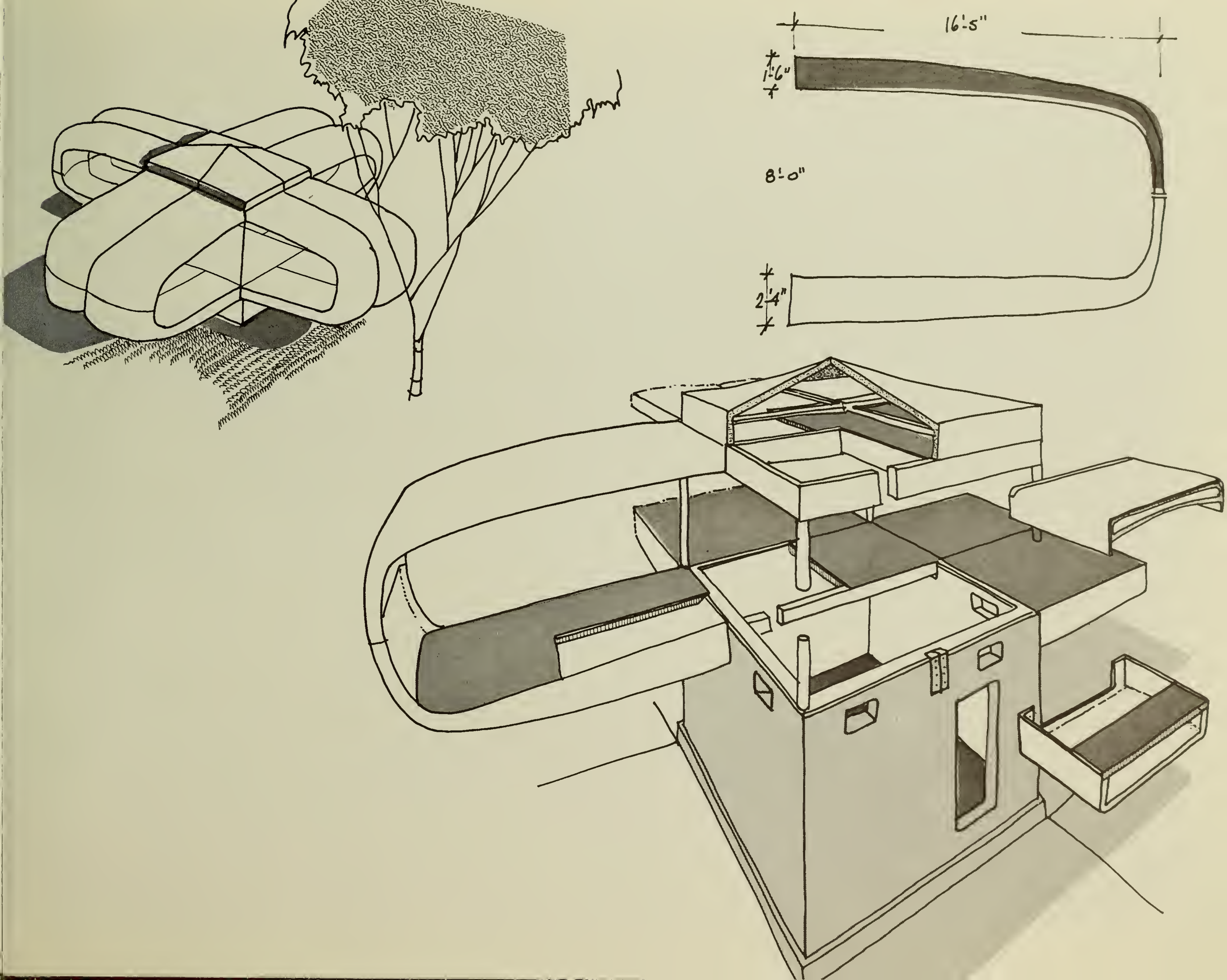
The sandwich components, which are eight feet wide, sixteen feet long, and four feet high, are designed to cantilever from a central utility core, the only part of the house which is in contact with the site. This small base minimizes site preparation. By using more than one core, the plan can be varied from the cross shape illustrated.

The size of the structural unit, which was limited by the capacity of a standard trailer truck, makes it best suited for buildings of domestic scale. Because of the closed shape, a long row of units placed side by side to form a large space could get natural light only at the ends.

The very special shape of the component, which was designed to have maximum strength as a cantilever structure, demonstrates the versatility of presently available molding techniques. The fabrication method used for this experiment was based on exacting hand layup of the glass cloth reinforcing and polyester resin. As such, it was rather costly. Large-scale production of such components would invite cost-cutting mechanization of the work.

The space between the two skins of the sandwich is large enough to include a foam core providing shear strength and insulation as well as space for mechanical equipment and a plenum chamber for conditioned air.

The engineering of the house is reported in detail in Richard W. Hamilton, et. al., *Architectural Evolution and Engineering Analysis of a Plastics House of the Future*, Massachusetts Institute of Technology, Cambridge, Massachusetts, 1957. The completed design is shown in *Industrial Design*, Volume 4, (August, 1957), pages 48-57.


16'-5"
1'-6"
8'-0"
2'-4"

NON-GEOMETRIC SHELL

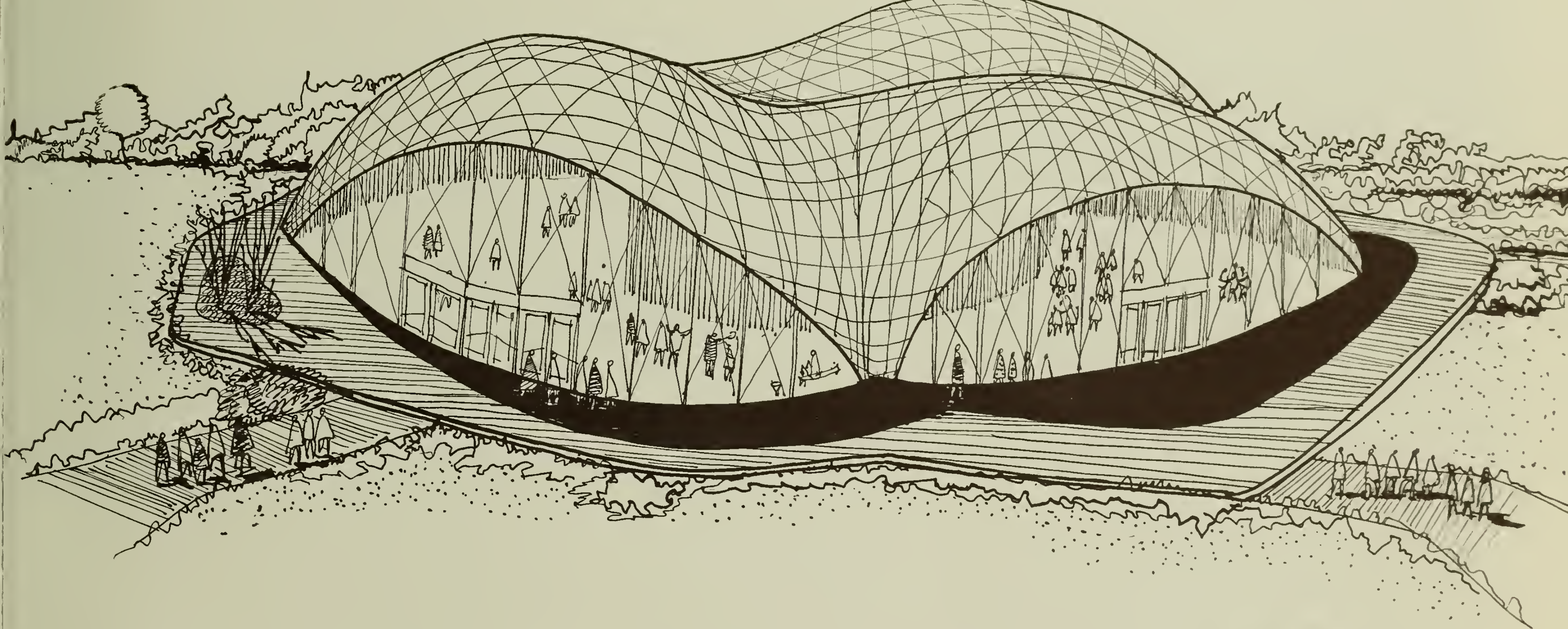
The large-scale shell of irregular shape which is illustrated here houses an auditorium. The doubly curved surface is made up of triangular and trapezoidal sandwich panel units. It demonstrates the ability of plastic materials to fit themselves to an extremely complex volume with a structurally efficient curved form.

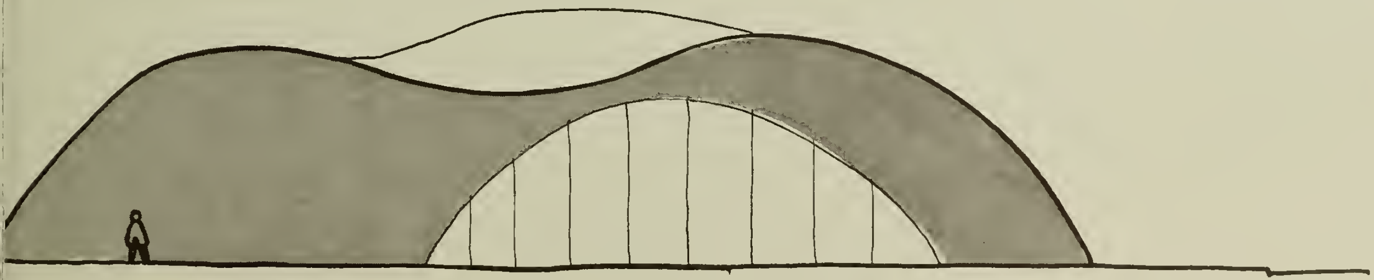
The efficiency is the result of a shape that resolves imposed loads mainly into direct axial stresses which follow the plane of the shell itself. No regular mathematical curve is used to generate the form, but it is shaped by the designer to enclose and express the activities planned for. Mathematical analysis would be impossible, and the model analysis would probably have to be used instead. A form such as this is directly related to a specific activity and allows little latitude for other uses. Dividing the interior space in any other way than initially planned would defeat the purpose of the special shaping.

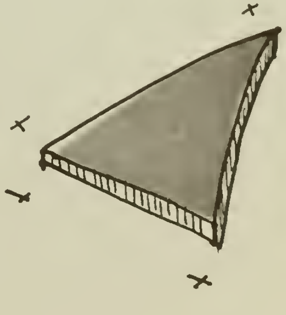
Fabrication today would undoubtedly be costly and complex. An enormous number of different units would have to be molded and painstakingly assembled into the final form. Supports would have to be highly reinforced in the example shown to resist the great concentration of loads coming down from the shell. Joint conditions would also be varied and require a versatile system of gasketing and sealing.

Most of the prefabricated systems illustrated in this chapter have had the advantage of requiring little or no supporting scaffolding during the erection process. An amorphous form like this one, however, would probably require a fairly complicated system of supports during the erection process. One possibility of simplifying the construction process would be to form the skins in place against a one-piece, site-built matrix of rigid reinforcing material.

In an auditorium such as this, the acoustical design need not require a separate construction to achieve a desirable room shape, for the structural shell itself can create this shape.







STRUCTURAL ANALYSIS

This chapter was prepared by Frank J. Heger, Jr., Assistant Professor of Structural Design, M.I.T.

INTRODUCTION

As with any conventional structure, strength analysis and design of a sandwich panel structure involves two basic steps. The first is an analysis for moments, shears, and axial forces in the structure, resulting from loads applied to the structure. Then, using the internal effects on the structure given by this analysis, the sandwich panel section can be designed for strength and stiffness. The first step, structural analysis, is no different for sandwich structures than for conventional structures. When the structure is indeterminate, relative stiffness properties of the sandwich construction must be computed or estimated before an elastic analysis can be made.

Methods for analyzing the various structural types for which sandwich construction may be employed are not peculiar to sandwich design and will not be further treated here. However, it will be shown later in this chapter that sandwich construction may be well suited for use with many of the three-dimensional surfaces that can be used for medium- and long-span roofs in building construction. Thus, it will be of interest to discuss the general requirements of such construction and to present a list of references giving mathematical methods of analyzing these structures.

THE USE OF SANDWICH STRUCTURES WITH THREE-DIMENSIONAL GEOMETRY

The most efficient means of transmitting load to supporting foundations is by means of direct internal axial force, rather than through the development of internal forces to provide bending resistance. This principle applies to sandwich construction as well as to the conventional systems of construction.

Sandwich construction, when used either as a flat panel or for curved structures, offers a method of attaining high structural efficiency in the development of bending resistance. When thinking in terms of long-span flat sandwich beams or slabs, however, the structural requirements for facing and core become formidable; and the cost of flat sandwich construction, compared with conventional construction systems, becomes most unfavorable. The use of a structure with a three-dimensional geometric shape which will transmit loads more efficiently than a flat sandwich beam offers the possibility of spanning medium to long distances economically with sandwich construction. Use of such structural shapes would be possible wherever flat surfaces were not demanded by the functional requirements of the building.

Efficient geometric shapes for transfer of loads are, first, those which develop primarily internal axial stresses rather than bending stresses and, second, those which are shaped to provide great depth perpendicular to axis of bending. Structural forms of the first type are singly curved arches and various double-curved surfaces *(see figures 1a-1j)*. Structures of the second type are corrugated shapes, cylindrical shell structures, and folded plate structures *(see figures 1k-1p)*.

SINGLY CURVED STRUCTURES

Singly curved arch-type structures must conform in shape to the funicular curve associated with the loading system which is being supported, in order to be subject to only direct compressive stresses. The magnitude of these direct stresses is a function of the arch rise and span. In buildings where such structures must carry variable live loads, bending moments will exist in the arch under certain loading patterns. Moreover, sufficient stiffness in the arch itself is required to provide the necessary stability in the plane of the arch. Sandwich construction can economically provide the relatively small stiffness required for bending moments under variable live loading as well as the necessary resistance to buckling.

Singly curved arches require both horizontal and vertical supporting reactions. The arch structure is most efficient where these reactions are continuous *(see figure 2)*. Where the

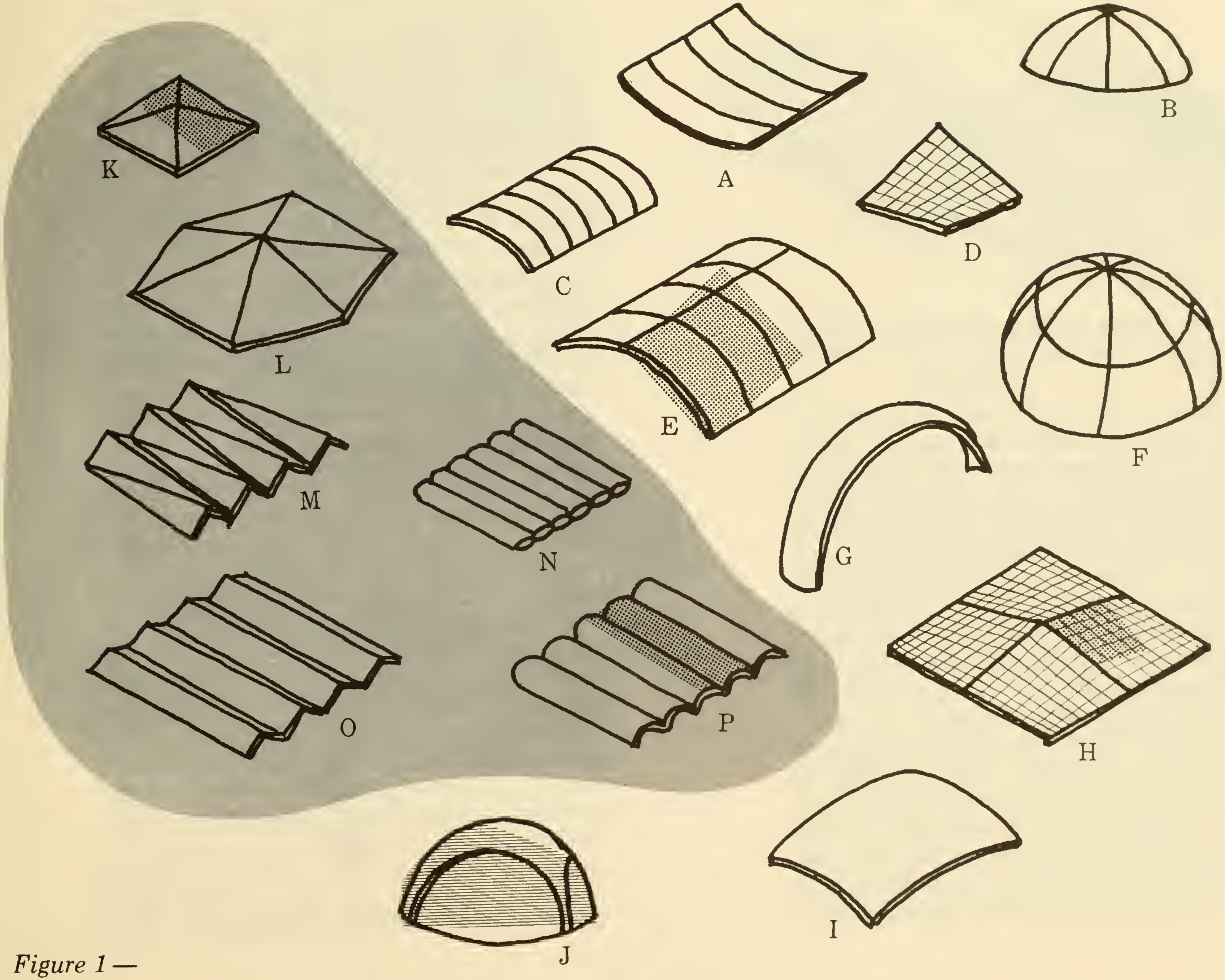


Figure 1 —

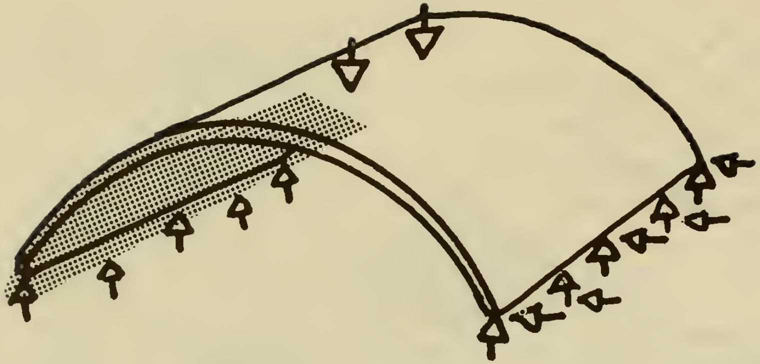


Figure 2 — Arch Surface, Continuous Support

reactions are not continuous, as where tension tie rods or columns are used at certain intervals, transverse beam action occurs between supports. In this case there are two alternatives. Beams must be provided to transmit the arch thrust to the supports, *(see figure 3)*, or the lower portion of the arch surface must act as a deep beam which transmits loads through development of longitudinal forces and local longitudinal and transverse moments *(see figure 4)*. It would be possible to accomplish this beam action with a suitably designed sandwich construction. Arch-type surfaces may be analyzed approximately by the conventional arch theory available in any standard text on indeterminate structures. Coefficients for analysis of typical circular arches common to roof construction are given in reference 1.

If a singly curved surface is inverted as in a suspension structure, applied forces are transmitted primarily in tension. The magnitude of the direct tension will depend on the span and the amount of sag. To avoid bending stresses, the shape of the curve again must conform to the line of force created by the loads. With flexible cable suspension structures, the structure will automatically conform to this load line. However, a rigid suspension structure must provide sufficient bending resistance to absorb the effect of variable loading. Again, sandwich construction is well suited to this requirement. Suspension structures are not often used in building construction because of the difficulty of providing the large horizontal tension reactions required *(see figure 5)*.

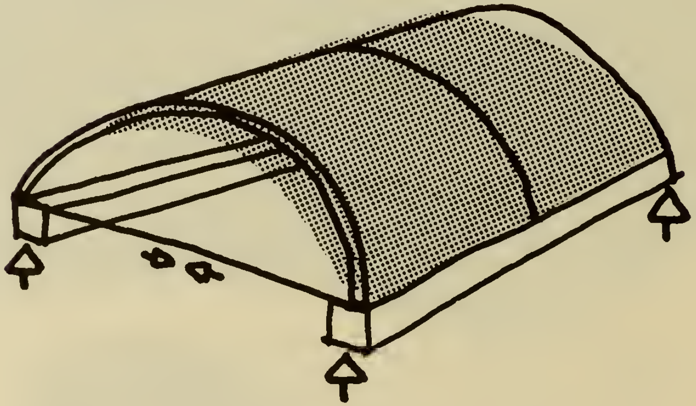


Figure 3 — Arch Surface Supported by Beam

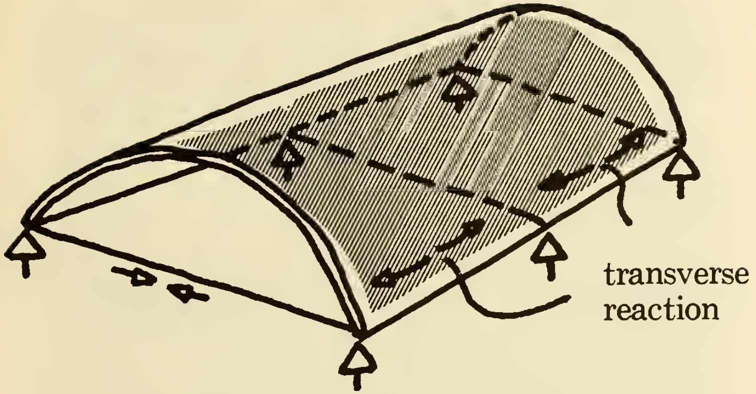


Figure 4 — Arch Surface Shell Action Between Intermittent Ties and Posts

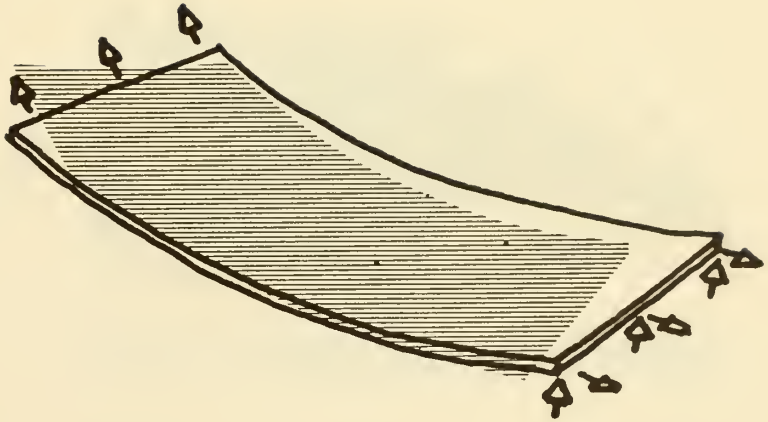


Figure 5 — Sagged Surface with Continuous Support

Singly curved rigid suspension structures can be analyzed by the same methods employed in arch analysis.

Some of the action characteristic of singly curved arch construction can be attained with the use of pitched roof construction employing inclined flat panels which are given proper vertical and horizontal support at the base and are mutually self-supporting at the peak. An inverted "V" surface *(see figure 6)* will carry vertical loads by a combination of direct compression and bending transverse to the plane of the sandwich. Bending moments will be relatively large, since the shape of the funicular load line differs appreciably from the inclined plane of the inverted "V." However, for a roof spanning on the order of 24 feet, sandwich panels of reasonable proportions could be economically employed in this way. Horizontal base reactions could be provided by tension ties across the structure at intervals, or could be transmitted to the foundation by shear partitions. Unless a beam were used at the base, however, stress distribution near the base would be complicated by transverse distribution effects between the ties. The action of this structural shape is similar to that of the traditional attic rafter and joist system used in house construction, where the inclined rafters form a three-hinged arch with bending between hinges, while the joists take the horizontal base reactions.

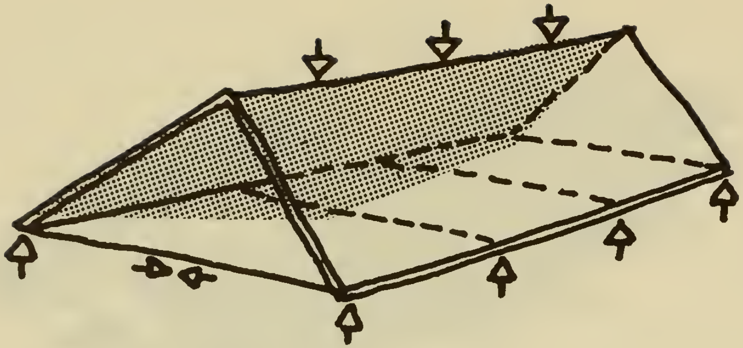


Figure 6 — The Prismatic Roof

DOUBLY CURVED SURFACES

Doubly curved surfaces have an added advantage over their singly curved counterparts, because with such surfaces variable loading can be supported principally by direct stress. To do this, the proper reactions must be provided at the edges. It is seldom possible, however, to provide the exact reactions necessary to insure that there will be direct stress only. Some bending usually does occur in the vicinity of the edge supports and is usually local in nature. The greater part of the structure away from the edges most often carries only direct stress. Where this direct stress is compressive, failure of the structure because of local buckling must be considered. A doubly curved surface derives from its shape a great inherent resistance to buckling. Additional stiffness obtained with sandwich construction permits an economical solution for load transmission over long spans with doubly curved surfaces, particularly when easily formed materials such as plastics are used.

The geometry of many doubly curved surfaces can be represented mathematically. Some of these surfaces are susceptible to direct mathematical stress analysis, while others can be analyzed by various approximate methods. The simplest doubly curved surfaces to analyze are the domes of revolution under axi-symmetric loading with continuous supports. Such structures are circular in plan and are formed by the revolution of

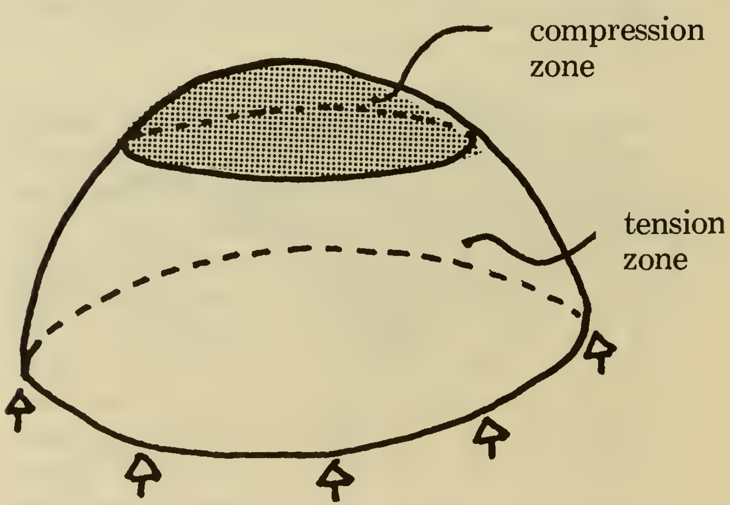


Figure 7 — Hemispherical Dome

a circular arc, ellipse, or other shape about a vertical axis. A spherical dome, for example, results from rotation of a circle about a vertical axis through its center. It carries external loads primarily by direct stress. For vertical loading, for example, the direct stress would consist of compression throughout the dome in a radial direction; and, in a circumferential direction, of compression in the upper portion and tension in the lower portion *(see figure 7)*. Only vertical reactions are required for a full hemisphere. For low-rise domes, consisting of an upper segment of the hemisphere, the entire dome is in compression, but a tension base ring is necessary to carry lateral thrust at the base *(see figure 8)*. Circular domes do not efficiently transmit large, concentrated loads. Such loads cause large local stresses in the dome; and since the dome is usually very thin, overstress is possible.

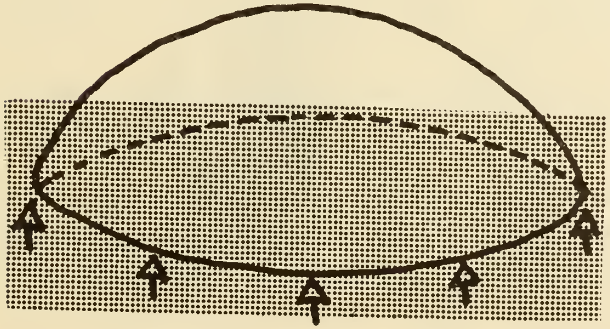


Figure 8 — Low Rise Spherical Dome

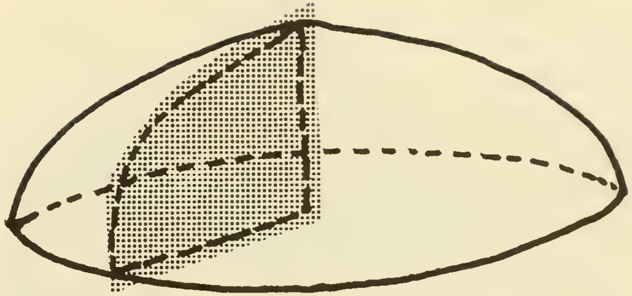


Figure 9 — Elliptical Surface of Revolution

Sandwich design would be an efficient method of providing the resistance to buckling and local bending needed in circular domes. The stress analysis of surfaces of revolution is discussed in references 2, 3, 4 and 5. A stability analysis is given in reference 30.

Other surfaces of revolution shown in the sketches are an elliptical dome formed by rotating an ellipse about its minor axis *(see figure 9)*, a cone formed by rotating an inclined straight line about a vertical axis *(see figure 10)*, and a connoidal dome formed by rotating a circular arc having its center outside the axis of rotation *(see figure 11)*.

The structural behavior of a dome can be approximated by a construction having a series of contiguous flat planes *(see figure 12)*. In the design of such a structure, provision must be made for resistance to local bending moments due to slab action in the flat portions. The use of sandwich design makes it possible for these bending stresses as well as the direct stress associated with shell action to be carried. Horizontal reactions for this type of structure can be provided with a tension ring at the base. This ring must also carry some bending, due to its deviation from a circular plan.

Another class of doubly curved surfaces are those formed by translating two mathematical curves at right angles to each other. Perhaps the simplest of such translational curves is the hyperbolic paraboloid, the surface of which can be formed by moving an inclined straight line along another inclined straight line which is at an angle (usually but not necessarily 90°) to the first *(see figure 13)*. Such a shell, when subject to uniform vertical load and when provided with suitable edge reactions, will be stressed in direct tension in one diagonal direction and in direct compression in the other diagonal direction. The edge beams will be straight members, providing the shell with shear and vertical reactions only. They will be loaded in either direct tension or compression, with no bending.

Hyperbolic paraboloid surfaces may be combined in many ways to span an area and can be arranged to utilize common edge members

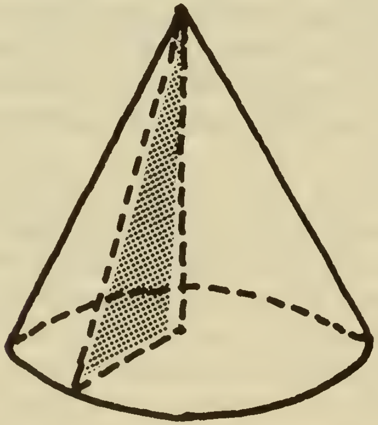


Figure 10 — Triangular Surface of Revolution

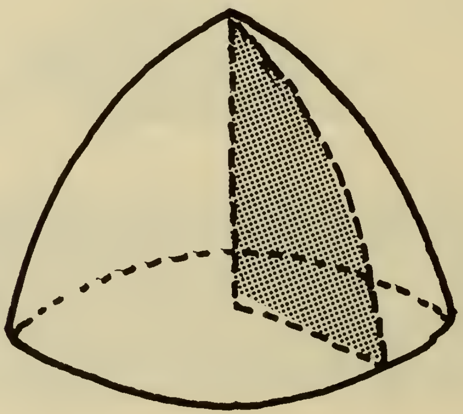


Figure 11 — Conoidal Dome

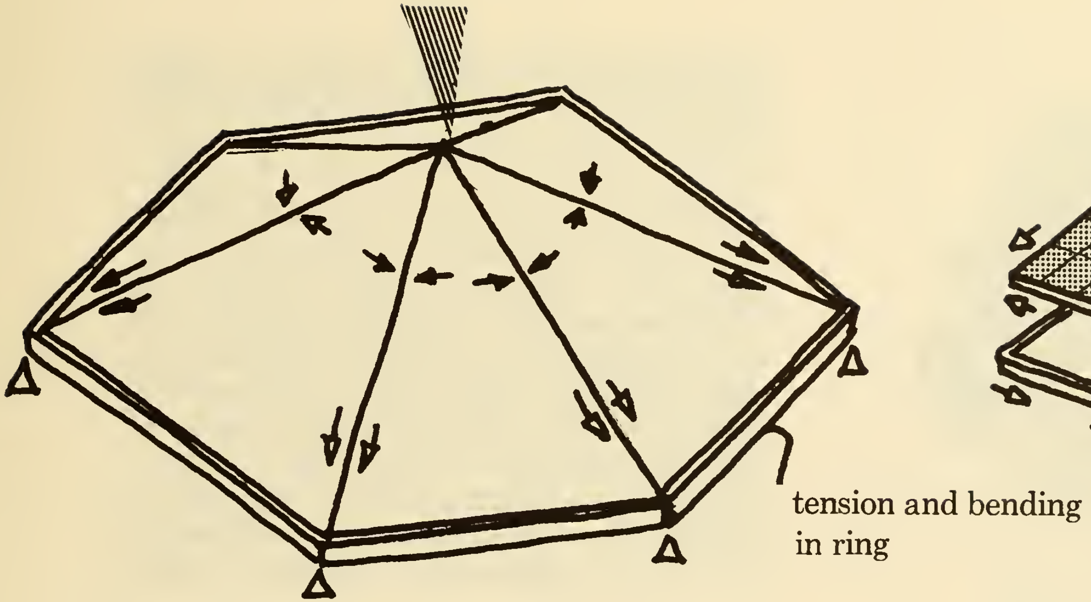


Figure 12 — Stressed Skin Surface

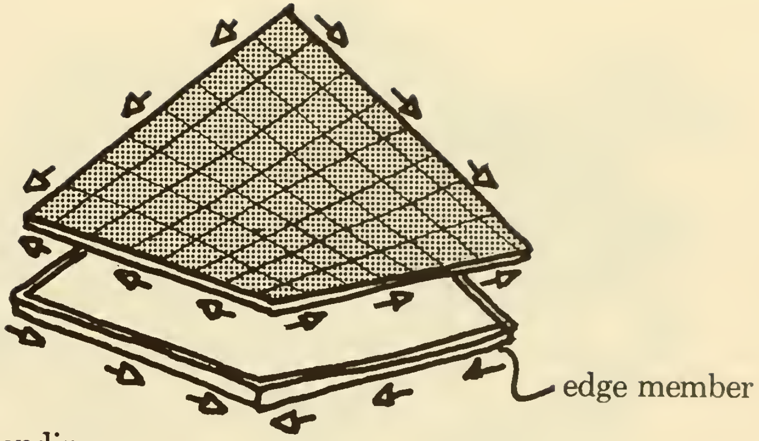


Figure 13 — Hyperbolic Paraboloid

and supporting reactions. Supports for hyperbolic paraboloid shells subject to vertical load must provide a vertical reaction. With some arrangements of hyperbolic paraboloid shells, a horizontal reaction is required *(see figure 14)*. Other arrangements provide for mutual cancellation of the horizontal reaction under symmetrical vertical loading *(see figure 15)*.

Even a slight yielding of the supports will cause local bending in this kind of shell. For this reason and also because some compressive buckling resistance is required, sandwich design would again prove useful for a moderately long-span structure of this type.

Stress analysis of this type of shell is discussed in references 6, 7, 8, 9 and 10. Stability analysis is discussed in references 12 and 29.

Another type of translational shell susceptible of stress analysis is an eliptical paraboloid *(see figure 16)*. This structure is formed by moving one parabola along another parabola at right angles to the first. Again, edge members are required in order to have only direct stresses in the shell. In this form, as in the hyperbolic paraboloid, edge members need provide only longitudinal shear reactions when the loads are vertical. Hence, edge beams are parabolic arches subject to axial load and bending. Deflection of the

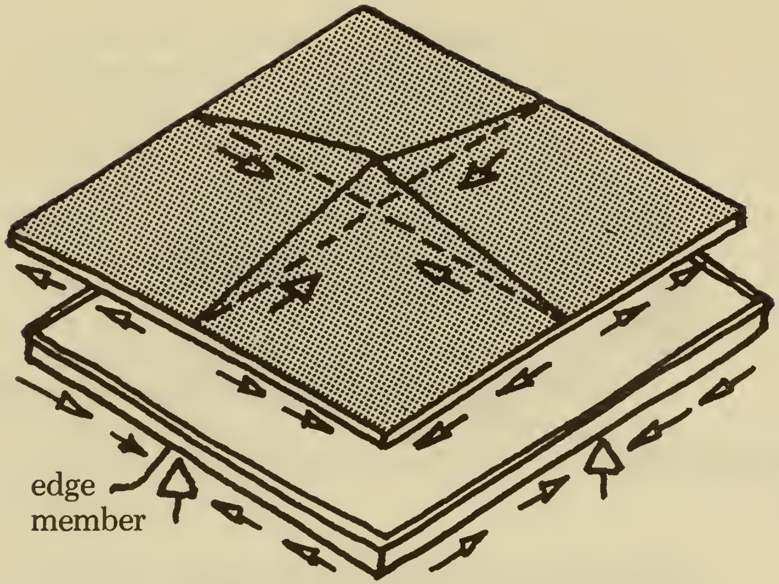


Figure 14 — Four adjacent hyperbolic paraboloids. External support at midpoint edges.

edge members causes local moments in the shell, and use of structural sandwich construction, because of its ability to take bending stresses, would appear desirable. For stress analysis of this type of structure see reference 6.

These and many other types of doubly curved shells have already been built in reinforced concrete. Such structures have often been designed by approximate methods. Some of these methods are discussed in references 11, 12 and 13.

CYLINDRICAL SHELLS AND OTHER CORRUGATED BEAMS OVER LONG SPANS

The structural efficiency of three-dimensional geometrical structures may also be attained with cylindrical shells spanning between transverse supports *(see figure 17)*. Over a single span, such structures act in a way similar to a deep beam, since longitudinal direct tensile stresses are developed on the lower portion of the shell and longitudinal direct compressive stresses in the upper portion. These longitudinal stresses provide an internal couple at any transverse section

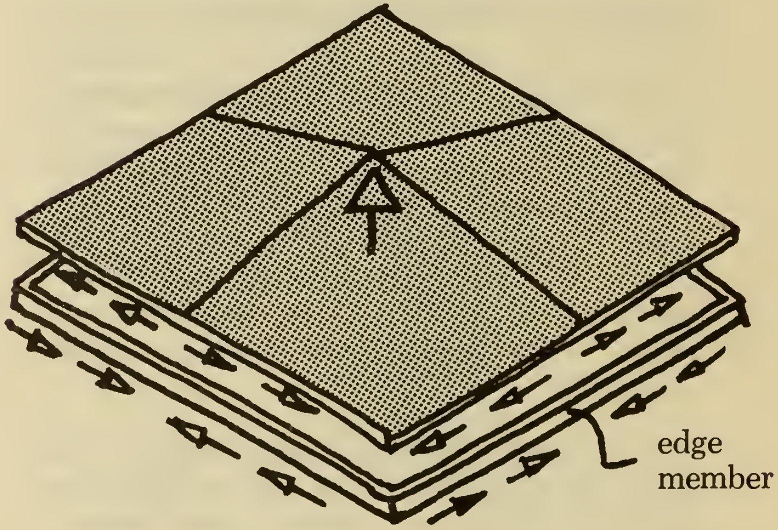


Figure 15 — Four adjacent hyperbolic Paraboloids with central support

similar to that developed in an ordinary beam. In general, transverse direct stresses, longitudinal and transverse shear stresses, and small transverse bending moments are also developed in a long cylindrical barrel shell.

Structures of this type, utilizing relatively thin sandwich panels to provide the necessary bending and buckling resistance, would be efficient for relatively long-span roof construction. Reactions required for this type of structure could be transverse supports in the form of transverse beams, trusses, or sandwich-panel bearing walls.

Stress analysis for cylindrical shell design is greatly facilitated by the use of reference 14. References 15 through 22 also treat this subject.

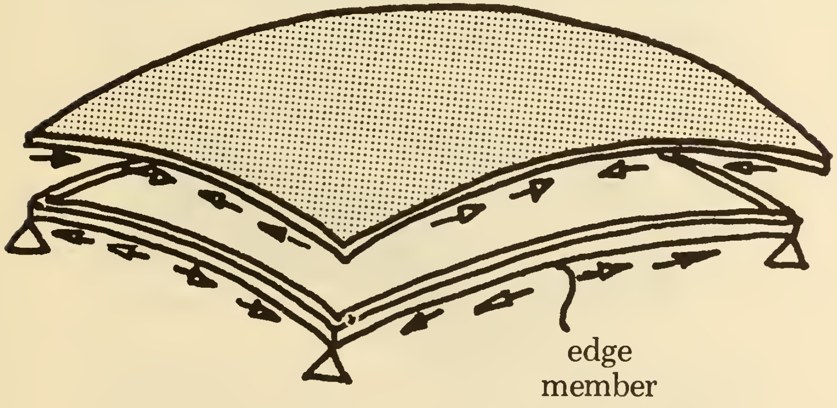


Figure 16 — Elliptical Paraboloid

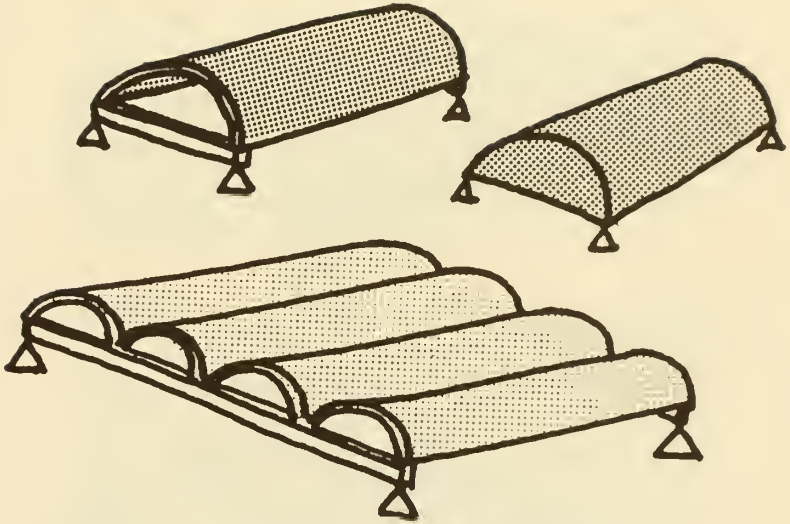


Figure 17 — Cylindrical Shell Roof — single or multiple

Folded plate construction is a variation of the long cylindrical barrel shell arrangement discussed above. It utilizes flat surfaces to approximate the cylindrical shell geometry. A large depth for efficient spanning of space between transverse supports is thereby provided *(see figure 18)*. The structural action of this form under vertical load can be analyzed by breaking up the loads into components normal and components parallel to the plane of the panels. The normal components are resisted by slab action, or bending across the short dimension of the panels. This bending action causes reactions on the

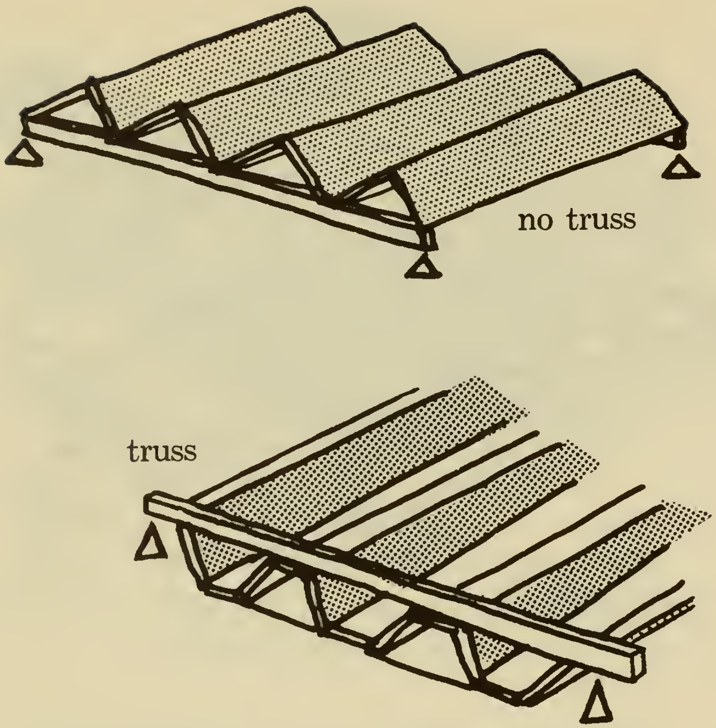


Figure 18 — Folded Plate Roof

adjacent panels. The components parallel to the plane of the panel as well as the reactions to the aforementioned slab action are carried by plate action, or bending in plane of the panels. If the folds in the structure are not too far apart, the moment due to slab action will not be large. If relative inclination of plates is steep enough and plate depth is large enough, the stresses due to plate action will be relatively small.

Structural sandwich panels seem ideally suited to forms of this kind, as they naturally provide resistance to stress in two directions and can have ample strength for both slab action and plate action. In designing such a panel, the thickness of the facing material can first be selected to provide necessary resistance through plate action. A core thickness can then be selected to make this facing material provide necessary resistance through slab action.

Details of stress analysis of folded plate structures are discussed in references 23 through 28.

A variation of the folded plate form involves using inclined end supports to form a pyramidal surface. This arrangement leads to the development of horizontal tension along the perimeter of the base *(see figure 19)*. Stress analysis is discussed in reference 26.

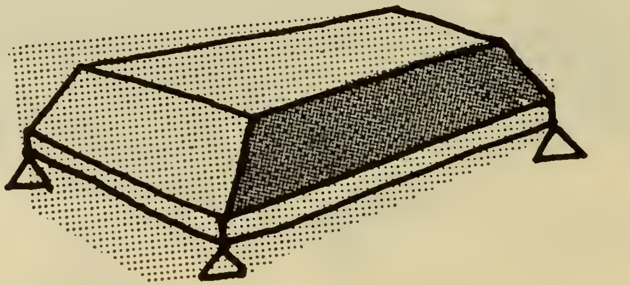


Figure 19 — Prismatic Roof Structure With Sloped Ends

It is well to note that for all the structural types discussed above, use of sandwich construction would require the development of a continuous curved or flat joint, whenever the spans were so great that the structure could not be made in one piece. The majority of structures would, of course, fall into this category. In fact, it should be emphasized that such factors as properties of core and facing materials, method of fabrication, extent of prefabrication, degree of standardization of parts, sizes of units, methods of joining in shop and field, and methods of field erection will all have a great influence upon the feasibility of sandwich design for shell construction. These factors are discussed elsewhere in this report.

STRUCTURAL BEHAVIOR OF SANDWICH SECTIONS

In order to present a clear picture of the structural efficiency of sandwich design, it is pertinent to discuss the structural behavior of a section taken through a typical sandwich structure. The internal moment, shear, and axial forces acting on such a section would be determined from the structural analyses discussed above.

Essentially, such a sandwich section acts as a composite member of two or more materials having different strength-stiffness properties. The usual sandwich design employs relatively thin facings of strong, dense, stiff, expensive material bonded to relatively weak, light, less stiff, less expensive material. As noted above, however, the over-all economic picture is greatly influenced by factors other than cost of materials, such as fabrication expense or joint requirements.

Facings provide almost the entire flexural resistance to bending action. The core must only be strong enough to carry shear stress associated with bending action and to provide restraint to local buckling of the skins. Thus, the usual sandwich construction acts in a manner similar to the well-known I-beam. I-beam flanges correspond to sandwich facings; the web corresponds to the sandwich core. If the elastic properties of the component materials are known or assumed, the section may easily be analyzed by the conventional elastic beam theory, using the well-known "transformed area" method.

Using the "transformed area" method, analysis of many sandwich-type sections having core material of much lower stiffness than facing material can be greatly simplified by assuming the modulus of elasticity for bending of the core as zero. This means that the facings are assumed to carry all flexural stress and direct axial stress, and the core is assumed to carry none. Under this assumption, the core cannot be overstressed in flexural tension or compression. When the facings are relatively thin compared to the core, shear stress can be assumed constant between center lines of each facing. This means that core plus one-half each facing carries all the shear stress. Bond between facing and core must be adequate to transmit the maximum shear stress on the section.

Strength and stiffness criteria for use with sandwich design are similar to those used with typical steel, wood or reinforced concrete structures. Design must consider bending stress, direct axial stress, shear stress due to bending, shear stress due to racking, deflection due to both bending and shear, overall buckling of members in compression, and local buckling of compression elements. Allowable stresses are established, based on the strength properties of the component parts.

Design of sandwich-type sections is often accomplished using a cut-and-try procedure. That is, based on knowledge of available materials and previous experience with sandwich economics and design, a trial section is selected for detailed analysis of the strength and stiffness criteria discussed above. However, if certain limitations are imposed and design approximations accepted, and if unit costs for facing and core materials are established, then economic relative proportions for face and core thickness in a sandwich construction can be easily established, to obtain the optimum design for strength or stiffness properties.

For example, if proportioning of a certain sandwich element is controlled by bending strength, and if a symmetrical section of thin, stiff faces (relative to core) is used, the economic relative proportions for face and core thickness will be attained by making the square-foot cost of both facings together equal to the square-foot cost of core in the final sandwich section, the section being designed to have just the required section modulus. However, the more usual situation with sandwich construction is for the stiffness deflection of the sandwich element to be the controlling design criterion. Applying the same limitations as above to this case, the economic relative proportions for face and core will be attained if the square-foot cost of both facings is made equal to one-half the square foot cost of core in the final sandwich section, the section being designed to have just the required moment of inertia.

When determining required moment of inertia for a given sandwich structure, the importance of deflection due to shear delow-density core materials than in conventional steel I-beam construction.

In sandwich structures which carry mainly axial compression, resistance to buckling is determined by the stiffness of the sandwich, again with a slight modification for shear deformation of the core. Therefore, once the required moment of inertia is determined, the same rule for economic proportioning of the sandwich as given for sandwich constructions controlled by deflection would apply.

Of course, due consideration must be given to use of minimum thicknesses for face material, based on requirements for local stability and practical fabrication.

When considering the use of the plastic and plastic laminate materials for sandwich skins, it must be noted that the relatively low modulus of elasticity of these materials, rather than their strength properties, frequently determines the sandwich design. In many instances the very considerable tensile and compressive strength of the so-called high-strength laminates of plastic and glass fibers cannot be effectively utilized in a particular design because of their relatively low stiffness (in the order of 1/10 to 1/30 the stiffness of steel). Nonreinforced plastic materials have even lower stiffness properties, and design with these materials always involves careful consideration of buckling and deflection characteristics. Also, for the various reinforced plastic laminates, an increase in stiffness is obtained only by increasing the cost of the material. Hence, structural design of sandwich panels utilizing plastic materials requires very careful cost analyses of available plastic materials.

Creep characteristics of both core and skin materials may also be important considerations affecting the structural design of plastic sandwich panels. In evaluating creep characteristics, knowledge of working temperature and stress levels is necessary.

References 31 through 35 discuss methods useful for the design of sandwich constructions.

CONCLUSIONS

In conclusion, some consideration might be given to a general economic comparison of sandwich design with conventional structural systems which gather loads using short-span slab constructions carried by deeper supporting members — for example, wood sheathing over joists, concrete slab or metal deck between steel beams, and others.

The use of sandwich construction as a complete structural system generally implies a constant depth section over an entire area. Facings are usually very thin, stiff, expensive material and must be continuously supported by the core. If flat construction is required and the spans are long, bending moments will be high and the required depth of the sandwich will be quite large. Large depth for a continuous element means a large volume of material and implies a high cost, even when much of the depth is made up of relatively low unit cost core material.

On the other hand, use of intermittent deep framing members permits concentration of high-strength material in a few very deep members having thin webs; hence, high structural efficiency is achieved with a smaller amount of expensive material in the flanges. Consequently, there does not appear to be a future for use of flat sandwich construction over long spans. The greatest potential for flat panels would seem to be for relatively short span slabs between supporting members. For long-span roof structures, the greatest potential for sandwich use would seem to be with the three-dimensional structural forms.

Thus, for structures in which requirements for bending resistance are not large and in which surface coverage plus moderate bending resistance are the prime requisites, or with the singly and doubly curved long-span surfaces discussed above, sandwich construction may well prove to be a practical and important method of bringing more effective methods into building construction.

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MATERIALS TECHNOLOGY

Today it is a formidable task for the average architect to make an understanding choice of plastic materials. In designing with the conventional materials, he draws on knowledge developed in school and through experience to help him make the proper selection for a given set of requirements. Ordinarily he will have a good sense of how the well-known building materials should be shaped and joined to give their best performance.

The range of properties of the relatively new structural plastics can in some ways be almost as broad as those of the whole gamut of familiar materials — from stone, concrete, and glass, to wood, ferrous, and nonferrous metals. To further complicate matters, the uninitiated architect finds that many of these different plastics are very similar in look and feel. This makes it even more difficult to learn how performance will vary with the formulation.

Before architects can make more widespread use of these plastics, there must be an intensive educational campaign to make available much more information on how the various plastic materials behave. Only in this way will an architect be able to make a discriminating choice among manufactured plastic products. A close relationship between the designer and the plastics engineer is also important, for working hand in hand with a specialist is the most promising approach for the designer who wants to use plastics to develop his own construction details.

Many of the advantages of plastics as a building material exist for the most part as potentialities and can be purchased today only as premium-priced specialties. But a broader knowledge of the capabilities of plastic materials will pave the way for greater demand. This alone can prompt the developments which will bring forth new plastic materials capable of performing economically in a wide variety of structural uses.

Plastics are used in sandwiches in the facings, in the cores, as adhesives, or in combination with other materials. Indeed, the latter is one of the most widespread uses of plastics in sandwiches, because the combination often has desirable properties not attainable in any of the constituents.

This chapter will review briefly the general characteristics of the plastics now used in sandwich panel construction as measured against the basic design requirements for the three elements of the sandwich: skins, core, and adhesive. Several new materials now in the development stage are also mentioned. These new materials, which promise even better performance than the materials currently used, are indicative of the intense research activity presently aimed at finding plastics that can meet all of the designer's most stringent requirements.

SKIN MATERIALS

The outer layers of a sandwich panel must be of dense material capable of doing a major portion of the structural work. These skins should also be able to give a great deal of stiffness to a panel while adding minimum weight. Other desirable characteristics for sandwich panel skins are resistance to weathering, denting, and puncture. They should have dimensional stability and low thermal conductivity, and they should adhere easily and adapt well to the manufacturing process.

For most applications it is preferable to have sandwich skins which are not highly inflammable. A wide variety of colors, textures, sizes, and shapes should be possible. And finally, a skin material must have potential economy.

Relatively few plastics are used in the unmodified state as facings for structural sandwiches. Even though the facing material may be considered to be a plastic, it is usually reinforced with some other material such as sheet stock or fiber. The principal types of plastics employed as facings in commercially produced sandwiches will be briefly described.

ACRYLIC

This is a thermoplastic material, notable for its crystal-like clarity. Like most plastics, it is warm to the touch. It is a hard, stiff material, somewhat brittle but shatter-resistant. It can be made in a variety of brilliant colors, from clear to opaque. Usually it is seen with a highly polished surface which scratches easily; however, it may be textured to minimize the effect of scratching. Decorative effects may be obtained by adding fillers. Textured fabrics, rice paper, and natural leaves are among the materials that have been used successfully as decorative fillers.

Acrylic plastics stand up well when exposed to the weather, though the clear plastic may show slight yellowing after prolonged exposure to sunlight. The material is highly impermeable to moisture and is dimensionally stable. It has a slow burning rate. The heat-distortion temperature can be as high as 200°F. It is about one-third as stiff as structural lumber, with a modulus of elasticity of 450,000 psi. However, it is comparable in bending strength to wood, having compressive yield stresses as high as 19,000 psi and ultimate tensile strengths as high as 10,000 psi.

HIGH PRESSURE LAMINATES

High pressure laminates employed in building are almost entirely based upon a high strength paper, such as Kraft, impregnated with a phenol formaldehyde resin and pressed under high temperatures and pressures into a hard, dense, strong, homogeneous sheet. If just paper and phenolic resin are employed, the product is a relatively dark-brownish colored sheet, although other dark-colored pigments can be added to give a range of greens, blues, browns, and purples, in the darker hues. If decorative quality is desired, the phenol paper backing can be faced with a decorative sheet, such as printed paper or wood veneer, in turn impregnated and overlaid with melamine formaldehyde to provide the familiar high-pressure decorative laminate widely employed in building. These sheets can be bonded to a wide variety of core materials to provide a structural sandwich.

When exposed to the weather, phenolics show some surface degradation, color change, and loss of gloss. Paper based laminates have a tendency to absorb some moisture but are resistant to decay. They do not burn readily but will char and burn when exposed to fire. They can tolerate temperatures in the vicinity of 250°F for indefinite periods of time. Strength properties depend largely upon the type of paper filling and the ratio of filling to resin employed. Modulus of elasticity is approximately 1,800,000 psi lengthwise and about 1,300,000 psi crosswise. Tensile strength is about 20,000 psi in the lengthwise direction and about 16,000 psi in the cross direction. Flexural and compressive strengths run somewhat higher.

REINFORCED PLASTICS

This rapidly growing family of plastics-based materials consists of one or two types of resins — polyester or epoxy — combined with a wide variety of reinforcing materials. Unlike the high pressure laminates, which require high pressures and high temperatures and therefore call for heavy presses, the epoxies and polyesters do not demand elevated temperatures. Nor do they demand pressures beyond contact or vacuum pressure up to some 10 to 15 pounds per square inch; however, when higher pressures are employed, somewhat higher density materials result.

Polyesters. Of the two, the polyesters are by far the most extensively employed and have the longest history of use in the building fields. Three principal varieties of polyesters are found. The "straight" polyesters are by far the most commonly employed of these. They begin as liquids of viscosities varying from thin as water to thick as syrup, and they harden by the addition of catalysts and hardeners at room temperatures. Their rate of hardening is accelerated as the temperature is increased. They form the great majority of the various types of corrugated and flat sheet stocks widely used in the building field.

The straight polyesters will burn, although not rapidly under most conditions. If increased resistance to flame is required, the chlorinated polyesters can be employed. These are self-extinguishing but do not have as good weathering characteristics as the straight polyesters. Modifications of the straight polyesters which have superior weathering characteristics are appearing. For example, those in which acrylic resins are incorporated show promise of having considerably enhanced resistance to weathering, as compared to the straight or the chlorinated types of polyesters.

In order to obtain a good bond between the polyester resin and a reinforcing fiber such as glass, it is generally necessary to treat the glass with a finishing material which enhances the bond between polyester and fiber.

Epoxies. The epoxy resins, in contrast to the polyesters, form an inherently strong and tenacious bond to glass fibers and, in general, to all of the reinforcing materials employed with plastics. The epoxies, in fact, are among the strongest of the adhesives materials employed in sandwich manufacture. They are more expensive than the polyesters and are somewhat trickier to handle, but they provide strong reinforced plastics materials and are of growing importance in the field.

Reinforcing. The reinforcing materials most commonly employed in the reinforced plastics are based upon glass fiber in the form of mats of randomly distributed chopped glass filaments or in the form of woven fabrics in a wide variety of weights and weaves. For a general purpose, low-cost reinforced plastic, the mat materials are employed. When maximum strength and stiffness are required, the woven fabrics are used, or layers of fibers are laid down parallel to each other in a unidirectional format, with individual layers oriented in arbitrary directions with respect to each other. Especially when unidirectional filaments are employed, strengths well in excess of those obtained with many high strength steels are available; on a strength-to-weight ratio, these materials rank high in the entire category of materials.

The random fibers used in mats may well penetrate through the surface of a reinforced plastics sheet, particularly when polyesters are employed. The protruding fibers act as wicks to draw moisture into the interior, and it has been demonstrated that they hasten the degradation of such sheet stock upon exposure to weather. To overcome this, various very fine cover sheets, either of mat or of woven filaments, may be employed. The cover sheets prevent the protrusion of filaments to the surface. By preventing the wicking action which otherwise would occur, the cover sheets greatly increase resistance to weather and erosion. Cover sheets may be glass fiber, or they may be some one of the synthetic fibers, such as dacron.

Although the glass fibers have, to date, been by far the most important of the reinforcing materials, other fibers, both natural and synthetic, may be and are employed to some extent. Among the natural fibers are jute, hemp, sisal, and cotton; and among the synthetics are nylon, dacron, and the like.

Depending upon the ratio of mat or fabric to resin, the light transmission characteristics of a well-made reinforced plastic sheet may be high, and in some instances range as high as 70 to 75 per cent of the incident sunlight. For many purposes this may be too great, and consequently fillers of various types are employed to reduce the light transmission. Fillers may also be employed to increase resistance to weathering. Color may be imparted in the form of dyes or pigments; but, as is generally true, dyes are less permanent than pigments, and for maximum permanence the most durable pigments should be employed.

Strength properties of the reinforced plastics cover a wide range. Mat reinforced polyesters with low mat content may range in the vicinity of 8000 to 10,000 pounds per square inch tensile strength, whereas the unidirectional materials with maximum packing of fiber in a polyester or epoxy base may easily run 150,000 to 200,000 pounds per square inch. Modulus of elasticity may vary from about 1,000,000 psi to 4,000,000, and in some instances above 5,000,000 psi. Resistance to impact, in general, is superior; and a severe blow, although it may cause some bruising of the surface, seldom causes actual breakage. Resistance to moisture is good; with most of the building type reinforced polyesters, temperatures up to 250°F can be tolerated more or less indefinitely.

On another front, the development of flake glass as a reinforcing material may markedly increase resistance to combustion. Made in much the same way as glass fibers, the glass flakes are only a few microns thick and run through a wide spectrum of sizes, from the size of a pinhead to a silver dollar. When they are used as a reinforcing material, the ratio of glass to the polyester resin binder can be raised from the former maximum of 50 per cent to as high as 85 or 90 per cent by weight. With the volume of combustible resin thus reduced and the resin confined between the glass flakes, this form of laminate should effectively inhibit combustion and flame spread.

At the present stage of development, the strength characteristics of the glass flake laminates fall below those with fiber reinforcement. However, there is hope that greater strength can eventually be achieved. The formability and adaptability to manufacture for this new material are both good. Since these new combinations of materials are able to utilize smaller amounts of the improved types of polyester and flakes of colored glass, they hold great promise for sandwich panel skins of notable beauty and economy, in addition to greater durability and fire resistance.

Although the reinforced plastics can be and are employed by themselves as facings in structural sandwiches, they are frequently combined with a backup sheet such as plywood, metal, hardboard, or cement-asbestos board for economy. The reinforced plastics are relatively expensive, and consequently are employed as a thin sheet for strength and for surface appearance, as well as for resistance to erosion and impact; the backup material is employed to provide resistance to indentation and to increase the stiffness of the over-all facing.

POLYVINYL CHLORIDE

Polyvinyl chloride is available both as soft, plasticized material or as relatively hard, rigid, unplasticized sheet stock. Although the latter has fairly good rigidity and strength properties for sandwiches, it is usually applied over a backing of another material. In this instance, the polyvinyl chloride is essentially a tough decorative coating over the more rigid backup sheet. As is true of the reinforced plastics, this allows a thinner layer of the relatively expensive resin to be employed and reduces the over-all cost. Polyvinyl chloride — particularly in the unplasticized, rigid form — has had a good history of outdoor exposure, although this history is more extensive in Europe than it is in the United States. Good color retentions have been reported for polyvinyl chloride formulations; but, in general, it would be expected that loss of gloss would occur and fading might also occur, depending upon the pigments employed.

CORES

While structural sandwich skins resist essentially all the direct bending or edgewise compressive loads, the core must be strong and stiff enough to support the skin laterally against buckling, especially under a compressive stress, and the core must be strong enough in shear to withstand the shear stresses. The bond between core and skins must be strong enough to resist shear and lateral tension caused by the tendency of the skins to buckle under stress.

When a panel is used for the outside wall of a building, the core may also serve as thermal insulation. Ideally, a core material should be light in weight, inert, incombustible, unaffected by moisture, and a vapor barrier as well. In addition, it should be relatively stiff, crush resistant, easily formed and handled, and, of course, be potentially economical. There are two basic forms of plastic core material — the expanded, or honeycomb type, and the rigid cellular or foam type.

RIGID CELLULAR PLASTIC FOAMS

Many plastic foams can meet the strength requirements for structural sandwich panels at moderate densities, for example: cellulose acetate, epoxy, phenolic, polyethylene, polystyrene, polyvinyl chloride, silicone, urea formaldehyde, and the urethanes. The density required depends on the loads; but even at the two-pound-per-cubic-foot density found in typical low density foams, the mechanical properties are good enough for many structural sandwich panels. Today, the most active contenders for widespread use are polystyrene and the urethanes, with the phenolics showing some good potentialities. Other materials may come strongly into the picture when present limitations of cost, high densities, susceptibility to moisture, or other impediments are overcome.

Foamed cores of sandwiches may either be prefoamed or foamed-in-place. When prefoamed, slabs of the foam are usually simply bonded to the facing by means of adhesives which must not have a softening or solvent effect on the core.

Foaming-in-place may employ a variety of techniques, which can be classified roughly as open or closed panel. In the open panel technique, for example, one facing of the sandwich is placed in the bottom of a fixture and the liquid foaming material is poured directly over that face. The other face is then quickly dropped into place over the foam, and the fixture is closed to hold the faces rigidly in position against the outward pressure of the foaming material until the reaction is complete. In the closed panel system, facings are preassembled in the form of a hollow box, which is placed in a fixture, again having sufficient rigidity to prevent bulging of the facings during the foaming operation. The foaming mixture is then poured into a metering hole and allowed to foam up and to fill the panel completely.

Polystyrene. Polystyrene foam has, at the present time, the longest and most widespread history of use in buildings. It is most widely used in the form of prefoamed logs cut into slabs, boards, or simple tailored shapes, such as curved sections. More recently, polystyrene beads incorporating a volatile constituent have appeared. When heated, they become soft, and are expanded by the volatile constituent into beads of low density. These have been developed for foaming in place, and are particularly good where complex shapes are to be made. They have the advantage of little or no waste; they require an enclosure made to the desired finished shape and a source of heat, usually steam, which can be incorporated into the enclosure together with the polystyrene beads.

Polystyrene foam has adequate structural strength for most building applications and good resistance to water. Its relatively low heat-distortion point limits high-temperature applications, but for most building uses the heat distortion point is high enough to be adequate. Unmodified polystyrene burns, but self-extinguishing varieties are now available.

A promising recent development is the combination of expandable polystyrene beads with epoxy resin. When these are mixed, the epoxy gives off heat as it cures, thereby causing the beads to expand at the same time that the epoxy bonds them firmly together; the result is a stronger and more rigid bond than is possible with the beads alone. If the expansion takes place against a surfacing material, such as the skin of a sandwich, the epoxy at the same time bonds to the skin. An outside source of heat is unnecessary.

Urethane. In the urethane foams, a reaction occurs between the two constituents mixed in liquid form, giving off carbon dioxide gas which causes the resulting polyurethane to swell as it cures into its final form. The resulting foam may be flexible or it may be the hard, rigid form which is useful for building components. All of the ingredients may be mixed in either a "one-shot" procedure or as a "pre-mix" combination. The one-shot procedure is probably best used in the shop, where there are better mixing equipment or controls available than in the field, where the pre-mix approach is more suitable. In either event, the reaction is fast and requires that the final mixing be done thoroughly and quickly so that the mixture can be deposited rapidly, before foaming has substantially advanced. Foaming is usually completed within a few minutes, although the final strength and hardness of the foam may not be achieved for hours or days at ordinary temperatures. Usually the foam is rigid enough after a few minutes to be free of tackiness and able to support at least its own weight.

The urethane foams, because of the wide variety of possible reactants, are quite versatile and can be given all degrees of rigidity. They can be given good structural strength, and their heat distortion points are well above the temperatures usually encountered in building. Low thermal conductivity can be achieved, as is true of all of the foams. Large volume sections may be molded in relatively simple molds. However, they do require suitable (even though simple) mixing equipment and proper precautions in the use of the isocyanates, which themselves are toxic, although the finished foam products are not.

Phenolics. The phenolics, like the urethanes, can either be prefoamed or foamed-in-place. Recent developments indicate that the phenolics could be made to rise in relatively high, narrow spaces, such as those found between the studs in house frame construction. Foaming is accomplished by the incorporation of chemical blowing agents, which cause gas formation as a consequence of the reaction of the phenol formaldehyde as it cures. They may be beaten into the resin in addition to the curing agents, to provide seeding nuclei for the expansion process.

Of the three types of rigid cellular core material, the phenolics are favored from the standpoint of cost; but when made in the densities most useful for building, they tend to be brittle and relatively weak. Polystyrene is intermediate in cost between phenolic and urethane for a given density. In the two-pound-per-cubic-foot density, generally suggested for building applications, the costs for all three are not out of line with the cost of conventional materials—realizing that other advantages can be obtained with the plastics.

HONEYCOMB CORES

When kraft paper is impregnated with phenol formaldehyde resin and is bonded together with stripes of glue in a manner which allows the resulting material to be expanded in much the same way as paper Christmas bells, the type of sandwich core material known as honeycomb results. This method, borrowed from the aircraft industry, has become well established in the building field as a means of creating cores for a wide variety of structural sandwiches.

Depending upon the weight of paper, the ratio of resin to paper, and the cell size, a material with a wide range of weight and strength properties is obtained. When bonded between the facings of a structural sandwich, the honeycomb provides excellent lateral stability for the facings and prevents buckling under compressive loads which are either perpendicular to the facings or in the plane of the facings. The honeycomb also provides the necessary shear strength in a sandwich subjected to bending. If it is desirable to vent the core of the sandwich to the atmosphere, the individual cells of honeycomb can easily be pierced during fabrication, before the honeycomb is expanded into its final form. This allows for breathing and for equalization of the pressure inside the panel with changes in temperature if this proves to be desirable.

If the resin content is high enough, the resistance of the honeycomb to moisture is good. Raising the resin content too high, however, not only increases the cost but also tends to make the honeycomb brittle. An optimum resin content therefore is sought, to provide the necessary moisture resistance together with the desirable strength and toughness which the paper can provide.

The insulating value of honeycomb alone, although fair, is not outstanding. If maximum insulation is required, therefore, the cells of the honeycomb can be filled with an insulating material, such as one of the various loose granular materials. One of the various types of foaming plastics may also be incorporated into the cell structure.

ADHESIVES

Adhesives play a key role in the functioning of a structural sandwich because they provide the essential bond between core and facing which allows the sandwich to perform its structural function. The adhesive must be capable of withstanding the shear stresses which are developed between facings and core as well as the tensile stresses which tend to separate the facings from the core. This separation may occur particularly under edgewise loading — for instance, in the compression face of a sandwich subjected to bending, or in the faces of a sandwich, such as a wall panel, subjected to vertical load. The nature of adhesive bonding is still imperfectly understood; but it is evident that although some mechanical keying action of adhesives into the surfaces of porous materials may occur, in most instances a specific chemical bond of some type is developed.

The ideal adhesive must have high peel and shear strength with good resistance to impact. Equally important, it must be free of any tendency to creep and must be able to accommodate itself to the changing dimensions of core and facings with changes in temperature or moisture content. It must also, of course, be resistant to decay and any possible chemical attack, and it must be able to resist whatever temperatures are required in service. Adhesives should be stable, long lived, nonstaining, easily handled and applied, and have a sufficiently long pot life during fabrication to avoid excessive waste.

Adhesives may be classified on the basis of the mechanism by which they harden and develop their joint strength. There are air drying, fusible, pressure sensitive, and chemically reactive types. Some, the thermoplastic types, soften upon heating and harden upon cooling. Others, the thermosetting types, harden once either at room temperatures or at elevated temperatures; having hardened, they will not soften again. The latter are generally favored for structural purposes such as the manufacture of structural sandwiches, but some of the thermoplastic types are also widely employed, because their heat softening points are high enough to be above the service temperature. Selection of an adhesive type will evidently influence greatly the way a panel is to be fabricated.

Before the advent of plastic-based adhesives, many natural types derived from various animal proteins, casein, albumen, vegetable starches, asphalt, and pulping residues were, and are still, reasonably widely used. Generally, they have not been completely satisfactory for building products exposed to the weather, although the asphalts have shown themselves to be excellent adhesives for cement-asbestos board and similar materials.

There is a wide range of plastic-based adhesives available today, and the selection of the appropriate one for a given situation requires careful study.

Phenol Formaldehyde and Phenolic Derivatives

Phenol formaldehyde is the oldest of the adhesives and in many respects is still the standard by which all other adhesives are judged, from the standpoint of general usefulness and durability. With wood, for example, this thermosetting adhesive requires temperatures in the vicinity of 250 to 300°F and pressures in the vicinity of 200 pounds per square inch to effect a cure. When such temperatures and pressures are available, a hard, strong, and completely waterproof adhesive bond results. This type of adhesive is widely used in the manufacture of such materials as waterproof plywood and is excellent for bonding together organic materials such as wood and the various types of organic fiber board materials.

For bonding hard impervious materials — metal, glass, high pressure laminates, and similar materials — phenol formaldehyde by itself is too hard, brittle, and inextensible to accommodate itself to the changing dimensions occasioned by differences in temperature. For this purpose, phenol formaldehyde is formulated with a variety of other more elastomeric materials, such as natural rubber and other synthetic rubbers, as well as various vinyl-based materials, such as vinyl chloride and vinyl butyral. These provide a large proportion of the high-strength engineering adhesives employed in the manufacture of a wide variety of sandwiches which may or may not incorporate plastics as part of the facings or the cores. They are particularly effective in bonding metal to metal and in bonding other impervious materials.

Resorcinol formaldehyde has many of the attributes of phenol formaldehyde, with the advantage that it can be catalyzed and formulated to harden at room temperatures so that additional heat need not be applied. At room temperatures the curing cycle is slow, but strength sufficient to allow the panel to be handled is achieved overnight; full strength is achieved in about a week. Resorcinols are more expensive than the phenols, but they are widely used in place of the phenols when a source of heat is not available.

Urea Formaldehyde. Urea formaldehyde has many of the attributes of resorcinol, but its resistance to moisture is somewhat inferior; therefore it cannot be considered an outdoor, completely waterproof adhesive. However, its cost is less and it does not tend to stain, as do the dark colored resorcinol and phenol adhesives. For many applications it is satisfactory. It is the most widely used bonding agent in the manufacture of the various types of wood particle boards.

Epoxies. These relative newcomers to the adhesives field have advanced rapidly because of their remarkably high strength and their ability to bond tenaciously to a wide variety of porous and nonporous surfaces, including wood, fiber board, glass, metal, high pressure laminates, reinforced plastics, and others. They can be formulated in a wide variety of viscosities, from thin to thick. Like the resorcinol and urea adhesives, they require no elevated temperatures for a complete cure, although in all three adhesives the cure is accelerated at temperatures above room temperature. The epoxies are among the most versatile of the adhesives available today.

Elastomers. Various elastomers, most of them based upon natural or synthetic rubber or upon elastomeric plastics such as vinyl chloride and vinyl butyral, are available for bonding many materials together. They are particularly effective when materials to be bonded show markedly different coefficients of thermal expansion and therefore require an adhesive with considerable elasticity.

Transparent Adhesives. Occasionally it is necessary to bond transparent materials, in which case a transparent adhesive is required. The acrylics have found use in this type of application, as have the polyesters and other transparent plastics, such as the cellulosics, when dissolved in strong solvents. These are mostly special-purpose applications and have found some limited use in transparent sandwiches.

COMPOSITE SANDWICHES

Plastics are widely employed as ingredients in a variety of composite materials. Two that may be mentioned are plywood and the particle boards made of wood chips, shavings, and sawdust pressed together, generally with a urea binder. There is a rapidly growing variety of wood-based boards of this type. Plastics are widely employed as coatings on metal, hardboard, cement-asbestos board, and other materials where durable, colorful, and easily applied coatings are required.

Many composite sandwiches in which plastics play a key role are being used. For example, a wide variety of sandwiches use aluminum, porcelain enameled steel, stainless steel, or coated steel facings, on cores of plastic foam or impregnated honeycomb. Other sandwiches employ plywood, cement-asbestos board, hardboard, or concrete with foam or honeycomb cores. In other instances, the plastics are used only as adhesives to bond nonplastic materials, such as certain types of sandwiches, with porcelain enameled steel and asbestos-based honeycomb cores.

Examples — A few examples will illustrate several new types of composite sandwiches available today in which plastics are employed. They will also serve to point out some of the trends for the future.

1. *Reinforced plastic facings with aluminum grid core.* This sandwich was used for the roof of the United States Pavilion at the Brussels International Fair. The reinforced plastics facings consist of glass fiber mats with a cover sheet and polyester resin binder. The facings are bonded to an aluminum extrusion core with a synthetic rubber vinyl type adhesive. Different percentages of fillers

in the facings are employed to control light transmission. Colored inserts within the hollow grid core provide for uniform color throughout the panel or for accents of color, as desired.

2. *Reinforced plastics facings with foamed styrene core.* In this sandwich, the facings are bonded to the foamed styrene core by means of a variety of adhesives, depending upon the degree of light transmission required. Light weight panels result from this type of construction. If a thin reinforced plastics facing is employed alone, however, it is subject to damage by denting. This is overcome by incorporating a sheet of hard material — such as cement-asbestos board, plywood, or hardboard — behind the thin reinforced plastics facing; the entire combination is then bonded to the foamed styrene core. While the styrene core is usually of the prefoamed type, it is possible to foam the core in place by means of expansible styrene beads.

3. *Metal facing with foamed-in-place polyurethane core.* In this panel, the metal facings are first assembled in the form of a hollow box and placed in a jig to hold the cover sheets flat while the urethane is foaming in place. The foaming constituents are then poured into the panel and allowed to foam up; this procedure fills the space completely and effects a better bond directly with the facings, without requiring any intermediate adhesive. Another procedure is to lay down one face of the sandwich in an appropriate jig, pour in the foaming ingredients, drop in the other face, and close the jig against the pressure of the foaming urethane. In either case, the panel can be removed from the jig once foaming has been completed.

4. *Reinforced concrete faces, foamed styrene core.* Large panels of this type are most often employed in industrial buildings. The facings customarily consist of 1½ to 2 inch thick concrete enclosing a foamed styrene core. They may be precast to full wall height, and range in lengths from perhaps 10 to 20 feet.

Clearly, a vast number of different combinations of plastics and conventional materials in the form of skin, core, or adhesive may be developed into successful structural sandwich panels. Each combination may have characteristics which make it uniquely suitable for a specific set of building design requirements. The designer who wishes to take advantage of the exciting visual and functional capabilities of the plastic structural sandwich panel will have to devote careful and detailed study to the properties and capabilities of the varied plastic materials. Having done so, however, he will be rewarded by having at his disposal a remarkably versatile palette.

FABRICATION PROCESS

We have come to expect a pattern of increasing mechanization and productivity from our American industries. The examples of the automotive and appliance industries are often cited to illustrate the fact that mechanized industrial production can raise productivity and bring ever greater value for the consumer dollar. The high cost of building has been frequently explained by the fact that this is one industry which has not yet widely adopted mechanization and factory production techniques.

Early attempts to mechanize the production of single-family houses failed to bring about any significant reductions in the cost of the product. It was found that there are a number of conditions surrounding the production and marketing of houses which are quite different from the conditions that prevail in our successful mass-production industries. This situation applies as well to most other building types.

The industrially produced building is not yet radically different from the handmade products which it attempts to replace, nor is it markedly superior to them in performance. This was not true of the automobile, automatic washing machine, or television set. The consumer saw all three of these products through a costly development period because he desperately wanted them and could not get them from nonindustrial sources. But there has been no inclination to pay more for an industrially produced building when a handmade one of similar quality is available on the market.

Other industries can count on their products to wear out and to need replacement in a relatively short period of time. Buildings are tied to the land, which does not wear out; a building is seldom replaced because a better, newer model becomes available. This means that the principle of the trade-in, which allows old cars or refrigerators to be scrapped periodically, does not work in the building industry. Local differences in custom, in building and zoning ordinances, and in labor practices also hamper the potential efficiency of producing building in a mechanized central plant.

Because of these differences and the difficulty of altering established methods of distributing building products and financing construction, the great swing from site-crafted to industrially produced buildings has not yet taken place, though it has often been predicted.

But there can be no doubt that since the end of World War II there has been a slow, step-by-step increase in the number of prefinished, factory-made components which go into the average building. Windows, doors, heating or air conditioning units, and, most recently, curtain wall panels have come to the building site with the greatest part of the work already done on them in the plant. There is no reason to believe that this evolution toward factory-made building components will not continue until we have reached the logical goal of a building made entirely of components produced by our more efficient and productive modern manufacturing techniques.

This pattern of shifting more and more work from the site to the factory cannot fail to be accelerated as we find new and better building materials and assembly techniques to perform the familiar tasks of supporting loads, enclosing space, and controlling the internal environment of a building. Lacking the training to use these new materials and assembly techniques, the present labor force of site craftsmen will defer to the plant-based machine. This is what is happening to the bricklayer — once the backbone of any construction job — on many a curtain wall sheathed building. It takes years to accomplish all the social and economic adjustments that accompany such a change, but these changes seem, in the long run, to be inevitable.

As more capital is gradually invested in machinery for making building components, as a wider market develops for such components, and as their cost is reduced, much of the single-operation machinery which we know today will probably be made obsolete. When most of the parts of a building are made by machine, there will be obvious advantages in consolidating and combining in one production process parts and operations which are today handled by separate trades.

Automation of the manufacturing process can make it possible to join together in one production line and in one product the functions of structure, enclosure, and environmental control. The product of such consolidation could be a component that looks quite different from anything we now see in a building. Such basically different components will fit together to make whole buildings that look quite different from today's.

In order to predict what our future buildings will look like, we must know more about this new kind of unified component. Some of the questions about its nature can only be answered in time, as the technology which will produce it develops. However, we can examine the range of possibilities and their probable consequences for architectural design.

The products of a mechanized building industry may tend to become more standardized; or they may, with the further development of new techniques of automation, become more varied than at present. The nature of the finished unit may be simpler than the components we use today, if specialization of function is increased; or more complex, if a greater number of functions are performed by each unit. Industrialized components may be produced on order to fill a specific building need, or they may become stock items to be used universally for many kinds of buildings in all parts of the country. Basic to this entire range of choices is this one question: Will the component manufacturer shape his technology to the diverse needs that exist in our society, or will society shape its needs and expectations to the capabilities of our new building technology? No one can be sure at the present moment which influence will predominate, but we can expect that each will have to make constant adjustments to pressures from the other.

The design possibilities suggested in this report do not attempt to achieve the depth of refinement that will result from this likely process of gradual mutual accommodation of a society and its technology. They are based more on the simple assumption that it will be the nature of our new technology that will have the predominant influence on future architectural design.

DIMENSIONAL COORDINATION

In order that components made in a factory may eventually fit together and form a building on the site, they should have joints and dimensions that match. A coordinating dimension or module for all of the parts in a building is a necessary concept when we eliminate handwork, cutting, and fitting as part of the construction process.

There are three quite different bases that are used to establish a useful module for building: the design process, the manufacturing process, and the construction process. The design process calls for a module that is a convenient unit of space, multiples of which will suit reasonably well all the space needs of the building being designed. The construction process calls for a module that creates parts which are easily handled and installed. The manufacturer's module will tend to depend on the size of available raw materials and the capacities of the most efficient machinery.

Because these three uses for the module can often result in a conflicting basis for dimensional coordination, a smaller unit, small enough to be a common denominator for all needs, has come into use. Albert Farwell Bemis worked out the rationale for the cubical modular system and established the use of the four-inch module, which has been the basis for most of the subsequent work in this field*. In 1939 the practical application of the four-inch module was further developed by Committee A62 of the American Standards Association. However, this work had but little influence on building practice. Only a small portion of any building's materials came to the site in a form that was actually difficult to alter. In a building industry which was still based on hand assembly of small bits and pieces of material, the majority of our manufacturers were not prepared to change their standard sizes, established through the years, for the slight or perhaps even illusory advantages of modular sizes.

In Sweden, where the clarity and logic of the modular theory had enormous appeal, designers made a great effort to use it. They discovered, as did enthusiasts in many other countries, that the four-inch module was too large to allow a sensible flexibility in design in the smaller dimensions — as, for instance, in concrete floor slabs — and too small to give an economical range of stock sizes of larger dimensions, as with window or wallboard units. Most important of all to the Swedish was the discovery that the problem of tolerances in the joints between adjoining factory-made components was the one which caused the greatest practical difficulty.

Even if their building components were made in some multiple of the four-inch (ten centimeter) module, they could not be sure such parts would actually fit together. No large mass-produced building component

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*Bemis, Albert Farwell, *The Evolving House*, Volume 3 The Technology Press, Cambridge, Massachusetts, 1936.

can be economically manufactured to the exact size required every time. Allowances must be made to permit products a fraction of an inch larger or smaller than the dimension on the designer's plans.

Between 1949 and 1952 the Swedish Standards Association worked out a system for designing joints between components which would allow for normal variations in product sizes, depending on the nature of the materials and the fabrication process used. Since 1952 they have been establishing standard sizes for various building components. These are established by careful study of how components function in practice and of the sizes traditionally made by their manufacturers and only finally modified to fit into the nearest four-inch modular interval.

The problem of the inflexibility of the four-inch module was tackled by an American architect, Ezra Ehrenkrantz, at the British Building Research Station in 1954 and 1955. He developed a series of modular sizes based on doubling, tripling, and the additive Fibonacci series of numbers. The resulting Building Research Station number pattern lacks the immediate clarity of the four-inch module but is better related to the everyday problems faced in the dimensioning of a building. It provides a larger range of modular sizes in the smaller dimensions and a smaller range of easily combined modular sizes in the larger dimensions.

In the years since it was first proposed by Bemis, and all through the subsequent developments described here, the modular theory has had only a slight effect on the actual operations of the building industry, even though the concept has constantly provoked much interest and attention. This lack of application has resulted mainly from the fact that the modular theory goes hand in hand with a more fully industrialized way of building, which has only in the last few years begun to develop. The Modular Building Standards Association, formed in 1957, proposes to carry the concept further into practice through an intense promotion campaign.

In the first phase of the industrialization of building, the machinery which is presently available will probably be used to make components modelled after the familiar building parts evolved in the craft tradition. Looking beyond this to the next stage, in which more advanced types of automated machinery will probably make rather differently conceived integrated components, we can foresee need for the universal adoption of a more complex system of standards than the four-inch module.

With such things as structure, space-enclosing skin, fenestration, insulation, acoustical treatment, lighting, heating, air conditioning, and perhaps even sanitary systems all capable of being integrated by future manufacturing processes into a single component, the problem of making components fit together in the field will change. As long as a component of a factory-made building system has edges which can be easily joined to all the other components of that system, there will be only the slightest further gain if their over-all size is controlled by a set module.

In order to facilitate replacement of worn out or faulty components, there will still be some advantage to having certain standard sizes which can be kept in stock. However, these sizes can be determined precisely by such functional criteria as the width of a door, office, or storage unit; by manufacturing or handling requirements; or by the demands of good proportion. They need not necessarily be modified to meet the nearest four-inch modular dimension.

FABRICATION OF PLASTIC SANDWICH PANELS

Noncontinuous hand methods of fabrication are still used for most large and complex plastic units (for example, boat hulls) which are comparable to the integrated sandwich panel component suggested here. The manufacture of simple flat sandwiches does lend itself to machine production for part of the fabricating process. But no completely automatic production line for plastic panels has yet been set up, although it would be technically possible to do so.

Looking to the future and the possibility of a fully automated machine production of plastic sandwich panels, it seems that the plastic fabricating and finishing processes most likely to be used will be the automatic and continuous ones. Further developments in the continuous processing of plastics will most likely occur before the production of integrated plastic panels becomes a reality. Today the continuous processes commonly used are:

Calendering. A continuous sheet or film is formed by passing the raw plastic through banks of heated rollers.

Extrusion. Raw plastic (usually in the form of powder) is forced through a heating cylinder and a die which produces a continuous strip. The strip can be varied in form by changing the die.

Molding. There are a number of molding processes which involve the injection of heated plastic into a self-clearing mold and which can be continuous processes.

Post forming. Flat sheets or films of plastics can be formed into fairly complex shapes by the pressure of heated dies.

Vacuum forming. Heated thermoplastic sheets can be drawn into a female mold by means of a vacuum. This process is successful in forming rather large parts.

High pressure laminating. Alternate layers of binding plastics and reinforcing are subjected to heat and pressure in a hydraulic press. This method is in common use in making flat laminated sandwich panels today. At considerable expense, the surfaces of the press may be shaped to simple or compound curvatures. With present types of equipment, large volume production is needed to justify the setting up of such curved presses.

With new refinements in technique, it seems possible that some of the noncontinuous processes such as casting or low-pressure laminating (also known as bag molding) can be adapted to automatic continuous production. The casting of plastics is similar to the familiar metal-casting processes. Bag molding involves placing a stack of impregnated sheet material over a male or a female mold, surrounding it with a flexible enclosure which is drawn down by air pressure or vacuum, and pressing the sheet into close contact with the mold. This method may be used to make very large parts.

It is not easy to determine at present which fabrication process or combination of processes will prove most satisfactory in making the complex integrated sandwich panels of the future. But some of the advantages and limitations that all of the fabrication processes have in common will be a determining factor in the exact shape and appearance of panels made with plastics.

A basic difference in design made possible by the nature of plastic materials will be the elimination of many separately fabricated subassemblies having different functions. With plastics it is often possible to shape one large, homogeneous part into a form that will, if carefully designed, do the work of a whole group of smaller differentiated pieces made of less amenable materials.

Another design factor is the requirement of most high-speed plastic fabricating processes for intersections of planes or changes of contour that curve gently with generous radii in place of sharply defined angles. The wall thickness of parts should remain constant wherever possible. Where changes in thickness are essential, they should be drawn out gradually over a large area.

Parts must also be shaped so that they may be rapidly drawn away from their mold. To do this they should flare outward with an ample so-called draft angle. Reverse draft angles or undercuts slow down the fabricating process to an uneconomical pace.

Perhaps one of the most significant differences in design approach made possible by the use of plastics is the ease and economy with which very intricate detail may be incorporated in a part, once the proper molds and dies are set up. This is what makes it possible to imagine that such diverse functions as lighting, heating, ventilation, and sanitation may be incorporated in a plastic building component during its run through an automated production line. Not only the inner workings of the panel but also its outward appearance can benefit from simply achieved intricacy. Anyone who has enjoyed the delightful and meaningful articulation of detail on the body of a plastic model railroad engine might imagine the enrichment of fine sense of scale that may be possible when skillful design hands turn to the plastic sandwich panel building component.

HANDLING OPERATIONS

The size, shape, strength, and durability of manufactured building components must be determined with an eye to how they will be carried from the production line to their final position in the structure — that is, if the potential economies of manufacture are not to be wiped out by excessive handling costs. Storing building materials and transporting them to the site is now recognized as an area in which more careful planning is needed to keep costs down. Some prefabricated-house manufacturers find that roughly 3 per cent of the cost of their product goes to pay shipping bills. Not included in this figure is the cost of warehousing or handling the parts between the production line and the transporter and between the transporter and the building site. When a structure is not carefully designed to make maximum use of available handling facilities, this percentage can easily mount. Thus the designer of plastic structural sandwich panels must study carefully the most likely method of handling the product before he can make some basic decisions about the form of the unit.

If components are to be stocked in a warehouse at the fabricating plant, the capacity of the warehouse may influence decisions on the number of panel types to be included in a system, how strong and what shape they must be in order to stack to a given height, and how they can be grouped for ease in filling orders. The future holds some promise for automated warehouses which can be stocked and drawn upon with the help of an entirely mechanical, continuous belt type of system and electronic selecting circuits. This is likely to put additional demands on the designer to incorporate a coding system which the electronic device can "understand" and to use sizes and shapes which this automatic machinery can handle.

It should be possible to organize parts being shipped from the warehouse into loads that can be handled easily by fork-lift trucks or other devices used to place them in the carrier. The parts must be designed to withstand the impact loads produced by the typically rough handling they get at such times. Delicate edges or flanges which may help in installation are easily broken in handling.

Ideally, a plastic sandwich component should require no further packaging to protect it from damage in handling or from exposure to the weather in storage or in transit. It is a challenge to the designer to give the additional durability required to allow the panels to be handled without protective packaging. The long-term savings that could be achieved by the design of an easily handled, self-sufficient panel would undoubtedly justify extensive study.

Since cargo space which is paid for should not be wasted, the sizes of standard freight carriers — the railroad car and the trailer truck — impose definite limitations on the size and shape of what can be shipped. Not only the maximum size but also the basic dimensional module of a manufactured building component might be affected by the dimension of a truck or freight car. The carrier dimensions are, in turn, affected by the critical conditions along the network of roads or tracks.

At present, the largest load that can be placed on an open platform trailer truck is about thirty-five feet long, eight feet wide, and nine and one-half feet high. For a closed trailer truck, the dimensions are a few inches less. A railroad flat car will accommodate a load fifty feet six inches long, nine feet four inches wide (eleven feet if an overhang is allowed), and twelve feet high. In a closed box car, all dimensions are again shortened by several inches.

It is possible that in a few years our new coast-to-coast highway system may allow the use of larger trucks and that the railroads may also find ways of increasing their efficiency, with radical changes in equipment bringing greater payloads. The future also holds the possibility of an increased use of air transport for freight shipments. Substantially large cargo planes are already in use. The Lockheed Super Constellation, for example, has a capacity of 43,000 pounds and a cargo hold that is seventy-eight feet long, ten feet eight inches wide, and slightly more than seven feet high. Most observers seem to feel that we may expect even larger planes and rates more competitive with traditional carriers in the years ahead.

The helicopter may also have a role to play in the handling of sandwich components in the future. It would have the advantage of being able to do the work of a crane in installing components high up on tall buildings. The present capacity of the larger helicopters is about 1000 pounds. If a two-engine model which has the greater factor of safety necessary in congested areas is developed, it might prove the most efficient way of transporting the components from a plant on the outskirts of a city directly to their final place in a tall building in the city's center. Such an installation would have to wait for favorable wind and weather conditions, a familiar problem in the building industry.

A more down-to-earth future development might be a vehicle designed to pick up and carry components from the plant or warehouse, bring them to their place of installation on the building site and, with an integral small power crane, fit them into the structure. This could eliminate all intermediate transferring of the load from one type of carrier to another as well as a good portion of the man-handling usually required.

A prototype of this kind of versatile vehicle might exist in the hydraulic lift trucks which are now used for picking up and transferring stacks of lumber along the highway and which perform at a fairly good speed. As it would probably be economically unsound to make any new all-purpose vehicle for a specialized product, the design of components will more likely have to take the size and capacity of such vehicles into account.

Virtually any component system of building involves some parts of special size and shape. A great deal of time can be saved on the site if such special parts are packed together with the more standardized parts so that they are immediately at hand when their time for installation arrives. Pre-packaging groups of components in their order of use requires more careful planning and coordination of the steps of the building process than we ordinarily employ today. But large building components like plastic structural sandwich panels will lend themselves more easily to carefully timed handling than a great variety of small parts arriving from a whole array of suppliers at different times.

If structural components of compound curvature — such as some of those suggested in the chapter on Design — are to be used, the designer will have an added problem in finding ways to make them fit economically into our rectangular storage and transportation facilities. A system which is so shaped and dimensioned that the parts will nest together compactly would cut the costs of handling significantly. Space that must be left void around the outside of a nested stack of curved parts might be filled with packages containing special tools, fittings, or secondary parts.

One thing that seems clear from this discussion of the influence of the handling process on the design of a factory-made building component system is that the designer must search much farther and consider many conditions in addition to the ultimate appearance of a building in establishing the form of his product. This by no means implies that the mechanics of handling need determine the form of our future buildings, but rather that greater resourcefulness and imagination must be brought to bear on the design of components to arrive at a form which is at once practical and satisfying, yet also economical in its appreciation of the limitations imposed by a well-ordered method of handling.

ERECTION PROCESS

One segment of the total building process has managed lately to incorporate some of the advantages of industrialization without radically changing its own character or the character of the product. That progressive segment is the process of erecting a building on its site. During and after World War II, many new factors which helped advance the erection process were introduced. These included the use of power-operated tools, gang cutting of parts, jigs, the specialization of labor, and attention to careful scheduling.

As the labor cost factor has, in most trades, continued to rise in relation to the cost of materials, a great many builders have felt compelled to seek new devices to increase productivity. The use of power equipment, specialization, and scheduling for efficient use of work time were three well-known basic techniques that had long served our more advanced industries.

Although there has been resistance to the reorganization of the erection process on the part of some trades which have well-established methods of accomplishing their work, the industry as a whole is becoming more willing to accept a greater degree of industrialization. Largely because of this trend, the labor-to-materials-cost ratio did not rise rapidly enough to precipitate the significant changes that might otherwise have occurred in the organization of the building industry. One explanation for the industry's failure to make the widely predicted shift to prefabrication and its attendant changes in distribution and marketing was the success of the new techniques of field erection.

A wide-open field remains for the continued introduction of careful operation planning, specialization of labor, and mechanization of equipment by our building contractors. The larger general contractors, who have for the most part gone as far as anyone can today with the introduction of new erection techniques, are still faced with rising costs and are pressing for further gains in productivity.

It is just beginning to be apparent that there are definite limitations in applying new erection techniques to buildings designed with our conventional small-scale materials. Further benefits from industrialization of the erection process can result only from the use of new kinds of materials and the changed design techniques they imply.

In the currently growing use of curtain wall panels we can see the tendency toward larger components and a limited inventory of parts. We can also see that much attention is paid to detailing wall components for higher buildings so that they may be erected from the inside to eliminate costly staging. Small maneuverable vehicles are being designed to bring components quickly from the stockpile to their place of installation. Such motorized equipment may even be designed to take the major burden of lifting a part into place and thus make larger, heavier, and more complex components practicable.

We have progressed from poorly organized hand methods of erection to more carefully scheduled and mechanized ways of putting conventional building products in place. Today we appear to be on the threshold of an era in which the use of larger, factory-made components will increase along with more sophisticated kinds of mechanical aids to installation. The next step we are likely to take, once most of the potential productive efficiency has been wrung out of the use of simple large components, might be the elimination of any remaining conflict in timing the work of the separate building trades and subcontractors.

This conflict in timing — which commonly occurs between those concerned with the building structure itself and those installing equipment for heating, ventilating, electricity, plumbing, and the like — is known to be a major source of delay in the erection process. Separate unit mechanical cores — or alternatively, complex components with mechanical services integrated during their manufacture, such as suggested in the chapter on Environmental Controls — are concepts that will perhaps bring on the next step in the clarification of the erection process.

Unless there are great changes in transportation methods, the size of components is more likely to depend on the capacity of the vehicle which brings them to the site than on the capacity of mechanized erection equipment. As long as the joint between components remains the critical factor in the cost and functioning of the components, as is the case today, there will be a continued striving for the largest transportable size as a basic unit.

There is a possibility that sustained research on the problem of panel joints will turn up new tools and techniques that will allow simplification of joint details, speed up installation, and lessen the present severe demands for attentive and highly skilled workmanship to assure a successful joint seal. Work done on a joint system for stainless steel curtain walls at Princeton University approaches these goals with the use of a special tool which places the joining batten strip in such a way that the joint is kept constantly under stress. This lessens the possibility of the joint's working open due to normal thermal- or stress-induced movements in the building wall.

Any distinct improvement in the ease or cost of making joints will mean that components are more likely to be sized to provide the most conveniently stacked, handled, and installed unit, rather than the largest transportable unit.

When the panels of maximum size are used, they must be designed to withstand the local stresses that will be imposed on them by the erection machinery. In some cases these may become the critical stresses, surpassing those expected in service, and may therefore influence the required strength, shape, and appearance of the component.

A significant problem that must be solved before plastic sandwich panel components of compound curvature can be further developed is the simplification of the curved-moment resisting joint. Larger curved shapes with significant engineering advantages, such as those suggested in the chapter on Design, are practicable to construct with sandwich panels only when they may be broken down into smaller segments for fabrication, handling, and erection at the site. Today, the type of curved joint needed to bring the smaller segments into a homogeneous structure requires so much time and care that the structural advantages of the curving surfaces are greatly reduced.

The simplest way to make a joint that will resist bending — and thereby to make a shell of many parts act about the same as if it were one continuous structure — is to force adjacent components into tight contact with one another. However, this method does not allow for the tolerances needed in the erection process, where parts that are not precisely of the right size and shape must be used. The difficulty of obtaining precise parts at reasonable cost is discussed in the chapter on Fabrication Process.

The work done in preparing a site to receive a building represents another important part of the cost of a building. The improvements in the earth-handling equipment used to prepare foundations represent one of the most significant gains made by the building industry in the past ten years.

Thinking of the growing scarcity of easily managed and buildable land, some designers have conjectured that the use of more widely separated point foundations (instead of the type in continuous contact with the ground, commonly used today) can lead to greater efficiency in the building process. Load-carrying floor sandwich components that might be used with a system of point foundations will have to come down drastically in cost before they can compete with the conventional concrete slab on grade. When truly large-scale production runs of components become a practical reality, their cost may actually drop enough to permit their use in place of foundations wedded to the earth. If that should happen, the advantages of rapid, orderly, machine-aided installation that can be brought to the erection process by the use of sandwich components may carry over to site preparation work as well.

ENVIRONMENTAL CONTROLS

It was only in order to gain better control of his physical environment that man, like the beaver, became a builder of structures. Protection from enemies, which once formed an important part of this need to control the environment, is a motivation for building that has only recently disappeared. What remains, however, is an ever-growing desire to free people of the burden of adjusting constantly to the vagaries of the elements and to release more and more human energy for other tasks, productive or recreative.

It seems apparent from the accelerating amounts of time, energy, and money which our era is willing to spend on the mechanical and structural means of easing our struggle with nature, that it is a profitable effort. The returns in energy conserved must still be greater than the energy spent creating the devices we use to control the environment. And today we seem to be far from reaching the practical limits of our desire for command of our surroundings. We still have a great deal to gain by providing more comfort through controlling a building's temperature, humidity, air purity, sanitation, and seeing and hearing conditions.

If we examine building costs of fifty years ago, we find that a small fraction of the budget went for mechanical equipment used to modify the interior environment. The cost of the structural shell and the finish was virtually the whole cost of the building. Today the cost of environment controlling equipment has grown so that it is typically about half of the total cost of building, and it shows no sign of stopping there. Modern methods of building have made it possible to enclose space much more efficiently. The present high cost of building can largely be laid to the demand for more elaborate and effective ways of providing comfort for man's five senses.

Some of the ways of providing more comfort inside buildings, as for example the proper location and orientation of a building on its site, cost no more; they require only good planning and forethought. But for the most part, added comfort comes only as a result of adding such things as acoustical tile, insulation, and sun shades to the structure of a building and adding, in addition, more and more mechanical equipment to regulate temperature, humidity, air, light, and sanitation.

It is significant that these additions have been made slowly enough so that the major effect their accumulation has on building costs has only recently been fully realized. The economic facts have made necessary a re-evaluation of what a building actually is. It is no longer simply the enclosure of space. About half of its value is devoted to a complex group of systems devoted to filtering discomfort out of the natural environment.

In the same way that the cost of environmental control equipment has grown, almost imperceptibly, to a dominating position, the amount of new material and equipment that has to be accommodated by a building has also mounted. Building contractors now expect that their most difficult task will probably be to squeeze all of the environmental control devices in behind the scenes so that they will not intrude in the spaces and become a factor in the appearance of the building. To do this they must carefully and painstakingly intertwine a tangle of ducts, pipes, and wires in wall and floor spaces that formerly contained only the structure of the building. Even with the best engineering design, the installation of mechanical equipment usually requires a great deal of complex hand labor, constant intelligent engineering supervision, and inevitable compromises of effectiveness to meet the reality of the limited, awkward, and inconvenient space most often available for the installation.

Many engineers and architects, taking a step back from the day-to-day problems of installation to review the whole situation, have pointed out that we need a fresh approach to the relationship of building and equipment. In brief, their suggestions center about the idea that equipment must no longer be thought of as something to be added to the finished building. The building space and the equipment which controls the environment within this space are now of equal importance. The design procedure must give them equal weight from the start.

In addition, the equipment must somehow be integrated to eliminate the confusion which results from the present method of having each of the various components designed, manufactured, and installed independently of the others. The human organism which benefits from the workings of the equipment is a unified whole, despite its varied functions; so may the equipment itself become when the problem is reconsidered as a whole.

There seem to be two basic approaches to putting this new theory of integration of building space and control equipment into practice. The first, which involves the combination of all mechanical services into self-contained packages or unit cores, is already being pursued by a number of manufacturers. The package heating and air conditioning units that have appeared on the market are the first step in this direction.

The next step in this approach, which will probably involve the creation of more complete packages containing more than just one kind of service, will be more difficult to make. Interests vested in the design, manufacture, distribution, and installation of individual parts of the total mechanical plant will tend to stand in the way of a unit which could combine two systems — say the plumbing service and the heating and power supply — into one package.

However, pioneering efforts have already been made in working out the design of integrated packages which cut across the established jurisdictions. As early as the 1930's, R. Buckminster Fuller proposed a one-piece bathroom stamped out of metal. His work was the basis for the one-piece plastic washroom being used on some of our modern lightweight trains. The one-piece molded plastic bathroom installed in the Monsanto House of the Future is a further development of this concept. Another early suggestion of Fuller's was the complete unit core for a single family house. This factory-built unit, easily convertible to a small trailer for transportation to the site, was to contain all of the heating, air conditioning, and sanitation equipment necessary for a house.

A post-World War II attempt to produce a package based on the complete-service core concept was made by Ingersoll. The ease and speed with which builders in the postwar house-building rush could use the established channels of supply contrasted with the slowness and uncertainties connected with this newly developed product and worked against its success at that time.

A similar development, with a more realistic eye to the nature of the housing market, is being pursued at the present time by the General Electric Corporation. Their unit kitchen combines, under a single nine-foot-long counter top, the sink, garbage disposal unit, range, oven, dishwasher, clothes washer and dryer, appliance plug-in center, and even some storage space. Only one plumbing connection and one electrical connection is necessary for the whole group of appliances.

At the same time that a market is being developed for the G.E. unit, the standard line of kitchen equipment is being designed of components that fit together to look very much like a single unit. This will no doubt ease consumer acceptance of the shift to the unified package kitchen.

As the unit equipment core develops, integrates more functions, and becomes a purchasable reality, the planning of building spaces will naturally change to accommodate the new idea. The planning for the use of space may tend to revolve more around the location of such service cores than around traffic patterns, as it does today. More widespread use of electronic communications devices, such as television intercom circuits, may make this possible with no loss of convenience. Regular spacing and stacking of such unit service cores in large buildings will promote greater flexibility of use.

Few alterations of mechanical equipment would have to be made when the uses or arrangements of space were changed, provided that the units were regularly spaced and self-contained. Regular spacing of units might give us a building with more service capacity than it actually needs at the time it is built, which would ordinarily increase the costs. However, factory production of standardized units could easily drive the cost below the present costs for the specially fitted ducts, pipes, and wires that thread through today's less amply serviced buildings. The additional capacity would provide two valuable assets for the future of the building: flexibility and expansibility.

The second basic approach to the integration of a building and its equipment, although physically quite the opposite of the first concept discussed, is not really in competition with it. The idea that the environmental controls may become an integral part of industrially produced building panels awaits a considerable development of new scientific knowledge and advanced production techniques. It is likely to follow once we have achieved the unit service core.

Reports on two new laboratory discoveries bring the possibilities of the more distant future into focus. A method of heating and cooling directly with a single electrically powered panel, called thermoelectronic heating, is being pursued by the Radio Corporation of America. Based on the so-called Peltier effect — which involves the heating of a joint between two dissimilar metals when the current is run in one direction, and the cooling of the joint when the current is reversed — the system at present does not yet have anything like a practical efficiency. But with increased efficiency and lower-priced electric power, it may become a method of heating and cooling that will eliminate all pipes and ducts in favor of thin panels of dissimilar metals that can become a part of a building's walls or ceilings.

A similar development, in which thin layers of material take the place of a cumbersome system, is electroluminescent lighting. A plastic film containing phosphors can be made to glow when placed between two electrically conducting layers. Luminaires and lamps can thus be eliminated; and lighting, too, may become an integral part of space-enclosing wall and ceiling panels. If the electroluminescent panels with a gentle glow, which is what the Westinghouse laboratories have so far been able to produce, can be developed so that they are brighter and more efficient in their use of power, another important step in making environmental control devices part and parcel of the building envelope will be made.

As industry perfects the technique of producing large building components in the factory (see the chapter on Fabrication Process), it seems possible that such components may become even more complex and refined in their construction. Intricate details and operations impossible with hand labor can be made economically practical when a firm market is established for manufactured building components and enough capital is drawn into the industry to create high-capacity automated production lines. Among the intricacies and complexities of the future sandwich panels, we may find not only such refinements as foolproof built-in joints but also such things as lighting, heating, and water and power supply channels in their new forms built right into the panels at the plant.

By allowing the panel to perform more than the space-creating functions of structure and skin, by allowing it to become in itself the device which controls the interior environment by means of heating, cooling, insulating, lighting, filtering air and natural light, and controlling sanitation and sound, we will have achieved an integrated but versatile form of building, similar in principle to that most remarkable of organisms, the human being.

DISTRIBUTION, FINANCING, AND LEGAL CONTROLS

A new and unfamiliar problem that the building designer must face when he works with a product which will ultimately involve mass production is that of distribution and marketing. Even when the designer has solved all the technical and planning problems of a component system of construction, his buildings cannot become realities until they are placed within the physical and economic reach of consumers in every part of the country. Unless his design can fit easily into the intricate mechanisms of shipping, warehousing, sales, financing, and local controls, it has slim chance of going beyond the prototype stage.

Immediately after World War II, some manufacturers attempted to enter the booming housing market with prefabricated buildings that incorporated innovations in construction. Their experience indicates the key position of distribution in the total design picture. At least four systems which could have substantially raised the productivity and standards of the housing industry — the Dymaxion House of R. Buckminster Fuller, the Lustron House, Carl Koch and Associates' Acorn House, and Gropius and Wachsmann's General Panel System — all foundered. This was due in large part to the difficulties they encountered in establishing distribution channels, obtaining realistic financing, and breaking through the web of local or federal controls.

A prefabricated sandwich panel component system of building would be a new kind of product requiring a great deal in the way of professional consulting service. Ideally, it should have its own system of distribution and sales outlets. However, it is not likely to reach this goal in the immediate future. The staggering cost of setting up a system of wholesaling, retailing, and advertising, added to the cost of tooling up for a new product, is something that only an industrial giant could undertake. And so far, our large and diversified corporations, even in the face of considerable urging by well-informed people in building, have understandably shown little inclination to take the sizeable risk of being the first to attempt a revolutionary change in the industry.

A potential starting place for a new kind of sandwich product might be in a large-scale building scheme under government or private sponsorship. An enormous order for a giant project might well pay initial development costs. The high price of bringing a new product to the general public might then be more easily borne by a producer.

In all likelihood, the first factory-produced component systems of building will find their way into the marketplace through some of the well-established channels used today by conventional building products. As the building industry is noted for the considerable variety of means used by different producers to get their product to the market, the use of existing marketing procedures still offers a substantial range of choice for the introduction of a new product.

Some building product manufacturers maintain their own complete sales force, while others rely to varying degrees on their local distributors to establish sales contacts. Manufacturers may have their own center of distribution in each area, or they may work through subcontractors, builders' supply dealers, lumberyards, or others. Two or three producers may share the facilities of one distributing agent in a given locality, but the same combination of producers does not necessarily occur in other areas. Some products need the services of a middleman or jobber, while others do not. Many companies are flexible enough to be responsive to local conditions to the extent of having a number of quite different methods of distribution for their products.

For the designer, the important factor in all this complexity is the way in which it can impose limiting conditions on the product or system he is designing. Each of the combinations of sales, jobbing, and distributing agents will have different capacities for such determining factors in design as storage space or financing available for inventory. Each operates at a different level of the market and places heavy emphasis on the special interests of that level, be they in initial price, discounts, shipping charges, size of inventory, quality and kind of labor required, speed of delivery or adaptability to local custom, to name just a few. Each of the existing channels of distribution is differently equipped to provide auxiliary services and technical advice when and where it is needed.

One tendency in meeting such diverse conditions is to sacrifice any number of technical or design advantages that are inherent in a product, in order to reach a common denominator of acceptability that will permit a wide market. Another contrasting tendency has been to ignore complex demands of marketing to arrive at an excellent product design that has no ready market. When an innovation was proposed for the building industry in the past, the choice between these two alternatives seemed to depend largely on whether the businessman or the designer had the last word.

Certainly this divergence of interests with its imperfect results have benefited neither the industry nor the consumer. There is no doubt that the designer and the businessman have the same ultimate interest: making a better building product available to the consumer. Largely because of their traditionally contrasting training and background, the designer and the producer have not yet been able to coordinate their separate approaches.

However, a new atmosphere is gradually being created, encouraging the formation of teams of businessmen, engineers, and designers with common goals. These men can cooperate in finding answers for the highly complex problem of making a radically improved and inherently different product, such as the plastic structural sandwich component building system, fit into the somewhat conservative channels of distribution which now exist. To be successful, such teams should have at their disposal better information than we have at present about the exact nature of the marketplace and the restrictions that a well-established and smoothly functioning distribution system may impose on design.

Public and industrial acceptance of a new system of building could be speeded by a scheme of distributing through established outlets as, for example, the lumberyards. Once established, the fullest potentials of such a system could subsequently be realized by the creation of special local distributors who would be able to give more attention to special services. Ultimately, a successful component system may find the substantial financial backing necessary to establish a well-stocked, supermarket-like distribution outlet which is accessible to contractor and general public alike. A building may be assembled in scale model form by the customer, with competent professional advice. The components chosen could then be drawn from stock by automatic handling equipment and delivered to the building site when required.

A great deal of attention is being given to the confused and restrictive local regulations, organization of labor, and mortgage financing systems which strongly influence building procedure today. Before very long, the great waste of resources brought about by the many conflicting specification-type building regulations will become a prominent issue on the national scene. Pressure may be brought to bear on existing building regulations when consumers at last realize that such codes deprive them of value for their dollar and that health and safety may be protected just as well by less restrictive, uniform, performance-type codes. Their voice will be added to that of the producers of building products, who would like nothing better than to have the way opened for the transfer of more and more work from the field to the shop, where it may be done more effectively. Uniform codes are needed before this can happen.

The designer has an important stake in the kind of building law that comes out of the forthcoming upheaval. While performance codes will limit his innovation in design far less than the current specification codes, their wording will still have a significant influence on the look of tomorrow's building product. He will undoubtedly want to take an active part with building officials, manufacturers, and engineers in writing the new regulations and establishing the system of administration and inspection that will gradually emerge.

The use of plastics for primary structural members, as suggested in the chapter on Design, is not recognized by any of the major building codes at present. The use of the plastic structural sandwich panel's unique properties — such as high strength-to-weight ratio, formability, and integral finish — may be considerably delayed if those interested in increasing efficiency and productivity in the building industry do not press for the inclusion of fair performance standards for these new plastic structural materials in our building codes.

APPENDIX

ANNOTATED LIST OF CORRESPONDENTS

During the course of this study we made inquiries to 377 sources including manufacturers, testing organizations, architects and engineers who we felt might have had experience with laminated sandwich panels or the materials which can be used to make them. We received replies from 155 for a return of 41 per cent.

This great body of correspondence served a very useful purpose in revealing the current status of a new product in the building industry. As noted in the preface of this report, the great majority of manufacturers are in the development stage or in limited production of sandwich panels. A separate list of manufacturers who publish literature on their panels is included in Appendix B.

We present the names, addresses and interests of our correspondents primarily as a guide to others wishing to do further research on this relatively unexplored field.

Alsynite Company of America
4654 De Soto Street
San Diego 9, California
Corrugated glass fiber reinforced sheets for building trade.

Aluminum Company of America
New Kensington, Pennsylvania
Aluminum products.

American Collo Corporation
525 Oritan Avenue
Ridgefield, New Jersey
Chemicals and resins.

American Cynamid Company
30 Rockefeller Plaza
New York 20, New York
Chemicals and resins.

American Latex Products Corporation
3341 West El Segundo Boulevard
Hawthorne, California
Adhesives, foams, and resin formulations.

American Society for Testing Materials
1916 Race Street
Philadelphia 3, Pennsylvania
Testing and standard-setting organization.

Angier Adhesives Division
Interchemical Corporation
120 Potter Street
Cambridge 42, Massachusetts
Adhesives.

Antara Chemicals
85 Tockwotten Street
Providence 3, Rhode Island
Chemicals.

Architectural Forum
9 Rockefeller Plaza
New York 20, New York
Professional Publication.

Architectural Porcelain Constructors
2827 Union Street
Oakland 8, California
Porcelain enameled steel, laminated panels.

Armco Steel Corporation
5164 Curtis Street
Middletown, Ohio
Iron and steel mill products.

Armour Research Foundation
Illinois Institute of Technology
3422 South Dearborn Street
Chicago, Illinois
Research foundation.

Armstrong Cork Company
Lancaster, Pennsylvania
Adhesives and insulation.

Bakelite Company
River Road
Bound Brook, New Jersey
Chemicals, resins.

Balsa Ecuador Lumber Company
500 Fifth Avenue
New York 36, New York
Balsa wood products.

Barrett Division
Allied Chemical and Dye Corporation
P.O. Box 27, Station 1
Toledo 14, Ohio
Chemicals and resins.

Barrows Porcelain Enamel Corporation
Langdon Road and Penn R. R.
Cincinnati 13, Ohio
Porcelain enameled steel, building panels.

The William Bayley Company
1200 Warder Street
Springfield, Ohio
Windows and curtain walls.

Bestwall Gypsum Company
P.O. Box V
Paoli, Pennsylvania
Gypsum products for building.

The Bettinger Corporation
Gore Street
Waltham, Massachusetts
Porcelain enameled steel, building panels.

Carl H. Biggs Company, Inc.
2255 Barry Avenue
Los Angeles 64, California
Adhesives.

Bloomingdale Rubber Company
Aberdeen, Maryland
Adhesives.

Brown & Grist, Incorporated
25 Tyler Avenue
Warwick, Virginia
Windows and curtain wall systems, laminated panels.

The Brunswick-Balke-Collender Company
Marion, Virginia
Building panels, doors.

Cadet Chemical Corporation
Lockport-Olcott Road
Burt, New York
Chemicals.

Canadian Plastics
341 Church Street
Toronto 2, Canada
Canadian publication.

The Philip Carey Manufacturing Company
Lockland
Cincinnati 15, Ohio
"Thermoboard" laminated building panels.

Carson Construction Company
1236 Sixth Avenue
P.O. Box 1153
Helena, Montana
Building contractor.

The Carwin Company
North Haven, Connecticut
Chemicals.

Ceco Steel Products Corporation
5601 West 26th Street
Chicago 50, Illinois
Windows, curtain wall systems, and mechanically fastened panels.

Celanese Corporation of America
290 Ferry Street
Newark 5, New Jersey
Chemicals, resins.

The Celotex Corporation
2022 Lewis Tower Building
Philadelphia 2, Pennsylvania
"Cemesto" laminated building panels.

Chance Vought Aircraft
P.O. Box 5907
Dallas, Texas
Aircraft.

Cincinnati Development and Manufacturing Co.
5614 Wooster Pike
Cincinnati 27, Ohio

Clad-Rex Corporation
Fortieth and Ulster
Denver 7, Colorado
Plastic-metal laminates.

Coast Pro-Seal and Manufacturing Company
2235 Beverly Boulevard
Los Angeles 57, California
Caulking and sealant compounds for building construction.

Colton Chemical Company
1747 Chester Avenue
Cleveland 14, Ohio
Resin compounds and chemicals.

Committee of Stainless Steel Producers
American Iron and Steel Institute
150 East 42nd Street
New York 17, New York
Manufacturers' organization.

Concrete Products, Inc.
Brunswick, Georgia
Concrete and wood chip panels for building use.

Continental Can Company, Inc.
100 East 42nd Street
New York 17, New York
Plastic laminates, paper honeycomb, asbestos honeycomb.

Davidson Enamel Products, Inc.
Lima, Ohio
Porcelain enameled steel, veneer and mechanically fastened panels.

DeBell and Richardson, Inc.
Hazardville, Connecticut
Resin formulations.

Department of the Navy
Bureau of Aeronautics
Washington 25, D. C.
Research.

Douglas Aircraft Company, Inc.
Santa Monica, California
Aircraft, paper honeycomb, custom laminator.

Douglas Fir Plywood Association
1119 A Street
Tacoma 2, Washington
Manufacturers' association.

Dow Chemical Company
Midland, Michigan
Chemicals, resins, metals, etc.

Dow Corning Corporation
P.O. Box 592
Midland, Michigan
Chemicals, resins.

E. I. duPont de Nemours & Company, Inc.
Wilmington 98, Delaware
Chemicals and resins.

Durez Plastics Division
Hooker Electrochemical Company
North Tonawanda, New York
Chemicals and resins.

Dyfoam Corporation
New Castle, Pennsylvania
Styrene Foam.

F. Eggers Plywood and Veneer Company
Two Rivers, Wisconsin
Wood and plywood products.

The Englander Company, Inc.
227 North Warwick Avenue
Baltimore 23, Maryland
Sandwich panels for building.

Federal Adhesives Corporation
210-220 Wythe Avenue
Brooklyn 11, New York
Adhesives.

Fenestra Incorporated
2250 East Grand Boulevard
Detroit 11, Michigan
Curtain wall components including mechanically bonded panels.

Ferro Corporation
4150 East 56th Street
Cleveland, Ohio
Enameling frit and dyes, glass fiber.

Flush-Metal Partition Corporation
46-10 11th Street
Long Island City, New York
Metal partitions.

Michael Flynn Manufacturing Company
(Lupton brand)
700 East Godfrey Avenue
Philadelphia 24, Pennsylvania
Curtain wall components including mechanically fastened panels.

Forest Products Laboratory
North Walnut Street
Madison 5, Wisconsin
Government sponsored research organization which also contracts testing and research for private organizations.

Fostoria Manufacturing Company
Hissong Avenue
Fostoria, Ohio
Interior partitions.

General Aniline and Film Corporation
435 Hudson Street
New York 14, New York
Chemicals and resins.

General Bronze Corporation
Garden City, New York
Windows and curtain walls.

General Electric Company
Chemical and Metallurgical Division
1 Plastics Avenue
Pittsfield, Massachusetts
Chemicals and resins.

General Mills, Inc.
South Kensington Road
Kankakee, Illinois
Resins.

The Glidden Company
11001 Madison Avenue
Cleveland 2, Ohio
Chemicals, resins, paints.

B. F. Goodrich Chemical Company
3135 Euclid Avenue
Cleveland 15, Ohio
Chemicals and resins.

Great American Industries, Inc.
Rubatex Division
Bedford, Virginia
Synthetic rubber.

H & B Enterprise Corporation
P.O. Box 307
Trenton 8, New Jersey
Aluminum extrusions used in panel construction.

Harbor Plywood Corporation
Aberdeen, Washington
Resin treated paper-faced plywood.

Haskelite Manufacturing Corporation
Grand Rapids 2, Michigan
Laminated products for building construction.

Hexcel Products Inc.
951 61st Street
Oakland 8, California
Aluminum, glass fabric, and stainless steel honeycomb.

Higgins Industries, Inc.
Box 8169
New Orleans 22, Louisiana
Wood and plywood products.

Holiday Plastic, Inc.
1301 Fairfax Trafficway
Kansas City, Kansas
Plastics laminator.

Holoplast Ltd.
New Hythe near Maidstone
Kent, England
Laminated plastic building panels in Great Britain.

Honeycomb Company of America, Inc.
3 Burroughs Street
Bridgeport 8, Connecticut
Aluminum and glass fiber honeycomb, contract lamination.

Hope's Windows Inc.
Jamestown, New York
Windows, panels, and curtain wall components.

Ingram-Richardson Manufacturing Company
Beaver Falls, Pennsylvania
Porcelain enameled steel used in laminated or mechanically fastened building panels.

Inland Homes Corporation
501 South College Square
Piqua, Ohio
Prefabricated homes.

Insulrock Company
Division of the Flintkote Company
Linden, New Jersey
Insulating material.

Interchemical Corporation
1754 Dana Avenue
Cincinnati 7, Ohio
Chemicals and resins.

Isocyanate Products Inc.
P.O. Box 1681
Wilmington, Delaware
Resins.

Johns-Manville
Research Center
Manville, New Jersey
"Transitop" laminated building panels.

Kawneer Company
Niles, Michigan
Standard laminated panel for "Unit Wall" system.

Keyes Fibre Company
Waterville, Maine
Pulp moldings.

Kreidel Plastics Inc.
16 North Van Buren Avenue
Barberton, Ohio
Plastic extrusions.

Lockheed Aircraft Corporation
Burbank, California
Aircraft.

L-O-F Glass Fibers Company
1810 Madison Avenue
Toledo 1, Ohio
Roving and yarn for glass fiber cloth and woven roving.

David E. Long Corporation (DEL)
220 East 42nd Street
New York 17, New York
Sealants, caulking compounds, protective coatings.

Lunn Laminates Inc.
Huntington Station, New York
Laminator of reinforced plastics.

The Marblette Corporation
37-21 30th Street
Long Island City, New York
Resin formulations.

The Marietta Concrete Corporation
Marietta, Ohio
Concrete building panels.

Masonite Corporation
111 West Washington Street
Chicago 2, Illinois
Hardboard.

Metcalf and Eddy
1300 Statler Building
Boston, Massachusetts
Engineers.

Minnesota Mining and Manufacturing Company
900 Fauquier Avenue
Saint Paul 6, Minnesota
Adhesives, sealants, resin formulations, and preimpregnated laminates.

Mirawal Division
Birdsboro Steel Foundry & Machine Company
P.O. Box 928
Baltimore 3, Maryland
Porcelain enameled steel strip and sheet.

Mobay Chemical Company
St. Louis 4, Missouri
Polyurethane foam.

Modigliani Glass Fibers Inc.
55 West 42nd Street
New York 36, New York
Glass fibres.

Monostructure Inc.
Sarasota-Bradenton Airport
Sarasota, Florida
Sandwich panels and panel structures.

Narmco Resins and Coatings Company
600 Victoria Street
Costa Mesa, California
Adhesives, structural plastics, resins, coatings.

National Aniline Division
Allied Chemical and Dye Corporation
40 Rector Street
New York 6, New York
Chemicals and resins.

Vibrin Plastics Division
Naugatuck Chemical Company
Naugatuck, Connecticut
Chemicals, resins.

Nickey Brothers Inc.
2700 Summer Avenue
Memphis 12, Tennessee
Wood products, veneer, plywood.

North American Aviation Inc.
International Airport
Los Angeles 45, California
Aircraft.

Overly Manufacturing Company
Greensburg, Pennsylvania
Metal fabricator.

Owens-Corning Fiberglas Company
Newark, Ohio
Glass fiber products.

Panelfab Products Inc.
2000 Northeast 146th Street
North Miami, Florida
Sandwich panels.

Parkay Inc.
Louisville 9, Kentucky
Wood flooring.

Pease Woodwork Company Inc.
900 Forest Avenue
Hamilton, Ohio
Woodwork and prefabricated homes.

Pelron Corporation
7847 West 47th Street
Lyons, Illinois
Chemicals, resins.

Perlite Institute
45 West 45th Street
New York 36, New York
Light weight aggregate manufacturers' association.

Pittsburgh Corning Corporation
One Gateway Center
Pittsburgh 22, Pennsylvania
Glass, "Foamglas".

Pittsburgh Plate Glass Company
Paint Division
Colfax Street
Springdale, Pennsylvania
Paints and resins.

Polyplastex United Inc.
870 Springfield Road
Union, New Jersey
Decorative plastic sheet.

Porcelain Enamel Institute
1145 19th Street
Washington 6, D. C.
Manufacturers' association.

Prefabricated Home Manufacturers' Institute
908 20th Street N.W.
Washington 6, D. C.
Manufacturers' association.

Princeton University, School of Architecure
Princeton, New Jersey
Research.

Products Research Company
3126 Los Feliz Boulevard
Los Angeles 39, California
Sealant and caulking compounds.

Reflin Company
5730 Kearney Villa Road
San Diego 11, California
Reinforced laminates.

Reichold Chemicals Inc.
RCI Building
White Plains, New York
Chemicals, resins.

Resolite Corporation
Zelienople, Pennsylvania
Reinforced polyester structural sheets.

Reynolds Metals Company
Richmond, Virginia
Aluminum mill products, sandwich panels.

Rezolin Inc.
5736 West 96th Street
Los Angeles 45, California
Resins.

Richards-Wilcox Manufacturing Company
375 Centre Street
Boston 30, Massachusetts
Laminated doors.

Rigidized Metals Corporation
658 Ohio Street
Buffalo 3, New York
Patterned sheet metal.

Rippolite Plastic Products, Inc.
3910 Cohasset Street
Burbank, California
Reinforced plastic laminator.

H. H. Robertson Company
Farmers Bank Building
Pittsburgh 22, Pennsylvania
Polyester resins.

Roddis Plywood Corporation
Marshfield, Wisconsin
Wood products.

Rubber and Asbestos Corporation
225 Belleville Avenue
Bloomfield, New Jersey
Adhesives.

Eero Saarinen
West Long Lake Road
Bloomfield Hills, Michigan
Architect.

St. Regis Paper Company
Panelyte Division
Enterprise Avenue
Trenton, New Jersey
Laminates.

Schenectady Varnish Company, Inc.
P.O. Box 1046
Schenectady, New York
Varnishes and resins.

Seaporcel Metals Inc.
28-20 Borden Avenue
Long Island City, New York
Porcelain enameled steel for veneer, mechanically fastened and laminated building panels.

Shell Chemical Corporation
380 Madison Avenue
New York 17, New York
Chemicals, resins.

Skidmore, Owings & Merrill
100 West Monroe Street
Chicago 3, Illinois

and
575 Madison Avenue
New York, New York
Architects and engineers.

Southwest Research Institute
8500 Culebra Road
San Antonio 6, Texas
Testing and research.

Spee-D-Rect Corporation
1004 First Avenue
Asbury Park, New Jersey
Laminator.

Superior Window Company
5300 N. W. 37th Avenue
Miami, Florida
Sun shades, louvers.

Synco Resins, Inc.
Bethel, Connecticut
Resins.

Techfab, Inc.
10800 Hanna Street
Beltsville, Maryland
Concrete wall panels.

Tectum Division
Peoples Research and Manufacturing Co.
246 North High Street
Columbus, Ohio
Lightweight concrete panels.

Thiokol Chemical Corporation
Trenton 7, New Jersey
Synthetic rubber.

The Tremco Manufacturing Company
8701 Kinsman Road
Cleveland 4, Ohio
Sealants.

The Unifab Corporation
Suite 224
300 Mt. Lebanon Boulevard
Pittsburgh 34, Pennsylvania
Laminated sandwich panels.

Union Bag-Camp Paper Corporation
233 Broadway
New York 7, New York
Paper products, paper honeycomb.

United Merchants Industrial Fabrics
1412 Broadway
New York 18, New York
Fabrics and woven roving.

United States Gypsum Company
300 West Adams Street
Chicago 6, Illinois
Gypsum board.

United States Plywood Corporation
55 West 44th Street
New York 36, New York
Wood products, laminates.

United States Rubber Company
Mishawaka, Indiana
Chemicals, resins.

Universal Corporation
6710 Deuton Drive
Dallas 19, Texas
Mechanically bonded sandwich panels.

The Upson Company
Lockport, New York
Paper based building boards.

Vermont Marble Company
Proctor, Vermont
Marble.

Westinghouse Electric Corporation
Hampton, South Carolina
Industrial laminates.

Wilross Products Company
20 Fourth Avenue
Hawthorne, New Jersey
Adhesives, coatings.

Winner Manufacturing Company Inc.
Trenton 3, New Jersey
Custom laminator.

Wolverine Porcelain Enameling Company
3350 Scotten Avenue
Detroit 10, Michigan
Porcelain enameled steel for veneer, mechanically fastened, and laminated panels.

Zonolite Company
135 South LaSalle Street
Chicago 3, Illinois
Vermiculate aggregate.

LIST OF MANUFACTURERS' CATALOGS

List of manufacturers of laminated structural sandwich panels who made their catalogs available to the Project Staff. Where addresses are not given, they appear in the list of correspondents above. The letter "S" indicates that the catalog appears in Sweet's *Architectural File*, 1958 edition, under the index number cited.

Alliance Wall Division S 3c/Al
Alliance, Ohio

Artex Division S 17a/Art
Altex Aluminum Company
120 Industrial Road
Summerville, South Carolina

Atlas Enameling Company S 3c/At
2020 North Broadway
St. Louis 6, Missouri

The Bettinger Corporation S 3c/Be

Brown & Grist, Inc. S 3a/Br

Caloric Architectural Porcelain Division S 3c/Ca
Topton, Pennsylvania

The Philip Carey Manufacturing Company
S 8b/Ca

The Celotex Corporation S 10a/Ce

Emco Porcelain Enamel Company, Inc. S 3c/Em
Port Chester, New York

The Englander Company, Inc.

Michael Flynn Manufacturing Company
(Lupton Brand) S 3a/Fly

Haskelite Manufacturing Corporation S 3c/Ha

Holoplast Ltd.

Ingram-Richardson Manufacturing Company
S 3c/Ing

Johns-Manville S 8b/Jo

Kawneer Company S 3d/Ka

Kalwall Corporation S 3c/Ka
41 Union Street
Manchester, New Hampshire

Mirawall Division S 3c/Mi
Birdsboro Steel Foundry and Machine Company
Birdsboro, Pennsylvania

Panelfab Products, Inc. S 3c/Pa

Reynolds Metals Company

Seaporcel Metals, Inc. S 3c/Se

Stribuload, Inc.
1605 Ortonville Road
Ortonville, Michigan

Sunlight Metal Products Company S 3d/Su
2301 South Delaware Street
Denver, Colorado

Superior Window Company

Texlite, Inc. S 3d/Te
3305 Manor Way
Dallas, Texas

Winner Manufacturing Company, Inc.

Wolverine Porcelain Enameling Company
S 3c/Wo

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Aircraft Committee Munitions Board. *Sandwich Construction for Aircraft.* U. S. Government Printing Office, Bul. ANC-23, Washington, D. C., 1951. Physical and mechanical properties of many sandwich materials under various environmental conditions.

"Architects and Prefabrication." *Architectural Record*, Vol. 107 (May, 1950), 152-158. A report on the Acorn House, with pictures and details.

Building Research Institute. National Research Council, *Adhesives and Sealants in Building.* Publication 577, Washington, D. C., 1958. A detailed review of the use of adhesives and sealants, particularly as applied to laminated building panels.

— *Architectural Metal Curtain Wall Workshop-Conference; Reports of Five Workshops, October 15 and 16, 1956, Washington, D. C.* Charles R. Koehler, editor. Washington, D. C., 1956. Detail problems of curtain wall construction, reviewed by experienced workshop groups.

— *Metal Curtain Walls.* Publication 378, Washington, D. C., 1955. An extensive review of the design and engineering problems of curtain wall construction.

— *Plastics in Building.* Publication 337, Washington, D. C., 1955. A review of laminated panels incorporating plastics and discussion of their application to buildings.

— Plastics Study Group. *Report of the Meeting at the University of Michigan, November 14-15, 1955.* Washington, D. C., 1956. The use of plastics in the Monsanto House of the Future, in the Unistrut System, and for piping and vapor barrier.

— Plastics Study Group. *Report of a Meeting at the Massachusetts Institute of Technology, July 14-15, 1956.* Washington, D. C., 1956. Applications of plastics in building for insulation, for gasketing and sealing materials, and for weathering problems.

Curtain Walls of Stainless Steel. Princeton University, Princeton, N. J., 1955. A pioneering study on the practical and aesthetic problems of curtain wall construction; includes references to laminated sandwich panels.

Davidson, Robert L. and Fisher, Howard T. "The Wall of Thin Self-Framed Metal Panels." *Architectural Record*, Vol. 103 (February, 1948), 135-139. Details of one of the first sandwich panels for commercial buildings to be given a fire rating.

Development of a Spandrel Wall Construction System. U. S. Department of Commerce, Industrial Research and Development Division, Project No. 38, May, 1948. The development of an incombustible laminated wall panel, including test data.

Dietz, Albert G. H. *Engineering Laminates.* John Wiley & Sons, New York, 1949. A comprehensive survey of laminated constructions, with special emphasis to those used in building construction. Detailed presentation of design formulae and properties.

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