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9. ABSTRACT
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In 1962 the University of Michigan received a USAID grant to explore the potential of foam plastics for solving housing problems in developing nations. A feasibility study completed in 1962 (see PN-AAD-174) established the desirability of investigating the use of foam plastics as structural material. The project was conducted in two phases. The first phase involved experimentation to obtain information on a variety of foam plastics. Several structural systems were established as scale models before two structural concepts were selected for full-scale construction and testing. One concept involved application of spray polyurethane foam on a folding wood lattice armature. The other concept involved production of large structural components made of paper-laminated polyurethane foam board. During the second phase of the project, four prototype structures representing different techniques were built. One consisted of seven umbrella-shaped components made of sprayed polyurethane foam. A second was a two-story structure made of triangulated bents of folded paper-laminated polyurethane foam board. A third consisted of four square umbrella-shaped components made of flexible foam coated with reinforced polyester. The fourth was a room-sized unit in which polyurethane foam board served as the mandrel for filament-wound polyester. The research program also investigated requirements for production and marketing of chemicals and foam plastic products for structures and building components in underdeveloped countries. The major recommendation stemming from the project was

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hat AID collaborate with the U.S. plastics industry in sponsoring construction and evaluation of suitable prototype dwelling units in developing countries. Interim reports of the project activities during 1964 and 1965 are available as PN-ADD-177 through PN-AAD-182.

REVIEW OF WORK PERFORMED

Work on the development of four prototype structures and the related testing program is progressing according to schedule. The intent is to investigate a range of possibilities for using foam plastics, either as primary structural materials or for the resolution of structural problems in conjunction with other materials.

a. The folded plate system. The objective is to investigate the potentials of paper-skin polyurethane-foam board as a structural material. Window mullions and a plywood floor have been installed in the prototype two-story structure erected to demonstrate a system utilizing this material. Acrylic panels and synthetic gaskets for the enclosure of the upper floor have been ordered. The polyester resin-coated surface of the structure will remain exposed to the elements until the latter part of the spring, at which time the structure will receive a final surface treatment. Materials for this purpose are presently being investigated. At the same time, a study to determine some other possibilities of utilizing this material in building construction is nearing completion. The data is being correlated for presentation in a paper now in preparation (see Section 3).

b. The folding armature system. The objective in this case is to determine the parameters for utilizing spray polyurethane foam in shell construction. On the basis of experience obtained through the erection of a test structure at Wyandotte (see previous reports), of test data collected from subjecting samples of various spray-foam formulations to creep, and of research conducted on the shape of a shell to minimize bending stresses, a 32 foot square wooden armature was erected which is intended to serve as the form-giving device for a structure to be sprayed in the spring. At the same time, an identical armature was erected in half-scale (16 foot square) to serve as the form-giving device for experimental spray applications in order to obtain additional data prior to the full scale application. Data on the research to determine advantageous shell shapes is being correlated for presentation in a paper presently in preparation (see Section 3).

c. The rigidized flexible system. The objective in this case is to produce double-curved structures by forming flexible polyurethane foam and rigidizing it to the desired shape. After having completed a preliminary investigation of this system (see preceding quarterly report), a 12 foot square umbrella

shaped structural component was produced by impregnating and rigidizing the flexible foam with a moisture-curing urethane resin and by spraying the surfaces with glass fiber reinforced polyester resin. The system was demonstrated to Professor Charles Thomsen from the Architecture Department of Rice University. Professor Thomsen represented a group of faculty members and students involved in a community development project in Chile under a grant from the Ford Foundation. He requested that a demonstration of this system of construction be made to his group for possible future application in Chile. Rice agreed to reimburse our project for the time, travel, and materials required for this demonstration. Since it was to the advantage of the project to have a full scale test structure erected at an early date to parallel our laboratory research on this system, and since weather conditions in Texas permitted us to do so, it was agreed to erect the first experimental structure with this system at Rice. Mr. Haecker, from our project staff, demonstrated the system there and directed the production of a 12 x 12 foot umbrella structure. After his departure, Mr. Thomsen's group produced three additional identical structural components and erected a 4-umbrella pavilion in accordance with details obtained from our laboratory. The system and the process followed at Rice are illustrated in a series of photographs attached to this report as Appendix A. The structure will be inspected at various intervals to study its behavior. At the same time a testing program has been set up here involving similar components, prior to the erection of the final prototype structure. This data is to be correlated with that obtained from the demonstration at Rice.

d. The filament-winding system. The objective in this case is to investigate the feasibility of utilizing a continuous production system for the creation of finished, room-size elements. Foam plastics are to be used as the inner lining of the structure and at the same time as the surface of the mandrel around which the reinforced plastics skin is to be wound. Preliminary structural analysis indicates that acceptable deformation levels can be obtained for a rectangular tube, 11'-6" wide and 7'-6" high with a wall thickness of 2 inches, by spacing 2" x 2" reinforced plastic ribs at approximately 32 inches on center. Model studies are under way to determine an economic design for the mandrel. The latter will have a bearing on the economic feasibility of this system. It is expected that the question of feasibility will be resolved by the end of February.

2. The study on cellular plastics materials from the standpoint of their market potentials in emerging nations is also in progress. Subject matters for which data is being accumulated include: (a) the status of these materials in mature economies (this is to assist in formulating assumptions for developing countries with oil, natural gas, and coal resources), (b) problem areas inhibiting the use of plastics, (c) facts and figures regarding applications, and (d) process and production requirements from raw materials to final products. A portion of the material accumulated to date is attached to this report as a separate document. This material should not be viewed as a portion of the final report on this study. It is presented for the purposes of reporting progress, and represents data which is being accumulated to assist in the formulation of final assumptions and conclusions.

3. A paper on the structural potentials of foam plastics has been prepared for the Institutional and Commercial Building Conference, to be held in Detroit in March 1965. The paper includes a series of tables comparing foam plastics with other materials in various structural applications on the basis of properties and cost. A copy of this paper is attached as Appendix B.

   The project was invited to submit abstracts of proposed papers on current research to be presented at a conference on the use of plastics to be held in London in June 1965. The conference is co-sponsored by the British Plastics Institute, the Royal Institute of British Architects, the Society of Structural Engineers, and the Society of Civil Engineers. Abstracts of the two papers were submitted; one on the use of paper-skin foam board and the other on the application of minimum structure to foam plastics shell construction. Both were approved by the conference board, and are attached to this report as Appendix C. The two papers are presently in preparation.

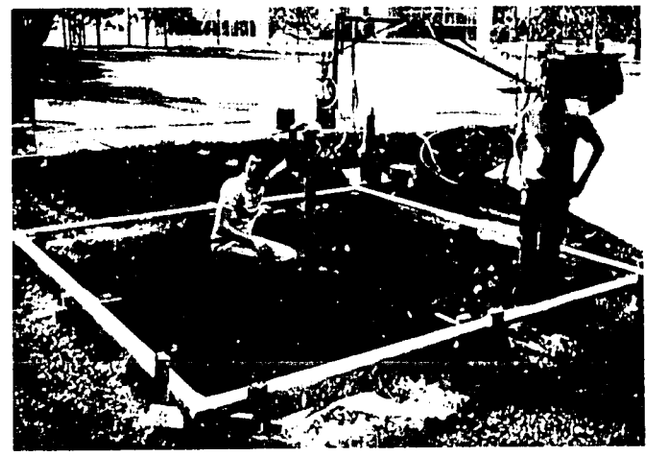
   The Society of the Plastics Industry requested that a conference on the use of plastics in building be held in Ann Arbor under the auspices of our Department of Architecture and in cooperation with the American Institute of Architects. The objective is to bring the architect and chemist together in order to determine the orientation of future research to better serve the building industry. Meetings were held in Ann Arbor and it was agreed to set the conference for September 22-24, 1965. A committee was elected, consisting of Hugh Gallagher (SPI), Bruce Smith (AIA) and Theodore Larson (U of M) to organize the program and review the papers. One of the sessions devoted to new directions will encompass the research conducted under the AID grant.

Appendix A

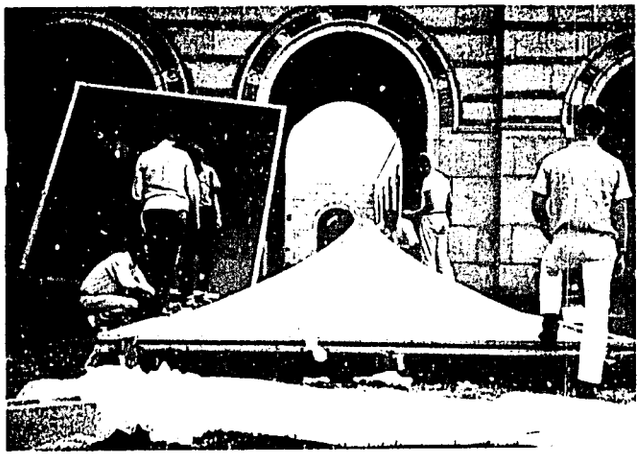
ERECTION OF A RIGIDIZED FLEXIBLE FOAM STRUCTURE

ERECTION OF A RIGIDIZED FLEXIBLE FOAM STRUCTURE

Adhesion of flexible foam sheets to obtain a 12' x 12' size.

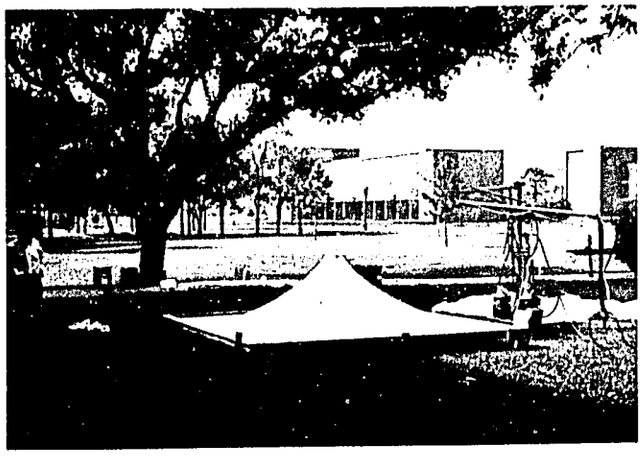


Erection of a template for the stretching of the foam to an umbrella-shaped component.

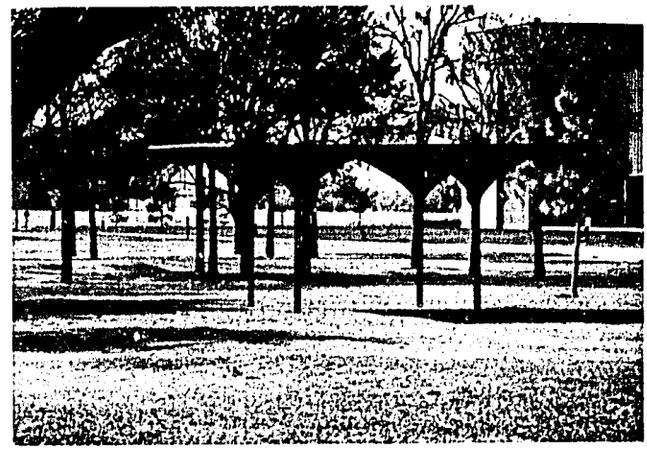


Stretching of a urethane resin impregnated 12' x 12' flexible foam sheet on the template.

The rigidized flexible foam is sprayed on both sides with glass fibers and polyester resin.



The sprayed components are allowed to cure.



Four such components are erected on top of tubular columns to form a 24' x 24' structure.

Industrial, Institutional, and Commercial Building Conference
Detroit, Michigan
March 8-11, 1965

Session 2. The Growing Use of Plastics in Buildings

ADVANCES IN STRUCTURAL USES OF PLASTICS

by

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Text of a paper delivered at the First Industrial, Institutional, and Commercial Building Conference, held at Cobo Hall, Detroit, Michigan, March 8 - 11, 1965. Contents are copyrighted. Permission is hereby given to daily, weekly, bi-weekly, and monthly publications to publish the text provided appropriate credit is given to the speaker and the Conference.

ABSTRACT

General criteria for the selection of a structural material are reviewed, noting specifically positive and negative features of the structural characteristics of plastics. Foam and reinforced plastics are compared to steel, concrete, and wood as beam slabs, arch slabs, and shells. Conclusions from the comparative study point to the use of plastics in the forms of arches or shell structures or in situations where stresses can be kept to a minimum and large deflections resulting from creep accepted. Examples of research conducted at The University of Michigan sponsored by the Agency for International Development of the U. S. Department of State, are cited in support of the design principals developed in the study of comparative structures.

ADVANCES OF STRUCTURAL USE OF PLASTICS

ıe concept of the structural use of plastics in buildings can be practically all inclusive. Plastic materials in common supply such as cellular insulating boards, skylights, translucent wall panels and sandwich panels, depending on the specific use, do perform certain structural functions. As an example, polystyrene foam board is used as core material between skins of plywood and gypsum wall board for supporting walls of certain mobile homes. Further, rigid polyurethane foams are used with metal skins as roof sandwich panels. The monolithic nature of the sandwich panel is such that all parts perform a structural function and the total performance is related to the mechanical properties of each of the specific parts. The emphasis in this paper will not be on these uses but on what may be described as the primary structure of a building.

The primary structure of a building is that sum of minimum parts or element which is necessary for the over-all stability of a building. Many millions have seen and walked through the Monsanto House of the Future at Disneyland, California. Reinforced plastics together with rigid plastic foams are used as the basic structure of this building. An inverted umbrella system of doubly curved shells formed the primary structure for the Plastics Pavilion in the 1959 American Exhibition, Moscow. More recently, a demountable school research structure was erected on the M.I.T. campus, Cambridge, Massachusetts. This consists of Hypar umbrella shells in which sandwich panels consisting of reinforced polyester skins and a rigid polyurethane foam core formed the basic shell surface. Although these examples demonstrate uses of plastics as primary structural elements they are all essentially experimental in nature. To date, one cannot report on any substantial major building applications in the commercial market. Many reasons may be cited for the lack of progress in this area. The plastics industry, although one of the major industries in our economy, is essentially a young industry. Specific applications in buildings do not have a long history of use to substantiate their application in permanent building situations. As an example, the application of fifteen-year use criteria in a recent housing development for the military, eliminated any significant use of plastics. Further, any new material is usually considered as a substitute and as such is evaluated on the basis of the past performance of the material it replaces. Applications based on the performance requirements of buildings and specific potential of plastics would seem to be indicated.

Criteria for the Selection of Structural Material

Materials used as structural components satisfy to a certain degree the following criteria: (1) Adaptability to varied architectural needs; (2) Ease of processing and construction; (3) Limited time related deformation in relation to specific loads and forces; (4) Maintenance of desirable mechanical and physical properties under adverse conditions of weathering and unwanted fire; and (5) Minimum over-all costs.

Plastics are the most adaptable of all materials and present research and development point to efficient production and construction methods. Translucent skylights; filament wound pressure vessels and rigid foam domes indicate the range of possibilities. Broadly considered, plastics as an organic material may be limited in architectural application where a combustible material will give satisfactory performance. As such, it could be compared to wood. However, the flexibility of formulating basic plastic materials and varied techniques of processing do indicate a potential for structural forms capitalizing on the unique mechanical properties and minimizing the effect of the less desirable features. The positive features are: (1) high strength per weight ratio of glass reinforced plastics, (2) minimum weight of rigid structural foams, and (3) ease of producing a monolithic surface. Problem areas are those of the relatively low service temperature and high creep under sustained stress.

Comparison of Structural Materials

All structural materials subject to sustained stress under normal service conditions do exhibit some creep. However, as is shown in Plate A of the Appendix, unreinforced plastics are subject to more creep than any of the other materials noted. The factors for and the nature of creep can be explained by assuming that a series of weights are supported by rods of the several materials. If the weights were such that each of the materials would stretch one inch upon loading, after a period of twenty years one would find varying lengths. The wood would have stretched to 2.3 inches and the rigid plastic foam to 7.5 inches. Negating or at least minimizing this effect is a necessary prerequisite for successful major structural application of plastics.

An examination of the comparative costs of the materials noted in Plates B and C indicates that the use of rigid foam or reinforced plastics in bending as a slab beam is unfeasible. One may, of course, observe the same fact in relation to steel. Steel is used in more efficient structural forms as wide flange shapes or light metal decking. The sandwich panel noted in

Plate D is an attempt to do the same with plastics. Applications of the sandwich panel may still be a problem where sustained load and low shear modulus of the core material may lead to excessive deflections. It should be noted that cost comparisons, when isolated, can be unrealistic, for ultimately it is the total cost of the building which is significant. As an example, if wood decking were compared to a plastic sandwich panel, the cost of the roofing should be added to that of the wood assuming that the plastic skin will resist weathering. However, such a detailed approach is beyond the scope of this paper.

In all cases in the bending comparisons the rather rigid limitation for deflection was imposed. The same limitation does not apply to an arch form in which the material is subject essentially to a compressive stress. The minimum weight of the foam plastics is an advantage here, however, the most significant factor is that the relatively large deformations do not add to the cost as was the case of the beam slabs. An arbitrary thickness is assumed for the arches compared in Plate E. The deflection of the crown is determined from Plate F after calculating the maximum unit deformation considering elastic and creep deformations due to the sustained load of self weight and elastic deformation due to live loads. The cost comparison of 2.5 pounds per cubic foot polyurethane rigid foam arch is most favorable as compared to that of using concrete in the arch form. However, should one compare this with concrete cost of 3.6 cents per pound for a normal beam girder system, the plastic is still superior. The latter is a better comparison since the arch form is suggested as a means of overcoming the negative aspects of creep of the plastics.

The same favorable comparison for cost of plastics is further illustrated in comparing the materials in the form of a dome shell. The calculated deflections of the polyurethane and polystyrene foam domes are far in excess of that of reinforced concrete but even at 4.2 inches the deflection would not be critical for a thirty-foot diameter dome six feet in height. The assumed thicknesses are realistic values for the material and with these thicknesses the cost of the foam plastics is less than that of the concrete. The significant difference comes in the cost of erection. Formwork for a doubly curved dome would be very expensive and as such, the structure would cost much more than that of the systems proposed for rigid foam plastics. The "Airform" concrete dome shaped house, developed by E. Noyes and W. Neff, represents an attempt to reduce the formwork costs and obtain the material advantages of a shell dome.

The comparisons used for the arches and shells have not included wood since the monolithic curved surface is difficult to obtain in wood, however, the cost of a plastic dome would compare favorably with that of standard wood flat roof construction on a per square foot basis.

It can be concluded from the comparative studies that the "proper" structural form is extremely important, not only for an efficient use of materials, but also to minimize the effect of the creep of plastics under sustained stress. The following experiments conducted at the Architectural Research Laboratory, The University of Michigan, support these conclusions.

Research on Structural Systems

Research on plastics as a basic structural material is part of the program of research being sponsored by the Agency for International Development of the U. S. Department of State in the interest of using foam plastics as a material for housing in underdeveloped areas of the world.

Although polymer science, empirical and engineering design with plastics, has advanced greatly in recent years, little information is available to evaluate the structural potential of plastics or to design with them. The principal void is that of the creep characteristics of plastics in relation to stress, temperature, and relative humidity. Compression set information intended for evaluating insulations is difficult to translate into meaningful conclusions on deformations in relation to sustained stress. As a consequence, a limited materials testing program has been conducted to determine the essential structural properties for the materials used in the test structures. In cases where testing is used to evaluate materials for proposed structures these are paralleled by appropriate tests by the cooperating industries. Although preliminary conclusions are included in the charts noted in the Appendix, much remains to be done before the behavior of structures in plastics can be reliably predicted.

Exploration of the structural properties of materials has been paralleled with a study of techniques of construction consistant with the specific material involved. Two construction methods have been utilized in obtaining doubly curved shells of rigid foam plastics.

The technique of spraying polyurethane foams on a semi-rigid wood armature provides a simple economical approach to forming a plastic dome. The first basic experiment was made in collaboration with The Wyandotte Chemicals Corporation. The wood armature (Figure 1), a collapsible lattice of wood strips, was pulled unto double curved shape. The rectangular type dome, 21 feet x 21 feet, between supports, is tied circumferentially to give the necessary rise of the crown. The form (Figure 2) of the dome is based, in part, on the bending resistance of wood strips. The wood lattice was covered with a stapled on nylon reinforced paper skin.* The polyurethane

*"Kaycel" contributed by Kimberly Clark Company.

foam was sprayed* from the underside enveloping the wood armature. Approximately four inches of 2.5 pounds per cubic foot foam was used for an approximate total of 700 pounds on the entire structure.

A comparison of the completed dome (Figure 3), with the unloaded armature, indicated that the armature was not supporting the weight of the foam and that deflection had occurred before the foam reached full strength. After three weeks the crown of the arch edge deflected another 6 inches (Figure 4). This distortion could only be accounted for by the continuous deformation of the triangular type column. This deformation resulted essentially from the creep in bending of the foam in the column.

The maximum bending stress in the triangular column was approximately 18 pounds per square inch. From subsequent evaluations this value was found to be excessive for the particular foam. Corrective measures involved a slow pull back (Figure 5) at the column. This, in effect, introduced opposite bending in the columns. The property of creep which caused the aforementioned distortion also permitted the return of the column to the original position. After return to the original form additional wood stiffeners were installed to take the bending stress in the column (Figure 6). This experiment gave dramatic proof that the structural form and mechanical property of creep were important factors in the design of plastic structures.

A second order of wood lattice armature dome will be constructed in a similar manner to that shown on the model (Figure 7). The form of this dome will be carefully controlled to eliminate bending. Further, the compression stress in the materials will be kept at low levels to minimize total deformation. Although certain negative factors developed in the first experiment, it is anticipated that the improved plastic dome will perform satisfactorily. A second technique for forming a plastic foam dome is the "Spiral Generation"** process introduced to the project staff by the Dow Chemical Company. The process involves the use of specially designed machine which bends, places, and fastens the polystyrene foam boards together in a predetermined shape. The machine head is mounted on a boom which turns around on a pivot mechanism. Each board is sealed layer upon layer into a rising spiral. Although some limitations are placed on the specific form, a variety of shapes could be obtained by programming the machine.

A 45-foot diameter hemispherical dome was erected (Figure 8) in cooperation with the Dow Chemical Company. The shell was completely generated consistent with the process and then cut away for the two window walls. One

*A Binks Model 18 FM spray gun.

**Invented by Donald R. Wright, an engineer in the long-range plastic application laboratory, of the Dow Chemical Company.

wall is shown removed in Figure 9. The remaining shell, although not a complete surface, has performed well over the period of 18 months' use as a golf clubhouse (Figure 10). The stress levels are sufficiently low and the dome, a hemisphere, is of sufficient rise to minimize any negative effects from creep.

A third type of structure utilizing flexible foam* as a form-giving device is currently under development. A 12 foot x 12 foot inverted umbrella (Figure 11) is obtained by raising the center point while restraining the edges in a wood frame. The 3/4 inch reticulated foam, impregnated with urethane resin, is coated with chopped Fiberglas and polyester resin on both surfaces. The sandwich-type shell should have sufficient bending strength to take unequal loads and the form should be such a minimum stress for sustained load that a stable structure will result. Four of the inverted umbrellas will be erected on columns in a similar manner to that shown for the 4 foot x 16 foot component (Figure 12).

Detailed information on this structural research is expected to be published later this year by the Architectural Research Laboratory.

Conclusions

This research has shown that the use of plastics as a primary structural material can be both technically and economically feasible. However, before this is accepted by the building industry more research is needed in the chemistry, production, and behavior of these materials to insure predictable long-term performance.

Acknowledgments

The research noted in this paper was conducted in cooperation with my colleagues on the research staff: H. J. Borkin, J. S. Crandall, R. M. Darvas, J. L. Haecker, C. T. Larson, Research Coordinator, and S. C. A. Paraskevopoulos, Project Director. In addition to the companies already mentioned in the text, and whose collaboration has made this work possible, we should like to express our appreciation to the E. I. du Pont de Nemours and Company, as well as to the entire plastic industry for the information and resources made available to us.

*Scotfoam contributed by Scott Paper Company.

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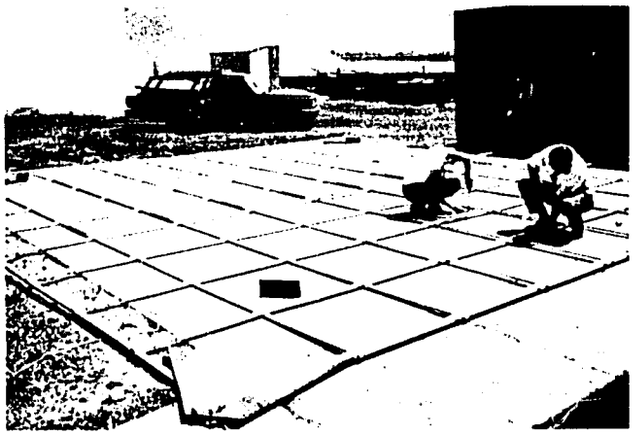


FIG. 1

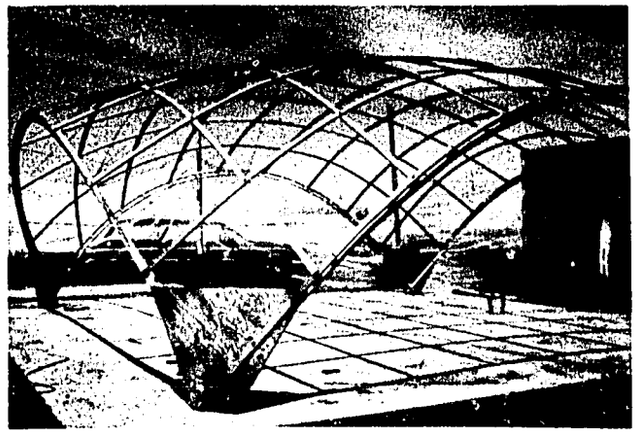


FIG. 2

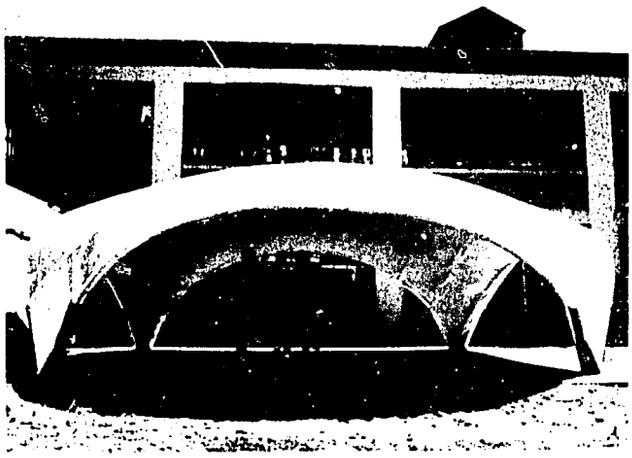


FIG. 3

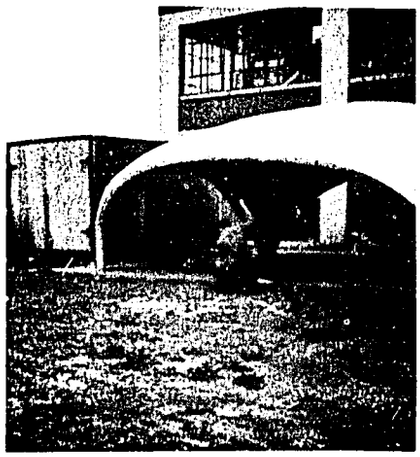


FIG. 4

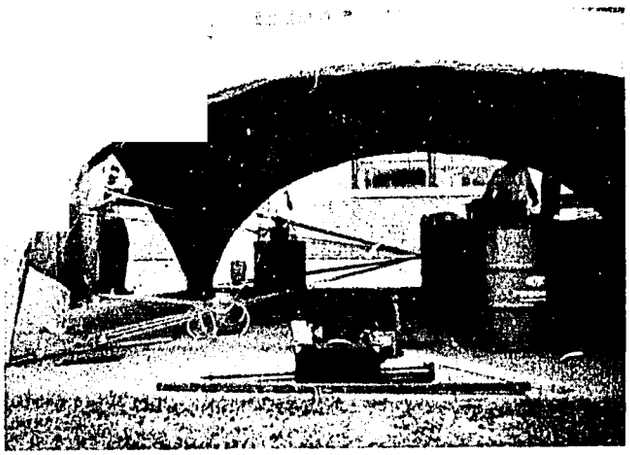


FIG. 5

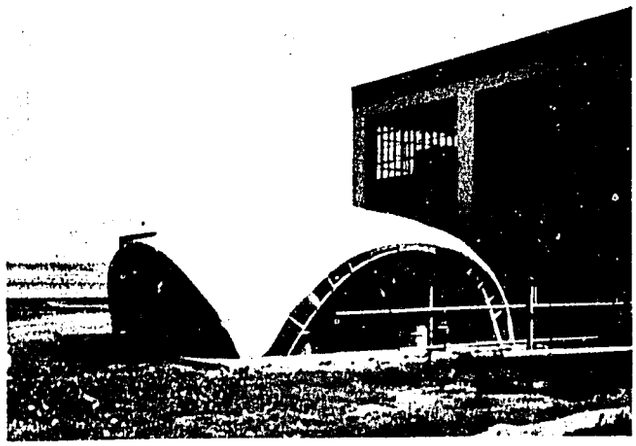


FIG. 6

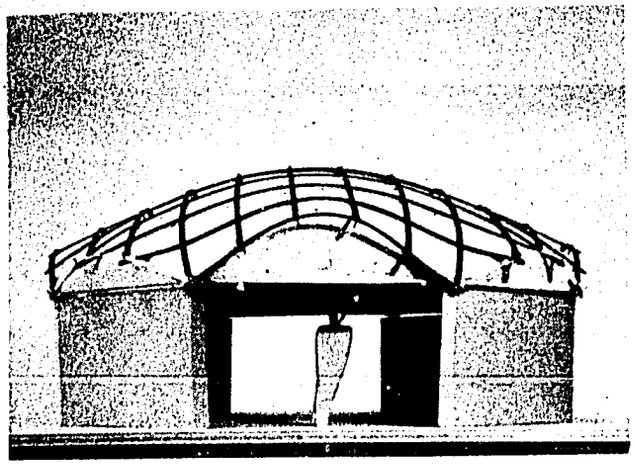


FIG. 7

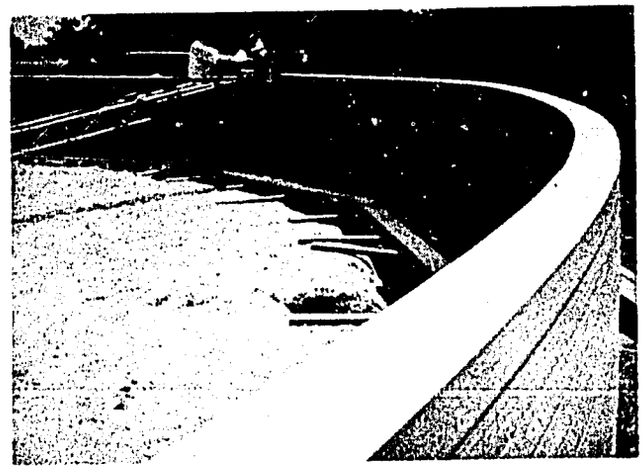


FIG. 8

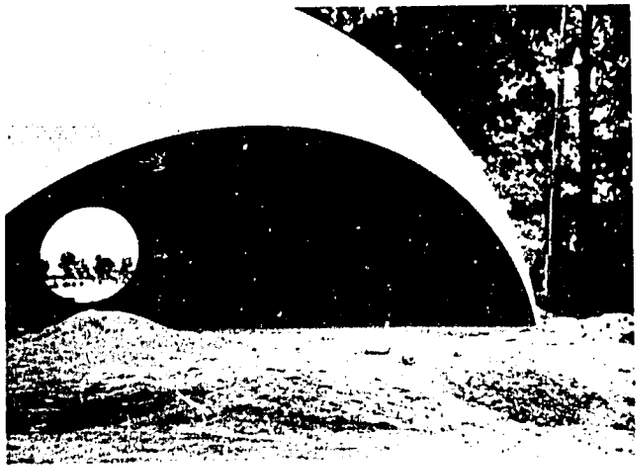


FIG. 9

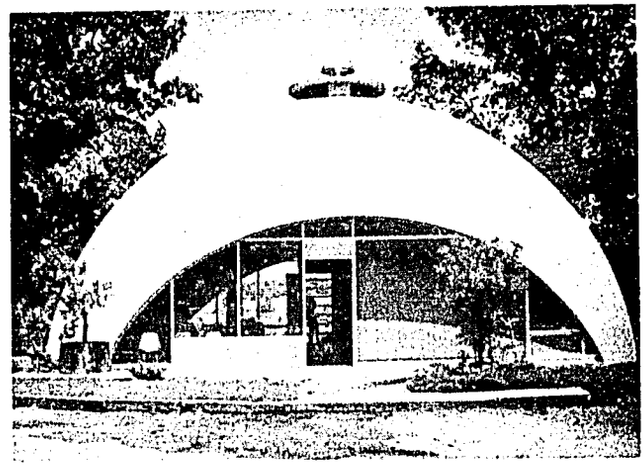


FIG. 10

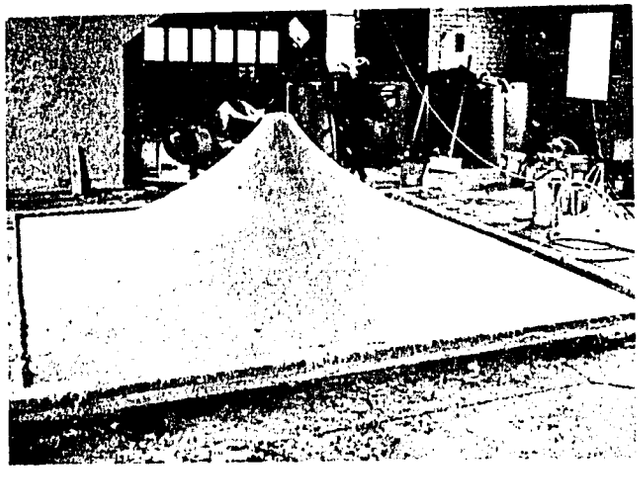


FIG. 11

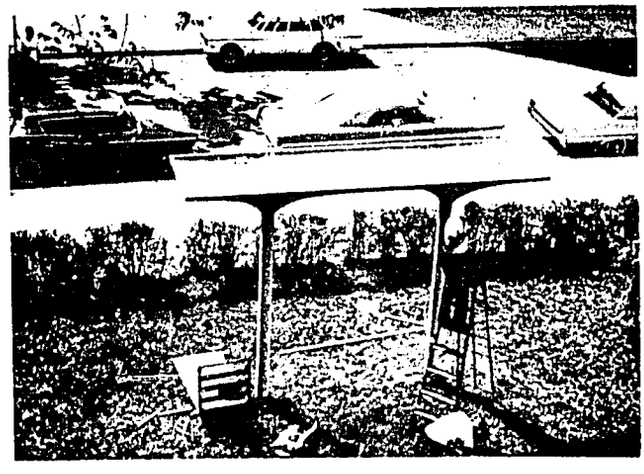


FIG. 12

APPENDIX. COMPARATIVE STRUCTURES

One of the most critical requirements of structural components in a building is that of limited deflections or movements. Excessive deflections of a structural member such as a beam will in many cases be considered a condition of failure. The limitation extends throughout the useful life of a building and as such any effects of time must be considered. The deflection of members is related to both the modulus of elasticity and the creep characteristic of the structural material. The magnitude of the effect of each is dependent on the stress level and the structural form. These factors are explored in these notes to suggest directions for the development of economically feasible structures in plastics.

Mechanical Properties

The mechanical properties for common structural materials and several plastics are listed in Plate A. The creep factor has been included to indicate the probable deformation within a twenty-year period. The figures are estimates since even for materials such as wood and concrete the creep factors are extremely complex and only predictable within a wide range. The values for plastics are based upon an extrapolation from a plot of strain vs. the logarithm of time. The factors for plastic foams are based on the work of R. H. Harding and R. A. Stengard. The values for reinforced plastics are based on limited testing conducted at the Architectural Research Laboratory, The University of Michigan.

The cost data is included for comparative purposes. The material costs are intended to be in place of costs for normal structural situations. As an example, concrete costs noted would be that of erected precast planks. The values for polyurethane foam includes the cost of spraying. The structural costs noted consider formwork for concrete, an armature for the sprayed urethane dome and "Spiral Generation"* cost for the polystyrene foam. In all cases estimates for labor and material are included.

*Invented by Donald R. Wright, an engineer in the long-range plastic application laboratory, of the Dow Chemical Company.

Bending Structure

The chart in Plate B shows the comparison of slab-type beams of the several materials designed for the limiting deflection of 1/240 span with the slab supporting only its selfweight. Plate C is similar except that in addition to its own weight, the slab supports a superimposed load. In the latter case creep is only considered for the selfweight of the slab, which is assumed to be the only sustained load. In both cases the costs are based on the material costs noted in Plate A.

Sandwich Panel

The computations shown on Plate D are included to demonstrate the factors that effect the movement of plastic sandwich panels. The effect of shear deformations normally neglected in beam design must be considered when using a material with a low modulus of elasticity as a core of a sandwich panel.

Arch Structures

The limiting criteria of maximum deflection are less important in arches than in beams. A common thickness is assumed for the concrete and polyurethane arch slabs with unit strain determined on the basis of creep for the selfweight and elastic deformation for the superimposed load.

Bending is neglected in the computations. The deflection of the crown noted is determined from curves on Plate F for the corresponding unit strains. Cost of the concrete is based on a higher cost of formwork normally associated with arch or shell construction.

Shell Structures

Reinforced concrete is compared with two types of plastic foams in Plate H. The equations shown in Plate G neglect any bending action. As in previous examples the effect of creep on a twenty-year basis is used to determine the deflection for the selfweight of the shell. Costs are related to the construction methods utilized to form a dome shell in each of the materials.

Bibliography

1. Harding, R. H. "Some Relationships Between Cell Structure and Foam Properties," Engineering Summer Conference, The University of Michigan, Ann Arbor, Michigan, 1964.

2. Stengard, R. A. Properties of Rigid Urethane Foams, Elastomer Chemicals Department, E. I. du Pont de Nemours and Company, Wilmington, Delaware, 1963.

MECHANICAL PROPERTIES

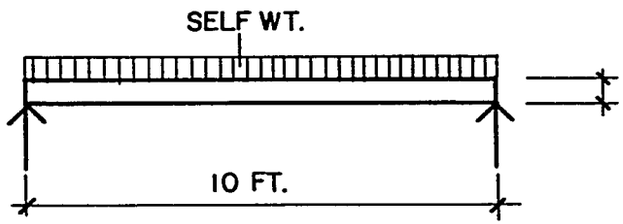
STRUCTURAL-MATERIALS	CONCRETE	WOOD	STEEL	REINFORCED POLYESTER (PAPER)	REINFORCED POLYESTER (30% GLASS)	POLYURETHANE SPRAYED FOAM	POLYURETHANE SPRAYED FOAM	POLYSTYRENE FOAM BOARD
DENSITY P.C.F.	150	35	490	75	82	2.5	6	1.9
COST-MATERIALS ¢/LB.	2.7	6	10	—	48	55	55	66
COST-STRUCTURAL* ¢/LB.	9	10	17	—	107	132	132	106
COMPRESSIVE STRENGTH P.S.I.	3000	7200	33000	—	15000	65	225	30
FLEXURAL STRENGTH P.S.I.	2700	7400	33000	13000	16000	45	320	60
MODULUS OF ELASTICITY P.S.I.	3×10^6	1.96×10^6	29×10^6	0.7×10^6	1.0×10^6	1000	3800	170(
MAX. STRAIN 20 YRS. RATIO $\frac{\text{CREEP STR.}}{\text{ELAST. STR.}}$	2 x	1.3 x	0.04 x	4 x	2.3 x	6.5 x	6.5 x	6.5 x
SERVICE TEMP. MAXIMUM °F	2000	—	1000	220	250	250	250	175

*ESTIMATED IN PLACE COST FOR EITHER EXISTING OR DEMONSTRATED EXPERIMENTAL STRUCTURAL APPLICATIONS

PLATE A

BENDING - COMPARATIVE STRUCTURES

STRUCTURAL-MATERIALS	CONCRETE		WOOD		STEEL		REINFORCED POLYESTER (30 % GLASS)		POLYURETHANE FOAM (2.5 LBS.)		POLYURETHANE FOAM (6 LBS)	
	1 YR.	20 YRS.	1 YR.	20 YRS.	1 YR.	20 YRS.	1 YR.	20 YRS.	1 YR.	20 YRS.	1 YR.	20 YRS.
DEPTH INCHES	1.37	2.37	0.86	1.3	0.78	0.80	1.82	3.2	9.7	26.5	7.7	21.0
MAX. STRESS P.S.I.	680	–	255	–	3930	–	1	–	1.5	–	4.9	–
WEIGHT LBS/SQ. FT.	17.1	29.5	2.5	3.8	32	33	12.4	21.9	2.00	5.45	3.85	10.50
COST $/SQ. FT.	0.46	0.80	0.15	0.23	3.20	3.30	5.80	10.50	1.10	3.00	2.12	5.74

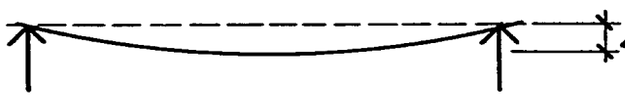


$$h = \sqrt{\frac{37.5 \times 10^3 \times D}{E}}$$

h – INCH
D – P.C.F.
E – P.S.I.

$$f = \frac{6.25\ D}{h}$$

f – P.S.I.



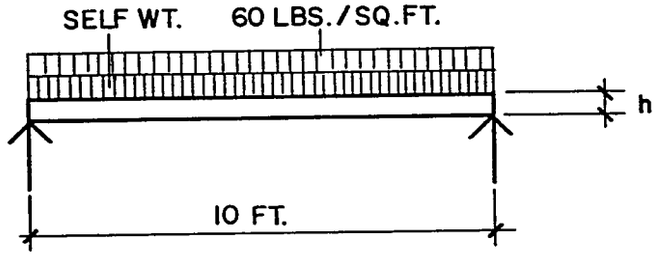
$$\Delta = \frac{1}{240}\ \text{SPAN}$$

$$= \frac{1}{2}\ \text{INCH}$$

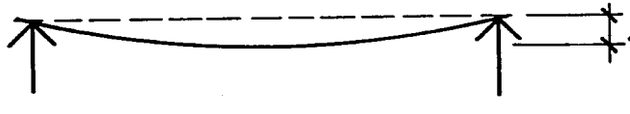
PLATE B

BENDING - COMPARATIVE STRUCTURES

STRUCTURAL-MATERIALS	CONCRETE	WOOD	STEEL	REINFORCED POLYESTER (30 % GLASS)	POLYURETHANE FOAM (2.5 LBS.)	POLYURETHANE FOAM (6 LBS.)
DEPTH INCHES	3.0	2.7	1.2	4.1	38.0	26.5
WEIGHT LBS./ SQ.FT.	37.5	7.9	48	28	7.9	13.3
COST $/ SQ. FT.	1.00	0.47	4.80	12.60	4.35	7.30



D — P.C.F.
W — P.S.F (60)
h — INCH
E_2 — P.S.I. SUSTAINED (20 YRS.)
E_1 — P.S.I. INSTANTANEOUS



$$\Delta = \Delta_{SW} + \Delta_{LL}$$

$$= \frac{1}{240} \text{ SPAN}$$

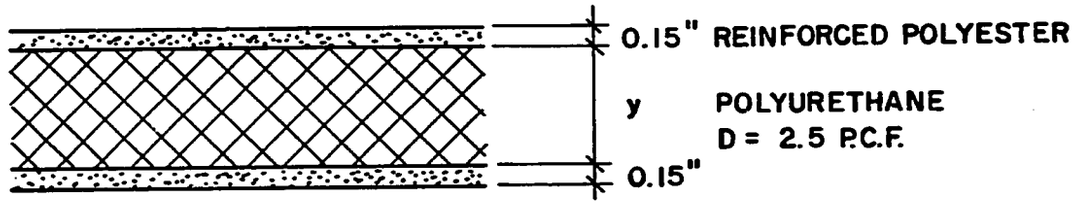
$$= \frac{1}{2} \text{ INCH}$$

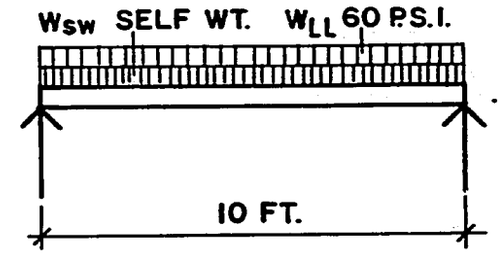
$$\Delta = \frac{1.87 \times 10^4 D}{E_2 h^2} + \frac{2.25 \times 10^5 W}{E_1 h^3}$$

PLATE C

SANDWICH PANEL

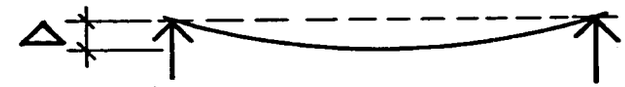
DETAILS





ASSAMPTIONS

SELFWEIGHT IS THE ONLY SUSTAINED LOAD
DEFLECTION CRITERIA IS APPLIED ON A 20 YEAR BASIS



$\triangle = \frac{1}{240}$ SPAN

$= \frac{1}{2}$ IN

MATERIAL PROPERTIES

SKINS D = 82 P.C.F. $E_1 = 1 \times 10^6$ P.S.I. $E_2 = 3 \times 10^5$ P.S.I.

CORE D = 2.5 P.C.F. $G_1 = 450$ P.S.I. $G_2 = 60$ P.S.I.

EQUATIONS

$\triangle$ (SHEAR – CORE) + (BENDING – SKINS) = $\triangle$ (TOTAL)

$$\triangle S_1 + \triangle S_2 + \triangle B_1 + \triangle B_2 = 0.5 \text{ IN}$$

$$\frac{0.187\ W_{sw}\ l^2}{A\ G_2} + \frac{0.187\ W_{LL}\ l^2}{A\ G_1} + \frac{0.013\ W_{sw}\ l^4}{E_2 I} + \frac{0.013\ W_{LL}\ l^4}{E_1 I} = 0.5 \text{ IN}$$

$$\frac{1.33}{y} + \frac{2.5}{y} + \frac{1.5}{y^2} + \frac{3.8}{y^2} = 0.5 \text{ IN}$$

$$y^2 - 7.66y = 37.6 \qquad y = 11.1 \text{ IN}$$

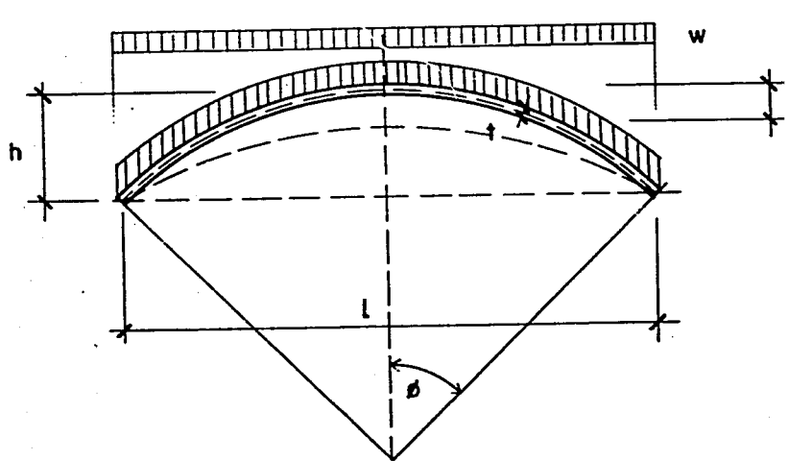
COST

SKINS	2.05 LBS/SQ.FT	x 0.48	= $ 0.98	
CORE	2.31 LBS/SQ.FT	x 0.55	= $ 1.27	
		TOTAL	$ 2.25 /SQ.F.T.	

PLATE D

COMPRESSION – COMPARATIVE STRUCTURES

STRUCTURAL MATERIALS	POLYURETHANE (2.5 P.C.F.)	REINFORCED CONCRETE (150 P.C.F.)
MODULI E_1 (ELASTIC)	1000 P.S.I.	3×10^6 P.S.I.
MODULI E_2 (SUST. 20 Y.)	134 P.S.I.	1×10^6 P.S.I.
$\delta = \delta_2 + \delta_1$	$2.08 \times 10^{-3} + 9.06 \times 10^{-3}$ $= 11.04 \times 10^{-3}$	$1.66 \times 10^{-5} + 0.298 \times 10^{-5}$ $= 1.958 \times 10^{-5}$
COST $/ SQ. FT.	1.20	4.95
$\triangle$ MAX. (20 YRS.)	2.76"	—



ASSUME
$h = 0.2\ L$
$\sin ø = 0.689$
$w = 30$ P.S.F.
$l = 20$ FT.
$t = 4$ IN.

w — SUPERIMPOSED (P.S.F.)
$\frac{D \times t}{144}$ — SELI
D — P.C.F.
t — INCH
L — FT.

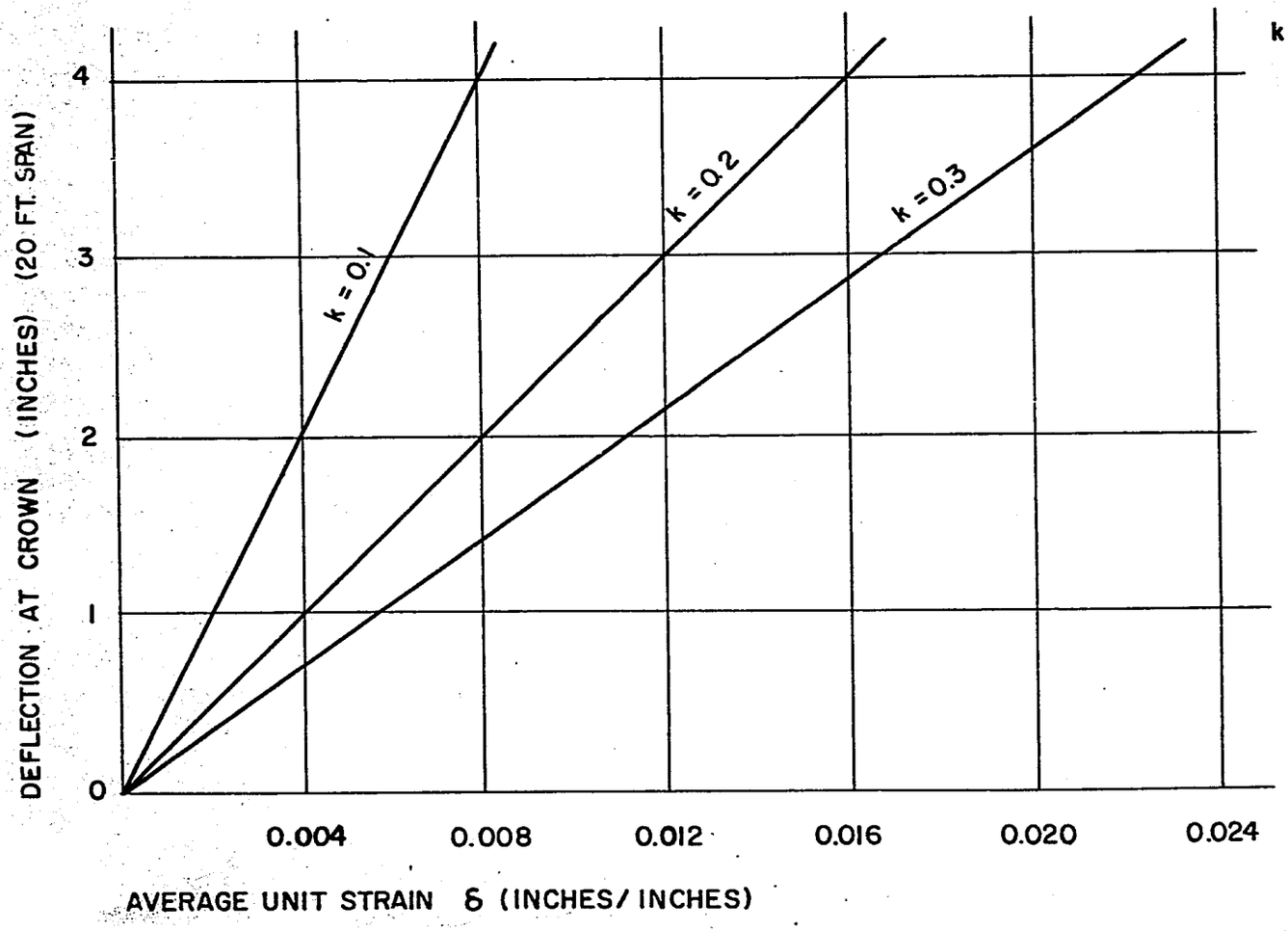
$\delta = \delta_2$ (SELF WT.) $+ \delta_1$ (SUPERIMPOSED)

$$\delta = \frac{3.82 \times 10^{-3} D\ L}{E_2 \sin ø} + \frac{4.16 \times 10^{-2} wl}{E_1\ t \sin ø} \quad \text{(APPROXIMATE)}$$

δ = UNIT STRAIN (IN./IN.)

PLATE E

ARCH DEFLECTION AND UNIT STRAIN



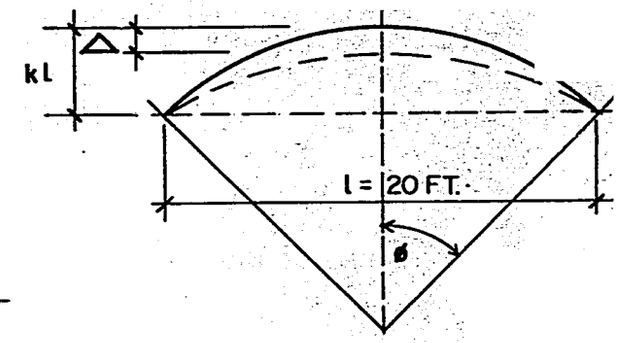
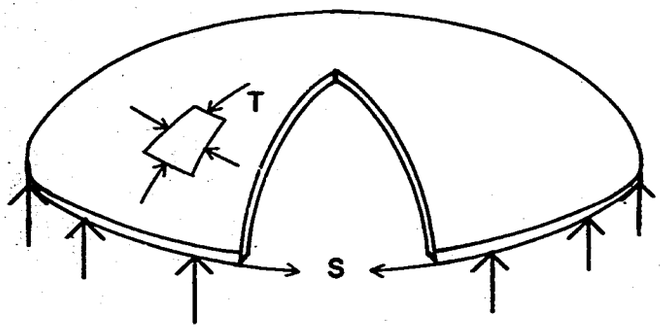
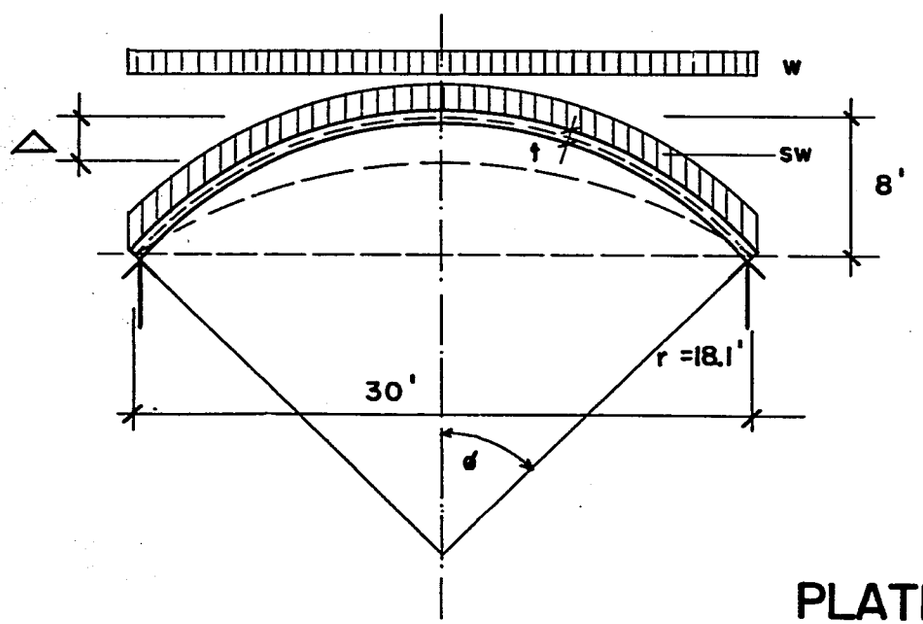


PLATE F

SHELLS – COMPRESSION – COMPARATIVE STRUCTURES





POISSON'S RATIO

$$\mu = \left(\frac{E}{2G}\right) - 1$$

MERIDIONAL SURFACE STRESS

$$T = \frac{W}{(12\,t)\,2\pi r \sin^2 \phi}$$

RING TENSION

$$S = \frac{W \cos \phi}{2\pi \sin \phi}$$

DEFLECTION AT THE CROWN (APPROXIMATE)

$$\triangle = \triangle(\text{SUPERIMPOSED LOAD}) + \triangle(\text{SELFWEIGHT})$$

$$\triangle = \frac{r^2 w}{E_2 t}\left(\frac{1+\mu}{2} - 1\right) + \frac{r^2 D}{E_1\, 144}\left(\frac{1+\mu}{2} - 1\right)$$

W = TOTAL LOAD

w = SUPERIMPOSED LOAD (30 P.S.F.)

sw = SELFWEIGHT $\frac{D\,t}{144}$

PLATE G

SHELLS - COMPRESSION - COMPARATIVE STRUCTURES

CONSTRUCTION	REINF. CONCRETE POURED IN PLACE WOOD FORMS	POLYURETHANE SPRAYED WOOD ARMATURE	POLYSTYRENE PREFORM. PLANKS SPIRAL GENERATION*
DENSITY (P.C.F.)	150	2.5	1.9
MODULI OF ELASTICITY COMP. (ELASTIC) E_1 COMP. (SUST. 204 r) E_2	 3×10^6 1×10^6	 1000 134	 1000 134
SHEAR (ELASTIC) G_1	1.27×10^6	450	900
POISSON'S RATIO (μ)	0.18	0.11	0
THICKNESS (t - IN)	2.5	4	4
MERIDIONAL STRESS (P.S.I.)	21.3	7.8	5.9
RINGTENSION (LBS)	5300	2370	2380
DEFLECTION (Δ - IN)	0.0052	4.2	4.3
COST ($/SQ. FT.) MATERIAL AND STRUCTURE (a)	3.40 (b)	1.41 (c)	0.85 (d)

ASSUMPTIONS

1. SHELL DOME SUPPORTS ITS SELF-WEIGHT AND A SUPERIMPOSED LOAD OF 30 P.S.F.
2. DEFLECTION IS BASED UPON SELFWEIGHT ON A 20 YEAR BASIS AND AN INSTANTANEOUS LIVE LOAD.
3. APPROXIMATE ANALYSIS BASED UPON MEMBRANE THEORY.
4. DIMENSIONS : DIAMETER 30 FT.
   RISE 8 FT.

NOTES

a ASSUMPTIONS FOR COSTS ARE AS NOTED. PERFORMANCE ARE NOT NECESSARILY COMPARABLE.

b BASED ON LOCAL CONCRETE PRICES AND ESTIMATES FOR SHELL FORMWORK.

c BASED ON INDUSTRY PRICES AND EXPERIMENTS BY THE PROJECT STAFF.

d BASED ON COMMERCIAL PRICE OF "STYROFOAM" AND LABOR REQUIRED FOR ERECTION OF EXPERIMENTAL DOME.

*DEVELOPED BY DOW CHEMICAL CO.

PLATE H

Appendix C

ABSTRACTS OF PAPERS FOR THE CONFERENCE ON PLASTICS IN BUILDING STRUCTURES, LONDON, 14-16 JUNE, 1965

ORA Project 05687

Abstract of proposed paper

Title: STRUCTURAL POTENTIAL OF PAPER-SKIN POLYURETHANE FOAM BOARD
Author: J. S. Crandall

The introduction will examine the present status of paper-skin polyurethane foam board as a building resource. Aspects to be reviewed are manufacturing processes, commercial availability, quality control, production capacity and cost.

Testing programs completed and in progress at our laboratory will form the basis for a discussion of design criteria. Data presented will relate principally to flexural capacity and modulus of the material used in various structural applications and will involve considering in some detail the effect of "creep" upon the apparent modulus of the material. The role of resin impregnants, reinforcing materials, and varying papers in the fabrication of sandwich panels and structural components will be evaluated from the standpoint of cost and performance.

The constraints imposed by the use of paper-skin polyurethane foam board will be presented in the light of structural systems developed for this material. This will include material production and handling, component fabrication, building assembly and enclosure. As part of an on-going research effort, the data presented will offer such observations and conclusions as are available prior to the publication deadline.

ORA Project 05687

Abstract of proposed paper

Title: APPLICATION OF MINIMUM STRUCTURE TO CELLULAR PLASTICS
Author: W. A. Oberdick

The full utilization of cellular plastics in significant structural applications is dependent on the degree to which the form of the structure is compatible with the properties of the material. Rigid cellular plastics under stress are subject to certain time-related deformations. Further, limitations of stress are related to specific structural forms. The concept of minimum structures compatible with the deal load of cellular plastics has been developed to obtain optimum structural shapes.

The main portion of the paper will present results of research at The University of Michigan. Background information on the development of the concept will consist of results of material tests as well as those of spirally generated polystyrene shell and an umbrella shell of rigidized polyurethane foam. Details of the concept will be reviewed on the basis of model testing and analysis. Structural design criteria to be presented will be based on data from full-scale structures presently under development.

NOTE: It is anticipated that the oral presentation will review the principles outlined in the paper and report specifically on the construction and behavior of a large structure employing the concepts of minimum structures.