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As ably summarized by Ruhle [1][1], two principal relations influence the development of every new form of shell structure:

1. The relation between shape and load-carrying capacity which governs the proportion of the costs for materials;
2. The relation between shape and construction procedures, which governs the proportion of the costs for labor and construction equipment.

The interaction between these two relations is quite complex; however, since there is an inherent economy of materials in most doubly-curved thin shells, the relationship between shape and construction procedures becomes of paramount importance in minimizing the high cost of labor.

It is not surprising, therefore that there has been considerable interest recently in simplifying construction for shell structures. This is evidenced by the many ingeneous structural concepts which have been suggested by numerous researchers. The following paragraph, although not intended to present a complete history of this work, does serve to illustrate the breadth of potential solutions to the problem that have been proposed.

Waling, Ziegler, and Kemmer [2] describe a method of forming concrete hyperbolic parabaloid shells using gridworks of wires along with plastic foam boards, thereby eliminating shoring, bracing, and formwork. Marsh [3] Otto [4] and Paraskevopoulos et al [7] discuss variations of a lift-shape process which involves lifting a deformable gridwork of bars from a flat to a shell shape. Otto [4] also describes pneumatically formed shells. Paraskevopoulos et al report on rigidized minimum-surface structures [7] the bases of which are suspended cores of plastic foam. Industrialized building concepts form an important aspect of methods studied by Gilkie and Robak [6], Brainov [8], Piano [9], Boley and Tandom [10], and Paraskevopoulos et al [11]. Along these same lines, Makowski and Derning [13] have developed a method of using a plastic webbing as an economical form for manufacturing segments of glass reinforced plastic shell structures.

All of the above processes are seen to be designed to reduce the cost of constructing shell structures either by minimizing formwork and bracing or by industrializing as much of the construction as possible. It is also noteworthy that many of the concepts described entail the use of structural plastic either as an essential part of the finished structure or as part of the forming technique. Makowski [5, 12] who has described the role of plastics in building construction very clearly, indicates that plastics should be used not as substitutes for conventional materials but rather they should be used in such a way as to exploit their unique advantages while minimizing their disavantages.

A New Concept - "The Buckle-Shell"

A new method for shell roof construction conceived about five years ago by Waling[4] not only fulfills these criteria for proper use of plastics, but in addition also optimizes Ruhle's shape-construction relationship with little or no detrimental interaction on the shape-load carrying relationship. This so-called "buckle-shell" method virtually eliminates formwork and is potentially adaptable to industrialized construction.

This new method consists of the following: (1) A core of relatively soft, low modulus material is assembled as a flat plate of the desired shape; (2) a high modulus thin stiffening skin is applied to the upper surface of this plate; (3) the plate is then buckled from its flat position by a finite number of forces applied to its perimeter, the buckled configuration being amplified sufficiently to obtain adequate curvature to provide good esthetic and structural qualities for the shell; and (4) a stiffening skin is then placed on the under surface of the shell completing the "buckle-shell" structure. This sandwich construction results in an extremely strong, rigid and lightweight shell requiring neither shoring nor temporary stiffening during construction. With the proper choice of materials the resulting shell would be weatherproof, and would possess excellent innate insulting qualities. Possible areas of application seem limitless ranging from private dwellings to sports arenas and from housing in underveloped countries to great airplane hangers. It quickly becomes evident that many parameters are available as likely candidates for variation to create a never ending array of "buckle-shell" shapes. For example, such things as core thickness to shell span ratio, core and/or skin moduli, shape of original plate, arrangement of buckling forces, and amount of buckling deformation imposed, to a name a few, will have an effect on both ultimate shell shape as well as shell behavior. For this reason a set of small scale qualitative experiments were carried out as the first phase of a "buckle-shell" feasibility study sponsored by The Dow Chemical Company.

Small-Scale Experiments

Qualitative experiments concerned with examining the post-buckling behavior of flat plates of various configurations yielded many interesting possible "buckle-shell" roof shapes, one of which is shown in Figure 1 along with an artist's rendering of how it might be used. The range of possible shapes can, of course, be further broadened by constructing the shell in segments from independently buckled plates. This method was used in developing the cruciform shown in Figure 4, and is discussed in the following section with the other large-scale experiments.

Large-Scale Laboratory Experiments

This portion of the research was in the nature of a feasibility study. Two questions had to be answered: (1) Could a "buckle-shell" be developed which would meet the most severe load-carrying requirements in the contiguous United States; and (2) Would such an erection technique work on a full-scale roof structure?

In considering question number one, it was decided to concentrate on one size, shape, and buckling load distribution throughout the series of experiments. A square plate 9 ft on a side was chosen because of its half-size relationship to the largest shell that would fit into the laboratory work area (18 ft square). It was anticipated that the 18 ft square plate could be used subsequently to form a full-size shell to answer question number two. A diagonal buckling load

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(1) Numbers in brackets refer to items in list of references.

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configuration was used in all of these experiments. In addition to the nine foot and eighteen foot square models, experiments were also run on so-called cruciform shells.

Nine Foot Square Models

A series of six experiments with "buckle-shell" models based on nine foot square plates resulted in the development of a shell with the following characteristics:

Core:	polystyrene [3] foam 1" thick
Skins:	one layer of 18 oz woven roving on each face impregnated with epoxy [3] adhesive. In addition for added strength 19" and 6" wide arches of 18 oz epoxy-impregnated woven roving, respectively, along two diagonals and four edges on each face of shell.
Rise to Diagonal Span Ratio:	18"/132" achieved by an 8% shortening of each diagonal chord during buckling.

This shell proved to possess a short-term ultimate strength under uniform load of 80 psf, providing a factor of safety of 2 over a very high working load of 40 psf. Although this is not a generous factor of safety for plastics materials (a more common factor of safety being in the range 3-5), it is felt to be adequate in view of the fact that measured strains were exceedingly low. The highest strain measured in the skin [4] was 612 MII under a load of 80 psf; therefore, stresses in the skin were only a fraction of the skin's short term ultimate strength. Strains in the cores were not measured; however, modes of failure have usually been through separation of the top skin and the core, local buckling of the top skin or separation of shell from the support mechanism, rather than a strength failure of either skin or core. Buckling of the shell as a whole has also not proved to be a problem.

A load deflection curve for this shell (Shell No. 6) compared with prior shell models is shown in Figure 2. It is seen from this figure that although Shell No. 6 is by far the stiffest of the square shell models, the deflection is still rather large. This is due, of course, in part to the low modulus materials from which the shell has been constructed. It is due even more however, to the relative flatness of the central region of this shell. An improvement of the geometry in this region would, of course, result in a marked increase in strength of the shell. This consideration lead to experiments with what was termed a cruciform shell.

Cruciform Shell

The cruciform shell was formed by buckling a 2" thick flat cruciform plate into the shell configuration shown in Figure 3. The chords of the shell arches are 10% shorter than the original flat cruciform legs giving an arch with good curvature properties in the central region. To complete this shell structure the open segments were partially filled in with 1" thick buckled trapazoidal plates and 1/2" thick buckled triangular plates as shown in Figure 4. Skins over the entire shell consisted of only one layer of 18 oz woven roving except near the supports where two layers were used. The completed shell was instrumented with dial gauges and loaded to 80 psf on the horizontal projected area of the shell. This shell, which withstood this 80 psf load with deflection at the center of only .287 in. (See Figure 2), is seen to be over four times stiffer than Shell No. 6. It is believed that this experiment accomplished two things. It demonstrated that an extremely stiff, strong, and lightweight "buckle-shell" roof was possible to achieve. It opened the way for more innovative thought with regard to future "buckle-shell" types.

(3) Urethane foam and polyester adhesive have been used in constructing "buckle-shells" also, but are not reported herein.

(4) Strains were measured top and bottom only at the following selected locations; at center of shell, at center of edge, and along diagonal near point of maximum curvature.

Eighteen Foot Square Shell

With the successful completion of the nine foot shell series and the cruciform shell experiment it was decided to fabricate and erect a full-scale (18 ft. square) "buckle-shell" to determine whether or not the "buckle-shell" technique would work on a larger scale. Also it was intended that this shell be placed outside for observation of its capacity to withstand the elements. The West Lafayette Park Department accepted an offer to install it in one of the local parks for use as a picnic shelter. The steps taken during construction and erection of the 18 ft model were similar to those already described for the 9 ft. shells. To date (September 1970) after more than three years of service, the shell has successfully withstood numerous intense natural live loadings.

CONCLUSIONS

From this research three important conclusions about "buckle-shells" can be drawn. First, from the small-scale experiments, it appears that there are great many "buckle-shell" shapes that are both attractive and practical. Secondly, it is now possible to construct a "buckle-shell" that will meet the most severe load-carrying requirements in the contiguous United States; two different "buckle-shell" shapes--a cruciform and a 9 ft square model--withstood live loads of up to 80 psf. Finally, the "buckle-shell" technique does work on full-scale models. An 18 ft model was successfully erected and placed in a local park as a picnic shelter, and to this date (September 1970) the shell has retained its structural integrity under severe loading effects. Current experimental research efforts are aimed at determing size limitations, optimizing the design, and investigating other possible materials for "buckle-shell" structures. A finite element analysis of the erection procedure as well as the completed shell is also underway.

ACKNOWLEDGEMENTS

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APPENDIX I - REFERENCES

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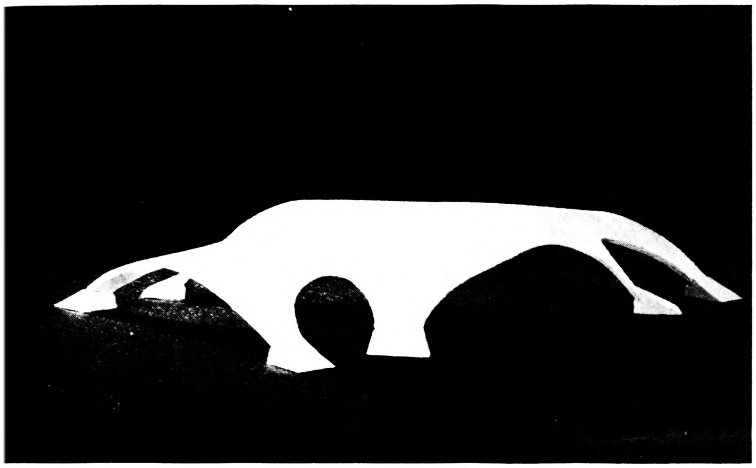

Figure 1a Office Building Model

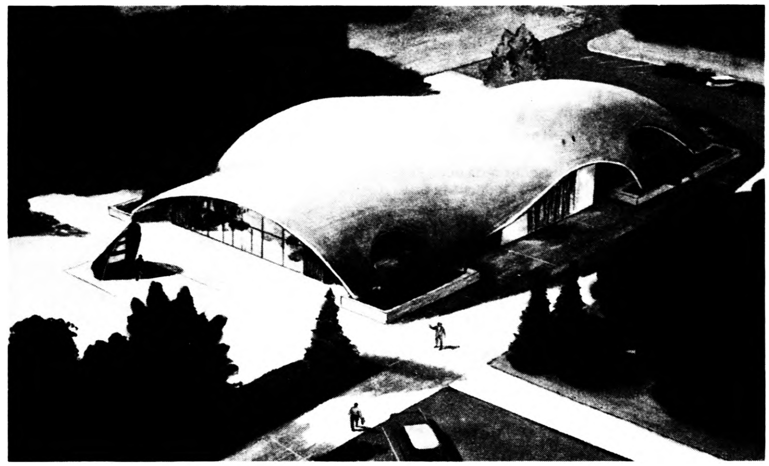

Figure 1b Office Building - Artist's Concept

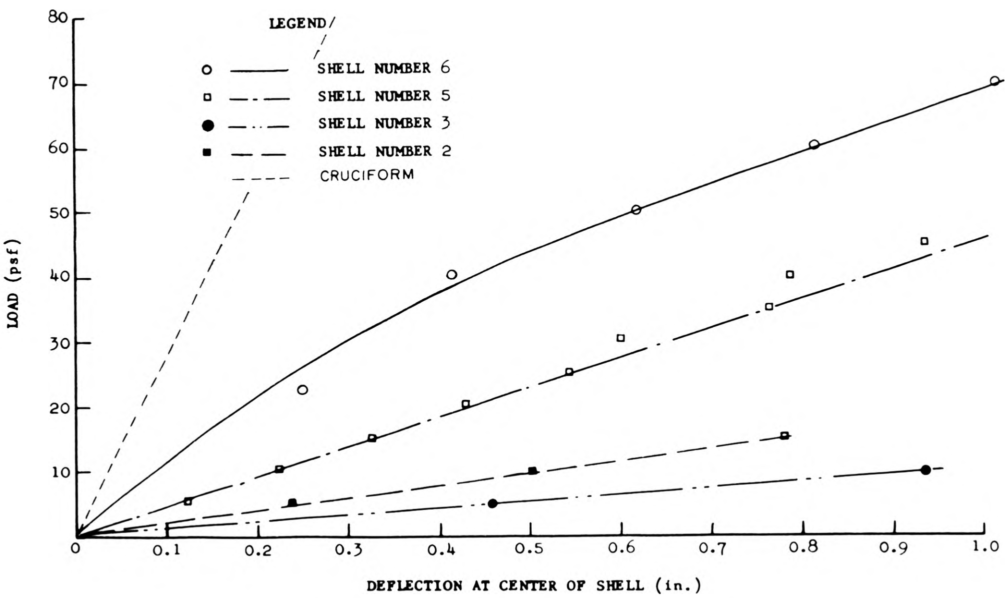

FIGURE 2 LOAD VERSUS DEFLECTION AT CENTER OF SHELL

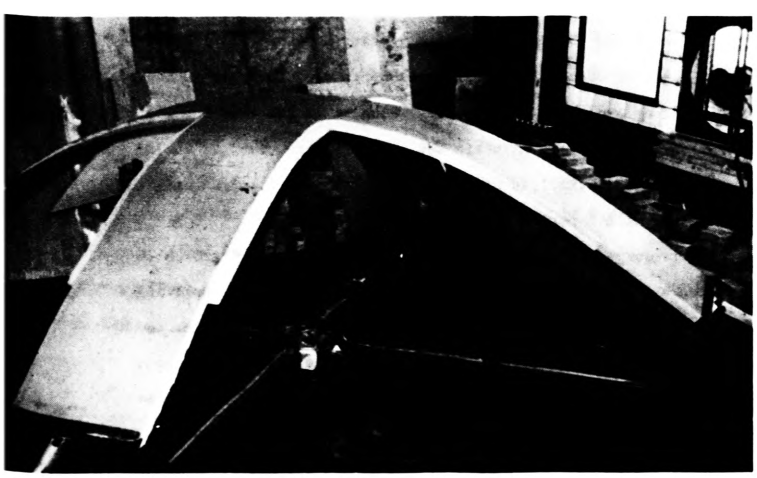

Figure 3 Buckled Cruciform Arches

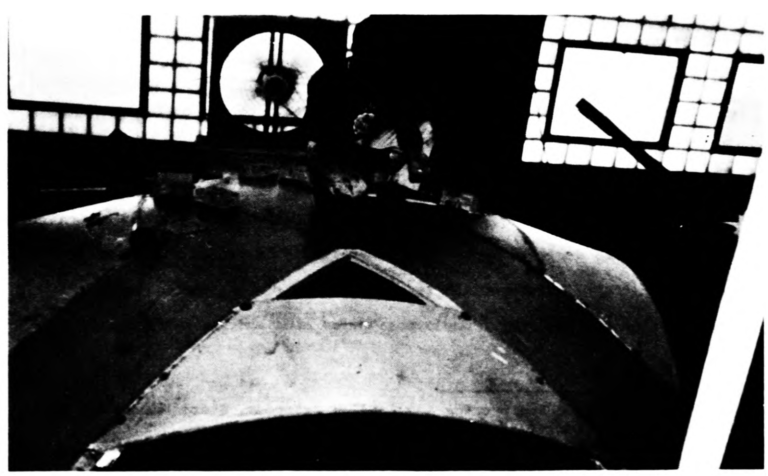

Figure 4 Filling of Cruciform Voids