The use of air-supported forming as a method for controlling forming costs for concrete shells is under study at the Institut für Massivbau of Stuttgart University in Germany. The possible shapes for shells have gone past conventional geometries and experimental and mathematical methods are being used to design shell shapes. Studies of the technical feasibility of these shapes include the control of formwork deformations and their effect on the setting concrete.

Keywords: concrete construction; deformation; forming techniques; formwork (construction); **inflatable structures;** precast concrete; **shells (structural forms);** **structural design.**

Suitable shell shapes

exploration of air-supported forming in Germany has centered around form-finding techniques for shell shapes and formwork deformation control

by J. Schlaich and W. Sobek

Only with lightweight structures is it possible to bridge large spans or provide roofs over large areas at a justifiable expense. The fewer members a structure contains which are subjected to bending stresses, the lower its deadweight will be. Therefore, structures having only members subjected to axial forces in tension or compression are optimal for such applications.

Among structures which are principally subjected to compressive stresses, shells with a thin depth and curved surface have special importance. They combine the functions of enclosing space and of very efficient load transfer (Fig. 1). Since bending capacity is only of subordinate importance in shells, the shell shape and load-bearing behavior are interdependent.

Concrete is a material with high compressive strength with which structures of any shape can be made on site, and which is also cheap, durable, and easy to work with. Hence, it is an ideal material for making shells. Conversely, when the properties of concrete as a material are considered it becomes apparent that the shell is an appropriate structure for concrete. This was recognized in the early stages of concrete construction and a wide range of interesting shell structures was built in that period (Fig. 2,3).

It is regrettable that hardly any concrete shells are built today. The reason for this is the great amount of work involved when conventional formwork methods are used to create the spatially curved shell surface. In countries where wage rates are high, only a very few concrete shells have been constructed using conventional formwork techniques in the last 10 to 20 years. The work of Heinz Isler is the one major exception to this.

Fortunately there has been a series of developments in various countries in recent years attempting to resolve the problem of expensive formwork. Such developments include the standardization and reuse of formwork, the use of prefabricated components, the use of earth embankments as formwork, the use of composite structures, free cantilevering construction with cast-in-place concrete or precast elements, and the use of air-supported forms.

So far, little indigenous research has been done in these areas in Germany. Two developments in these fields, however, have been researched at the Institut für Massivbau of Stuttgart University:

- The use of glass fiber reinforced concrete (GFRC), a material with high tensile and compres-

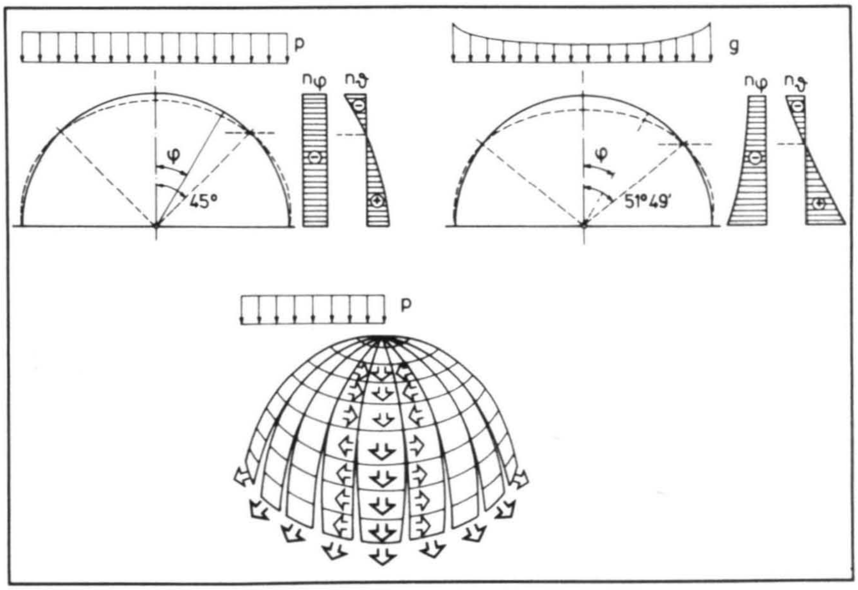

Fig. 1 — Shell of revolution: load-bearing behavior under different load cases.

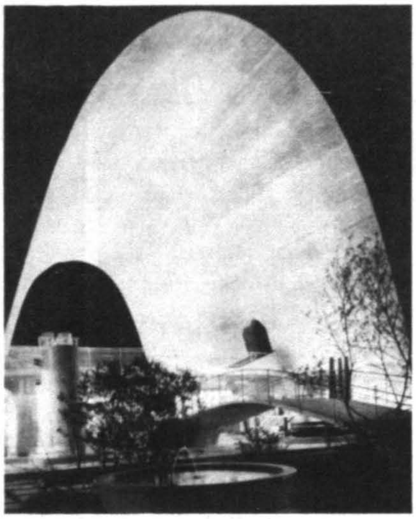

Fig. 2 — The "Zementhalle" by R. Maillart, Zürich, 1938-39.

sive strength, for constructing very thin shells. When constructed on site these lightweight shells exert only a very slight stress on the formwork, so that it can be made at lower cost. If they are precast, the shells or shell components are easy to transport. A prototype shell with a span of 31 m (102 ft) and only 12 mm (0.5 in.) thick was built in Stuttgart in 1976 (Fig. 4).

- The use of air-supported forms.

Construction of the forms

Air-supported forms are made of thin membranes subjected only to tensile forces. These membranes are usually made of high-strength plastic-coated synthetic fiber fabrics (Fig. 5); however, other materials such as thin sheet metal might also be suitable.

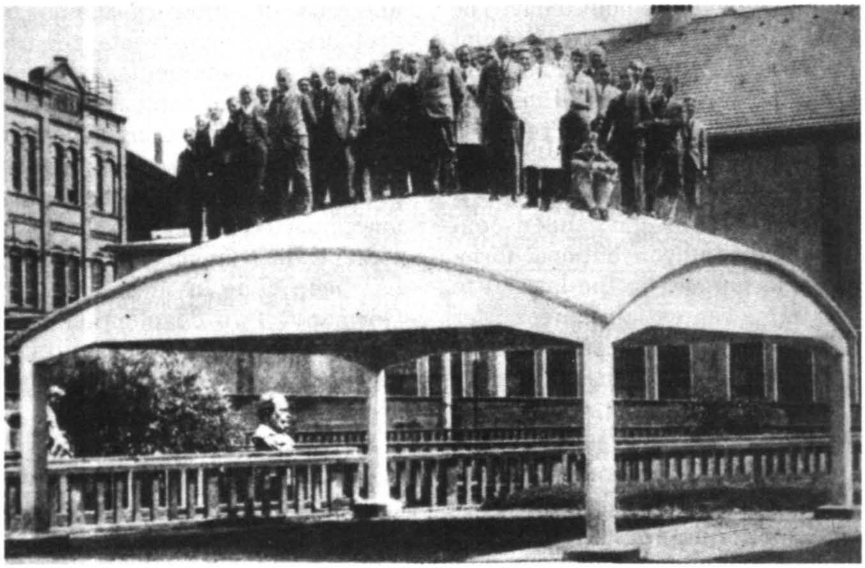

Fig. 3 — Experimental shell by Dischinger, 1939. The depth of the shell is 1.5 cm (0.6 in.).

When manufacturing a form membrane the individual strips of fabric are cut to size and subsequently combined to form spatial curved surfaces (Fig. 6). Surfaces of almost any shape, including bags, can be produced. The form membrane can be joined to existing building elements such as foundations.

By creating a pressure difference between the interior of the structure and its surroundings, the formwork is prestressed. Thus, the formwork can be stabilized either by partial vacuum or by pressure. Gases, fluids, granulates, or a combination of these can be used to fill the formwork (Fig. 7).

Unresolved questions

If one wishes to construct concrete shells using air-supported forms one is soon confronted with a series of questions which have not yet received adequate study. The most important questions can be classified in two categories.

The first category includes questions related to methods of designing suitable shell shapes. Up to this time, shells have for the most part been designed with surfaces which can be simply described geometrically and easily produced with regular forms: barrel-shaped,

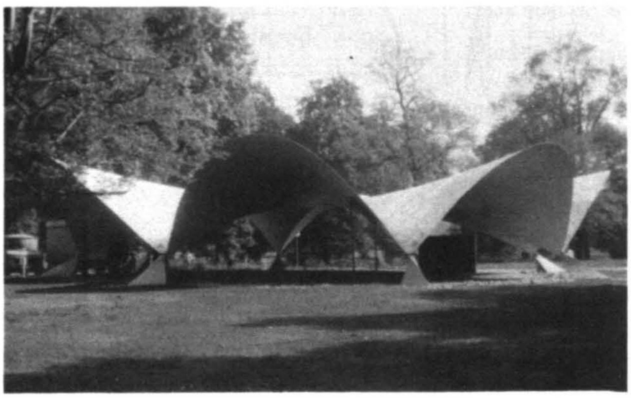

Fig. 4 — Glass fiber reinforced shell, Stuttgart, 1976.

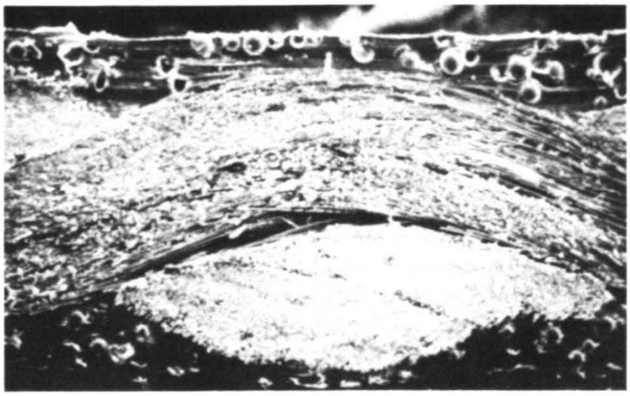

Fig. 5 — Section of PVC-coated polyester fabric. The membrane is about 1.2 mm (0.05 in.) thick.

conoid, hyperbolic paraboloid, and spherical.

If air-supported forming is used, a wide variety of shell shapes can be built. It is no longer a problem to produce complex geometries. In view of the broad range of available shapes, however, questions arise as to which of them exhibits particularly desirable characteristics and what design methods are effective for finding these shell shapes.

The second category contains questions concerning technical feasibility such as the likely deformations of the air-supported forms, the effects of these deformations on the setting concrete, and questions of pressure control during concreting and subsequent setting of the concrete.

Design

With air-supported forming one leaves the realm of surfaces which can be described analytically. Forms can no longer be designed by hand drawing. The form-finding process becomes a necessary part of the design process.

In the form-finding process, a structural shape with defined characteristics under a form-defining load is developed either by experiment or by calculation.

The experimental formfinding methods, such as pneumatically created shapes or suspension models, are readily understood thanks to their visual impact. Precisely because they are so visual they often represent the first stage of design work. After determining the essential boundary conditions one can then proceed to computer-assisted, mathematical form-finding methods.

The most common mathematical form-finding methods are based on vector analysis, the finite-element method, or the force-density method. The mathematically determined geometric data are also used for the structural analysis and for calculation of the cutting pattern of the formwork membrane (Fig. 8).

For form-finding of concrete shells, the deadweight of the shell will usually be taken as the form-defining load. Only in the special case of permanently present or frequently recurring external loads of fixed magnitude will the combination "external load plus shell deadweight" be used as the form-defining load. This applies, for example, when there is a permanent earth pressure acting on the shell. With regard to the stress state in the structure, it is desirable to achieve a biaxial compression stress state in the structure which is as homogeneous as possible.

If the concrete shell is to be produced on air-supported forms, the

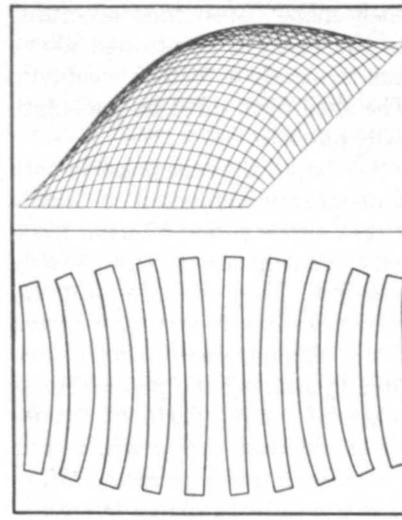

Fig. 6 — Shape of a pneumatically formed soap film and the cutting pattern typically used for this type of shape.

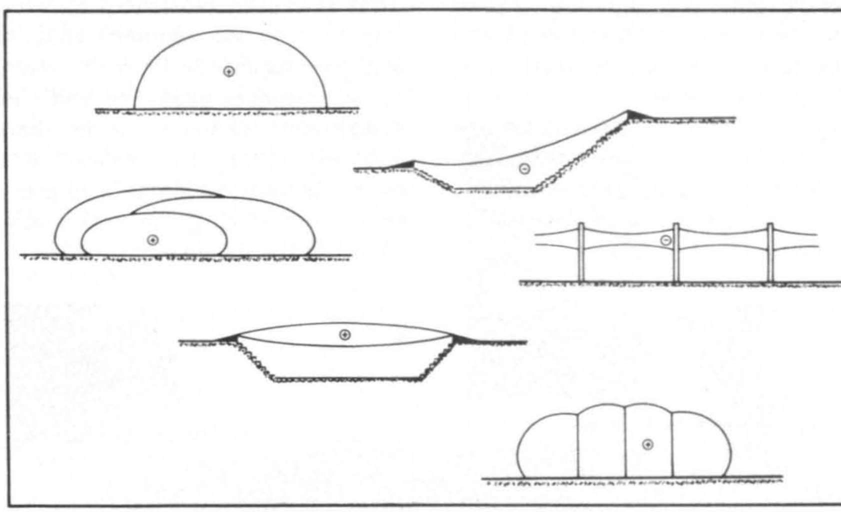

Fig. 7 — Different methods of stabilizing the formwork membrane: air-supported forming, membrane stabilized by partial vacuum, fluid-filled bags, cushions stabilized by partial vacuum, air-inflated cushion, cable-structured inflated bag.

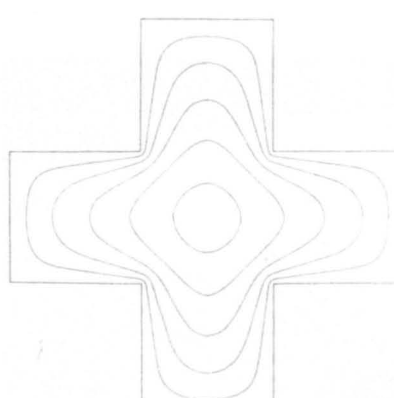

Fig. 8 — Cross-shaped ground plan of an air-supported soap film. The surface is described by its contour lines.

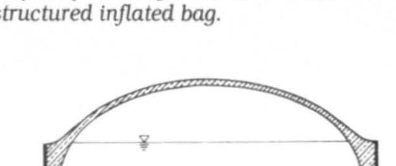

Fig. 9 — Air-inflated bag, partially water-filled. This type of formwork was developed by the authors for the construction of tanks used for fluid storage.

Fig. 10 — An air-supported form made of thin sheet metal.

shell shape determined according to the criteria mentioned above has to satisfy a further condition. The shell form must be pneumatically possible.

All shapes that are possible with a membrane subjected to tensile stress alone under internal pressure loading are pneumatically possible. They include spheres, cones, and cylinders. We prove that a shape is pneumatically possible by proving the possible existence of a pure state of tensile stress in that shape while it is loaded by internal pressure. Often it is possible to prove the existence of more than one state of tensile stress. In such cases, the forces occurring in the formwork can be manipulated by introducing restrictions, and thus matched to the membrane material used and the cutting pattern. Nevertheless, it should be pointed out that proving that general, free shapes are pneumatically possible can be very time-consuming and complicated.

The difficulties associated with proving that a given shape is pneumatically possible can be circumvented if, in the form-finding process, one designs not the form of the concrete shell, but the shape of the formwork loaded by internal pressure. The formwork is then in and of itself pneumatically possible.

It can be shown for a certain category of formwork shapes that the concrete shells which they produce have particularly advantageous load-bearing behavior. These shapes include certain soap films pneumatically spanned over a given ground plan. Under internal pressure, the formwork membrane is subjected to the same isotropic tensile stress at all points. Thus it can be fabricated at very low cost. If one assumes that in shallow shapes the lines of action of the internal pressure and the deadweight almost coincide, then concrete shells of this shape will be under uniform biaxial compressive stress at all points when subjected to the deadweight load.

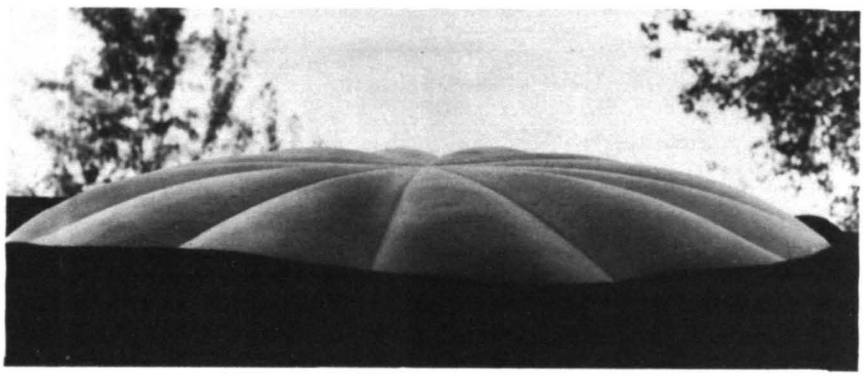

Fig. 11 — Model of a roof for an ice stadium 100 m (328 ft) in diameter.

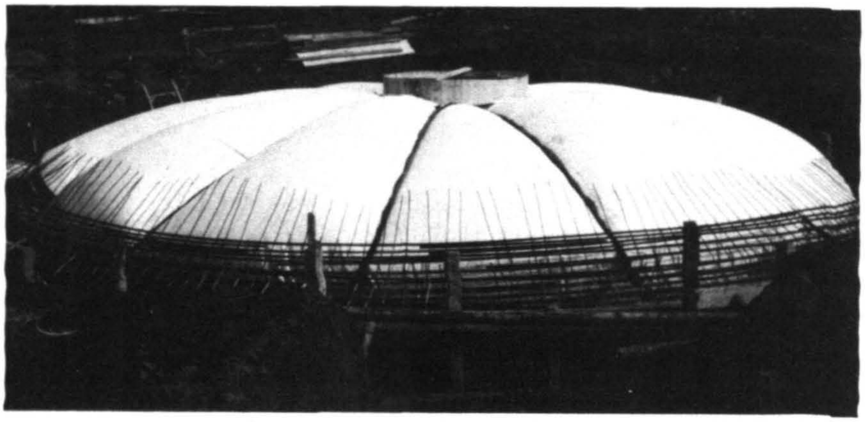

Fig. 12 — Inflated formwork for a rainwater interceptor tank.

This uniform state of stress, however, does not occur with all concrete shells having the shape of pneumatically spanned soap films; certain categories of shapes have to be excluded and the concrete shell must have a suitable support. This can be illustrated very easily. When the internal pressure in the formwork is relieved the concrete shell is loaded by its deadweight. The resulting state of stress which builds up in the shell depends on the possible deformations. At the edge these deformations will largely depend on the type of support of the shell and the shell shape.

Concrete at early ages

Depending on its mixture and environmental conditions, concrete strength increases after it has been mixed and placed. At the same time its initially large deformability decreases appreciably. When it reaches minimal ultimate strain, concrete is still very weak. This is the critical phase of green concrete.

As soon as the concrete placed on the formwork reaches a measurable degree of strength, it stiffens the formwork membrane. This stiffening effect is initially very slight. The concrete, however, is also very sensitive to deformations at this time, such as those that may occur in the formwork as a result of concreting. Therefore, the concreting process and the concrete mixture must be very carefully matched to exclude the risk of permanent damage to the fresh concrete by crack formation or weakening of the internal structure of the concrete. Similar considerations apply to inflation pressure regulation after the completion of concreting. Investigations carried out on dome shells at the University of Stuttgart showed that the minimum permissible internal pressure fluctuation occurs prior to the critical phase of the fresh concrete.

Whenever possible an attempt should be made to minimize the deformations of the formwork membrane by taking additional measures. These can include a formwork which is as rigid as possible, and stiffening the formwork.

Rigid formwork

One way to minimize the deformations of the formwork is to maximize the internal pressure. However, uplift forces on the foundations and the limited strength of the polyester and polyamide fabrics normally used (for reasons of cost) limit the internal pressure level, especially in formwork with large curvature radii. In the case of shallow shells it is often impossible to use an internal pressure more than twice the concrete load.

If high internal pressure is required because of locally high hydrostatic pressure levels of the fresh concrete, a partial or complete filling of the form with fluid or granulate, instead of with air, can produce very good results (Fig. 9).

Another very good means of keeping the deformations of the formwork to a minimum consists of structuring the formwork appropriately. Cables or cable nets laid over it are suitable for this. One can thus create shells with small global curvature, but with high local curvature. With appropriate structuring the load-bearing behavior of the shell is improved and the architectural form is made more interesting (Fig. 10).

Stiffening of the formwork

Stiffening of the formwork can be achieved by

- stiffening of the supporting medium in the interior,
- stiffening of the formwork membrane before concreting, or
- stiffening of the formwork membrane while concreting is in progress.

The individual methods can also be combined.

The supporting medium in the interior can be stiffened by

- using thixotropic fluids,
- temporarily freezing a fluid filling, or
- evacuating the fluid when using fluid-granulate mixtures.

The formwork membrane can be stiffened before the concrete is placed by

- spraying plastic foams onto the interior or exterior of the formwork membrane, or
- fastening the reinforcement to cables lying on the formwork membrane or connected to it.

The spraying on of plastic foams is a widely used method. It makes especially good sense when thermal insulation of the concrete shell is necessary. This method has been used frequently with success in the U.S.

Step-by-step stiffening of the formwork membrane while concreting is in progress can be accomplished by

- concreting section by section, with sufficiently long hardening intervals, or
- concreting in layers which is appropriate when shotcreting.

The last method has a tradition extending back over almost 40 years. It was introduced in the U.S. as early as 1948 by Wallace Neff, one of the pioneers of this construction method. Since then it has been used in several hundred shells constructed with air-supported forms.

Use of precast elements

The laying of precast concrete elements on the air-supported forms also represents a suitable means of minimizing the deformations of the formwork while the fresh concrete is hardening. Since only small quantities of concrete have to be placed to grout the joints, the formwork is hardly deformed at all while concreting is in progress. Moreover, concreting can be completed before the concrete enters its critical phase.

Examples

As an example of air-supported forming structured with cables, Fig. 11 shows the design of a roof for an ice stadium 100 m (328 ft) in diameter. The formwork membrane is fixed to a perimeter wall topped with a ring. This ring is subjected to compressive stress during the construction of the shell. After completion the ring is subjected to tensile stress. It is therefore prestressed.

Fig. 12 shows a rainwater interceptor tank. Following construction of the floor slab, a closed membrane bag was placed on the floor slab and structured, like the ice stadium, with guyed ropes in a parachute shape. This resulted in the formation of tightly curved segments between the valleys. As a result of the deadweight and earth pressure, these segments are subjected to compressive stress in such a way that no reinforcement was necessary. Only the valleys and the ring chord were reinforced.

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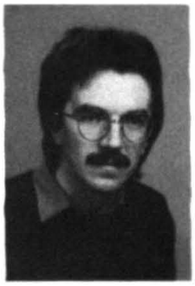

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