ON DESIGN AND CONSTRUCTION OF CONCRETE SHELLS

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Architects and engineers have to face the fact that formwork techniques have more influence on the shape of today's concrete structures than the characteristics of the structural material itself. The art of building concrete shells has nearly completely died out. Therefore, it is important to take notice of the development of pneumatic formwork systems, which offers an economical construction method for concrete shells. The construction of concrete shells could be revived.

Concrete is the outstanding material used for structures, the shape of which has been designed in accordance with their internal flow of forces. Concrete offers many advantages, including:
- easy processing;
- high compression strength;
- high durability;
- low price.

and a further very important aspect: it can be formed into any shape, on the construction site.

However, concrete is preferably used today in rectangular shapes. The reason for this is less the requirements of the clients than the compulsion to reduce the costs of the formwork. Architects and engineers, therefore, have to face the fact that formwork techniques have more influence on the shape of today's concrete structures than the characteristics of the structural material itself, or the flow of forces within the structural elements.

Concrete structures which rely on an appropriate shape can only be realized with some difficulty in such a situation. As one of the results of this, the art of building concrete shells has nearly completely died out.

Shells are thin-walled structures which combine the function of loadbearing and space enclosure. Their high effectiveness is quite well known from natural shells such as mussels, diatoms, plant structures and the eggshell.

Shells in technical applications such as steam-boilers, cooling towers, wings or large-span roofs are impressive examples for the possible applications of this type of structure.

Shells are principally subjected to biaxial stresses. Since load transfer by bending action is, or should be of subordinate importance, the shell shape and the load bearing behaviour are interdependent [1, 2].

Form finding

It is known that shells cannot be designed by hand drawing, not only because of their spatially curved surface but also because the structure should show, if possible, uniform states of stress, under different load cases.

The shapes of shell structures are created today on the basis of different form finding techniques. The entire design procedure is called a 'Form finding process'. Within such a form finding process, a structural shape with defined characteristics under a form-defining load case is developed either by experimental or computer based methods.

Experimental form finding methods, such as pneumatically created shapes or suspension structures, are readily understood because of their visual impact. Precisely because they are so visual they are usually used for the first stage of the design process. After determining the essential boundary conditions and the structural principles, one then proceeds to computer based, mathematical form finding methods.

Some of the shapes which can be realized with pneumatic stabilized membranes

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The different principles of pneumatic stabilisation of a fabric membrane:
A: air-supported structure
B: air-inflated bag, partially water-filled
C: internal pressure below atmospheric pressure
D: a series of cushions which are prestressed by reduced internal pressure
E: air-inflated cushion
F: an air-supported membrane, the shape of which has been structured by cables

finding methods.
The most important experimental methods are:
- suspension structures;
- shapes created by plastification of thin sheets;
- pneumatically created shapes.

The computer based methods may be split into two groups: direct and indirect methods [3].
The direct methods are:
- the solution of the set of (differential) equations which describes the membrane shell [1];
- indirect methods in combination with optimization procedures.
The indirect methods are:
- the geometric non-linear finite element method;
- the force density method;
- methods based on vector analysis;
- algorithms limited to certain geometric conditions.

The direct methods facilitate the computation of the shape of a structure which shows a prescribed state of stress under the so-called form-defining load case for a given set of geometric and static boundary conditions.

It is important to note that the direct methods may not always yield a result, because the prescribed state of stress and the associated load case exclude any solution. The indirect methods may be used advantageously here because they always have a result. However, the state of stress within the shell, obtained at the end of such a computation, may vary from that required.

Construction methods
The curved geometry of a shell does not only add a degree of complexity to the design process, it also makes the construction of the building more complicated. Concrete requires a formwork, the shape of which is also the shape of the shell. In addition, this formwork has to carry the heavy dead weight of the fresh concrete.

Conventional formwork systems, such as shuttering with boards, are too expensive to be used for double curved shells. There are, however, only a few methods available which may reduce the costs for the formwork and thereby bring back the building of shells into the bounds of economic feasibility. Some of the most important of these alternative construction methods are:
- free cantilevering construction with cast-in-place concrete or precast elements;
- shotcreting onto a fine wire mesh net;
- earth embankments as formwork;
- use of pneumatic (air-supported) formwork systems.

The current level of knowledge indicates that only the method of pneumatic formwork fulfills the requirements:
- high level of prefabrication;
- quick erection and dismantling;
- almost unlimited spatial curvatures;
- large spans;
- multiple use.

Because of these interesting features, discussion in this paper will be restricted to this type of formwork (fig. 1-2).

Pneumatic formwork systems for concrete shells
The history of pneumatic formwork systems goes back to 1936. Since that time, a number of different systems and a series of different erection-procedures have been developed.
A water and air-filled formwork for concrete water-tanks

The inflated formwork is stabilized by the reinforcement; concrete is applied by shotcreting in several layers.

The most important are:
- high internal pressure formwork systems;
- concreting in single layers, appropriate when using shotcreting techniques;
- concreting in sections with hardening intervals;
- stabilizing the formwork with additional cables, also in combination with the reinforcement;
- stabilizing the formwork with plastic foams;
- finish concreting before the material starts hardening.

The individual measures can also be combined.

All of the methods mentioned above are characterized by the intention to reduce deformation in the formwork. This limitation and the control of formwork deformations are of importance because the formwork can change shape remarkably, under the load of the concrete. In addition, the concrete usually starts hardening while the concreting is still in progress. While it is hardening, the initially large deformability of concrete decreases appreciably. When it reaches minimum ultimate strain, the concrete is still very weak. In this phase, formwork deformations can lead to permanent damage of the concrete [1].

The simplest way of stiffening the formwork is to increase the internal pressure. However, this is only possible within narrow limits; on the one hand commercially available membranes, and in particular their joints, have a limited mechanical strength; on the other hand the uplifting forces rapidly become so great, that as a result of the measures necessary to anchor them, it is questionable whether the construction method is still economical. Therefore, a high internal pressure is only suitable for closed systems with small radii of curvature. This applies, for example, in the case of tubular formwork, used in Italy as early as 1938, to construct water lines (photo 3).

A system developed by Haim Heifetz, with which numerous smaller shells have been constructed since 1960, in particular in Israel, can also be described as a high-pressure formwork system. With this system, the membranes are connected to a rigid, easily transportable base construction. The forces are thus 'short-circuited' within the system itself, so that nothing need be done to anchor the formwork on the actual structure. Since the membranes are tightly curved, internal pressures of up to 10 kN/m² are possible. PVC-coated fabrics were used as membranes (fig. 4).

Partial or total filling with fluids, e.g. water, also increases the stiffness of the formwork. In addition, fluid and air filling allows one to enlarge the range of pneumatically formable shapes (fig. 5).

Whereas the application of high-pressure systems is limited, a wide range of structures can be built by concreting in single layers. This method was developed as early as 1948 by Wallace Neff, one of the pioneers of pneumatic formwork construction (fig. 6). Harrington uses the same principle today. He lays a system of
radially arranged cables over his dome-shaped formwork. The formwork is additionally stabilized by the cables and by the reinforcement fixed to them. Gunite is then carried out in several layers. A large number of shells, with spans up to 57 m have already been constructed in this way (photo 7-8).

Besides concreting in individual layers, step-by-step stiffening of the membrane can also be accomplished by concreting in individual sections. The parts of the shell already concreted and hardened then limit deformations of the formwork under the load of the fresh concrete. The size of the sections of the shell to be freshly concreted has to be decided on in such a way, that the concreting work is completed before the ultimate strains of the young concrete attain the same magnitude as the actual deformations of the formwork.

A pre-stiffening of the membrane can be achieved by spraying polyurethane foams onto the membrane. The foams, which harden within seconds, can be sprayed onto the interior or the exterior of the air-supported membrane. Total foam thickness is usually in the range of 80-150 mm, depending on insulation requirements. The foam is applied in single layers, each of them with a thickness of about 20-40 mm. Special fixation elements are pinned to the foam-shell before the last PU-layer is foamed. These elements allow easy fixation of the reinforcement. The concrete is applied by shotcreting usually, again in single layers of 20-40 mm. More than 100 shells with spans of up to 105 m have been constructed with this method up to now, most of them in the USA (photo 9-10).

Jan van Eeden has established the method in some European countries over the last 2-3 years. He currently has several buildings for bulk storage under construction.

Finally, two construction methods employing unstiffened formwork deserve mention, since they may be regarded as special cases. With the first, the Bini method, hardening of the concrete is delayed until concreting is finished: the reinforcement is laid on the membrane while it is slack. The concrete is poured on, and covered with a second membrane. Only then is the formwork inflated (photo 11).

During the inflation, the reinforcement has to undergo the same deformations as the membrane. For this reason, the Bini method requires a special type of reinforcement.
The second method is the use of precast concrete elements laid on the membrane. Only small quantities of fresh concrete are required, to grout the joints (fig. 12). As a result, the formwork is hardly deformed at all while the final concreting is in progress.

**Aspects concerning the shape of the formwork**

There is an almost unlimited variety of shapes which can be realized with pneumatic formwork systems. These shapes are said to be 'pneumatically possible'. A pressure load vector normally acts at each point of the formwork's surface. It is an external force which has to be counterbalanced by the internal forces within the formwork membrane. This relation is represented by the equations of equilibrium. A formwork membrane may be subjected to tensile stresses exclusively. The principal stresses within the formwork membrane are restricted, therefore, to the non-negative. These inequalities also have to be fulfilled at each point of the formwork.

The question whether a given shape can be realized with a pneumatic formwork or not must be answered on the basis of this characteristic set of equations and inequalities. The curvature of a structure is no criterion as to whether it is pneumatically possible or not.

The work and - sometimes - 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, itself, pneumatically possible.

The question whether the concrete shell with such a shape shows an advantageous load bearing behaviour can be answered mostly in the affirmative: 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 dead weight load, while the associated formwork membrane is only tensioned by the internal pressure load. However, the described state of stress does not occur with all concrete shells with the shape of a pneumatically-spanned membrane, because of effects caused by the boundary - or support - conditions [1]. The designing engineer knows these exceptions, and he will take the appropriate measures.

**Prospects**

It is obvious, that the construction of concrete shells may be revived by the use of pneumatic formwork systems. It is equally clear, that the art of building with concrete will profit greatly from it.

We, therefore, should take up the methods evolved by a few engineers throughout the last fifty years and completed by scientific research within the last decade. The method of the pneumatically stabilized formwork not only allows the realization of large-span structures within economic bounds - it also allows us, once again, to match structural shape and material properties.

**References**

2. Schlaich, J., Sobek, W., Suitable Shell Shapes. *Concrete International* 8, Heft 1, 1986.