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CONCRETE SHELLS CONSTRUCTED ON PNEUMATIC FORMWORK

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INTRODUCTION

In recent decades the number of concrete shells constructed has continued to decline. This is in large measure attributable to the high costs of the formwork: construction of the spatially curved formwork surface using conventional formwork methods is labor-intensive and rates of pay in industrialized countries are high. Consequently, the design solutions based on conventional methods are not economically justifiable. /1//2/.

There was, therefore, reason enough to make concrete shell construction competitive again by developing less costly formwork methods. One such method is pneumatically supported formwork. It combines a number of advantages, such as

- short erection and dismantling times
- low weight
- re-usability
- simplicity of construction of curved surfaces
- an almost unlimited range of shapes.

Thus, it appears to represent a particularly appropriate way of resolving the formwork problem. However, on closer examination of this method a series of questions immediately arise, concerning which there is only insufficient information available, or none at all:

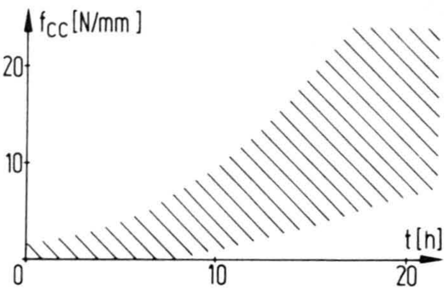
1) Questions related to methods of designing suitable shell shapes
2) Questions related to the materials:
   - suitable materials for the formwork membrane
   - questions of concrete technology
3) Methods of limiting the deformations of the formwork during and following termination of concreting work.

The questions entailed in (1) and (2) above are investigated in detail in /3/. The questions related to (3) above are considered in greater depth in the following.

PNEUMATIC FORMWORK AND CONCRETE AT EARLY AGES

Under normal exposure conditions the compressive strength of concrete develops within the range shown in Fig.1. The corresponding tensile strength always closely approximates 10 % of the compressive strength.

The constant increase in the strengths is accompanied by a constant decrease in ultimate strains. The minimum ultimate strain under compression is reached in the period from the eighth to the twelfth hour after mixing. Fig.2. Chronologically, the minimum ultimate strain under tension occurs shortly before the minimum ultimate strain under compression. /3//4/.



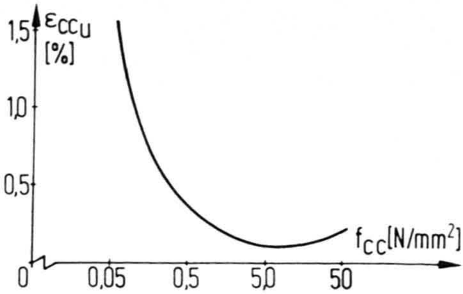


Fig.1: Concrete compression strength as a function of time: Range for concrete mixtures usually used. /3//4/.
Fig.2: Ultimate strain of concrete under compression as a function of compression strength. /3//4/.

During concreting pneumatically supported formwork undergoes comparatively large deformations. The concrete applied to the formwork is subject to these deformations. The higher its initial strength and the faster its strength develops, the more the concrete will reduce the deformations of the formwork caused by the loading with fresh concrete. Fig.3. However, the advantage of the resulting decrease in the deformations of the formwork is counterbalanced by the drastic reduction in the ultimate strains of the young concrete.

Theoretical investigations on domed shells /3//5/ and the study of structures built so far show that special measures usually have to be taken to reduce the deformations of the formwork and thus prevent damage to the young concrete.

METHODS OF LIMITING THE DEFORMATIONS OF THE FORMWORK

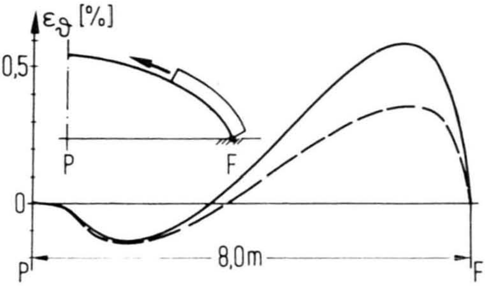
Increasing the internal pressure and fluid-filling

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.

Pneumatically supported tubular formwork systems were used in Italy as early as 1938, to construct water lines. Today, tubular formwork up to 3 m in diameter and 100 m long is in use. The systems can be used up to 350 times and are inflated to pressures of up to 35 kN/m^2. Most of them are made of polyamide fabrics coated with highly resistant synthetic rubber. /6/.

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. Fig.4. Since the membranes are tightly curved internal pressures of up to 10 kN/m^2 are possible. PVC-coated fabrics were used as membranes. /7/.



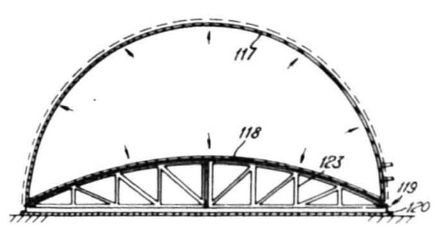


Fig.3: Theoretical investigations on domed formworks: Concrete deformations at the end of concreting, hoop direction. /5/.
Concrete without stiffness
Concrete was hardening while concreting was in progress
Fig.4: Haim Heifetz System. /7/.

The freshly poured concrete can build up high hydrostatic pressures. This occurs, for example, where there is lateral counterformwork against steeply inclined parts of the membrane. If this locally-acting concrete pressure is taken as a basis for calculating the required air pressure in the system, completely uneconomic designs will result, since there is then a high differential pressure acting on the whole of the rest of the membrane and this latter has to be designed accordingly. The problem can be resolved by complete or partial filling with fluid. Fig.5 shows a design by the author for a shell, in which the problem was countered by partially filling the formwork system with water: a high internal pressure is provided where a high external pressure is acting.

Partial or total filling with fluids also may be used to enlarge the range of pneumatic formable shapes and therefore to enlarge the range of shell-shapes which can be built using pneumatic formwork: e.g. it is well known that air-inflated shells of revolution with a height-to-span ratio "g" of less then 0.2996 cannot be built. On the other hand fluid-drops with vanishing g are nothing special. By combining fluid and air filling any desirable ratio g can be designed easily. Fig.6 shows an ultra-flat air-inflated formwork, partially water-filled. The structure was designed by the author for an underground fluid-storage project. Shapes with the height-to-span ratio of the structure shown in Fig.6 cannot be built using air-inflation!

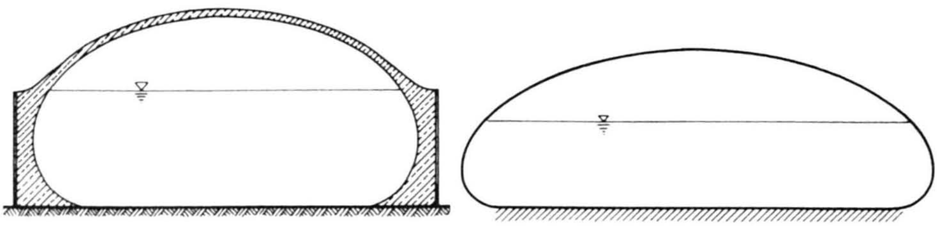


Fig.5: Air-inflated bag, partially water-filled. This type of formwork was developed for the construction of tanks used for fluid-storage. /3/.
Fig.6: Ultra-flat formwork, air-inflated and partially water-filled.

Large formwork systems with small curvatures can be stiffened by other means than an increasing of the internal pressure:

Three methods can be distinguished:

- stiffening of the medium in the interior
- stiffening of the formwork membrane
- designing formwork with a stiff shape.

However, the single methods may be combined.

While stiffening of the filling medium, e.g., by

- freezing a water filling
- evacuating a fluid-granulate filling
- using thixotropic fluids

has not been used so far, the various methods of stiffening the membrane are woven into the history of this building method like a red thread.

Concreting in single layers

Wallace Neff, one of the pioneers of the method, stiffened the membrane step by step by guniting in individual layers. In addition, he used the formwork to prestress the reinforcement. By so doing he not only had a prestressed concrete shell when the formwork was deflated, but also contrived to give the membrane additional stiffness during concreting work. It was thus possible to limit the internal pressure to approx. 2 kN/m^2. The materials he usually used for the formwork were neoprene-coated polyamide fabrics. /8/. Fig.7.

Harrington employs a similar method. 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. Guniting is then carried out in several layers. A large number of shells, with spans of up to 57 m and wall thicknesses of approx. 9 cm, have already been constructed in this way. Fig.8.

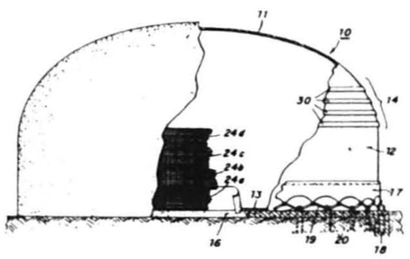


Fig.7: Drawing excerpt from the patent of Wallace Neff. /8/.
Fig.8: One of Harrington's shells during construction.

Concreting in sections

Beside 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 the 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.

Stiffening the formwork with plastic foams

Spraying of polyurethane foams onto the membrane makes sense if subsequent thermal insulation of the concrete shell is necessary. The foams, which harden within seconds, can be sprayed onto the interior or the exterior of the membrane. Correspondingly, the concrete can afterwards be applied to the interior or the exterior of the formwork. On the basis of these many possible combinations a series of company-specific methods have been developed, and they have been used hitherto for many different applications, e.g., residential buildings, churches, warehouses, and manufacturing facilities. /9//10/.

Formwork with stiff shape

Apart from stiffening of the membrane, deformations of the formwork can also be limited by designing formwork with a stiff shape. Hardly any use has so far been made of this possibility, even though it is very easy to structure a shape with cables or cable nets, for example. If the overall shell curvature is only slight, the tight local curvatures not only produce very stiff formwork; they can also improve the loadbearing behavior of the concrete shell thus constructed.

This idea was put into practice by J. Schlaich, F. Bacher, and the author for a rainwater interceptor tank. Fig.9 shows the formwork. Radially arranged cables stabilize the formwork and create a shell structured by ribs. This advantageous shell shape made it possible to dispense with reinforcement in the upper part of the shell almost completely. The shell will later be entirely covered with soil. A PVC-coated polyester fabric was used as a formwork membrane. The internal pressure was 10 kN/m^2. The formwork was deflated just 28 hours after concreting was started.

Concreting onto the slack membrane and use of precast elements

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 it and covered with a second membrane. Only then is the formwork inflated. The reinforcement has to undergo the same deformations as the membrane and for this reason the Bini method requires a special type of reinforcement. /11/. Fig.10.

It is conceivable that the need for expensive special reinforcement with the Bini method can be obviated by using fiber-reinforced concrete. To this end the U.S. Army has performed a series of tests with steel fiber-reinforced concrete and small formwork membranes up to 2,75 m in diameter. However, the method is not known to have been used for larger shells. /12/.

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. As a result the formwork is hardly deformed at all while concreting is in progress. Fig.11 shows the design for an ice-stadium with a span of 100m which is based on this idea. The structure was designed by J. Schlaich. A structured formwork surface is created with cables, so that not only is the stiffness of the formwork increased but also the architectural appearence of the shell thus produced is more interesting.

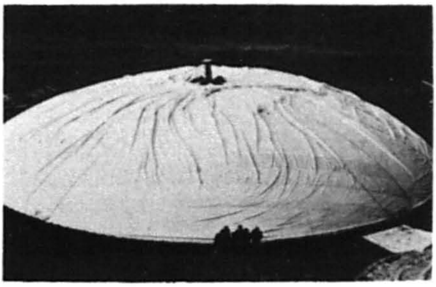
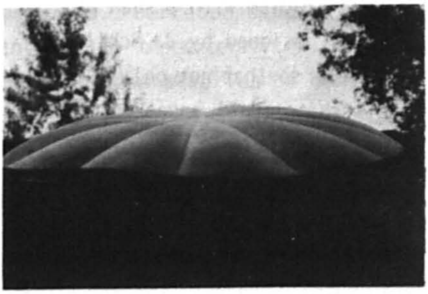


Fig.9: Rainwater interceptor tank: Inflated formwork.
Fig.10: Bini-Method: Formwork during inflation.

FURTHER DEVELOPMENTS

It is remarkable that most of the shells which have been built up to now using a pneumatic formwork system are shells of revolution. And it is remarkable that stiffening the formwork membrane is the only method usually used to reduce formwork deformations. Structured and therefore stiffer shapes have only occasionally been used. The structuring and above all the combinations of the two methods have advantages which are related not only to the formwork membrane but also to the loadbearing behavior of the concrete shell and in particular to its architectural appearance. Further development, therefore, should be done with this in mind. However, the design of these shapes is much more difficult than the design of the shells of revolution usually built up to now. Easy-to-use methods therefore have to be developed: methods aimed at finding ideal shapes for concrete shells and procedures for showing that the formwork membrane of the same shape is pneumatically formable. The present author has been working in this field for some years. As a basis for further research, he developed a computer-based method for form-finding plus form-analysis plus check of pneumatical formability. Fig.12. The method developed to check pneumatical formability is reported in /3/.



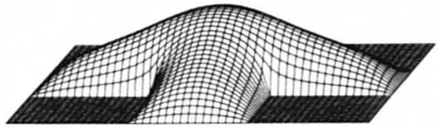


Fig.11: Roof for an ice stadium 100 m in diameter, model.
Fig.12: Formfinding of structures using computer-methods: pneumatically spanned soap-film, cross shaped ground plan.

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