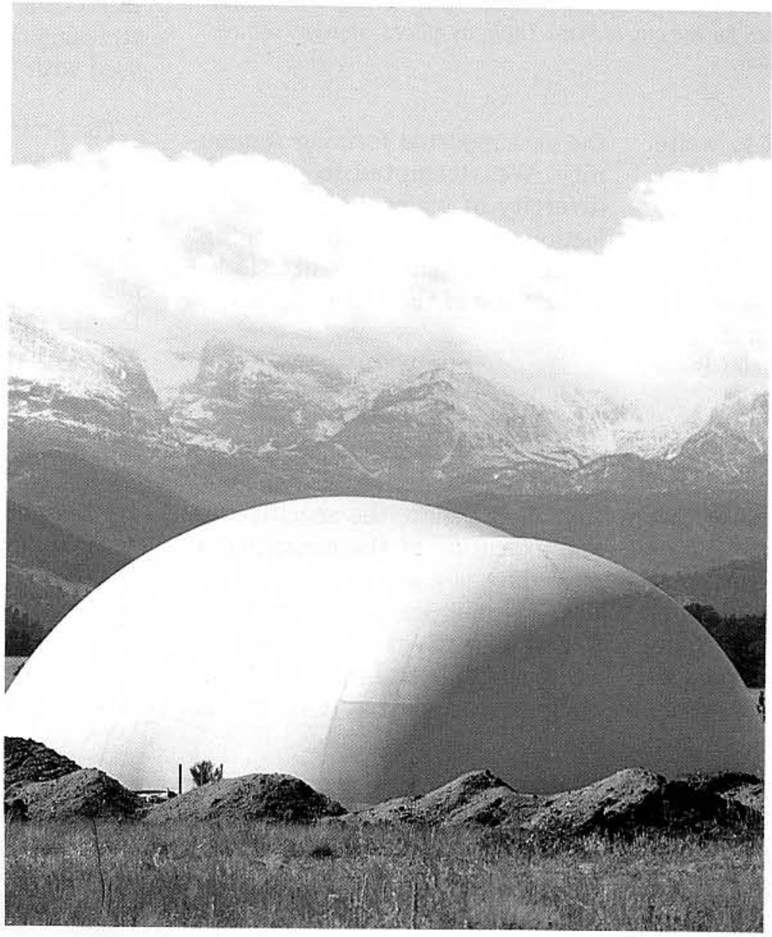
Air-Supported Forming: Will It Work?

an overview, some prudent suggestions, and a prognosis for the future

by Robert B. Haber

In 1984, ACI-ASCE Joint Committee 334 on Concrete Shell Design and Construction decided to organize a technical session on "Concrete Shells Constructed on Air-Supported Forming" for the March 1985 ACI annual convention in Denver. The session would include presentations on various systems for concrete shell construction in which inflated membranes replace conventional forming systems. While the committee was aware of some activity in this area, there had been little direct contact between the committee members and designers and contractors using this construction method. Finding participants for the session proved to be more difficult than expected: the call for papers went unanswered, and active searching turned up only a few potential speakers.



Steele Street Studios, Photographer: Durango Steele

This double spherical air form located near Estes Park, Colo. will become a beautiful mountain home, according to the design of architect Jonathon Zimmerman.

It appeared that the session would have to be cancelled, when some serendipitous telephone calls led to the identification of an enthusiastic group of shell designers and contractors working with air-supported forming systems. Seven presentations were made at the Denver session, which was well-attended and well - received Through the session activities it became clear that although shell construction using conventional forming techniques had declined, air-formed concrete shell construction was enjoying a period of active growth; no doubt due to the construction cost savings possible with this method. At its meeting following the technical session, Committee 334 voted to form a subcommittee, "Air-Supported and Non-Traditional Forming Systems for Shells," to establish closer ties with this "grass-roots movement" in shell construction.

After the enthusiasm generated by the convention session, the staff of *Concrete International* proposed a special issue of the magazine to increase the engineering community's awareness of air-supported forming methods for concrete shells. Several of the ses-

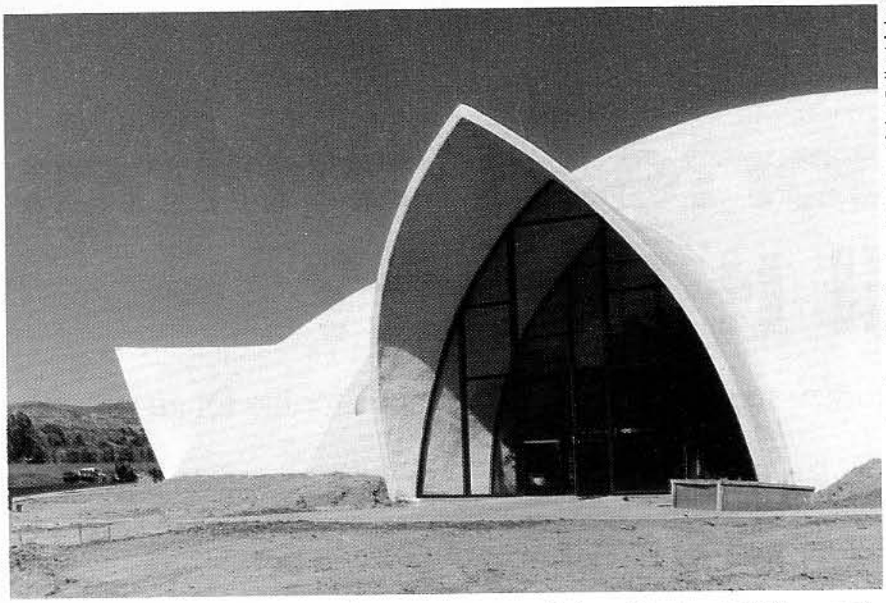


Photo courtesy Monolithic Constructors Inc., Idaho Falls, Idaho

These four domes with gothic arch entryways were designed by Arnold Wilson and built by Monolithic Constructors for the city of Price, Utah, as offices, storage, vehicle storage, shops, and a fire station.

sion participants agreed to write articles for the issue, and other shell designers and builders were invited to contribute. The responsibility for selection and review of articles was shared between the *Concrete International* staff and Committee 334. This special issue is the result of that effort.

Articles were selected to survey the technical issues unique to this construction method, and to represent the varied architectural and industrial possibilities of air-formed shells. We found that there are differences of opinion regarding certain technical points within the air-supported forming community. We attempted to include a diversity of viewpoints in our selection of articles, in the hope that continued discussion will help resolve some of these questions.

Overview

In addition to the usual strength and serviceability requirements of thin shell design, the specification and execution of the construction procedure is a key concern of air-formed shell designers. The competing objectives of cost control and quality control need to be reconciled. Various solutions to this technical problem have been proposed and used successfully.

One commonly used method is described in Arnold Wilson's article. Here a layer of urethane foam is applied to the inside surface of an inflated membrane. This stiffens the air form, and provides a support for attachment of reinforcing steel. Concrete is then sprayed inside the foam layer. Domes up to 200 ft (61 m) in diameter have been built with this method.

Another way is to apply the concrete to the exterior of the fabric air form; an article on page 65 details this technique. Both prestressing and post-tensioning are used with these shells.

The article by Roessler and Bini describes a patented system in which wet concrete and reinforcing are placed over the air form at ground level, and then lifted into place by inflating the membrane. Domes up to 118 ft (36 m) in diameter have been constructed by this method.

In a method proposed by Robert Nicholls, a mortar mix is placed dry between layers of nonwoven, needle-punched fabric that serves as both the air form and the tensile reinforcing for the dome. Hydration of the concrete is performed after inflation. This approach reduces the need for spe-

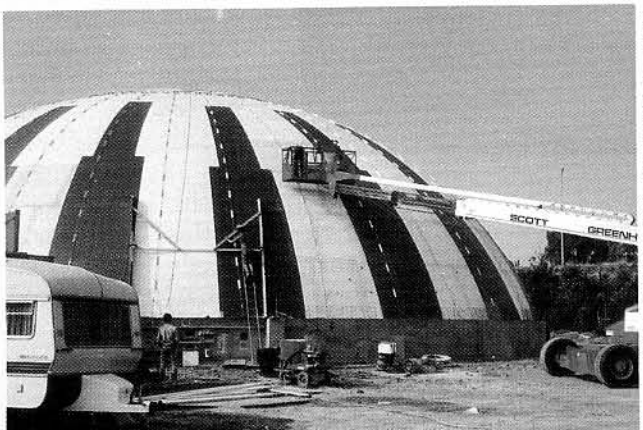
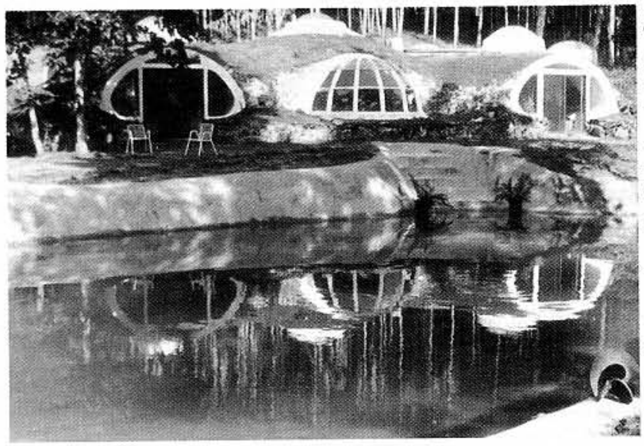


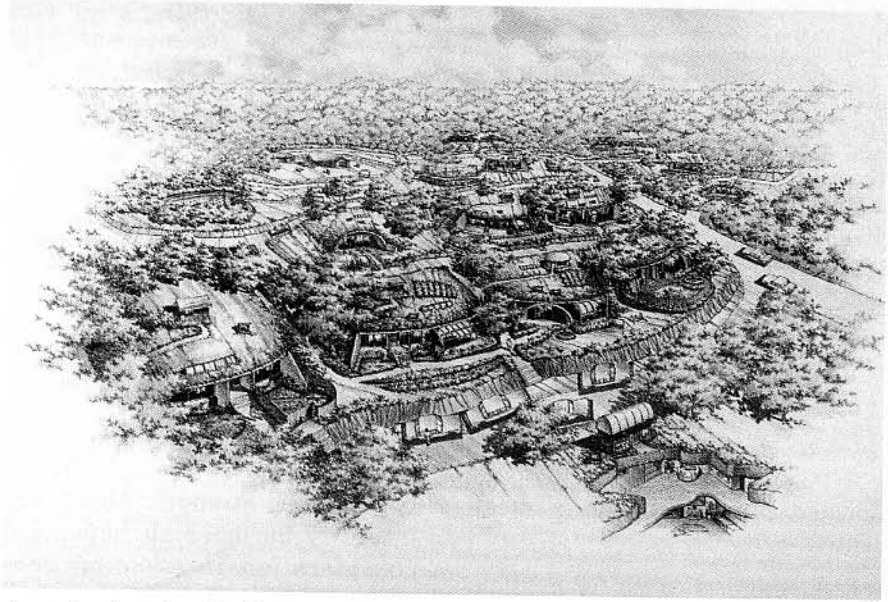
Photo courtesy HP Domes, Pittsburgh, Penn.

A prestressed and post-tensioned dome to store road salt was recently built in Northampton, England, under the supervision of Horrall Harrington.



This cluster of domes was designed by Utopia Design of Eugene, Ore., to form an earth-sheltered home.

cialized construction equipment, but is probably best suited for shorter-span, low-rise domes.



Courtesy Wukasch and Associates

An entire housing development of earth-sheltered homes built using air-supported forms, is the vision of architect Eugene Wukasch.

In addition to construction cost savings, an intriguing feature of air-supported forming systems is that the shapes defined by inflated membranes subjected to pure tension can also be desirable shapes for compressive shell structures. Proper shape design for given loads and support conditions is an important aspect of shell design, particularly for larger structures. The problems of designing suitable air form shapes for shells is discussed in the article by Schlaich and Sobek, which also provides an indication of the level of activity in air-formed shell construction in West Germany.

Technical requirements for the fabrication and erection of inflated forms are surveyed in the article by Jack Boyt, a supplier of fabric air forms. Balloons can be manufactured as spheres, ellipsoids, or other more complex shapes.

Air-formed concrete domes have been used in a wide variety of architectural and industrial applications. The largest domes of this type have been used for bulk storage of materials, as described in the article by Jack Brunk.

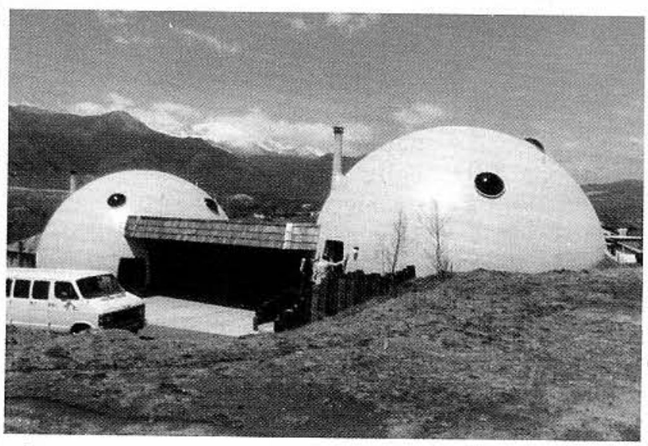
The smooth doubly-curved forms that result from this construction method have sparked the imagination of architects. The architectural implications and possibilities of air-formed construction are explored in a trio of articles by Lloyd Turner, Jonathan Zimmerman, and Eugene Wukasch.

Some problems have been encountered by contractors during the relatively short history of this technique. An article by David South reviews the history and outlines some of the problems.

Other developments in the field are described in a series of articles in the "Concrete Kaleidoscope."

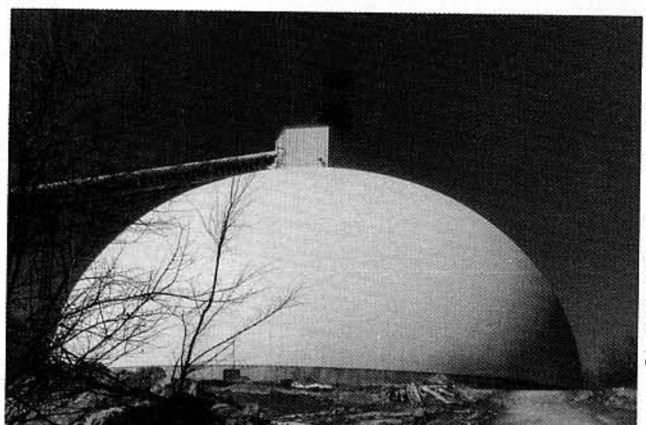
Prospects for further development

Engineers interested in thin shell concrete domes are sure to be gratified that shell construction in the United States is not as dormant as many would have believed. Air-supported forming appears to provide an economically viable construction method that could be the basis for a new program of shell design and construction. At the same time, there is a very enthusiastic group of designers and builders, buoyed by previous successes with the method. It would appear that the prognosis for further development of air-



Precision Air Structures, Des Moines, Iowa

This duplex near Colorado Springs, Colo., was built using two 35 ft diameter air forms supplied by Precision Air Structures.



Precision Air Structures, Des Moines, Iowa

Porter Grain Co., is building some of the biggest air-formed concrete shells in America; this one is in Weeping Water, Neb.

Photo courtesy Lloyd Turner, Boulder Creek, Calif.

Architect Lloyd Turner built his home to illustrate his architectural theory that a house should "fit" its site.

formed concrete shells is excellent.

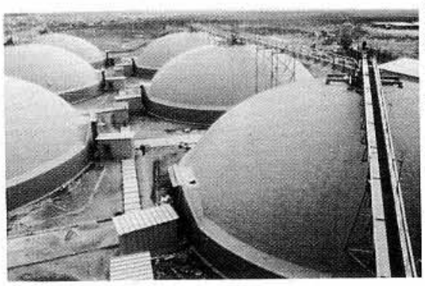
Still, there is cause for caution. A good deal (although not all) of the previous experience with air-formed concrete shells has been with domes of small to moderate span and large curvature. Under these conditions only rudimentary engineering design is required because the basic necessities of construction and the natural efficiency of shell forms guarantee more than adequate strength.

An entirely different situation prevails for large-span shallow-curvature shells, which require careful and specialized engineering design methods. At this scale, the effects of creep, shrinkage, temperature, and large deflections under load must be considered; stability considerations may also govern shell strength. Membrane integrity becomes an important consideration in avoiding construction failures, creating a need for cable reinforcing of the membrane. Reduced membrane curvatures decrease the capacity of air-supported forming to carry wet concrete. Increased inflation pressure provides only limited relief to this problem. Geometry imperfections, which may have negligible effect at small spans, can lead to critical loss of stiffness in shallow shells.

Claims that the air-supported forming concept will permit the construction of domes of "unlimited span" are clearly unfounded. Erection procedure is not the only issue limiting the feasible span of concrete dome structures. The history of structural failures is littered with examples of structural concepts that perform very well at one scale, but are entirely inappropriate at another. Sophisticated design procedures, executed by well-trained engineers, are required if the air-supported forming concept is to be applied to large-span structures.

Photo courtesy Concepts in Concrete, Tulsa, Okla.

Showing that air-formed structures can be used for things other than domes, Concepts in Concrete built this bridge culvert.



Howe International, Ottawa, Ont.

This seven dome module for storage of 30,000 tons of grain in Iraq was built by Howe International using the Binishell technique.

The resolution of some of the disputes in the design community might depend on the scale of the dome under consideration. For example, cheaper erection procedures that sacrifice some degree of quality control might be most effective for smaller shells; while more expensive techniques that permit more accurate placement of concrete and reinforcing material might serve better for larger projects. The need for accurate control of the concrete section thickness might determine the choice of erection procedure, particularly for larger domes.

Another debate has centered around the possibility of replacing conventional reinforcing steel with fiber reinforcing — a subject of active debate for general concrete construction. This issue is far from settled, but it can be safely stated that accurate and controlled placement of reinforcing — whether bar or fiber — within the shell section is important. Extra care is needed to guarantee this control with any of the construction methods under consideration. Pure fiber reinforcing might be adequate in smaller domes, but some conventional bar, mesh, or cable reinforcing is probably required to insure continuity in larger projects and to provide local strength around openings and at supports.

If there is a key issue in shell design, it is shape. The ability of air-supported forming to economically generate complex curved geometries indicates that significant returns could be realized by further research into shell form. These explorations should include architectural and esthetic studies, along with research into the relations between shape, construction procedure, and structural performance. To date, only simple surfaces of revolution, spheres and ellipsoids, have been used in the larger air-formed shells. More efficient shell shapes, that emphasize membrane response over bending deformations, are known to exist.

Computer-aided design methods, widely used in the fabric structure industry, are available to determine suitable membrane shapes. Procedures for automatically determining precise two-dimensional fabric cutting patterns for general membrane shapes are also available. These automatic procedures will be needed to effectively exploit the possibilities of free-form shell geometries and cable-reinforced membrane shapes. Manual patterning methods are laborious and can lead to unacceptable deviations from the design geometry.

Detailed modeling of the erection phase might be required for the design of major structures. The weight of wet concrete and reinforcing will generate significantly different membrane shapes than are predicted by "weightless" membrane theory. If the concrete is placed in layers, with time allowed for old layers to set before a new layer is placed, then a simulation of the construction sequence might be necessary to predict the final geometry and state of prestress in the shell.

In summary, it is likely that significant progress is possible in the design of concrete shells constructed on air-supported forming. Refinements of construction technique and structural and esthetic design could lead to new architectural and industrial design solutions. As always, safety and reliability, based on sound engineering practice, should guide the design of large-span structures.

Robert Haber *is an associate professor of civil engineering at the University of Illinois at Urbana-Champaign. His research interests include structural mechanics, and computer-aided structural design and optimization. He has consulted in the design of membrane tension structures, and is the chairman of the newly-formed subcommittee on Air-Supported and Non-Traditional Forming Systems for Shells which is under ACI-ASCE Joint Committee 334, Concrete Shell Design and Construction.*