Construction of Concrete Shells Using Inflated Forms

Reported by Joint ACI-ASCE Committee 334

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This report provides information on the construction of structural concrete shells using an inflated form. Major facets of the construction process are covered, including foundations, inflation, monitoring, and backup systems. Other aspects, such as the geometric variations of inflated forms, thickness of polyurethane foam, and mixture proportions for shotcrete, are also considered.

Keywords: dome; fabric; inflation; polyurethane foam; reinforcement; shotcrete; thin shell.

CONTENTS

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CHAPTER 1—GENERAL

1.1—Introduction (Fig. 1.1)

For centuries, arched and dome-shaped structures have efficiently enclosed large clear-span volumes. The strength of compound-curved surfaces allowed early builders to construct self-supporting thin-shell buildings from a variety of materials. Due to the tremendous amount of time and effort needed to create the desired shapes, construction of these thin-shelled structures sometimes spanned several decades.

Knowledge of the design and construction of thin-shell concrete structures has greatly increased over the past 100 years, both from research and practical experience. In the past 40 to 50 years, the use of inflated forms has allowed shells to be constructed more economically (South 1990). This new type of construction process presents new challenges and concerns. Safety measures and construction tolerances are addressed in this report for many types of systems using inflatable forms.

1.2—Scope (Fig. 1.2)

This report contains the lessons learned in the construction of thin-shell concrete dome structures using inflated forms. As this method of construction continues to gain popularity, additional research is needed to increase understanding of the behavior of this type of shell so that inflated-form structures continue to meet adequate levels of safety and serviceability. Included are construction procedures, tolerances, and design checks to ensure that the finished structure meets adequate safety and serviceability levels. This document focuses primarily on inflated form thin shells using polyurethane foam as part of the construction process. Many structures are built using fabric forms where the concrete is applied directly to the form either from the outside or the inside. These general guidelines apply to all methods.

1.3—History (Fig. 1.3)

Since the early 1940s, several methods of construction using inflatable forms have been used. These methods include

Fig. 1.1—Faith Chapel Christian Center, Birmingham, Ala.: 280 ft (85.35 m) diameter and 72 ft (22 m) tall that includes a 3200-seat sanctuary, classrooms, and an administration building.

Fig. 1.2—Price City Works Complex, Price, Utah. Four domes: 130 x 43 ft (40 x 13.1 m) fire station; 130 x 43 ft (40 x 13.1 m) storage facility; 130 x 43 ft (40 x 13.1 m) maintenance shop; and 90 x 40 ft (27 x 12.2 m) office and administration building.

Fig. 1.3—U.S. Borax and Chemical Co., Boron, Calif.: two 20,000 ton (18,000 tonne) borax storage domes, 150 x 79 ft (45.7 x 24.1 m).

shotcrete applied to the form exterior, and foam and shotcrete applied to the form interior.

In 1942, Wallace Neff received a patent on a system where the form was inflated to the shape of the structure, and then the reinforcing bar and shotcrete were placed on the exterior of the form (Neff 1942). Dante Bini later developed and received a patent on a system where the reinforcement and concrete were placed on the exterior of the form before it was inflated. It was then raised by air pressure to form the dome (Fig. 1.4) (Bini 1986).

In 1972, Lloyd Turner received a patent on a process in which the inflated form was sprayed with foam on the inside to a desired thickness creating a self-supporting foam dome

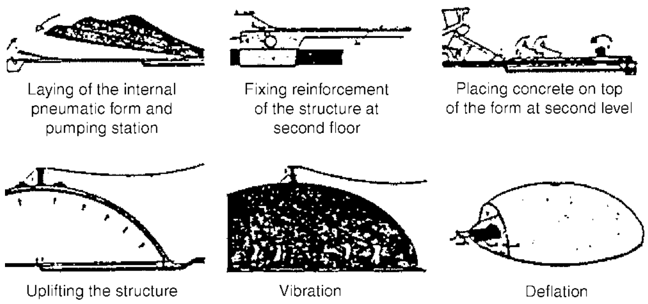

Fig. 1.4—Construction of Bini shell.

(Turner 1972). The patent was later reissued with concrete applied to the interior of the foam (Fig. 1.5).

In 1979, David and Barry South were issued patents on a method similar to that of Turner's (South 1979). Their method differed in that the structure was self supporting only after the shotcrete was in place (Fig. 1.6) (South 1986).

All patents for the use of inflated forms in construction of thin shells are now in the public domain with one exception: the Crenosphere™, the technique patented by David South for the construction of thin shell domes of diameters larger than 300 ft (91 m) using a cable net restraint system and ribs.

When the concrete is placed on the outside of the form, the cables will be buried in the concrete and function as reinforcement. When the concrete is placed on the inside of the form, the cables are removed once the structure is solid.

Bridges and arch buildings have been built using inflated forms where inflation forces are restrained by steel hoops placed on the exterior of the inflated form. Some very large dome-type structures have used steel tie-down systems to allow higher inflation pressures.

1.4—Methods (Fig. 1.7)

Inflated-form, thin-wall shotcrete construction has become one of the most common and widely used methods in the construction of domes. The Monolithic Dome Institute estimates over 2000 thin shells have been built over the last 30 years using the fabric form method, whereas those built with conventional forming methods are few in number.

Until recently, only a few contractors have possessed the skills and the equipment necessary to undertake this type of construction. As architects and engineers are becoming aware of the advantages of this inflated form method and its use increases, industry design and construction standards are needed.

Shotcrete can be placed on the inflated form from either the outside or inside. Some systems use higher air pressure and the inflated fabric form to support all the loads, whereas others support some construction loads with a reinforcement layer and initial layers of shotcrete.

Although each method has unique construction challenges, they all have many similar characteristics. This report does not distinguish between the different methods or make judgments as to the validity of each. It discusses the construction factors that are common to all of the inflated form methods:

- *Inflated form manufacturing*—shape, size, fabric, and fabrication;

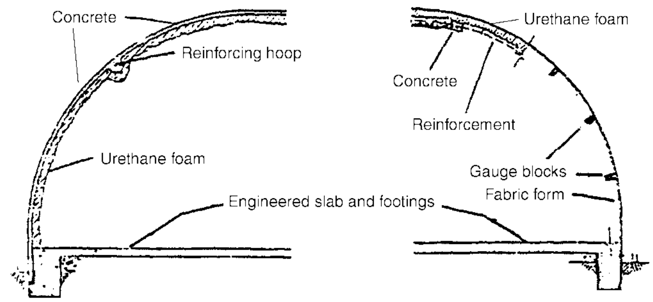

Fig. 1.5—Construction of Turner shell.

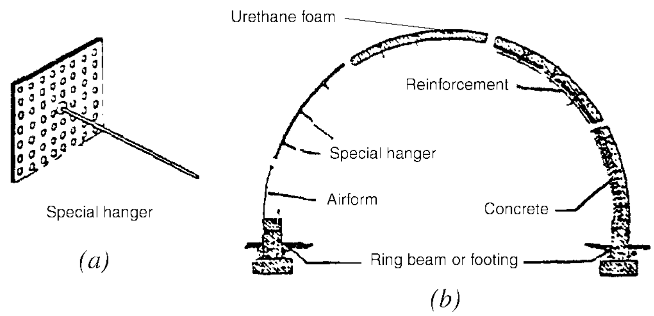

Fig. 1.6—Construction of South shell.

Fig. 1.7—"Eye of the Storm," Sullivan's Island, S.C.: prolate ellipse residence—80 ft (24.4 m) long, 57 ft (17.4 m) wide, and 34 ft (10.4 m) tall.

- *Foundation details*—anchor system, uplift prevention, layout, and form tension;
- *Air pressure*—backup system, monitoring, and collapse prevention; and
- *Applied loads*—live loads and dead loads.

1.5—Definitions

basket—the personnel aerial lift platform that raises workers to work on the dome.

dead loads—the fixed weight of a structure plus any fixed loads such as attached equipment, bridges, supports, head houses, platforms, catwalks, ceilings, and conveyors resting or hanging from the structures.

embeds—anchor bolts, inserts, pipe sleeves, pipes, conduits, reinforcement, wiring, flashing, instruments, and other devices encased in the concrete.

inflator—the fan or blower assembly.

manometer—the pressure gauge for measuring the air pressure within the inflated form.

preliminary reinforcement mat (premat)—a grid of No. 3 or 4 (No. 10 or 13) bars at approximately 2 ft (0.6 mm) on center, which gives the dome additional stiffness and strength before the first layer of structural reinforcement is placed.

rebound—aggregate and cement paste that ricochets off the surface during the application of shotcrete because of collision with the hard surface, reinforcement, or other aggregate particles.

shear key—a longitudinal notch in the footing that acts as a mechanical shear connector between the dome shell and the footing.

shotcrete (for construction of thin shells using inflated forms)—generally a mixture of cement, sand, pea gravel with a maximum aggregate size of 3/8 in. (10 mm), and water projected at high velocity onto a surface. See ACI 506R for more information on shotcrete.

1.6—Preconstruction

All-weather road access to the site should be provided for the constructor's personnel and vehicles during construction.

The contract documents should provide the general layout of the dome, including a center point and orientation for doorways. The preconstruction and construction testing procedures should be agreed upon between the owner and the constructor. (The owner usually provides for all testing either in-house or by use of a testing agency.)

1.7—Work schedule

Most of the work done inside and outside the dome is from baskets. Because only a few people can work out of any single basket, production can be increased by working longer hours or, on larger structures, using more baskets. When spraying foam or shotcrete, schedules are greatly influenced by weather conditions or how much work that can be done at once, so flexibility is important in creating the work schedule. The constructor may work one, two, or three shifts, arranging their work to best fit the project requirements. Job site cooperation is important to assure a quality, safe, and productive project, as well as to minimize the risk associated with this method of construction (for example, relying on fans to hold up the dome).

CHAPTER 2—FOUNDATIONS

2.1—General

The dome foundation usually consists of a reinforced concrete ring-beam footing, circular in plan, rectangular in section, and designed for anticipated loadings and soil bearing conditions. The footing usually acts as a tension ring to resist vertical and internal loads. Design considerations include the size of the dome, the occupancy, local building codes, relevant national standards, and soil report (Fig. 2.1) (Billington 1982).

The footing ring beam provides the foundation for the finished structure, anchorage points for the inflated form (Fig. 2.2), the weight to resist the upward pressure of the inflated form, and the air seal to prevent the pressurized air from escaping. The footing ring can also be used as a tension ring to resist the horizontal thrust of internal loading.

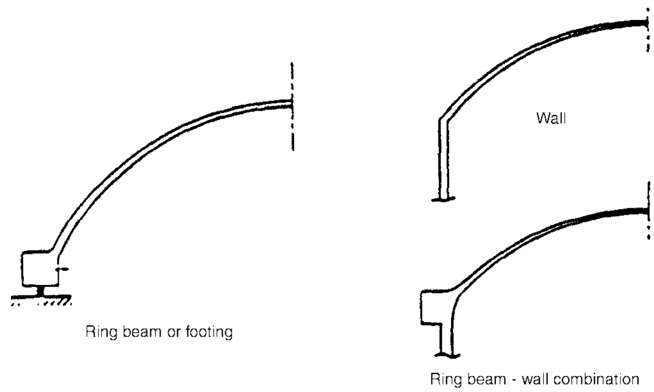

Fig. 2.1—Dome edge constructions (Billington 1982).

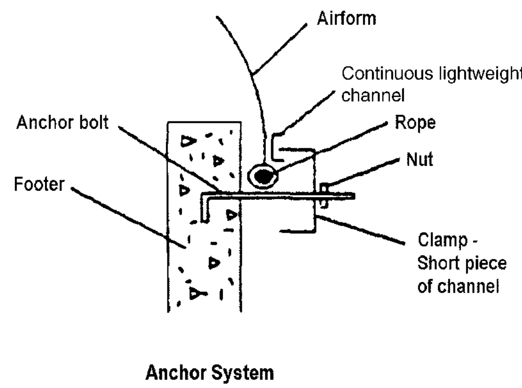

Fig. 2.2—A typical anchoring system.

2.2—Concrete

Certification that the concrete meets ASTM C 94 should accompany each concrete delivery.

Concrete properties and handling should conform to ACI 301 and the following:

- Minimum 28-day compressive strength of 3000 psi (210 MPa);
- Maximum coarse aggregate size of 1 in. (25 mm);
- Air entrainment of 6.5 ± 1.5% (these are higher levels than in ACI 214R);
- No added calcium chloride;
- Water-cement ratio of 0.55 or less; and
- Slump of 2 in. (50 mm) minimum to 8 in. (200 mm) maximum at the point of discharge.

If placed on aggressive soils, greater strength or chemical resistance can be achieved by adjusting the mixture proportions. For instance, the use of sulfate-resistant cement may be required.

2.3—Soil conditions

When soil conditions allow, excavating a trench to the required dimensions and placing the concrete and reinforcing bars in the trench is acceptable. If trenches are not practical, then wood or metal forms can be used. The top of the footing should be formed and finished to final grade and geometry for proper inflated form attachment.

Because the dome is light and the shell is monolithic, it is generally tolerant of differential settlement. Spread footings are normally used, but if the soils do not have adequate bearing capacity, pilings can be used to support the dome. The ring beam and the dome must always be integral. If piles or columns are used, the ring beam can be set on top of the piles. The conventional grade beam may not be needed, but the ring beam is required. If the dome is built or resting upon columns and walls, the dome will be able to withstand differential settlement, but the columns and walls may not.

The footing trench should be inspected for proper bearing voids or loose compaction. Because of the bridging ability of the concrete dome, small areas of uncompacted material (less than 15% of the footing), can be tolerated.

The footing and shell structures should, in all cases, be separated from the floor system when bulk storage of material is expected on the inside. This will prevent the floor settlement from damaging the shell footing and foundations. There are many cases, however, when the footing and floor should be placed together then connected to the shell, creating one continuous piece that moves together. These options and needs should be discussed with the engineer.

2.4—Reinforcement material

Reinforcement properties should conform to ACI 301. File copies of standard mill-run metal are used to confirm that the quality and quantity of reinforcement delivered to the project is in accordance with the contract documents. An inspection should be made of each shipment, and the inspection report should become part of the quality assurance record. The reinforcement for the dome is usually placed on cribbing inside the foundation area and then covered before spreading the fabric form out and connecting the form to the foundation.

2.5—Placement of reinforcement

Foundation reinforcement should be placed in conformance with ACI 301 and to the position shown on the contract documents. Reinforcement supports, such as chairs, should be used to attain proper vertical positioning (Fig. 2.3 and 2.4).

Concrete domes usually require significant reinforcement at the sides of the doorways and matching dowels from the foundation. To prevent field bending of bars larger than No. 7 (No. 22), pipe sleeves can be placed in the foundation. Reinforcing bars can then later be inserted into the sleeves and grouted in place with nonshrink grout (Peterson 1998). Mechanical splice connectors can also be used to connect short vertical dowels placed in the footing. The pipe sleeves will generally not be longer than the lap length of the particular reinforcing bar that is going to be inserted.

The reinforcement should be inspected for proper placement, including lap length and lap staggers.

2.6—Placement of anchors

Several different anchor systems are available to secure the inflated form to the foundation ring beam. Each system needs to ensure that the loads will be properly transferred to the foundation. The inflated form tie-down bolts should be accurately positioned in the formwork before concrete placement.

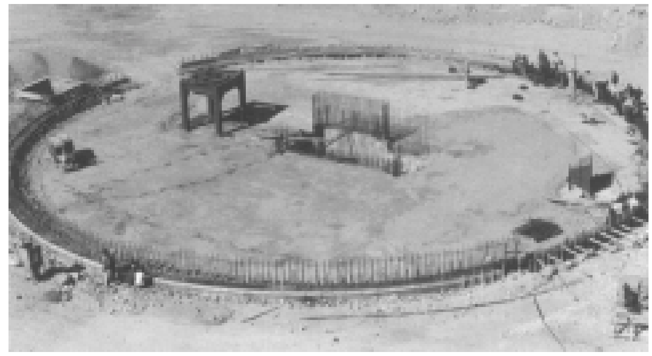

Fig. 2.3—Ring beam footing.

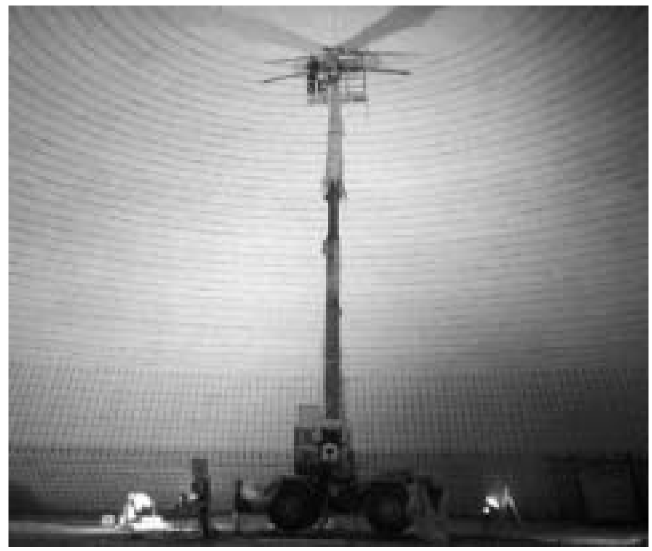

Fig. 2.4—Attachment of reinforcement.

Some manufacturers of inflated forms insert a continuous rope in the bottom of the inflated form and anchor the form by clamping a steel strap or bar above the rope to the foundation. Along with transferring the loads to the foundation, the anchoring system should provide an adequate seal to prevent excessive air leakage (Boyt 1986). Anchors should not impart high local stresses to the inflated form.

2.7—Concrete placement

The concrete should be placed in accordance with ACI 301. Concrete should be placed continuously, or to preplanned construction joints, as described in ACI 304R. Construction joints, if used, should be located away from entranceways, because the additional reinforcement usually placed there can cause joint-forming problems. The concrete should be consolidated by vibration, as described in ACI 309R.

The top of the footing should have a scratched finish, in conformance with ACI 301. The top of the footing should also have a preformed or hand-formed shear key. Before applying the shotcrete to the dome shell, the foundation should be cleaned of dirt and loose debris.

Fig. 2.5—Vertical dowels field-bent down.

2.8—Foundation dowels

If required, after the concrete is placed and sufficient strength is attained in the footing, the vertical dowels should be field-bent down (Fig. 2.5). This field bend should be in accordance with ACI 301. Vertical dowels should be secured and padded so they do not interfere with spreading of the fabric form. After the fabric form is inflated and the foam is placed, these bars will be bent back up to the vertical position to be lapped with the shotcrete reinforcement. If a dowel breaks, it should be replaced by drilling into the footer, embedding a new dowel in the hole, and applying an appropriate epoxy.

Foundation vertical dowels, when lapped with the dome reinforcement, should connect the dome to the footing. The dowels can be placed and tied before the concrete is cast or inserted and consolidated into fresh concrete. Insertion into fresh concrete requires that the foundation depth exceed the development length of the dowels to provide proper reinforcement clearance to the ground. For more information about reinforcing bar bending, see ACI 318.

2.9—Uplift prevention

The designer of the foundation should consider the possibility of uplift. The concrete foundation weight should have an adequate factor of safety against vertical displacement or ground anchors added to resist uplift caused by the form inflation pressure. A factor of safety of 1.25 is the minimum recommended. If the shape is asymmetrical, the foundation should also be designed to prevent horizontal movement (Wilson 1986).

CHAPTER 3—INFLATED FORMS

3.1—General

The fabric form consists of a single-ply membrane that stretches when attached to the foundation (Fig. 3.1). Several variables affect the actual shape of the inflated forms, including weather and tolerances in fabrication. Predicting the exact inflated dimensions of the fabric form is impossible. The material used in making inflated forms can differ in how much it stretches, producing slight variations in the shape of the inflated form. These variations are usually within the tolerances allowed for the dome. The height of the fabric form should be within 3% of the total height of the design measured at the center of the building. For example, a 200 ft (61 m) diameter hemisphere may have a measured height at the center that varies ±3%, which equals ±3 ft (±0.9 m) or between 97 and 103 ft (29.6 and 31.4 m).

Fig. 3.1—Inflation of Natural Ovens Bakery, Valparaiso, Ind.: 220 x 64 ft (67.1 x 19.5 m).

Fig. 3.2—"Xanadu" residence, Sedona, Ariz., consisting of 10 shells including spherical, oblate ellipsoid, prolate ellipsoid, and cylindrical shapes ranging from 20 to 36 ft (7 to 11 m) in diameter.

3.2—Inflated form material and manufacturing

The inflated form is an engineered fabric structure. The form's shape, size, fabric, and fabrication need to be considered before a thin-shell inflated-form structure is designed.

3.2.1 *Shape*—The spherical shape, or portion of a sphere, is the simplest inflated form to manufacture and is the most common. Ellipsoids, barrel, and cylindrical shapes can also be used. Because improved technology has provided the ability to create different shapes, the designer should contact the form manufacturer for more detailed information about the shape limitations for a particular inflated form (Fig. 3.2).

3.2.2 *Size*—Dome sizes up to 260 ft (79 m) in diameter and 130 ft (40 m) high have been successfully built using inflated forms (Fig. 3.3). Larger sizes are possible by modifying the methods. Larger domes require ribs to be sprayed either inside or outside to prevent snap-through buckling.

3.2.3 *Fabric*—Fabrics for inflated forms should be selected to meet the requirements of strength, elongation, fabrication, ruggedness, durability, and desired surface characteristics (Boyt 1986). Commonly used are architectural fabrics, constructed of a polyester scrim impregnated with PVC, with weights ranging from 16 to 51 oz/yd^2 (550 to 1730 g/m^2).

The strength requirements are based on the radius of curvature and inflation pressure. Ruggedness and durability should be sufficient to withstand handling during spreading and fastening to the foundation. Inflated forms can weigh several tons. Although the fabric forms are designed to withstand loading, care should be taken to prevent accidental puncture, tearing, or overinflation.

3.2.3.1 *Fabric stress*—Fabric stresses are proportional to the air pressure and the radius of curvature. Structures 160 ft (49 m) in diameter or larger require more precise air pressure controls to provide a stable inflated-form surface and prevent excessive fabric stress. Because a flexible fabric form cannot tolerate a compressive stress, the design should ensure that the desired size and shape is obtained when inflated.

When large structures are contemplated, the low air pressure dictated by the allowable fabric stress may not be sufficient to support the shotcrete during construction. Cable nets used on the outside of the inflated form as a secondary restraint of the inflated form can allow increased inflation pressure required to support the shotcrete during construction without over stressing the inflated-form fabric (Jacobs 1996; South 1990).

3.2.3.2 *Allowable fabric stress*—Most inflated forms are constructed by splicing specially patterned flat pieces that need to inflate to form a smooth compound curve. Whereas the seams are usually as strong as the parent material under short-duration loads, for sustained loads, these seams can fail well below the tensile strength of the fabric. Therefore, inflated-form fabric stresses are limited to 20% of the breaking strength of the fabric.

Designers should be familiar with the maximum allowable force of the specific inflated form used for their project and inform the manufacturer before building the fabric form.

Breaking strength is measured by using either the cut strip test method or the grab test method as outlined in ASTM D 751. Samples of a material are tested both in the warp and fill directions, and three to five samples are taken across the width of the material.

3.2.4 *Fabrication*—An inflated form cannot be fabricated to duplicate a specific design, shape, or size. Some inflated form fabrication variables that influence actual size and shapes are: fabric stretch factors of raw materials, fabrication tolerances, temperature variations after inflation, and slight distortions from the weight of the initial thin layers of shotcrete. When an inflated form is attached to the footing and inflated, it stretches. The anticipated stretch factors are based upon inflation to a predetermined pressure, and should be taken into consideration in the design of the inflated form.

3.3—Field layout

The inflatable form should be carefully unfolded and fastened to the foundation at predetermined locations marked on both the foundation and the inflatable form. The inflated form should be handled without using sharp instruments. Lift operators should be cautioned against tearing the fabric form accidentally. It should be placed and unrolled per manufacturer's directions. It should not be unrolled on wet ground or over sharp objects.

3.4—Form protection

Before the form layout begins, all items that can damage the form should be padded. For instance, the vertical dowels extending above the top surface of the foundation should be bent down and padded during the layout and attachment.

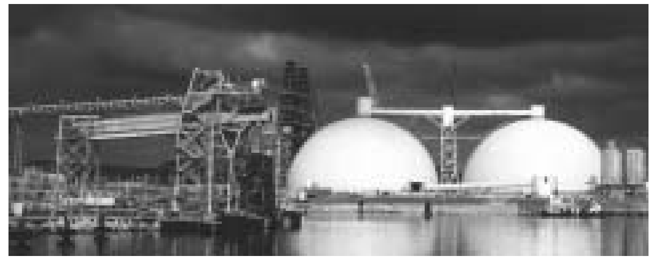

Fig. 3.3—Hovensa Oil Refinery, St. Croix, U.S. Virgin Islands: petroleum coke carbon storage domes, each 254 x 127 ft (77.4 x 38.7 m) with 44,000 ton (40,000 tonne) capacity.

Generally, inflated forms are manufactured with a small opening that attaches to an air lock to allow personnel movement during construction. Large equipment that is needed inside during construction will not fit through these openings. This equipment is placed within the foundation perimeter before the form attachment process is finished. This can include the door frames, man lifts, scaffolding, and skylight frames. These items, equipment, and stockpiled reinforcement within the perimeter of the structure should be padded before the form is rolled out.

3.5—Initial stretching

The inflatable form will have a very different shape before inflation than after inflation. Less obvious is that the fabric form continues to acquire its final shape as it remains under consistent pressure for 24 hours. This is especially true for larger, more highly stressed inflated forms. The inflatable form diameter is usually 1 to 2 in. (25 to 50 mm) smaller than the foundation, and thus requires some stretching to fit the attachment position. Applying tension on the bottom edge stretches the inflatable form. This stretching helps to minimize folds, wrinkles, or bunching of the inflatable form that remains visible on the finished structure. It is important to stretch the form evenly during attachment.

Discontinuity in curvature can alter the forces at the bottom of the structure, where they are most critical, and should be kept to a minimum. Therefore, it is important that the layout be as precise as possible, and that some uniform initial tension is applied to the inflated form during installation. After attaching the form to the foundation, the air lock(s) and inflators are attached.

3.6—Inflation

Once the fabric form is tensioned in place, bolted down, and thoroughly inspected, it can be inflated. It should be inflated as fast as is practical. The form should not be subject to winds in excess of 15 mph (25 kph) during inflation. For domes 200 ft (60 m) in diameter or larger, the recommended maximum wind speed is 10 mph (15 kph) (Fig. 3.1). The fabric form is inflated with one or more sets of inflators, each consisting of one or two blowers. High-volume, low-pressure inflators should be in proper running order, and can be powered by electricity, gasoline, or diesel. The inflators

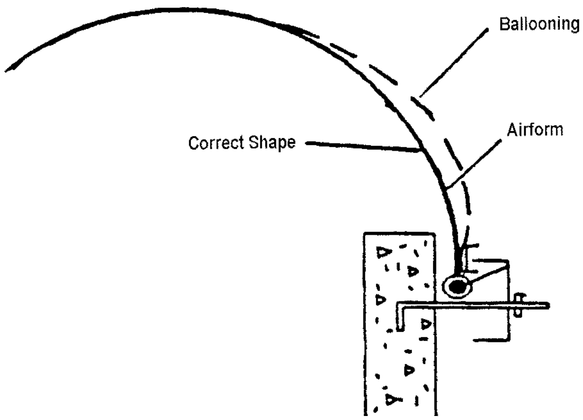

Fig. 3.4—Distortion due to ballooning.

should be equipped with check valves to prevent escape of air pressure if an inflator shuts down.

The general procedure for inflating the fabric form is:

1. The inflators are attached and checked to verify they are operationally sound;

2. The manometer (air pressure gauge) is installed to measure the inflation pressure;

3. Inflators are started and continue to operate throughout the construction process. They should be monitored regularly; and

4. As the fabric form inflates, the manometer is monitored and the inflator regulators are adjusted to keep the form at proper pressure.

The properly inflated form will maintain its shape (Fig. 3.4) and support the anticipated construction loads without rupturing. The manufacturer provides the recommended inflation pressure range.

After the form is inflated, work by other subcontractors within the dome is usually limited or suspended until the dome structure is solid enough for the inflators to be shut off and the dome opened. Until then, the only access is usually through an air lock approximately 2.5 ft (0.75 m) wide by 6.5 ft (2.0 m) high. After the fabric form is inflated, getting the dome structurally sound as quickly as is practical is important to maintain the construction schedule.

3.7—Construction tolerances

Dimensional tolerance of an inflated form will normally be within ±3.0% of the design radius of curvature, except at the foundation, which is normally ±0.2% of the building radius. When tighter tolerances in the size and shape of the dome are required, the contractor should explicitly agree to them before construction begins. When the inflated form is out of tolerance, the shape should be reviewed for possible changes.

3.8—Air pressure maintenance

The more constant the air pressure, the less chance there is of deforming the shape of the dome during the application of the foam and the concrete. If pressure is increased while hanging the reinforcement, the reinforcement hangers may be pulled out of the foam (Wilson 1990). In addition, if there is any overinflation after the initial concrete is applied, the inflated form can stretch and crack the concrete.

The air pressure should be maintained within the manufacturer's recommended tolerance at all times (usually ±25% of the target pressure). Some field conditions, however, may dictate that the air pressure be set higher or lower. All air pressure management should be done by personnel with a thorough knowledge of the relationship between air pressure, inflated-form stress, placement of reinforcement, and placement of the initial layers of shotcrete. Major considerations are: the shape of the inflated form; the size of the inflated form; and the rate and placement of the polyurethane foam, reinforcement, and shotcrete (Wilson 1986).

3.8.1 *Backup air pressure systems*—Most inflation systems consist of at least two different nonoverloading centrifugal blowers (Boyt 1986). The extra blowers are for backup only, and are an important safety measure. At least one working backup is recommended. Maintaining more than two systems during certain times of construction may be necessary, such as during the initial inflation period when the inflated form is easily affected by external winds. If the primary inflation system is powered with electricity, backup power supplies, such as generators, should be available on site.

3.8.2 *Air pressure monitoring*—All air pressure systems should have a built-in air pressure control mechanism to ensure that the inflated form does not overinflate or underinflate. This dome internal pressure range is usually 1.5 to 3 in. (40 to 75 mm) of water column, depending on the size of the structure. Other methods, especially those using shotcrete on the outside of the inflated form, usually have an internal pressure range of 6 to 8 in. (150 to 200 mm) of water column. Overinflation can cause the uplift force to exceed the foundation weight or can cause the fabric tension to exceed the maximum allowable by design, possibly resulting in a failure of the inflated form. Weather conditions also influence the air pressure.

The pressure gauge (manometer) can be as simple as a container half filled with colored water having a small (1/8 in. [3 mm]) clear tube running from the water through a hole in the inflated form to the outside. The additional air pressure inside the inflated form will force water up the tube to a level higher than the water in the container. The difference in vertical distance is the actual air pressure reading in inches of water column.

3.9—Collapse prevention

Care should be exercised during construction to prevent local sags, which can lead to total collapse of the structure. Shotcrete applied thicker than specified causes additional dead load, which can overcome the internal air pressure resistance. Investigations of dome failures have concluded that the majority were caused by either poor judgment or poor craftsmanship used during the shotcrete process.

3.10—Miscellaneous connections

Maintaining the design shape of the finished shell structure is one of the most important issues during the construction process. The designer should allow for some flexibility in the interior and exterior connections to later miscellaneous attachments, such as ceilings, stairs, and walkways, so these differences between the assumed final shape and the actual final shape will not be critical construction problems. Final connection detailing for interior or exterior miscellaneous attachments to the dome should use the actual measurements from the inflated concrete dome after the dome shell geometry is stabilized.

The miscellaneous connection design should take possible deviations from design profiles at the point of attachment to the base structure into account. Deviations can occur when the diameter of the foundation varies or when the inflated form's assumed shape does not properly anticipate the transition from the fixed fastening of the inflated form to the foundation. The transition location is usually the lower 4 to 6 ft (1.2 to 1.8 m) of the inflated form.

3.11—Fabric form repair

An inflated form can be cut or torn during construction. When this happens, the tear or cut can be field-repaired with different combinations of heat welding, gluing, and riveting strips of fabric over the tears. The repair does not affect the general shape or quality of the inflated form.

3.12—Polyurethane foam (when used)

After the form is inflated, polyurethane foam is applied to the inside of the form. The finished minimum thickness is usually 1.5 in. (40 mm), but each dome project should specify a required thickness and tolerance. The polyurethane serves the following purposes:

1. To help insulate the completed dome;
2. To provide a means to anchor the reinforcement hangers for tying reinforcing bars in place; and
3. To stiffen the fabric form before applying shotcrete.

The polyurethane foam should be inspected for specification compliance upon arrival at the job site and placed in a location protected from traffic, and, if necessary, from extreme heat or cold.

3.13—Preparation

Before polyurethane foam can be applied to an inflated form, the surface should be dry, because polyurethane foam does not stick to wet surfaces. When the weather is cold, a significant amount of dry heat can be required within the inflated form to remove condensed water. The inflated form is inspected before beginning the foaming operation to ensure that it is dry. It is advisable to apply a primer if recommended by the manufacturer. Openings and embeds should be marked out before and after the foam is applied.

3.14—Foam application

When the foam is applied, the workers should wear appropriate safety gear as suggested by the manufacturer. The first layer should be approximately 3/8 to 5/8 in. (10 to 15 mm) thick. After the second layer is applied, approximately 5/8 in. (16 mm) thick, the shotcrete reinforcement hangers can be placed. Placement of these hangers corresponds to the size and future location of the reinforcement that they will support. The base of the reinforcement hangers is usually embedded within approximately 1.2 in. (30 mm) of foam. If the hangers are not adequately embedded, they can pull out when the reinforcement is installed. Depending on the structure being built, additional thickness of foam can be required, but it is suggested that all reinforcement hangers should have a minimum of 1 in. (30 mm) of urethane foam over the base plates of the hangers.

3.15—Construction hazards

Some hazards for inflated forms during construction include wind, snow, and unanticipated construction dead loads.

3.15.1 *Wind*—Inflated forms are at greatest risk of wind damage during initial inflation (Boyt 1986). Blowers should be sized to inflate the form as quickly as possible to minimize this risk. Once the inflated form is at design pressure, the inflated dome should withstand winds up to 40 mph (60 kph).

3.15.2 *Construction loads*—The contractor should ensure that construction loads do not alter the geometry of the structure before the polyurethane foam is applied. After the foam has been applied and cured, the form has additional stiffness. All loads imposed on the inflated form during construction should be given serious consideration. The construction sequence and techniques should be carefully planned to avoid unanticipated loadings before completion of the shotcrete process.

3.15.3 *Proper venting*—If internal combustion engines are to be used inside the dome under construction, they should have their exhaust piped to the outside.

CHAPTER 4—SHOTCRETE DOME

4.1—General

Shotcrete is mortar or concrete that is pneumatically projected at high velocity onto a surface. General information about shotcreting is available in ACI 506R. Shotcrete applied to an inflated form should satisfy the following criteria:

1. The shotcrete should be able to be pumped through the length of hose required. Very stiff mixtures cannot be pumped through long lengths of hoses; however, they may be suitable when pumped through a limited length of hose. In some cases, the mixture passes through a hose 200 to 300 ft (60 m to 90 m) in length;
2. The reinforcement should be fully encased by the shotcrete. Proper nozzle operation, in concert with the appropriate mixture proportioning, should ensure this result. The shotcrete should be applied sufficiently wet so that proper flow around reinforcing bars is achieved; and
3. The shotcrete should meet the project-specified compressive strength. The minimum recommended compressive strength is 3000 psi (21 MPa). Most actual mixtures reach higher strengths, some as high as 6000 psi (42 MPa). The recommended minimum amount of portland cement for the shotcrete mixture is 705 lb/yd^3 (418 kg/m^3); however, 100 lb/yd^3 (59 kg/m^3) of cement can be replaced with 120 lb/yd^3 (71 kg/m^3) of fly ash. The maximum recommended water-cementitious material ratio is 0.55. For additional information about shotcrete and shotcrete additives, see ACI 506R.

4.2—Reinforcement material and size

4.2.1 *Material*—Reinforcement for shotcrete should comply with ACI 506.2.

4.2.2 *Size*—The maximum size of reinforcement should be No. 11 (No. 36) bar; however, for bar sizes greater than No. 5 (No. 16), it should be shown by preconstruction tests that adequate encasement of bars can be achieved. Many larger insulated thin shells with interior shotcrete application have reinforcing bar sizes between No. 5 and No. 11 (No. 16 and No. 36).

4.3—Clear spacing between bars

The minimum recommended clear distance between parallel reinforcing bars is 2.5 in. (60 mm). When two or more layers of reinforcing bars are used, the first layer should be tied in place followed by shotcrete covering the first layer, then the next layer is tied in place followed by shotcrete; this is continued until all layers are installed and covered by shotcrete. The recommended minimum clear spacing could be reduced when the contractor can demonstrate proper encasement of the reinforcing bars by preconstruction tests.

4.4—Splices

The dome is a complex three-dimensional structure. The reinforcement within insulated thin shells constructed with interior shotcrete construction should be spliced with mechanical splices or contact lap splices. Contact lap splices should only be used when adequate encasement of the bars can be achieved, and also when the splice is oriented so that a plane through the center of the stacked spliced bars is perpendicular to the surface of the shotcrete. Lap splices, where used, should be firmly wired together to add stiffness to the reinforcement grid during construction. Lap connections for reinforcing bar sizes of No. 5 (No. 16) or larger should be stacked to ensure a minimum shadow. Where splicing reinforcing bars using a noncontact lap splice method, a minimum clear spacing of 2 in. (51 mm) between bars is recommended.

4.5—Cover

Spraying a layer of shotcrete against the foam before the dome reinforcement is placed allows the reinforcing bars to be tied tight against a concrete surface, ensuring that the reinforcing bars will have a measurable shotcrete cover between them and the foam, and will thus be encased with shotcrete. In general, there should be a minimum of 3/4 in. (20 mm) shotcrete between the foam and the reinforcement.

4.6—Preliminary reinforcement mat (premat)

In larger domes (over 150 ft [46 m]), the contractor sometimes places a premat of reinforcing bars. The premat is normally No. 3 or 4 (No. 10 or 13) bars at 2 ft (0.6 m) on center, tied tight against the polyurethane foam using separate bar hangers. The premat gives the dome additional stiffness and strength for construction purposes by allowing the shotcrete nozzle operator to embed a layer of reinforcing bars in the first pass. This first application of shotcrete is reinforced, and has sufficient strength and stiffness to support hanging the heavier mat(s) of reinforcing bars without significant deformation of the dome shape.

Premat reinforcing bars are generally not considered in the final design of the dome, and therefore are placed according to the contractor's requirements.

4.7—Shell reinforcement

The structural dome reinforcement should be placed according to the contract documents. When the shell requires more than one mat layer, the first mat is usually placed and embedded with shotcrete to at least the backside of the reinforcing bar before an additional structural mat is placed. An exception to this can be around a doorway where more than one layer is placed. The shotcrete can be started from the bottom and completely embed the reinforcing bars as it is built up vertically in a column.

The hanging of the reinforcing bar begins directly above the foundation, where the vertical footing dowels are bent to an upright position. Any embeds, cutouts, sleeves, bearing plates, or other inserts are placed along with the reinforcing bars. Electricians place conduit at this time. Such action should not affect the structural integrity of the dome and should not disrupt the overall dome construction effort. The designer should approve the size of the conduit or wall piping. Embeds, openings, and reinforcement locations should be inspected and approved before applying shotcrete.

Fiber reinforcement is not an acceptable substitute for reinforcing bars in a shotcrete dome structure.

4.8—Preconstruction shotcrete tests

Preconstruction testing should conform to ACI 506.2. As an alternative to preconstruction testing, the dome contractor, personnel, equipment, and procedures may be prequalified using previously documented experience. A contractor prequalification could include requirements such as five years of experience constructing domes of similar size and design and certification of the nozzle operator.

4.9—Shotcrete compression tests

Strength tests for shotcrete should be made by an approved agency on specimens that represent the work. Testing of shotcrete during construction should be made in accordance with ACI 506.2, except that grading of cores is not recommended. Test cylinders or panels can be used as agreed to by contractor and owner.

Test panels are usually shot for each day's shotcreting. Test panels are approximately 18 x 18 x 3 in. (460 x 460 x 75 mm) and are shot in a position to the dome construction (vertical, horizontal, or overhead). These panels should be cured inside the dome. Cores or cubes cut from panels are then tested.

Cylinders can be taken as an indicator. Unless they are special shotcrete cylinders, they will generally show slightly weaker results.

4.9.1 *Sampling*—Specimens should be taken from test production panels.

4.9.2 *Panel criteria*—When the maximum size aggregate is larger than 3/8 in. (10 mm), the minimum dimensions of the test panels should be 18 x 18 in. (460 x 460 mm). When the maximum size aggregate is 3/8 in. (10 mm) or smaller, the minimum dimensions of the test panels should be 12 x 12 in. (305 x 305 mm). The nozzle operator who performs the work should shoot the test panels in the same relative position as the actual work. The conditions under which the panels are cured should be the same as the work.

4.9.3 *Acceptance criteria*—The acceptance criteria for strength test results should conform to ACI 506.2.

4.10—Proportions and materials

Proposed shotcrete materials and proportions should be in accordance with ACI 506.2. The mixture proportions and shooting orientation should be tested in accordance with ACI 506.2.

4.10.1 *Fine aggregate (sand)*—Well-graded sand should be used for shotcrete applications. Sand is recommended to be generally consistent with ACI 506.2

The fineness modulus should fall between 2.70 and 3.00.

4.10.2 *Coarse aggregate*—Coarse aggregate may be left out of the final finish coat for a smoother surface. When coarse aggregate is used in the mixture, pea gravel with a maximum aggregate size of 3/8 in. (10 mm) should make up 10 to 30% of the mixture proportion.

4.10.3 *Water*—The water should be potable.

4.10.4 *Admixtures*—Admixtures should not impair the density or strength of the shotcrete and should not be corrosive to the reinforcing bar and shotcrete. The designer should approve use of admixtures.

4.10.5 *Rebound*—The rebound amount varies with the position of the work, air pressure, cement content, water content, maximum size and gradation of aggregate, amount of reinforcement and thickness of the layer, and, more importantly, nozzle distance to work, nozzle angle, and nozzle movement.

Initially, the percentage of rebound is large, but it becomes less after a concrete substrate has been built up. Rebound is generally more lean and coarse than the original mixture. The cement content of the in-place shotcrete tends to increase because of rebound, which increases the in-place strength. The rebound can become excessive when the aggregate is 3/8 in. (10 mm) and larger, because the shotcrete is applied in thin layers.

Rebound materials should not be used for shotcrete work and should never be worked into the construction by the nozzle operator. If the rebound materials do not fall clear of the work, they should be removed. It is strongly recommended to remove rebound materials from the bottom areas and corners of the wall before spraying additional layers. Rebound material does not have adequate cement paste to consolidate and provide good concrete. Rebound encapsulated by shotcrete is virtually equal to a void.

4.11—Field practice

See ACI 506R for general information on shotcrete field practice, and ACI 304R for general information on field handling of concrete.

4.12—Nozzle operator qualifications

Nozzle operators directly control all shotcreting on the job. ACI CP-60 provides for testing and certification of nozzle operators.

A qualified nozzle operator should have an ACI shotcrete certificate, which requires 500 hours of verified experience and passing a written test. Different, project-specific qualification requirements can be adopted when agreed to by all parties.

If the constructor chooses to train a nozzle operator on a project, a qualified nozzle operator should be in the company of the trainee at all times during training.

4.13—Shotcrete operation

The batching equipment should proportion the shotcrete mixture accurately. The nozzle should be held at approximately a right angle to the surface and be kept at the proper distance from the surface, as described in ACI 506R. Any nozzle operator who habitually fails to direct the nozzle at a proper angle to the surface should be replaced.

When encasing a reinforcing bar, the procedure of shooting other than at a right angle can be modified to help direct the material around the bars. The nozzle operator should apply the material at a wet enough consistency that only a small shotcrete buildup will take place on reinforcing bars whenever shotcreting on, around, through, and behind reinforcing bars is required. Shooting through two curtains of reinforcing bars should not be permitted except in unusual areas, such as columns with ties. The reinforcement for the second curtain should be placed after the first curtain has been embedded in shotcrete.

The inflated form cannot support all of the shotcrete at once; thus, the shotcrete is placed in layers, usually 0.25 to 2 in. (6 to 50 mm) thick. Sufficient time should be allowed for each layer of shotcrete to set so it can take the next layer without sagging. In large domes, 24 hours or more may be needed before applying the next layer of shotcrete. The exposed, unfinished shotcrete surfaces should be left rough.

Several project-specific factors are considered when deciding the geometry and the rate of shotcrete application. These factors include size and shape of the dome, density and weight of the reinforcing bar, ultimate dome shell thickness, and weather. If a construction premat of reinforcing bars is used, it should be encased with a 0.25 to 0.5 in. (6 to 13 mm) layer of shotcrete. The total thickness of shotcrete embedding the premat usually will be 1.5 to 2 in. (40 to 50 mm). Until the dome is self-supporting (when the inflators are turned off), shotcreting is generally started at the base of the dome and then worked up over the top. After the premat has been encased and cured, shotcrete layers from 0.5 to 2 in. (13 to 50 mm) are usually applied in a single pass near the base of the dome, tapering to 0.5 to 0.75 in. (13 to 20 mm) in a single pass over the top.

Gauges for monitoring the concrete thickness for various sections of the shell should be placed on the inside surface of the foam. These gauges can be reinforcement hangers or pieces of reinforcement that have been cut to length. These gauges are usually placed perpendicular to the surface of the foam and in a grid over the entire surface of the shell spaced approximately 10 ft (3 m) horizontally and 6 ft (2 m) vertically.

When the structural reinforcement is placed, the nozzle operators should concentrate on properly embedding and covering the reinforcing bar. Next, they should focus on adding sufficient thickness to cover the depth gauges. If smoothness is a project requirement, then the last layers of shotcrete should be sprayed with finer sand mixtures and no coarse aggregate.

Judging the depth of the shotcrete being applied is sometimes difficult. The nozzle operator should check the depth of spray during production. The constructor should verify that a uniform spraying pattern is being followed. Lighting should be adequate to allow the nozzle operator to see the work clearly.

4.14—Discharge time

Normally, the nozzle operator sprays shotcrete that has a slump of 4 to 8 in. (100 to 200 mm). Because it usually takes 25 to 45 minutes to unload a truck, the concrete gets stiffer as time goes on. By using high-range water-reducing admixtures and retarding admixtures, the time available to discharge a load can be greatly extended. Water can also be added to maintain the same slump as long as the specified strength is maintained and the maximum specified water-cement ratio is not exceeded.

The quality control technician taking samples should be certified as a Concrete Field Technician or Concrete Inspector and have a working knowledge of the relationship between the strength of the shotcrete and the time sitting in the truck.

4.15—Joints

Unfinished work should not be allowed to stand for more than 30 minutes, unless edges slope to a thin edge. For structural elements that will be under compression and for construction joints shown on the approved construction documents, square joints are recommended. Before placing additional material next to previously applied work, sloping and square edges should be clean and damp.

4.16—Multi-pass technique

Close review of existing insulated thin shells constructed by the interior shotcrete method shows that the shells are not stratified but monolithic, and contain almost no cold joints. Thin shells with interior shotcrete application cannot be constructed by applying all of the shotcrete in one layer because the level of air pressure that would be required to hold the full-depth weight of the wet shotcrete far exceeds how much air pressure the inflated fabric form can hold. Research (Bingham 1997) and experience show that the layering of shotcrete does not cause cold joints in insulated thin shells with interior shotcrete construction.

4.17—Curing

During the curing period, shotcrete should be maintained above 40 °F (4 °C) and in a moist condition. Shotcrete should be kept continuously moist or should be sealed with an approved curing compound as discussed in ACI 506R. However, most dome construction using the internal method of spraying shotcrete inside an inflated form retains a humid environment and does not require additional moisture for curing. Curing should continue for 7 days after shotcrete is applied, or until the specified compressive strength is obtained.

Where concrete is applied to the outside of an inflated foam, proper curing methods must be maintained. These methods may include soaking the concrete with water or applying curing compound. If curing compound is used, it should have the design professional's explicit agreement.

4.18—Shotcrete placement tolerance

Shotcrete cannot be placed perfectly. A certain amount of voids or shadowing around the reinforcing bar is always present. Small voids should not be considered a defect. The definition of a small void depends on the thickness of the wall and size of the reinforcing bar. A 0.5 x 0.5 x 0.5 in. (13 x 13 x 13 mm) void in a 2 in. (50 mm) wall should be considered as small. As the wall becomes thicker, slightly larger voids should be tolerated. Shadowing behind a reinforcing bar should not be considered excessive if the shotcrete embeds at least 80% of the surface of the bar. Continuous voids indicate poor shotcrete practice and should not be accepted.

Because of the dome shape, the shotcrete shell is largely in compression, but the compressive forces are small. Usually, the average compressive stress in a shotcrete dome is less than 500 psi (3.4 MPa). When shotcrete is placed in tension areas of the dome, the proper embedment of bar splices is the most important consideration. ACI 318, Chapter 19, requires that the length of the overlap of a reinforcing bar at the splice be 1.2 times greater than the lap length in conventional concrete but not less that 18 in. (460 mm). This is because, in a thin shell structure, the bar can be close to a surface. Also, in a shell placed by the shotcrete method, it allows for a degree of shadowing or voids at a splice. Even where the reinforcing bar is properly embedded and is at the specified thickness, the pattern of the reinforcing bar grid can be visible on the inside surface, sometimes called “reinforcing bar ghost lines.”

When a qualified nozzle operator places shotcrete, there should be few defects. If defects are suspected, random cores can be taken. If more than 15% of the cores taken have excessive defects, then additional cores should be taken to decide an actual amount of defective work in the dome.

To ensure that the finished dome will behave as anticipated, the shotcrete thickness should not be less than the specified thickness by more than 10%, nor exceed the specified thickness by more than 25%, so as not to increase the dead load at any specific location.

4.19—Shotcrete damage

When poor workmanship is discovered or placement tolerances are exceeded, the designer should be informed. Shotcrete that exhibits sags, sloughs, segregation, honeycombing, sand pockets, or other obvious defects should be removed and replaced while still plastic. Hardened shotcrete defects should be reviewed by the designer to determine whether the structural integrity of the dome is in question. The designer should present the findings to the contractor. The constructor and designer should agree on the method and extent of the repairs.

4.20—Completion

After the final shotcrete is applied, the air pressure should remain constant until the designer determines that the structure is self supporting. In domes with thicker wall sections, the inflators can be turned off after the designer determines enough shotcrete has been placed and sufficient strength gained for the dome to be self supporting, and able to take the load of successive layers of shotcrete. This is generally after the first mat of structural reinforcement is placed and fully embedded with shotcrete.

When the blowers are turned off and the shotcrete operation is completed, finish work, such as plumbing, painting, and interior framing, can begin.

CHAPTER 5—REFERENCES

5.1—Referenced standards and reports

The standards and reports listed below were the latest editions at the time this document was prepared. Because these documents are revised frequently, the reader is advised to contact the proper sponsoring group if it is desired to refer to the latest version.

American Concrete Institute

214R Evaluation of Strength Test Results of Concrete
301 Specifications for Structural Concrete
304R Guide for Measuring, Mixing, Transporting, and Placing Concrete
309R Guide for Consolidation of Concrete
318 Building Code Requirements for Structural Concrete and Commentary
506R Guide to Shotcrete
506.2 Specification for Shotcrete
CP-60 Workbook to ACI Certification of Shotcrete Nozzlemen

ASTM International

C 94 Standard Specification for Ready-Mixed Concrete
D 751 Standard Test Methods for Coated Fabrics

The preceding publications may be obtained from the following organizations:

American Concrete Institute
P.O. Box 9094
Farmington Hills, MI 48333-9094

ASTM International
100 Barr Harbor Dr.
West Conshohocken, PA 19428

5.2—Cited references

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Boyt, J., 1986, “Up, Up and Away,” *Concrete International*, V. 8, No. 1, Jan., pp. 37-40.

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Wilson, A., 1986, “Controlling Construction Mishaps,” *Concrete International*, V. 8, No. 1, Jan., pp. 33-36.

Wilson, A., 1990, “Very Large Air-Formed Concrete Shells,” *Concrete International*, V. 12, No. 8, Aug., pp. 21-23.