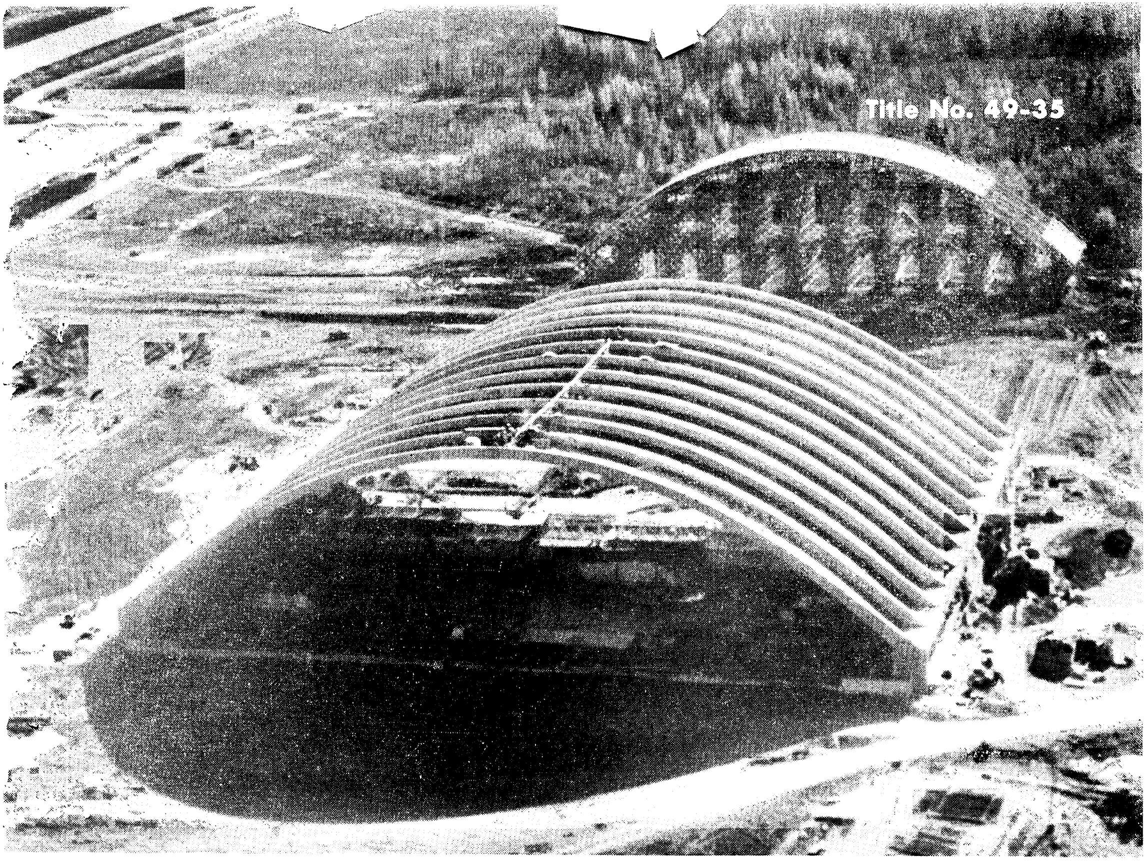

Fig. 1—Aerial view of partially completed 340-ft span hangar with centering in background

Construction Aspects of Thin-Shell Structures*

By ANTON TEDESKO†

SYNOPSIS

Form design, handling of formwork, and labor take on added importance because a relatively lower percentage of total cost is represented by material costs for thin-shell structures. Construction techniques—form centering, concreting, decentering and movement of forms—are discussed. Costs and labor requirements for typical small and large span projects are given.

INTRODUCTION

Man's accomplishments are always measured in relation to the framework within which he must work. Many of the great construction achievements of past days would be routine problems to the engineer and builder of today. The technology of building construction has made great strides;

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never before has there been an age offering such a variety of materials, tools and skills. In this atmosphere, so conducive to new developments, it is surprising that it took so many years for reinforced concrete shell construction to become firmly established as part of the building industry.

Considering the abundance of material resources in the United States, and their scarcity in Europe, it is quite understandable that European designers were among the first to develop and make use of shell construction. The great reduction in material made possible by the curvature and space action of the shell aroused widespread interest. However, what appeared so good on the designer's table became a real problem to the builder. Cost of concrete and steel materials for this type of construction represented a relatively lower percentage of the total cost, and therefore form design, form handling, and labor increased in importance. As Europeans began to solve their shell problems within their economic framework, this country saw its first counterpart built at the Chicago World's Fair in 1933. In the following years the Roberts and Schaefer Co. were in the forefront of this unique engineering development.

High speed concrete erection is common today. Flat plate construction, prestressing, precasting, and tilt-up construction indicate the popular trend towards mass production in the field. This trend, if not initiated, certainly was anticipated in shell construction. Improvements in construction technique are primarily responsible for the success of shell structures, this having been accomplished under the aegis of a single group of engineers, numbering among them the writer. Many ingenuous contractors have cooperated in job applications of new ideas during the years of pioneering, contributing to the development of procedures which today can be considered almost "standard."

American designs are based on local labor-material cost relationships. The job is planned from a production angle. A builder meeting a stringent time schedule can ill afford to work under conditions imposing laboratory controls. These factors sometimes result in acceptance of penalties in material quantities which can be offset by savings in labor. The successful structure is as much a product of the designer as the work of the construction man, and the resourceful engineer must visualize the construction job as it will develop while the structure is still in the design stage. It is therefore appropriate at this time, when so many fresh minds are ready to make their contributions in this field, to review the status of construction techniques.

Concrete men have long recognized such basic production facts as (1) cost of production varies with the number of units fabricated, and (2) cost of "tooling up" can be spread over the number of units to be produced. Consistent with the desired rate of progress, it is desirable to build the greatest number of units with the same tools, that is with the same set of forms. An economical construction set-up requires at least several re-uses of a centering and of forms which should not stay in place longer than really necessary.

Repetition of operations on each unit produces low unit cost. Any group of construction workers, even if unskilled at the beginning, becomes more skilled as the same operation is repeated. Taking a lesson from industry, it has been found advantageous to organize a job on a straight-line production basis. The order in which construction work is done is nearly alike for similar jobs, but the timing schedule for different operations varies. The required time for operations on a first unit may be as much as 60 percent higher than the estimated average, but the required time decreases rapidly at first and eventually becomes nearly constant for operations on successive units as the work is repeated in a planned cycle.

Thin shell structures are economical if forms can effectively be re-used. The emphasis, therefore, especially for structures of smaller area, is on design for sufficient form uses rather than on design for the lowest material quantities. During the last war, U. S. Navy hangars in Maryland were designed for the use of a centering left over from a much larger hangar; this centering could be floated down the river on a barge to the job site at low cost. The dimensions of these available form trusses, rather than theoretical design considerations, established the shape of the structure; greatest economy and speed of construction were thereby accomplished.

Besides keeping the amount of formwork to a minimum it is desirable that the forms be kept as simple as possible. Hence, shells with curvature in two directions, or layouts unsuitable for form re-use, should be utilized only when their choice is dictated by esthetic or functional requirements. For most conditions the simple cylindrical shell is preferable. With curvature in one direction, a smooth form surface can be attained with no greater difficulty than in ordinary flat plate construction. Shell surfaces steeper than 45 deg, requiring either top forms or very stiff concrete, should be avoided.

FORM CENTERING

Use of mobile form centering is often advantageous, permitting re-use of forms by moving them intact to their new location. Such movable form travelers become especially simple when the shell structure consists of one or more unbroken barrels with a smooth unobstructed ceiling. Form centerings have been built of wood and steel; delivery time for timber forms, in most cases, has proved shorter than for steel unless existing steel forms or tubular scaffolds were available. The original cost of steel forms is higher, but not prohibitive for larger jobs. As the number of repetitive building units increases, forms and plant set-up can be more substantial and elaborate without appreciable influence on the unit cost of the structure.

The size of units comprising a form centering assembly depends upon available construction equipment. The time element and type of available labor may influence a decision with regard to the amount of fabrication or prefabrication. The expected salvage value may have a bearing on the choice of materials, sizes, and lengths.

Where labor cost is low, such as abroad, centerings have been assembled, dismantled and re-erected for successive concrete pours with hand labor and with savings in material. On the average domestic job, heavy equipment is used and the handling of larger units is preferred. Centering assemblies usually consist of timber ring-connected trusses or curved laminated beams supported by a system of timber towers or braced posts. The trusses in turn carry joists covered with treated plywood or sheathing. Usually, a group of screw jacks, inserted between towers and trusses, or near ground level, takes care of proper adjustment and ease of decentering. The centering is designed for a simple moving and concreting cycle; in construction position, it is supported rigidly from the ground and properly guyed against wind; in its moving position it travels on wheels and rails.

Fig. 1 to 8 illustrate various types of formwork accommodating different shell designs. Fig. 2 shows the first (1937) timber ring-connected truss used for forming purposes, arranged to slide on what will be the crane runway of the finished building. The center tower, on pipe rollers during the moving operation, supported most of the construction loads during placement of concrete.

Fig. 3 shows the steel traveler for a small span structure built in 1939, Fig. 4 and 5 a similar design in wood construction a few years later. The valley portions of the forms were hinged to clear the columns during the forward move. Such a design was used recently in the construction of a factory for Western Electric Co.

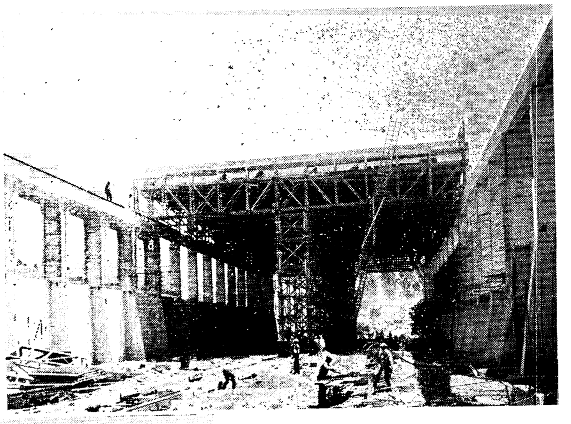


Fig. 2—First use of split ring-connected trusses for centering. Storage building for cement plant, Hudson, N. Y.

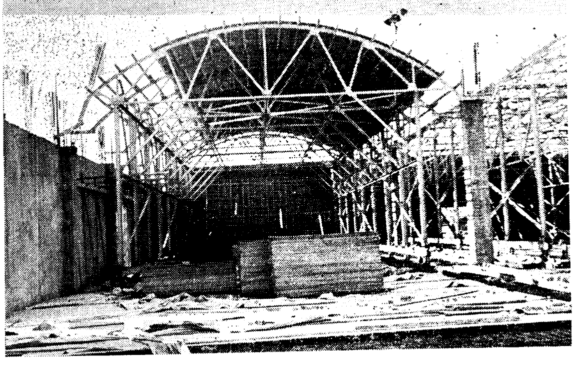


Fig. 3—Steel form travelers, 43 ft wide, for Richmond, Va., marine terminal warehouses; 6-in. H-columns at 12-ft centers support steel trusses 6 ft apart. Chords and knee bracing consist of 4 x 3-in. angles; web members and wind bracing are 3 x 3-in. angles. The plywood roof deck is supported on staggered 4 x 6 in. timbers at 2-ft centers. Cast steel wheels of 14-in. diameter are attached to each post between two 8-in. channel stringers. A pair of jacks are built into these stringers at each wheel

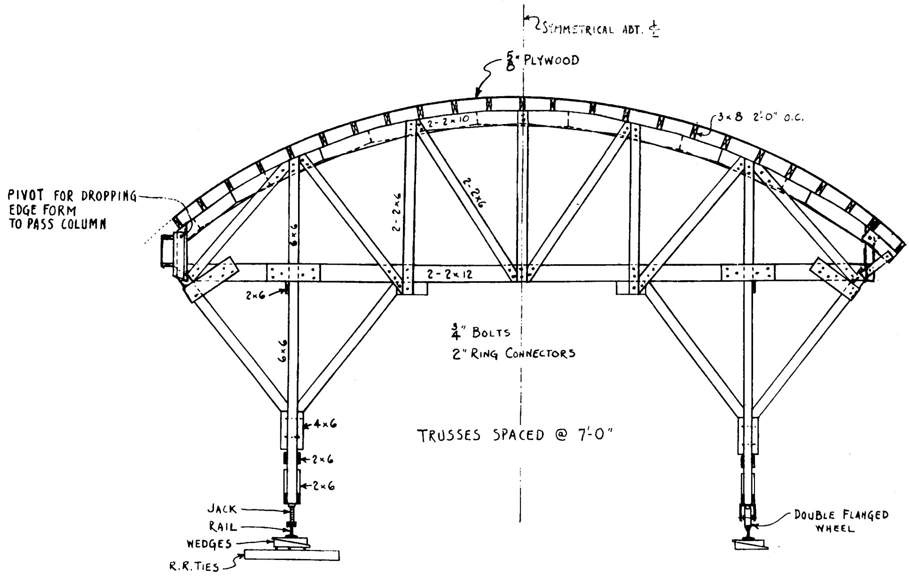


Fig. 4—Sketch of typical timber traveler

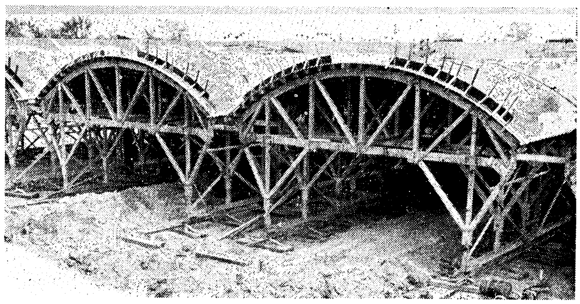


Fig. 5—Typical timber traveler, first used for 45-ft bay multiple span warehouses for U. S. Army and U. S. Navy

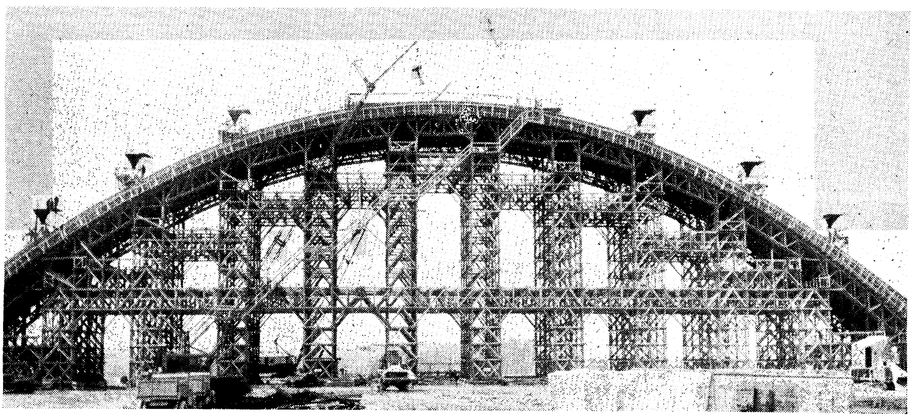


Fig. 6—Centerings for 340-ft span U. S. Air Force hangars. Timber ring-connected trusses are supported on light braced towers consisting of 6-in. posts and 2 x 6-in. diagonals. Screw jacks are located both at rail level and at bottom chord of trusses. Note arrangement for lifting concrete by cranes

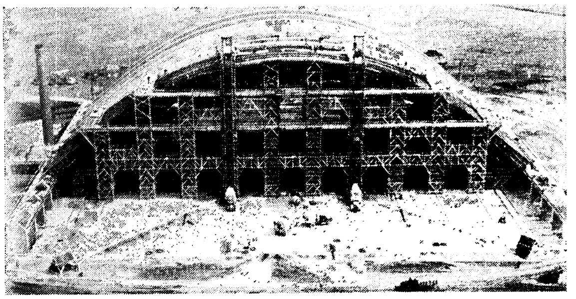


Fig. 7—Another method of lifting concrete. Hoisting towers are integral part of centering; towers with "added booms" are used to hoist reinforcing steel

The centerings shown in Fig. 6 and 7, for 340-ft span U. S. Air Force hangars, are built of timber trusses, supported on light towers. Except for built-in hoisting towers and cross runways identical centerings were designed for different locations. Variations of this design were used in recent years for the construction of arenas at St. Paul; Denver; Victoria, B. C.; Quebec; and even in Argentina. Sometimes it is advisable to support the traveler from previously constructed floors or bleachers, resulting in centering trusses of considerable span such as those used for an arena in Washington, D. C. The centering shown in Fig. 8 was used for the construction of a 165-ft span hangar designed for the U. S. Navy at Buckley Field, Colo., in 1951.

Construction of shell structures progresses with the building of foundations, columns, etc., during the several weeks required for erection of the centering.

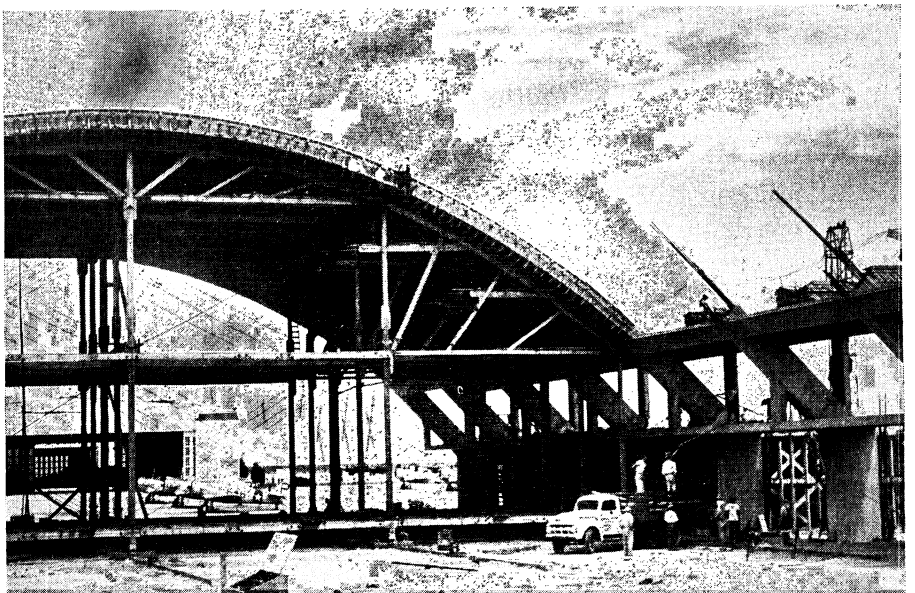


Fig. 8—Hangar for U. S. Navy. Centering consisted of 10-in. posts and ¾-in. round steel diagonals supporting wood trusses with glued laminated chords. Truss web members utilize wood for compression and steel rods for tension. Horizontal struts are of built-up channel section with 2 x 10-in. side pieces and a 2 x 14-in. piece on top and with spacer blocks as required for stiffness

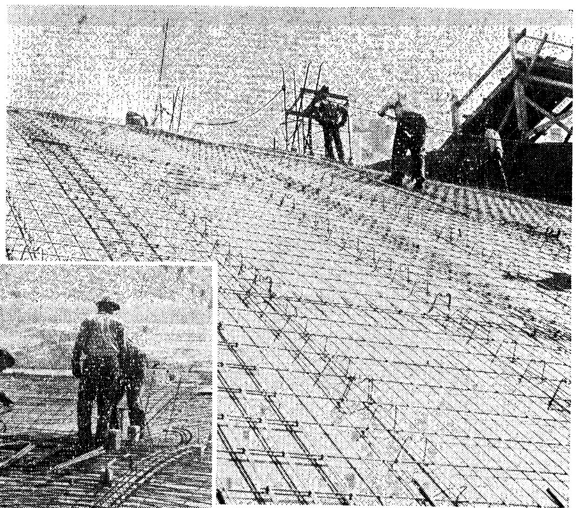


Fig. 9 (right)—Details of reinforcing, mesh mats, and bar supports for hangar roof

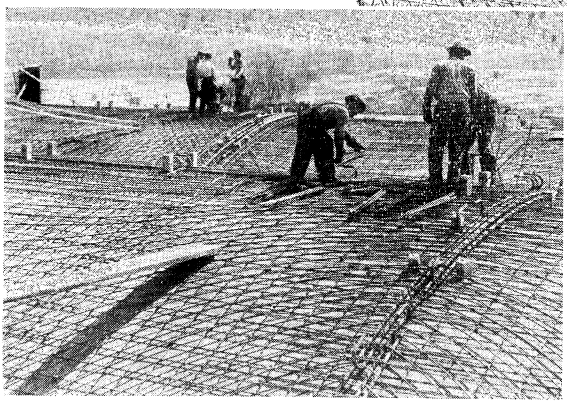


Fig. 10 (left)—Details of reinforcing, mesh mats, and bar supports for warehouse roof

REINFORCING STEEL

Steel reinforcing for shells is essentially wire mesh with additional bar reinforcing as required by edge conditions and diagonal tension. The reinforcing is simple and little if any bending is required. The steel mesh is supported by continuous chairs about 4 or 5 ft on centers. Mesh in mats was found preferable to the use of mesh in rolls because of easier handling. Steel men quickly get used to the requirements of shell work and place reinforcing steel on roof forms of moderate curvature for the tonnage price customary for flat decks.

It has been found helpful to paint the location of key reinforcing bars on the forms before covering the form surface with clear lacquer and form oil, for guidance in placing bars of inclined diagonal pattern. Fig. 9 and 10 illustrate details for placing reinforcing steel and bar supports.

CONCRETING OPERATIONS

A roof shell slab with its stiffening and supporting members, between expansion joints, is considered as one unit and except for the columns should be constructed monolithically. This determines the size of a major concreting operation, which proceeds evenly from the springing line up and usually is planned so it will take one working day, and no overtime, to place the concrete. Depending on the yardage involved and the surface area to be finished, the contractor can determine the equipment and labor necessary to place the concrete within the planned number of hours, after which time only the concrete finishers remain on the roof.

Usually a 5½- or 6-bag mix is used of 3- or 4-in. slump with ¾-in. maximum aggregate size. Contractors have come to like air-entraining concrete, especially in the steep portions of a shell, because of its greater cohesiveness and resistance to segregation.

Hoisting and distributing

Concrete has been lifted by cranes (Fig. 6), by hoisting towers (Fig. 7) usually attached to and moved with the centering, or by pump.

Maximum yardage usually handled by one crane or tower is about 40 cu yd per hr. The maximum hoisting rate depends upon the speed at which the concrete can be properly placed, vibrated and finished. The minimum rate is governed by the requirement that all concrete edges must remain alive, and that cold joints must be avoided. It is recommended that the hoisted concrete be dumped into distributing hoppers, often located at various levels, on the leading edge of the centering.

Placing of concrete has been accomplished by:

(1) Runway and buggy from the distributing hoppers to small chutes or directly into the forms. The runways are placed on trestle legs at convenient levels and often laid out for one-way traffic. They sometimes are dismantled as the work progresses and they become unnecessary.

(2) Crane bucket dumping directly into the forms. This permits the use of a lower slump. The method often is slow as a crane usually must boom up and down for every bucket. A crane, even with a jib, may not have full reach over the entire placing area; a combination with some other distribution method may become necessary. It is important that the concrete be placed not lower than its point of usage. Much time and labor will be expended in shoveling concrete uphill if placed too low.

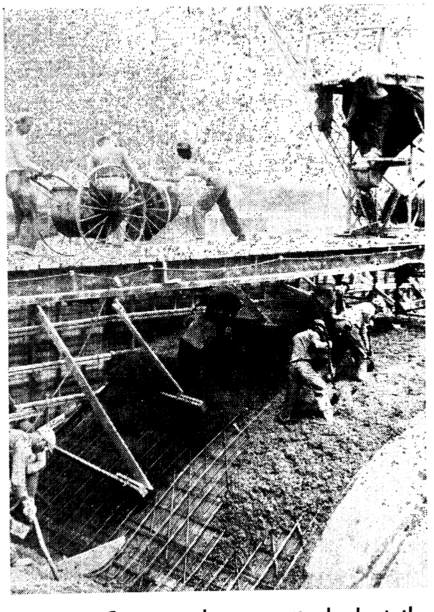


Fig. 11—Concrete hopper attached at the head of mobile runway feeds buggies for placing concrete on multiple shell U. S. Army warehouse

(3) Pumping directly into the forms. Good results have been obtained on short span projects. Usually, the small unit quantities of concrete required do not justify the cost of a pumping installation. The method is considered less flexible than operation with buggies, especially in case of breakdowns.

(4) Shotcreting. This usually is not economical except for repair work. Good results are obtained only with experienced operators. Considerable shrinkage has been observed in shotcreted shells.

(5) Movable conveyor system. This should be considered as a transport rather than a placing method. The result is satisfactory when the conveyed concrete is dumped into distributing hoppers where it can be re-mixed; otherwise, trouble has been encountered with the mix losing its fines as the paste sticks to the conveyor belt.

Experience on many projects has shown that the most practical way to place concrete on shells is by buggies operating on a runway and from there dumping into small chutes or directly into the roof forms. A movable concreting runway, first devised for the construction of a big warehouse roof in 1941, was mounted on wheels and rails, extending across the width and running the length of the concrete placing area (Fig. 11). A hopper which fed the buggies was attached at the head of the runway and was filled with concrete by crane bucket from below. The buggies were operated by four men who were able to cart 320 cu yd of concrete each day in approximately eight hours or less. Movable runway bridges have been used since, where the job was large enough to justify the convenience and initial expense and where the arrangement of a few fixed runways was not considered cheaper or sufficient.

Placing and finishing

Except on very short shells, placing of concrete is started at the springing lines, where the slope of the roof is a maximum. Care is necessary to prevent segregation when concrete is placed by chutes. Labor should be properly supervised and instructed how to work as a team. Dumping of concrete from buggies into chutes should produce a steady flow without surging. The moving of chutes to place concrete in the designated areas should be uniform. Concrete is placed alternately into ribs and on the slab forms, usually in 8- to 12-ft lifts. The size of these lifts, the number and positioning of workmen depend on the decided rate of placing and on the time required to vibrate and finish the concrete without developing cold edges against which the next lift is to be placed. Individual vibrators or vibrating screeds are used to obtain a dense concrete slab. Too much vibration causes the concrete to sag downhill in the steep portions of the forms.

A reliable method of placing the shell slab without honeycomb consists of covering a given form area fully and to the specified thickness with the concrete available for it. Only then is this area systematically vibrated by placing the vibrator head in the concrete for a few seconds at points about 1 ft apart, working in horizontal rows from the bottom up. Vibrators should not be used to spread the concrete; the concrete should not be raked; the vibrators should not lie in the concrete nor be in contact with the mix longer than required for optimum results.

Simple depth gages have been used as an aid to striking off the concrete to the right depth, as well as mechanically operated scaffolds with screeded strike-offs. Removable metal screed supports made of flat bars or pipes with short legs have been found useful; also spacers of job-made concrete blocks for varying thicknesses of slab are sometimes used and located along lines where slab thickness changes.

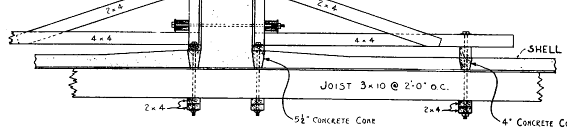


Fig. 12—Detail of forms, bracing, and supporting devices for roof shell and rib

Runways and forms for ribs, if required, are supported on precast blocks secured to the forms and remaining in the concrete. It has been found advantageous to give these blocks the shape of inverted, truncated cones. Fig. 12 and 13 show the arrangement of blocks, form details for the ribs, and bracing arrangements successfully used for forming concrete shells.

Finishing of the shell slabs is done by hand with the use of wood floats. Finishers stand on a light, narrow scaffold which is dragged over the finished shell surface as the work progresses (Fig. 14). It is good practice to have a finisher follow up about one hour later to float off rough areas and, where necessary, to fill small holes with grout. Attempts have been made to use a road finishing arrangement for large scale operations. The top surfaces of exposed ribs are trowel finished and beveled to facilitate drainage.

Special attention is necessary on warm or windy days to avoid cold joints during the placing of a roof shell. Concrete along the edges is prevented from setting during unforeseen interruptions by keeping these edges "alive" with small quantities of fresh concrete.

A contractor may do well to start slowly with the placing of the roof concrete so that the men working in the steeper portions of the shell have enough time to finish the placed concrete properly. The rate of placing will increase as the men get used to the operation and as the angle of the roof flattens. A contractor's headache in connection with his first roof concreting experience is almost always due to lack of proper finishers and vibrator operators. On the second day of placing roof concrete, the output is increased as the time and the cost of placing are substantially decreased. After further savings on the placing operations which follow, time and output after the fifth or sixth placing operation usually remain fairly constant.

Tarpaulins should be available in case of rainstorms for the protection of the shell slab portions which have not yet set. If the work must be discontinued, it is recommended that bulkheads and small keys along construction joints be provided and that these be located if possible along lines of low stress; the placing of shear dowels may be required at joints in ribs; the joints should be cleaned and slushed with mortar before concreting is continued.

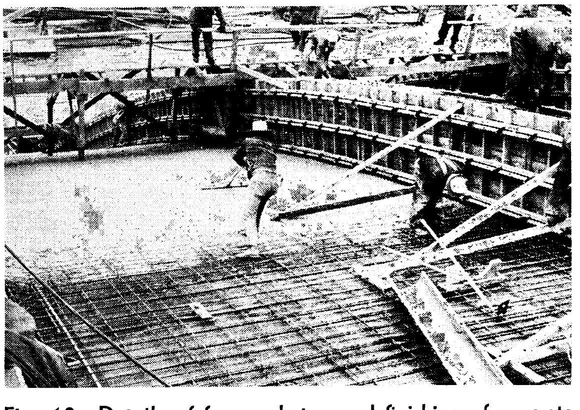


Fig. 13—Details of forms, chutes, and finishing of concrete

Sometimes in the past, large summer concreting operations have been successfully performed during the night. The work is performed evenly without distractions, the concrete consistency remains uniform, and the mix does not lose moisture such as it may on hot days.

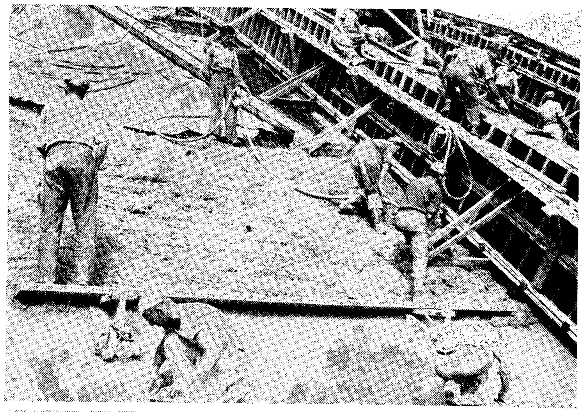


Fig. 14—Chuting and vibrating of concrete ahead of finishing operation. Note the protection of reinforcing from spillage of concrete

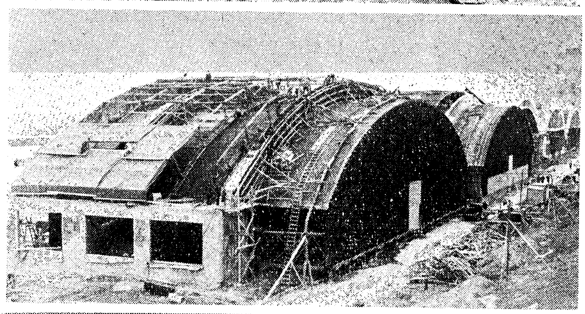


Fig. 15—Winter operations at U. S. Air Force hangars of 160-ft span. Note the pipelines for pumping concrete and the extensive protective housing

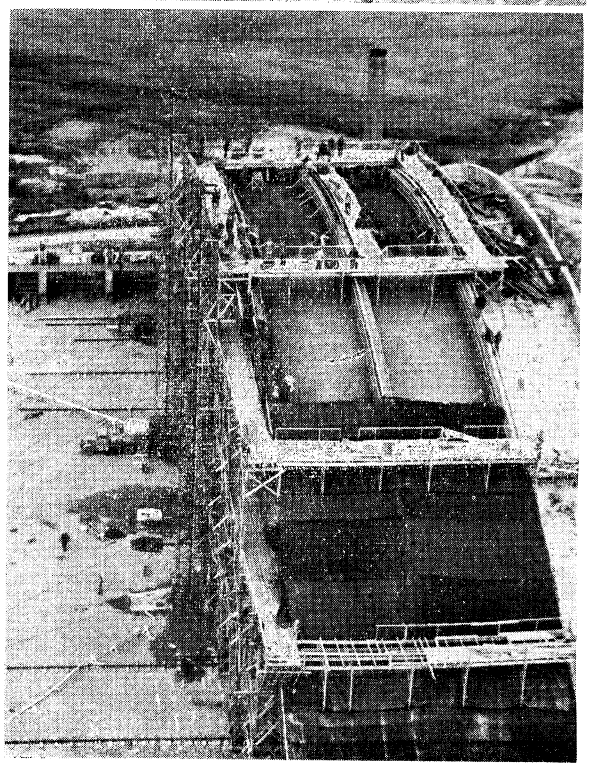


Fig. 16—Cold weather concreting at U. S. Air Force base, Rapid City, S. D. Note the runway arrangement, protective housing, steam pipe leaders for heating, and track installation for centering

During winter, standard rules for cold weather concreting should be observed. The space occupied by the form centering has been enclosed and heated on past jobs and the roof has been covered with insulation or housed with tarpaulins a few feet above the shell (Fig. 15 and 16); sometimes a few holes have been left open in the shell forms and slab through which warm air could rise and circulate. Use of high early strength cement, strict temperature control, and the curing of test specimens under job conditions at roof level are almost mandatory. (Laboratory-cured cylinders, however, should also be tested.)

The designing engineer should be conscious of the rising construction cost when the rate of strength increase of the concrete is low. At times it may be economical to employ designs using greater material quantities and of decreased slenderness so as to have a sufficient safety factor at an early decentering age. An early form re-use and a saving in the cost of winter protection and heating may offset the greater material costs.

A light spray of water may be useful for curing the shell slab. Various membrane curing compounds have been used and sprayed on the concrete shell with apparent success.

DECENTERING AND FORM MOVEMENT

Since the quick re-use of forms is essential to the contractor, he will often be more interested in obtaining a high concrete strength at an early age than to get the ultimate 28-day strength which the designer usually specifies. This may lead to the use of richer mixes than called for, or the use of high early strength cement to obtain a saving in formwork, a speed-up of construction, and better use of labor.

Usually a structure can safely carry the dead load and construction loads when its concrete has reached 70 to 85 percent of the specified design strength. Assuming a design strength of 3000 psi, and that the contractor wishes to strike his centering after 5 to 7 days, this would require 2500 psi on the decentering day or a concrete of an actual 28-day strength of 4000 psi or more.

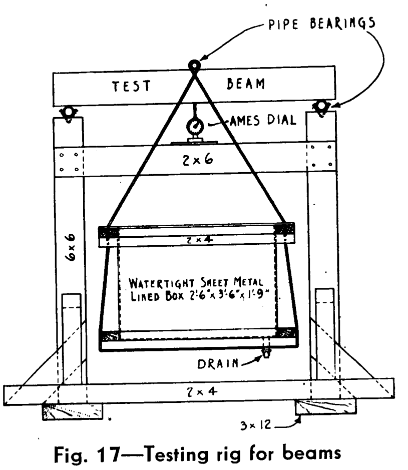
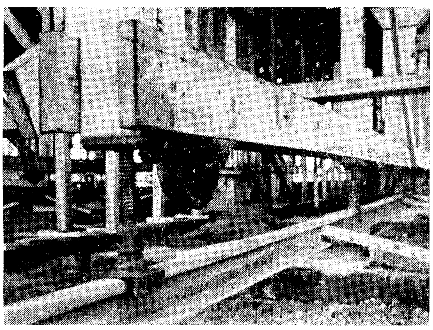


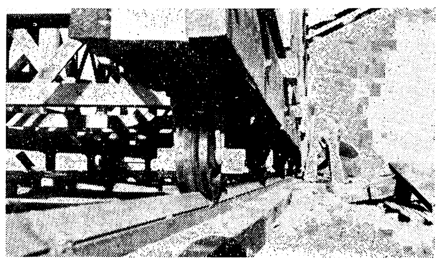
Fig. 17—Testing rig for beams

Where elastic requirements and buckling considerations are used to govern the time of decentering, it has been found practical to make the decentering time dependent on the deflection of small test beams, reinforced to simulate the bending condition within the roof shell. These beams are field tested on consecutive days, whereby the load usually is applied by filling a metal lined box slowly with water (Fig. 17); permission to decenter is given when the daily deflection has become smaller than a specified value, *i.e.*, the apparent modulus of elasticity measured by deflection of test beams must be greater than the value specified.

When the concrete has reached the desired strength and deflection characteristics, the formwork is lowered evenly, or in a predetermined manner. As a convenience for the workmen, the amount of vertical movement is expressed as the number of turns or fractions of a turn on a screw jack. A centering for a sensitive structure is lowered by operating screw jacks in proper sequence so as to provide for deflections proportional to the final deflection curve of the structure. (This operation should take about 30 to 45 min.) When the forms have separated completely from the concrete, all blocks and wedges used for distribution and transfer of the loads at ground level are removed and the assembly is lowered onto rails so that it can be rolled into position for the next unit. (See Fig. 18 to 20 for wheel, rail and jack details.) The form traveler sometimes is pulled ahead by winch-operated cables, or it is "walked out" by a tractor, or it may be pushed ahead with rail jacks. The entire hangar centering shown in Fig. 6 was pulled ahead by a system of cables attached to the rear of the towers and converging at one point where a single winch provided the moving power.

The moving operation itself usually takes little time for a low height structure, where it is convenient to repair minor imperfections of the concrete ceiling from a separate movable tower scaffold. It is, however, advantageous to clean and to point imperfections of high concrete ceilings from the form traveler as the stripped concrete surface becomes exposed during the moving operation. Men can finish the concrete ceiling and install equipment from a working platform at ceiling height attached to the rear of the traveler about 6 ft below the arched slab. The moving operation in this





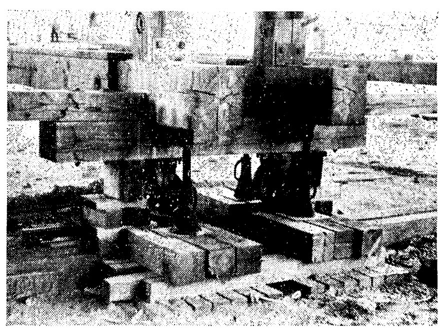


Fig. 18 (above)—One arrangement of wheels, rails, and jacks for the support and rolling of mobile centering

Fig. 19 (above, right)—Mobile centering resting on rails

Fig. 20 (right)—Jacking mobile centering off rails

case may take several hours; however no special effort or scaffold is required later for follow-up work. When the traveler has reached its new position, it is lifted off the tracks; supporting blocks are again inserted between falsework and floor or ground, and the screw jacks are operated to re-adjust the roof curve to the correct shape, elevation and camber.

A comparison between the centering types shown in Fig. 6 and Fig. 8 indicates that initial material costs are about equal and that the type represented by Fig. 8 may be somewhat cheaper to erect. The first type (Fig. 6) has far superior truss articulation, an advantage in following a planned decentering procedure; also auxiliary scaffolds, such as platforms underneath the deck where carpenters must tighten up bolts, can be attached more easily. A finisher's platform for the second type can be supported only from the joists of the form deck, and clearance for finishers requires that this centering be lowered 8 in. for moving as compared to about 2½ in. for the first type.

From the standpoint of form movement, the best design is offered by a structure with a constant clear profile in the direction in which the forms travel; this means that no concrete girders or ribs should project below the ceiling and that the columns should be outside the profile of the form centering (Fig. 21). For designs where beams or ribs project below the ceiling, the side forms of these members, if built into the centering, should be splayed; the centering must be equipped with jacks providing for such vertical movements of the forms as required after each successive use to clear the obstructions to form travel. In spite of precautions, the forms around projecting beams or ribs often do not come loose easily from the concrete during decentering. Wedges sometimes have to be driven, or jacks inserted, between forms and concrete to force separation. Streams of water under pressure have been used between concrete and forms and even the insertion of compressed air has been helpful in forcing separation.

Arch structures with tension ties cutting across the profile of the form centering do not provide great difficulties to the form move. In these cases the centering, at tension tie level, is divided into an independent lower and an upper section. A screw jack is provided at this level for every post. Each jack is removed and replaced as the post, of which it is a part, clears the tension tie during the move. The centering must be properly braced in the direction of its travel to permit removal of jacks without excessive deformations.

DETAILS

Insulation, when required, is placed either above or below the roof shell. Insulation slabs made of loose materials or sheets of organic fibers should always be placed on top of the shell; this type of insulation, when placed below the roof slab, may become loose, blister, or disintegrate due to condensation. Rigid cork slabs, or insulation composed of cement covered fibers, can be placed below the shell and the concrete slab may be placed directly thereon. Little, if any, mechanical anchorage is required to fasten the insulation to the structural slab placed upon it. This arrangement is acoustically beneficial and it brings about a saving in the form decking; however, slight difficulties are encountered in the support of the reinforcing steel, as standard bar chairs have a tendency to penetrate or settle into the insulation. Insulation below the shell becomes expensive when many inserts are to be placed in the concrete and openings for them have to be cut through the insulation.

Wood nailing strips are used where top insulation and roofing are to be anchored in the steep portion of large roof surfaces. These wood strips, usually of the same thickness as the insulation, are nailed into the finished surface of the concrete while it is still green. Spacing of the strips is such that insulation slabs just fit between the strips and with them form a smooth base for the application of the built-up roofing. Roofing felt is applied and secured in standard manner; for small steep roof shells it is preferable to run the roofing felt in the direction of the roof curvature, as the pull of the roofing will then balance over the crown of the roofs and no trouble with sliding will be encountered, even where roofing is not nailed to the deck. A 45 deg lightweight concrete cant strip and the usual flashing and reglet is provided where the roof deck meets exposed concrete ribs or other vertical surfaces.

Electrical conduits are embedded in the concrete shell and seldom require an increase of its thickness. The heavier conduit runs are brought up through

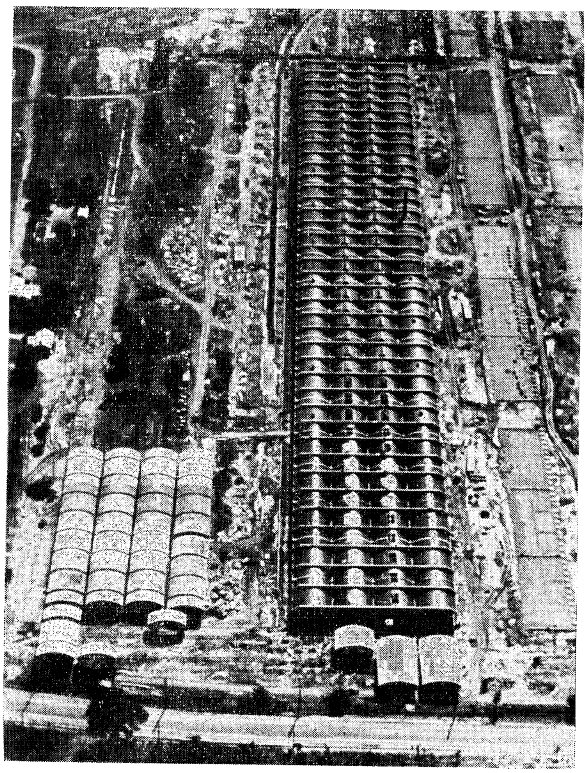


Fig. 21—1562 ft long multiple span concrete shell warehouse, built in 34 calendar days (1941). Note the simplicity of the top surface of form travelers

the columns, beams and stiffening members, avoiding points of stress concentration. Conduits are placed within the shell with at least ¾ in. concrete coverage, often near the neutral axis and in the same layer of reinforcing with which the conduit is parallel.

Where a sprinkler system is required, most pipes are carried straight and supported along the longitudinal straight lines of the cylindrical shell. Occasional headers are welded to polygonal shape and supported along the curve of the ceiling. Inserts for sprinklers, or for the support of other light loads, do not require special anchorage except for a small distributing rod through the hole of the insert within the concrete. The transfer of concentrated crane or monorail loads through roof inserts usually requires additional bending reinforcing for the shell; this reinforcing assists in transforming the concentrated loads into an area load of such magnitude as the shell can safely carry.

LABOR AND COSTS

For a large shell-type warehouse structure, the low bidder recently figured with the following costs:

Forming including centering—Material and labor less than 30 cents per sq ft plan area.

Reinforcing steel—Material 6 cents per lb; labor 2½ to 3 cents per lb.

Concrete in place—$18 per cu yd, including plant and equipment, but excluding forms, reinforcing steel and accessories.

When concrete was placed recently on a unit of a hangar structure of 165-ft span, the placing area covered 9000 sq ft in plan and involved 184 cu yd of concrete. Ready-mixed concrete was delivered in 5-cu yd trucks at a maximum rate of 35 cu yd per hr, and concrete was hoisted by two cranes. The following organization was required to hoist and place the concrete in a little over 7 hr or at an average rate of 26 cu yd per hr:

On the ground—Two crane operators, two oilers, and two laborers (loading buckets).

In the form centering—One carpenter (watching and adjusting forms).

On the roof—Two laborers (signalling the crane operators), two rodmen (including one foreman), 14 laborers placing concrete (two of these were used later for wetting forms and curing concrete), eight vibrator men, one electrician, 16 cement finishers (including one foreman), and two labor foremen.

The personnel further included Navy inspectors, one surveyor (checking movement of the forms), one technician (making tests and taking samples) and two supervisory men not on the contractor's job payroll.

A labor cost of about $525 resulted when an 8-hr day spent by the contractor's crews was multiplied by the applicable labor rates. (This does not include the time of the cement finishers.) The total cost divided by the yardage is the labor cost for hoisting and placing—$2.85 per cu yd. The cost of finishing is about 4 cents per sq ft additional.

All the observations presented in this paper have been obtained from actual experiences in research, design, and construction. The difficult pioneering is behind; the idea has become a reality, and a new phase in the field of shell construction is ahead. The future should see many more installations, based on wider knowledge and the growing appreciation of shell structures.