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Construction methods and quality control for concrete shell roofs

Mircea MIHAILESCU[a], R. SUNDARAM*

* Member of the IASS Advisory Board,
President of Structural Engineers World Congress [SEWC] Inc.
Sundaram Architects Pvt. Ltd.
19 Kumara Krupa Road, Bangalore-560 001, India
edp@sundaramarchitects.com

[a] The late Prof. Mihailescu (1920-2006), Technical University of Cluj-Napoca, Romania, and Honorary Member of IASS, was the first author for the initial drafts of this paper

Abstract
Concrete shells are moldable to any shape and can be made aesthetically beautiful. This paper discusses the suitability of various methods of concrete shell roof construction, necessary precautions and quality guidelines. Good construction practice for concrete shell roofs is also highlighted.

Keywords: concrete shell roofs, construction methods, formwork, precasting, prestressing, quality control, waterproofing, thermal insulation.

1. Introduction
Concrete shells are aesthetically pleasing, structurally efficient, construction-wise challenging, and are optimized structures. Shells derive their structural action through their form and are unique in their behavior and many other ways. Hence, shells are used in multi-various situations as coverings of convention centers, exhibition places, industrial buildings, etc. (Figs. 1a, 1b, & 1c). They look light and beautiful.

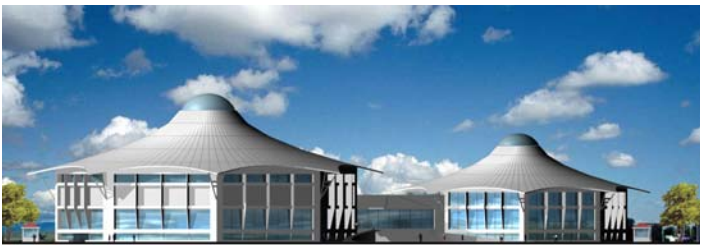

Figure 1(a): Example of cast-in-place shell

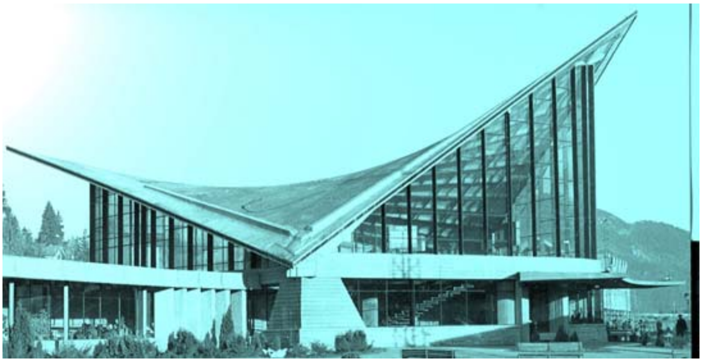

Figure 1(b): Asymmetric hyperbolic shell

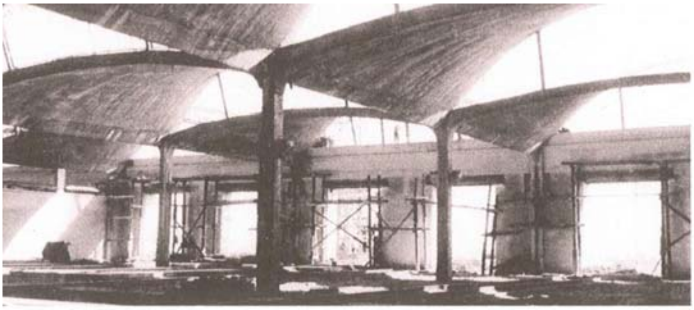

Figure 1(c): Conoidal shells for a depot

The analysis of a concrete shell using the latest software with a reasonable computer can be done in a design office. The software uses finite element techniques. The following factors can be recognized in the analysis: non-linear behavior either geometrical or material, imperfections in the geometry, creep and buckling.

Concrete can be cast to any shape and this being a distinct advantage, offers a practically unlimited range of the shell shapes that expresses variety and novelty in form.

The transition from pure sculpture to utilitarian architecture includes a great spectrum of variations. Thin shells are probably the best morphological structures to express this range through their inherent plasticity of form which lends them to diverse expressions. Thin shells come in an immense variety of structural forms. No structural form perhaps does greater justice to the special attributes of concrete than thin shell construction. They derive strength through form rather than through mass.

During the last few decades the development of thin concrete shell roofs as a structural form has added an interesting chapter to contemporary architecture. The curvature of a shell can be of the same sign throughout, Say concave or convex, or can be of different signs, both concave and convex at the same time. The former is called synclastic and the latter is called anticlastic.

Of course form work and manpower costs for cast *in-situ* shells have to be recognized.

Proper form and shape, optimum design, and good construction technique will yield economical and durable high-performing shells. Good quality control and improved construction techniques are necessary to enhance the performance of the shells including safety features, durability and least maintenance.

Concrete of ordinary and high strength can be produced easily anywhere in the world and can be lower in cost than structural steel. So reinforced concrete thin shell roofs can be the structural system for long span structures. Thin shells still have a bright future.

This paper is a first version of a chapter for a State-of-the-Art Report by IASS Working Group 5: Concrete Shell Roofs. The objective of this overview is to look into the key issues of construction that play an important role in performance of concrete shells. The paper aims to analyze the methods of achieving efficient and economical shells so that they become competitive when compared to other type of structures. The recommendations and ideas are based on the authors' extensive experience in shell design and construction rather than upon particular building codes.

The key construction issues to be considered in enhancing the performance of concrete shells are the following:

- Techniques of Shell Construction (Section 2): ∗Cast-in-place construction ∗Precast construction ∗Prestressed construction
- Construction Details (Section 3): ∗Formwork/shuttering ∗Concrete thickness ∗Reinforcement ∗Concrete mix design ∗Concreting ∗De-shuttering
- Durability Aspects (Section 4): ∗Waterproofing ∗Thermal insulation ∗Fixture of service installations ∗Cover to reinforcement
- Quality Control (Section 5): ∗Tests in situ ∗Curing ∗Tolerances

2. Techniques of shell construction

2.1. Cast-in-place construction

Cast-in-place shells are suitable for unique and complicated shapes and in situations where the geometry of the shell is not conducive for splitting the shell surface into precast elements, whether factory made or cast *in situ*. The following factors are to be considered for cast-in-place shells:

The size, geometry and the components of the shell for a given application should be judiciously decided to maximize reuse of formwork and feasible concrete pour.

If the shell facilitates dividing into convenient sectors or segments that are repetitive, movable reusable formwork can be employed. Movement can be either by translation or rotation or both.

The design of formwork must be such that it will be possible to remove the formwork after the setting of the concrete in segments so that the de-centering can be done quickly and without causing any damage to the formwork.

The geometrical form being the predominant controlling factor, the formwork should be done carefully to be stiff and to retain the geometry under the action of forces developed during the concreting process.

The levels and dimensions should be checked frequently and rectification, if any, should be attended to immediately.

- When concreting is done, the shuttering should cause neither pockets nor unwanted additional thickness, either of which might lead to redistribution of the load.
- Top shuttering is necessary whenever the angle between the surface and the horizontal exceeds about 45º.
- Properly preplanned control sequences have to be provided for all the erection phases such as shuttering, reinforcement, pouring, de-shuttering, and fresh concrete protection.
- Inflated forms can also be used for cast-in-place shells.
- Any honeycombing formed should be investigated after de-shuttering and properly grouted before applying waterproofing and/or thermal insulation.
- Marine plywood for shuttering and steel props and bracings for scaffolding are well suited.
- Concreting should be planned such that the weather conditions like rain, low temperature and snow do not interfere with concrete pouring. Emergency measures like covering of the shell with plastic sheets have to be in place for any eventualities.
- The rejection of poor quality of concrete work in cast *in situ* construction is often infeasible, and in this case the only alternative is to strengthen the shell by an acceptable method.

2.2. Precast construction

Precast concrete technology can be efficiently employed for construction of concrete shells (Figs. 2(a), 2(b), 3, & 4). Precast shells have the following advantages compared to cast-in-place shells. (Melaragno [3])

Figure 2(a): A dome of 90m x120m using precast folded plate elements

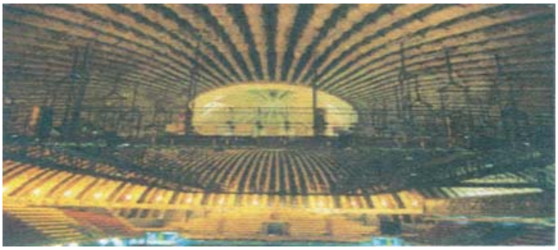

Figure 2(b): Example of precast folded plate dome

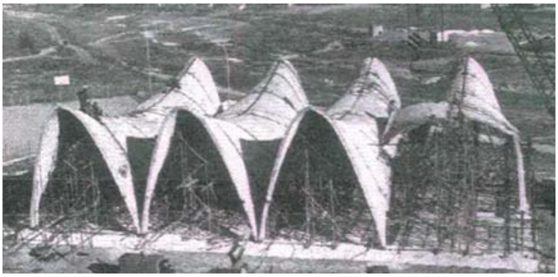

Figure 3: Precast shells during assembly

Figure 4: Precast elements being placed in position

Due to controlled conditions better quality of concrete can be achieved as the inspection of concrete can be done at the ground level itself. Hence, the other qualities of the concrete like homogeneity, compactness, and strength can be ensured properly. For example, should for some reason the specified concrete characteristics are not achieved in precast concrete construction, this product can be rejected or can be strengthened by the accepted methods.

Precast techniques can be made effective by dividing the shell into a number of identical units ensuring the geometrical compatibility and proper structural connection. Due to this a number of repetitions in the usage of the mould can be achieved with a consequent reduction in the cost. The scaffolding that is required for a cast-in-situ shell is almost nil in this case.

The size of the mould and the weight of the precast elements depend on the handling capacity of the erection system either through a movable crane or through a moving tripod system etc.

The completion time of the shell is reduced by organizing parallel activities in the site like concreting of columns, fabrication of the mould and casting of the precast units in the workshop etc.

The other advantages are as follows:

- The moulds are placed at the ground level.
- The moulds can be inclined or horizontal depending on the shell design.
- Pouring and compaction of concrete can be made easy while the whole procedure can be protected against the atmospheric disturbances.
- The casting of precast shell can be done fast.

The material that is used for mould can be either concrete or wood or steel or a combination of any of the two or three materials, so that maximum number of re-uses can be achieved. The surface finish of the mould should be satisfactory so that it is easy to de-mould the precast elements. Consequently good concrete finish is achieved.

In order to reach acceptable levels of accuracy of assembling and to obtain match casting between different elements, it is recommended to provide special networks, used as settings for the precast panels (Figs. 5, 6, & 7).

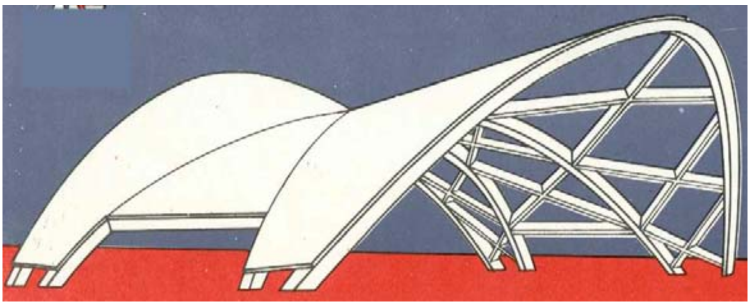

Figure 5: Concrete rib lattice serving to seat ferrcement precast panels

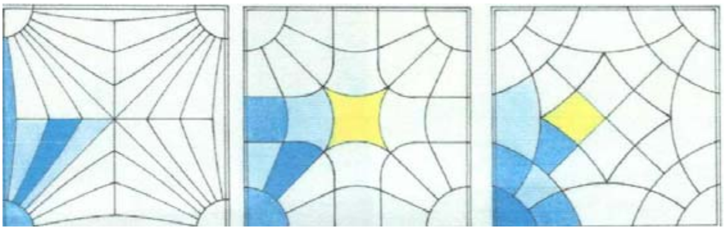

Figure 6: Modalities of dividing the shell surface for precasting

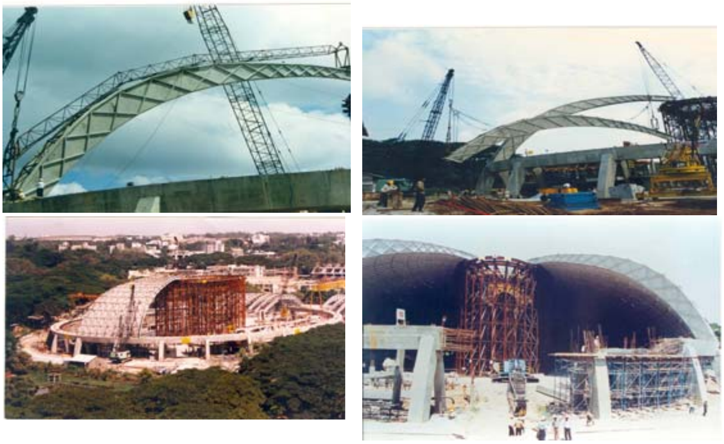

Figure 7: Erection process of precast elements

In some cases shells are built by a combination of cast-in place and precast construction methods. A set of ribs is constructed and precast concrete provisional formwork is placed and supported by the ribs. Finally concrete is cast in place and the formwork embedded in the shell thickness.

Setting structures can be achieved in the following ways:

By erecting in final position a concrete rib lattice serving to seat ferrocement precast panels, all together being afterwards assembled by concrete topping (Fig. 5).

By *installing a self supporting metal network* in shell final position on which concrete precast elements are placed and then joined together by cement mortar grouting:

By using ground assembly and lifting.

By demoulding and lifting the shell up to its final position and by launching the whole form to the following bay.

Suitable storage facilities should be available to store the precast units. The erection of the individual units forming the total structure should be done in a manner that will minimize the erection stresses. Based on the shape/size of the precast elements suitable type and number of cranes have to be used for erection. Balancing truss or a strong back fixed to the element is effective in taking care of erection instabilities.

Joints between adjacent precast elements have to be studied carefully. Joints in any precast structure including precast shells are very important and critical. The philosophy is that joints must be both designed and constructed such that the structure must behave monolithically. In addition they must be leakproof. Several methods of joints include welded connections for non-seismic areas, grouting the reinforcement dowels for seismic areas, etc. Waterproofing methods include sealing the joints with non-shrink grout, polysulphide, silicon compounds, etc.

2.3. Prestressed construction

Prestressing is effective in long span shells to take care of the tension developed at both the boundaries and the bodies. The objectionable deflections and cracks are avoided.

Following are the advantages of prestressing shells:

- Edge beams deflection can be reduced and hence can be made sleek.
- Prestressing of shells reduces the quantity of reinforcement thereby reducing congestion.
- Pre-compression in concrete prevents the formation of temperature and shrinkage cracks.
- The compressive state of stress in the shells results in water tight construction

Concrete shell prestressing may be achieved in several ways (Fig 8). Methods of prestressing both pretensioning and post tensioning are well established. Shell prestressing can even be realized by only prestressing boundary elements, beams, or ties. A feasibility experiment of external prestressing was performed on a concrete shell model of elliptic form, put in a pre-compression state by wires placed below the inside shell surface (Fig. 9).

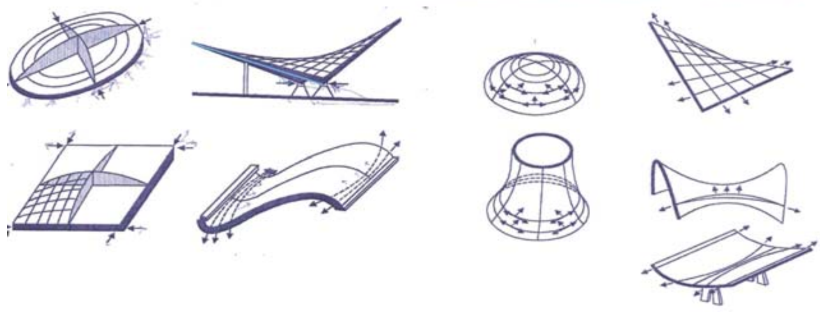

Figure 8: Prestressing of shells – only cable actions are depicted

Figure 9: Elliptic shell prestressed by inside

3. Construction details

3.1. Formwork/shuttering

Formwork should be designed to take up the shell concrete weight and construction loads and should be supported by properly braced props. Bracing should consider the lateral forces due to partial loading of wet concrete, vibrations due to the usage of mechanical vibrators and lateral forces generated due to geometry. Formworks may be produced in several versions such as described in the following:

Made of *many rows of props, properly braced* (Fig. 10). This solution ensures tough supports, is simply done, but is very expensive because it cannot be reused by moving.

The most effective solutions allowing reusing are formed of several steel or wood plane trusses supported on scaffoldings placed at shell boundaries (Figs. 11 & 12). The outside truss profiles have to suit the shell shape. Between trusses, timber boards are provided at convenient centers. Plywood panels can sit on these timber boards. The entire formwork, well braced, after de-shuttering, can be moved by translation or rotation or by a combination of both, serving for other casting.

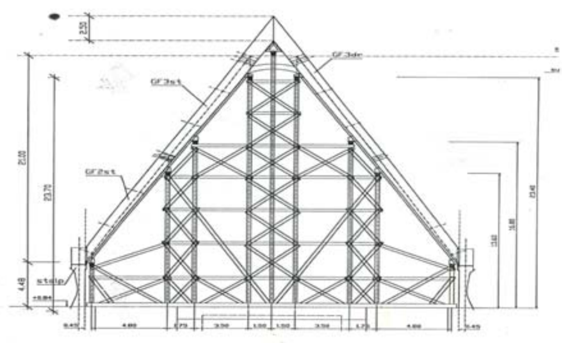

Figure 10: Fixed scaffolding made of braced props

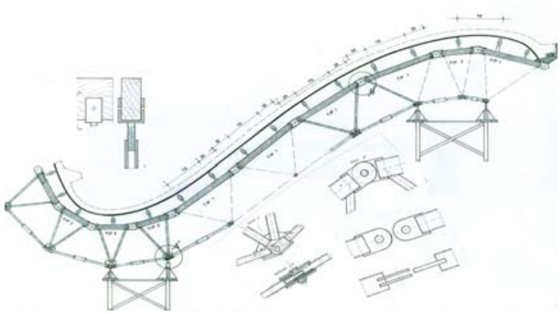

Figure 11: Steel truss scaffolding for curved shape

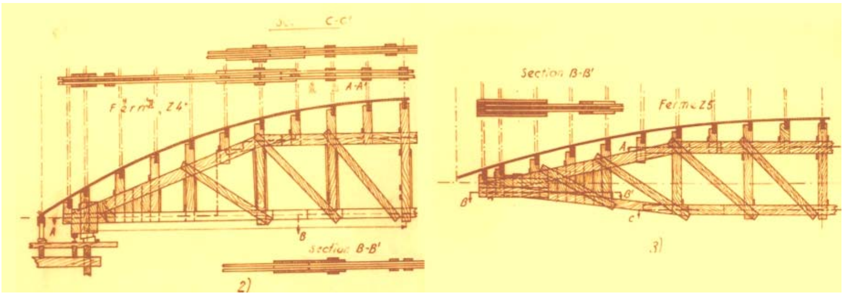

Figure 12: Two timber truss types for formwork of a conoidal shell

Some of the important points to be kept in mind during formwork erection are:

- After floor concrete is done to get a firm ground, an approved system of scaffolding should be erected along valley/gutter portion. Steel walers (parallel ribs) at the bottom of the valley should be placed to suit the shape of the shell.
- In between these two valley/gutters, timber waler (parallel supports) member should be shaped to suit the profile of the curve and are placed as per the design requirement of the formwork.
- In between these two waler (parallel supports) members, smaller pieces of timber are provided spaced at a minimum distance on which the plywood can easily span.
- The total grid system and top curve profile are checked before placing the plywood.
- The marine plywood is nailed on the top of the timber support on the already profiled timber to suit the curvature. The plywood joints have to be plugged with a suitable filler and the curve should be smoothed.

- Appropriate measures to prevent the bulging of formwork have to be taken after a thorough inspection.
- In case of shell roof in a multi-storied structure, the lower floors supporting the formwork have to be suitably propped.
- Special Pneumatic Forming: A membrane is inflated to generate a tensile surface capable of supporting a concrete layer that is then applied on top of it. Concrete spraying has been the most practical method of constructing shells by using pneumatic forms. The membrane is generally of neoprene material.
- Alternative methods using inflatable neoprene membranes are also available.

3.2. Concrete thickness

- The thin shell's thickness and reinforcement must be proportioned to satisfy the strength provisions, so as to resist internal forces obtained from an analysis, an experimental model study, or a combination thereof. The thickness of the shell is often dictated not by the requirements of strength, but by the limitation of deflection of edge members, by the requirements of stability or by the required reinforcement cover and the construction exigencies.
- Concrete thickness depends on the shape of the shell (Fig. 13), size or span of the shell, and the strength of concrete, environmental issues and fire protection requirements.
- Thickness can start right from 3 cm.
- Building codes vary from country to country and each country prescribes a different minimum thickness.
- Thickness is arrived at after an analysis of the shells and with the limits of allowable compressive stresses. Creep and buckling have to be studied.
- Currently available are high strength concrete mixtures and such new strengths greatly reduce the thickness of concrete shells. It is therefore possible to design shells which are efficient, costs less, consumes less steel and cement and with larger spans.
- Long-span shells can be strengthened by ribs depending on the shape, size and concrete strength. This will reduce large deflections and will also add to the buckling strength of the shell.
- Whenever the areas are larger than 1,200 square meters, to provide economically designed shells there are two effective solutions for supplementing the shell thickness by ribs, namely:
    - *bidirectional rib networks* placed on the inside face of the surface.
    - *box cross sections* provided with bidirectional ribs inside the surface.

  In both situations the equivalent thickness values he for shell analysis can be found by using homogenization techniques. However for practical purposes the following heuristic expressions are often applied:

for axial effort: $h_{ea} = h + \dfrac{A_r}{a_r}$ (1)

for bending moment: $h_{eb} = \sqrt[3]{h^3 + \dfrac{12 I_r}{a_r}}$ (2)

In which *h* is:

- the slab *surface thickness* without rib height for ribbed plates,
- the *sum* of *upper* and *lower* surface thicknesses for box cross sections;

A_r and I_r represent the area and inertia moment of the entire rib without any shell-surface participation; and a_r is the distance between ribs.

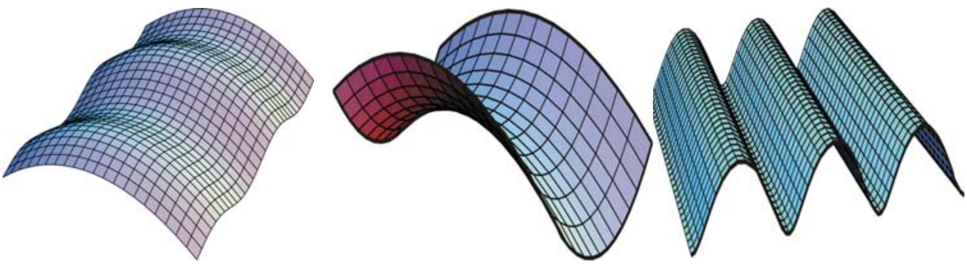

Figure 13: The three fundamental types of shell forms: elliptic (positive Gaussian curvature), hyperbolic (negative) and parabolic (zero)

3.3. Reinforcement

While theoretically free-form concrete shells designed to be in pure compression need no reinforcement, shells must resist various forces/stresses that require reinforcement to be provided.

The principal tasks of reinforcement are to enhance the homogeneity of concrete throughout the entire shell surface and to take care of tensile stresses produced by bending and twisting moments due to boundary conditions, unexpected concentrated loads, and shape irregularities. The additional tasks of reinforcement are to take care of shrinkage and temperature stresses, limiting crack width, and its spacing. Additional reinforcement is required in edge beams and ribs and also around openings and at locations of load attachments. (Medwadowski and Samartin [2])

3.3.1. Provisions for reinforcement

Principal tensile stresses should be entirely resisted by reinforcement. Steel provided to resist the tensile stresses is assumed to act at the middle shell surface. It should be placed either in the direction of principal tension lines or in two or three directions on the surface.

Shells with thickness on the order of 8cm should be reinforced with two overlapped layers of steel bars, ensuring the needed concrete covering. Two layers at top/bottom faces are preferred to resist possible local bending moments.

In shells whose thickness is around 4 cm thick, the reinforcement can be provided in the middle surface in two perpendicular directions.

In both previous situations, the steel percentage should not be less than 0.4 and not greater than 4.0. Minimum reinforcement should be provided wherever not required by the analysis.

Minimum laps to be provided are 30 times the diameter of the bar or 450mm, whichever is greater. Bar splices should be staggered with not more than one third of all bars spliced at one cross section.

Bar nets have to be held in the designed position by the concrete either by little cubes or by metal loops. Attention should be paid to the steel bars curvature in the vertical plane of the shell in order to resist the generated deviation forces.

Steel or carbon fiber reinforcement in a recommended dosage, almost of 0.5-0.6 KN/m^3 of concrete, may be effective to reduce the concrete shrinkage, as well to improve its homogeneity and compactness. Fiber reinforcement can be effectively used to reduce the shrinkage cracks.

Deformed bars of smaller diameter are preferred in the body of the shell. For a singly curved shell, a welded fabric is preferred. However welding is not preferred in seismic zones.

Additional steel reinforcement should be provided in the junction between beam and shell, where crack appearance due to shrinkage differences due to distinct thickness can occur.

3.3.2. Prestressing reinforcement

Prestressing tendons have to be laid in the middle surface of the shell so that they act tangentially to the central face.

When prestressing tendons do not lie tangentially to central surface, the exerted forces have to be resolved in two components, which should be accounted for in the design.

Where prestressing tendons are anchored in the boundary elements, special reinforcement should be added to accommodate locally produced tensile forces.

3.4. Concrete mix design

Many methods of design of concrete mix are available. Concrete mix design for shells should be based on the following:

- Type of construction – In-Situ/Precast

- Thickness of the shell
- Weather conditions
- Grade of concrete

Sufficient measures have to be taken to reduce the heat of hydration as shell structures are thin and susceptible to thermal/shrinkage cracks. A smooth shell thickness transition between the edge beams and the shell area is desirable.

Reduction of water cement ratio and high workability are prime requirements of the mix design. Plasticizers can be used to reduce the water cement ratio to around 0.4. Silica fumes can also be added to concrete to result in more dense concrete with less permeability. Considering environmental issues, it is also recommended to use fly ash/ slag cement / Pozzolona cement as a replacement to portion of cement.

In hot weather concreting the aggregates should be chilled and ice cooled water should be used in making concrete. In cool weather on the contrary, warmed aggregates together with warm mixing water has to be used.

Sufficient number of cubes/cylinders should be tested at 3, 7, 14, 21, and 28 days to monitor the strength which aids in deciding the de-shuttering date.

Self-compacting concrete can also be used especially where the shell surfaces are steep and where the shuttering length is long.

3.5. Concreting

Quality control of concrete is very important aspect of the shell construction. Proper behavior of the shell depends on the mechanical properties of concrete and hence on strict quality control of concrete. The following points should be kept in mind during the concreting of a shell structure:

- The concrete placing should produce a smooth dense solid texture on the undersurface of the shell with no pockets or honey-combing.
- Concreting should be done starting from the supporting beams and stiffening beams working upwards from lower end to higher end.
- Maximum size of aggregate should be 20mm. Depending on the thickness of the shell, less than 12mm can also be used.
- Construction joints should preferably be located in zones of compressive stresses and the concreting should be done in a symmetrical manner.
- High-performance concrete will have a higher modulus of elasticity to control deflections but will cause shrinkage cracks in the thinner members of the shell. Appropriate grade and mix design may reduce the cracks.
- Concrete can be placed by pumping or by bucket and mobile crane.
- Form vibrators can be used for shell proper and needle vibrators for beams.
- Construction joints should be treated with bonding agents.

3.6. De-shuttering

De-shuttering should be carried out progressively in accordance with a carefully designed program with proper supervision. De-shuttering as a general principle should be done from the point of maximum deflection to the point of minimum deflection, symmetrically. Any wrong method of de-shuttering may endanger the structure.

De-shuttering should be done when the compressive strength of the concrete is at desired level. However with conventional curing of concrete, de-shuttering may take place after a minimum period of 14 days.

De-shuttering of the form work should be guided by the general code of practice for concrete. One of the codes suggests that the de-shuttering should be done when the concrete achieves a strength of at least twice the strength to which the concrete may be subjected to at the time of de-shuttering. The verification of the concrete strength should be done by testing the concrete cubes/cylinders at various times, i.e., 7, 14, and 28 days.

If early removal of forms is required the magnitude of the modulus of elasticity at the time of proposed form removal must be investigated in order to ensure the safety of the shell with regard to buckling.

4. Durability aspects

4.1. Waterproofing

Waterproofing is the method adopted to prevent the ingress of water through the roof. Inadequate waterproofing is manifested as:

- Dampness/water droplets
- Discoloration
- Streaks

Since most of the shells have excellent slope the water naturally drains off and stagnation is rarely possible. Good dense concrete would therefore be efficient and any other extraneous media would not be required. The waterproofing may be required only in places where there is continuous rainfall over a period of several months resulting in the presence of continuous moisture and, concrete being not entirely impermeable, certain dampness may occur.

Hence, generally more often than not water proofing is provided. With regards to waterproofing two methods are followed:

- In the first, on the outside layer of concrete, a timber lattice is made on which a layer of slate or copper is fixed.
- Alternatively, the outer face is covered by brushing with a cement grout containing additional water inhibitors or by applying a tight membrane on the entire shell.

A few of the other methods of waterproofing are as follows:

- 1 mm thick Acrylic coating can be adopted.

- Three or five layer bitumen felting provides effective water proofing media.
- Polymeric or polyethylene membrane is in wide use, which is simply unrolled and fixed over the concrete by torching.
- Coating with chemical waterproofing grout which produces the crystallization of the upper layer of concrete.
- A number of other methods is available. The type must be chosen depending on factors like type of shell, weather, etc.
- Many times corrugated galvanized sheets are used as a waterproofing material which is also used architecturally. The sheets are fixed on a wooden or steel grid on the top of the slab.

4.2. Thermal insulation

Shells being thin elements, the heat that is put in through the shell can be significant. This is particularly valid in tropical countries. In a similar manner in cold countries loss of heat through the shell is possible.

Insulating material can be either on the top of the shell or on the underside of the shell.

As far as methods of thermal insulation are concerned, currently, the following procedures are used:

In the first alternative, the thermal insulation is applied on the concrete upper face, fixed with cement mortar, which is then protected by a layer of waterproof covering. Thermal insulation on the external surface can be provided in two ways:

- Polyurethane base primer is applied on the dust-free concrete and 20mm thick polyurethane foam is applied on the same.
- Expanded Polystyrene of 50mm or 25mm can be fixed to the dust-free concrete with the help of bitumen of desired grade.

With the help of bonding agents, the waterproofing media such as integrated polymeric system or bitumen felting can be applied on the thermal insulating layer.

The second alternative provides the thermal insulation to be directly applied on the shuttering. After de-shuttering the insulation layer finally remains fixed on the inner face of the concrete shell. If aesthetics and fireproofing regulations permit, insulation can be on the underside of the shell.

The third alternative inserts the thermal insulation in the middle of concrete layer of the shell. Subsequently special connectors are used and both layers of concrete are joined together. The positive features of this approach are:

- An appreciable increase in the plate inertia moment and the buckling limit.
- Both faces, inner and upper of the shell, remain as concrete, promoting an exposed concrete look (Fig. 14).

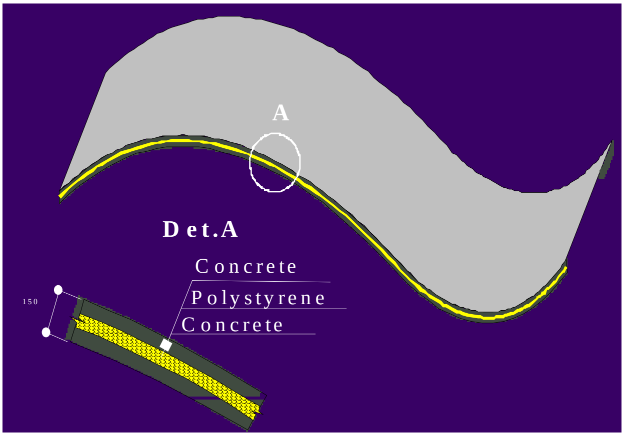

Figure 14: Thermal insulation insertion

4.3. Fixing of service installations

A special mesh of reinforcement should be provided in order to strengthen locally the concrete plate and thus allowing it to hang suspenders.

As for electrical ducts, they should be laid, in the central part of the concrete thickness, parallel to the main reinforcement.

Heavier conduits as for ventilation or water drainage should preferably be located in edge beams, ribs or columns. Moreover these conduits may be placed extraneously to the structural elements, thus avoiding damages created if eventual deteriorations occur.

4.4. Cover to reinforcement

A few of the important factors to be considered in determining the amount of cover are:

- Fire resistance
- Environmental issues.
- Thickness of the shell
- Based on environmental factors and the thickness of shell, Table 1 provides some guidelines for possible covers. Generally the cover is a minimum of 12mm up to 25mm.

It will be more efficient to protect the top and bottom surfaces by applying appropriate protective coating to protect the concrete from environmental deleterious effects.

Table 1: Covers for cast *in-situ* shells suggested as per authors' experience

Degree of exposure	**Thickness of the element**	**Grade of concrete**	**Diameter of Bars (mm)**	**Recommended value for cover (mm)**	
				Cover (mm)	**Plastering Notes**
Mild	75 mm	M 25	< 12	12	Plastering done with epoxy mortar will increase the life span of the structure and delays corrosion. Judicious reduction in the cover can be considered.
			> 12	15	
		M 30 & above	< 12	12	
			> 12	15	
Severe and above	100 mm	M 30	< 12	25	For precast shells 70% of the indicated cover can be used.
			> 12	25	
		M 35 & Above	< 12	22	
			> 12	25	

5. Quality control

Here *quality control* refers to the following actions:

- The confirmation of correct shaping of moulds, shuttering, and settings. Checking the dimensions provided in the design.
- The control concrete qualities established in the project concerning strength, ductility, and compactness according to the pouring procedures specified for the site and in confirmation with standard provisions.
- Referring to the reinforcement, a special attention has to be paid to verify the steel or carbon qualities as well as the accurate bar positioning.
- The yield strength of steel specified in the design should be achieved in the site. This can be ensured by testing the steel reinforcement frequently for yield strength.

5.1. Tests *in situ*

After de-shuttering, some tests could be performed on the entire achieved shell by loading it with a percentage of the service load value so that the concrete shell behavior concerning displacements and deformations may be examined.

5.2. Curing

Shells develop shrinkage cracks if not cured properly. Also the ultimate strength of concrete is reduced. In moderate weather, ordinary methods of curing such as wet curing or use of membrane curing are adequate. However, in hot weather, water curing is advisable. Sprinklers can be placed on top of the shell for better curing. There are many admixtures /

additives available in the market as curing compounds in which case water curing can be avoided.

Steam curing is extremely efficient for precast concrete components. It is possible to demould the precast element within 24 hours of the start of this curing method provided the concrete has attained at least 70% of its ultimate strength. This certainly speeds the construction process. A small boiler can produce stream at the site near the casting yard. (Ambili and Rajamane [1])

5.3. Tolerances

Tolerance is the permissible limit of deviation in the constructed dimension to those assumed in the design. While the tolerances are generally left to the discretion of the project/site engineer, it is recommended that the working drawings prepared by the designers/manufacturers should indicate the tolerance to serve as guidelines in the site. Tolerance is applicable to all of the following:

5.3.1. Form work/geometry

The formwork should be designed and constructed to the shapes, lines and dimensions shown on the drawings within the tolerance specified which can be termed as dimensional deviation.

5.3.2. Dimensional deviation

It is impossible to achieve absolute accuracy in the erection of the formwork and certain amount of inaccuracy has to be expected. The permissible deviation or tolerance that is specified should be as large as possible to facilitate easy construction without rendering any part of the finished shell un-acceptable for the purpose for which it is intended. An unrealistic attitude for dimensional variations can result in considerable increase in the cost.

If the construction results in any deviation from the shape other than specified tolerances, an analysis should be made and any required remedial action should be taken to ensure safe behavior. Some geometric imperfections of a shell structure can lead to a drastic reduction of the overall buckling load.

The deviations can be different for the following categories:

Precast concrete elements. For precast concrete elements, overall dimensions of the member should not vary more than 0.5% or 10mm, whichever is less.

Cast in-situ. For cast *in-situ* shells variation in plan dimensions should be 1 percent or 20 mm whichever is smaller. However, in the vertical direction, it should be restricted to 1 percent or 15 mm, whichever is smaller.

5.3.3. Thickness

The thickness may vary from place to place depending upon the design. The tolerance in thickness is as follows:

For ***precast*** concrete elements:

- $\pm$ 1.5 mm for sections less than 75 mm thick
- $\pm$ 3.0 mm for sections more than 75mm but less than 450mm
- $\pm$ 6.0mm for sections thicker than 450mm

For ***cast in-situ*** shells structures the variation in the thickness can be 5% or 10 mm whichever is smaller.

5.3.4. Cover

Concrete cover is always referred to in terms of the nominal cover and is to be provided to all reinforcement. Tolerance/deviation in the cover depends on (i) the type of shuttering, (ii) the thickness of the element, and (iii) the location of the reinforcement. Recommendations on the tolerances are as shown in Table 2. (Sundaram [5])

Table 2: Tolerances on the upper bound of cover

Type	**Single-layer reinforcement**	**Double-layer reinforcement**
Precast shell	5 mm	5 mm
Cast *in-situ*	10 mm	5 mm

5.3.5. Formwork/shuttering

The degree of unevenness of shuttering also affects the cover. Hence, the degree of unevenness should be related to cover and the tolerance to the cover. As the tolerances recommended to the cover is 5mm to 10mm, the tolerance to degree of unevenness should be limited to 2mm.

5.3.6. Reinforcement spacing

Shells are usually lightly reinforced. The tolerance in the spacing should be 5% of the spacing or 10 mm whichever is lesser.

6. Future development

The ability to predict whether or not a given concrete will correctly fill a given formwork is being researched in the field of rheology of concrete and further research and findings are needed to understand better the laying of concrete on formwork. (Roussel [4])

Environmental factors have to be considered. Cement production involves emission of carbon dioxide into the atmosphere which is a part of the problem of global warming. Suitable replacement of cement with fly ash/ slag cement/ pozzolona cement has to be used. Continuous research and updates are required in this area.

To ensure the best performance of shells, use of newer materials like light-weight concrete, fiber-reinforced concrete and composite panels should be investigated and encouraged.

Self-compacting concrete should be explored more fully for usage in shell construction, and its properties like long-term durability, creep, etc. must be studied thoroughly.

7. Conclusions

Key construction issues related to concrete shell roof construction have been discussed.

The Importance of exercising control on quality of concrete, placement of concrete, design of form work, waterproofing methods and thermal insulation have been discussed with suggested tolerances for enhancing the overall performance of concrete shell roof construction.

Precast construction, its advantages and speed of construction are also discussed.

With the minimum use of materials like cement and steel and with efficient design and construction of formwork, concrete shell roofs have a bright future especially where labor is not expensive

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