# *High Performance Ferrocement Dome*

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## *Abstract :*

A successful case history of the construction of the main dome (22' dia) for a Sikh temple is discussed in this paper. The uniqueness of this project lies in the high performance FC mix used as well as the efficient management of the construction sequence.

The dome sits 90' above the ground on top of an RCC framed structure. Based on an FEM analysis, the dome shell was designed to be 1" thick with 24 nos. longitudinal stiffener ribs in the form of truss frames, projecting inwards. 6 layers of high quality G.I. wire meshes were wrapped on the armature.

The plaster mix proportions were finalized after significant testing of several trial mixes. For giving a high performance, suitable additives were included to enhance properties like shrinkage cracking, high impermeability, and high long term strength. At the same time adequate training for a good workmanship was ensured. The plastering was completed in a single one shot operation. Testing indicates a doubling of compressive strength in 180 days over the 28 day strength.

## *Introduction :*

*Ferrocement* – a composite of steel & cementitious material is an ingenious invention of the mid 19th century which has a good potential for use in a wide variety of applications. It is basically a scaled down variation of concrete – as we know it today. The large size reinforcing steel bars are replaced with wires or meshes, while the coarse aggregate is removed completely from the cementitious matrix. The resultant composite – called *Ferrocement* lends itself to casting in thin sections – sometimes less than 1". The properties of Ferrocement, such as strength, water-tightness, toughness, light weight, durability, fire resistance & environmental stability are hard to match with any other thin constructional material. Applications include fishing boats, water tanks, silos, roofing channels, dwellings etc.

Natural disasters like earthquakes have shown increasing unpredictability and intensity in recent years, forcing structural engineers to revise their earthquake safety codes frequently. Unnecessary weight is always unwelcome in buildings. Greater the weight and greater its height from the ground, the more severe is the effect of an earthquake on the building. That is why overhead water tanks experience far higher base shears than a multistorey of the same height & weight.

*Gurudwara Brahm Bunga Trust* is building a temple in Doraha, Punjab for weekly congregations. The four storey RCC framed building reaches a height of 70', above which sits an architectural dome of 22' dia.

If built conventionally with brick masonry, this dome along with its base would have weighed 160 tons. In order to reduce the earthquake damage potential to the building, a need was felt to make the dome lighter. A thin shell in Ferrocement was a strong candidate and necessary analysis with detailing was carried out. The following paras describe the construction with respect to detailing, materials used, sequence as well as the construction management.

## *Geometry :*

The dome rises from a 20' dia circular concrete wall, 6" thick & 4' high. The top edge of this wall is a 9" x 9" crest ring beam. The circular wall (also called the dome neck in local lingo) has reinforcement on both faces. After every 2 ½' along the circumference, two dowel bars 12" long spring out of the crest beam. These bars would be welded to the rib trusses of the dome.

The dome which is nearly 3/5$^{th}$ of a flattened sphere starts with 20' dia. at the base and bulges outwards to a maximum dia. of 22'. It terminates at a 10' dia. ring beam, on which sits a concave, conical finial. The height of the spherical dome between the neck & where the finial starts, is 12'- 8". The finial also done in Ferrocement, is 5' high, topped by a SS spire.

## *Analysis:*

The dome shell was analyzed on STAAD. The shell was idealized as trapezoidal plate elements, which gradually become smaller in both directions as one moves up. The aspect ratio is kept within 1 : 1.2. The ribs were given the properties of beam elements and were joined to the plates of the outer shell by sharing the same nodes at the junction. The maximum thickness of the architectural finishes was to be 3" making a total maximum thick of 4". To take this dead weight into account, the plate elements were given a thickness of 25mm but a density of 4 times that of concrete. The finial load including the spire was distributed equally on all the nodes of the ring beam.

The Analysis showed a maximum hoop tension of 9.5 kg/cm2 near the middle part of the shell, reducing to 1.6 kg/cm2 near the crest.

In the orthogonal direction along the longitudes the maximum vertical compressive stress was 7.6 kg / cm2 near the base reducing as one goes up.

The maximum bending moment in the frame rib was .06 T-m at the base (tension inside face) and .04 T-m at the crest (tension outside) with negligible moments in between.

## *Structural Details & Construction* :

The dome is a 1" thick FC shell stiffened with 24 longitudinal ribs projecting 6" inwards and 1" thick. The rib frames are similar to the those in the truss frame method widely used in FC boats. The truss consists of 2 – 8 mm bars connected with zig-zag lattice bars. These curved trusses are nearly 15' long and follow the profile of the dome. These were fabricated on a simple jig prepared by driving 6 mm dia pins into a level brick floor.

The trusses were then erected on the ring beam at the dome base, welding them to the dowels left in the beam for the purpose. At the top, these trusses were, arranged & held in place with the help of a 10' dia. pipe ring (broken at one point to allow stringing). This pipe ring would later be embedded in a concrete beam.

The trusses once erected, (like a water melon) were then wrapped around by hoop steel – 6mm dia MS bars @ every 3”. The maximum distance between the trusses at the point where the dome is the widest is nearly 3’. In order to reduce this gap, two 8 mm bars run vertically between

each pair of trusses, serving as distribution steel for the hoop bars.

The FC dome shell has 6 layers of G.I. square woven meshes embedded, 3 on each side of the armature. The mesh has ½” square openings and is made from 20 SWG, G.I. wire with a Zn coating of 40 – 50 g/m2. G.I meshes normally available in the market are electro galvanized with a zinc coating of only 5 – 10 g / m2. Square meshes supposedly resist orthogonal forces better than hexagonal wire nettings. The mesh size was chosen so that the openings are neither too big, (to let a pencil back poke through the mesh layers), nor too small so as to act as delaminating partitions in the cement matrix. Woven meshes can be laid better on a double curvatured dome compared to weld meshes.

3’ wide meshes were then stretched over the steel armature, such that every area had at least 3 layers over it. On the inside, the meshes were cut to shape so as to fit between the rib frames. Each rib frame was also covered with 3 layers of wire mesh.

The 3 outer and the 3 inner mesh layers were then mutually tied with the help of hairpin shaped GI wire ties. The worker would push the hairpin form the inside & the outer worker would twist & then cut it from the outside using a piano wire cutter. Roughly 2400 of these wire ties were installed.

Experience has shown that voids remain after FC application in T junctions, like in our case - the junction of stiffener rib to the skin shell. PVC grouting nipples were therefore placed from outside @5’ on each truss, to be grouted later. Before the plastering, a thorough checking of the dome shell was carried out ensuring that no part of the mesh was bulging or loose. Extra ties were installed wherever required.

## *Training :*

One day before the final plastering, the masons were given a ½ day training familiarizing them with Ferrocement, and with hands on experience on a small bathing tank – specifically made for the purpose. These masons had no previous experience with Ferrocement. They were taught to concentrate on proper penetration of the mortar rather than a smooth finish. The masons got a chance to try different tools including the small trowel, the wooden float & gloves in difficult areas, and get a feel of the creamy plaster mix – which was different from the usual harsh one they were used to.

## ***Plastering & Quality Control :***

The high performance plaster mix used a high content of fly ash, a high dosage of SP as well as an integral crystal forming waterproofing compound. The sand was a clean washed river sand, sieved below 2mm. A galvanic reaction inhibitor was also added to the mixing water. The resulting mix was a very creamy, dough like, workable mix.

***Mix Proportions***

| | |
|---|---|
| OPC 43 Grade | 1 (By Volume) |
| Fly Ash | 1.5 (By Volume) |
| River Sand below 2mm | 2.5 (By Volume) |
| Super Plasticizer Napthalene based | 1.2 % of OPC |
| Water | 37 ltrs. / bag of cement |

On the plastering day, the necessary steps for QC were enforced. Exact measures in the form of boxes / buckets / liter measures etc. for the ingredients were organized. In order to maintain the consistency of the mortar over different batches a flow table was kept in shade close to the mixer. A small sample of the mortar was filled in the cup placed on the flow table. After lifting off the cup, a blow count of the flow table gave the measure of consistency. The blow count remained between 13 & 14, owing to the rigorously trained workforce and a strict control over the ingredients including water.

6" cubes were filled from 2 batches and placed next to the dome wall on the inside after demoulding, in order to receive the same curing as the in-situ material. After a months' curing, each of the cubes was sliced into eight smaller cubes for later age testing. Since an HVFA mix had been used, strengths were monitored for over a year showing a phenomenal gain in strength over time. The results are as per table below :

| ***Age in Days*** | ***30*** | ***90*** | ***180*** |
|---|---|---|---|
| Cube Compressive Strength (kg/cm2) | 356 | 563 | 715 |

Suitable work platforms at 3 levels along the 13' height of the dome both inside & outside were erected. A small bridge to convey the plaster mix to the dome interior from over the top ring was also erected to avoid any disturbance to the dome skeleton by worker movement.

The plastering day began at 6.30 am with the first plaster load reaching the dome by 7.00 am. Eighteen masons – nine outside & nine inside, worked for 11 hrs with 2 tea breaks & a lunch break in between to finish the plastering in a one shot operation. The cycle time on each one bag mix, which depended on how fast the masons could use up the material, was 20 – 25 minutes. A water mist spray was kept ready to avoid drying out from the sun and the wind, but was used little. Work proceeded smoothly from bottom up towards the top. Each pair of masons working inside & outside ensured that the mix penetrated both ways to create a monolithic layer 25 mm thick.

3 hours after the plaster application started, one pair of masons started putting on 2 – 3 mm thick finished coat with the same plaster mix ensuring that no mesh was left exposed.

## *Durability Assessment :*

Since cementitious materials with embedded steel usually deteriorate due to ingress of atmospheric elements into the matrix through its numerous pores and micro cracks, any reduction in porosity and micro cracking potential is seen as longer durability.

The Chloride ion permeability as per ASTM 1202 was checked on 28 day cured specimens and found to be superior to ordinary cement mortar without fly ash of the same consistency. Long term testing could not be carried out due to unavailability of more samples. However, previous testing of HVFAC has shown a multifold improvement in permeability with age. This indicates that the Ferrocement mix used on this project will be much more impermeable and hence durable compared to conventional Ferrocement mixes. The increased compressive strength at long term ages ( table above ) supports this hypothesis. The mechanism that makes this possible is :

The high volume of pozzolona (fly ash) in the mix participates in a secondary reaction with $Ca(OH)_2$ – a byproduct of the cement hydration. This secondary pozzolonic reaction continues for several months, and the reaction products keep filling the pores in the cementitious matrix making the final product much more dense and impermeable. This consequently improves the properties like strength, durability, elastic modulus and reduces the corrosion potential of steel inside. The lower cement content in such a mix further contributes to a durable matrix by virtue of reduced shrinkage and reduced heat of hydration. This in turns reduces the risk of micro cracking thereby ensuring that detrimental elements do not find pathways into the cementitious matrix. Hence the high performance of this mix.

## *Curing & Post Treatment :*

The day after plastering, an elaborate curing system was set up. The dome was wrapped with jute sacks, further covered with a plastic sheet tied all over. A rubber hose with tiny holes in it & connected to a 500 liter water tank, ran along the circular crest keeping the sacks continuously wet. This was kept in place for a month. The inside was sprayed liberally several times a day with a pressure hose.

12 days later, the crest beam at the dome top was cast along with a 2" thick arched slab with 6 radial ribs to take the load of the metal spire.

After 30 days the interior was plastered with a polymer modified cement plaster to serve as a weathering protection to the Ferrocement shell. 3 days following the plaster, grouting of the nipples left in the shell earlier was carried out. A hand operated Killick Nixon pump along with a polymer modified cement – Fly ash slurry was used for grouting. Nearly four cement bags were used in the grouting, revealing that inspite of the extraordinary workmanship and the extra workable mortar mix, a great number of voids are left inevitably in Ferrocement construction of this type.

### *The Finial:*

The conical finial cap is also a hollow shell sitting on the 10' dia. crest beam at the top of the dome.

This concave conical shell was created hollow by first erecting a framework of steel bars – 8mm dia following the desired shape. This was covered with a jute fabric wrap immersed in a cementitious slurry mix. This was further sprayed with cementitious grout & allowed to set & harden for four days. On this hollow finial shaped structure, a steel armature using 8mm bars was erected, then covered with 2 layers of G.I. square mesh. The shell was then plastered 1" thick with the same plaster mix as used on the dome, and then covered well with PVC sheet to cure for 3 weeks.

### *Conclusion :*

Ferrocement being a labour intensive and a material saving technique, has never been able to compete with reinforced cement concrete. However, innovative structures in different parts of the world have clearly indicated the unique, unmatched properties of this material and therefore the vast potential waiting to be explored. These special structures in the past include aircraft hangars & the famous *Turin Hall* built by Nervi. More recently the laminated Ferrocement technique developed by Martin Iorns by spraying an engineered mortar on layers of mesh holds a great promise. This has been demonstrated in various offshore structures, bringing down labour costs and improving the Ferrocement matrix.

The application of Ferrocement to the dome structure has made it possible to construct a light but strong, durable weather resistant shell with a weight reduction to almost $1/10^{th}$ of the conventional material. The addition of a high volume of fly ash and other additives have given a mix which should be able to protect the underlying steel meshes for a far longer time than conventional plaster mixes. The extra ordinary workmanship and careful attention to detailing has also played its part in ensuring a sound, long lasting structure.

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