Building Optimised Domes without Formwork

Satprem Maïni
Auroville Earth Institute, India
UNESCO Chair Earthen Architecture / CRATerre-ENSAG
E-mail: earthinstitute@auroville.org.in

Our research on domes and vaulted structures aims to revive and integrate in the 21st century the techniques used in past centuries and millennia, such as those developed in Egypt or during the period of gothic architecture in Europe.

This R&D seeks to optimize the structures by increasing the span of the roof, decreasing its thickness, and creating new shapes. Note that domes and vaulted structures are normally built with compressed stabilised earth blocks, which are laid in "free spanning" mode (without formwork), which has been developed by the Auroville Earth Institute. This technique is a development of the Nubian technique.

The stability method developed at the Auroville Earth Institute optimises arches, vaults and domes, especially the profile and thickness, so as to get the lightest structure for the widest span. The stability of domes is derived from the stability of a vault of the same section of the dome.

Keywords: *Stability study, Free spanning technique, Compressed stabilised earth blocks.*

1. Introduction

Domes built by the Auroville Earth Institute are built in free spanning mode, meaning without formwork. This is a development of the Nubian technique, used for millennia in Egypt. Domes are usually built with Compressed Stabilised Earth Blocks (CSEB). Blocks are laid with stabilised earth glue, a very fluid mortar composed of a little cement, earth, sand and water.

A stability calculation method has been especially developed for designing and building vaults without centrings. This graphical method is also used for the stability calculation of domes. The dome is studied like a vault of the same section. When the section of the vault is stable, the dome of the same section is considered to be stable. The optimal section of the dome is defined by the lightest section, which has the line of thrust within the middle third of the arch section.

At present this method does not take into account hoop forces which are helping in a way the dome stability. Therefore, it is a safe method for the stability of domes. Our research focuses these days on the calculation of hoop forces with a simple graphical method.

This stability calculation method combines first the Catenary method which defines the ideal shape of the arch section of the dome. It goes on with the Funicular method which defines accurately the direction and intensity of forces into the dome.

2. Stability study

2.1. Catenary study

The arch section of the dome is drawn reversed and fixed on a study board. A chain which has the length of the arch centre line is hung freely on the board. The chain is then loaded with other small chains which represent the various loads needed to bring the line of thrust within the middle third of the arch. This curve will also be a catenary, but modified by the various loads applied on it. It represents the line of thrust.

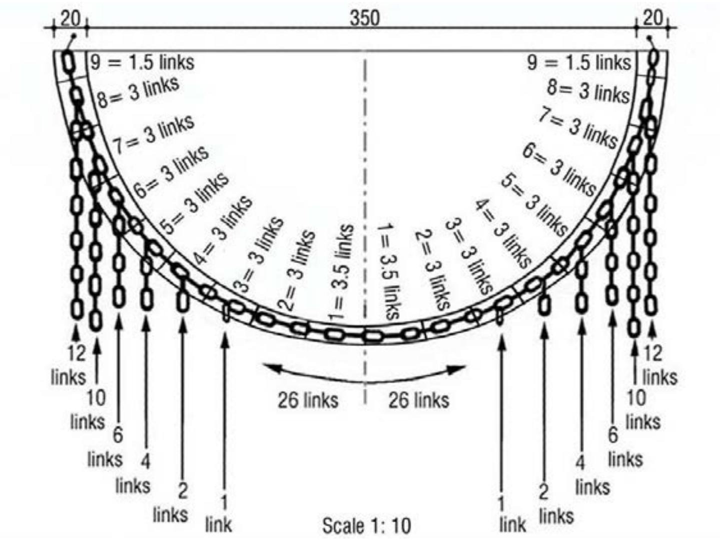


Fig. 1. Catenary study principle of the arch section of a hemispherical dome

The catenary method gives only the exact and ideal curve of the line of thrust, which represents the line of compressive stress in the arch. But it does not give the intensity of these forces. The funicular method will determine the value of the forces acting in the arch.

2.2. Funicular study

Half of the arch section of the dome is drawn at a large scale and divided into short segments which are preferably of equal length. Their weights are calculated and the centre of gravity (CG) of each segment is defined. The vertical lines where the CGs is applied are also drawn.
The intensity of the horizontal thrust (HT) is evaluated first in order to start the study. HT is the horizontal component of the line of thrust (LT), and thus LT is horizontal on top of the arch. It represents the balance of the second half of the arch section.

When HT encounters the line of the CG of the first segment, the direction of LT will change. The resultant

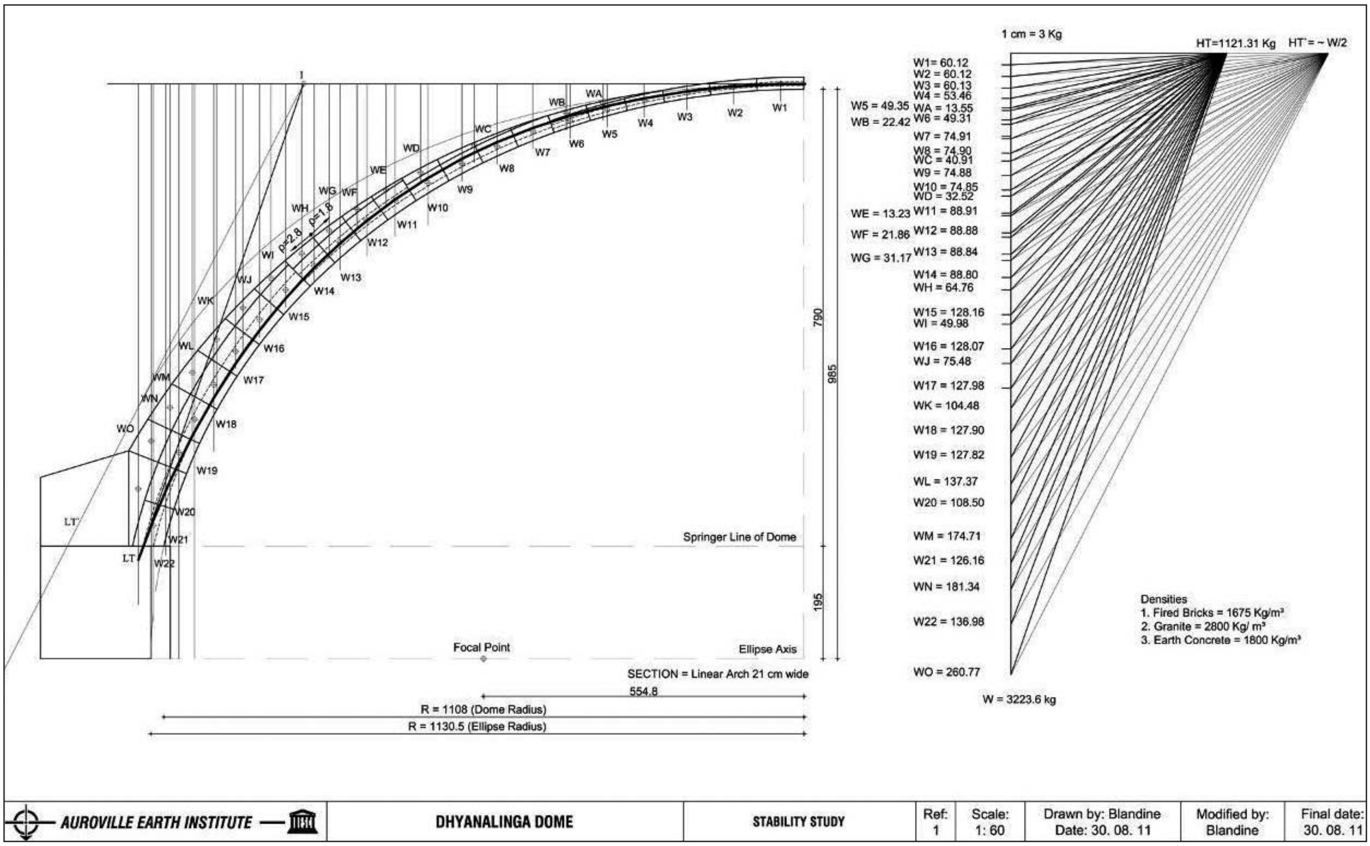


Fig. 2. Funicular study of the arch section of the Dhyanalinga dome – 22.16m diameter

force will encounter also the next line of the CG of the next segment and will change again direction. This goes on till LT encounters the last vertical line of the last CG. This final direction of the resultant will be the thrust T, and its angle and intensity will be known.

The arch section of the dome is considered stable when LT remains in the middle third of the section.

3. Construction of domes with the free spanning technique

The free spanning technique is a development of the Nubian technique. The basis of the technique is that CSEB are stuck to each other with stabilised earth glue. This fluid mortar is composed, most of the time, of 1 cement: 6 soil: 3 sand. This ratio varies with the soil quality.

3.1. Dhyanalinga dome

The Dhyanalinga dome has a diameter of 22.16 m and was built free spanning in 9 weeks. Its construction started on 23rd November 1998 and was completed on 31st January 1999. The cross section is a segmental ellipse of 22.16 m diameter and 7.90 m rise.

The dome thickness varied in 4 courses from springer to apex: 53 cm, 42 cm, 36.5 cm and 21 cm at the top. The Dhyanalinga dome was built with fired bricks and not with CSEB for the reason that the schedule was too tight to produce the compressed stabilised earth blocks in time.

About 214, 000 fired bricks were laid in 9 weeks without any support by about 25 masons and 200 workers. The brick dome itself (bricks and mortar) weighs around 420 tons, to which is added around 150 tons to load the haunches for stability (mainly done with granite stones). The total estimated weight was 570 tons.

3.1.1. Definition of the dome section with a cord

The elliptical section of the dome could be defined with a cord, from its two focal points. Therefore the shape of the dome was given, for every layer, by a cord fixed on these focal points. In relation to the geometrical theory of an ellipse, the cord length was the long diagonal.

A small ring with a small rope was inserted on the cord and could slide on it, so as to follow the progressive change of the curve (radius and angle). This procedure with the cord defined quite accurately the location of every first brick and thus the dome's section.

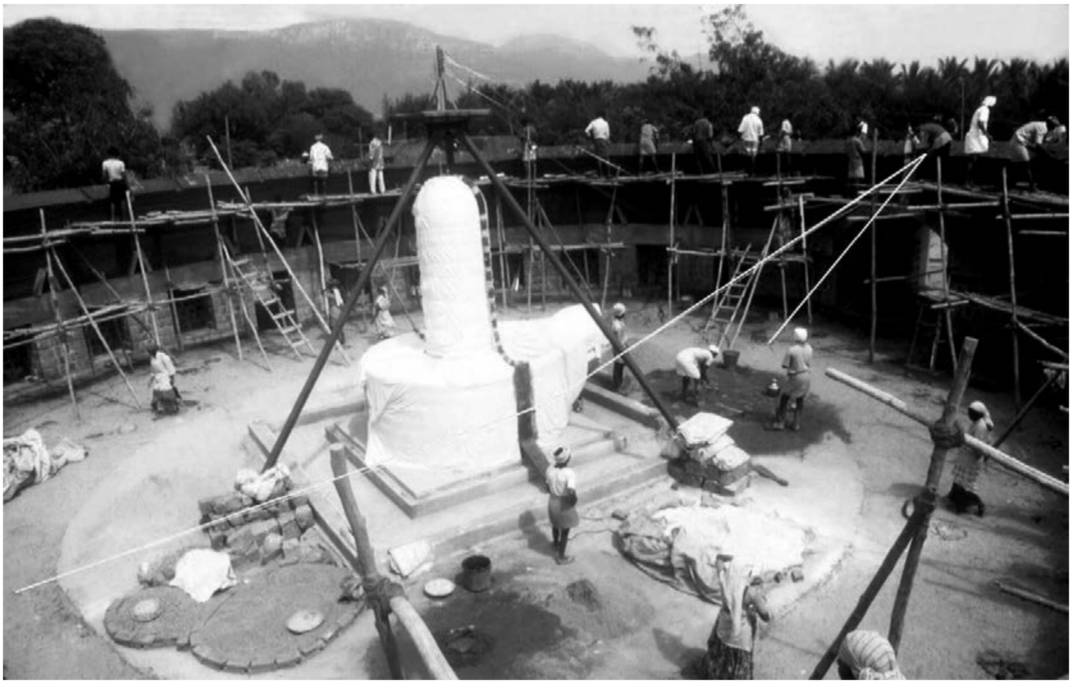


Fig. 3. Defining the dome section with a cord

3.1.2. Control of the dome curve

The method to define the section of the ellipse with a rope was fine in theory, but less so in practice. The nylon rope used was too stiff and did not allow the ring to slide properly on it. The length of the rope (22.61m), which needed to be stretched a lot, so as to be in line, emphasized this problem. At the 57th layer the dome was checked with the ellipse formulas (See below) and it appeared that it was 5cm outside theoretical curve. Going on with the same procedure would have meant the impossibility of controlling the shape and a dome out of shape, with probable risks for stability.

Thus the ellipse proportion was changed, so as to be on the actual portion already built and the stability was checked again. The work could proceed further. For the next layers an extreme care was taken for handling the rope and they were regularly checked.

At the 120th layer the rope method was abandoned and it was preferred only the calculation method with the ellipse formulas: Every first brick was laid and the radius & height surveyed. Then, the actual radius (x) was taken as correct and height (y) calculated with these formulas:

$$y = \frac{d}{2}\sqrt{1-\left({}^{2x}/_{D}\right)^2} \qquad x = \frac{D}{2}\sqrt{1-\left({}^{2y}/_{d}\right)^2}$$

Where y is the ordinate, x the abscissa, d the ellipse small diameter and D the ellipse long diameter.

A difference up to 2 or 3 mm was accepted, but more needed to lay again the brick so as to change its height. Then the height was taken as correct and the radius was checked again with the above formula. After a few trials the brick was within 2-3mm difference, in height and radius, and it was accepted. This adjustment near the apex was taking a long time: a difference of 1mm in height could affect the theoretical radius by 4 – 5mm. Therefore a larger tolerance of 3-4mm was given.

3.1.3. Compasses to insure proper ring layers

Once the brick position was accepted, meter tapes of 15 m were marked with the proper radius for this course and used as compasses fixed on a tripod above the lingam. Eight measuring tapes insured the radius, but this method was kept up to a certain height and radius.

3.1.4. Acoustic of the dome

To limit echo, single resonator absorbers (Helmholtz resonators) were installed in three layers, to absorb 12 frequencies between 120 Hz and 1.50 kHz. These single resonator absorbers were done by inserting, during the construction, PVC pipes of a studied outer diameter and length. Pipes were pulled out once the next course was laid

Loading the haunches began when the dome was half built. The dome was supposed to be visible from outside and therefore this load was studied to follow the shape of a dome. At the base, granite stone masonry in lime mortar was assembled in steps.

These ones were rounded with earth concrete and they gave the load. Higher up, a filling with broken bricks in earth concrete insured this load, especially to round the steps from the different layer thickness.

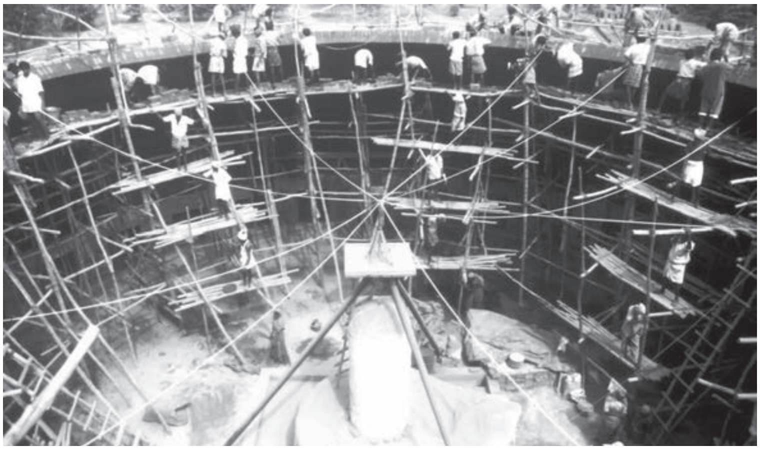


Fig. 4. Dome diameter being checked with meter tapes, after 5 weeks.

Fig. 11. Laying granite stones on the haunches.

Fig. 5. Positioning a brick with the cord.

Fig. 6. Marking a 15m tape at the proper radius.

Fig. 7. Resonator for 120 Hz.

Fig. 8. Resonator for 219 Hz.

Fig. 9. Resonator for 622 Hz.

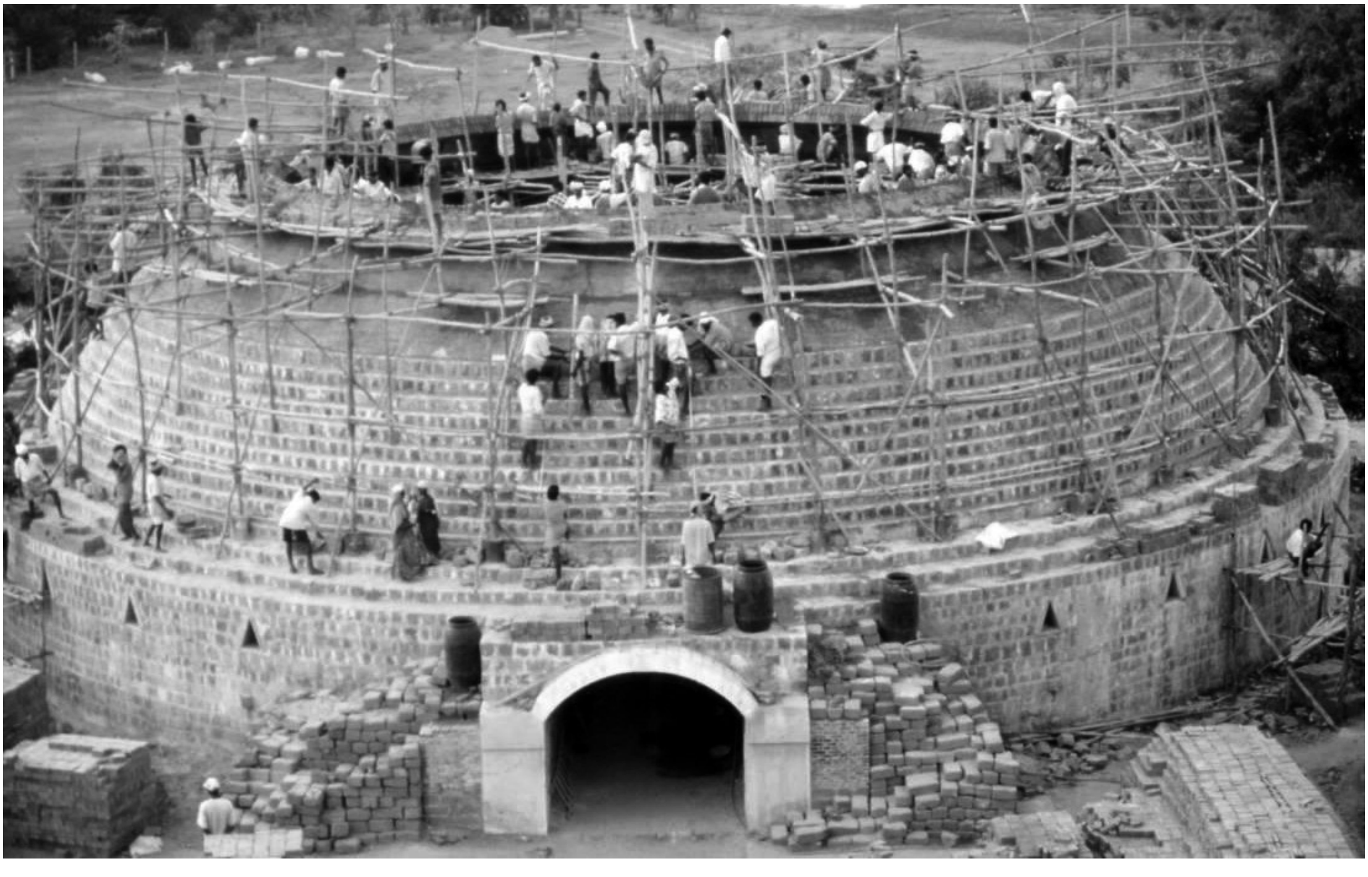


Fig. 10. Loading the haunches with granite stones.

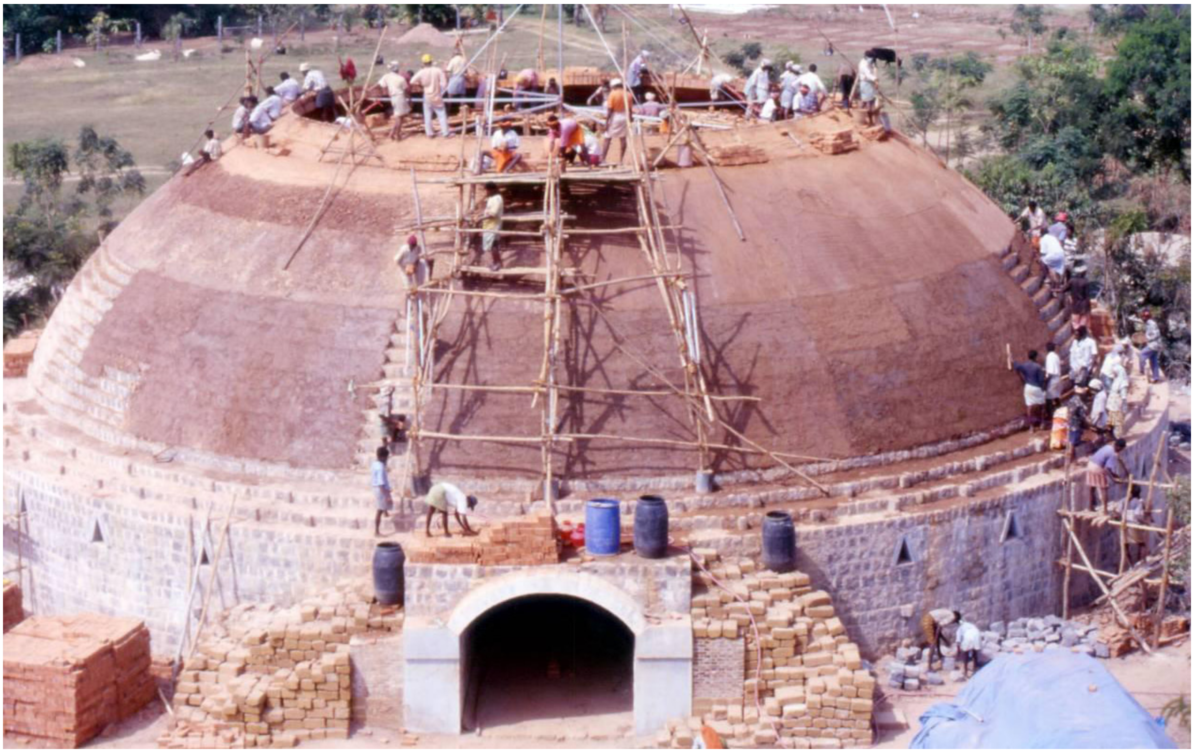


Fig. 12. Dome after 8 weeks.

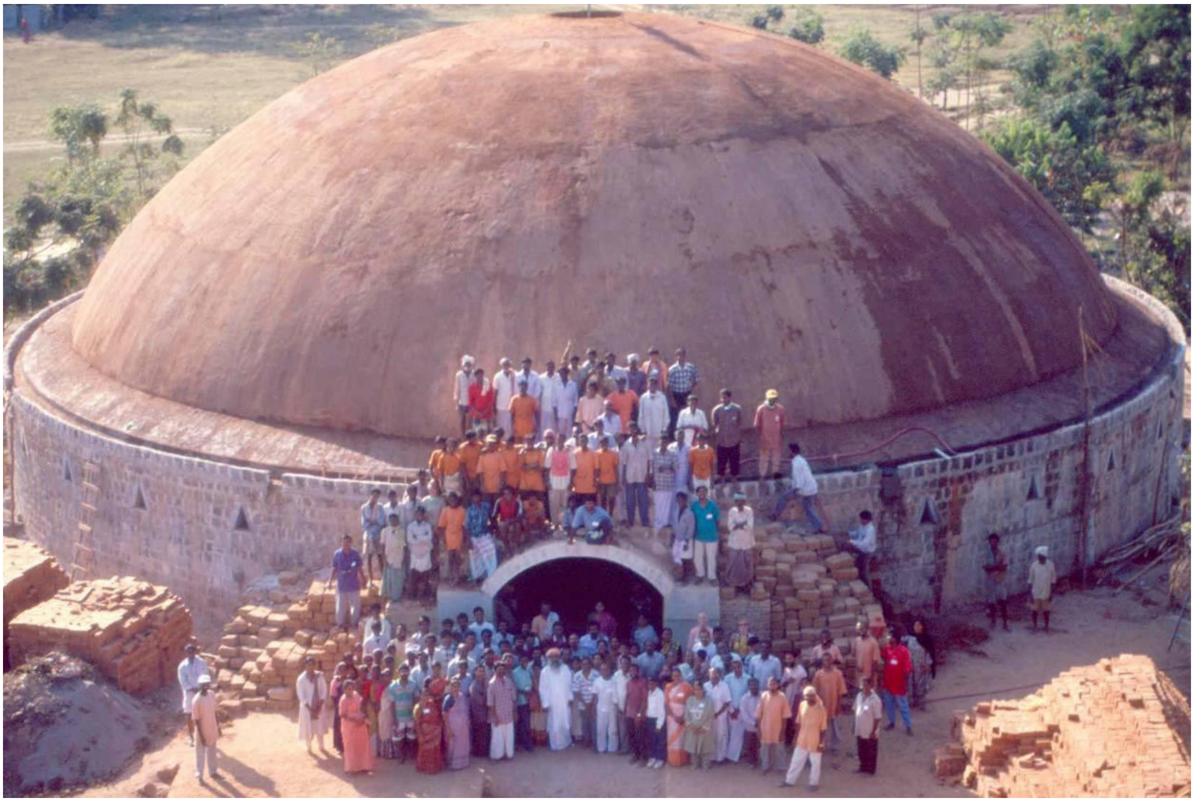


Fig. 13. Dome completed after 9 weeks

Fig. 14. Dome completed with the Dhyanalinga

3.2. Sri Karneshwar Nataraja Temple

The Great Pyramid of Egypt is the origin of the concept and the proportions of Sri Karneshwar Nataraja Temple are based on the proportions of this Great Pyramid. The proportions of the latter generate also the pointed dome which houses Lord Nataraja.

The main material for the dome and pyramid is CSEB and stabilised earth concrete. The dome chosen for the temple was a pointed square dome, called cloister dome. Foundations were made with reinforced concrete. The base of the dome, pyramid and the walkway are made of CSEB, which acts as retaining walls for a sand and rubble filling on which the pyramid will rest.

Fig. 15. Beginning the cloister dome.

Fig. 16. Keys to link the dome with earth concrete.

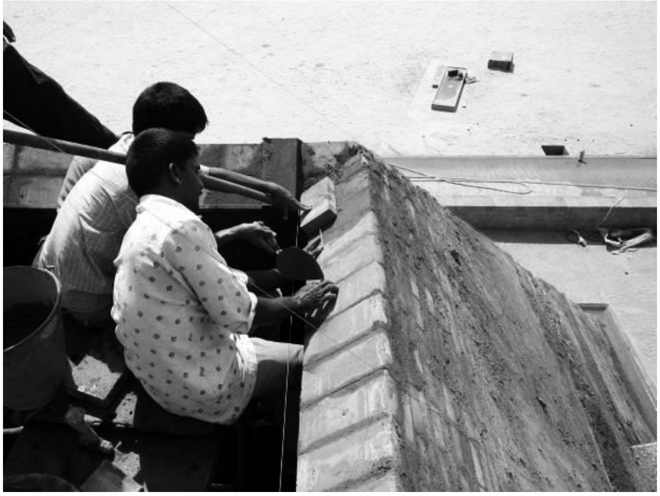
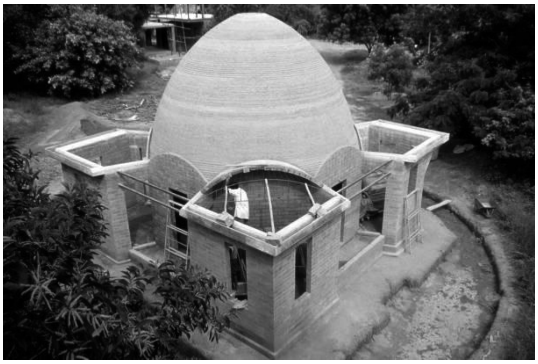


Fig. 17. Laying blocks without support .
Fig. 18. Laying blocks in a corner.

Fig. 19. Dome completed with Nataraja statue.

Fig. 20. Completed Karneshwar Nataraja temple.



3.3. Various domes built with the free spanning technique

3.3.1. Gayatri dome

Pointed dome for a pavilion, built on an octagonal plan of 6.40m span. Dome thickness is only 7 cm.

3.3.2. Equilateral cloister dome

Half cloister dome of 3.6 m span, 3.12 m rise built with varying thickness from 34 cm at the bottom to 7 cm at the top.

Fig. 21. Laying blocks without support.
Fig. 22. Laying blocks in a corner.

Fig. 23. Half cloister dome to close an equilateral vault.