

## Use of Bamboo in Structural Applications of a 34 Meter Diameter Dome

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**Abstract:** Bamboo has been rarely used in structural elements of the buildings. In beams, bamboo has been used as reinforcement in the form of bamboo strips embedded with cement concrete on experimental basis. Due to inadequate bond strength with concrete and durability requirements, bamboo reinforced cement concrete has not gained momentum and as such use of bamboo remained restricted to only non-structural members in the buildings.

In the Shanghai World Expo 2010, a 34 m diameter bamboo dome was constructed as a component of the India Pavilion which was designed to take dead and live loads and in which the dome was supported entirely on bamboos. Joining of bamboos was done in a well designed manner so as to take loads without using the concept of reinforced bamboo cement concrete. Treated *Moso* bamboos (*Phyllostachys edulis*) were used as structural members for taking the dead load of entire dome and live loads expected over the dome. Large numbers of ornamental plants were planted over the dome, dead load of was also accounted for, showing that treated bamboos can be successfully used in structural elements of a building.

*Keywords:* Moso bamboo, dome, treatment, bamboo buildings

### INTRODUCTION

Bamboo is one of the fastest growing plants in the world but rarely used in the construction as a structural member except in temporary structures, although it has been widely used non-structural members in interior applications and furniture. Bamboo boards manufactured with resins are also used in panelled and flush doors, wall panelling, flooring and false ceiling. Bamboo has also been used as an infill material in the form of strips fixed between the horizontal and vertical wooden members in the walling, normally known as *ekra walling* of semi permanent structures (also known as *Assam type* houses) over which cement plaster can also be applied. In all such applications, bamboo replaces timber, brickwork or cement concrete thus qualifies for an environment friendly green material.

India participated in Shanghai World Expo 2010 and wanted to showcase green construction. Green building concept which gives emphasis on green construction is

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mostly based on products manufactured from waste products, but the committee approving the concept wanted to include a natural material also as a part of green construction. Thereafter, it was decided to use bamboo as the main construction material in India Pavilion. The committee also approved the concept of dome submitted by the designer for the Pavilion being an amalgamation of varied Indian culture and religions. Thus, bamboo was used for the first time in structural members of the India Pavilion on a very large scale for the 34 m diameter dome at World Expo 2010 held at Shanghai.

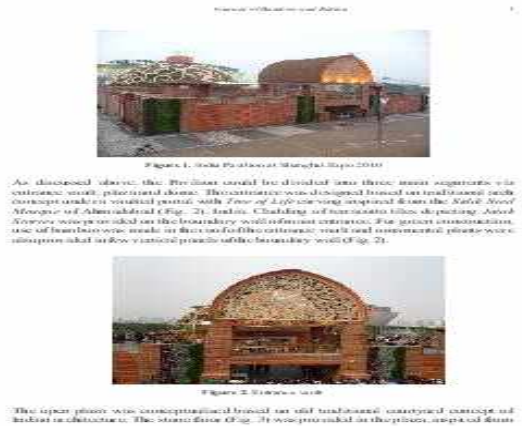
Mature *Moso* bamboos (*Phyllostachys edulis*) were used in the Pavilion sourced from Anji district near Shanghai. The bamboos were treated in hot boric acid/borax solution and shaped as per the requirements in a pre-fabricated jig. Main beams of the dome were fabricated by joining six bamboos which were like ribs. Bamboo was also used in many other applications in dome, entrance vault and corridors. Special arrangements were made for joining bamboo to bamboo lengthwise, bamboo to concrete at the junction of beam and bamboo to bamboo for acting as a single member. The bamboo assembly for the dome was designed for its dead load, waterproofing system, irrigation system, solar PV panels, wind mill and ornamental plants planted over the dome including live loads. A mock-up structure was erected before the construction to check the feasibility and efficacy of the structure due to non-availability of codes of practices for such a design. Successful application of bamboo in structural members demonstrated that treated bamboo can be used as the structural members in the buildings.

Bamboo was also used in other applications like false ceiling in corridors, railings of the staircase and parapet, and benches provided in amphitheatre and theme area to showcase green building concept of the Pavilion.

## **MATERIALS AND METHODS**

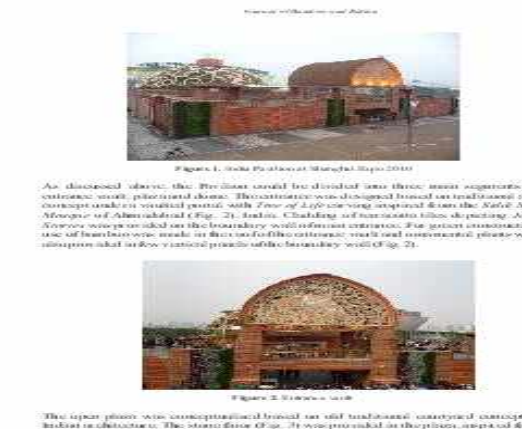
### **Brief of the India Pavilion**

The India Pavilion was constructed on a plot of 4000 m<sup>2</sup> having dimensions of 80 m x 50 m (Soni, 2010). The Pavilion was conceptualised and designed to showcase the Indian culture and the concept of green building construction as shown in Figure 1. It had three main components as entrance, plaza and theme area. The theme area was designed for display and exhibition, while the plaza for commercial area, amphitheatre and offices. The commercial area included souvenir shops and restaurants, offices, small conference room, and a small amphitheatre. Use of bamboo was envisaged in the Pavilion on a large scale to spread a message of its being an environment friendly material and substitute of reinforced cement concrete and steel generally used in beams.



**Figure 1.** India Pavilion at Shanghai Expo 2010

As discussed above, the Pavilion could be divided into three main segments viz entrance vault, plaza and dome. The entrance was designed based on traditional arch concept under a vaulted portal with *Tree of Life* carving inspired from the *Siddi Syed Mosque* of Ahmadabad (Fig. 2), India. Cladding of terracotta tiles depicting *Jatak Stories* was provided on the boundary wall of main entrance. For green construction, use of bamboo was made in the roof of the entrance vault and ornamental plants were also provided in few vertical panels of the boundary wall (Fig. 2).



**Figure 2.** Entrance vault

The open plaza was conceptualised based on old traditional courtyard concept of Indian architecture. The stone floor (Fig. 3) was provided in the plaza, inspired from

the *Palace of Rampur* in Varanasi, India. The plaza area had commercial space in the form of shops and restaurants, a small amphitheatre, and offices. The corridor of shops had carved colonnade, a collage of various Indian columns prepared from glass fibre reinforced boards (Fig. 4).



Figure 3. Plaza flooring

Figure 3. Plaza flooring. The image shows two photographs of the Plaza flooring. The left photograph shows a wide, open space with a polished floor and some structural elements. The right photograph shows a similar area with more defined walkways and lighting fixtures.



Figure 4. Carved colonnade

Figure 4. Carved colonnade. The image shows two photographs of the Plaza's carved colonnade. The left photograph shows a corridor with a carved colonnade made of various Indian columns. The right photograph shows a similar area with more defined walkways and lighting fixtures.

Figure 3. Plaza flooring

Figure 4. Carved colonnade

Main theme was exhibited inside the dome area. The theme pavilion was built in a circular form for easy circulation and its roof conceptualised in the form of a dome, intended to be a strong statement of amalgamation of diverse Indian culture and religions. The design of the dome was derived from the *Sanchi Stupa*. Bamboo was used as a main construction material in the dome. The dome had a diameter of about 34 m making it world's largest bamboo dome. Display was planned along the periphery of the inner space while in the centre, holographic display was organised. The seating for enjoying holographic display was also made from the bamboos. Green building concept was depicted through solar panels, a small wind mill and green ornamental plants provided on the roof of the dome. The plants also helped in reduction of the air-conditioning load.

The entry of the Pavilion was planned from the elevated highway side existing at the Expo site as large number of visitors were expected to be coming through the highway and the dome was clearly visible from the distance. The visitors entered from the gate on South – West side as shown in lower floor plan of the Pavilion in Fig. 5 via small lobby and veranda. From the veranda, they could either go to the restaurants and shops provided on both the sides or sit and enjoy performances in the amphitheatre located just in the front. On both sides of the amphitheatre, there were ramps. From the left ramp, they could go up to enter the dome. After visiting the theme pavilion inside the dome, the visitors had two options and they could either go on the terrace of the shopping area and enjoy the performances being held in the amphitheatre or just sit there and enjoy Indian cuisine and the beauty of the dome or come down from the ramp and walk over to the shops and restaurants again, and finally take exit route available on both sides of the veranda. Bamboo was used in some form right from entry to the exit in the Pavilion.

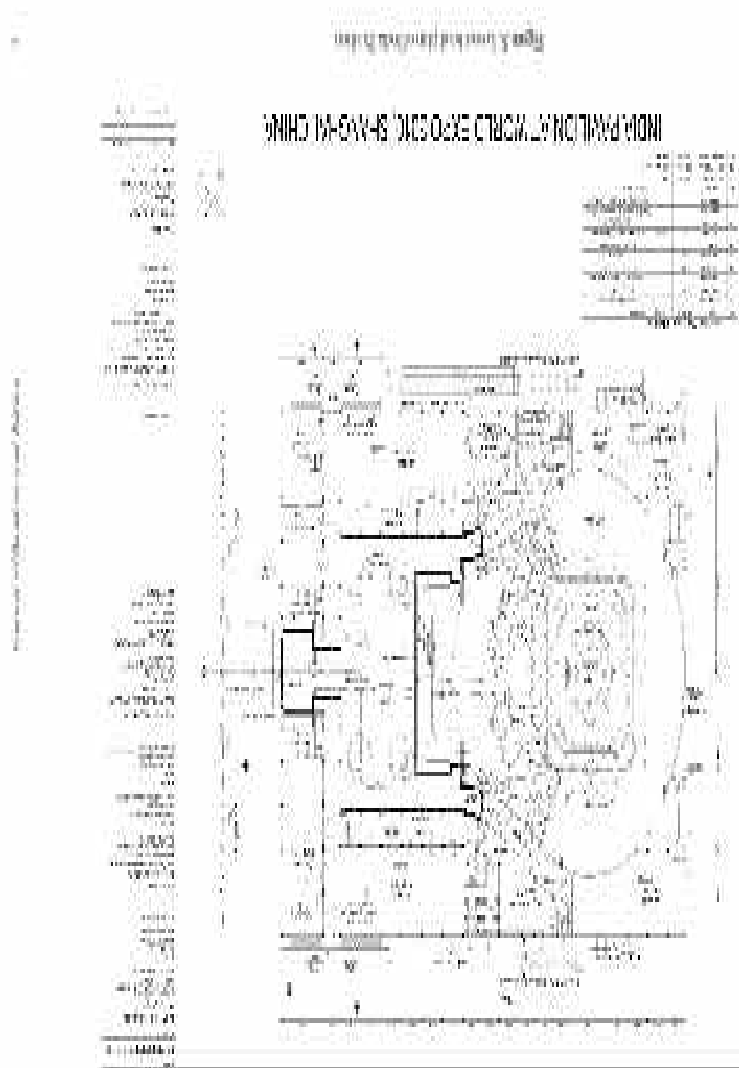


Figure 5. Lower level plan of India Pavilion

### MATERIALS

Before commencement of the construction of the Pavilion, geotechnical investigation was carried out. RCC (Reinforced Cement Concrete) isolated/combined footings were provided for the entrance and the plaza area, being low loaded portion compared to the dome. In the dome area, steel piles of 18 m length were provided as the steel was recyclable. Structural steel was used in the columns and beams in the Pavilion in entire portion (Fig. 6) and up to ring beam level in the dome area. Bamboo was used for construction of the vault (Fig. 7). RCC slab was provided in the commercial area as the roof was used for the assembly of the visitors. As explained above, bamboo assembly was provided in the dome (Fig. 8) for supporting roof, waterproofing system, ornamental plants and live loads. As shown in Figure 8, bamboo was used in both the directions in the dome like a basket placed on ring beam. Completed dome is shown in Figure 9. Architecturally designed stone flooring was provided in the open Plaza. The bamboo was used in the scaffolding, railing, seating/benches, railing top and false ceiling of the corridors. Air-conditioning was provided in all the covered areas except service areas.



Figure 6. Steel structure for the vault



Figure 7. Vault construction



Figure 8. Bamboo assembly for the dome



Figure 9. Roof of the dome

Bamboos for the structural members used in the vault and dome were treated in a solution of boric acid and borax. Over the bamboo assembly in the dome, wire mesh (Fig. 10) was used to support ferro-cement layer provided with nominal reinforcement. Membrane waterproofing was then provided over the ferro-cement layer. A PVC board was fixed over the waterproofing membrane on which three geotextile layers were provided for irrigation assembly and the plants. Copper pipes having nozzles (Fig. 11) were inserted inside upper two geotextile layers to irrigate the plants. *Tree of Life* was then made on the top of the dome from copper sheet and in the remaining portion ornamental plants were planted except in the area where solar panels were installed. To showcase energy efficiency, few solar panels were installed on the roof and a small wind mill provided in the central portion.



Figure 10. Wire mesh to support ferro-cement layer



Figure 11. Mock up for irrigation assembly

As explained above, bamboo was used in the structural elements of the dome to take the dead load and live load. The roof being inaccessible for visitors was designed for a live load of  $0.75 \text{ kN/m}^2$  as per IS 875- 1987 but the same was also checked as per the Chinese codes according to the Expo requirements. Over one lakh plants were provided of the size ranging from 200 mm to 300 mm height at a distance of 150 mm to 200 mm on the dome. The species used for planting on the dome and vertical surface of the boundary wall included *Euonymus alatus*, *Gardenia jasminoides*, *Calibrachoa*, *Dianthus chinensis* etc.

For irrigating the plants, liquid nutrients were circulated in the network of copper pipes laid over first layer of the geotextiles (Soni and Dhusia, 2011) in which nutrients were pumped from the ground floor level. The nozzles were protruded above the second layer so that water/nutrient was sprinkled on and around the plants. In the liquid nutrients, Plantex, a water soluble fertiliser, nitrogen based liquid plant nutrient of 0.50 % concentration was used, mixed @ 180 ml in 200 litres of water. A mock up was prepared to examine the method to fix the plants on geotextile layers and checking the feasibility of the irrigation system (Fig. 12).

Since the dome had a diameter of about 34 m, length of a single bamboo was not enough. To join two bamboos as per required length, RCC concept was adopted. The same concept was used for the joint connectivity of the bamboos with ring beam. Steel bolts were used for joining the bamboos together in required numbers for beams. Stainless steel covering plates/sockets were used to house/seat the bamboo to avoid splitting and slippage at the junction of bamboo and the ring beam. Overall, about 30 km length of bamboo was used in the Pavilion. Thatch was used in the roof of the vault over which fire retardant paint was applied.

Terracotta tiles were provided on the front boundary wall to depict *Jatak Stories* (Fig. 13).



Figure 12. A mock up for plantation



Figure 13. *Jatak Stories* on terracotta tiles

**METHODS**

As already mentioned, mature *Moso* bamboos were used in the pavilion of average 100 mm diameter and 6 m length. Since design methodology for use of the bamboos in structural members was not available in the codes, a mock up structure (Fig. 14 and 15) was prepared to understand the method for their fixing in structural members. Also, methodology was required to be assessed for providing ferro-cement layer and waterproofing on bamboo assembly. It was also essential to finalise jointing details and methods for fixing bamboo with the RCC/steel ring beam, bamboo to bamboo for combining them to be used as one member, and bamboo to bamboo for increasing the length as per the requirements.

The bamboo was required to be bent according to the shape of the dome and thus method of bending was also to be finalised. For durability of the structure, chemical treatment was essential. Thus, the process of fixing the bamboos in the dome included selection, drying, treatment and shaping of bamboos. For the same, mature round bamboos were first sorted out having sufficient length of required diameter without any splits. The sorted bamboos were stored for drying and treatment. For the chemical treatment, two holes were drilled internode in each bamboo i.e. between the nodes in opposite direction so that chemical mixture enters the inner hollow space and





Figure 14. A mock up for dome

connected drilled up. After drilling the holes, the bamboos were immersed in the hot water tank filled with borax acid and borax mixture in the ratio 1:1.5. After treatment, the bamboos were taken out and air dried on horizontal supports prepared for that specific purpose. In case the bamboos were to be shaped as per the curvature of the structure, the bamboos were clamped in the specifically prepared arrangement of steel flats (jig) having clamps. The heated bamboo was placed and kept clamped for a certain period to obtain the desired shape/curvature and prevent it to return into its original shape.

For the structural members in the dome, bamboos of different lengths were prepared. Since the diameter of the dome was about 34 m, the bamboos were required to be jointed. For this purpose, a reinforcement bar was inserted inside both the bamboos, micro concrete was inserted making it as RCC joint inside. The bamboos were also joined together in a bunch as per the requirements of the beams. Main beams had six bamboos. These bamboos were joined together by the galvanised iron bolts as shown in Fig. 16. Three bamboos were on upper layer, two below and one in the lowermost. To join the beam of these six bamboos with the steel ring beam on which cement concrete was laid, six reinforcing dowel bars were grouted in the concrete as shown in Fig. 17. The bamboos were inserted directly first in reinforcing bars in the mock up exercise. Micro concrete was then inserted through the holes so that RCC provided inside the bamboo gets connected with the ring beam. This procedure was followed in the mock up structure, but realising that the bamboo may split, stainless steel covering plate/socket was inserted into each reinforcing bar and thereafter bamboos seated in the covering plate (in reverse portion from the covering plates shown in the mock up of Fig. 18). With this arrangement, bamboos got housed adequately. The stainless steel covering plates were used to avoid corrosion.

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Figure 15. A mock up for fixing bamboo main beams

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Figure 15. A mock up for fixing bamboo main beams

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Figure 16. Fixing arrangement of bamboos

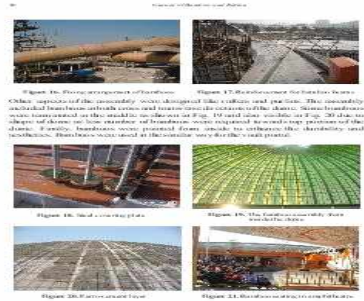


Figure 17. Reinforcement for bamboo beams

Other aspects of the assembly were designed like rafters and purlins. The assembly included bamboos in both cross and transverse directions of the dome. Some bamboos were terminated in the middle as shown in Fig. 19 and also visible in Fig. 20 due to shape of dome as less number of bamboos were required towards top portion of the dome. Finally, bamboos were painted from inside to enhance the durability and aesthetics. Bamboos were used in the similar way for the vault portal.



Figure 18. Steel covering plate



Figure 19. The bamboo assembly from inside the dome



Figure 20. Ferro-cement layer



Figure 21. Bamboo seating in amphitheatre

Over the bamboo assembly, a layer of wire mesh was laid to hold mortar. Ferro-cement layer was then provided with nominal reinforcement on the bamboo assembly. To avoid leakage and seepage, water proofing membrane treatment was provided on ferro-cement layer. Over the water proofing membrane, the plantation system was laid. Earlier it was assessed that geotextile layers will be laid over the waterproofing membrane directly but during fixing of the geotextile layers, geotextile layer was found susceptible to slipping and also there were chances of waterproofing layer getting damaged due to planting assembly, copper pipes and nozzles for irrigation system. To avoid such problems, a PVC board was laid over the waterproofing membrane.

Over the PVC board, a non-woven geotextile layer was stapled and then the irrigation system laid. Thereafter, non-woven geotextiles were laid in two layers, one for supporting the roots and helping in irrigation and other upper one to hold the plants. A cut was made in the upper layer in which the plants were inserted as shown in mock up in Figure 12 so that roots remain between upper two layers and only the plant's upper part remained exposed. Non-woven geotextiles were used as they had both filtration and drainage characteristics. Following this the copper *Tree of Life*, solar panels, wind mill and signage were provided.

### Use of bamboo in other applications

Bamboos were also used for seating in the amphitheatre (Fig. 21) and also inside the theme area/dome to view holographic display (Fig. 22). Further, bamboos were used in the false ceiling of the corridors leading to commercial area and dome (Fig. 23) on which even services like fire detectors, lights and signage were installed. Bamboo railings were provided at various places near amphitheatre, first floor and staircases etc (Fig. 24 and 25). An external view of the India Pavilion is shown in Fig. 26 and an internal view in Fig. 27.



Figure 22. Holographic display



Figure 23. Bamboo false ceiling

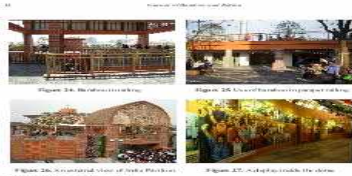


Figure 24. Bamboo in railing

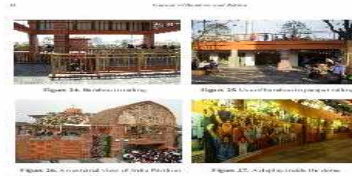


Figure 25. Use of bamboo in parapet railing



Figure 26. An external view of India Pavilion



Figure 27. A display inside the dome

## RESULTS AND DISCUSSION

In the absence of Indian standard specifications or code of practices for bamboo design for structural applications, the dome was designed taking leads from the literature. Hence, it was decided to have a mock up structure and load it for desired loading which provided the confidence. During the Expo period of six months, the India Pavilion attracted 5.3 million visitors and the structure was adequately tested for the loads. The plants were maintained for the entire period of Expo of six months and the dome was tested for full load conditions. It indicates that bamboo can be successfully used as the structural members in engineering applications. The Pavilion was awarded *People's Choice Award* instituted by EXHIBITOR magazine.

## CONCLUSION

This was the first time that bamboo was used in a large dome having diameter of 34 m, designed as per the loading requirements. Bamboo being an environment friendly material was part of green building concept adopted in the construction of India Pavilion. Efficacy of the structure was tested through mock up structure prepared before actual execution and suitable modifications were made.

Bamboo was chemically treated for the durability before use. Bamboo jointing was done through bolting to make the assembly monolithic. Reinforced cement concrete concept was adopted to join the bamboos with the ring beam as well as for joining two bamboos to increase the length.

Bamboo assembly was loaded with reinforced ferro-cement concrete, water proofing system, irrigation assembly and plants proving that bamboo assembly can be designed and prepared as per the required loads. Bamboos have sufficient strength to take heavy loads. The operation and maintenance of the dome during the Expo period also showed that designed bamboo assembly can be successfully used in structural members. The application of full dead loads and live loads proved the efficacy of bamboo structures in bamboo buildings.

### ACKNOWLEDGEMENT

The Pavilion was constructed by India Trade Promotion Organisation on behalf of Ministry of Commerce and Industry, Government of India. M/s Design C prepared the design of the pavilion. M/s Pavilion and Interiors were the construction agency. The design concept was made by Sanjay Prakash and Associates and Pradeep Sachdeva Design Associates on behalf of Design C. Structural design was done by Prem Krishna of Roorkee and checked by Indian Institute of Technology (IIT), Roorkee. Further, the design was checked and updated by China Jingye Engineering Corporation Limited, Shanghai and finally approved by Expo authorities.

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