Analyzing the Thermal Performance of Building Envelope with Bamboo as a Composite Material

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Abstract: *The mechanical and structural strength of bamboo as a building material has been proven through various studies and its qualities as a green material has been realized globally. It is now being called "green gold" and the "future of sustainability". India is the second largest producer of bamboo in the world and it has always been a common vernacular material as various species grow all over the country. The study attempts to quantify and validate the importance of choosing appropriate building materials in general, and bamboo in particular for better energy performance. There is a lack of experimental validation & quantitative analysis of the thermal performance of bamboo structures, which needs to be addressed. Firstly, the Sustainability Index of bamboo is calculated using CPWD guidelines and certain modifications in the calculation procedure has been proposed. In the next stages, two bamboo residences in India have been taken up for detailed studies of their wall sections and variations of the same building designs are modelled by altering only the envelope materials & testing the changes in thermal performance. Various wall sections are then identified through literature and case studies, which are analyzed for heat transfer coefficients. Inferences lead to the design of a primary school building with bamboo as the main building material. Simulations are carried out to quantify its energy use & is compared to the thermal performance & energy consumption of conventional brick & RCC buildings & also against the ECBC recommended envelope.*

Keywords: ***Thermal Performance, Bamboo Envelope, Wall Assemblies, Heat- Transfer Coefficients, Sustainability Index***

1. INTRODUCTION

Insensitivity towards the choice of material selection in buildings have led to increased energy consumption, higher manufacturing costs, and higher transportation costs and increased waste production. With this rising concern, traditional materials are being modified and treated to increase their strength and durability. One such material is bamboo, which has various applications in a building as it contributes towards the design of almost all the parts starting from the roof to the foundation. We can quantify how sustainable a material is, using the Sustainability Index developed by CPWD, and is calculated for bamboo.

This study aims to quantify the thermal transmittance values of 8 wall assemblies with bamboo as a walling material, derived from field studies and case study readings. It is tested in combination with mud, cement mortar, concrete blocks, straw-bale, etc. Field studies include visits to the residences of two renowned Indian architects who have designed their own homes with bamboo. Indoor and Outdoor temperature differences have been taken along with wall assembly details. Another visit was to KONBAC-Konkan Bamboo and Cane Products Pvt. Ltd. to get hands- on exposure in the bamboo factory.

Further, the proposed primary school building at Kaldongari in Maharashtra is designed, keeping in mind the sustainable parameters of a building using the appropriate wall assemblies. The energy consumption of this proposed design is simulated by changing only the envelope properties for comparison with conventional brick-RCC envelope and ECBC prescribed envelope. It was found that bamboo envelope performs better than conventional brick & reinforced cement buildings. It may not be possible to change the entire scenario of building industry overnight, but little steps like rethinking the walling systems while keeping the structure intact can lead to a significant change in the choice of building materials.

2. LITERATURE REVIEW

2.1. Best Bamboo Species in India for Construction

The table below is compiled with data from CIBART [Center for Indian Bamboo Resource and Technology], INBAR [International Network for Bamboo and Rattan] & National Bamboo Mission Reports. It is a list of bamboo species in India best suited for building construction and the regions where they are found in abundance.

Table 1. Best Bamboo Species in India for Construction

Species	Height	Diameter	Wall Thickness	Regions
	m	cm	cm	
Bambusa Nutans	6-15	5-10	1.5-4	Throughout India 600-1500m altitude
Dendrocalamus brandisii	19-33	13-20	2-5	North-East India
Dendrocalamus stocksii	9	2.5-5.8	1-3	Central India Western Ghats
Melocanna bambusoides	10-15	2-7.5	1-3.5	Tropical regions of India
Dendrocalamus strictus	6-20	2.5-7.5	1-3	Arid and Semi-arid zones of India
Dendrocalamus hamiltonii	12-25	10-18	1.25	West, Central and Eastern India
Dendrocalamus giganteus	30-40	15-25	4-10	North-East & East India
Bambusa bambos	30	15-18	2-4.5	Throughout India up to 1200m altitude
Bambusa polymorpha	15-25	7-15	1-4	Throughout India
Bambusa balcooa	12-20	8-15	3-5	North-East & East India

2.2. Thermal Performance Evaluation Equations

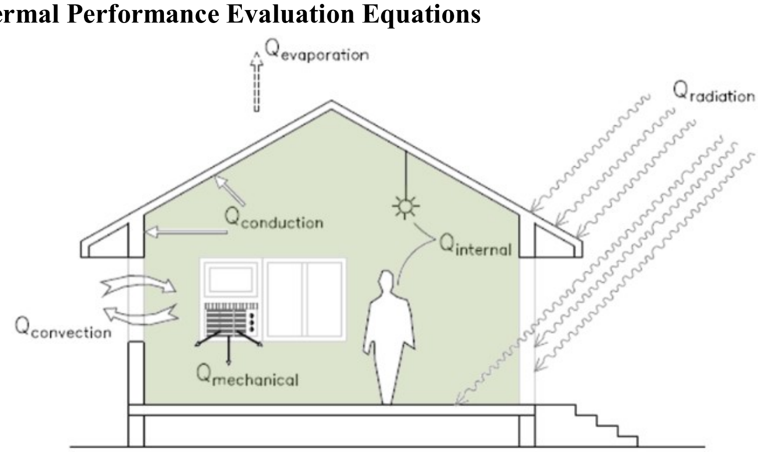


Fig. 1. Heat exchange in a building

2.2.1. Thermal Performance Evaluation

It is the process of modeling heat transfer between a building and its surroundings (Berisha, 2014).

2.2.2. Heat transfer

Transfer of thermal energy from a body at a higher temperature to a body at a lower temperature. Steady state conditions: Temperature variation does not change with time (Joseph et.al, 2015).

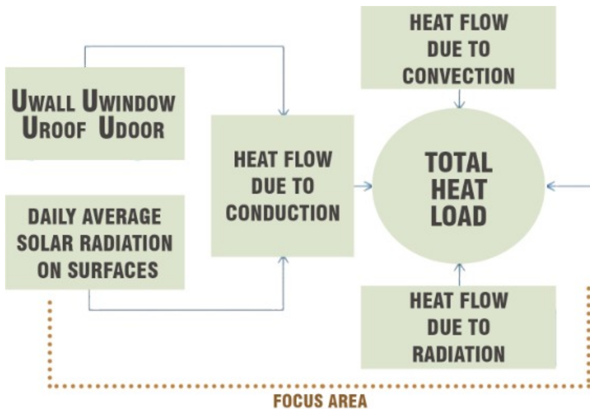


Fig. 2. Total Heat Load Diagram

2.3. Studies on Thermal Performance of Vernacular Materials and Bamboo
2.3.1. Simulation & on-Site Measurement Methods to Study Thermal Performance of Rural Mud Hut

Location: Ranchi, Jharkhand [23.4°N 85.3°E]
Climate Zone: Composite [ECBC]
Building Materials: Walls- 450mm wattle & daub- mud & bamboo [u=3.44 W/sqm K] Roof- Mangalore Tiles on bamboo frame [u=3.1 W/sqm K]
Field Readings: Hourly temperatures inside the house to validate simulation results
Dates: 29th may, 4th January & 27th July
Instruments Used: Raytek gun, Magnetic compass
Simulation/Software: Ecotect
Methodology Steps:

- Field temperature readings
- Validation with software results
- Identifying trends in differences of outdoor & indoor temperatures
- Testing changes in roof insulation & orientation
- Arriving at conclusions


Fig. 4. Photo of the studied hut

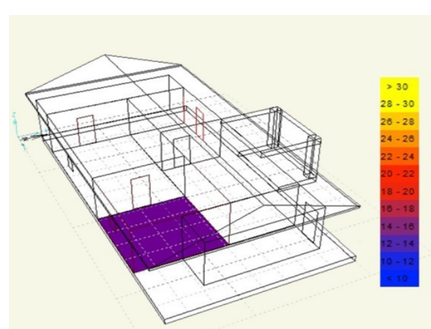


Fig. 5. Simulations in Ecotect

Outcomes & the Way Forward:

1. Constant temperatures inside the room maintained in spite of fluctuating outside temperatures, due to the thermal lag.
2. Proper insulation of roof causes decrease in heat gain in summer and heat loss in winter. (Modern industrial thatch 12'' [u= 0.35 W/sqm K] Durability: 60 years)
3. Shading west and east walls, temporary summer shading of east wall.
4. No shading on Southern walls needed.
5. White color external finish on façade.

2.4. Calculating the U-Value Of complex Composite Walls

U-value (or thermal transmittance co-efficient) is a measure of how much heat will pass through one square meter of a structure when the temperature on either side of the structure differs by 1 degree Celsius. The lower the U-value, the better is the thermal performance of a structure. The U-value is expressed in

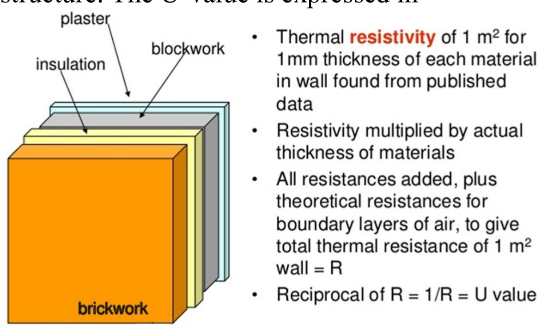


Fig. 6. U-value calculation of a wall

2.5. CPWD Sustainability Index & Guidelines for Materials

S.No.	Proposed Parameter	Weightage
1	Recycled content	10
2	Embodied Energy	10
3	Rapidly Renewable	5
4	Locally Available Material	10
5	Functional Life Period	10
6	Capital Cost	10
7	Maintenance Cost	10
8	Construction Waste Management	5
9	Flyash Content	10
10	Reduced Weight	5
11	Reduced Time of Construction	5
12	Toxicity/Indoor Air Quality/Safety	10
	Total Points	100

Fig. 7. Parameters for CPWD Sustainability Index evaluation

Each material can be evaluated on a set of criteria to determine if the use of the material is sustainable. The proposed parameters and their weightage is based on CPWD's experience with working on these materials and emphasis laid on in LEEDS and GRIHA rating systems. Thus, a material which is performing better in this index will automatically help in securing points in various building rating systems'/m2K.

2.6. Walling Systems developed by various Research Institutes

Availability of industrial wood from natural forests have been on decline for many years now, creating a raw material crisis for the wood based panel industry in the country. The national forest policy 1988 lays emphasis on development of wood substitute. Timber available from fast growing plantation species generally have lower strength properties, dimensional stability and service life. Building materials accounts for nearly 60 to 65% of the cost of house construction. With the constant rise in the cost of traditional building materials and with the poor affordability of large segments of our population. The cost of an adequate house is increasingly going beyond the affordable limits of more than 30-35% of our population lying in the lower income segments. This calls for wide spread technology dissemination and availability at decentralized locations of cost-effective building materials and construction techniques.

2.6.1. Bamboo Mat Veneer Board Walling developed by IPIRTI

Indian Plywood Industries Research and Training Institute is an autonomous body under the Ministry of Environment & Forest Govt. of India. Ministry of Environment & Forest Govt. of India. In the field of composites based on wood and other lignocellulose material, they have developed environmentally sustainable technologies for making plywood like sheet materials from Bamboo. Extensive research using Bamboo Mat in combination with plantation wood for sheet material has resulted in development of Bamboo Mat Veneer Composite. BMVC is a preferable panel material due to its superior physical mechanical properties compared to Bamboo Mat Board (BMB) and general-purpose plywood and on par with structural plywood. Bureau of Indian Standard has already brought out a standard on "Bamboo mat veneer composite for general purpose IS: 14588/1999". 4” thick concrete walls have treated with BMVBs as alternate design.

2.6.2. Bamboo Mat Board Sandwich Walls developed by BMTPC

The Building Materials and Technology Promotion Council (BMTPC) was setup in 1990 as an inter-ministerial apex organization to develop and operationalize a comprehensive and integrated approach for technology development, transfer and investment promotion to encourage application of environment-friendly & energy-efficient innovative materials, manufacturing technologies and disaster resistant construction practices for housing and buildings in urban and rural areas. Since mats are woven from bamboo, which is a very fast growing grass, its promotion has direct ecological advantage. Production of BMB is based not only on an ecologically sound technology, but also is socially uplifting as it provides employment to various village-based small industries. Bureau of Indian Standard has released- IS 13958:1994 Specification for Bamboo Mat Board. Sandwich walls with concrete or straw-bale blocks between BMBs have been developed.

2.6.3. Bamboo Lattice Walling System developed by DFID

The Department for International Development (DFID) is a United Kingdom government department responsible for administering overseas aid. The goal of the department is "to promote sustainable development and eliminate world poverty". They have developed a bamboo walling system where a bamboo lattice forms the frame of the wall, which is plastered with regular cement concrete with the help of chicken mesh.

3. METHODOLOGY

Stage 1:

- Readings on thermal transmittance calculations & bamboo as a building material
- Defining the problem and research questions
- Readings on walling systems developed by research institutes
- Understanding the calculation of Sustainability Index for building materials developed by CPWD

Stage 2:

- Field Studies of two residences where indoor and outdoor temperature differences have been taken along with wall assembly details
- Hands-on exposure in bamboo factory
- Identification of walling systems

Stage 3:

- Calculation of CPWD Sustainability Index for bamboo
- Calculation of U-values for the wall assemblies identified.

Stage 4:

- Design of proposed primary school building at Kaldongari in Maharashtra
- Energy consumption of this proposed design is simulated by changing only the envelope properties for comparison with conventional brick-RCC envelope and ECBC prescribed envelope.

4. STUDY AREA

4.1. Field Studies

Methodology of the field studies at Wondergrass:

- Identifying 4 walls facing the 4 cardinal directions.
- Understanding the assembly of the chosen walls.
- Taking readings inside and outside the chosen walls.
- Calculating U-values of the walls & confirming it with the temperature differences recorded.
- Simulating the cross-sections of the walls using Therm software to visualize heat flow.
- Simulating the building in ResBUILD Software to compare energy consumption of bamboo envelope with conventional Brick & RCC envelope.

4.1.1. Architect's Residence at Wondergrass, Maharashtra

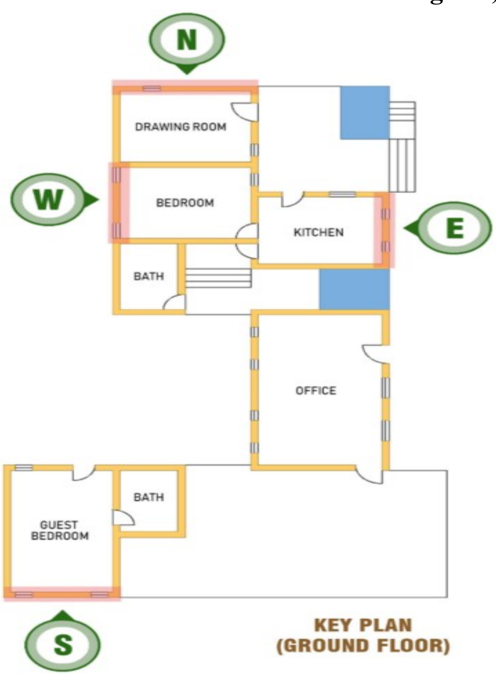


Fig.9. Exterior of the residence

Fig.8. Key Plan

Fig.10.Interior of the residence

The residence of Ar. Vaibhav Kaley is located in Pethkaldongari in Maharashtra. The walls are made of bamboo and mud in the wattle-and-daub method.

Fig.11. Hourly temperature differences recorded in the East Wall

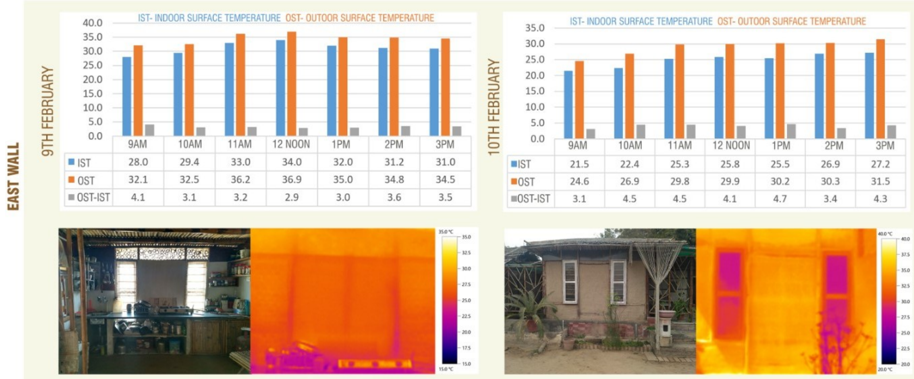


Fig.11. Hourly temperature differences recorded in the East Wall

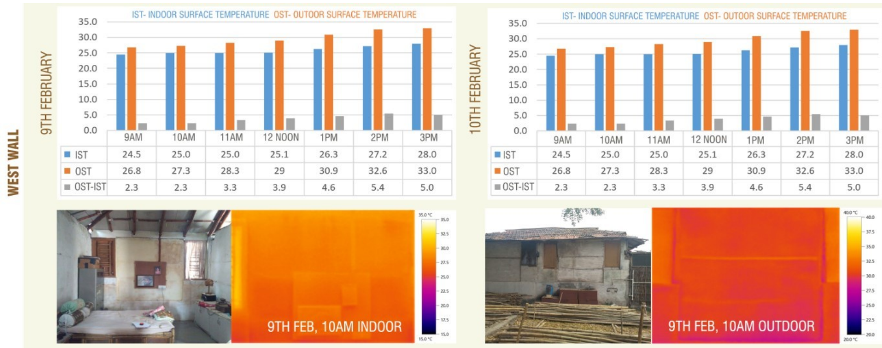


Fig. 12. Hourly temperature differences recorded in the West Wall

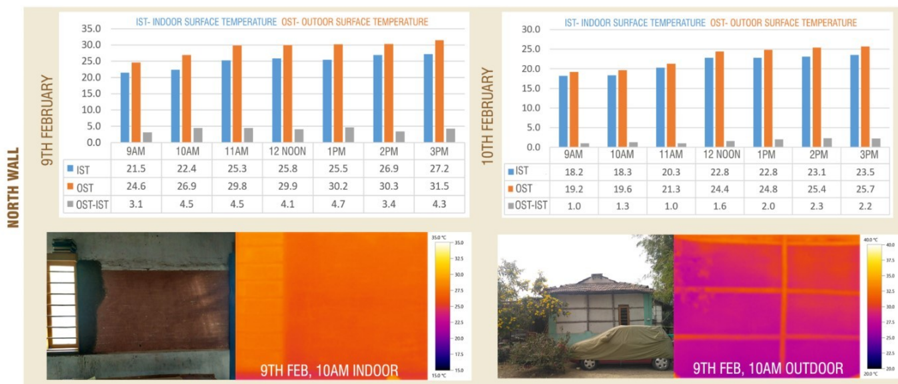


Fig. 13. Hourly temperature differences recorded in the North Wall

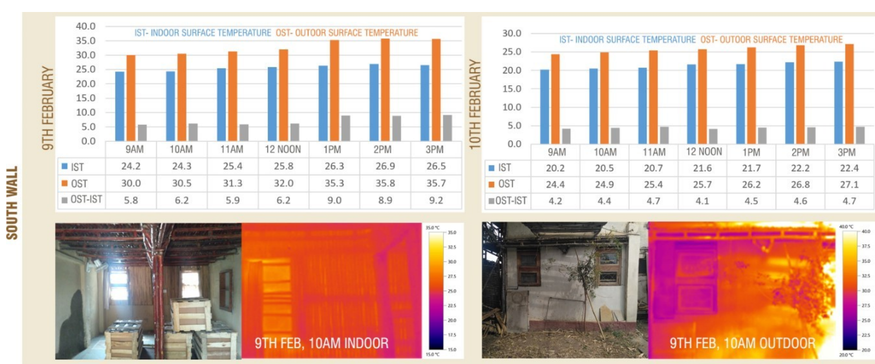


Fig. 14. Hourly temperature differences recorded in the South Wall

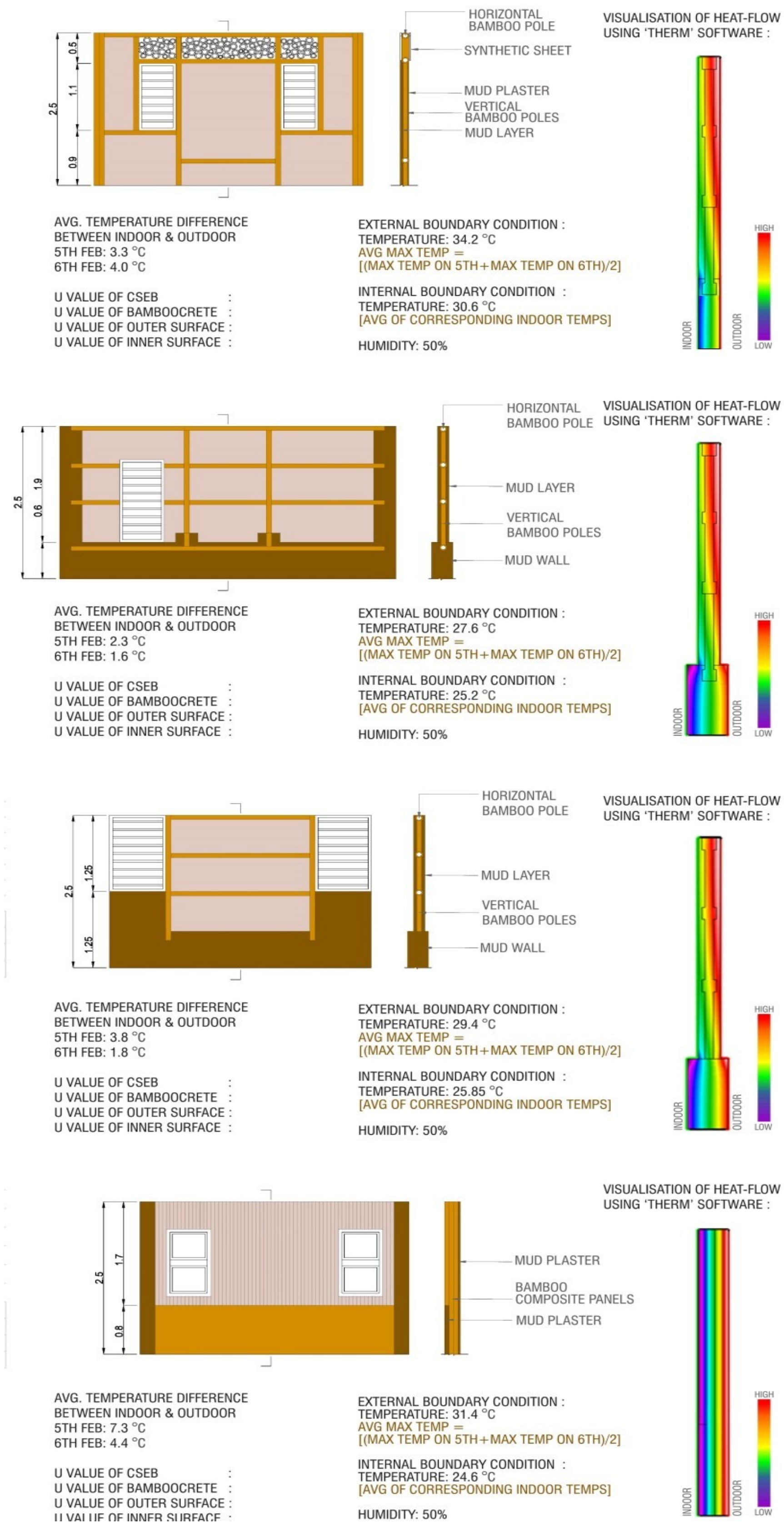


Fig. 15. Details of walls & heat transfer visualization in Therm

4.2. Visit to KONBAC bamboo factory

Fig. 16. Procedure for treatment of bamboo poles documented at KONBAC

4.3. Project Description

Sadhana Village School is a Registered Trust [1994] in Pune. 2 primary schools are being run by them currently, one in Kule and another in Nelgunda, both in Maharashtra.

Fig. 17. Photographs of the existing campuses [Source: sadhana-village.org]

4.4. Quality of Spaces

They believe that learning depends on the cognitive conditions and the aim is to create and provide spaces that allow natural learning.

4.4.1. Requirements

- Classrooms for 30 students each from Classes 1-5
- Staff & admin rooms
- Art & craft room
- Multipurpose hall
- Outdoor Spaces: farming area, domestic animal shed, games field

4.4.2. Building Material

Bamboo is the new upcoming material in the area with various organizations in Maharashtra working extensively with bamboo. The Sadhana group has decided to include bamboo in their next campus design.

4.4.3. Project Description

4.4.3.1. Site Location & Access

Proposed site for new campus is at Kaldongari at 21.08ºN 78.86ºE] (near Nagpur) Maharashtra, India. Access to site is via 6m abutting NH-16 service road along south side.

Fig. 18. Site Location on map

Fig. 19. Google Earth snapshot of site

- Site adjacent to NH-6, well connected to various villages along the highway.
- 10 no. of villages within 5km radius to benefit from the project.
- Site abuts the NH-6 service road, highway traffic is avoided.
- Wena dam & reservoir at 500m distance to majorly affect microclimate.

4.4.3.2. Site Specification

Site Area: 2.2 Acres

4.4.3.3. Site Topography

- Relatively flat site with no topographical features.
- Negligible slope- maximum difference in elevation is 4m across 120m.
- North-east corner is the lowermost region.

4.4.3.4. Site Soil Type

- Sandy soil, light texture & loose structure
- Drains quickly, bad water retention & percolation
- Good soil bearing capacity

4.4.3.5. Site Vegetation

- Total 4 nos. Of existing trees on site
- 8.5m -12m diameter of canopies: 2 nos. Karam tree & 2 nos. Pipal tree

4.4.3.6. Site Noise Levels

Adjacent road nh-6 is noisy and noise buffers like dense vegetation is required

4.4.3.7. Existing Structures

There are no existing structures on site.

4.4.3.8. Views to and from site

- North views: agricultural land & dam Windows can be provided without significant gain
- South views: NH-6 must be treated for onlookers
- East views: residences Selective filtration
- West views: barren land Unknown future development

5. CONCEPTUAL DEVELOPMENT

5.1. Design Evolution Concepts

The site is located in the composite climate zone in a rural area. A design approach had to be adopted which considers climate as well as social and functional relevance. Since ‘courtyards’ are one of the suggested passive design strategies for a composite climate, it is combined with the concept of ‘chaupals’ or village trees under which there is a seating area for all village meetings & interactions. Such a setting is appropriate for an interactive learning space as well.

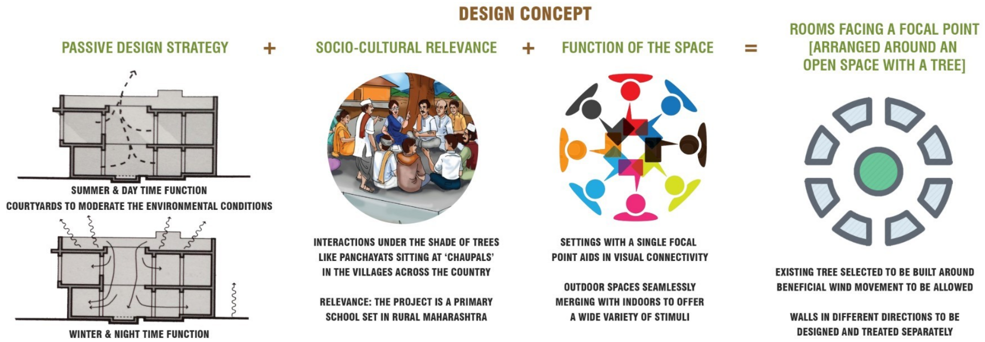


Fig. 20. Explanation of the design concept

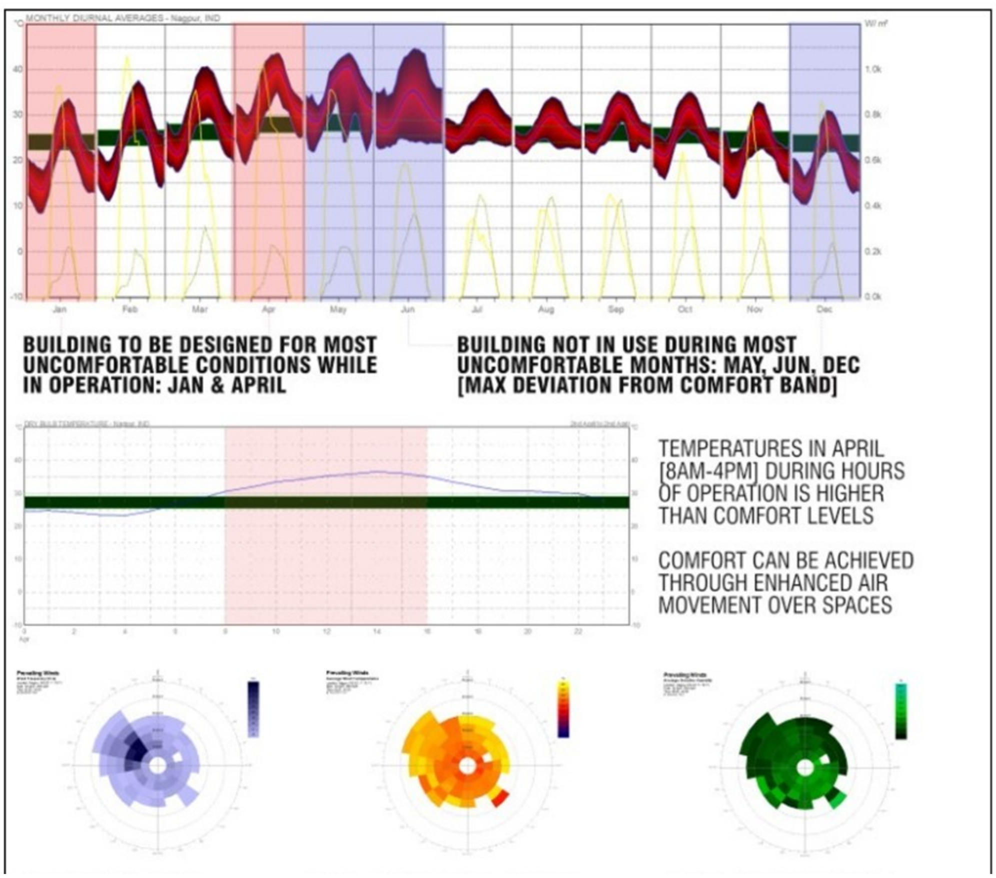
5.2. Climate Study

The primary school is to be designed for the working months and hours to maximize comfort of occupants and energy efficiency during its operation.

Table 2. Occupied months & hours

Working Months	Jan-April	July-November
Working Hours	8am-4pm	(All Days)

It was found that during the occupied periods, the most uncomfortable conditions were the months of January & April. Since the project is a Naturally-Ventilated building, the wind analysis was done to increase comfort levels during these months. The placement of the rooms were done accordingly.



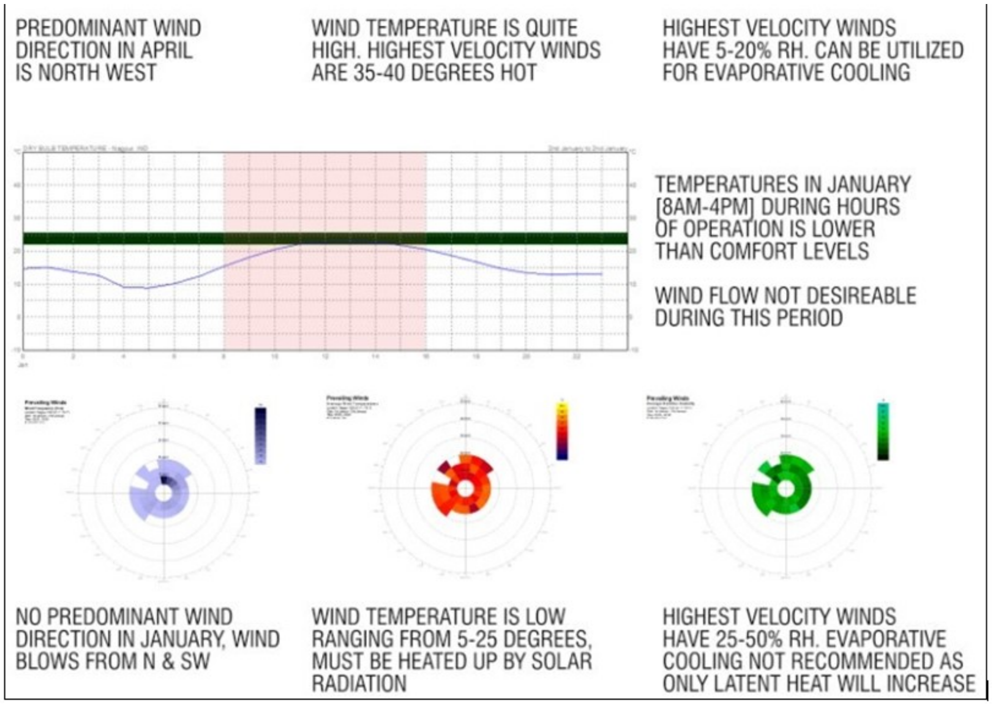


Fig.21. Climate Study

5.3. Placement of Blocks

The rooms were arranged as per the wind analysis as explained in Figure 22.

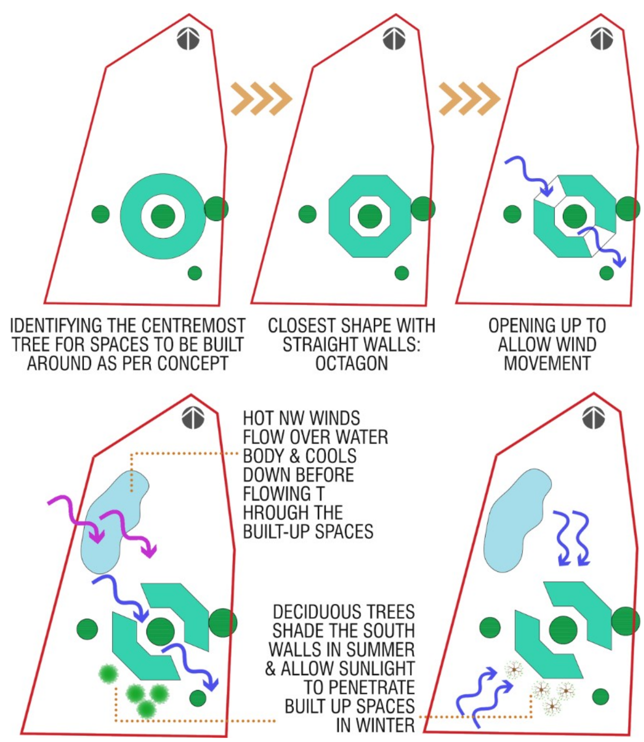


Fig 22. Placement of Blocks

5.4. Wall-type Selection

A basic study of the sun-path for the site location results in the following observations:

- The altitude angles are low for the East and West Walls. Maximum radiation & heat gain occurs through these walls. High U-values & minimum openings are recommended.
- North walls do not receive direct radiation and can have large openings.
- South walls receive high altitude angles and can be protected from receiving high radiation levels by providing horizontal projections.

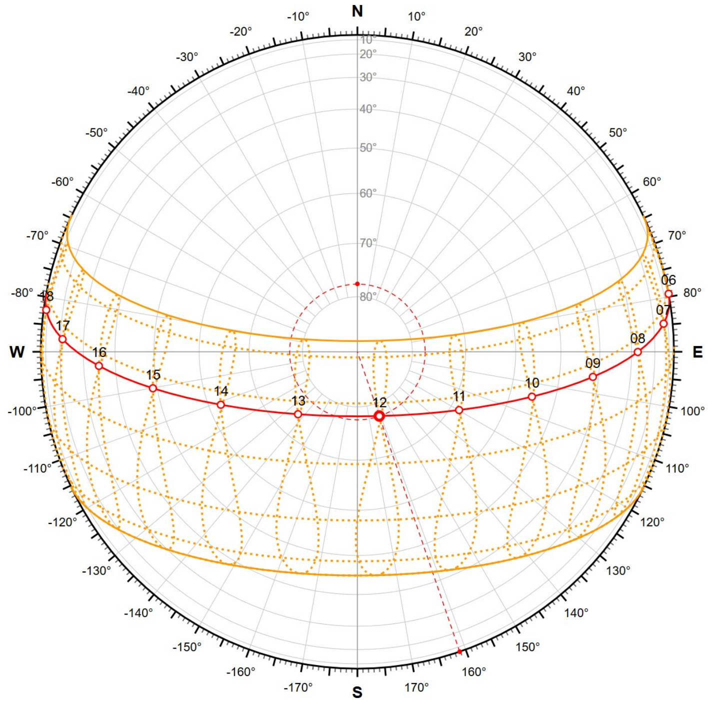


Fig 23. Sun-Path diagram for the site

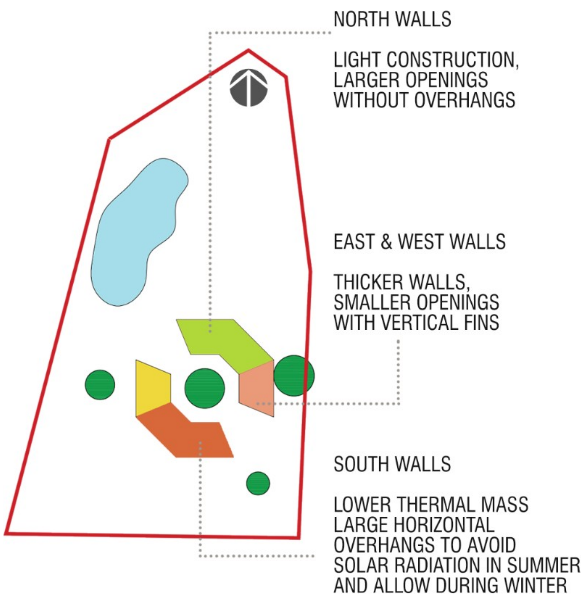


Fig 24. Wall-type Selection

6. ANALYSIS AND RESULTS

6.1. CPWD Sustainability Index Calculation for Bamboo:

1. RECYCLED CONTENT: 1. RECYCLED CONTENT FOR AL = 50%, RECYCLED CONTENT FOR UPVC = 70% RATING FOR UPVC = 10 (HIGHEST) RATING FOR ALUMINIUM = 50*10/70 = 7	1. RECYCLED CONTENT FOR POLE BAMBOO = 70% RECYCLED CONTENT FOR ENGINEERED BAMBOO PRODUCTS = 50-100% PROPOSED RATING : PERCENTAGE / 10 HENCE, POLE BAMBOO RATING = 7 ENGINEERED BAMBOO PRODUCTS = 5-10
2. EMBODIED ENERGY: 2. FOR ALUMINIUM = 6000MJ/UNIT, FOR UPVC = 2980 MJ/UNIT THEREFORE, RATING FOR UPVC = 10 (LOWEST) AND, RATING FOR ALUMINIUM = 2980*10/ 6000 = 5	2. EE OF BAMBOO = 1.5 MJ/UNIT PROPOSED RATING : POINTS ALLOTTED TO EXISTING LIST HENCE, POLE BAMBOO RATING = 10
3. RAPIDLY RENEWABLE: 3. BOTH ALUMINIUM AND UPVC ARE OBTAINED FROM RAW MATERIALS WHICH ARE NOT RAPIDLY RENEWABLE. THUS, BOTH SHALL BE AWARDED ZERO	3. BAMBOO GROWS IN 5 YEARS HENCE RATED WITH 5 POINTS AS PER THE TABLE
4. LOCALLY AVAILABLE MATERIAL: 4. IT IS ASSUMED THAT CONSTRUCTION SITE IS IN DELHI. ALUMINIUM WINDOWS FRAMES ARE MANUFACTURED IN PERIPHERAL INDUSTRIAL AREAS OF DELHI BUT ITS EXTRACTION IS FROM THE STATE OF ORISSA IE BEYOND 400 KMS FROM DELHI. THUS IT HAS BEEN AWARDED 8 UPVC WINDOW FRAMES ARE MANUFACTURED IN REWARI (WITHIN 400 KMS) AND RAW MATERIAL IS OBTAINED FROM BEYOND 400 KMS. UPVC SHALL ALSO BE RATED AS 8	4. BAMBOO FOR CONSTRUCTION IS AVAILABLE THROUGHOUT THE COUNTRY RATED WITH 10 POINTS
5. FUNCTIONAL LIFE PERIOD: 5. FUNCTIONAL LIFE PERIOD FOR ALUMINIUM WINDOW FRAME IS >80 YRS HENCE 10 RATING FOR UPVC, IT IS 25 YRS & HAS BEEN RATED AS 5	5. FUNCTIONAL LIFE PERIOD FOR WELL TREATED BAMBOO STRUCTURES IS 40-60 YEARS HENCE RATED 7 AS PER THE TABLE
6. CAPITAL COST: 6. COST OF UPVC WINDOW IS 2 TIMES THAT OF ALUMINIUM WINDOW FRAME. THEREFORE, AL RATING = 10 UPVC RATING = 10/2 = 5	6. PROPOSED RATING : POINTS MUST BE ALLOTTED ACCORDING TO RANGES OF RATE PER VOLUME OF CONSTRUCTION OF A LIST OF MATERIALS COST OF BAMBOO CONSTRUCTION IS LOW BAMBOO CAN BE RATED 10
7. MAINTENANCE COST: 7. ALUMINIUM AND UPVC ARE MAINTENANCE FREE AND HENCE HAVE BEEN RATED 10	7. PROPOSED RATING : POINTS MUST BE ALLOTTED ACCORDING TO COST OF MAINTENANCE PER SURFACE AREA PER YEAR COST OF BAMBOO MAINTENANCE IS HIGHER BAMBOO CAN BE RATED 5
8. CONSTRUCTION WASTE MANAGEMENT: 8. BOTH UPVC AND ALUMINIUM AFTER THEIR SERVICE LIFE WILL BE RECYCLED AND RATED 5	8. BAMBOO IS NOT ONLY BIODEGRADABLE, BUT ALSO CAN BE RECYCLED TO FORM MORE PRODUCTS/ FUEL WITH LOW ENERGY METHODS BAMBOO IS RATED 5 AS PER THE TABLE
9. FLYASH CONTENT: 9. BOTH ALUMINIUM AND UPVC HAVE NO FLYASH CONTENT HENCE HAVE BEEN RATED ZERO	9. PROPOSED RATING : THIS PARAMETER IS INVALID FOR MOST MATERIALS AND MUST BE INCORPORATED IN 'RECYCLED CONTENT' SECTION BAMBOO IS RATED 0
10. REDUCED DEAD WEIGHT: 10. ALUMINIUM WINDOWS ARE LIGHTER THAN UPVC WINDOWS & BEEN RATED AS 5 AND UPVC WINDOW AS 4	10. PROPOSED RATING : POINTS MUST BE ALLOTTED ACCORDING TO RANGES OF WEIGHT PER VOLUME BAMBOO CONSTRUCTION IS LIGHTWEIGHT & IS RATED 5
11. REDUCED TIME OF CONSTRUCTION: 11. NEITHER ALUMINIUM NOR UPVC LEADS TO REDUCED CONSTRUCTION TIME HENCE AWARDED ZERO	11. BAMBOO CONSTRUCTION IS QUICK & IS RATED 5
12. TOXICITY/INDOOR AIR QUALITY/SAFETY: 12. TOTAL POINT FOR ALUMINIUM = 1+2+2+4 = 9 TOTAL POINT FOR UPVC = 2+1+1+2 = 6	12. TOTAL POINT FOR BAMBOO = 1+1+1+2 = 5 PROPOSED RATING : POINTS MUST BE ALLOTTED FOR TOXICITY & EMMISSION OF GASES/LEACHATES

With the example of Aluminum & UPVC as given in the CPWD manual, the Sustainability Index of bamboo is calculated. It was found that:

- The rating promotes comparison within only the materials of a particular project. Even if all the materials are not sustainable, they will end up with high points due to comparative advantage.
- The rating of parameters 1, 2, 6, 7, 9, 10, 12 are vague and need to be defined and tabulated within fixed ranges.
- Ratings for parameters 1 - recycled content & 3 - rapidly renewable must be reconsidered & more weightage should be given to renewability than recyclability.
- Parameter 9 - flyash content is not applicable for all materials & can be incorporated into parameter 1 - recycled content

According to the present procedure, bamboo scores 74 out of 100 points.

6.2. Energy Consumption Comparison of Field Studies

Energy consumption of the field study residences are simulated by changing only the envelope properties for comparison with conventional brick-RCC envelope.

6.2.1. Residence at Wondergrass Initiatives Pvt. Ltd.

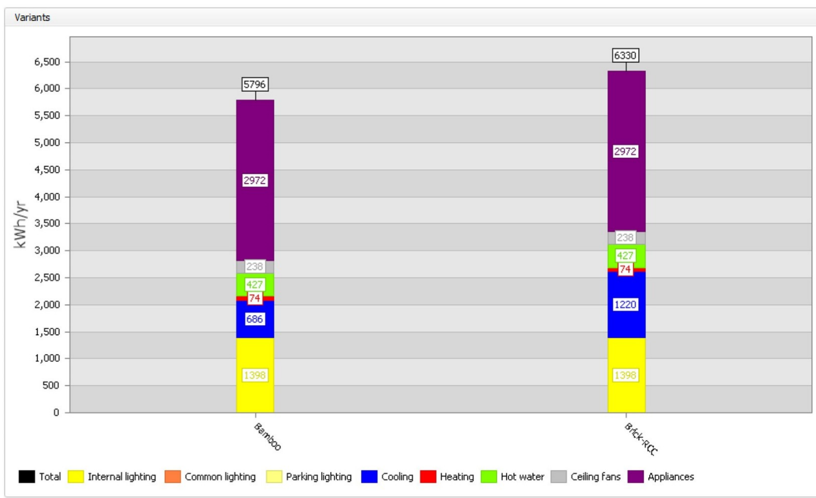


Fig 25. Energy consumption comparison of residence at Wondergrass

It was found that there was a significant change in cooling loads by changing only the envelope properties. The bamboo envelope building showed a cooling load of 686 KWh/yr as compared to 1220 KWh/yr exhibited by the Brick- RCC envelope.

6.3. U-value Calculations

6.3.1. Wattle & Daub Wall

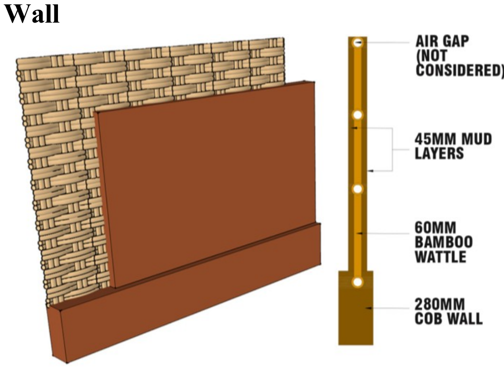


Fig 26. Wattle & Daub Wall

Table 3. U-value calculation for Wattle & Daub Wall

Part of Wall	Material	Thickness	Conductivity	Resistance Thickness
		(t)	(k-value)	(R-value)
		m	W/mK	m²K/W
Cob	Outside Surface	_	_	0.06
	Mud	0.280	0.323	0.867
	Inside Surface	_	_	0.15
	Total R			1.077
	U-value = 1 / Total R			**0.929**
Wattle & Daub	Outside Surface	_	_	0.06
	Mud	0.045	0.323	0.139
	Bamboo	0.060	0.227	0.264
	Mud	0.045	0.323	0.139
	Inside Surface	_	_	0.15
	Total R			0.753
	U-value = 1 / Total R			**1.328**

Part of Wall	Area	%	U-Value
Cob	0.168	37	0.929
Wattle & Daub	0.285	63	1.328
Total	**0.453**	**100**	**1.18**

6.3.2. Bamboo-Crete Wall

Table 4. U-value calculation for Bamboo-Crete Wall

Part of Wall	Material	Thickness	Conductivity	Resistance Thickness ÷ Conductivity
		(t)	(k-value)	(R-value)
		m	W/mK	m²K/W
Panels & Split Poles	Outside Surface	–	–	0.06
	Concrete	0.150	0.800	0.188
	Bamboo Strips	0.050	0.227	0.220
	Inside Surface	–	–	0.15
	Total R			0.618
	U-value = 1 / Total R			**1.619**

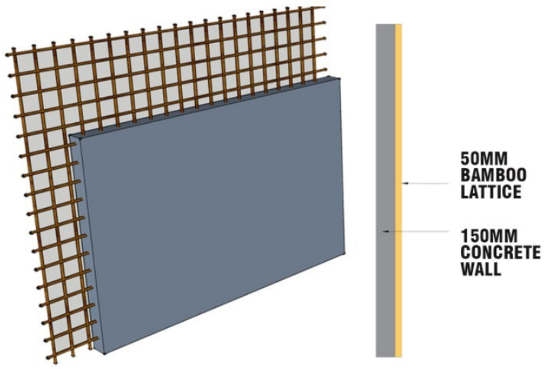


Fig 27. Bamboo-Crete Wall

6.3.3. Panels & Poles Wall

Table 5. U-value calculation for Panels & Poles Wall

Part of Wall	Material	Thickness	Conductivity	Resistance Thickness
		(t)	(k-value)	(R-value)
		m	W/mK	m²K/W
Panels & Split Poles	Outside Surface	–	–	0.06
	Mud	0.030	0.323	0.093
	Composite Panel	0.120	0.275	0.436
	Bamboo Strips	0.060	0.227	0.264
	Inside Surface	–	–	0.15
	Total R			1.004
	U-value = 1 / Total R			**0.996**
Panels & Mud	Outside Surface	–	–	0.06
	Mud	0.030	0.323	0.093
	Composite Panel	0.120	0.275	0.436
	Mud	0.060	0.323	0.186
	Inside Surface	–	–	0.15
	Total R			0.925
	U-value = 1 / Total R			**1.081**

Part of Wall	Area	%	U-Value
Panels & Split Poles	0.357	68	0.996
Panels & Mud	0.168	32	1.081
Total	**0.525**	**100**	**1.02**

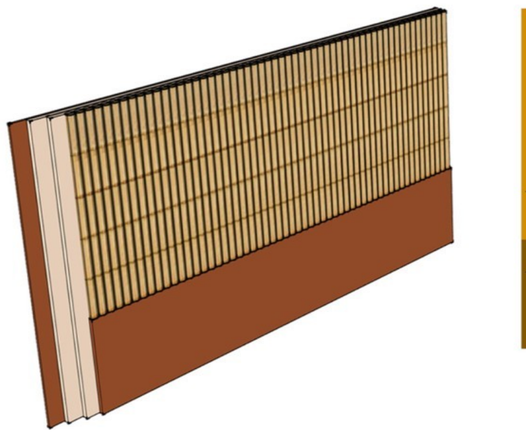


Fig 28. Panels & Poles Wall

6.3.4. Polystyrene & Ply Wall

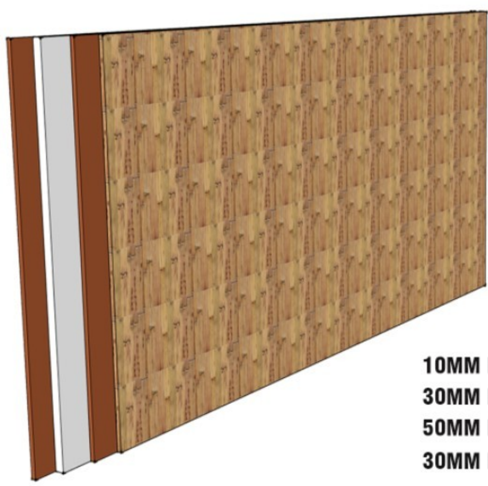


Fig 29. Polystyrene & Ply Wall

Table 6. U-value calculation for Polystyrene & Ply Wall

Part of Wall	Material	Thickness	Conductivity	Resistance Thickness / Conductivity
		(t)	(k-value)	(R-value)
		m	W/mK	m²K/W
Thermocol & Bamboo Ply	Outside Surface	–	–	0.06
	Bamboo Ply	0.03	0.47	0.06
	Polystyrene Sheet	0.05	0.033	1.52
	Bamboo Ply	0.03	0.47	0.06
	Flattened Poles	0.01	0.227	0.04
	Inside Surface	_	_	0.15
	Total R			1.897
	U-value = 1 / Total R			**0.527**

6.3.5. BMVC with Concrete blocks Wall

Table 7. U-value calculation for BMVC with Concrete blocks Wall

Part of Wall	Material	Thickness	Conductivity	**Resistance** Thickness
		(t)	(k-value)	(R-value)
		m	W/mK	m²K/W
Concrete Blocks with BMVC Panel	Outside Surface	–	–	0.06
	Concrete Blocks	0.100	0.300	0.333
	BMVC	0.025	0.137	0.182
	Plaster	0.010	0.600	0.017
	Inside Surface	–	–	0.15
	Total R			0.742
	U-value = 1 / Total R			**1.347**

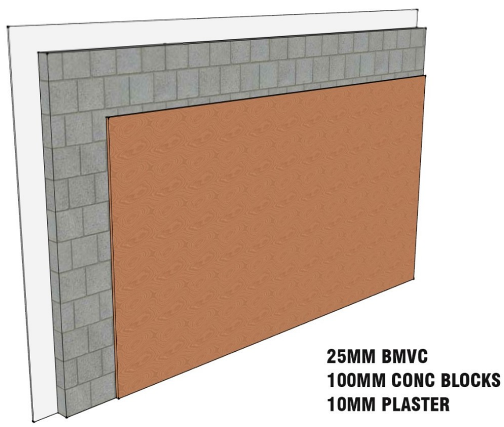


Fig 30. BMVC with Concrete blocks Wall

6.3.6. BMB with Concrete blocks Wall

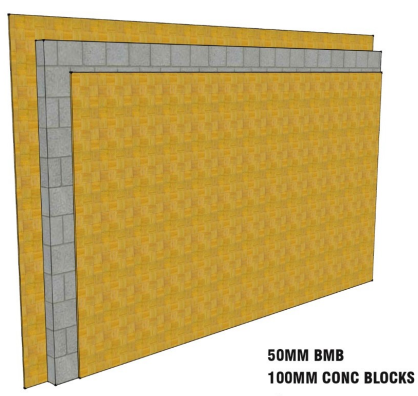


Fig 31. BMB with Concrete blocks Wall

Table 8. U-value calculation for BMB with Concrete blocks Wall

Part of Wall	Material	Thickness	Conductivity	Resistance Thickness
		(t)	(k-value)	(R-value)
		m	W/mK	m²K/W
Sandwich Walls-Concrete Blocks & BMB	Outside Surface	–	–	0.06
	BMB	0.050	0.193	0.259
	Concrete Blocks	0.100	0.300	0.333
	BMB	0.050	0.193	0.259
	Inside Surface	–	–	0.15
	Total R			1.062
	U-value = 1 / Total R			**0.942**

6.3.7. Lattice & Plaster Wall

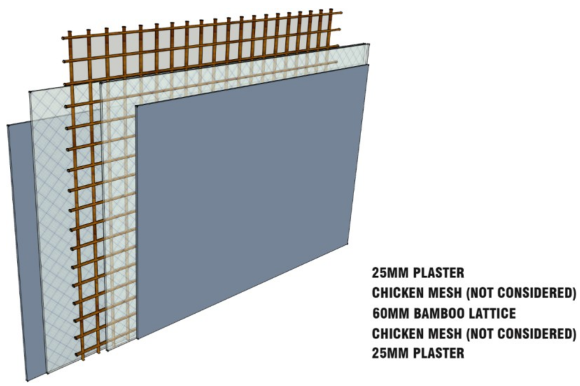


Fig 32. Lattice & Plaster Wall

Table 9. U-value calculation for BMB with Concrete blocks Wall

Part of Wall	Material	Thickness	Conductivity	Resistance Thickness
		(t)	(k-value)	(R-value)
		m	W/mK	m²K/W
Bamboo Frame & Cement Plaster on Chicken Mesh	Outside Surface	–	–	0.06
	Plaster on Mesh	0.050	0.600	0.083
	Air Gap	_	_	0.180
	Bamboo Poles	0.060	0.227	0.264
	Inside Surface	–	–	0.15
	Total R			0.738
	U-value = 1 / Total R			**1.356**

6.3.8. BMB with Straw-bale blocks Wall

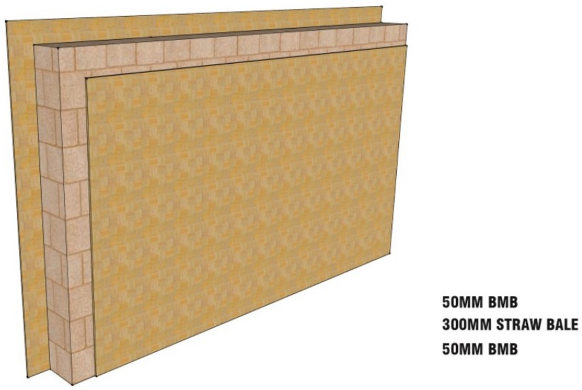


Fig 33. BMB with Straw-bale blocks Wall

Table 10. U-value calculation for Straw-bale blocks Wall

Part of Wall	**Material**	**Thickness**	**Conductivity**	**Resistance** Thickness
		(t)	(k-value)	(R-value)
		m	W/mK	m²K/W
Straw Bale Blocks & BMB Sheets	Outside Surface	–	–	0.06
	BMB	0.025	0.193	0.130
	Straw-Bale Blocks	0.300	0.100	3.000
	BMB	0.025	0.193	0.130
	Inside Surface	_	_	0.15
	Total R			3.469
	U-value = 1 / Total R			**0.288**

6.4. Energy Consumption Comparison of Proposed Design

The proposed design is simulated for energy consumption in ResBUILD software. Three variations of the same design is simulated by changing only the envelope properties. The monthly energy consumption projection is as follows:

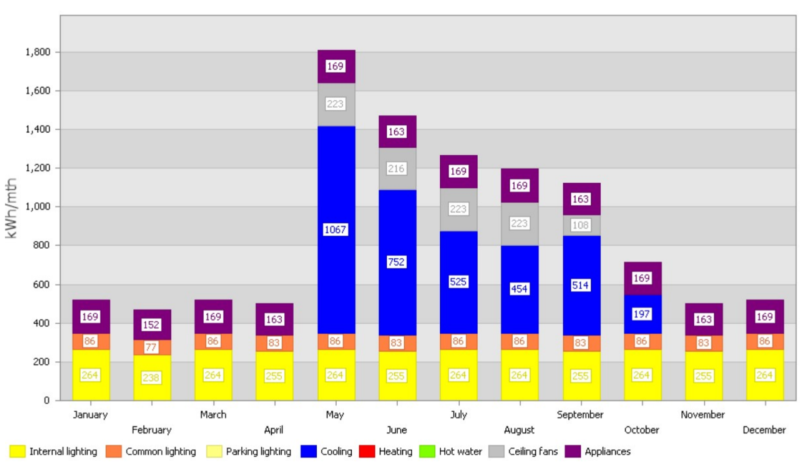


Fig 34. Monthly Energy Demand for Bamboo Envelope

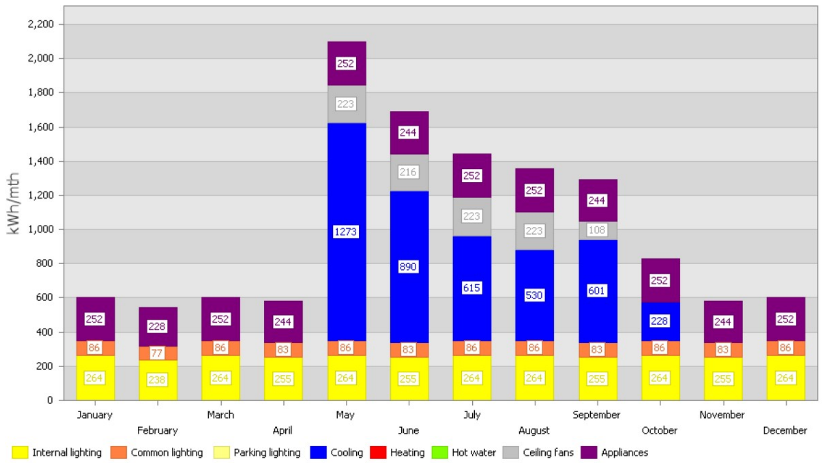


Fig 35. Monthly Energy Demand for Brick-RCC Envelope

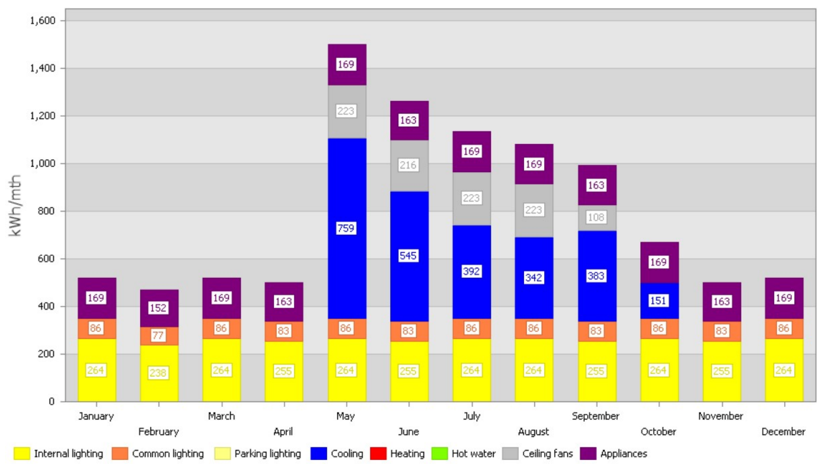


Fig 36. Monthly Energy Demand for ECBC Envelope

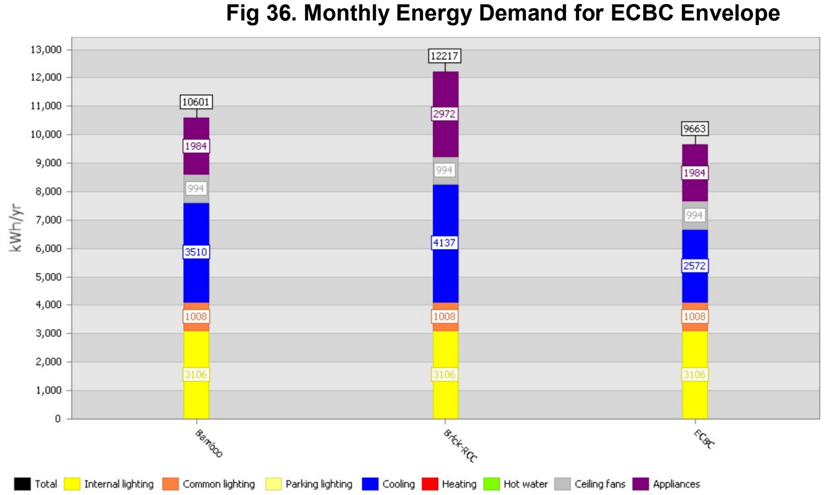


Fig 37. Annual Energy Demand Comparison for Proposed Design

It was found that ECBC envelope performed best with 2572 kWh/yr annual demand for cooling, followed by the Bamboo envelope with 3520 kWh/yr annual demand and the Brick-RCC envelope had the maximum cooling load at 4137 kWh/yr.

7. CONCLUSION

In the quest for achieving energy efficiency, an architect has various factors to keep in mind in order to build a sustainable building. Right from site selection & planning to water supply, waste management, energy demand, lighting efficiency, etc. it is a meticulous process of calculations & sensitivity towards the environment. This thesis deals with only a part of the entire process of designing a sustainable building and focusses on the performance of a building envelope, & its contribution towards changes in energy consumption. The material selected for detailed analysis is bamboo, which is "green gold" indeed. It is the future of sustainability due to its strength, flexibility in application, quick growth & bio- degradability.

At the end of the study, it was found that bamboo walls perform better than the conventional brick & RCC envelope that is the general trend in almost all types of construction in India. If even the walls of buildings could be redesigned & rethought, there can be a colossal change in the trends in energy consumption for heating and cooling. ECBC compliant envelope was found to perform the best, but not chosen for this thesis as high-embodied energy products like Expanded Polystyrene is inappropriate for a rural setting, considering the manufacturing process, cost of production & transport, and waste management after the life of the building is over.

The purpose of this thesis is to sensitize people about the importance of material selection while designing a building. Location, climate and even the orientation should define the materials used. In my opinion, rapidly renewable materials like bamboo, mud and straw must be chosen over recycled ones, so that the waste demand is minimized in the first place. It is futile to produce materials out of fly- ash and PVC as it will not discourage the creators to not produce them in the first place. The future of the sustainable building industry must be complimented with overall sustainable living.

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