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Original Article

Comparative Analysis of Bamboo Poles and Metal Pipes for Hybrid Space Grid Structures: The Case of Vidarbha Region, India

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Abstract - *Space grid structures are preferred, equally, by architects and engineers for their versatility to span, short, medium and large arenas of regular and diverse geometric shapes. Space grid structures are chiefly composed of two components: strut (pipe) and internodes. In the age of sustainability, ways and measures are being employed to include more and more renewable resources in engineering and architecture. For the same reason, eco-friendly hybrid versions of space grid structures are preferred for certain spans and applications. In hybrid bamboo space grid structures, metal pipes (struts) are wholly or partially replaced by nature-grown pipes (bamboos), whereas internodes remain that of mild steel. In space grid structures, as the span increases from short to medium and large, dead load increases, resulting in the usage of high-strength struts and internodes. In factory-made pipes made of mild steel, stainless steel, and aluminium alloy, medium to high strength grades are available. But it is not the same in the case of nature-grown pipes, i.e. bamboo. In bamboo, wall thickness and density vary as per the species of bamboo and also due to variations in climatic conditions. Although bamboo has a tubular hollow section, just like any metal or non-metal pipe, being naturally grown, it has certain uniqueness and limitations. The undertaken research encompasses a comparative study of the physical attributes of factory-made metal pipes and nature-grown pipes (bamboo), especially in the Vidarbha region of the Maharashtra State of India. The research helps strategise and find ways to augment the mechanical strength of bamboo for hybrid bamboo space grid structures.*

Keywords - *Augmentation, Bamboo, Metal pipes, Physical Properties, Sustainable Material, Vidarbha, India.*

1. Introduction

Space Grid Structures are a common element in product design, industrial design, architecture and building construction. [1] They are a versatile tool for the architect, designer, and engineer in the search for new forms, owing to their wide diversity and flexibility. A space grid structure or space frame is a rigid, lightweight, truss-like structure constructed from interlocking struts in a geometric pattern. [2] They can be used to span medium to large areas with few or no intermediate supports. Like the truss, a space frame is strong because of the inherent rigidity of the triangle; flexing loads (bending moments) are transmitted as tension and compression loads along the length of each strut. [3]. Space grid structures can be utilised for industrial buildings, factories, sports halls, warehouses, swimming pools, conference halls and exhibition centres, stadiums with long-span distance, museum and fair houses, shopping centres and malls, airports and canopy, mosque and atrium, etc. The legendary Eifel Tower is one of the finest examples of space grid structures. Space grid structures are chiefly composed of two components: strut and internode. The struts are, generally, hollow tubular sections (pipes) of galvanised or chromium-plated Mild Steel (MS) or Stainless Steel (SS) or Aluminium Alloy (AA), and internodes are of mild steel or stainless steel.

The construction industry contributes to a staggering 37% of the global emissions generated. [4] Under sustainable practices, ways and measures are being employed to include more and more renewable resources in engineering and architecture. For the same reason, eco-conscious architects and engineers prefer eco-friendly hybrid versions of space grid structures for certain purposes and applications. In hybrid space grid structures, metal pipes (struts) are wholly or partially replaced by nature-grown pipes (bamboos) or cardboard pipes (tubes), whereas internodes remain that of mild steel. Here, hybrid bamboo space grid structures are under consideration.

In space grid structures, as the span increases from short to medium and large, the dead load increases, resulting in the usage of high-strength pipes (struts) and internodes. In factory-made pipes made of mild steel, stainless steel, and aluminium alloy, medium to high-strength material grades are available. In factory-made pipes (struts), the load-bearing capacity can be augmented by changing the struts' thickness, composition and density. But it is not the same in the case of nature-grown pipes, i.e. bamboo. In bamboo, wall thickness and density vary according to the bamboo species and due to variations in climatic conditions in different regions of India.

Although bamboo has a tubular hollow section, just like any metal or non-metal pipe, being naturally grown, it has certain uniqueness and limitations. The undertaken research encompasses a comparative study of the physical attributes of factory-made metal pipes and nature-grown pipes (bamboo), especially of the Vidarbha region. The research helps strategise and find ways to augment the strength of bamboo for hybrid bamboo space grid structures.

1.1. Background of the Study

- Consideration of partly replacing metal pipes with bamboo poles in hybrid bamboo space grid structures
- Similarities and dissimilarities between nature-grown pipes (bamboo poles) and factory-made metal pipes
- Focus on selected bamboo from the Vidarbha region of Maharashtra, India, for their structural applications.

1.2. Objectives of the Present Study

- Understanding the physical attributes of selected bamboo, particularly of the Vidarbha region of Maharashtra, India
- Comparative understanding of nature-grown pipes and man-made metal pipes with respect to their physical attributes
- Role of the above comparative study in strategising to augment the strength of bamboo poles for structural purposes

1.3. Study Flow Chart

Figure 1 shows the research study flow chart.

2. Literature Review

In order to get a larger view of the comparative analysis, the literature review has been undertaken. Selected case studies are here:

2.1. Case Study I: Mechanical Properties of Bamboo and Bamboo Composites

A Review by Calvin Yap Thai Ming, Wong King Jye, Haris Ahmad, Israr Ahmad [5].

This article is the compilation and review of various research works related to the study of the mechanical properties of bamboo. The mechanical properties of bamboo depend on many factors, such as species, age, soil, height and so on. It is nearly impossible to study the mechanical properties of all the bamboo species, but this paper studies about the tests conducted on some of the prevalent species in the Malesia region.

The mechanical properties of bamboo, which are crucial for its practical applications, have been discussed here. Major properties that are the subject matter of this research paper are tensile strength, compressive strength, impact strength and fracture toughness. Additionally, the effects of moisture content on the mechanical properties have also been discussed in this paper. It is shown that moisture content drastically impacts the mechanical properties of bamboo. Bamboo's tensile strength, compression strength and fracture toughness are all reduced when exposed to water.

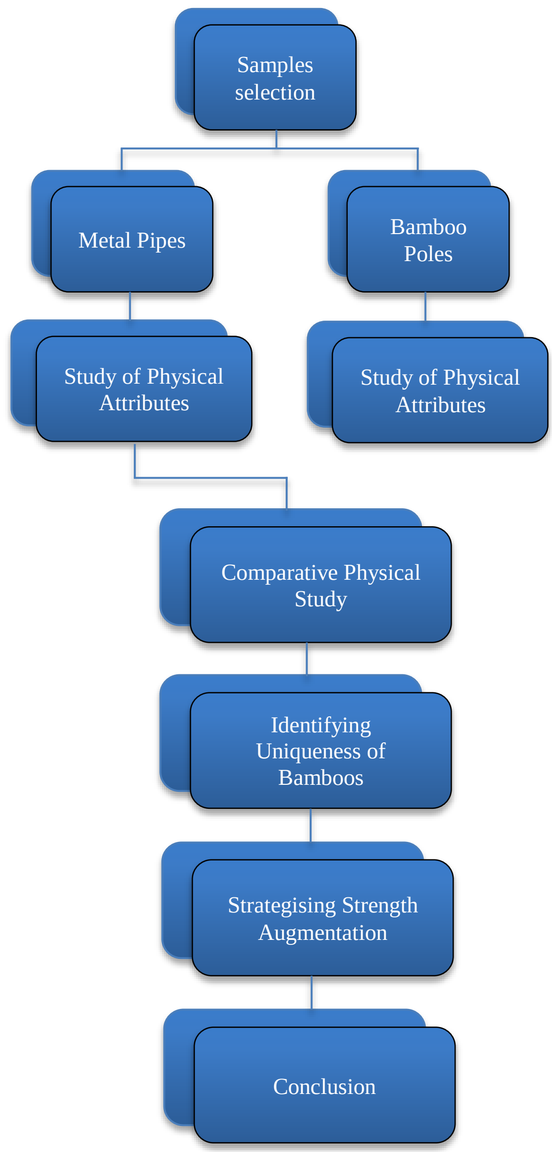

Fig. 1 Study flow chart

2.1.1. Objectives

- To review studies on the mechanical properties of bamboo;
- To analyze factors affecting the mechanical properties of bamboo;
- To compare the mechanical properties of different species of the region;
- To assess the impact of moisture content on the mechanical properties of bamboo;
- To highlight bamboo's potential as a sustainable material.

2.1.2. Results

- The mechanical properties of bamboo depend on various factors like species, age, soil, wall thickness, internode distance, moisture content and other environmental factors;
- Studies have shown that the fracture toughness of bamboo varies across its structure, with the outer region having higher fracture toughness due to more fibers, while the fracture toughness decreases towards the inner surface.
- The impact strength of bamboo depends on factors like thickness, position, and preparation method,
- Reformed bamboo has improved mechanical properties as compared to natural bamboo.
- Moisture content significantly affects the mechanical properties of bamboo;
- Bamboo aged 3 to 7 years shows optimal properties;

2.2. Case Study II

Mechanical properties of different bamboo species by Dinie Awalluddin, Mohd Azreen Mohd Ariffin, Mohd Hanim Osman, Mohd Warid Hussin, Mohamed A. Ismail, Han-Seung Lee, and Nor Hasanah Abdul Shukor Lim1. [6]

This paper deals with the mechanical properties of bamboo, which is available mainly in Malaysia. The tests have been conducted on 4 prevalent species viz. Bambusa Vulgaris, Dendrocalamus Asper, Schizostachyum Grande, and Gigantochloa Scortechinii.

Mechanical properties of all 4 bamboo species were tested for moisture content, compressive and tensile strength and their mutual relationship.

Mechanical testing was carried out in various parts of the bamboo pole along the culm of 4 specified bamboo species to examine their compressive and tensile strength differences. All the poles used for the testing purposes were duly treated. These bamboo species' strength development and moisture content were also monitored at a five-month interval.

2.2.1. Objectives

- To evaluate the potential of bamboo as a construction material through compression, tensile, and moisture content tests to determine its mechanical properties and suitability for various applications
- To investigate the impact of moisture content on the compressive strength of different species over a period of five months.
- To compare the mechanical properties of 4 commonly prevalent bamboo species in the region and identify the species with the highest compression and tensile strength
- To examine the durability of bamboo structures based on species and age ranges to determine their design life and suitability for heavy-duty applications, aiming to provide insights into the long-term performance of bamboo in construction.

2.2.1. Results

- Bamboo is one of the most suitable sustainable construction materials.
- Bambusa Vulgaris shows the highest compressive strength among 4 species.
- Out of 4 species tested, Dendrocalamus Asper is found to have excellent tensile strength performance.
- Compressive strength is found to be inversely proportional to moisture content in the bamboo, and it is observed over a period of 5 months.
- Gigantochloa Scortechinii and Schizostachyum Grande follow in strength rankings.
- Bamboo can substitute structural timber, aiding environmental preservation.

2.3. Case Study III

Economic analysis of bamboo cultivation in Nagpur district by N. V. Shende, U. T. Dangore, N. T. Bagde and V. J. Rathod [7].

This paper analyzes bamboo cultivation costs and returns. The study is conducted in the Nagpur district of Maharashtra state, during 2019-2020. The average family size of selected cultivators is five members. The total land holding per farmer is 4.60 hectares, with a cropping intensity of 112.74%. Bamboo cultivation area constitutes 40.59% of the total land area and requires 478.36 mandays. The total forest area in Maharashtra is 947,992 hectares; out of that, bamboo plantation is 474,915 hectares.

2.3.1. Objectives

- To analyze the cost and returns of bamboo cultivation.
- To evaluate the profitability of bamboo farming.
- To assess the Internal Rate of Return (IRR) for bamboo.
- To determine the Benefit-Cost (B-C) ratio of bamboo cultivation.

2.3.2. Conclusion

- Bamboo cultivation significantly contributes to India's economy, with initiatives like the National Bamboo Mission supporting its growth.
- India has a large area under bamboo cultivation, making

it the second-largest producer of bamboo in the world after China.

- Bamboo is considered a 'poor man's timber' and has multiple uses, contributing to the livelihood of rural populations and the national economy.
- Bamboo cultivation enhances farmers' income and ecology.
- Bamboo contributes significantly to India's socio-economic development.
- Internal Rate of Return (IRR) indicates long-term profitability. Cost-Benefit ratio aids in project selection for bamboo cultivation.
- Government initiatives support bamboo industry growth and sustainability.

2.3.3. Results

- Bamboo cultivation is profitable with positive NPW.
- The B-C ratio of bamboo cultivation is 1:1.91.
- IRR for bamboo cultivation exceeds 24.50%.
- Bamboo area in Maharashtra increased to 4486 hectares by 2017-18.
- Bamboo biomass per hectare increased from 400 to 644 tons.
- Gross returns per hectare rose from Rs. 313286 to Rs. 504551.

3. Materials and Methods

For the comparative study, the materials used are pipes and selected bamboos of the Vidarbha region of Maharashtra. The study focuses on the physical attributes of selected pipes and bamboo poles.

3.1. Pipes

Generally, pipe stands for all the hollow tubular sections in the construction industry, uniform throughout the length. They can be square, rectangular, or circular, irrespective of the material, such as MS, SS, AA, CPVC, HDPE, etc. However, in space grid structures, the pipes used are either made of mild steel or stainless steel. Thus, the selection of pipes for the comparative study is limited to hollow tubular cylindrical (all through uniform dia.) sections made out of mild steel, stainless steel and aluminium alloy (Figure 2).

Fig. 2 Factory-Made Metal Pipes & Nature-Grown Bamboo Poles

3.2. Bamboo Poles

In the construction industry, bamboos are commonly used for scaffolding. Bamboo's harvested culms are green (freshly harvested, high in moisture content) or dry (low in moisture content) and seasoned, commonly known as bamboo poles.

Although the plantation of bamboo, on government or private land, more or less, is found in all the states of India, here, for the sake of comparative study, the selection is limited to the bamboo from the Vidarbha region of Maharashtra, India. The species of bamboo that are identified for the study are i). Bambusa bambos, ii). Dendrocalamus Strictus, iii). Bambusa balcoa and iv). Oxytenenthara stocksii

3.3. Machines Used

The machines used are i). cut off Saw with a 14” inch dia. cutting wheel to cut selected bamboo poles and pipes, and ii). an angle grinder with 4” inch dia grinding wheel to fine finish the edges of cut pieces.

4. Research Methodology

Keeping in view the design, fabrication and assembly of hybrid bamboo space structures, the methodology adopted is as follows.

4.1. Selection Process

Bamboo is selected so that two species of bamboo have a bigger outer diameter and two species of bamboo have a relatively lesser outer diameter. The bigger dia. bamboos are ‘Bambusa Bambos’ and ‘Bambusa Balcoa’ with outer dia. in the range of 75 mm plus, whereas ‘Dendrocalamus Strictus’ and ‘Oxytenenthara stocksii’ have outer dia. in the range of 38 mm approximately (Figure 3).

Fig. 3 Thick and thin diameter common Bamboos of Vidarbha

Another consideration when selecting bamboo for structural purposes is the wall thickness of bamboo. With a simple formula, the wall thickness of bamboo can be deduced. Outer dia. minus inner dia. equals wall thickness. The significance of wall thickness lies in the fact that the load-carrying (transferring) capacity of bamboo is directly proportional to its wall thickness [8]. It implies that the greater the wall thickness, the higher the load-carrying (transferring) capacity and the lesser the wall thickness, the lesser the load-carrying (transferring) capacity (Figure 4).

While selecting factory-made pipes such as MS pipe, SS pipe and AA pipe, consideration is done that the outer dia. is 25 mm to 38 mm and the wall thickness is nearly 05 to 10 mm. The length of all the bamboo and pipes is 3 meters for the purpose of the study.

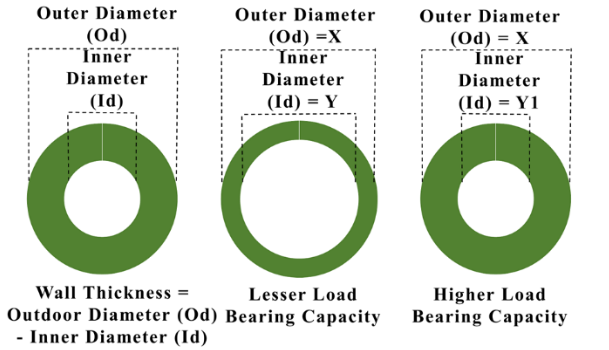

Fig. 4 Formula to deduce wall thickness of bamboo and showing that load carrying capacity of bamboo is directly proportional to its wall thickness

4.1.1. Special Considerations for Bamboo

Bamboo being a nature-grown pipe, special considerations while selecting bamboo for the physical comparative study are as follows:

For structural purposes, bamboo of the age of 4 years is termed as ripe and mature because inherent sap content in the mature bamboo stabilises in a manner that cross-sectional dimensions of bamboo, when cut, do not change considerably [9]. The inherent fibrous structure of bamboo becomes ripe and mature enough to take (transfer) loads of the structural type. Nature-grown pipes (bamboo) are never as straight as factory-made pipes. Instead, relatively straight or slightly curved bamboos are preferred. Bamboos with intermediate multiple bends (curves) are known as crooked bamboos and are not considered for the purpose of study and structural applications. Mature culms of identified species, for study purposes, are selected randomly from the identified bamboo groves from three different plots of bamboo plantations in the Vidarbha region. Three poles of each species, Bambusa Bambos, Bambusa Balcoa, Dendrocalamus Strictus, and Oxytenenthara stocksii, are taken (Figure 5).

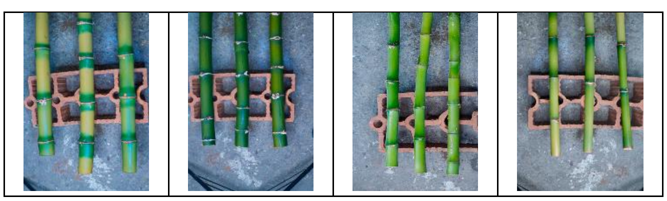

Fig. 5 Three poles of each species, bambusa bambos, bambusa balcoa, dendrocalamus strictus, oxytenenthara stocksii

Various IS Codes have been referred to carry out the present study. These are IS 6874- 2008, which describes the Method of Testing for Bamboo; IS Code 15912- 2018, which describes the Code of Practice for Structural Design Using Bamboo; and IS Code 9096- 2006, which describes the method of preservation of Bamboo for Structural Purposes.

4.1.2. Special Considerations for Pipe

MS, SS and AA pipes being factory-made, considerations while selecting pipes for the study are as follows:

Hollow tubular pipes of MS, SS and AA are available in the (Vidarbha) market of no. of brands like TATA, Jindal, Venus Pipes and Tubes, Hindalco, etc.

The quality and specification of branded pipes remain the same across the market, as they are manufactured per the given IS Code. Thus, unlike bamboo, just a single pipe is chosen randomly from the batch/ stock. One pipe of each of the Grade A pipes is taken for the study.

Various IS Codes related to Steel and Aluminium Pipes have been referred to carry out the present study. IS 3601-2006 describes the standards for Steel Tubes for Mechanical and General Engineering Purposes, IS 17875- 2022 describes the standards for Stainless Steel Seamless Pipes and Tubes for General Service, and IS 1285- 2002 describes the standards for Wrought Aluminium and Aluminium Alloys - Extruded Round Tube and Hollow Sections for General Engineering Purposes.

4.2. Sampling Process

Bamboo being a nature-grown pipe, unlike a factory-made pipe. The lower end of bamboo and pipe is termed the base end, and the upper end is called the top end. The process of samples making the comparative physical assessment is as follows:

- The selected bamboos are taken to the cutoff machine. From the base end and top end, four-inch-long pieces are cut.
- Three samples, from the base and top ends, are taken from three poles of each species (Figure 6).

Fig. 6 Single pipe of each type, i.e. MS, SS, AA, and Three samples, from base and top ends, from three poles, of each species

- From the selected MS, SS and AA pipes, one sample from the base and top end, is taken from each type of pipe.
- Three-meter-long bamboo and pipes were selected for the purpose of comparative study.

5. Results

After collecting the samples, physical data and physical attributes of the same have been noted and analysed, as under

5.1. Physical Data

5.1.1. Metal Pipes

Outer Dia. (OD), Inner Dia. (ID) and Wall Thickness (WT) of all pipes have been noted and graphically depicted in Figure 7 and Table 1.

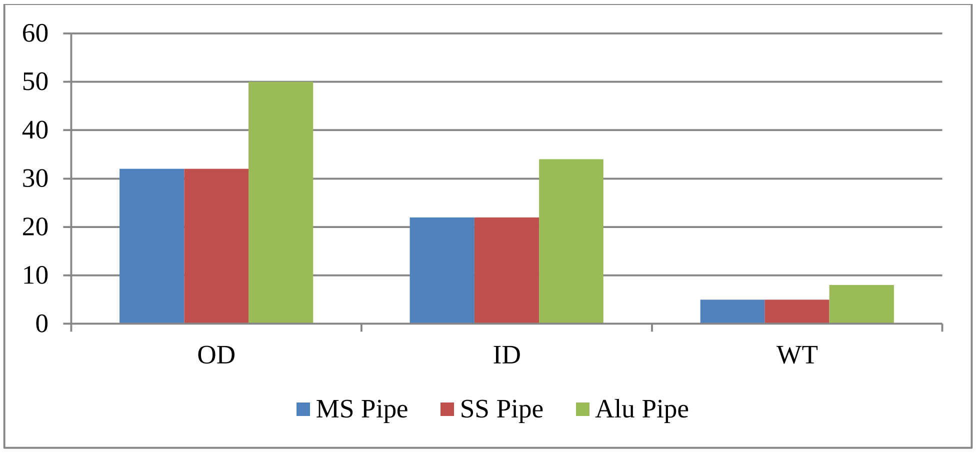

Fig. 7 Physical data of metal pipes, i.e. MS, SS, AA,

Note: In the selected metal pipes, OD, ID, and WT at the base and top are the same

Table 1. Physical data of bamboo pole samples

Physical Data of Bamboo Poles Samples (in mm)									
Sample	**Particular**	**B Bamboos**		**B Balcua**		**D. Strictus**		**O Stocksii**	
		Base	**Top**	**Base**	**Top**	**Base**	**Top**	**Base**	**Top**
1	OD	106	80	82	62	60	46	38	26
	ID	30	24	26	20	20	14	0	2
	WT	38	28	28	21	20	16	19	12
2	OD	100	74	84	64	64	50	40	26
	ID	28	22	28	22	22	16	0	2
	WT	36	26	28	21	21	17	20	12
3	OD	110	84	78	58	58	44	34	26
	ID	32	26	24	18	18	12	0	2
	WT	39	29	27	20	20	16	17	12
Mean	OD	105	79	81	61	61	47	37	26
	ID	30	24	26	20	20	14	0	2
	WT	38	28	28	21	20	16	19	12

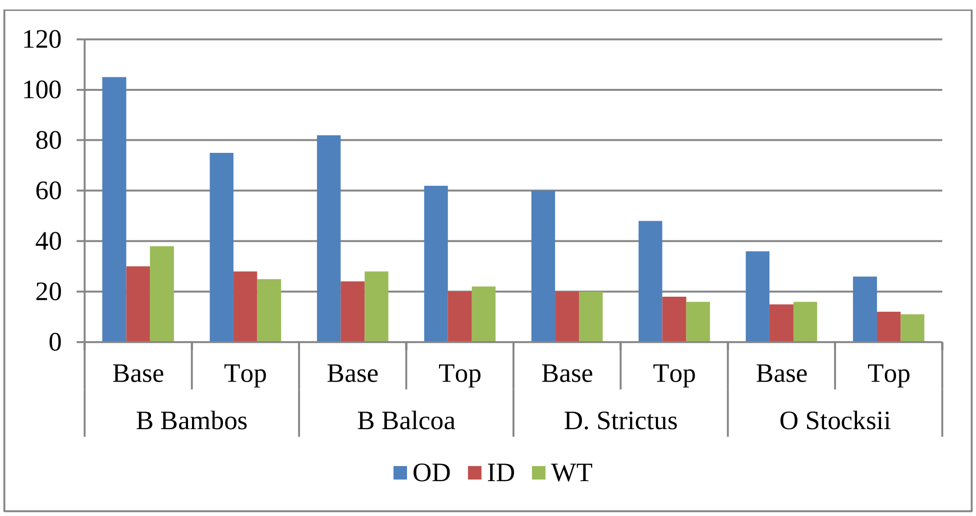

Fig. 8 Mean Physical Data of Bamboo Poles of 4 Species

5.1.2. Bamboo Poles

The physical data related to the base and top of bamboo poles, 3 samples each, of all the 4 species is tabulated below in Table 1, and the graphical representation of its mean values is given in Figure 8.

5.2. Physical Attributes

After studying the physical data of factory-made metal pipes and nature-grown pipes (bamboo poles), certain peculiar attributes of these materials have been observed and discussed below.

5.2.1. Physical Attributes of Metal Pipes

Being factory-made, the physical attributes of metal pipes (struts) are as follows:

- Section: hollow tubular
- Section uniformity: complete uniformity across the section at all points
- Wall thickness: 05 to 10 mm
- Thickness uniformity: complete uniformity of wall thickness across the length at all the points
- Length: 3 meters
- Coating: GI on MS, none on SS and AA
- Bend along length: none
- Internodes in between: none

5.2.2. Physical Attributes of Nature Grown Pipes

Being Nature grown, the physical attributes of selected bamboo poles are as follows:

- Culm: In a bamboo grove, the bamboos are known as culms. A culm attains its full growth within a period of 2-3 months. Also, the culm tapper towards the top to handle the stresses while swaying on high winds. The wall thickness goes on thinning towards the top to reduce the weight [9].
- Cross Section: Upon cutting the (transverse) cross section in a culm, one can see the details in Figure 9. The cross-section is filled with dots, which are denser near the external surface and gradually thinning towards the inner side. They are actually the bundles of fibres that are the ‘backbone’ of the culm. The lowest quarter of the culm has the highest density of fibres, which gradually thinned towards the top along the length.

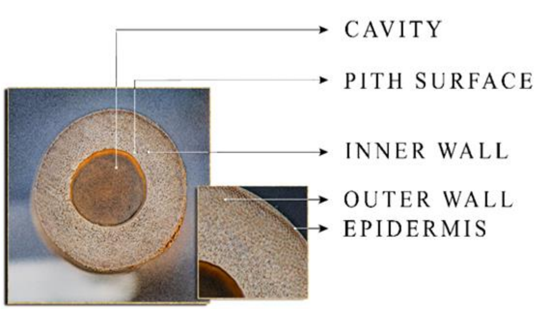

Fig. 9 Cross section of bamboo pole

- Skin: Unlike trees, bamboo doesn’t have bark. They have thin, apparently delicate-looking external skin that protects the culm from the weathering elements, animals and insects. Fortified by silica, the skin has a glass-like gloss and waxy smoothness, which protect the culm from hazards and pests. The skin is also known as the epidermis of culm.
- Veins: All the fibres and veins in bamboo culm run linearly, except at nodes. This characteristic is very helpful while working with bamboo and pushing sap or treatment liquids through it. Even a strand of human hair can be made to pass through a piece of bamboo vein rather easily.
- Nodes: Along the length of a culm, circumferential rings, at regular intervals, are the nodes of bamboo. At the node, a strong diaphragm connects the inside of the culm. The diaphragm strengthens the nature-grown pipe (culm) and acts as an effective counter structure to take bending stresses induced by the cantilever self-load and that of branches and also the wind load. Nodes are a characteristic feature of a bamboo culm [10]. It can be understood with the help of Figure 10.

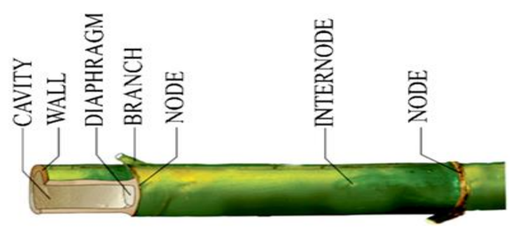

Fig. 10 Longitudinal Sectional View of Bamboo

5.3. Comparative Study

A comparative study has been done after studying the physical data and attributes of Metal Pipes and Bamboo poles. A comparison of physical data related to Outer Diameter (OD), Inner Diameter (ID) and Wall Thickness (WT) is shown in Figure 11.

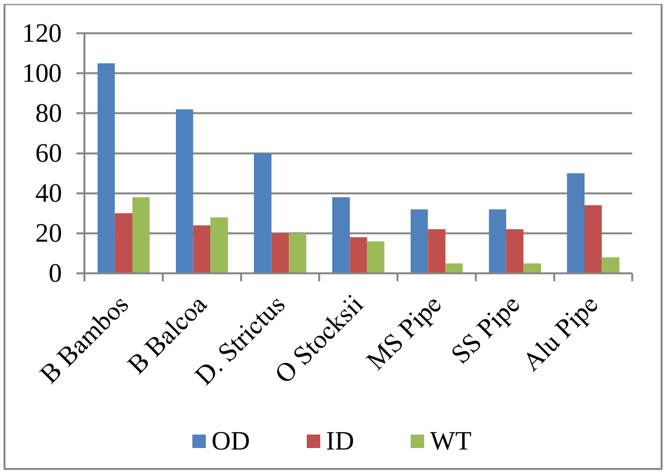

Fig. 11 Comparative of Selected Bamboo Poles and Metal Pipes

6. Uniqueness of Bamboo in Vidrabha Region

There are five regions in the state of Maharashtra, namely: i). Vidarbha, ii). Marathwada, iii). Western Maharashtra, iv). Northern Maharashtra, v). Konkan. Vidarbha region forms the Eastern part of Maharashtra having 11 districts.

6.1. Geography and Climate of Vidarbha Region

Vidarbha is the border region of Maharashtra as in its North lies Madhya Pradesh, in its East lies Chhattisgarh and, in the South, lies Telangana state [11]. Geographically, the Vidarbha region is an important of Central India. It has a tropical dry climate with the following characteristics:

- Temperature: The region experiences extremely hot summers from March to June, with May being the hottest month. The average high temperature in May is 45.7°C, and the average low temperature in December is 12.6°C.
- Rainfall: The region receives most of its rainfall during the monsoon season, which usually begins in July and lasts until September. The highest recorded daily rainfall was 304 mm on July 14, 1994.
- Seasons: The region has a dry season for most of the year, with winters lasting from November to February.

6.2. Sustainability of Bamboo in Vidarbha Region

Maharashtra Bamboo Development Board (MBDB) has its headquarters in Nagpur, region of Vidarbha. It has the mandate and responsibility to promote bamboo plantations on private and government lands in the state of Maharashtra. Although the promotion of bamboo plantations is a year-round activity but, it’s highest in the months of June and July, as the pre-monsoon arrives in mid-June. The report of ‘Assessment of Bamboo Plantation in 2020, Promoted by MBDB’ was prepared by a third party, an independent non-government organisation, Ms SEVAK Maharashtra State, Pune [12]. The following pie diagram shows the sustainability of Bamboo in various regions of Maharashtra (Figure 12).

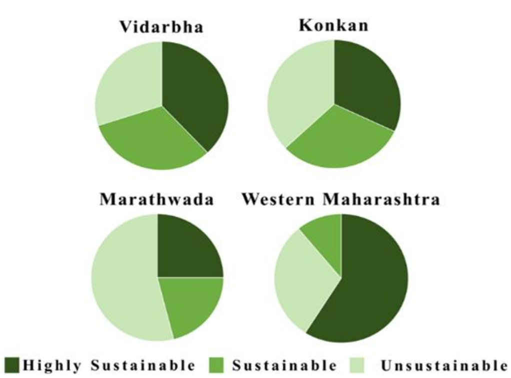

Fig. 12 Sustainability of Bamboo in Various Regions of Maharashtra

It is evident from the above pie diagram that the Vidarbha region is the second most conducive region in Maharashtra for the sustainable growth of bamboo plantations.

6.3. Specific Climatic Conditions Contribute to Uniqueness of Bamboos of Vidarbha

As per the Köppen climate classification, there are five main climate groups, namely: A (tropical), B (arid), C (temperate), D (continental), and E (polar) [13]. Interestingly, the geographical location of India on the globe is such that all five climate groups are found in India, spanning from Ladakh to Kanyakumari and from Gujrat, Rajasthan to Manipur. The bamboo species commonly found in the Vidarbha region are Bambusa bamboos, Dendrocalamus Strictus, Bambusa Balcoa, Oxytenenthara stocksii, table Bambusa Tulda. Interestingly, the same species are found in neighbouring and far-off regions of other states in India, too. It’s a known fact that the quality of, for example, Bambusa bamboos and Dendrocalamus Strictus found in the regions of Assam and Vidarbha varies considerably. Here lies the uniqueness that the climatic conditions of the Vidarbha region impart to the bamboos of Vidarbha

- Due to the tropical and humid climate of Assam, bamboo of the same species have relatively lesser wall thickness, whereas due to the tropical and dry climate of Vidarbha, the same bamboo species retain wetness and generate more wall thickness.
- Due to the same climatic reasons, to retain wetness, the bamboos of the Vidarbha region generate a thicker epidermis (the armour, the outer skin) than that of the regions of Assam.
- Climatic conditions of Vidarbha also contribute to the density of bamboo poles. Manufacturing Units of Assam and Vidarbha, engaged in the making of bamboo sticks and slats, shared their experiences that Bambusa bamboos and Bambusa Balcoa of Assam (tropical and humid) are relatively softer than that of Vidarbha (tropical and dry) region, which are relatively hard. They said that while working on the bamboo of Vidarbha, the wear and tear of their cutting tools increased due to greater abrasion compared to the bamboo of the Assam region, even when the bamboo species were the same.

Hence, specific climatic conditions of Vidarbha contribute to the uniqueness of bamboo in the way that they generate i). more wall thickness, ii). thicker outer skin, and iii). higher density.

It has been observed that even if the origin of the seed or sapling of a plant is the same, region-wise changes in soil and climate impact the quality of crop and harvest [14].

7. Discussion

The uniqueness of a space grid structure is that it provides the interplay of forces, and the struts are either under tensile forces or compression forces. Shear forces are absent. In hybrid bamboo space grid structures, mechanical strength implies that tensile and compression forces are under consideration.

7.1. Salient Features of the Study

Comparative physical study of metal struts (factory-made pipes) and selected bamboos (nature-grown pipes) of the Vidarbha region of Maharashtra pave the way to strategise the strength augmentation of Vidarbha bamboo poles. Salient features of the comparative study are the following:

- unlike a pipe, a bamboo pole, along its length, keeps on tapering, i.e. the outer dia. gradually keeps on reducing
- the wall thickness of a bamboo pole gradually keeps on reducing along its length, unlike a pipe
- unlike a pipe, the density of bamboo pole gradually keeps on decreasing along its length
- density varies across its cross-section in a bamboo pole, unlike a pipe
- bamboo pole can never be as straight as a pipe
- bamboo pole has nodes along its length, unlike a pipe

Also, the study was done to understand the contribution of the region's climatic conditions to imparting uniqueness to the bamboo of Vidarbha. Salient points are that bamboos of Vidarbha have relatively:

- higher wall thickness
- thicker epidermis, i.e. outer skin
- more density, i.e. weightier

7.2 Strategizing to Augment the Mechanical Strength of Bamboo

While strategising to augment the mechanical strength of factory-made metal pipe, the following attributes are taken care of;

- thickness of the cross-section, i.e. wall thickness
- density of the cross-section
- the alloy composition of the pipe
- surface jacketing of the circumference of the pipe

Interestingly, the above-mentioned points pave the way to strategise the augmentation of mechanical strength of Nature grown pipe, i.e. bamboo poles, as under:

- increment of wall thickness of bamboo
- increment of the density of bamboo
- change in the composition of a cross-section of bamboo
- length-wise, circumferential jacketing of bamboo

Based on the above leads, augmentation of the mechanical strength of bamboo can be strategised through various measures and methods.

7.3. Proposed Methods of Strength Augmentation of Bamboo

Keeping in view the above-mentioned salient points of study and the strategies for strength augmentation, given below are the proposed methods for strength augmentation of Bamboo:

7.3.1. Increment of Wall Thickness

Once the bamboo culm is mature at four years of age, its wall thickness doesn't change [15]. Thus, an increment of the wall thickness of harvested bamboo poles can be an effective measure. It can be done by identifying and applying a thick polymer or resin coating on the epidermis (outer skin) of the bamboo pole (Figure 13).

Fig. 13 Strength Augmentation by Increasing Wall Thickness

7.3.2. Increment of Density

In the brick-making industry, it's a well-known fact that the density of extruded bricks or blocks is higher than moulded bricks or blocks [16]. An increase in the density of bamboo poles can be a strategy for strength augmentation with the help of sap displacement under vacuum pressure with appropriate chemicals and solvents (Figure 14).

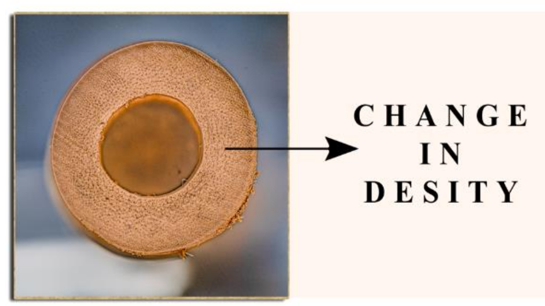

Fig. 14 Strength Augmentation by Increasing Density

7.3.3. Change in Composition of Cross Section

While doing treatment as per IS 9096-2006 (Preservation of Bamboos for Structural Purposes), sap displacement under vacuum pressure method is a common practice.

[17] The same strategy for strength augmentation can be applied to change the composition of cross-sections of bamboo poles.

It can be done by identifying the appropriate water or solvent-soluble, non-leachable chemicals that can be displaced into the porosity of the bamboo pole under pressure and react with the inherent carbohydrates of the bamboo pole. Later, while shade drying, the chemical gets fixed and changes the composition of the bamboo pole (Figure 15).

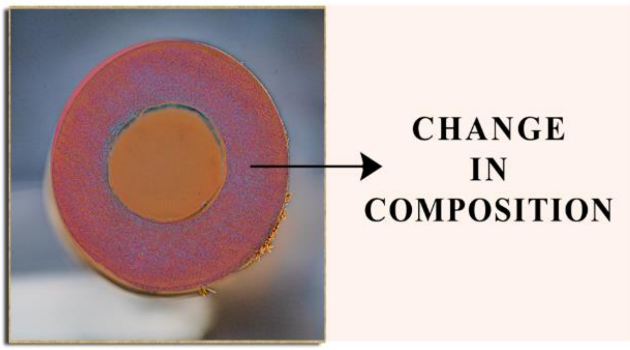

Fig. 15 Strength Augmentation by Change in Composition

7.3.4. Pith Jacketing

Jacketing of inner circumference is commonly done in the construction industry while boring for fluids like water, oil, gas, etc. The same strategy of strength augmentation can be applied to bamboo poles. For that, through and through, puncturing the intermediate diaphragms is done and then jacketing the pith (inner circumference). It can be done by inserting (forced sliding), say, a polymer or a metal pipe of appropriate dia. inside the bamboo pole (Figure 16).

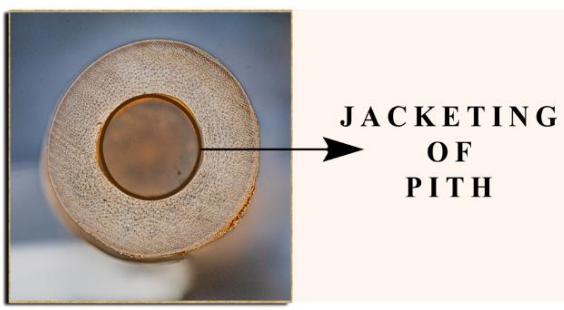

Fig. 16 Strength Augmentation by Jacketing of Pith

7.3.5. Epidermis Jacketing

Jacketing of columns and beams is a common strategy of strength augmentation in the construction industry. [18] The same strategy can be applied to bamboo poles by jacketing the epidermis (outer skin) of bamboo poles (Figure 17). It can be done by applying:

- Fibre Reinforced Plastic (FRP) coating
- carbon fibre mesh wrapping
- heat-induced polymer wrapping

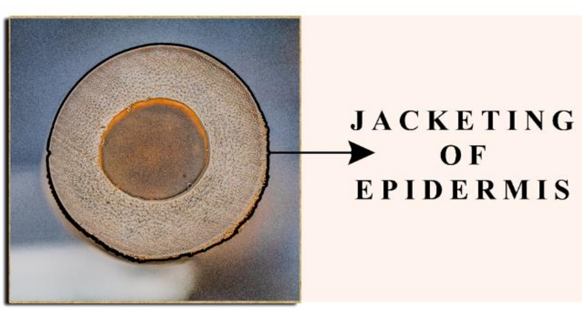

Fig. 17 Strength Augmentation by Jacketing of Epidermis

7.4. Applicability of Proposed Methods for Selected Bamboos of Vidarbha

The above-mentioned strategies of strength augmentation are applicable to most species of bamboo. In particular, for the selected bamboos of Vidarbha, the strategies are applicable by taking into consideration their characteristics i.e. i). outer dia., inner dia. ii) wall thickness iii). density iv). node types v). inter-nodal distance.

The four selected bamboos of Vidarbha are: i). Bambusa Bambos, ii). Bambusa Balcoa, iii). Dendrocalamus Strictus and iv). Oxytenenthara stocksii. Bambusa Bambos and Bambusa Balcoa are the species with outer dia. in the range of 70- 80mm plus at base; Dendrocalamus Strictus has outer dia. Approximately 50- 65mm plus at base, and Oxytenenthara stocksii has outer dia. in the range of 30- 40mm at base. Out of these four species, Oxytenenthara stocksii bamboo is such that, at the base, it has zero inner dia., i.e. at the base, it's like a solid bar, not a hollow pipe, unlike other species.

Hence, strength augmentation strategies can be identified and applied by considering the inherent characteristics of the selected bamboo of Vidarbha.

8. Conclusion

Eco-friendly hybrid versions of space grid structures are preferred by eco-conscious architects and engineers for certain spans and applications. In these hybrid space grid structures, it's very common that the metal pipes, i.e. struts, are replaced by bamboo poles, wholly or partially.

A comparative study of factory-made metal pipes and nature-grown pipes, i.e., bamboo poles, of the Vidarbha region is made for deeper insight. For the study, four bamboo species are chosen, viz. i). Bambusa Bambos, ii). Bambusa Balcoa, iii). Dendrocalamus Strictus and iv). Oxytenenthara stocksii. During the study, it was found that the peculiar tropical hot and dry geo-climate conditions of the Vidarbha region contribute to the uniqueness of bamboo in terms of its relatively higher i). Wall thickness, ii). Epidermis and iii). Density. Understanding the peculiarity of Vidarbha bamboo and the comparative study gives insight to strategising to augment the mechanical strength of bamboo poles, in general, and for hybrid bamboo space grid structures, in particular. The strategies discussed are, specifically, helpful in finding measures, methods, materials and processes to treat bamboo poles at par with their metal counterparts, not only just in hybrid bamboo space grid structures but in a wide range of structural applications in construction, architecture and product design.

8.1. Directions for Future Research

The extensive study and its significant conclusion give insight that can be considered for future research, is as follows:

The strategies for strength augmentation and the various measures and methods worked out during this research can act as the basis for a wide range of future research work. The present study is conducted with bamboo, devoid of any pest- and fungi-resistant treatment whatsoever. But, for future research, the effect of various kinds of treatments can be considered while strategising to augment the mechanical strength of bamboo. The present study is conducted with recently harvested bamboo. In future research, well-seasoned bamboo can be considered. With aging, hairline cracks appear on the surface of the bamboo, and some of those cracks later widen to affect the structural strength of the bamboo. Measures adopted to contain the development of such cracks can be considered in future research.

8.2. Limitations of the Present Study

Keeping in view the design, fabrication and assembly of hybrid bamboo space structures, the limitations of the study are as follows:

- The bamboo species selected are from the Vidarbha region of Maharashtra, India, only
- Bamboo taken are ripe and mature but not treated for pest resistance
- Pipes selected are in the range of 25mm to 38mm dia., only
- The study is limited to comparative analysis of physical properties only. Mechanical properties are not in the scope of the study.

8.3. Limitations of Using Bamboo

Although bamboo is a versatile material in the hands of architects, engineers and product designers yet, the limitations of bamboo need to be noted for its optimal application [19]. They are as under:

- Being a natural material, the cross-sectional dimensions of bamboo vary from pole to pole.
- Being a natural material, the straightness of bamboo can't be ascertained.
- Being a natural material, the impact of weather varies from pole to pole.
- The bamboo poles of the same species differ from region to region.

8.4. Environmental Impacts of Using Bamboo

Bamboo is a versatile engineering material. For many short- to medium-span, structural, and non-structural applications, bamboo can effectively replace RCC/ MS/ wood members. In view of this, the environmental impacts of using bamboo are as under:

- Bamboo, being not wood but grass, grows very fast. Unlike a tree, which, after cutting, takes almost 20 years to regrow, bamboo takes only 4 years to regrow and mature. Thus, it's a very fast replenishable resource
- The biomass of a bamboo grove is much higher than a tree's, making it a great carbon sink.
- The carbon sequestration capacity of bamboo is much higher than that of a tree, making it an excellent carbon dioxide sink.
- With a comparatively much higher green cover than that of the tree, the bamboo grove proves to be an effective heat sink.
- The carbon footprint of bamboo products is extremely low compared to similar wood, RCC, and steel products.
- Unlike trees, the bamboo groves clean the surface water around them, drastically reducing soil erosion and helping increase soil fertility.

With the above attributes, it's clear that the environmental impact of using bamboo is highly positive and beneficial to people and the Planet. That's the reason bamboo is a preferred material for sustainable development.

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