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Engineered Bamboo Structures: Development of High Capacity Fibre Reinforced Bamboo Composite Structural Members

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Abstract-- The increasing demand for construction materials has raised concerns regarding the environmental impacts associated with the production of conventional materials such as cement and steel. Bamboo, owing to its renewable nature, favourable strength-to-weight ratio, and rapid growth, offers significant potential as an alternative material for sustainable construction. However, its application in structural engineering is limited by variations in mechanical properties, relatively low stiffness, large deformations, and difficulties in developing reliable structural connections. The present research investigates the development and structural performance of Fibre-Reinforced Bamboo Composite (FRBC) elements for potential applications in building construction.

The experimental investigation focuses on the characterization of Dendrocalamus strictus, a commonly available bamboo species in India, through laboratory tests to determine its tensile, compressive, and shear strengths, along with its modulus of elasticity. Statistical evaluation of the experimental results is undertaken to establish characteristic material properties for structural analysis and design. A composite system is developed by integrating multiple bamboo culms using epoxy-based fibre adhesive and polypropylene fibres. In addition, a fibre–epoxy–aggregate composite, termed epoxycrete, is investigated for its potential application in the fabrication of structural joints.

The developed FRBC system is extended to beams and columns, which are experimentally evaluated under compression and flexural loading. Short-column tests are used to assess axial load capacity, while beam specimens are subjected to two-point loading to investigate their flexural behaviour and strain distribution. The experimental results indicate that the developed composite columns exhibit load capacities consistent with the proposed analytical formulations. The beam investigations demonstrate composite action in long-span specimens, whereas short beam specimens exhibit inadequate composite behaviour. Analytical formulations are also developed to predict the moment-resisting capacity of FRBC sections, with the predicted values showing good agreement with the experimental results.

The study establishes the potential of engineered bamboo composites as promising alternatives for sustainable and resource-efficient structural applications. The findings provide a basis for further research into structural connections, durability, serviceability, and the development of reliable design methodologies for bamboo-based building systems.

***Keywords*-- Bamboo composites, Fibre-Reinforced Bamboo Composite (FRBC), Dendrocalamus strictus, epoxycrete, structural elements, flexural behaviour, compressive strength, sustainable construction.**

I. INTRODUCTION

Since time immemorial, bamboo has been traditionally employed by humans for making articles of use in daily life, such as thermos flasks, chairs and tables, very strong ropes for mooring ships, hanging bridges and bamboo-based fibre ropes, especiallyin China and North East India. In fact, it has been used in making small houses. Despite the use of bamboo in various construction and household items, very few conclusive studies have been undertaken with respect to engineering analysis and design with computations based upon any scientific philosophy as based on the t heory of structural engineering. The problem partly lies in the availabilityof data on the mechanical properties of bamboo which maynot be relied upon. In the absence of a design philosophy, the structural capacity compared to a steel or reinforced concrete section used in construction cannot be easily estimated. This inhibits the use of bamboo as a structural material.

Secondly, bamboo being a product of nature, exhibits a large variation in its mechanical properties. Bamboo shoots are normally tapering (with its diameter continuously reducing), resulting in varying sectional capacity and properties along its length through varying wall thickness of culm. Bent and crooked bamboo are difficult to be employed for construction.

Thirdly, asingle bamboo shoot can grow into a tall slendermember along with leaves. In this condition, it is exposed to large stresses under high speed winds and storms. As the section modulus and inertia of a single bamboo culm are relativelylow, this section flexes and resists the forces caused by winds without failure, which indicates very high fibre strength.Although it is proven that bamboo fibres are relatively strong and have a high yield and ultimate stress values, comparing a single bamboo section to therequirementsof typical gross sectional capacities (in moment, shear and axial stress) of a real life structural element, it turns out to be quite inadequate.

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Hence, if bamboo is to find its place as a reliable construction material in the mainstream construction industry for structural uses just likesteel, reinforced cement concrete (RCC) and wood, the structural forms created usingbamboo must be reliable enough in strength and comparable to RCC, steel and wood in structural capacities to resist bending moment, shear and axial forces. At the same time, flexibility of a single bamboo culm must not create a scenario which prevents its use.

II. Research Motivation, Objectives And Scope

India, currently with a huge population of nearly 1.30 billion, is expected to witness substantial economic growth in the next decade. The government of India has coineda slogan "Housing for all by 2022" (www.pmindia.gov.in, "Housing for All by 2022" Mission- National Mission for Urban Housing dated 17th June, 2015, Union cabinet chaired by PM Narendra Modi). To meet the housing and permanent infrastructural need of the country in the near future, India needs an enormous quantum of resources in terms of steel, cement and naturally sourced construction materials in the next few decades coupled with huge investment to meet its expenditure on construction. India is currently ill equipped to undergo such a transformation in such a short period of time, with an added responsibility andpressure from the "world" to target sustainable construction as well.

The main targets for sustainable construction which India also needs to address are:

(a) Progress in construction related to innovation along with technology transformation to the overall Indian subcontinent for its needs.
(b) India (and the planet) needs to focus closely on environmental quality and construction material resource efficiency as well as on economic performance related to construction, ultimately targeting prosperity of the world without endangering the environment.
(c) Technical, aesthetic and contextual suitability of construction materials and their impact, indicating proficiency upon usage.

Keeping in mind the current and the near-future needs of the country for construction material resources availability with the above-mentioned constraints for sustainable construction, a possible feasible technology as an alternative natural construction material covering almost all the needs of material resource and sustainable construction can be rightly said to be "construction with bamboo".

The prime motivation and objectives behind the research work covered in this thesis is to develop a technologyto facilitate the use of bamboo in housing extensively all over India after successful tests, rolling out a proven technology to be implemented in construction to meet housing targets for the year 2022.

The extensive usage of bamboo in construction all over the country will ensure decreased usage of available construction materials like cement, steel and other resources and will result in abundantly available funds and construction materials (cement, steel) to be channelized into infrastructure development like highways, railways (such as bullet train tracks), airports and other major structure which demand availability of high capacity structural materials for heavy construction. Since bamboo is a natural vegetative material having a high strength value but low individual sectional capacity, it is difficult to build structural members using single bamboo culms to meet high capacity (strength) requirements, coupled with the inefficient design of a highly variable material with a suitable factor of safety.

This thesis aims at developing bamboo based composite sections (prismatic) endowed with high structural capacity, commensurate with modern frame type structural construction. For this purpose, multiple bamboo culms are integrated into a composite element using suitable adhesive/bonding agents with fibres as a binder reinforcement. The main expected contributions of this research are to develop beam and column composites (including joints) of high structural capacity, based upon its allowable tensile and compressive strength validated by laboratory tests. The design philosophy/methodology emerging from this thesis will make a significant contribution to high capacity bamboo structural design and theirfuture developments and its utilization in practice.

III. State-Of-The Artin Research Related To Bamboo For Structural Applications

Currently, bamboo is used primarily as a supplement in building or as a decorative element for fencing, fountains, grates and gutters, largely due to the shortage of quality timber. Traditionally, bamboo has been used for structural applications such as building houses, hanging rope bridges and other structures. However, it has neither been systematically tested for structural use nor designed considering the rigorous science of structural engineering.

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Further more, a lot of effort needs to be expended in mechanical testing to determine the material properties of bamboo, such as the Young's modulus of elasticity *(E),* tensile strength

(σ_t), compressive strength(σ_c), flexural strength(σ_b) and shear strength(τ). This chapter

covers a brief review of literature concerning material properties of bamboo and its use as a structural element, both traditional and modern, based on rigorous engineering.

IV. Bamboo Species Found In India

India has an abundance of bamboo with over 100 species which are native to India. (Choudhury etal., 2012) reported 136 species of bamboos occurring in India. 58 species of bamboo belonging to ten genera are distributed in the north eastern states of India alone. A few of them are solid but the vast majority are hollow in nature of the 20-bamboo species that have been systematically tested so far, 16 are recommended for structural use. The key

physical and mechanical properties of the 16 key species are summarized in Table 2.1 and 2.2 for air-dry and green conditions respectively National Building Code (NBC) 2005. NBC (2005) recommends that matured bamboo of at least four years of age is suitable forstructural use. It should preferablybe used at least six weeks after felling. Bamboo should be properly treated in accordance with IS 9096 (2009). Solid or hollow bamboo culms with wall thickness larger than one centimetre, having closely spaced nodes are considered suitable for structural purposes.

The 16 species of bamboo recommended for structural applications are classified into three groups A, B and C on the basis of their mechanical related properties, namely, the modulus of elasticity *(E)* in bending and the modulus of rupture *(R)* in green condition, as listed in Table 2.3. For structural use in piles and mining components, an additional criterion of compressive strength is also considered for classification. The limits in the ultimate strength values of these groups typically correspond to the spread of properties observed in structural timber. Here, group *"A"* possesses the maximum strength property, *"B"* the medium and *"C"* the least. The forthcoming sections of the chapter cover a comprehensive review of the literature organised along various structural engineering aspects.

V. Bamboo Joints

Traditionally, several jointing methods involving bamboo have been in use for a long time. Most bamboo joints are susceptible to crushing at the open ends and show a splitting tendency caused by variation in diameter, wall thickness and straightness. These issues need to be taken into account while designing and detailing any connections involving bamboo culms. Preferably, the joints should be designed to include force transmission in aprerequisite manner so that the load capacity and the predictable deformations are within the prescribed limits and specific geometry/load directions. Traditional jointing methods for bamboo revolve around lashing or tying the culms by rope or string with or without pegs or dowels. Though such joints lack stiffness and they have low efficiency, they have served mankind for generations in traditional bamboo structures of tribals. Figs. 2.1 to 2.4 showsome typical 2D/3D bamboo joints.

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(a) (b)

Fig.2.1: Typical bamboo connections
(a)A 3D connection without any plate orbolt
(b) Bamboo connections involving steel plates and bolts



Fig.2.2: Some typical bamboo joints compiled byJanssen (2000)

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Fig.2.3: Jointing of bamboo culmsusing epoxy and fibre



Fig.2.4: Typical bamboo joint involving U shaped plate, eyebolts and hexagonal bolts (Kushwaha, 2012)

Ingeneral, bamboo joints can be classified into the following categories.

(i) Lengthening joints (end jointing): In such joints, the end of one piece of bamboo is made to overlap with that of the other axially and the two are suitably fastened, in full lapping or half lapping, as shown in Fig. 2.5. Full section culms are overlapped by at least one internode and tied together in two or three places. The joint's efficiency could be further improved by using bamboo or hardwood dowels.

(ii) Butt joints: In this type of joint, bamboo culms of equal diameter are butted end to end, inter-connected by means of side plates, as shown in Fig. 2.6. The side plates follow the current use of bamboo culms, as shown in Fig. 2.6(b).

(iii) Sleeve and insert joint: Short lengths of bamboos of appropriate diameter may be used either externally or internally to join two bamboo culms together, as shown in Fig. 2.7.

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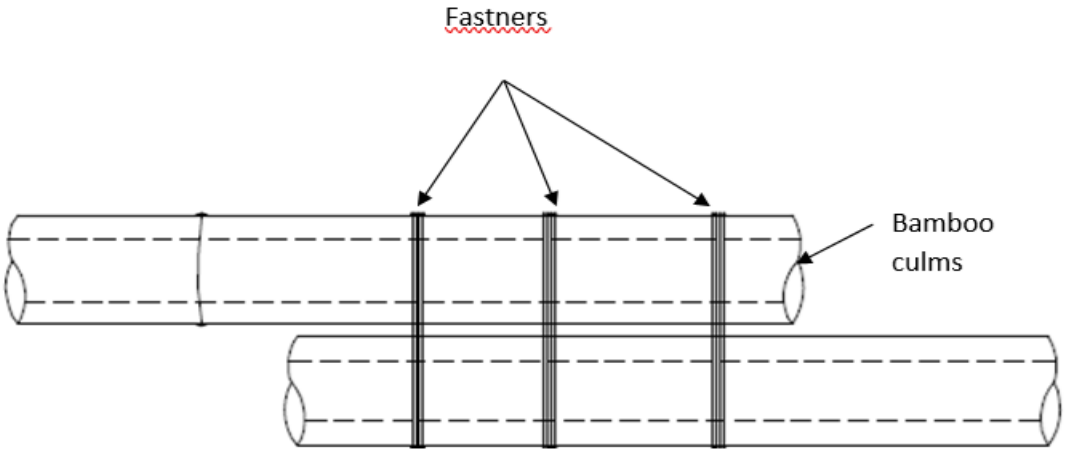


Fig.2.5: Lengthening joints (end jointing)

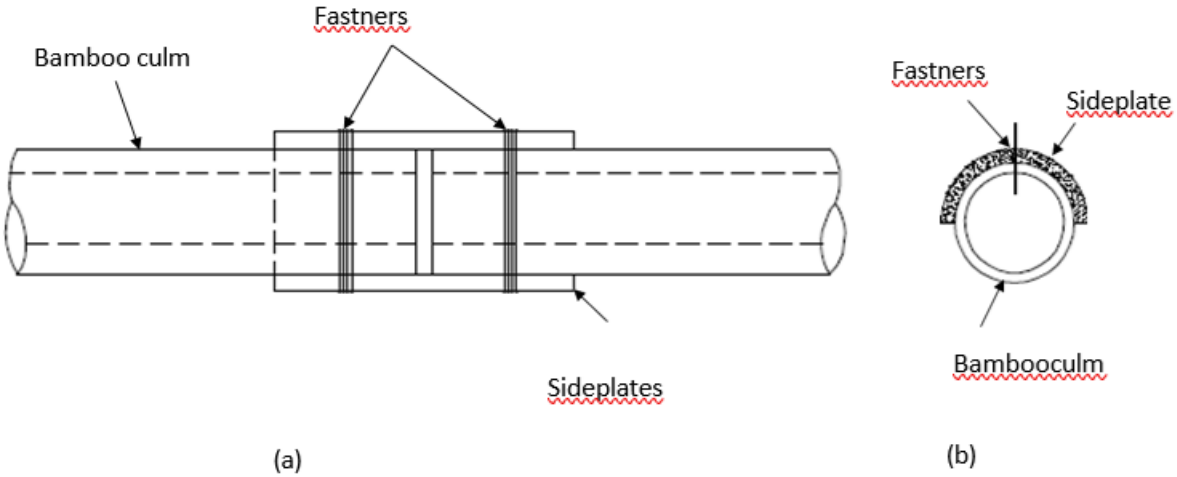


Fig.2.6: Bamboo buttjoint withside plates (a) Frontview (b) Sideview

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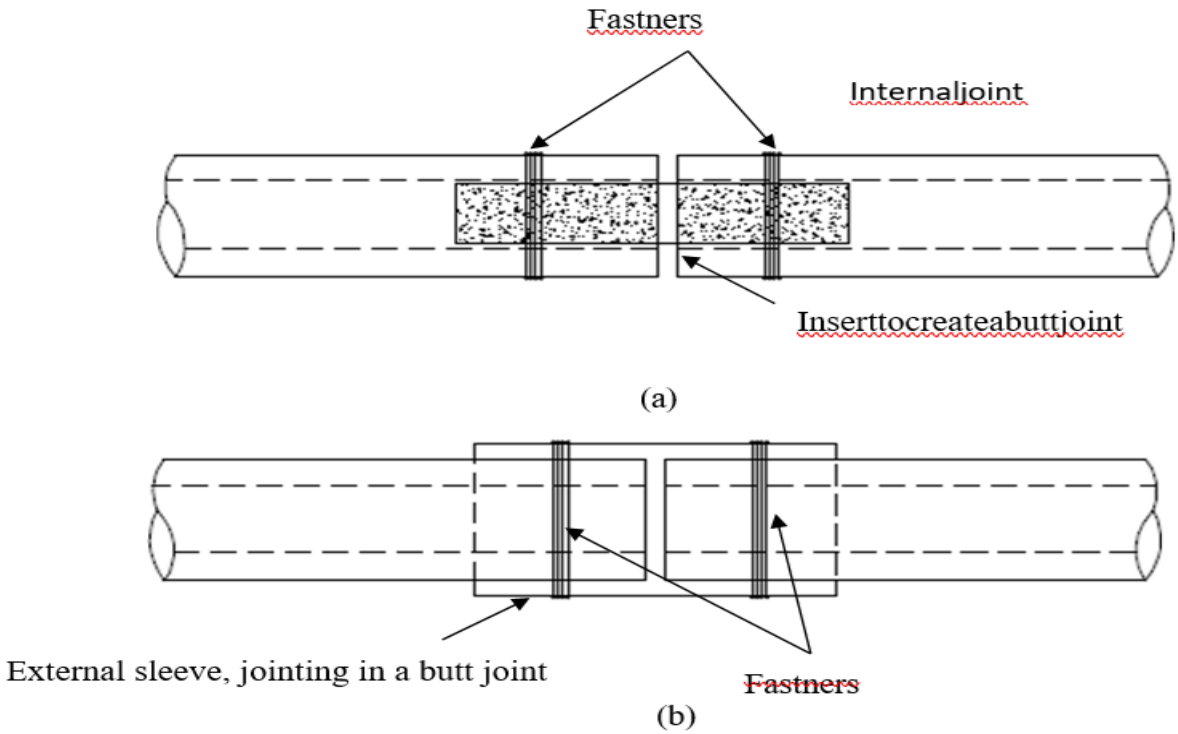


Fig.2.7: Sleeve and insert joints (a) Internalinsert (b) Externalsleeve

(iv) Scarf joint: A scarf joint is formed by cutting a sloping plane 1 in 4 to 6 on opposite sides from the ends of two similar diameter bamboo culms to be joined. They shall be lapped to form a continuous piece and the assembly suitably fastened by means of lashings or glued as shown inFig. 2.8.

(v) Bearing joints: For members which either bear against the other or cross each other or transfer the loads at an angle other than parallel to orthogonal axes bearing joints are formed, as shown in Fig. 2.9. However, making these joints requires a high level of skill since the surfaces need to be accurately finished.

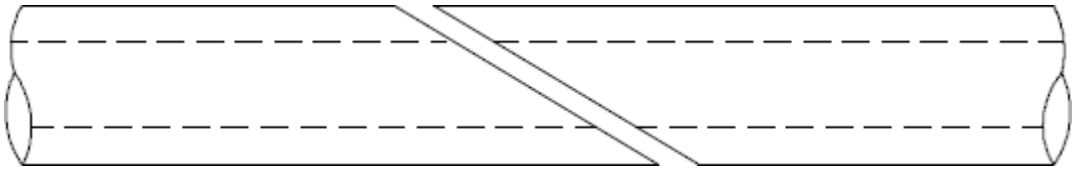


Fig.2.8: Scarf joint

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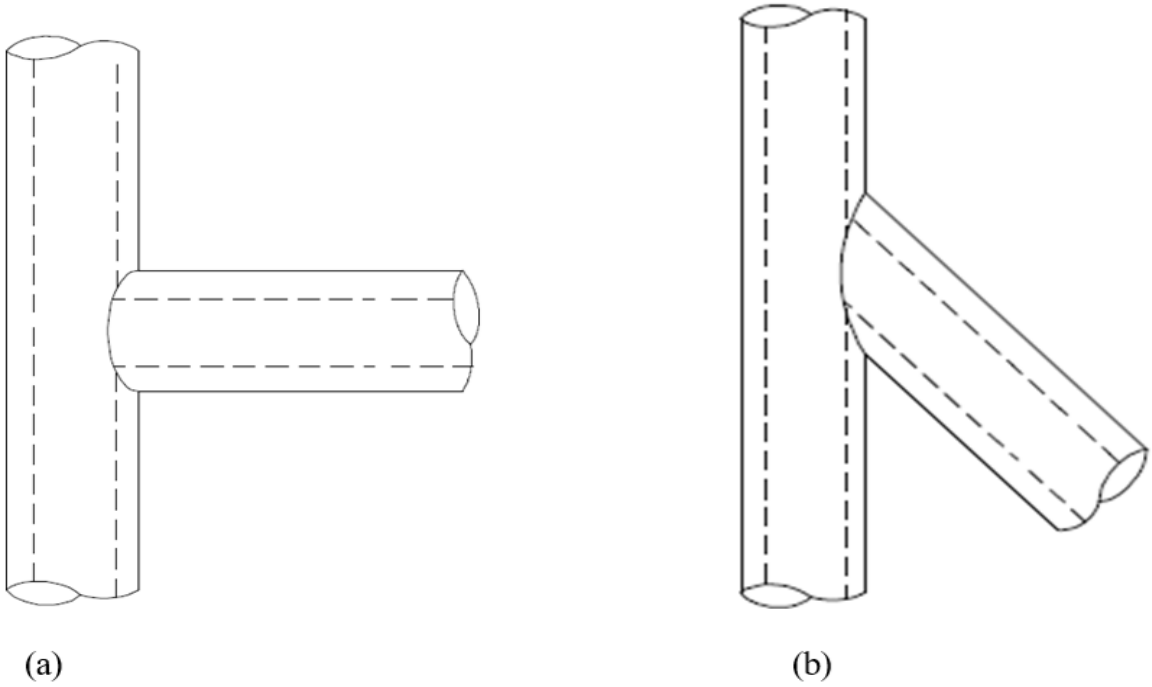


Fig.2.9: Bearing joints (a) Orthogonal members joint (b) Inclined members joint

Gupta et al. (2014) fabricated and tested steel bamboo composite connections for different specimens.

Built-up bamboo beams and columns were fabricated culminating in complete a portal frame, as shown in Fig. 2.10.



Fig.2.10: Model portal frame designed and fabricated at IIT Delhi

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Dash and Gupta (2014) developed a new type of wall structure using bamboo as a substitute for conventional masonry and an RC wall. It exhibited the characteristics of different types of bamboo walls. The bamboo-based wall not only act as bracing for two columns but can also provide ductility and energy absorption in the high intensity earthquakes expected in the North.

VI. Research Methodology

The methodology of the research adopted in this thesis is as follows:

(i) In order to do the analysis of the bamboo structural elements, it is necessary to obtain the characteristic strengths of local bamboo species in compression, buckling, tension and bending. Comprehensive tensile and compressive strength tests have been performed as part of the research work.

(ii) The next step has been to carry out fabrication and testing of individual composite units, in the form of FRBC beams, columns and joints to determine the capacities of the composite section under compression and flexure.

A. Material Characterization

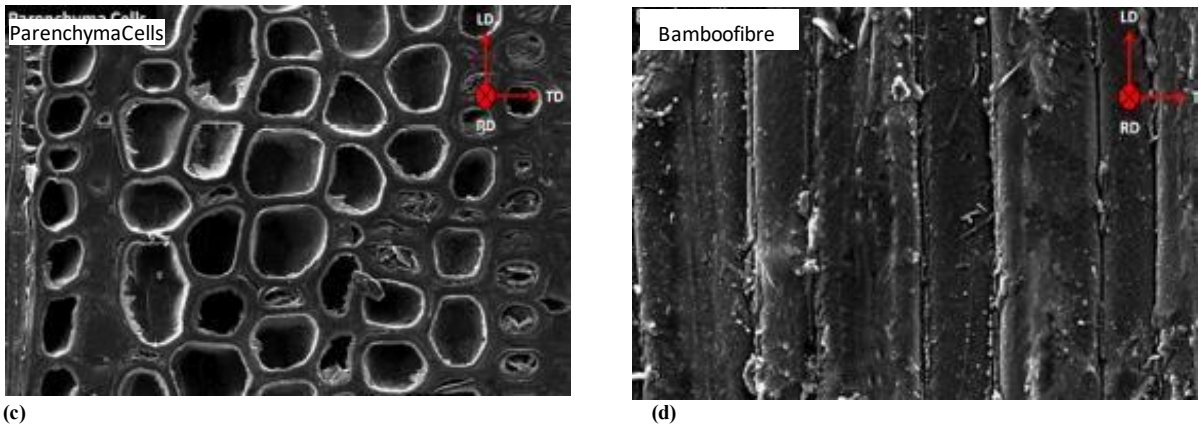
Bamboo being a natural vegetative product grown in nature under variable conditions, it is a structural element endowed with varied mechanical properties.

It is a typical functionally-graded composite and exhibits a strong perceptible correlation of its mechanical properties and their variation with its internal microstructure. The bamboo culms are cylindrical shafts with varying diameters and wall thicknesses with a substantial variation in coaxial alignment. Making a judicious selection of bamboo pieces for structural applications is a highly skilled task. A novel fibre epoxy aggregate composite, hence forth called 'epoxycrete' based upon fibres and aggregates, (to be used in fabrication of junctions) has been also tested for compressive strength and modulus of elasticity. This chapter deals with a study of the micro structure of bamboo followed by laboratory determination of its mechanical properties such as compressive, tensile and shear strengths.

VII. Microscopic Structure Of Bamboo

Bamboo under goes growth and development similar to other plants. It grows from less than 1 m height to may be over 15 m tall plant, entailing all the growth characteristics and phenomenon of plant origin, typically showing characteristics like storage cells and internal fibres. Bamboo fibres are typically closely spaced, surround the phloem (long hollow nano tubes carrying water and liquid matter from the roots to the top leaves).

(a) (b)



(c) (d)

Fig.3.1: SEM micro graphs of the raw bamboo culm with different constituents
(a) Cross-sectional view of bamboo culm
(b) Longitudinal view of bamboo culm
(c) Close-up view of (a)
(d) Close-up view of (b)

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Habibiand Lu (2014)*"Crack Propagationin Bamboo's Hierarchical Cellular Structure"*

These are accompanied by vascular bundles, which are similar to the bamboo fibres, but skewed and not perfectly linear, with intermittent locking and breakage. In addition, large parenchyma cells, which are locked in voided spaces, are also present.

Fig. 3.1 shows typical microscopic images of various components of bamboo's microscopic structure (Scales (a) 1mm (b) 1mm (c) 200µm (d) 50µm) Habibi and Lu (2014). Not only is there so much variation in internal structure of the bamboo, one can find lot of voided space between fibres and other components. Under tension, the fibres first get detached from each other and align themselves in a straight manner. There after, they actually start breaking up under applied tension.

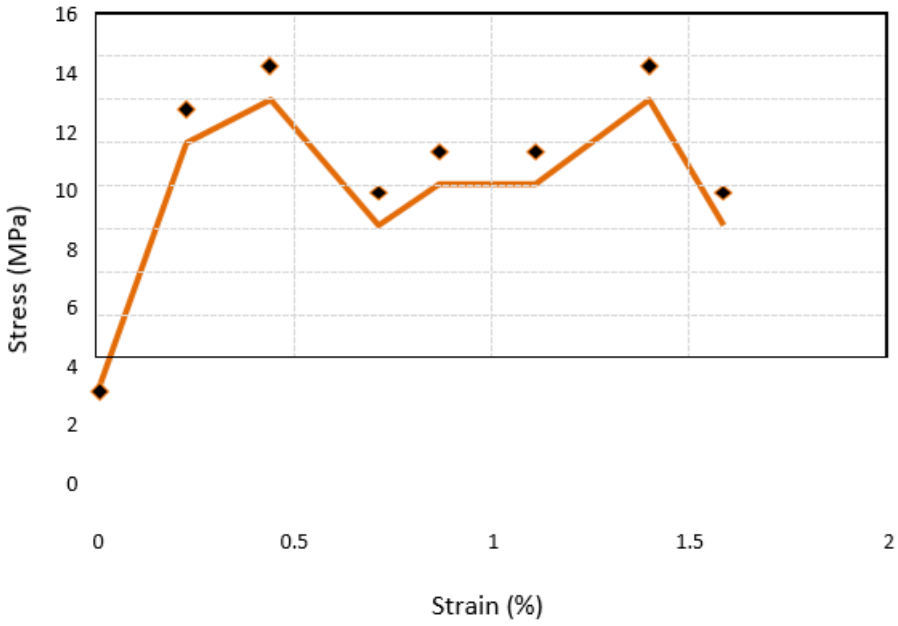


Fig.3.4: Typical stress vs strain curve for thin bamboo culms in compression

(a) Thick Walled Sections

Dendrocalamus strictus species based in Bengal was chosen for this test. This species is regarded as the best among the abundantly available species in India. The specimens for the test were again sourced from TERI for experimental purpose.

All the specimens tested had an age of three years when harvested and were brought to the laboratory after a minimum of two weeks after felling. In this particular category, two types of samples were tested-dry and wet as described below.

Dry Specimens

The range of wall thicknesses of these samples was 12 to16 mm, whereas the diameters ranged from 38 to 42 mm.

The lengths were fixed as 100-150 mm in order to keep the specimens as short columns i.e. *l/d* less than 12. A total of 30 samples were tested in the CTM under a loading rate of 0.01kN/s. Fig.3.5 shows the dry specimens conforming to thick walls just before testing. The thick-walled sections exhibited a characteristic difference in failure pattern and ultimate load capacity as compared to the thin walled sections covered earlier. The structural integrity of the bamboo section was maintained without any major rupture or separation of the longitudinal bamboo fibres, unlike the thin walled specimens. A typical cracking failure pattern is shown in Fig. 3.6. Two typical stresses versus strain plots are shown in Fig. 3.7. A precise yield point could not be ascertained in most cases. However, the stress-strain curves indicate a definite failure pattern. Failure typically initiated at 0.3% strain (in some cases 0.4% to 0.5% strain).

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As per the stress vs strain graphs (Fig. 3.7) a sudden substantial drop in load can be observed, after which the sample again started resisting load, with several instances of teething. This pattern indicates sequential rupture of internal fibres and their bonding mechanisms with increase in the load. The increase in strength (see Fig. 3.7) results from internal rearrangement and compaction of fibers, a mechanism similar to the phenomena of strain hardening.

This also indicates that a lot of energy was absorbed by the bamboo while reaching this failure stage. The sample specifications and test results for thick walled dry bamboo specimens are summarized in Table 3.1. The mean and the standard deviation values are enumerated in Table 3.2. An average strength of 30.6 MPa and a characteristic strength of 22.8 MPa were observed.



Fig.3.5: Thick walled specimens (30 nos) for uniaxial compression test



Fig.3.6: A typical failure pattern for thick walled section

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Table 3.1: Specifications and results for dry bamboo specimens tested in compression.

S. No	Sample No.	Diameter (mm)	Height (mm)	Wall thick-ness(mm)	Cross sectional area (mm^2)	Peak Load (kN)	Stress at Failure (MPa)	Strain at peak Stress (%)	Displace-ment at peakload (mm)	Young's modulus (MPa)
1.	2	38.9	104.0	9.5	1186.10	18	15.2	0.69	0.7	3189.2
2.	3	37.2	104.5	9.1	1087.40	22	20.2	0.75	0.8	2500.0
3.	4	36.2	105.2	9.0	1065.90	29	27.2	1.34	1.4	2307.7
4.	5	34.5	105.0	8.5	933.30	11	11.8	0.51	0.6	2435.2
5.	6	36.5	103.6	9.0	1046.90	30	28.7	1.94	2.0	2666.6
6.	9	30.3	104.0	7.7	721.17	34	47.1	2.88	3.0	3270.0
7.	11	37.5	104.7	9.2	1105.70	45	40.7	2.19	2.3	2750.0
8.	14	29.8	103.3	7.4	689.20	33	47.3	1.71	1.8	2764.7
9	12-1	36.8	104.0	9.0	1063.10	35	32.9	1.12	1.2	3428.6
10	12-2	36.8	104.0	9.0	1063.10	42	39.5	1.31	1.4	3333.3
11	42	25.7	105.0	6.3	518.90	11	21.2	1.06	2.0	3900.0
12	51	24.2	100.0	5.9	460.50	17	36.9	1.03	2.0	7500.0
13	61	24.9	105.0	6.1	486.30	23	47.3	1.63	3.0	5000.0
14	71	23.7	103.0	5.8	440.60	13	29.5	2.23	4.3	3750.0
15	BAMB -21	35.8	101.0	8.8	1006.00	8	30.9	2.75	1.0	3780.0
16	BAMB -7	38.0	104.0	7.5	740.81	20	27.0	2.35	4.8	3550.0

Table 3.2: Standard deviation mean and results of dry bamboo specimens tested in compression

Term	Diameter (mm)	Height (mm)	Thickness (mm)	Stressat failure (MPa)	Modulus of Elasticity(MPa)
Mean(μ)	33.4	103.3	16.3	30.6	3075
Standard Deviation(σ)	5.7	1.92	2.76	11.5	1662
Coefficientof variation	17%	1.8%	16.9%	37.5%	54%

(Coefficient of variation) $CoV=^{\mu}$ (3.1)

VIII. Conclusion

1. The major structural properties of *Dendrocalamus strictus*, the most common Indian species, have been comprehensively investigated for the first time by testing the individual elements in compression, tension and shear. Alongwith different strength results, the modulus of elasticity has also been obtained. Characteristic values of the strength parameters have been statistically obtained to be used for prediction of section capacities. Epoxycrete, another component of the joints of the frames, has also been thoroughly tested.
2. A new concept of FRBC elements has been proposed and experimentally tested and demonstrated. Forth is purpose, the bamboo culms are combined together withepoxy- fibre adhesive and polypropylene fibre.
3. The concept of FRBC is then extended to columns. Several short columns have been tested and found to behaving capacities in keeping with analytical formulations for uniaxial compression. The formulations have been extended to the case of axial loads and bending moments.
4. The bamboo culms have been integrated together in FRBC frameworks to fabricate short and long beam elements. The same have been tested in flexure via twopoint loading, along with acquiring strain measurements along the beam depths. The behaviour has been found to be truly composite from strain compatibility for long beams but not for short beams, which are not recommended. Analytical formulations have been proposed to predict the moment capacity of the FRBC section, duly validated with experimental results.

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