

**ENGINEERED BAMBOO STRUCTURES: DEVELOPMENT
OF HIGH CAPACITY FIBRE REINFORCED BAMBOO
COMPOSITE STRUCTURAL MEMBERS**

DIWAKAR BHAGAT



**DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
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by

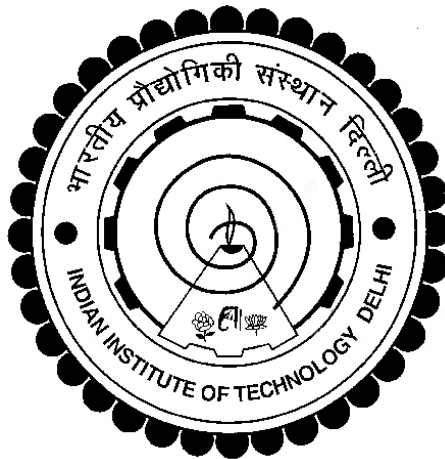
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Submitted

in fulfilment of the requirements of the degree of Doctor of Philosophy

to the



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*Dedicated to my family and teachers
for their support and guidance.*



CERTIFICATE

This is to certify that the thesis titled “**ENGINEERED BAMBOO STRUCTURES: DEVELOPMENT OF HIGH CAPACITY FIBRE REINFORCED BAMBOO COMPOSITE STRUCTURAL MEMBERS**” which is being submitted by **Mr. DIWAKAR BHAGAT** for the fulfilment of the requirements for the award of degree of **Doctor of Philosophy**, is a record of the student’s own work carried out at the **Indian Institute of Technology Delhi and Trinity College, University of Dublin, Dublin Ireland** under our supervision and guidance. The matter embodied in this thesis has not been submitted elsewhere for the award of any other degree or diploma.

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ABSTRACT

The last quarter of the century has witnessed substantial growth of China, India and a few other developing countries. The population of these developing countries, when put together, exceeds 60% of the world population. As a consequence of this huge population, these countries are generating the main demand for cement and steel owing to housing and related infrastructural development. Although not directly visible, the construction industry is one of the major sources of direct and indirect pollution. Wood, a pollution-free building material, has been in use in construction for a long time and is a green alternative, but it leads to severe deforestation, requiring 15 to 25 years to regenerate and causing ecological imbalance. India, a country of varied culture, religions and languages, is additionally plagued with the problem of overpopulation. In particular, the rural population is also struggling for basic livelihood. The government has been incapable of meeting the growing demands of basic shelter and education countrywide.

It is rightly said that “*necessity*” is mother of all inventions and innovations. Bamboo is not only the world’s fastest and strongest growing woody plant (often addressed as “*grass*”), but is also an enduring, versatile and highly renewable resource. Its adaptability to different climatic conditions makes it one of the most important species for mitigation of climate change. Considering the above facts, one finds that bamboo has high potential as a sustainable and renewable building material. Among the natural building materials, bamboo is unique for the extent of its *negative carbon footprint*, and it’s extremely short maturity time, typically ranging from three to five years.

This doctoral thesis embodies a comprehensive research devoted to development of high capacity bamboo based sections for real-life structural applications. As the first step, a comprehensive literature review is undertaken to understand the status of research on bamboo structures. Also, the most widely available species of India, *Dendrocalamus strictus*, which comprises almost 45% of Indian bamboo, has been judiciously selected for mechanical properties determination owing to its overall suitability for structural use. A large number of culms of “Bengal bamboo” (a member of the *Dendrocalamus strictus* family), have been put to compressive tests to obtain yield strength, modulus of elasticity and shear strength. In general, the tensile tests on bamboo are difficult tests to be conducted for results to be achieved correctly. However, tensile tests have been successfully done under this research by developing an innovative method of anchorage.

In order to bring bamboo into mainstream construction, one needs to alleviate the deficiencies of single shoot bamboo construction by evolving a structural member suitable for high capacity in compression and flexure, so as to be comparable to structural steel and R.C. in strength, structural capacity, performance and reliability. For this purpose, a novel fabrication methodology is proposed involving a collection of $m \times n$ bamboo culms as a matrix bound together by a mixture of polypropylene fibres and epoxy adhesive culminating in fibre-reinforced bamboo composite (FRBC) beams and columns. After achieving high compressive, tensile and flexural capacity, the next step has been the fabrication of waterless epoxyconcrete joints for integrating different members. The joints have performed exceptionally well in the tests to fully validate the purpose and main idea adopted in this research.

Finally, a series of full scale bamboo-epoxy portal frames have been fabricated in Structural Engineering Lab of Civil Engineering department, at IIT Delhi and tested at Trinity College,

University of Dublin, Ireland. A total of three such full scale portal frames were tested. First frame was loaded to fail in a combined mechanism. The second and third frames failed in sway and combined mechanisms respectively. The bending moment diagrams and collapse mechanism confirm and validate the adequacy of fabrication. The complex behaviour of the frames and their exceptional response has confirmed that this technology can be used to build houses and other structures. It may be noted here that the load versus displacement behaviour and complete recovery to the original form and shape without any rupture and collapse or brittle failure, clearly shows that a huge amount of energy has been absorbed and assimilated by the frame undergoing deformation under the vertical and lateral load forces combined as would happen in a real life situation of an earthquake. In this manner the frames have performed even better than an RC and steel frame.

The research findings will have a deep impact on the construction industry in India and the world, as it would be able to minimise the use of depletable natural resources (stone, iron etc). Millions of small farmers can safely go in for bamboo plantation in a big way and shall be financially benefitted. Bamboo can become a cash crop for the Indian agricultural industry, that is, it can prove to be "*Green Gold*". Engineered bamboo can be put to use in four to five storeyed buildings which can guarantee a house for every Indian without deteriorating the natural ecosystem of the country and also without burdening the Indian economy.

सार

सदी की आखिरी तिमाही में चीन, भारत और कुछ अन्य विकासशील देशों की पर्याप्त वृद्धि हुई है। इन विकासशील देशों की आबादी, जब एक साथ रखी जाती है, तो विश्व जनसंख्या का 60% से अधिक है। इस विशाल आबादी के परिणामस्वरूप, ये देश आवास और संबंधित ढांचागत विकास के कारण सीमेंट और इस्पात की मुख्य मांग पैदा कर रहे हैं। हालांकि प्रत्यक्ष रूप से दिखाई नहीं दे रहे हैं, निर्माण उद्योग प्रत्यक्ष और अप्रत्यक्ष प्रदूषण के प्रमुख स्रोतों में से एक है। लकड़ी, एक प्रदूषण रहित निर्माण सामग्री, लंबे समय तक निर्माण में उपयोग में रही है और यह एक हरा विकल्प है, लेकिन यह गंभीर वनों की कटाई का कारण बनता है, जिसे पुनर्जीवित करने और पारिस्थितिक असंतुलन के कारण 15 से 25 वर्ष की आवश्यकता होती है। भारत, विभिन्न संस्कृतियों, धर्मों और भाषाओं का देश, अतिरिक्त जनसंख्या की समस्या से ग्रस्त है विशेष रूप से, ग्रामीण आबादी भी बुनियादी आजीविका के लिए संघर्ष कर रही है। सरकार आधारभूत आश्रय की बढ़ती मांग और देशभर में शिक्षा को पूरा करने में असमर्थ रही है।

यह सही कहा जाता है कि "आवश्यकता" सभी आविष्कारों और नवाचारों की जननी है। बांस न केवल दुनिया का सबसे तेज और सबसे मजबूत वृक्षारोपण संयंत्र है (अक्सर "घास" के रूप में संबोधित किया जाता है), लेकिन यह एक स्थायी, बहुमुखी और अत्यधिक नवीकरणीय संसाधन भी है। विभिन्न जलवायु परिस्थितियों के अनुकूलनशीलता यह जलवायु परिवर्तन के शमन के लिए सबसे महत्वपूर्ण प्रजातियों में से एक है। उपरोक्त तथ्यों को ध्यान में रखते हुए, एक पाता है कि बांस एक स्थायी और नवीकरणीय निर्माण सामग्री के रूप में उच्च क्षमता है प्राकृतिक निर्माण सामग्री में, बांस अपने नकारात्मक कार्बन पदचिह्न की सीमा के लिए अद्वितीय है, और यह बहुत कम परिपक्वता अवधि है, आमतौर पर तीन से पांच साल तक होता है।

इस डॉक्टरेट की थीसिस वास्तविक जीवन संरचनात्मक अनुप्रयोगों के लिए उच्च क्षमता वाला बांस आधारित वर्गों के विकास के लिए समर्पित एक व्यापक अनुसंधान का प्रतीक है। पहला कदम के रूप में, बांस संरचनाओं पर अनुसंधान की स्थिति को समझने के लिए व्यापक साहित्य समीक्षा की जाती है। इसके अलावा, भारत की सबसे व्यापक रूप से उपलब्ध प्रजाति, डेंड्रोकेलेमस कडक, जिसमें लगभग 45% भारतीय बांस शामिल हैं, संरचनात्मक उपयोग के लिए इसकी संपूर्ण उपयुक्तता के कारण यांत्रिक गुणों के निर्धारण के लिए विवेकपूर्ण तरीके से चयन किया गया है। "बंगाल बांस" (दन्द्रक्रेमास कड़े परिवार के सदस्य) की एक बड़ी संख्या को उत्पन्न शक्ति प्राप्त करने, लोच और कतरनी ताकत के माप के लिए संक्रामक परीक्षण करने के लिए रखा गया है। सामान्य तौर पर, बांस पर तन्यता परीक्षण सही तरीके से हासिल किए जाने के परिणाम के लिए आयोजित किए जाने वाले कठिन परीक्षण हैं। हालांकि, लंगर के एक अभिनव पद्धति का विकास करके इस शोध के तहत तन्य परीक्षण सफलतापूर्वक किया गया है।

बांस को मुख्यधारा के निर्माण में लाने के लिए, एक को एक शूटिंग बांस के निर्माण की कमियों को कम करने की आवश्यकता होती है जिससे संरचनात्मक सदस्य तैयार होकर उच्च क्षमता के लिए संपीड़न और वजन में उपयुक्त हो, ताकि संरचनात्मक इस्पात और आर.सी. के बराबर हो। शक्ति, संरचनात्मक क्षमता, प्रदर्शन और विश्वसनीयता में इस प्रयोजन के लिए, फाइबर प्रबलित बांस कंपोजिट (एफआरसीसी) बीम और कॉलम में परिणत पोलीप्रॉपिलिन फाइबर और ईपीओसी चिपकने वाले मिश्रण के मिश्रण से एक मैट्रिक्स के रूप में एक मैट्रिक्स के रूप में एम × एन बांस कल्म के संग्रह से संबंधित एक उपन्यास निर्माण पद्धति का प्रस्ताव है। उच्च संक्रामक, तन्यता और फ्लेक्चरल क्षमता प्राप्त करने के बाद, अगले चरण अलग-अलग सदस्यों को एकजुट करने के लिए पानी रहित ऐपोकोट्रिक जोड़ों का निर्माण किया गया है। इस शोध में अपनाए गए उद्देश्य और मुख्य विचार को पूरी तरह से मान्य करने के लिए जोड़ों ने परीक्षणों में उत्कृष्ट रूप से अच्छा प्रदर्शन किया है।

अंत में, पूर्ण पैमाने पर बांस-एपीपीसी पोर्टल फ्रेम की एक श्रृंखला आईआईटी दिल्ली में सिविल इंजीनियरिंग विभाग के स्ट्रक्चरल इंजीनियरिंग लैब में गढ़ी गई है और ट्रिनिटी कॉलेज, डबलिन विश्वविद्यालय, आयरलैंड तीन ऐसे पूर्ण पैमाने पर पोर्टल फ्रेम का परीक्षण किया गया था। एक संयुक्त तंत्र में विफल होने के लिए पहले फ्रेम लोड किया गया था। द्वितीय और तीसरे तख्ते अनुक्रिया और संयुक्त तंत्र में क्रमशः विफल रहे। झुकने वाले पल आरेख और दहने के तंत्र की पुष्टि और निर्माण की पर्याप्तता को मान्य करते हैं। तख्ते का जटिल व्यवहार और उनके असाधारण प्रतिक्रिया ने पुष्टि की है कि इस तकनीक का उपयोग घरों और अन्य संरचनाओं के निर्माण के लिए किया जा सकता है। यहां पर ध्यान दिया जा सकता है कि विस्थापन व्यवहार और मूल रूप से पूर्ण विरूपण और किसी भी प्रकार के टूटने या पतन या भंगुर विफलता के बिना पूरी तरह से वसूली स्पष्ट रूप से पता चलता है कि ऊर्ध्वाधर के तहत विरूपण के दौर से गुजरते फ्रेम से बड़ी मात्रा में ऊर्जा अवशोषित हो गई है। और पार्श्व भार बलों को संयुक्त रूप से संयुक्त रूप से एक भूकंप की वास्तविक स्थिति में होगा। इस तरीके से फ्रेम ने आरसी और स्टील फ्रेम से बेहतर प्रदर्शन किया है।

शोध निष्कर्षों का भारत और विश्व में निर्माण उद्योग पर गहरा प्रभाव पड़ेगा, क्योंकि यह घटता प्राकृतिक संसाधनों (पत्थर, लोहा आदि) के उपयोग को कम करने में सक्षम होगा। लाखों छोटे किसान सुरक्षित रूप से बांस वृक्षारोपण के लिए बड़े रास्ते में जा सकते हैं और आर्थिक रूप से लाभान्वित होंगे। बांस भारतीय कृषि उद्योग के लिए एक नकद फसल बन सकता है, जो यह "ग्रीन गोल्ड" साबित हो सकता है। बांस को चार से पांच मंजिला इमारतों में इस्तेमाल किया जा सकता है जो देश के प्राकृतिक पारिस्थितिकी तंत्र को बिगड़ने के बिना हर भारतीय के लिए एक घर की गारंटी दे सकते हैं और बिना भारतीय अर्थव्यवस्था को भी बोझ उठा सकते हैं।

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LIST OF ACRONYMS

BMD	Bending Moment Diagram
CHT	Chittagong Hill Tracts
CTM	Compression Testing Machine
DG	Dendrocalamus Giganteus
ECB	Elasticity Compression Bamboo
ESG	Electrical Strains Gauge
GRP	Glass Reinforced Plastic
IS	Indian Standard
FRBC	Fibre Reinforced Bamboo Composite
FITT	Foundation of Innovation and Technology Transfer
GDP	Gross Domestic Productivity
LVDT	Linear Variable Displacement Transducer
PC	Personal Computer
RC	Reinforced Concrete
SBICA	Split Bamboo Infill Concrete Arch
TERI	Tata Energy Research Institute
UTM	Universal Testing Machine

LIST OF SYMBOLS

A_o	Unit depth
A_{BE}	Effective area of section
A_{BG}	Gross section of beam
A_i	Internal circular area inside bamboo
A_c	Area in the compression
A_i	Internal circular area inside bamboo
C_C	Compressive force in bamboo in compressive zone
E_l	External area of edge losses
CO_2	Carbon-dioxide
D	The overall depth of the beam
N	Neutral axis
$n/3$	Distance from top of centroid of compressive zone
E	Young's modulus of elasticity
E_{bcb}	Modulus of elasticity in compressive bending
E_{btb}	Modulus of elasticity in tensile bending
E_l	External area of edge losses
L	Span of beam
M_r	Moment of resistance
M_p	Plastic moment of resistance
M_y	Yield moment
M_t	Moment capacity of the section
M_c	Moment capacity
M	Modular ratio
R	Modulus of rupture
R_A	Area ratio
T	Tensile force in bamboo in tensile zone
t	Thickness of the bamboo

ϕ_o	Nominal external diameter
ϕ_i	Nominal internal diameter
σ_t	Tensile strength
σ_c	Compressive strength
σ_b	Flexural strength
τ	Shear strength
ϵ	Strain
α	Angle of rotation
δ_p	Deflection
σ_{bcb}	Allowable stress in compressive bending
jd	Lever arm
δ_H	Horizontal deflections
ϵ_c	Strain in compression
ϵ_t	Strain in tension
V_i	Area of internal voids
Z	Section modulus
f_p	Performance factor
γ_m	Material quality of bamboo
γ_b	Bonding material quality reliability