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Design Equations for Bamboo Reinforced Concrete Beams

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Abstract

Bamboo is a rapidly replenishing resource that is used as a practical building material in many nations. Despite the limitatiobs of natural bamboo, there is lack of well established design guide on bamboo reinforcemnt. This research reviewed and developed some design equations for bamboo reinforcement. Bamboo samples treated with various techniques were examined and used in this work. The results reveal some variations in tensile and flexural performance of bamboo as a construction material. Also, the work identified some design expressions developed by previous researchers and improved on it to accommodate the effects of treatment methods in bamboo design there by improving on the existing approach. The tensile strength obtained from experimental work was used to develop more design equations for bamboo construction.

Keywords: Design, Equations, Bamboo, Reinforced Concrete Beams, Construction.

Introduction

The employment of non-renewable resources in the construction field results in environmental consequences, contributing to the excessive consumption of energy and substantial material losses. Thus, the construction sector is in an ongoing search for improvement and innovation in their techniques, aiming the utilization of sustainable and alternative materials. According to [1, 2, 3], in response to the never-ending search for renewable

materials, the bamboo is an alternative with physical and mechanical characteristics that ensure its performance as a building material, being a low cost, fast growing and perennial plant. According to [2, 4], due to its heterogeneity, the absence of standardization restricts its utilization on the construction field; even though the great variability of species of bamboo exists has low cost, self-sustainability and is extremely easy to handle [3, 4, 5]. Since the 70s, some bamboo species are being studied and analyzed as reinforcement and molds for structural elements [6]. Even though being a sustainable material that has been used in Asia since ancient times, the overall number of researches in this subject is scarce [7, 8]. However, the use of bamboo as beams' reinforcements has received more attention due to the possibility of using the same structural design methods as reinforced concrete [9], making a pre-treatment. According to [10, 11, 12, 13], bamboo has a fast maturing cycle that could vary from three to five years, depending on local climate and soil. The bamboo's tensile strength accounts for between 50% and 75% of steel, being influenced by its absorption capability [14]. The bamboo's structural performance is impaired due to certain anatomy particularities, presenting low shear strength parallel to the fibers and irregular geometry. Besides that, the lignin present in its composition is a target to xylophagous insects [15]. The bamboo's anatomic constitution is composed by culm and rhizome. The culm can be divided into nodes and internodes, based on its fiber's orientation. On the internodes, the fibers are axially oriented to the growth direction, diverging from the axis and concentrating on the nodes, which enables the diaphragm formation, giving lateral stability to the culm [16]. In its natural state, being an organic material, bamboo is susceptible to organic decay. Nowadays, there are numerous treatments for bamboo's preservation. The durability of the material is ensured by protection against fungal rot, attack by insects and cracks with wood preservatives [17, 18]. Besides its susceptibility to insect attacks, the treatment could influence on the final material strength and adherence on concrete [19]. The bamboo's largest utilization difficulty as reinforcement is its water absorption rate. When in contact with fresh concrete and during the curing process, the excess of water is absorbed by the bamboo, which swells.

The high price of steel added to environmental concerns over its manufacturing process has motivated researchers to seek an alternative reinforcing material, in particular for developing countries. Bamboo is one such material under consideration for its high tensile strength. Bamboo shows the potential to provide a low-cost, readily available, quick growing, and replenish able alternative to steel as a reinforcement in concrete. However, the applicability of bamboo reinforced concrete (BRC) presents unique challenges, and research about its performance is still in its nascent stages. Bamboo is a natural material; its properties depend on species, climate, age, and geometric properties, among other factors [20, 21, 22]. Tests on bamboo specimens

have revealed high variance in their tensile strength [22]. The tests also indicated brittle failure of the test specimens. Bamboo is also susceptible to moisture changes and can shrink or expand based on its moisture content. The shrinking of bamboo while concrete cures can lead to a reduction in bamboo-concrete bonds, which can adversely affect the tensile performance of the assembly [23]. These issues, among others, must be addressed to present bamboo as a suitable reinforcement in concrete. Experimental tests on bamboo-reinforced concrete beams have generally indicated that while the bamboo reinforcement in a concrete beam increases its load-carrying capacity when compared to unreinforced concrete, it does not necessarily prevent the propagation of cracking in concrete due to its relatively low modulus of elasticity [24]. Flexural test results also mostly suggest a brittle failure of the bamboo beams [24] Such a behavior has been one of the causes of skepticism related to supplementing concrete with bamboo reinforcement [25]. However, it is evident from the literature review that most flexure tests on bamboo-reinforced beams were conducted on small-scale specimens (typically less than 1 m/ 3.28 ft. in length) with just two or three bamboo pieces as flexural reinforcement. Small-scale specimens may not provide sufficient development length for good bonding between bamboo and surrounding concrete. Additionally, as the tensile properties of each bamboo piece vary considerably, utilizing more bamboo pieces per beam helps negate the effects of individual variability, which small specimens cannot achieve [26].

As bamboo is eco-friendly material, limiting the use of steel can reduce the carbon dioxide emissions. In the green building concept, the use of bamboo reinforced concrete may be recommendable. Further study must focus on how to improve the bonding strength between bamboos and concrete. Water absorption of bamboo is very high and waterproofing agent is recommended to minimize the water absorption during concrete casting in order to improve the bonding strength between concrete and bamboo [27].

METHODOLOGY

The bamboo species utilized in this study was Bambussa Vulgaris. The bamboo culms were cut into approximately 2.44 m (8 ft.) lengths for easy transportation. Each culm was divided into between six and eight approximately equal radial segments using a machete.

The tension tests were performed using a Universal Testing Machine (UTM). The bamboo strips were cut into approximately of 12x12mm, 12x14mm, 12x16mm Vgrips were employed to clamp the specimens at both ends, each specimen's central section was ground into a dog-bone shape to ensure failure in the neck region.

The results show that the specimens exhibited a relatively linear relationship between stress and strain up to the point of failure. The failure mode of the specimens was

observed to be brittle, characterized by a sudden break at the neck region. All specimens with nodes in the neck region failed at the nodes. However, the presence of a node was not necessarily indicative of a weaker specimen. The peak stress and strain values varied considerably among the specimens.

Target mean strength of concrete was calculated. Considering the inherent variability of concrete strength during production it is necessary to design the mix to have a target mean strength which is greater than characteristic strength by a suitable margin. The formula used to calculate target mean strength: ft = fck+ k × S Where: ft = target of Strength fck = characteristic strength of concrete k = a constant depending upon the definition of characteristic strength S = standard deviation of the particular mix. The results of the tensile strength test is tabulated in table 1 to 4

Table 1.0: Results of Tensile Strength Test for Untreated Bamboo Samples

Bamboo Size mm	Bamboo Area mm^2	Treatment Method	Maximum Tensile Force kN	Tensile Strength N/mm^2
12x12	144	Untreated	12.00	83.33
14x12	168	Untreated	14.00	83.33
16x12	192	Untreated	16.10	83.85
20x12	240	Untreated	20.20	84.17

Table 2.0: Results of Tensile Strength Test for Binding Wire Treated Bamboo Samples

Bamboo Size mm	Bamboo Area mm^2	Treatment Method	Maximum Tensile Force kN	Tensile Strength N/mm^2
12x12	144	Binding Wire	14.40	100.00
14x12	168	Binding Wire	16.70	99.40
16x12	192	Binding Wire	19.20	100.00
20x12	240	Binding Wire	24.30	101.25

Table 3.0: Results of Tensile Strength Test for Epoxy Treated Bamboo Samples

Bamboo Size mm	Bamboo Area mm^2	Treatment Method	Maximum Tensile Force kN	Tensile Strength N/mm^2
12x12	144	Epoxy	14.40	100.00
14x12	168	Epoxy	16.90	100.59
16x12	192	Epoxy	19.40	101.04
20x12	240	Epoxy	24.35	101.46

Table 4.0: Results of Tensile Strength Test for Bitumen Treated Bamboo Samples

Bamboo Size mm	Bamboo Area mm^2	Treatment Method	Maximum Tensile Force kN	Tensile Strength N/mm^2
12x12	144	Bitumen Emulsion	14.00	97.22
14x12	168	Bitumen Emulsion	16.10	95.83
16x12	192	Bitumen Emulsion	18.90	98.43
20x12	240	Bitumen Emulsion	23.85	99.38

From the result of compressive test for concrete cubes on 28 days showed the value of 30.40 MPa. The peak stress values ranged from 83.33 MPa to 119.17 MPa, and a coefficient of variation (CV) of 0.156. The peak strain of the specimens varied from 0.0010 to 0.0196, with an average of 0.0011 and a CV of 0.540. Subsequently, the modulus of elasticity with an average of 26,516 MPa and a CV of 1.114. A negative correlation between peak strain and modulus of elasticity was observed for the test specimens, with a coefficient of correlation (ρ) of -0.8. The design methodology for the bambooreinforced concrete beams followed the same approach as that for a singly reinforced underreinforced concrete beam with steel reinforcement. The design was carried out using a deterministic approach. Table 5 shows the summary of the design values

Table 5.0: Design values for bamboo-concrete beams

Design feature	Description
Effective length (L)	3.05 m (10 ft)
Beam width (b)	25.4 cm (10 in.)
Beam height (h)	35.6 cm (14 in.)
Clear cover (cc)	5.1 cm (2 in).
Effective depth (d)	39.5 cm (12 in.)
Number of tension bamboo	6
Area of each tension bamboo	2.6 cm^2 (0.4 in^2)
Total area of bamboo	15.5 cm^2 (2.4 in^2)
Compressive strength of concrete (f'_c)	27.6 MPa (4 ksi)
Yield strength of bamboo (f_y)	117 MPa (17 ksi)
ϕ	n/a
Depth of compression block (a)	3.05 cm (1.2 in)
Ultimate moment capacity (M_n)	50.8 kN-m (37.5 k-ft)
Tensile stress of concrete (f_t)	3.27 MPa (474 psi)
Cracking moment (M_{cr})	17.5 kN-m (12.9 k-ft)
Shear strength of beam (V_c)	78.8 kN (17.7 kip)

For each simulation, the variables were randomly generated based on their respective distributions. Strain compatibility was assumed for this simulation (i.e., no slip between bamboo and concrete). Additionally, it was assumed that the bamboo pieces had no residual strength beyond peak strain. The simulation comprised of six stages, each associated with the failure of one of the six bamboo pieces. The compressive strain in concrete was also checked at each stage assuming a linear distribution of strain over the depth of the beam. The stress at each stage was determined by multiplying the modulus of elasticity by the strain at that stage. The moment capacity at each stage is given as:

$$M_{ni} = \sum_{k=1}^{6} (A_{bk}\varepsilon_i E_k)(d - a_i / 2) \quad \text{..... (i)}$$

Where, Mni = moment capacity at stage i, Abk = Area of bamboo piece k, ϵi = strain at stage i, Ek = Modulus of elasticity of bamboo piece k, d = effective depth, ai = depth of compression block at stage i calculated using the following equation:

$$a_i = \frac{\sum_{k=1}^{6} A_{bk}\varepsilon_i E_k}{0.85 f_c' b} \quad \text{..... (ii)}$$

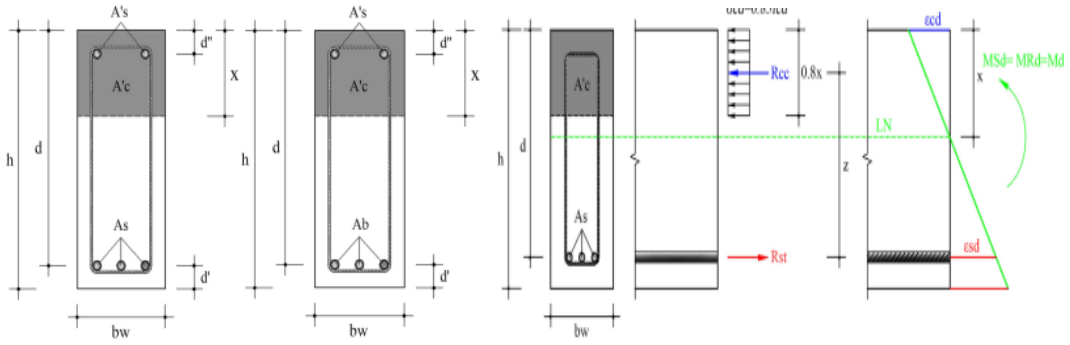
Where, f'c = compressive strength of concrete, b = width of the beam

Element Dimensions

The cross-section's height (h) and width (bw), the element's length (l) are necessary measurements. Then, the spreadsheet can determine the loading points (a) and the working height (d), equivalent to the distance between the gravity center of the reinforcement and the compressed edge of the cross-section.

Output Data

The output data are generated based on the input cited on the previous section, by the equations shown in this section, initially obtaining the steel reinforcement area and its correspondent bamboo reinforcement area. Figure 3(a) and Figure 3(b) shows the cross-section of rectangular beam of conventional reinforced concrete and bamboo reinforced concrete, respectively. The equations are obtained by constitutive law of materials (Materials Resistance) considering the internal balance of efforts. The external load (bending moment Md) are balanced with internal binaries, represented by the representative strength of compressed concrete (Rcc) and the representative strength of tensile steel (Rst), distance to a length (z). Figure 4 shows the internal equilibrium conditions



Neutral Line (LN) Position: The neutral line position (x) was obtained by the Equation (iii).

$$x = 1.25 \times d \times \left(1 - \sqrt{1 - \frac{M_d}{0.425 \times b_w \times d^2 \times f_{cd}}} \right) \quad \text{..... (iii)}$$

Being: Md is the bending moment by a ponderation coefficient (kN.cm); fcd is Compressive strength (kN/cm2); bw is the cross-section width (cm); x is the distance between the compressed edge and the point without deformation and stress (cm); d is the working height (cm).

Representative Strength of Compressed Concrete The representative strength of compressed concrete (Rcc) was obtained by the Equation (iv).

$$R_{cc} = 0.68 \times f_{cd} \times b_w \times x \quad \text{..... (iv)}$$

fcd is Compressive strength (kN/cm2); bw is the cross-section width (cm); x is the distance between the compressed edge and the point without deformation and stress (cm); Rcc is the representative strength of compressed concrete (kN). 2.2.3. Representative Strength of Tensile Steel The representative strength of tensile steel (Rst) was obtained by the Equation (v)

$$R_{st} = A_s \times f_{yk} \quad \text{..... (v)}$$

Being: fyk is the characteristic yield stress (kN/cm2); bw is the cross-section width (cm); x is the distance between the compressed edge and the point without deformation and stress (cm); Rst is the representative strength of tensile steel (kN). 2.2.4.

Bending Moment

The bending moment (Md) was obtained by the Equation (vi).

$$M_d = 0.68 \times f_{cd} \times b_w \times x \times (d - 0.4x) \quad \text{..... (vi)}$$

Being: Md is the bending moment by a ponderation coefficient (kN.cm); fcd is Compressive strength (kN/cm2); bw is the cross-section width (cm); x is the distance

between the compressed edge and the point without deformation and stress (cm); d is the working height (cm).

Service Bending Moment: The Service bending moment (Mk) can be estimated in the Equation (v), dividing the bending moment by a ponderation coefficient. d k f

The steel reinforcement area (As) was determined without the safety coefficients, according to Equation (vii).

$$A_s = M_k / (d - 0.4x) \times f_{yk} \quad \text{..... (vii)}$$

Being: As is the steel reinforcement area (cm2); Mk is the bending moment (kN.cm); d is the working height (cm); x is the distance between the compressed edge and the point without deformation and stress (cm); fyk is the characteristic yield stress (MPa).

Reinforcement Area Equivalence between Bamboo and Steel The corresponding bamboo reinforcement area was obtained by the equality of the needed force in the steel to resist the Service bending moment Equation (8) and the force admitted by a given bamboo area in Equation (9). It's very important to observe, the steel area can be partially or total replaced by bamboo. The combination with bamboo and steel could be made carefully, observing the total tensile strength Rst. This combination must be respecting the correlation shown in Equation (viii).

$$\sigma_{steel} = F / A_s \quad \text{..... (viii)}$$

Being: σsteel is the mean tensile stress of steel (kN/cm2); F = Acting force on the steel reinforcement (kN); As is the steel reinforcement area (cm2).

$$\sigma_{bamboo} = F / A_b \quad \text{..... (ix)}$$

Being: σbamboo is the mean tensile stress of bamboo (kN/cm2); F it the acting force on the bamboo reinforcement (kN); Ab is the equivalent bamboo area (cm2)

$$\frac{\sigma_{bamboo} \times A_b + \sigma_{steel} \times A_s}{R_{st}} \geq 1 \quad \text{..... (x)}$$

Being: σbamboo is the mean tensile stress of bamboo (kN/cm2); σsteel is the mean tensile stress of steel (kN/cm2)

As is the steel reinforcement area (cm2). Ab is the bamboo area (cm2). 2.2.9. Maximal Vertical Displacement The vertical displacement (Dmáx) limited by [14], was determined by the Equation (xi).

$$D_{max} = l / 250 \quad \text{.... ..... (xi)}$$

Being: Dmáx is the maximal vertical displacement allowed (cm); l is the element length (cm)

Conclusion

The findings of this research identified that bamboo is a viable reinforcement material. The short comings of bamboo can be overcomed by treatment methods so as to

improve it performance as a construction material. Also, there is no proper design guide for bamboo reinforcement. In addition to the design formulae by other researchers, this work present additional design equations for bamboo reinforcement especially for beams. This research also also present variations in bamboo design based on treatment methods. Hence, in all bamboo designs, treatment techniques should be taken into consideration.

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