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Bamboo as reinforcement in structural concrete elements

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Abstract

It is a fact that the construction industry is the main consumer of energy and materials in most countries. The pursuit of sustainable development, defined in the Brundtland Report 1987 as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs", has become a major issue when trying to meet the challenges in providing proper housing for the ever-increasing world population. To increase the amount of information concerning bamboo several successful research programs have been carried out since 1979 at PUC-Rio and in Brazil. Vegetable fibres can be used either alone or as reinforcement in different types of matrices such as soil and cement composites. This paper presents the results of some of the recent studies of the microstructure of bamboo as a functionally gradient material. These studies led to the establishment of bamboo's composite behaviour through the rule of mix. A concise summary regarding bamboo reinforced concrete beams, permanent shutter concrete slabs and columns is discussed. Finally, some recommendations for future studies are proposed with the hope that the newly developed material could contribute, on a large scale, to sustainable development without harming our globe.
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Keywords: Bamboo; Concrete; Composites; Non-conventional materials

1. Introduction

The present energy crisis provoked by indiscriminate industrial growth has caused increasing concerns about managing the energy resources still available and about environmental degradation. There is an intense on-going search for non-polluting materials and manufacturing processes, which require less energy. Attention of researchers and industries has turned to materials such as vegetable fibres including bamboo, soil, wastes from industry, mining and agriculture for engineering applications. In a global effort to find a substitute for the health hazardous asbestos cement new cements using all types of wastes are being developed and used for the production of composites, reinforced with fibres.

In this era of industrialisation, the selection of materials is based mainly on the price and the type of facility used for production or processing. *Industrialised materials*, such as ordinary Portland cement (OPC) and steel, find applications in all sectors and in the world to which a road leads. In the second half of the 20th century, advanced materials such as synthetic polymers (e.g. Rayon, Nylon, Polyester, Kevlar), new alloy metals and carbon fibres were developed. They were introduced in places where locally produced materials exist in abundance. In developing countries due to the educational system, which is mainly based on programs from industrialised nations, there are to date no formal education or research programs concerning the traditional and locally available materials and technologies. Lack of reliable technical information about the local materials makes the consumers use mainly industrialised materials for which the information is freely available.

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The main hurdle for the application of structural composites is the lack of sufficient information about the constituents of the composites and about their durability. The focus of this paper is to present a concise summary of the information about the range of material choices, which are locally available for producing concrete structural elements, reinforced with bamboo.

2. Bamboo as an engineering material

In consequence of the consumers choosing industrialized products, among other effects, activities are suppressed in rural areas or even in small towns, and renewable materials are wasted and causing permanent pollution. In this sense, it becomes obvious that ecological materials satisfy such fundamental requirements, making use of agricultural by-products such as rice husk, coconut fibres, sisal and bamboo and therefore minimizing energy consumption, conserving non-renewable natural resources, reducing pollution and maintaining a healthy environment [1–10]. Bamboo is one material, which will have a tremendous economical advantage, as it reaches its full growth in just a few months and reaches its maximum mechanical resistance in just few years. Moreover, it exists in abundance in tropical and subtropical regions of the globe [5–21].

The energy necessary to produce 1 m^3 per unit stress projected in practice for materials commonly used in civil construction, such as steel or concrete, has been compared with that of bamboo. It was found that for steel it is necessary to spend 50 times more energy than for bamboo [7,13,14]. The tensile strength of bamboo is relatively high and can reach 370 MPa [7]. This makes bamboo an attractive alternative to steel in tensile loading applications. This is due to the fact that the ratio of tensile strength to specific weight of bamboo is six times greater than that of steel [1,7].

The structural advantage, over other engineering materials is studied in terms of modulus of elasticity, E, and density, ρ, using the material selection method developed at Cambridge University [16,17] shown in Fig. 1. In this figure the line presenting the equation $C = E^{1/2}/\rho$ applies to the properties of bamboo. Materials, which have a better performance than bamboo, are situated above the line and those, which have a worse performance, are below the line. It can be seen that only timber from palm-trees and balsas are in the same range as bamboo whereas steel, concrete and aluminium are located far below the line. The closed area for each material shows the variation of the available data for the same.

In South American countries the natives have used bamboo intensively for centuries [4,5] but the European colonizers never knew how to use bamboo until 1970s. In Brazil the use of bamboo was limited to the construction of some scaffolding and simple dwellings. Systematic studies have been carried out on bamboo since 1979 at PUC and in Brazil. The greater part has been dedicated to the development of a methodology for bamboo's application in space structures and as reinforcement in concrete.

2.1. Basic characteristics of bamboo

Bamboos are giant grasses and not trees as commonly believed. They belong to the family of the *Bambusoideae*. The bamboo culm, in general, is a cylindrical shell, which is divided by transversal diaphragms at the nodes. Bamboo shells are orthotropic materials with high strength in the direction parallel to the fibres and low strength perpendicular to the fibres respectively.

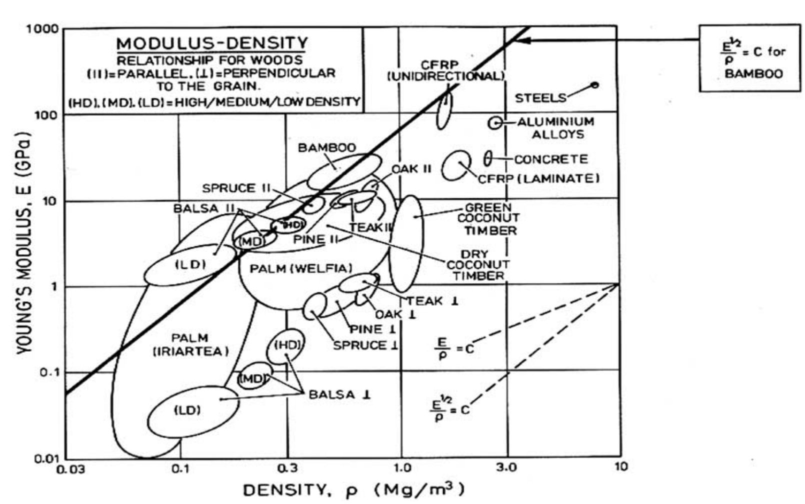

Fig. 1. Performance of bamboo and other materials, in relation to their E and ρ, [17].

Bamboo is a composite material, consisting of long and parallel cellulose fibres embedded in a ligneous matrix. The density of the fibres in the cross-section of a bamboo shell varies along its thickness. This presents a functionally gradient material, evolved according to the state of stress distribution in its natural environment. As seen in Fig. 2, the fibres are concentrated in regions closer to the outer skin. This is consistent with the state of stress distribution when the culm is subjected to wind forces [10,18–20].

In establishing the mechanical properties of bamboo, in the elastic range, the rule of mix for the composite materials is used. The properties of the fibres and matrix with their volumetric fractions are taken into account. Eq. (1) presents the calculation of the elasticity modulus, E_c, of the bamboo as a composite. In this equation E_f and E_m are elasticity moduli and V_f and $V_m = (1 - V_f)$ are the volumetric fractions of the fibres and matrix respectively. In the development of Eq. (1), long, uniformly spaced and aligned fibres are assumed in addition to a perfect bonding between fibres and matrix.

$$E_c = E_f V_f + E_m(1 - V_f) \tag{1}$$

In the application of Eq. (1) to the analysis of bamboo, the variation of the volumetric fraction of fibres, $V_f(x)$, with thickness should be taken into account. Considering that the $V_f(x)$ distribution follows an axis, x, with the origin at the internal wall and the maximum limit at the outer wall of the bamboo culm, Eq. (2) can be written. The variation of $V_f(x)$, was determined using the digital image processing, DIP.

$$E_c = f(x) = E_f V_f(x) + E_m(1 - V_f(x)) \tag{2}$$

Using the DIP method, the variation of the fibre volume fraction of the bamboo shell was determined for 10 culms of different species. For each culm, three samples were taken from the bottom, middle and the top part of the culm, as shown in Fig. 3(a) for bamboo *Dendrocalamus giganteus* (DG).

The variation, $V_f(x)$, at the three loci of culms, is presented in Fig. 3(b). It is observed that the fibre distribution is more uniform at the base than at the top or the middle part. This phenomenon could be explained

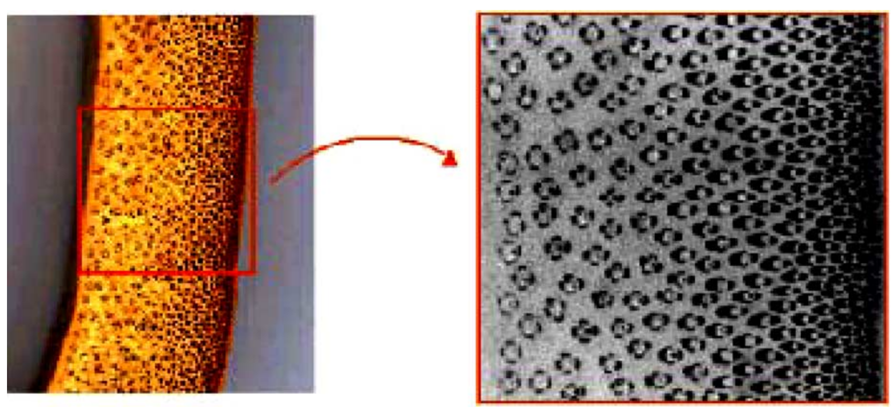

Fig. 2. Non-uniform fibre distribution on cross-section of bamboo.

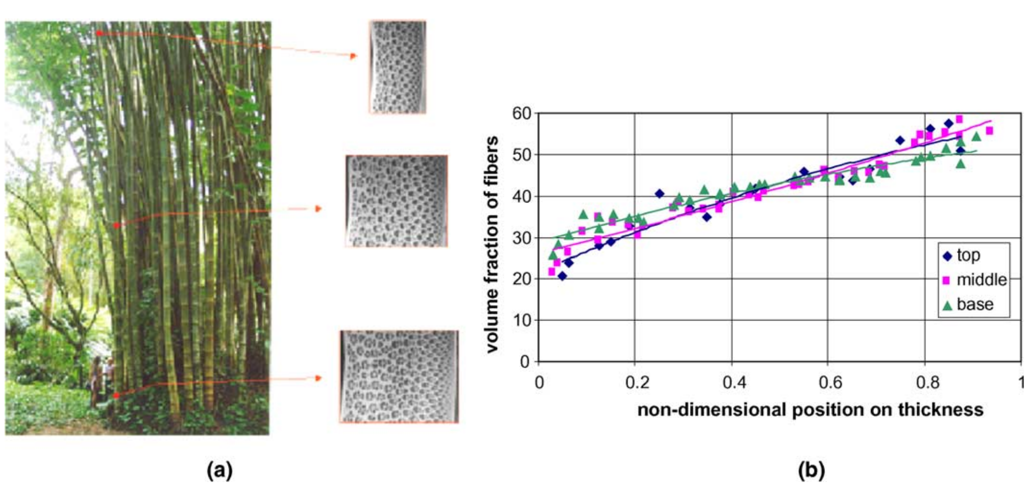

Fig. 3. Fibre distribution across the thickness using DIP method along bamboo. (a) Location of samples for DIP along the bamboo shell length DG. (b) Fibre distribution across bamboo thickness at base, middle and top part of DG.

knowing that the bamboo is subjected to maximum bending stress due to wind and its own weight in the base. However, the differences between the distributions are not very significant. Therefore all the data presented in Fig. 3(b) were used to establish Eq. (3) where the mean volume fraction variation of fibres across the thickness of bamboo DG is presented:

$$V_f(x) = 49.83x^2 - 0.49x + 12.01 \quad (3)$$

The variation of the shell thickness, t, and internodal distance, L, with the height of bamboo expressed in internode for the species *Dendrocalamus giganteus* (*DG*), *Moso*, *Matake*, *Guadua* and *Phyllostachys pubescens* is presented in Fig. 4. The internodal length is larger in the middle of the culm. The thickness, however, decreases from the base to the top of the bamboo shell. Based on the obtained data, a mathematical formula, which relates the thickness, t, to the position of the internode, n, is established for all species of bamboo studied. Eq. (4) gives the relation between t and n for bamboo DG. With the help of this equation the designer can choose the required thickness from the range of bamboo species DG.

$$t = -0.0003n^3 + 0.025n^2 - 0.809n + 16.791 \quad (4)$$

Similar mathematical formulas have been developed for diameter and internodal length of the bamboo.

The international norm for the evaluation of the mechanical behaviour of bamboo proposed by the international Bamboo Committee of INBAR [21] is being adopted by ISO and should be available to the general public soon.

2.2. Durability of bamboo as an engineering material

Just like timber, bamboo is vulnerable to environmental degradation and attacks by insects and moulds. Its durability varies with the type of species, age, conservation condition, treatment and curing. Curing should be initiated when bamboo is being cut in the bamboo grove. There is a strong relation between insect attacks and the levels of starch plus humidity content of bamboo culm. In order to reduce the starch content, bamboo receives a variety of treatments including curing on the spot, immersion, heating or smoke [1–5,12–15,19].

Drying bamboo is fundamental to its conservation for various reasons. Bamboo with low humidity is less prone to mould attacks especially when humidity content is less than 15%. Physical and mechanical properties of bamboo increase with a decrease in its humidity content. Bamboo to be treated with a preservative needs to be dry to facilitate penetration and obtain a better result and reducing transport costs. Bamboo can be dried in air, green house, and oven or by fire.

The durability of bamboo depends strongly on the preservative treatment methods in accordance with basic requirements: its chemical composition should not have any effect on the bamboo fibre and once injected it must not be washed out by rain or humidity. The preservative can be applied using simple systems such as leave transpiration, immersion, impregnation, Modified Boucherie Method, Boucherie Method to sophisticated modern equipment of cauldrons and special chambers working with vacuum or pressure [1–5,12,13,19,20].

Many steel and concrete structures built in the past 30 years reveal serious deterioration caused mainly by the corrosion of the steel reinforcement. In Fig. 5 a steel reinforced concrete column after 10 service years and the first bamboo reinforced concrete beam tested at PUC-Rio in 1979 [1–5] are presented and compared. The steel reinforced column is part of the tunnel structure of Rio's Metro. The bamboo reinforced beam after testing has been exposed to open air in the university campus. It can be observed that the bamboo segment of the beam reinforcement, treated against insects as well as for bonding with concrete, is still in satisfactory condition after 15 years.

However, the steel reinforcing bars of the column are severely corroded and need to be replaced. The bamboo segments of the beam were taken out of the tested concrete beam to establish its mechanical strength. Compared to the original untreated bamboo a slight deterioration of tensile strength was observed in the weathered samples of bamboo reinforcement. Beside the treatment of bamboo, extensive research how-

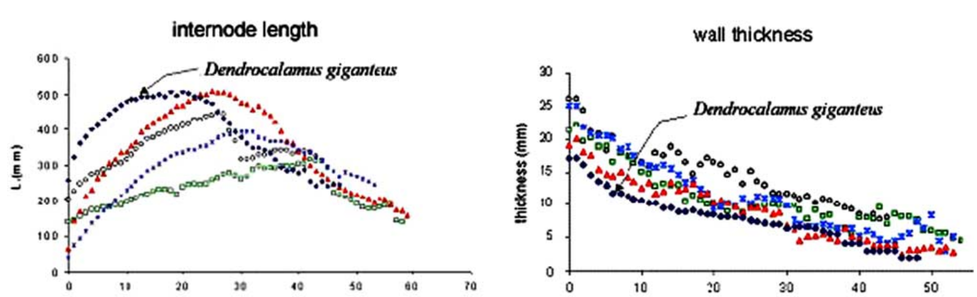

Fig. 4. Variation of thickness and internodal length along the whole bamboo culm.

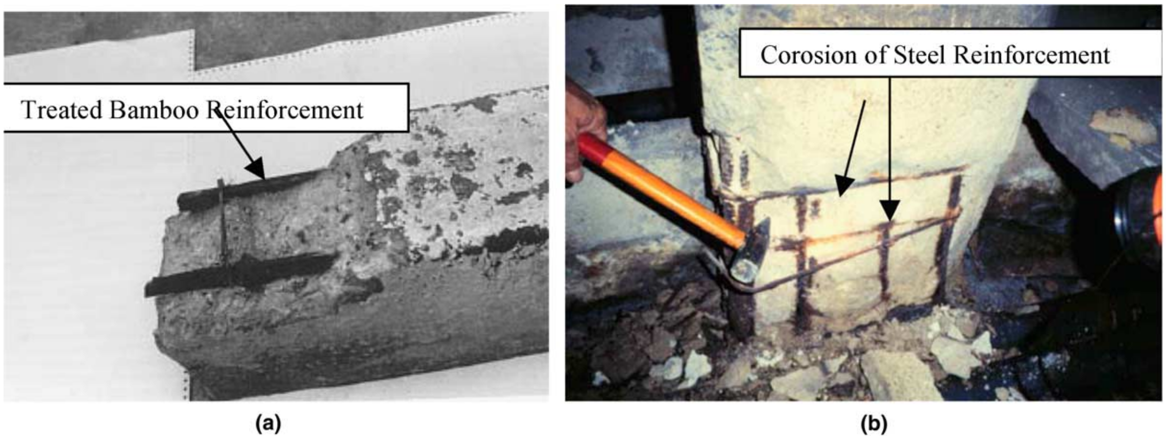

Fig. 5. Durability of bamboo and steel reinforcement in concrete elements. (a) Bamboo reinforcement of a tested beam exposed in open air after 15 years. (b) Steel reinforcement of a column in the tunnel of metro after 10 years in closed area.

ever shows that the combination of low alkali cementitious materials, chemical admixtures could improve the durability of concrete reinforced with vegetable fibres [21].

2.3. Effect of water absorption

One of the main shortcomings of bamboo is water absorption when it is used as a reinforcement and/or permanent shutter form with concrete. The capacity of bamboo to absorb water was studied on several species. A summary of the results is presented in Fig. 6. As seen from Fig. 6, *DG*, and *Bambusa vulgaris schard*, VS, absorbed the least amount of water among all compared species. The dimensional variations of the transversal section of bamboos DG and VS reached up to 6% after 7 days immersion in water [2,10]. The dimensional variation of untreated bamboo due to water absorption can cause micro or even macro cracks in cured concrete as shown in Fig. 7.

2.4. Bonding strength

A reinforcing bar in concrete is prevented from slipping by adhesion or bond between them. The main factors which affect the bond between the reinforcing bar and concrete are: adhesive properties of the cement matrix, the compression friction forces appearing on the surface of the reinforcing bar due to shrinkage of the concrete and the shear resistance of concrete due to surface form and roughness of the reinforcing bar.

The dimensional changes of bamboo due to moisture and temperature variations influence all the three bond characteristics severely. During the casting and curing of concrete, reinforcing bamboo absorbs water and expands as shown in Fig. 7(a). The swelling of bamboo

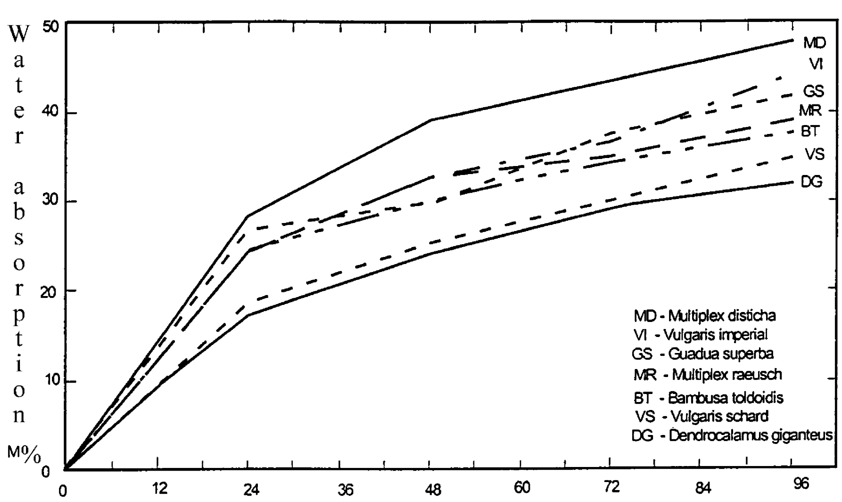

Fig. 6. Water absorption of different species of bamboo.

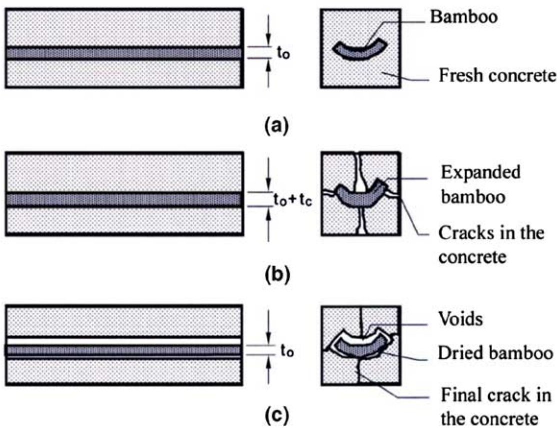

Fig. 7. Behaviour of untreated segment bamboo as reinforcement in concrete: (a) bamboo in fresh concrete, (b) bamboo during curing of concrete and (c) bamboo after cured concrete.

pushes the concrete away, shown in Fig. 7(b). Then at the end of the curing period, the bamboo loses the moisture and shrinks back almost to its original dimensions leaving voids around itself, shown in Fig. 7(c). The differential thermal expansion of bamboo with respect to concrete may also lead to cracking of the concrete during service life. The swelling and shrinkage of bamboo in concrete create a serious limitation in the use of bamboo as a substitute for steel in concrete. To improve the bond between bamboo segments and concrete, an effective water-repellent treatment is necessary. Various types of treatment have been studied with different degrees of success.

The impermeability treatment of bamboo is affected by three factors: The adhesion properties of the substance applied to bamboo and concrete, water repellent property of the chosen substance and the topography of bamboo/concrete interface. One effective treatment is the application of a thin layer of epoxy to the bamboo surface followed by a coating of fine sand. However, this is an expensive treatment in many countries including Brazil. Materials such as asphalt paints, tar based paints and specific bituminous materials satisfy all the impermeability requirements.

The bonding between bamboo and concrete for 20 types of products has been established in pull-out tests shown in Fig. 8. To avoid the effects of non-uniform shear stress distribution in conventional tests, only the middle part (100 mm) of the bar is subjected to shear [4,8,10]. The top and bottom parts are prepared such that the applied shear bond is zero at their locations as shown in Figs. 8 and 9. The application of a very fine layer of IGOL-T or Negrolin product on a bamboo, which is wrapped with a wire of 1.5 mm diameter, has shown to increase shear strength for the interface.

The bonding shear stress, τ_b, is calculated by Eq. (5).

$$\tau_b = \frac{F}{L \cdot S} \tag{5}$$

where F is the applied pulling load and S is the perimeter of the bamboo and $L = 100$ mm is the length of bonded interface. This treatment has shown (see Table 1) to improve the shearing bond strength of bamboo/concrete interface by up to 90% [10].

In most recent studies the product called Sikadur 32-Gel, which has been developed to prevent the corrosion of reinforcing bars, has been applied on the surface of reinforcing bamboo segments [8,9]. The results show that the new product Sikadur 32-Gel has increased the bonding strength of treated bamboo segments 5.29 times, compared with that of untreated segments of bamboo and steel, as given in Table 1.

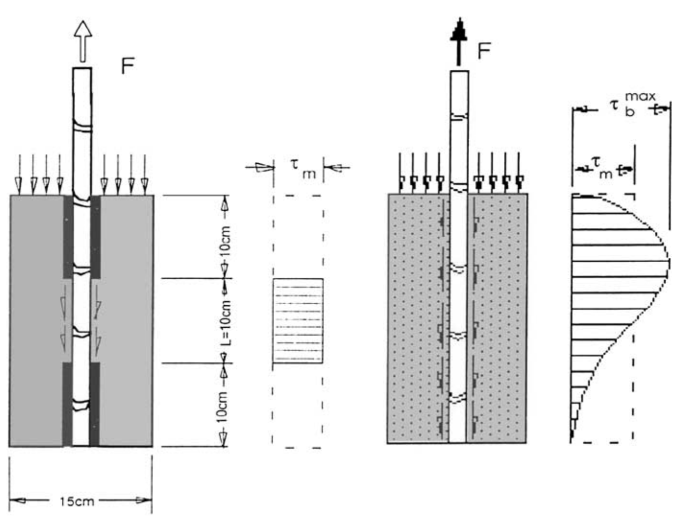

Fig. 8. Pull out test of the bamboo segments. (a) Improved pull-out test; (b) Conventional pull-out test.

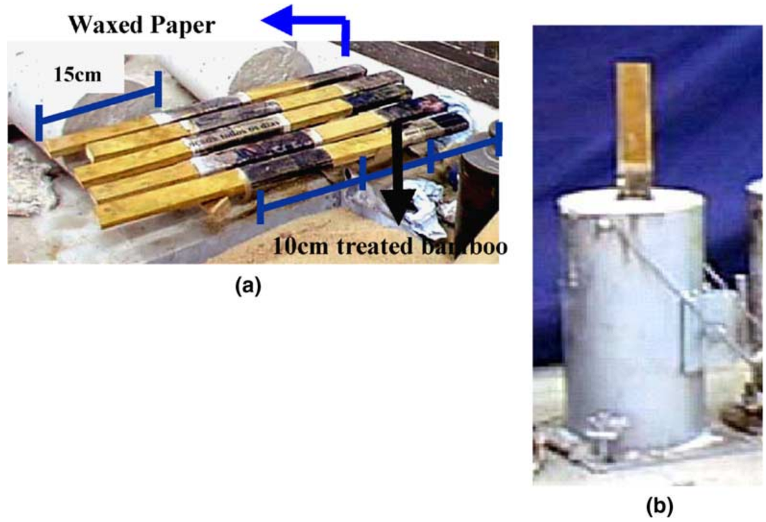

Fig. 9. Pull-out tests on untreated and treated bamboo segments. (a) 3 cm bamboo segments. (b) Test specimen before testing.

Table 1
Bonding strength of bamboo segment subjected to pull-out test

Treatment	Bond strength of treated bamboo τ_b	Bond strength of untreated bamboo τ_b/τ_{bnt}
Without treatment	0.52	1.00
Negrolin + sand	0.73	1.40
Negrolin + sand + wire	0.97	1.87
Sikadur 32-Gel	2.75	5.29
Steel	3.25	6.25

3. Bamboo reinforced concrete elements

3.1. Bamboo reinforced concrete beams

Simply supported bamboo reinforced concrete beams, fabricated with normal, lightweight and laterite aggregates of 20 mm maximum size have been tested. A beam, reinforced with steel bars, served as reference. Expanded clay, fabricated in Sao Paulo, is commonly used in the Southeast of Brazil as lightweight aggregate. In the Northeast, as normal aggregates do not exist, abundantly occurring laterite aggregates were considered. Throughout the research programs ordinary Portland cement CP-32 and natural-washed river sand were used.

The normal concrete was proportioned 1:1.4:2.4 by weight with a water cement ratio of 0.45; and the proportions for lightweight concrete were 1:3.22:0.78 of cement, fine and coarse aggregate with a water cement ratio of 0.55 respectively.

The compressive strength of the concrete was established on 15 cm diameter and 30 cm high cylinders. The ultimate compressive strength, f_{cc}, and modulus of elasticity in compression, E_c, varied between 20–40 MPa and 12–34 GPa, respectively [1–5,7]. The split bamboo culms were of 30 mm wide rectangular sections. The smooth surface of the bamboo splints was cleaned and slightly roughened before being coated with a thin layer of the impermeable product together with sand. The pieces were then wrapped with 1.5 mm wire at 10 mm distance and once more coated with the same product. Immediately after that, fine sand was manually pressed into the surface and the splints were allowed to dry for 24 h before being fixed inside the formwork as can be seen in Fig. 10(a). The bamboo reinforcing ratio, ρ, varied between 0.75% and 5.00%.

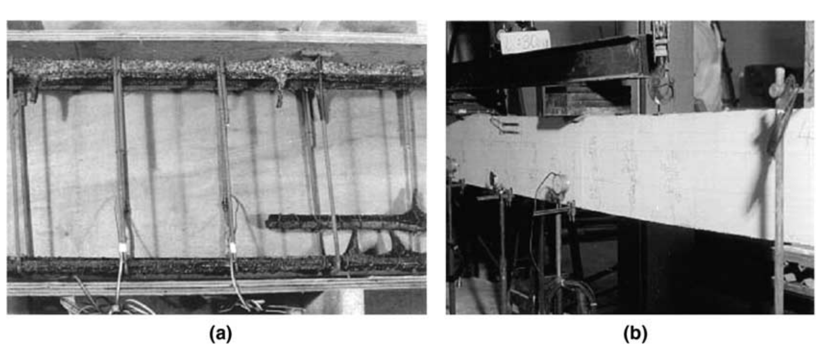

Fig. 10. Bamboo reinforcing concrete beams. (a) Detail of bamboo reinforcement in beam. (b) Bamboo reinforced concrete beam test.

The beams of dimensions $340 \times 12 \times 30$ cm, with a free span of 300 cm, were fabricated inside a form, into which concrete was poured in layers of 10 cm. Then the form was vibrated as recommended by the Brazilian Norms. The beams were tested after a curing period of 28 days, both at PUC-Rio and the Federal University of Paraiba (UFPb). Fig. 10(b) shows the experimental set up of a beam subjected to two-point load at the third span.

The test results showed that the treatment of bamboo prior to use improved the bamboo–concrete bonding by more than 100%. By adopting $\rho = 3\%$ as the ideal value, the ultimate applied load increased by 400% as compared with concrete beams without reinforcement [7].

3.2. Concrete slabs with bamboo permanent shutter forms

Bamboo finds an efficient application in concrete slabs reinforced with half bamboo sections, which work as permanent shutter forms [2,4,6,9]. The same methodology and concrete, as used for bamboo reinforced concrete beams, were applied to establish the mechanical and structural behaviour of a slab of maximum dimensions of $80 \times 14 \times 316$ cm, with a free span of 300 cm, as shown in Fig. 11.

A half split DG bamboo culm, which works as a tensile reinforcing bar and also as a permanent shutter form, schematically shown in Fig. 12(a), was filled with concrete as can be seen in Fig. 13. In the most recent experimental investigation different types of connecters, such as steel bars or entire diaphragms as shown in Fig. 13(b) have been investigated. In all cases the internal parts of bamboo were treated with a thin coat of Sikadur 32-Gel as shown in Fig. 12(b). In Fig. 13 the fabrication of permanent shutters is shown: with half diaphragms shown in Fig. 13(a), with entire diaphragms as connectors in Fig. 13(b) and the permanent shutter bamboo slab, before the lateral timber forms were taken out, in Fig. 13(c).

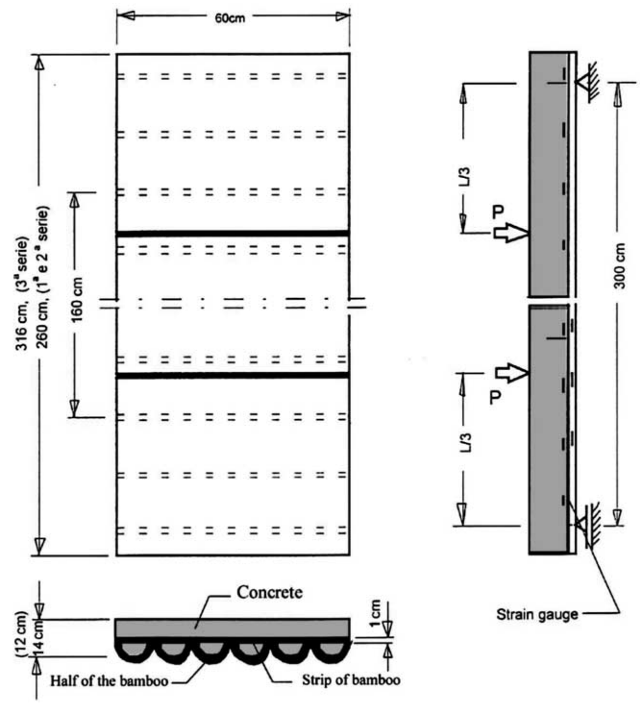

Fig. 11. Dimensions of the concrete slabs reinforced with bamboo permanent shutter forms.

The experimental results have been analysed using conventional analytical methods proved not to be sufficient enough as this type of structural elements work as composite slabs with the bamboo diaphragms acting as connectors. Therefore, for the analysis of the slabs, beside the normal semi-analytical method, the layer-wise theory and Finite Element method were used to realize a parametric study considering different variables influencing the behaviour of the composite slabs [2,9]. One of the important factors, which has a great influence on the ultimate load of the slab, is the shear resistance of the bamboo diaphragm.

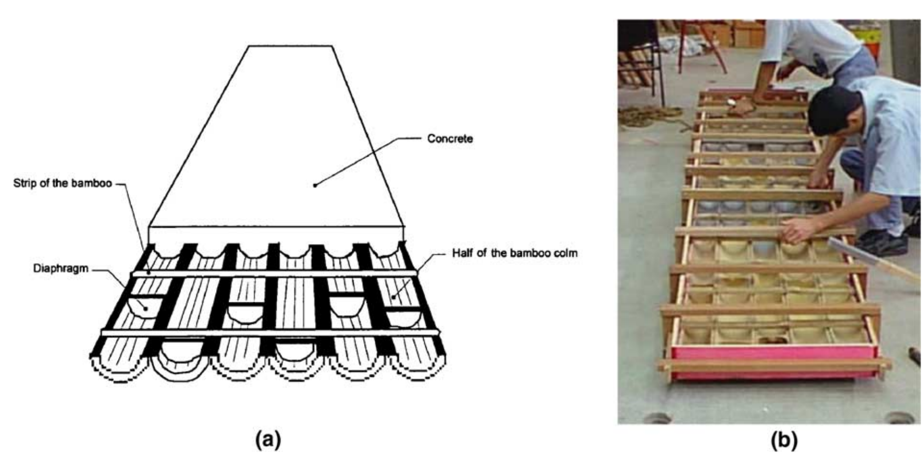

Fig. 12. Concrete slabs reinforced with bamboo permanent shutter forms (a) Schematic set up of the slab. (b) Bamboo of slab during treatment.

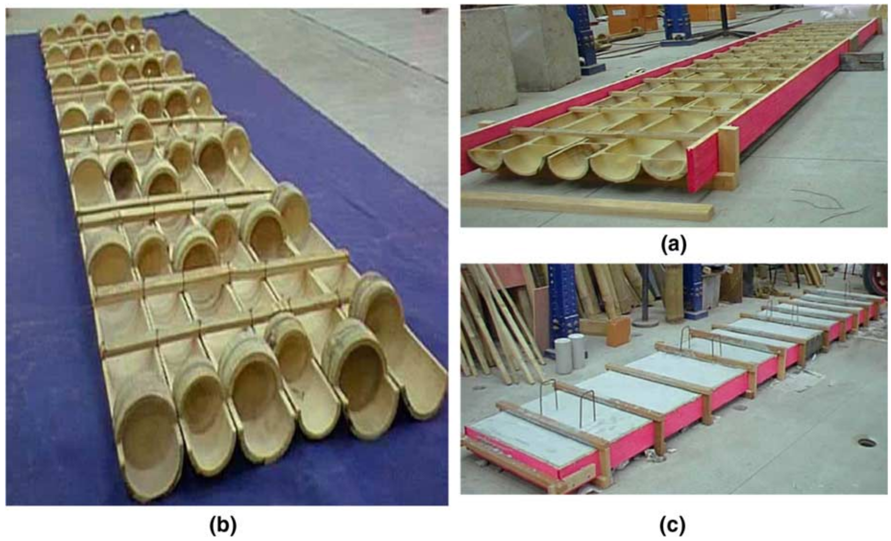

Fig. 13. Concrete slabs reinforced with bamboo permanent shutter forms. (a) Half bamboo diaphragm as connector. (b) Second type of connector. (c) Slab before testing.

The shear resistance of whole and half bamboo diaphragms of specie DG has been studied. For the half bamboo its shear strength has been found to be 10.89 MPa with a standard deviation of 2.56 MPa. Although the bamboo diaphragm creates a composite interaction between bamboo and concrete, its shear resistance is not sufficient enough to prevent its shear failure. Most of the tested slabs had first failed due to de-bonding and failure of the diaphragm then followed by concrete compression failure.

To increase the shear strength of half bamboo several alternatives were considered. One of the simplest methods was to consider the entire bamboo diaphragm as shown in Fig. 13(b). To improve further a strip of steel or bamboo rod close to the bamboo diaphragm passing through the bamboo diameter was fixed. These two methods almost doubled the shear strength of the diaphragm hence the ultimate load of the slabs. This type of slab is now successfully used in Brazil. However, at present, studies are being carried out to improve the bonding between bamboo and concrete with other new products available on the market beside the improvement of the shear connector behaviour of low cost.

3.3. Bamboo reinforced concrete columns

The structural component being developed, analysed and tested recently is a bamboo reinforced concrete circular column with permanent shutter form as shown in Fig. 14. The main reinforcement of this 30 cm diameter column is made entirely of treated 30 mm wide DG bamboo segments. The bamboo was treated with a new product, Sikadur 32-Gel, which gave a better bonding when compared to other products previously used. As it can be seen in Fig. 14 beside the bamboo reinforcement the concrete form is also entirely made of bamboo. Bamboo can be left to work as a permanent shutter as it has a pleasing aesthetic appearance and also can economize the finishing costs of the concrete [20].

As in the construction of the popular housing in Brazil the common practice is to use square steel reinforced concrete with a nominal cross-section of 20 cm × 20 cm an investigation was carried out to substitute the steel reinforcement with the treated bamboo segments. After the theoretical analysis, the required amount of bamboo culms of DG of at least 3 years of age were split with a wedged knife and cut into rectangular sections of 30 mm width and were used as reinforcement of the column as shown in Fig. 15. The surface of the bamboo splints was then cleaned and slightly roughened. The bamboo reinforcements were treated using Sikadur 32-Gel. The form, made from plywood of 15 mm thickness stiffened with 30 × 80 mm timber ribs at 40 cm spacing, improved the rigidity against the side deflection. The height of the columns was limited to the height of the testing rig, which was 200 cm. To obtain the data for comparison, a control column of steel reinforcement concrete was also prepared using the same mix proportions as for bamboo-reinforced columns. The columns were fabricated as recommended by the Brazilian Norms. All the columns wee cured for 28 days, using wet saw dust, before they were tested.

To measure the strain in the reinforcing bars 10 mm electrical strain gauges, fabricated by Kyowa, were fixed at predetermined points before pouring concrete as can be seen in Fig. 15. To establish the percentage of bamboo reinforcement in relation to the column's cross-section, ρ, three values as given in Fig. 15 for columns B4, B10 and B12 were chosen. They were covered by special resin to protect against accidental damage. Electrical

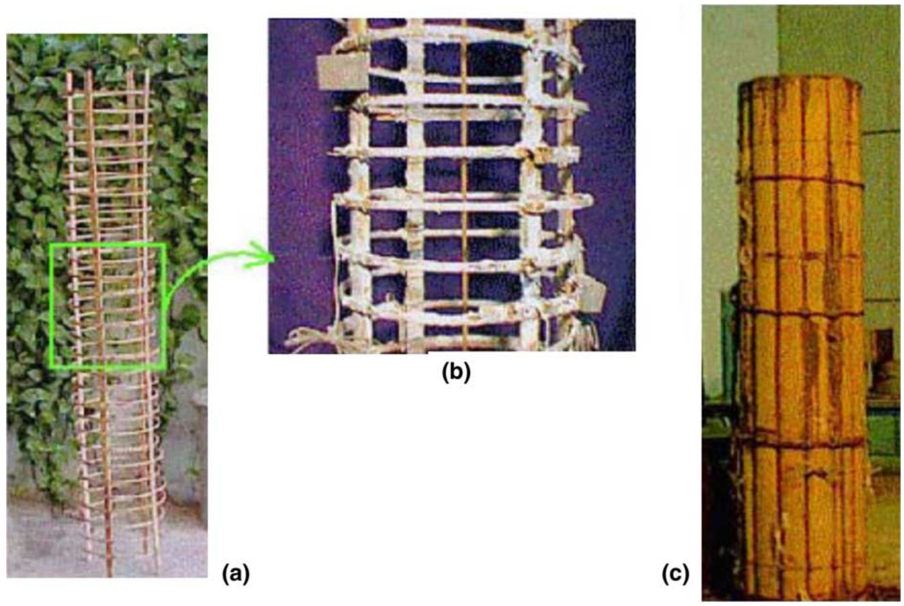

Fig. 14. Circular bamboo reinforced concrete column with permanent shutter: (a) column reinforcement, (b) details of reinforcement and (c) final product.

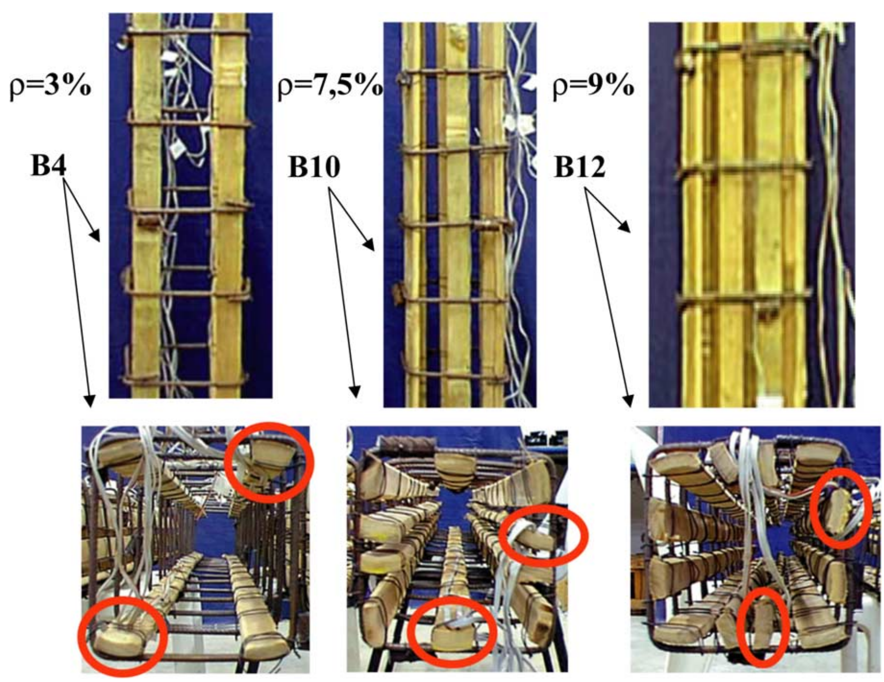

Fig. 15. Details of rectangular concrete column reinforced with treated bamboo.

strain gauges of 30 mm length also were fixed to the concrete at the middle of the columns as shown in Fig. 16(c).

The columns were tested in a steel frame of 1000 kN capacity and were subjected to axial load as can be seen in Fig. 16(c). The load was applied in increments of 2 kN. For each increment the strains, lateral deflection and crack initiation and propagation of concrete were recorded. The crack, which could be observed by a magnifying glass of ×5, was considered to be the first crack. All the columns failed almost at the same load due to crashing of concrete at the extreme end including the conventional steel reinforced concrete prepared in accordance with the Brazilian Norms. The main conclusion of this research program was that 3% of the bamboo reinforcement treated with Sikadur 32-Gel would be as good as the conventional steel reinforcement for normal concrete recommended by the Brazilian Norm.

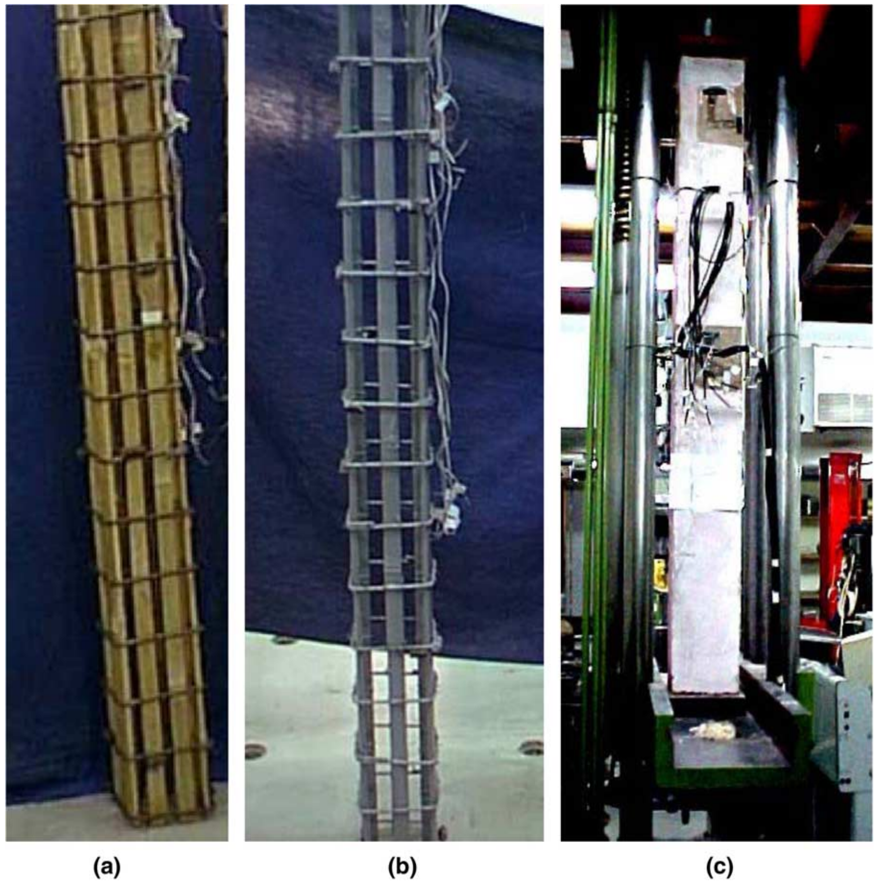

Fig. 16. Details of rectangular concrete column reinforced with bamboo segments and the testing rig: (a) Before treatment, $\rho = 9\%$; (b) after treatment, $\rho = 7.5\%$; (c) during testing, $\rho = 7.5\%$.

3.4. Analysis of bamboo reinforced concrete elements subjected to bending

As for conventional steel reinforced concrete beams and slabs subjected to increasing bending load up to collapse, the bamboo reinforced elements also go through three characteristic stages of stress and strains in their cross-sections as shown in Fig. 17. In this figure D, d and b are the total, the effective depth and the width of the bending element respectively. A_{bt} is the area of bamboo subjected to tension, ε_c and f_c are compression strain and stress of the concrete, ε_{bt} and f_{bt} are tensile strain and stress in bamboo.

In stage 1 for a small load, the stress and strain are in linear elastic range. The normal compression and tension stresses in a section in concrete are triangular. With an increase of the applied load the internal stress diagram of concrete along the depth of the section becomes non-linear until the ultimate tensile strength of the concrete is reached.

In stage 2 the bamboo at the cracked points and the concrete between the crack, in the tension zone, resists

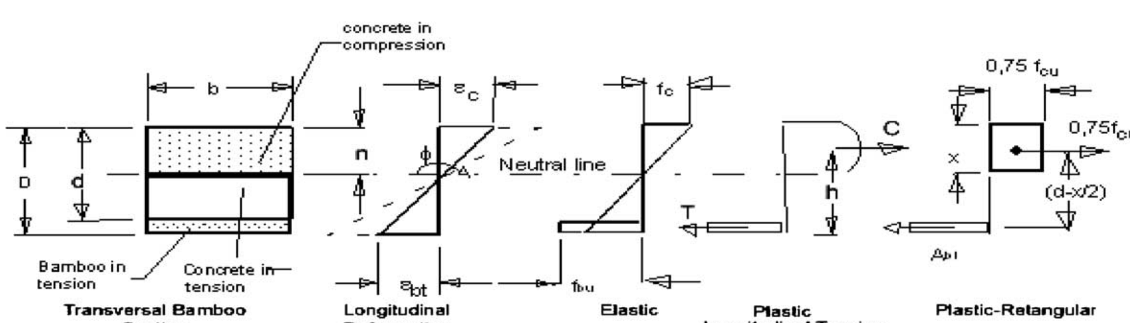

Fig. 17. Stress and strain distribution in an element subjected to bending at different stages.

the internal tensile stresses. The stress distribution in the bamboo in the un-cracked part is similar to the conventional pull out test i.e. the further from the crack point the higher the bonding shear stress, as the bond between bamboo and concrete in this region is still almost intact. With the increase of the applied load the stress diagram in the compression zone of concrete continues to be non-linear before its ultimate strength "f_{cu}" and bamboo in tension starts to break from its extreme lower layer and hence, starting the third stage.

In stage 3 the diagram of normal compression zone of concrete is of parabolic shape. However, for the development of formulae for the practical design a rectangular shape is adopted. Depending on the percentage of bamboo reinforcement three cases may occur: the case with under-reinforcement, where the failure of bamboo leads to the collapse of the bending element; with over-reinforcement, where the collapse of the element occurs due to compression failure of concrete; and the balanced case, where both concrete and bamboo could fail simultaneously. Based on the obtained experimental data of the beams and one way composite slabs and the explained failure modes formulae for the design of these reinforced concrete elements have been developed [1,2,4,6,7,9,10].

In all the bamboo reinforced beam tests realized up to present failure mostly occurred due to tensile failure of concrete and bamboo. Although in several cases the test beams were over-reinforced, no compression failure was provoked. This is mainly due to the impossibility to create a perfect bonding between bamboo and concrete. With the advent of new products a research program is underway to overcome this. However, in the permanent bamboo shutter slabs with only a diaphragm as connector the collapse was mainly due to shear failure of connector.

4. Concluding remarks

Environmental concerns have broadened during the last two decades. Initially it meant to analyse visible catastrophes such as a dying forest or dead fish on a shore and we slowly came to realize that any excessive or inefficient consumption of resources is in fact an abuse of the environment.

The understanding of sustainability in building construction has also undergone changes over the years. First attention was given to the issue of limited resources, especially energy, and how to reduce the impact on the natural environment. Now, emphasis is placed on more technical issues such as materials, building components, construction technologies and energy related design concepts as well on non-technical issues such as economic and social sustainability.

Since 1979 research has been carried out in Brazil on non-conventional materials and technologies. New building components were developed using vegetable fibre as reinforcement of cement mortar and bamboo as reinforcements in beams, columns, slabs and permanent shutter forms in concrete slabs and columns. Our concern was as well the dissemination of our work, which has occurred through publications and special courses. The Brazilian Association of the Sciences of Non-conventional Material Technologies, *abmtenc*, was founded to further the dissemination and the cooperation between engineers, architects, designers and civil servants related to housing.

Based on the research results of bamboo obtained in Brazilian universities and other institutes around the world the first norms for bamboo were created determining the physical and mechanical properties of bamboo. These norms have been evaluated by ICBO and will be included in the ISO norms in near future [22]. The results of the investigations show that bamboo can substitute steel satisfactorily. The structural elements developed and studied could be used in many building constructions. Many investigations are being carried out to establish the durability of bamboo reinforcement, besides improving the bonding of bamboo reinforcing bars. There is a need to establish the characteristic strength of bamboo for design purpose based on a rigorous statistical analysis. There is even a greater need in introducing courses at graduate and post-graduate level on the use of bamboo as a structural material in universities and technical schools besides establishing specific international norms for the design of structural elements using bamboo.

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References

[1] Ghavami K, Hombeeck RV. Application of bamboo as a construction material: Part I—Mechanical properties and water-repellent treatment of bamboo, Part II—Bamboo reinforced concrete beams. In: Proc of Latin American Symp on Rational Organization of Building Applied to Low Cost Housing, CIB, São Paulo, Brazil, 1981. p. 49–66.

[2] Ghavami K, Zielinski ZA. Permanent shutter bamboo reinforced concrete slab. BRCS1, Department of Civil Engineering, Concordia University, Montreal, Canada, 1988.
[3] Ghavami K, Culzoni RAM. Utilização do Bambu como Material em Habitação de Baixo Custo. 1° Simposio Int. de Habitação, PT, São Paulo, 1987. p. 181–8.
[4] Ghavami K. Application of bamboo as a low-cost construction material. In: Proc of Int Bamboo Workshop, Cochin, India, 1988. p. 270–9.
[5] Ghavami K. Desenvolvimento Alternativo para Construção da Habitação de Baixo Custo: Bambu. J Debates Sociais-Pobreza & Desenvolvimento, Rio de Janeiro 1994;27(52/53):119–32. [in Portuguese].
[6] Barbosa NP, Toledo Filho RD, Ghavami K. Comportamento de Lajes de Concreto em Forma Permanente de Bambu. XXVI Jornadas Sulamericanas de Ingenieria Estrutural, Montevideo, Uruguai, vol. 3, 1993. p. 191–202 [in Portuguese].
[7] Ghavami K. Ultimate load behaviour of bamboo reinforced lightweight concrete beams. J Cement Concrete Compos 1995;17(4):281–8.
[8] Pereira da Rosa SPA. Análise Teórica e Experimental de Colunas Armado com Bambu. MSc thesis, Civil Engineering Department, PUC-Rio, 2002 [in Portuguese].
[9] Navarro EHA. Lajes de Concreto com Forma permanente de Bambu. MSc thesis, Civil Engineering, PUC-Rio, 2002 [in Portuguese].
[10] Culzoni RAM. Características dos bambus e sua utilização como Material Alternativo no Concreto. MSc thesis, Department of Civil Engineering, PUC-Rio, 1986 [in Portuguese].
[11] Ghavami K, Rodrigues CS. Engineering materials and components with plants. In: CIB Symposium, Construction and Environment, Theory into Practice Proc., São Paulo, Brazil, CD-ROM, ISBN 85-88142-01-5, Global Seven Edition, 2000. p. 1–16.
[12] Dunkelberg K et al. Bamboo as a building material. Bamboo-IL 31, Institute for Lightweight Structures, University of Stuttgart, 1985. p. 1–431.
[13] Janssen JA. Bamboo in building structures, PhD thesis, Eindhoven University of Technology, Holland, 1981.
[14] Janssen JA. the importance of bamboo as a building material. Bamboos current research. In: Proc of the Int Bamboo Workshop, Kerala Forest Research Institute—India & IDRC—Canada, 1988. p. 235–41.
[15] Lopez OH. Nuevas Tecnicas de Construcion com Bambu. Estudios Técnicos Colombianos Ltda 1978. [in Spanish].
[16] Ashby MF. Materials selection in mechanical design. Oxford: Pergamon Press; 1992.
[17] Wegst UGK, Shercliff HR, Ashby MF. The structure and properties of bamboo as an engineering material, University of Cambridge, UK, 1993.
[18] Amada S. Bamboo—A natural, super-advanced and intelligent material. In: Proc 2nd Int Conf on Non-Conventional Construction Materials (NOCMAT-97), Bhubaneswar, India, 1997. p. 1–9.
[19] Liese W. The structure of bamboo in relation to its properties and utilization. In: Proc Int Symposium on Industrial Use of Bamboo, Beijing, China, 1992. p. 95–100.
[20] Ghavami K, Villela M. Coluna reforçada combambu. Course Report, DEC/PUC-Rio, 2000 [in Portuguese].
[21] Swamy RN, editor. New reinforced concretes, concrete technology and design, vol. 2, Blackie and Son, Glasgow, 1984.
[22] ICBO, AC 162: Acceptance criteria for structural bamboo, ICBO Evaluation Service Ltd., California, USA, 2000.