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Ultimate Load Behaviour of Bamboo-Reinforced Lightweight Concrete Beams

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Abstract

The classification of seven bamboos studied in accordance to their physical and mechanical properties, the type and method of application of water repellent treatment of bamboo splints and the bond strength between bamboo and lightweight concrete are described in this paper. The results of the experimental analysis of two simply-supported bamboo-reinforced lightweight concrete beams with an overall length of 340 cm and a cross-section of 12 cm by 30 cm width and height, respectively, subjected to two point loads up to collapse are presented. One beam of the same dimensions and concrete mix reinforced with steel was also tested for comparison of the results. Finally a recommendation based on the analysis of the results for the design of such beams is proposed.

Keywords: Lightweight concrete, beams, bamboo reinforcement, bending strength, ultimate load, bamboo treatment, deflection, cracking, structural behaviour, bond stresses, design.

INTRODUCTION

Low-cost housing construction both in developed and developing countries is a complicated and ever present problem. It has been created on the whole by the natural economic and cultural environment of the social group concerned. There are many difficulties, such as poverty, uncontrolled migration, and demographic growth, which should be considered when finding an appropriate solution to it.

In developing countries one of the main additional difficulties in the solution of housing problems is the shortage of scientists, engineers, architects and technicians, whose education and training can be adapted to the particular needs of low-cost construction. Inadequate training, materials, facilities for the construction and lack of exchange and dissemination of research findings and practical experiences should also be included. To overcome the housing problem, the author of this paper has been carrying out several research programs since 1979 using indigenously available local materials such as bamboo, coconut fibres, sisal and other natural fibres as construction materials.[1-10]

The advantages and disadvantages of bamboo when used as reinforcement in concrete are described in previous publications.[1-7] This paper is concerned with the physical and mechanical properties of seven bamboos and a series of experimental tests which were carried out on simply-supported lightweight concrete beams subjected to two point loads at a third of the span. The lightweight concrete mix proportions were 1:3·22:0·78 of cement:fine aggregate:coarse aggregate and water cement ratio of 0·55, all measured by weight. The width, depth and the length of the beams were 12 cm, 30 cm and 340 mm, respectively. One of the beams was reinforced with steel bars for the comparison. The results show that segments of bamboo can be safely used as a substitute for steel in reinforced lightweight concrete beams.

BASIC CHARACTERISTIC OF BAMBOO

Bamboos are giant grass-like plants and not trees as commonly believed. They belong to the family of the *Bambusoideae*. The bamboo culm is a cylindrical shell which is divided by transversal diaphragms at the nodes. The bamboo culm consists of up to 70% longitudinal fibres which are distributed non-uniformly across the section. The distribution is more dense in the exterior part. Bamboo basically is an orthotropic material. It has high strength along, and low strength transversal to fibres.[11–14]

The physical and mechanical properties of seven bamboos, available in Rio de Janeiro, have been studied. The average values of the length, diameter, internode distance, thickness of the culm, specific weight and the natural humidity of the studied bamboos are given in Table 1.

For each test group 12 tests were carried out. It can be observed that the mean specific weight of bamboo varied between 6·5 kN/m^3 and 9 kN/m^3, the diameter between 2 cm and 10 cm with a average natural humidity of 15·9%.

For each type of bamboo under study, the mechanical properties along the bamboo culm, in addition to the influence of the node, were also studied. One of the main problems in establishing the tensile, compressive, and shear strength of bamboo is the type of test specimen. The details of the test specimens used to find the mechanical properties of bamboo under study are given in Ref. 1. The summary of the results for each type of bamboo is given in Table 2. It can be noted that the tensile strength, σ_t, of *Bambusa vulgaris schard* and *Dendrocalamus giganteus* is about 170 MPa and 135 MPa, respectively. This makes the use of bamboo in civil construction very attractive, especially when the ratio of the tensile strength to the specific weight of bamboo is considered.

The compression strength, σ_c, of the bamboos was established using whole bamboo with the

Table 1. Physical properties of seven bamboos of Rio de Janeiro

Physical properties	*Bamboo*						
	Bambusa multiplex raeusch (MR)	*Bambusa multiplex disticha (MD)*	*Bambusa tuldoidis (BT)*	*Bambusa guadua superba (GS)*	*Bambusa vulgaris imperial (VI)*	*Bambusa vulgaris schard (VS)*	*Dendro-calamus giganteus (DG)*
Color	Green	Emerald green	Light green	Green	Yellow with green strip	Green	Dark green
Total length (m)	3·50	7·50	8·00	9·00	10·00	13·00	21·00
Average internode (cm)	45·00	48·00	40·00	35·00	35·00	40·00	50·00
Average diameter (cm)	2·00	3·20	3·50	9·00	7·00	8·00	10·00
Thickness (cm)	0·35	0·35	0·60	0·80	0·80	0·90	1·1
Specific weight (kN/m^3)	8·80	9·20	9·60	9·00	6·50	7·20	9·00
Natural humidity (%)	15·40	15·20	15·69	18·30	16·00	13·50	17·60

Table 2. Mechanical properties of bamboos given in Table 1

		Bamboo types						
		MR	*MD*	*BT*	*GS*	*VI*	*VS*	*DG*
No node	σ_t	124·7	124·5	119·5	146·5	134·4	170·6	135·0
	$E_t \times 10^3$	11·2	14·0	11·93	11·16	7·76	10·97	14·5
Node	σ_t	95·3	74·3	104·00	112·3	48·05	127·77	119·02
	$E_t \times 10^3$	10·05	11·54	9·27	9·12	6·05	8·81	11·75
No node	σ_c	35·7	28·25	38·05	47·80	41·10	52·67	45·54
	$E_c \times 10^3$	3·30	4·21	3·01	3·34	2·48	3·24	4·02
Node	σ_c	27·20	20·30	30·10	35·70	12·30	39·67	38·96
	$E_c \times 10^3$	2·80	3·30	2·90	2·65	2·10	2·59	3·58
No node	σ_b	98·30	80·80	100·00	113·50	115·00	141·33	124·36
	$E_b \times 10^3$	9·68	11·87	9·34	9·24	6·62	9·35	12·18
Node	σ_b	71·00	60·00	86·5	89·75	41·75	106·94	93·04
	$E_b \times 10^3$	8·03	8·63	7·26	6·73	5·18	7·35	10·00
Shear	τ (MPa)	62·00	53·00	54·50	48·00	40·08	41·17	44·00

σ_t=tensile stress; σ_c=compression stress; σ_b=bending stress.

height to diameter ratio of 2. It was found that the compression strength is much lower than the tensile strength and is in the range 12–53 MPa. The bending specimens used in the test were of variable size and depended on the thickness of the specimen, T. The width and the length of the test specimen were $4T$ and $16T$ respectively. The highest value was observed for *Bambusa vulgaris schard* and *Dendrocalamus giganteus* which are 141 and 124 MPa, respectively. The dimensions of the shear test specimens were 12 cm length and 1 cm width. The shear strength, τ, perpendicular to the fibres, of the studied bamboos was between 40 and 62 MPa.

WATER REPELLENT TREATMENT OF BAMBOOS

One of the main shortcomings of bamboo when used as a reinforcing bar is the effect of water absorption. The capacity of water absorption of the seven bamboos was studied and the summary of the results is given in Fig. 1. As it can be noted the *Dendrocalamus giganteus* prevails minimum capacity of water absorption in comparison with the other species.

In order to reduce the water absorption of bamboo culms several types of water-repellent treatments were studied.[1–4] The most suitable agent was found to be Negrolin produced by Sika in Brazil which after 96 h in drinking water allowed only 4% of water absorption. This is considered to be insignificant.

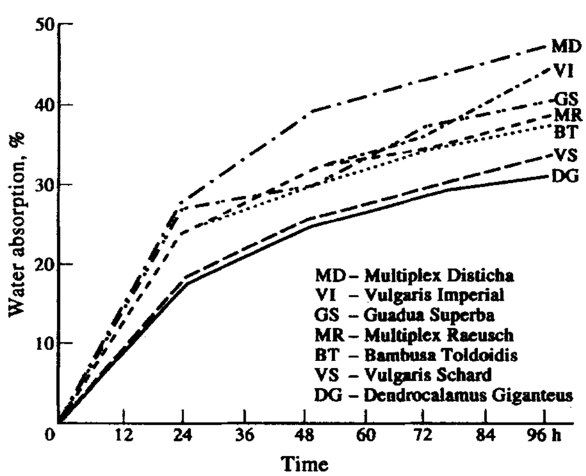

Fig. 1. Water absorption of seven types of bamboos studied.

BOND TESTS

To examine the bond between bamboo and lightweight concrete, a series of pull-out tests

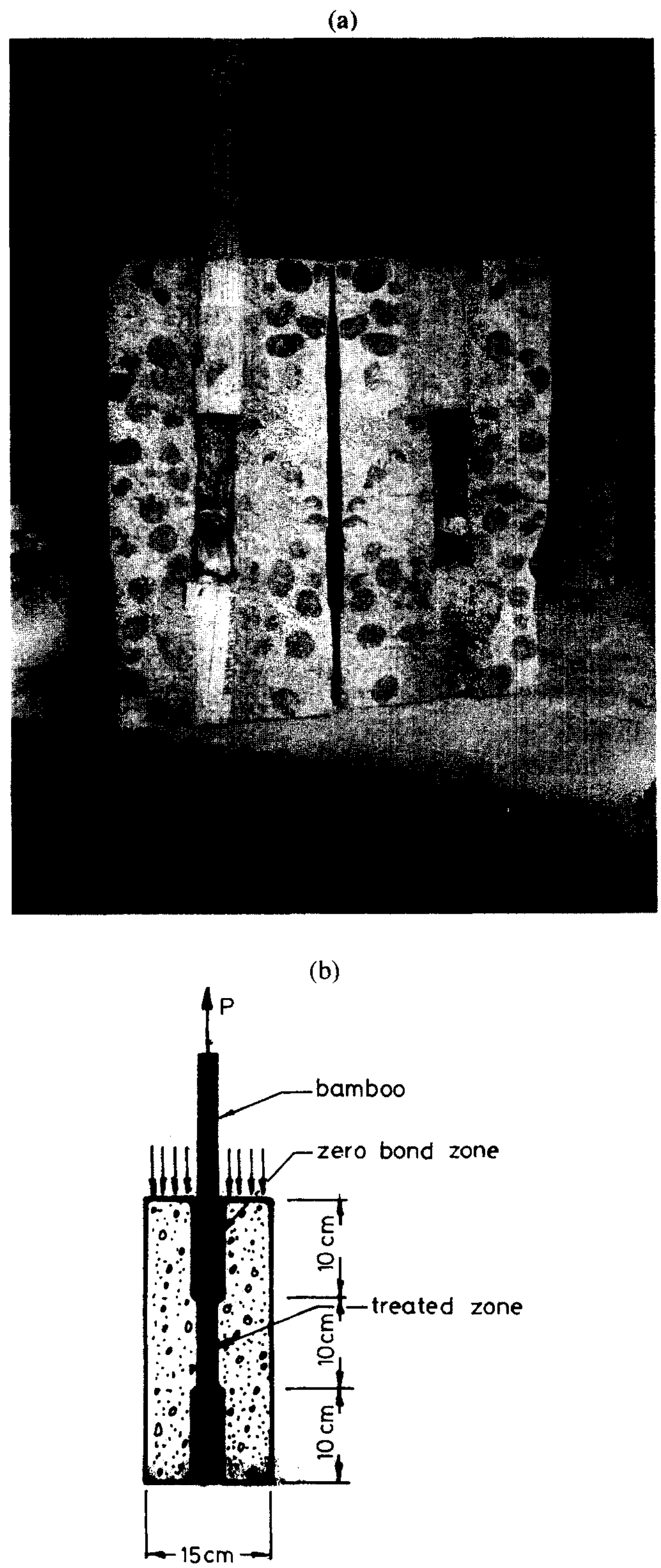

Fig. 2. Bamboo reinforced concrete pull-out test. (a) Position of bamboo in side concrete cylinder. (b) Dimensions of pull-out test.

on untreated and treated bamboos with Negrolin-sand was executed. In addition two series of tests on bamboo segments which were wrapped first with 1·5 mm diameter wire with about 4 cm spacing and then treated with Negrolin-sand were carried out.

In the pull-out test, the bamboo splints of 3·0 cm width were used in a lightweight concrete cylinder of 15 cm in diameter and 30 cm in height. To exclude the secondary stresses which occur in the conventional pull-out tests, only the 10 cm of the central part of the bamboo segments were treated with Negrolin-sand and the rest was covered with waxed paper, so that no bond in these regions could exist. This is shown in Fig. 2.

The test results were analysed considering a uniform stress distribution along the bonded zone. The bond stress, τ_b, in N/mm^2 was calculated by eqn (1).

$$\tau_b = \frac{F}{100.S} \tag{1}$$

where F is the applied pulling load in Newtons and S is the perimeter of the bonded bamboo in mm.

The test results are given in Table 3. It can be noted that the treated bamboo with Negrolin-sand and wiring has improved the bond stress up to 90%. Hence this method was used for the study of bamboo-reinforced lightweight concrete beams.

DETAILS OF BAMBOO REINFORCED CONCRETE BEAMS

The lightweight concrete used for the beams was made using ordinary portland cement CP-32 (Brazilian fabrication), natural-washed river sand and expanded clay aggregate, with a maximum size of 20 mm. The lightweight concrete mix proportions were 1:3·22:0·78 of cement: fine aggregate:coarse aggregate and a water–cement ratio of 0·55; all were measured by weight.

The compressive strength of the concrete was established on 15 cm diameter and 30 cm high cylinders. For each batch of concrete, five compression test specimens were prepared according to the Brazilian Association of Technical Norms. The tensile strength of the concrete was established according to the same standards. The mean value of the ultimate compressive strength, f_{cc}, tensile strength, f_t, modulus of elasticity in compression, E_c, their variations and the specific weight of the lightweight concrete are given in Table 4.

TEST BEAMS

After the analysis of the physical, mechanical and water absorption of seven bamboos, it was evident that the *Dendrocalamus giganteus*, DG, is the most appropriate bamboo for use in conjunction with bamboo-reinforced lightweight

Table 3. Bond stress between bamboo and lightweight concrete from pull-out test

Treatment	*No node*			*With node*		
	τ (N/mm²)	*Var (%)*	*τ/τ_NT*	*τ (N/mm²)*	*Var (%)*	*τ/τ_NT*
No treatment (NT)	0·52	17	1	1·2	17	1·0
Negrolin + fine sand	0·73	12	1·4	1·55	12	1·2
Negrolin fine sand + wiring	0·97	11	1·9	1·8	15	1·5

Table 4. Properties of the lightweight concrete

Compression (N/mm²)					*Tensile strength*		*Specific weight*	
Strength		*Elastic modulus*		*Design strength*				
fc (N/mm²)	*Variation (%)*	*E_c (N/mm²)*	*Variation (%)*	*fck (N/mm²)*	*f_t (N/mm²)*	*Variation (%)*	*(KN/m³)*	*Variation (%)*
19	5·5	12·040	4·6	15	1·9	6·6	17·00	1·9

concrete beams. Therefore the required amount of bamboo culms of the *Dendrocalamus giganteus* of at least 3 years of age was cut and allowed to dry at the bamboo patch for 30 days in the Botanical Garden of Rio de Janeiro. Then this bamboo was transported to the Structural and Material Laboratory of PUC-Rio and then seasoned for 20 days in sheltered space. Up to this point, no treatment was applied to the bamboo.

The bamboo culms were split with a wedged knife and cut into rectangular sections of 30 cm width. The smooth surface of bamboo splints was then cleaned and slightly roughened. Then the splints were wrapped with 1·5 mm wire at 1 cm distance after which they were treated with two coats of Negrolin. Immediately after the application of the second coat, fine sands were pressed into the Negrolin surface manually. Then it was allowed to dry for 24 h before fixing the splints inside the formwork. The formwork was made from plywood of 15 mm thickness, stiffened with 30 mm × 80 mm timber ribs at 40 cm spacings, to provide rigidity against the side deflection.

The dimensions of the bamboo-reinforced beams, denoted as VB1 and VB2, are given in Fig. 3. To obtain the data for comparison, a control beam of steel-reinforced concrete, denoted as VA, was also prepared using the same mix proportions as for bamboo-reinforced beams. The specification of the tested beams is given in Table 5. Lightweight concrete was poured into the formwork in layers of 10 cm. Then they were vibrated as recommended by the Brazilian Norms. All beams were cured for 28 days, using wet sawdust, before they were tested.

INSTRUMENTATIONS AND TESTING PROCEDURE

To measure the strain in the tension, compression reinforcement and the stirrups, 10 mm electrical strain gauges, fabricated by Kyowa, were fixed at the predetermined points before pouring the concrete. They were covered by special resin to protect against accidental damage. Electrical strain gauges of 30 mm length also were fixed on to the concrete compression zone at the middle of the beams. In general, for each beam up to 14 strain gauges were installed. To measure the deflection of the beams a total of 10 mechanical dial gauges with a precision of 0·01 mm were used throughout the test program.

The beams were tested in a steel frame of 1000 kN capacity and were simply supported as shown in Fig. 3. Before the application of the load, each beam was whitewashed with lime and then the surface was marked with black pen, with dividing lines every 10 cm, to facilitate the registration of cracks. After noting the initial value for strain and dial gauges, the load was applied in increments of 2 kN, by means of Amsler hydraulic jacks. For each increment the strains, deflection, initiation and propagation of cracks were recorded. The crack which could be observed by a magnifying glass ×5 was considered to be the first crack.

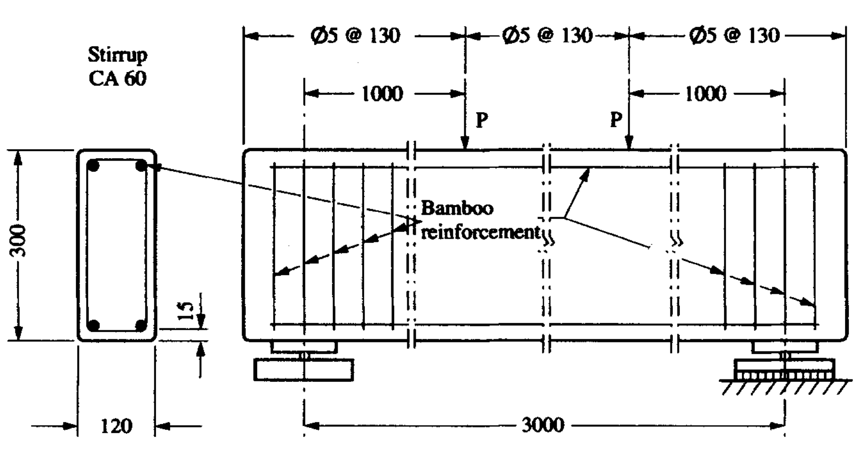

Fig. 3. Dimensions of a typical beam.

Table 5. Specification of the beams

Beam type	*Tension reinforcement*			*Reinforcement percentage ρ (%)*	*Compression reinforcement*	
	Material	*Section (mm)*	*Length (cm)*		*Section (mm)*	*Length (cm)*
VA	Steel CA-50A	2ϕ10 2ϕ12·5	338 240	0·78	2ϕ5	338
VB1	Bamboo DG-ma	2=30×10 2=30×10	338 250	3·33	2=20×10	338
VB2	Bamboo DG-ma	2=30×10 2=30×10 2=30×10	338 250 250	5·0	2=30×10	338

DISCUSSION OF RESULTS

The load-deflection at the middle of span, δ_3, and the horizontal load-displacement, δ_6, at the extreme end of the beam are given in Fig. 4. It can be seen that up to the appearance of the first tension crack in the central zone all the beams show the same rigidity. After the appearance of the first visible crack, the gradient of the curve for the steel-reinforced concrete beam, VA, does not change much, but there is a very noticeable change of gradient for the bamboo-reinforced concrete beams VB1 and VB2. The experimental load, P_{exp}, corresponding to the appearance of the first crack is marked by a cross. Comparison of the P_{exp} with those obtained theoretically, P_{exp}/P_{theo}, are 2·8, 1·3 and 1·75 for beams VA, VB1 and VB2, respectively.

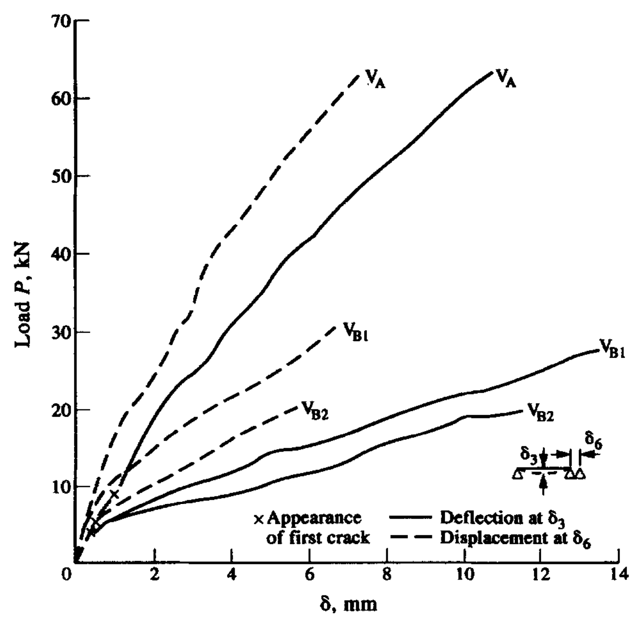

Fig. 4. Load-deflection p–σ_3 and load-displacement p–σ_6 curves.

Up to the load of 5 kN all the beams showed a linear behaviour. Then the deflections for beams VB1 and VB2 became greater than that for beam VA. In turn, beam VB2 produced a larger deflection in relation to beam VB1. The large increase in the deflections of the bamboo-reinforced concrete beams, as compared with that of steel-reinforced beams after the appearance of the crack, was attributed to the relatively low value of the elasticity modulus of bamboo, which was about 1/15 of steel (i.e. $E_b/E_s=1/15$), and also the lower bonding between bamboo splint and concrete when compared with that of steel and concrete.

The main variables in the tested beams were the type of reinforcement and the percentage of the tension reinforcement, ρ, which were 3·33 and 5·00% of the gross section for beams VB1 and VB2, respectively. In Fig. 5, the load-strain at each layer of the principal reinforcing bar is given. It can be seen that load strain for beam VB1 shows almost the same inclination as for beam VA, although the strain in the third layer of beam VB2 was higher than for beam VB1 after first crack. However, the ultimate load for beam VB2 was lower than for beam VB1.

The crack propagation on the beam surfaces was monitored using a magnifying glass. The results are shown in Fig. 6. It can be seen that the number of cracks for beam VA is more when compared with the cracks on bamboo reinforced beams. This is mainly related to the low elasticity modulus of bamboo and the bonding of bamboo with concrete. However, for beam VB2 the number of cracks is less than that for beam VB1. Some small horizontal cracks were observed at the support of beam VB2 when ultimate load was applied. In Fig. 7, the crack propagation on beam VB1 for the load of 16 kN is presented.

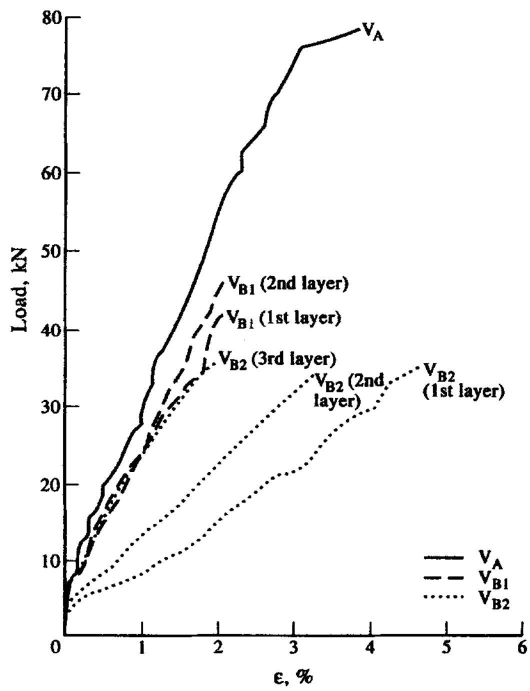

Fig. 5. Load-deformation in the principal reinforcing bar at the middle of span.

CONCLUSIONS

In many parts of Brazil, conventional construction materials such as steel are not only expensive but also difficult to obtain. In such situations, the application of abundant locally-available material such as bamboo is ideal as construction material. The results of this investigation show that for the bamboo-reinforced lightweight concrete beam, the ultimate applied load was increased up to 400% as compared with the concrete beams without bamboo reinforcement. It was also found that the 3% bamboo, in relation to the concrete section, is

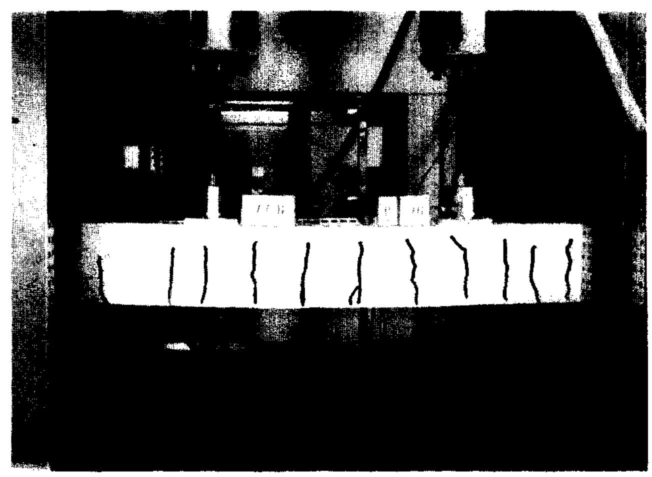

Fig. 7. Crack configuration of bamboo reinforced beam VB1 after failure.

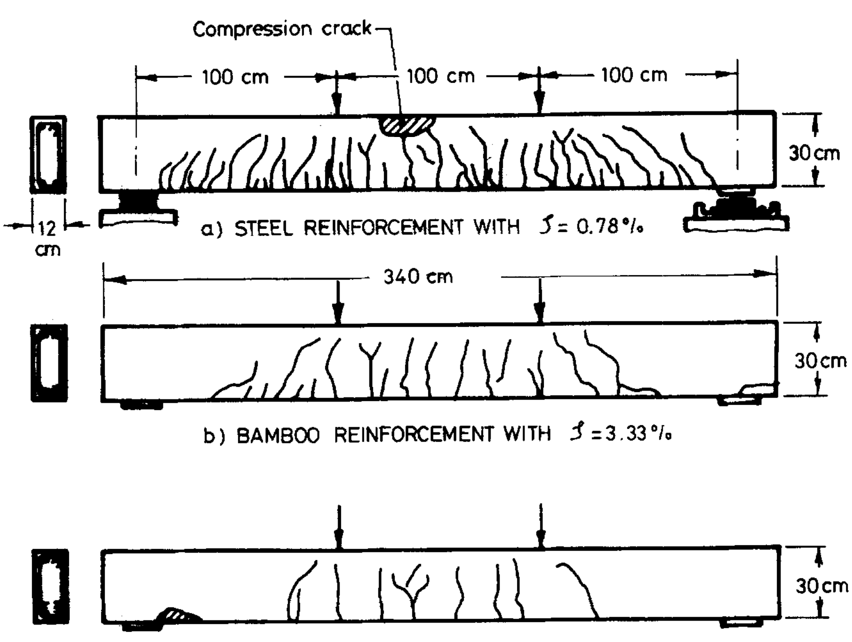

Fig. 6. Crack configuration of the tested beams.

the recommended value. The Negrolin-sand-wire treatment has improved the bamboo-concrete bonding by 90%. However, further research should be carried out on our treatment of bamboos, and on a statistical analysis of the bamboo-reinforced beams, based on experimental results, for the development of simple design code for the application of bamboo as a construction material.

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