The INRAR Working Paper Series

The International Network for Bamboo and Rattan (INBAR) is a network of scientists and development workers from universities, governments and, increasingly, NGOs, who are working on various aspects of bamboo and rattan. The principal objectives of the network are : to improve the well-being of small-scale producers and users of bamboo and rattan within the context of a sustainable bamboo/rattan resource base; to build skills and enhance capacity of national programmes to expand/orient bamboo and rattan research consistent with the priorities identified; and, to strengthen national, regional and international coordination, cooperation, and collaboration.

INBAR seeks to accomplish its goals by identifying and supporting research consonant with the priorities identified by national programmes. There is a strong emphasis on collaborative approaches to address problems which have regional and international relevance. The network's research and development activities are organised according to five themes : Socio-economics Research; Production Research; Post-Harvest Technology Research; Biodiversity and Genetic Conservation (jointly with the International Plant Genetic Resources Institute (IPGRI) and Information, Training, and Technology Transfer.

Communication is vital to any network. INBAR uses a variety of fora, including a quarterly newsletter, the INBAR Technical Reports Series, and this, the Working Paper Series.

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BENDING STRENGTH OF GUADUA BAMBOO
COMPARISON OF DIFFERENT TESTING PROCEDURES

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FOREWORD

In the context of diminishing natural resources, bamboo has emergaed as a viable alternative to wood, not only on account of its quick renewability, but its unique properties also · both physical and mechanical. Its potential as an engineering material is therefore receiving increasing attention.

To exploit its potential as an engineering material on an enduring basis, architects, engineers and users will need to be convinced of its suitability via Standards · national and international, building codes, etc. Although the structure and properties of a large number of bamboo species have been investigated, the information has largely remained restricted in its importance to biologists only. As methods of testing bamboo for its strength properties have not been standardized, the wealth of information on properties already available cannot be utilized to promote engineering applications. This was forcefully articulated in the Cochin International Bamboo Workshop (1988) and as a follow up, the International Development Reseach Centre (IDRC) coordinated with the Technical University of Eindhoven (TUE), Netherlands and brought out the annotated bibliography on bamboo as an engineering material (199 1). In the Chiangmai Workshop (199 l), the immediate need to develop Standards and Building Codes was stressed. This study is a beginning in that direction.

This intensive investigation, although confined to a new world bamboo species viz : Guadua angustifolia from Costa Rica in respect to just one important property, i.e., bending strength, has helped in confirming that strength values vary significantly depending on the form (round or split), span and position of skin surface of test specimens. Hence, it is clear that apart from parameters like age, moisture content, position in culm, distribution of node, etc., standardization of form, span and position of skin surface of the test procedures which will ensure replication of results, comparison of values and reliability in engineering applications.

This study is the result of collaborative effort between the Technical University of Eindhoven, Netherlands and Kerala Forest Research Institute, India. My sincere thanks to Prof. Jules J.A. Janssen, a long time adviser to IDRC in bamboo research, for making this collaborative study possible and to Dr. R. Gnanaharan for undertaking the research.

New Delhi
March, 1995

Cherla B. Sastry
Program Director; INBAR

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The Board of the TUE willingly provided free office space and laboratory and technical assistance to the first author.

Sincere appreciation is due to Dr. S. Chand Basha, Former Director, Kerala Forest Research Institute (KFRI) and the Executive Committee of KFRI for allowing the first author to undertake the study.

The bending tests could not have been carried out without the able assistance of Mr. **Eric** Wyen, Research Assistant. Mr. Huub Donders, Carpenter, helped in the preparation of test specimens of split bamboo. Mr. Ben Elfrink, Photographer, processed all the photographs within a tight deadline. Mr. Sip Overdyk, Head of the Laboratory, provided all the needed assistance. Our sincere appreciation goes to all of them.

Valuable statistical advice was given by Dr. K. Jayaraman of KFRI. Mrs. C. Sunanda and Mr. V. Sreekumar helped in carrying out the analysis and the latter also helped in arriving at the prediction models.

Ms. P.K. Sugatha Devi diligently did the word-processing. Mr. K.K. Ramakrishnan and Mr. V. Asokan ably handled the DTP work.

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SUMMARY

Bamboo, the fastest growing woody plant, has attracted the attention of not only biologists but also engineers and architects. Strength data are lacking for most species. Even available data are difficult to compare because different testing procedures have been used by different authors. Standardizing the testing procedures is essential to eventually arrive at a Bamboo Building Code. Towards this objective, a collaborative study between the Kerala Forest Research Institute, India (KFRI) and the Technical University of Eindhoven, the Netherlands (TUE) was undertaken.

Straight, large diameter culms of *Guadua angustifolia* were used in the study. Different types of test specimens were evaluated. Round, long specimens were subjected to 4-point bending tests with a span of 3000 mm while round, short specimens to 3-point bending tests with a span of 700 mm. Split specimens were subjected to 3-point bending, and half the number of specimens was tested with skin surface in tension and the other half with skin surface in compression. Strength properties like modulus of rupture (MOR) and modulus of elasticity (MOE) were determined and the data were analyzed statistically. Salient findings of the study are given below:

MOR and MOE values obtained from the tests using three different types of specimens (round, long; round, short; split) are significantly different from each other.

Bending tests of round, short specimens with span length in the order of 700 mm do not reflect the actual potential of bamboo. In short-span testing, the specimens are not subjected to true bending.

Density and outer diameter, in combination, can be successfully used in predicting the MOR and MOE of long specimens (R^2 values of 0.994 and 0.989 respectively). This needs to be confirmed by carrying out tests on long specimens of different bamboo species of large, medium, and small diameter.

The strength values of long members are evaluated by the 4-point test but this is cumbersome. This report shows that using some physical properties, strength can be predicted. This needs to be tested in other species.

CONTENTS

1. INTRODUCTION

Bamboo is a versatile fast growing species. It attains its full length in 2 to 3 months, its -maturity in 2 to 3 years. Though it occurs in different parts of the world, it is found in abundance in most of the Asian countries. Because of its ready availability, easy workability and high strength-weight ratio it plays a vital role in the rural economy of these countries. Bamboo has been used for centuries for a variety of purposes including material for low-cost housing.

For bamboo to be used as an engineering material in structural applications, strength data have to be generated. With the renewed interest in bamboo for structural applications, the commonly used bamboos in different countries have been evaluated for strength. However, different test procedures have been used by different authors and therefore comparison of results is not possible.

One of the earliest works carried out on the strength of bamboo was by Meyer and Ekelund (1924). They tested bamboo under 3-point bending with a span of 1800 mm and 2 100 mm and, under 4-point bending with a span of 2 100 mm. The tests were conducted by placing specimens on supports consisting of angle irons and by hanging a platform at loading point and loading with 20 pounds [about 9 kgl scrap iron at every stage. Mr. H.K. Chow commented "Evidently any comparison of results would be of little value if the character of specimen and method of testing are not clearly stated. The results can be divided into two main classes, viz. those on bamboo strips and those on bamboo poles. I am of the opinion that where a comparison of results is to be made, the strip of bamboo should always be used. These can be easily tested in accurate testing machines, and conditions of testing can thus be standardized. At present conditions governing tests are so variable that we naturally expect great variations in results, to say nothing of the non-homogeneity of the material itself. One may question what is the use of testing a strip of bamboo while in practice poles are always used. The answer is that, by testing strips, we are enabled to know the relative strength of one species from the other, and by applying a factor, after a long series of tests. the results of tests on strips can be appropriated for the whole pieces of bamboo."

No study has been reported in the literature comparing the results of split specimens with those of poles. When Espinosa (1930) conducted tests on short length round bamboo (1500 mm span), and split specimens (300 mm), no attempt was made to relate the two results. Atrops (1969) conducted 4-point bending tests on full culms (3600 mm span) and split specimens (300 mm). He also did not relate these results.

Limaye (1952) tested bamboo in a systematic way, with a statistical design, to understand the effect of drying, age, disposition of node and position along the length of the culm. However, all the tests were carried out on small specimens only. Heck (1950) and Limaye

(1952) followed as far as possible the USA ASTM Standard (ASTM D 143) for small clear specimens of wood with some modifications.

Based on the work of Limaye (1952) and Sekhar and Rawat (1956) an Indian Standard was formulated for testing bamboo in round form with a span of 700 mm (BIS, 1973). It is good to recall that small clear specimens of wood are tested with 700 mm span. Later, another standard was brought out for testing bamboo in split form (BIS, 1976). However, these two standards did not attach importance to relating the results from the two testing procedures. Also, there is no standard available for testing bamboo in longer lengths.

As different bamboo species have different diameters and wall thicknesses, for relative comparison purposes, testing bamboo in split form would be more appropriate than testing bamboo in round form in short span. Reports comparing tests of split specimens with those of short, round specimens of the same species are few. Recently, Shukla et al. (1988) reported such comparisons for three species.

Some workers have tried to relate strength with physical properties (see Espiloy, 1987; Shukla et al., 1988) and anatomical properties (see Liese, 1987; Abd. Latif et al., 1990). However, unless we standardize the testing procedures, relating strength values with either physical properties or anatomical properties will not lead us anywhere, as we see wide variations in the reported results.

This study was carried out at the Bamboo Laboratory of the Pieter van Musschenbroek Laboratorium of the TUE during April-May 1993. The study was limited to bending tests.

2. MATERIALS AND METHODS

Mature culms of Guadva angustifolia from Costa Rica were used in the study. Collection details of these culms were not known and they were already cut to lengths of about 5 to 6 m[1]. These culms had been stored in a room at the Bamboo Laboratory, maintained at 70% RH From a population of about 200 culms, apparently sound culms without any insect or fungal attack, cracks and crookedness were marked and from these 14 culms were randomly selected. These culms were serially numbered; length, outer diameter at base, middle and top of the culms[2] measured; number of internodes noted; and, weight determined.

The middle portion of each culm[3] was first tested in bending under 4-point loading with a total span of 3000 mm in such a way that the bottom-most and top-most portions of the culms were not stressed. Afterwards the unstressed portions from the base and top of these 14 culms were cut and removed. These 28 specimens* were tested in bending under 3-point loading with a span of 700 mm . After the tests were executed on the 28 extreme specimens. the bottom-most and top-most portions were cut and removed. Splits taken from the upper portions were tested by loading with the outer skin surface in compression in a 3-point bending and the bottom portions with the skin surface in tension. This is graphically illustrated in Figure 1.

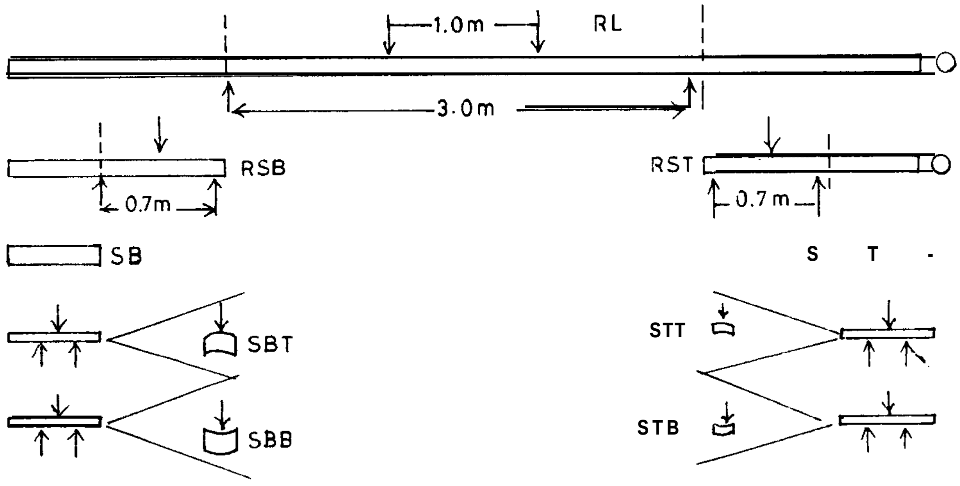

Fig. 1. Method of obtaining test samples from each test culm

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[1] The position of these test culms in the original culm was unknown.

[2] In this paper, the terms 'base', 'middle' and 'top' refer to the origin of samples in the test culms.

[3] Referred to as round long specimens (RL) hereafter.

[4] Round, short specimens (round, short, base (RSB) -14 specimens; round, short, top (RST) - 14 specimens).

2.1 Round, long specimens

For round, long specimens(RL), 4-point loading was chosen rather than 3-point loading. In 4-point bending, the central part is free from transverse forces and is subject to a constant pure bending moment.

Rollers were used at the supports, and the specimens were kept on the supports of the bending machine and were allowed to settle down to a position of equilibrium. A line was drawn to identify the upper middle longitudinal axis of the specimen, for posterior identification.

Load was applied through a loading head and the load was transferred to two points, 1000 mm apart, through a loading wooden block (Plate 1, Fig. 2). The specimen was supported on small saddles. Loading saddles were used as well so that load could be transferred to the nearby nodes (Plate 1, Fig. 3). (The distance from the loading point to the nodes was noted.) This arrangement helped in preventing the specimens from getting crushed at the loading points and from failing due to shear stress. This allowed the specimens to take load in a manner closer to true bending.

The load was applied gradually, to about 40% of the maximum load, and then it was released to about 10%. This enabled the specimen to "settle down". Then loading was continued until failure. An LVDT (Linear Variable Displacement Transducer) was used for measuring the displacement at the middle of the specimen. A data acquisition system (AUTOLOG 2005 Datalogger system; AUTOLOG Input Unit Series 502 of Peekel Instruments B.V.) was used to record the data on force and displacement.

The nature of failure of each culm, whether due to shear stress or crushing or tangential strain perpendicular to the grain, place of failure, etc. were noted.

2.2 Round, short specimens

The round, short specimens from base (RSB) and top (RST) were tested under 3-point loading with a span of 700 mm. This testing mode has been suggested by Indian Standard (BIS, 1973) and it is the only standard available on testing round bamboo. The same testing mode was adopted here for the sake of comparison and validation.

Here, half the specimens (RSB 01-07; RST 01-07) were tested with loading on a node and the rest on internode. The tests were carried out in a Universal Testing Machine (Schenck Trebel M 1600, 100 kN capacity) (Plate 1, Fig.4). The rate of deformation was kept at 6.5 mm/min. Both the supports had rollers. Small saddles and steel plates of 10 mm thickness were placed between the support rollers and the specimen. Load was applied through an iron plate and a loading saddle as well (Plate 1, Fig.5). The deformation was measured by a 'Mitutoyo' Digimatic Indicator with an accuracy of 0.0 1 mm. The force and deformation were recorded by the datalogger system. The nature of failure was observed and noted.

2.3 Split specimens

The Indian Standard (BIS, 1976) suggests positioning the outer skin of the specimens in tension while loading. It was decided to see whether there was any difference between keeping the outer skin surface in tension or in compression while loading. The split specimens from the upper periphery of the culms (from base, SBT: from top, STT)were tested with the outer skin in compression. The split specimens from the bottom periphery of the culms (from base, SBB; from top, STB) were tested keeping the outer skin in tension.

The Indian Standard (BIS, 1976) suggests-keeping the width of the specimen at least equal to twice the thickness. This is possible for thin-walled bamboos. However, when the wall thickness is very high, if we take width at twice the thickness, the specimen will no longer be rectangular in cross-section.

In wood, span length-thickness ratio has a significant effect on bending strength (Madsen, 1992). Split specimens are more like-solid wood and this was kept in mind in arriving at the span length. Depending on wall thickness, the width of specimens had to be varied so that the specimens had more or less rectangular cross-section. To take care of the stability problem during loading, span length was chosen as shown in Figure 6.

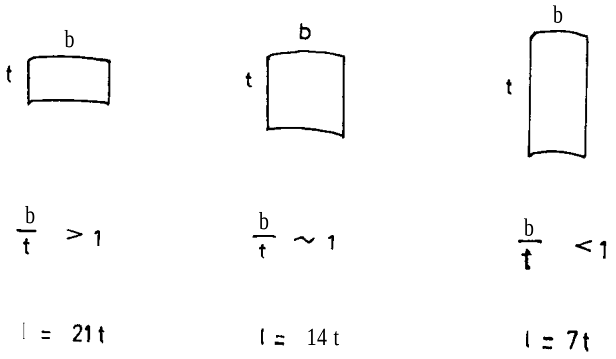

Fig. 6. Span length for split specimens of different thicknesses.

Depending on the configuration, corresponding span length was determined for each specimen. A span length of 140 mm was selected to represent calculated values ranging from 100- 170 mm, and 210 mm to represent values ranging from 180-300 mm. So, there were two span lengths depending on width and thickness of the specimens.

The tests were carried out in the Schenck Trebel M 1600 Universal Testing Machine. The rate of loading was maintained at 6.5 mm/min. An LVDT with a range of 40 mm and a resolution of 20 mm/100,000 steps was used for measuring the deflection. The force and deformation were recorded by the datalogger system.

As the internode length is very short at the base of the culms, most of the specimens had nodal portion. No attempt was made to keep the nodal portion away from the loading point. Most of the specimens from the culm top did not have nodal portion as the internode length was large enough. The nature of failure in each test was noted.

2.4 Moisture content, density

A small piece (ring in the case of round specimens) was collected from each specimen near the point of failure for the determination of moisture content and density. Moisture content was determined by oven-dry method and volume was determined by water-displacement method, not taking absorption into account, as experience has shown that absorption is negligible.

2.5 Data analysis

Emphasis is given to the statistical relationships between variables, with the aim of finding an easy way of determining mechanical properties. No attempt is made to explore the mechanical meaning of the findings. From this point of view, the research reported here is descriptive.

Different properties such as modulus of rupture (MOR), modulus of elasticity (MOE), density and wall thickness were analyzed statistically. Paired t-tests were run to see the relationships between specimens from the base and top of the same culms; between long and short round specimens of the same culms, etc. One-way ANOVA were run to see the difference between span length (in split specimens) and mode of testing (skin surface in tension or compression in split specimens; loading on node or internode in round, short specimens), etc.

Correlations between physical and mechanical properties were determined. Multiple linear regressions were run to see which factors would predict MOR and MOE efficiently.

Relationships between round long, round short specimens and split specimens were analyzed to observe size effects.

3. RESULTS

The physical characteristics of the bamboo culms are given in Table 1. Some of the culms were heavy (9.00-10.53 kg) and some were light (5.03-6.64 kg). This mostly depended on which portion of the original culms the test pieces came from. This was also reflected in the wall thickness (Table 2), and outer diameter (Table 1). The number of internodes ranged from 15 to 23. In general, density increased and wall thickness decreased from base to top along the test culms (Fig. 7). The average moisture content of the test specimens was 11.4 o/o. Variation in moisture content was minimal. This was mainly because the culms had attained equilibrium moisture content uniformly.

Table 1. Physical characteristics of Bambusa guadua culms used in the study

Culm No.	Length (m)	Weight (kg)	No. of internodes	Diameter (mm) base	middle	top
1	5.61	5.03	20	70.9	71.8	66.5
2	5.55	7.31	21	63.6	69.8	69.2
3	5.62	7.84	23	75.4	86.3	74.5
4	5.63	9.00	21	71.0	80.8	80.8
5	5.62	10.53	21	81.1	91.3	89.4
6	5.62	10.48	20	89.4	97.4	92.0
7	5.78	10.11	21	79.6	91.6	87.4
8	5.55	6.05	23	68.4	73.8	61.6
9	5.52	5.25	18	85.3	74.7	58.8
10	5.66	9.67	22	87.3	94.3	86.2
11	5.50	6.12	16	87.9	76.1	66.7
12	5.60	6.64	19	71.4	73.8	71.9
13	5.60	6.05	15	89.2	79.7	69.4
14	5.70	6.43	21	75.0	79.8	70.5

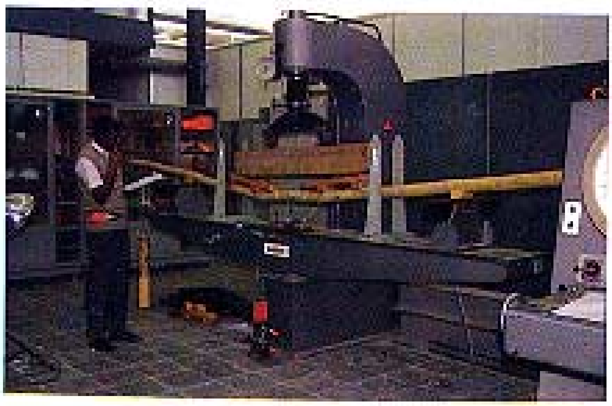

Fig. 2. Four-point bending test machine

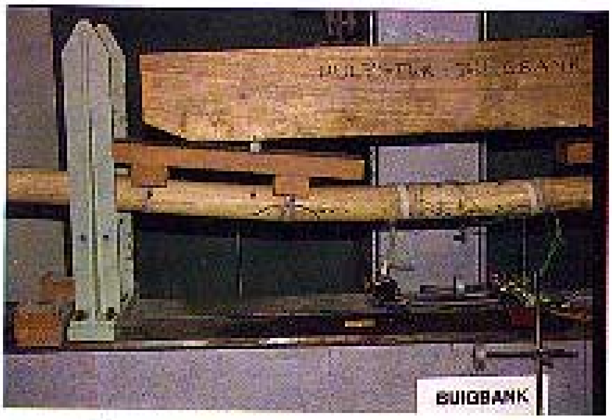

Fig. 3. Positioning of loading saddles

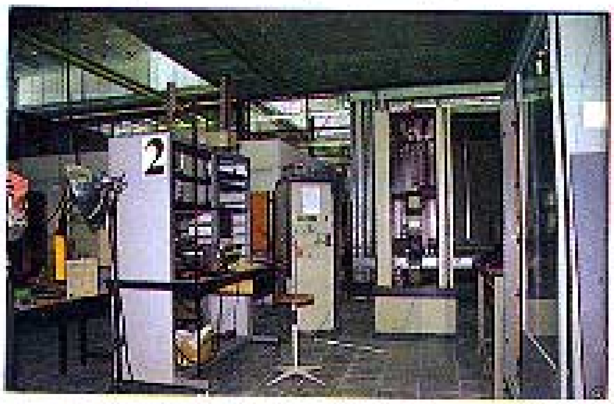

Fig. 4. Universal Testing Machine

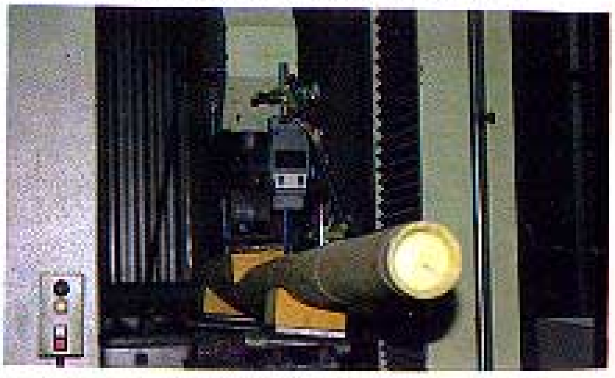

Fig. 5. Loading details for the short, round specimen

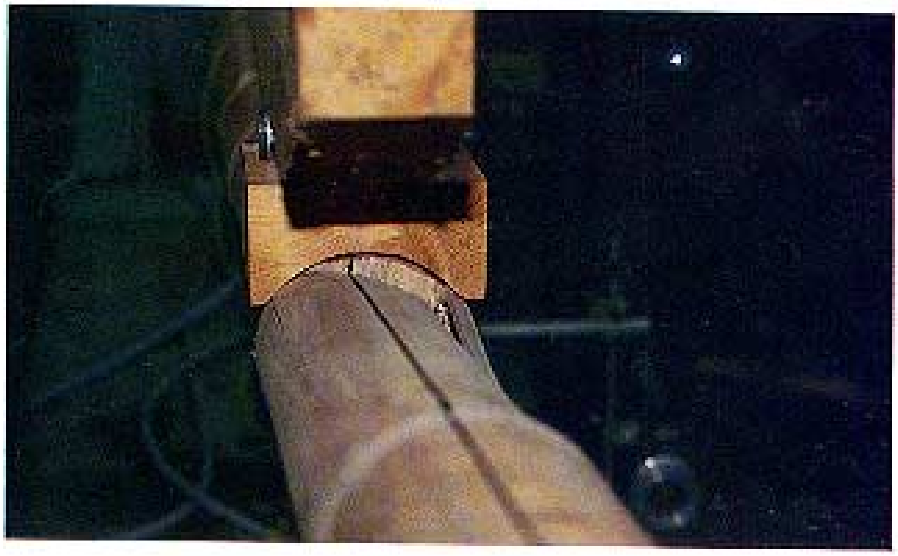

Fig. 8. Crushing effect on round, short specimen

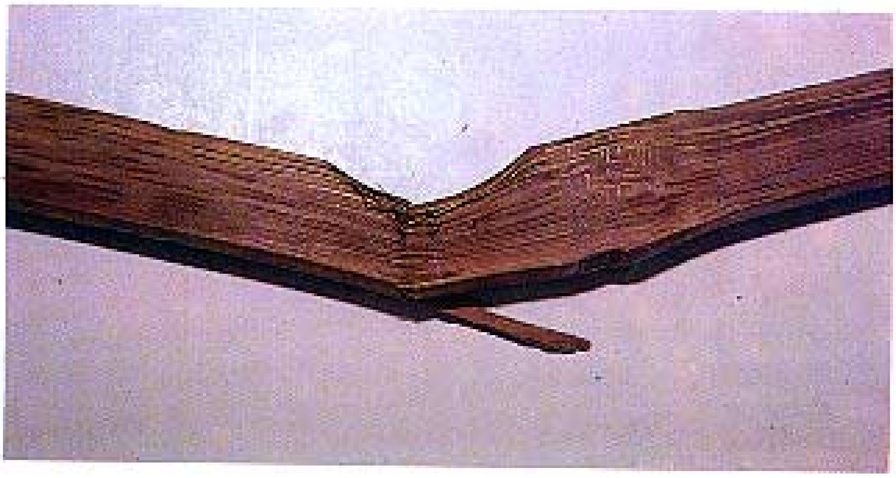

Fig. 9. Crushing effect on split specimen with skin surface in tension

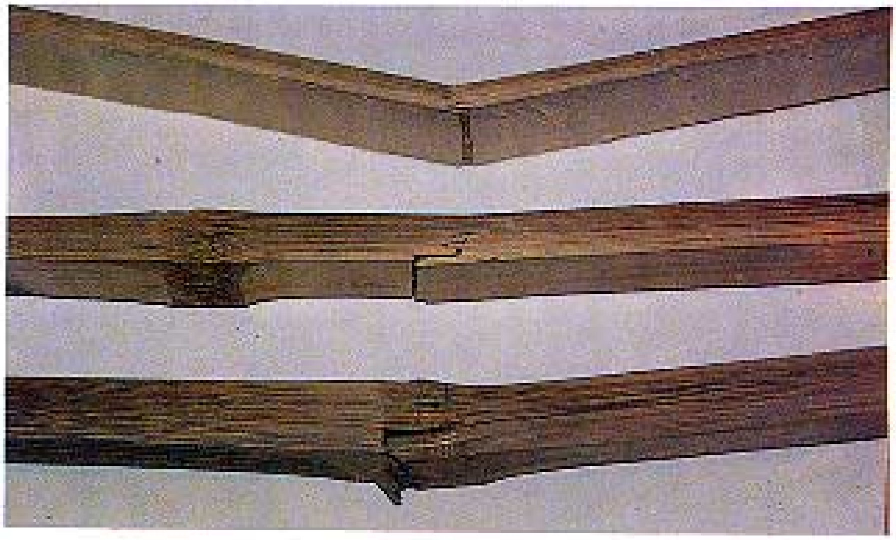

Fig. 10. Mode of failure of split specimens with skin surface in compression.

Table 2. Density (kg/m”) and wall thickness (mm) (in parenthesis) along the culm from base to top

Culm No. No.	Split, base	Round short, base	Round long	Round short, top	Split Top
1.	453.2 (11.70)	507.3 (9.63)	604.5 (5.63)	630.5 (5.00)	632.7 (4.75)
2.	504.7 (17.45)	602.5 (13.05)	614.6 (9.18)	673.0 (7.00)	668.7 (6.95)
3.	507.9 (18.30)	559.2 (11.83)	577.5 (8.03)	679.1 (5.38)	655.1 (5.25)
4.	507.1 (18.15)	610.1 (12.73)	717.6 (8.90)	734.6 (6.50)	734.9 (6.65)
5.	510.3 (18.70)	562.7 (14.33)	632.7 (9.95)	—	697.5 (6.65)
6.	485.0 (13.10)	609.6 (12.73)	662.7 (8.80)	678.3 (6.78)	(6.80)
7.	499.4 (16.45)	639.6 (11.95)	698.3 (7.68)	714.7 (6.50)	720.1 (8.00)
8.	482.1 (15.05)	491.8 (14.00)	574.0 (6.78)	638.1 (5.23)	626.2 (5.40)
9.	648.5 (6.10)	616.2	— (6.55)	— (4.85)	697.4
10.	460.7 (21.15)	526.6 (13.70)	622.0 (9.00)	651.4 (6.68)	664 2 (6.10)
11.	722.3 (6.05)	657.5 (6.75)	684.3 (5.98)	669.5 (5.43)	696.8 (6.85)
12.	631.5 (11.70)	632.2 (9.00)	602.5 (7.43)	645.7 (6.40)	653.8 (6.05)
13.	682.9 (6.05)	679.0 (6.15)	680.0 (6.10)	— (5.60)	715.5
14.	546.6 (12.60)	601.3 (10.55)	645.6 (6.00)	641.6 (5.05)	677.0 (4.75)

3.1 Round, long specimens

While testing the first specimen (RL 09), it failed prematurely due to a loading saddle problem. Also, data were not logged due to oversight while testing culm RL 01. For the remaining 12 specimens, MOR[5] and MOE were calculated and these are given in Table 3.

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[5] Some of the samples may have failed due to a combination of bending and shear, or just shear. In these cases. MOR does not correspond to ultimate strength and what has been calculated is only apparent modulus of rupture.

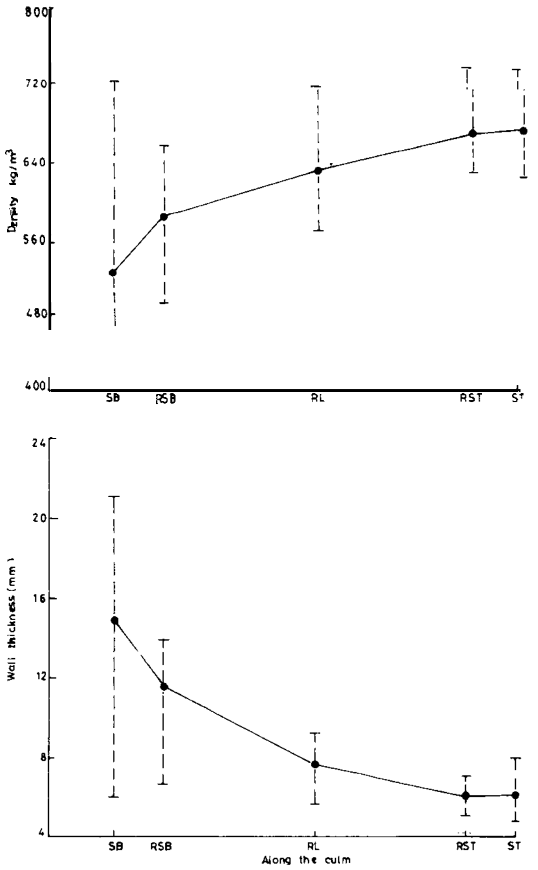

Fig. 7. Variation of density and wall thickness along the culm.

Table 3. Strength properties of long specimens

No.	MOR(N/mm²)	MOE (N/mm²)
02	81.7	17,397.5
03	59.1	15,411.9
04	79.4	20,025.1
05	73.1	17,820.5
06	54.5	18.304.8
07	78.2	23,005.8
08	65.3	13,793.0
10	68.2	15,779.2
11	76.0	18,206.1
12	76.7	19,174.7
13	71.2	15,629.0
14	67.8	16,752.3
Mean	72.6	17 608.3
S.D	9 1	2 444.6
CV(%)	12'.5 .	13.9

The correlation coefficients (r) for the various relationships are given in Table 4. Even though MOR and MOE were positively correlated to. density, the r-values are low and not significant. Hence, multiple regressions were run to see whether combinations of these variables could produce suitable models, with lines passing through origin. Even though, individually, density did not explain the variation adequately, in combination with outer diameter, good prediction models could be obtained (Table 5). These models explain 99.4% (R^2 = .994) of the variation in ultimate strength and 98.9% (R^2 = .989) of the variation in MOE.

Table 4. Correlation coefficients for MOR, MOE, density, wall thickness and outer diameter of long specimens

Correlations	MOR	MOE	Density	Wall thickness	Outer diameter
MOR	1.0000				
MOE	.5051	1.0000			
Density	,5661	.6220	1.0000		
Wall thickness	.0453	.1983	-.1563	1.0000	
Outer diameter	-.4978	.2196	.0539	.4480	1.0000

Table 5. Multiple linear regression to predict dependent variables MOR and MOE of long specimens

Y	x,	x_2	equation	R	R^2
MOR	density	outer dia	$y = 0.153\ x, - 0.324\ x_2$	.997	.994
MOE	density	outer dia	$y = 24.309\ x, + 25.557 x_2$	.995	.989

3.2 Round, short specimens

Except for 3 specimens, RST 05, RST 09 and RST 13, which had problems at the time of loading, data were recorded for 25 specimens. MOR_5 and MOE were determined and the values are recorded in Table 6. When a paired t-test was conducted, it was seen that MOR values of specimens from base (58.4 N/mm^2) were significantly higher (p=0.05) than those of specimens from top (51.7 N/mm^2) of the culms (Table 7). However, there was no significant difference in MOE values of specimens from base (7555 N/mm^2) and top (7565 N/mm^2).

A one-way ANOVA test was run to see whether there was significant difference between the modes of loading on node or internode. As seen in Table 7, MOR values of specimens tested on node (63.5 N/mm^{2}1 was significantly higher (p=0.01) than when tested on internode (44.2 N/mm^2). However, no significant difference was noticed in MOE values between node (7948 N/mm^2) and internode (6679 N/mm^2).

Table 6. Strength properties of short specimens from base (RSB) and top (RST)

No.	MOR (N/mm^2)		MOE (N/mm^2)	
	RSB	RST	RSB	RST
01	48.7	50.3	7,321.1	8,518.4
02	87.7	66.4	10,464.9	9,421.6
03	66.3	56.0	7,285.2	5,817.0
04	74.9	72.0	10,410.5	8,000.9
05	66.5	—	6,954.6	—
06	53.2	48.2	5,712.8	7,310.0
07	76.2	58.8	8,377.8	7,723.5
08	43.1	52.4	8,089.6	9,092.9
09	37.1	—	5.342.8	—
10	39.6	40.3	3,328.8	5,476.8
11	48.3	45.7	5,877.8	7,991.7
12	58.1	41.3	8,479.5	6,674.4
13	41.8	—	4,849.6	—
14	45.9	37.2	7,753.3	7,193.0
Mean	56.2	51.7	7,160.6	7,565.5
S.D	15.7	10.9	2,020.5	1,245.0
cv (%)	27.9	21.2	28.2	16.5

Table 7. Difference in MOR and MOE between base (RSB) and top (RST), and node and internode of short specimens

Test	Factor	Difference between	t-value/F-value
Paired t-test	MOR	base and top	2.39*
	MOE	—	-.02(ns)
One-way ANOVA	MOR	node and internode	23.94**
	MOE	—	3.88(ns)

* $p < .05$; ** $p < 0.01$

There was very poor correlation between density and MOR, and density and MOE (Table .8).

Table 8. Correlation coefficients for the relationships between factors MOR, MOE, density and wall thickness of short specimens

Correlations	MOR	MOE	Density	Wall thickness	Outer diameter
MOR	1.0000				
MOE	.6632*	1.0000			
Density	.1153	.0835	1.0000		
Wall thickness	.3997	.0833	-.7198**	1.0000	
Outer diameter	-.1521	-.6482	.0738	.2056	1.0000

** $p < .01$

As was done for long specimens, multiple linear regressions were run to see whether MOR and MOE can be predicted. When all the three physical properties, density, wall thickness and outer diameter, were used as independent variables, it was found that high R^2 values could be obtained. Suitable prediction models (Table 9) were arrived at with R^2 of .976 and .982 for MOR and MOE respectively.

Table 9. Multiple linear regression models to predict dependent variables MOR and MOE of short specimens

Y	X1	x_2	x_3	equation	R	R^2
MOR	density	wall thick-ness	outer dia	$y = .144x, + 3.818x^2 -.883x,$	.988	.976
MOE	density	wall thick-ness	outer dia	$y = 25.571x^1 + 475.843x^2 - 163.925x^3$	.991	.982

3.3 Split specimens

Data for two specimens (SBT 05 and STT 04) were not logged by oversight. MOR and MOE values were determined for the remaining 54 specimens (Table 10).

Table 10. Strength properties of split specimens from base (SBT and SBB) and top (STT and STB)

No.	MOR (N/mm2)				MOE (N/mm2)			
	SBT	SBB	STT	STB	SBT	SBB	STT	STB
01	72.8	47.2	99.8	108.4	7507.2	7418.2	11325.9	12005.3
02	74.0	88.7	117.2	114.2	5232.8	5498.9	11355.9	11110.6
03	48.9	21.4	117.9	95.6	4471.2	4942.0	12234.5	13352.2
04	69.4	73.8	—	112.3	7524.2	8402.1	—	11161.0
05	—	57.9	132.0	144.9	—	4487.1	12425.8	15510.2
06	69.9	120.0	111.6	94.6	6604.0	20365.4	10857.7	11924.3
07	66.3	74.7	155.4	52.7	7747.8	8228.6	14843.4	3456.8
08	80.9	61.6	99.2	104.9	7268.2	9434.0	10538.8	12277.4
09	131.9	89.6	133.3	124.9	15036.0	11907.2	14517.6	13198.3
10	58.3	45.1	121.2	103.1	4220.2	4104.5	13411.2	12451.5
11	127.9	163.2	128.3	78.1	13484.6	21749.8	12248.4	7101.0
12	82.0	86.3	116.7	114.1	9250.9	6322.3	11104.6	12988.3
13	146.6	116.1	136.4	117.5	19919.3	15608.4	12849.5	13102.7
14	75.7	61.8	127.6	104.5	8692.4	7315.4	12638.1	13562.8
Mean	85.0	79.1	122.8	105.0	8689.1	9698.9	12334.7	11657.3
S.D.	30.4	36.1	15.3	21.5	3825.2	5709.1	1338.4	3004.4
CV(%)	35.7	45.7	12.4	20.5	44.0	58.9	10.9	25.8

Difference between loading with the skin surface in tension or in compression was determined by paired t-test. There was no significant difference in MOR values of the specimens from the base (between SBB of 8 1.3 N/mm^2 and SBT of 86.3 N/mm^2) (Table 11). However, when loaded with the skin surface in compression, MOR values of the specimens from the top (STT) (122.1 N/mm^2) were significantly higher than when loaded with skin surface in tension (STB) (101.1 N/mm^2). Specimens from the top (STT+STB) (111.6 N/mm^2) had significantly higher MOR values than that of specimens from the base (SBT+SBB) (83.8 N/mm^2).

Table 11. Difference in MOR and MOE between two different factors of split specimens

Test	Factor (s)	Difference between	t-value/ f-value
Paired t-test	MOR	SSB and SBT	-.61 (ns)
		STB and STT	-2.42”
		(SBT + SBB) and (STT+STB)	-3.53*
		(SBT+STT) and (SBB+STB)	2.15
	MOE	SBB and SBT	1.04 (ns)
		STB and STT	-.87 (ns)
		(SBT + SBB) and (STT + STB)	1.97 (ns)
		(SBT + STT.) and (SBB + STB)	-.28 (ns)
One-way ANOVA	MOR		
	span 210 mm	$C^{\$}$ and $T^{\#}$	.35 (ns)
	span 140 mm	$C^{\$}$ and $T^{\#}$	6.72*
	MOE		
	span 210 mm	$C^{\$}$ and $T^{\#}$	-.51 (ns)

* $p < .05$; ** $p < .OI$; \$- skin surface in compression; #- skin surface in tension

When specimens were tested with a span of 140 mm, MOR values of specimens with skin surface in compression (125.2 N/mm^2) were higher than that of specimens with skin surface in tension (107.4 N/mm^2). Even though this was not significant for span of 210 mm (69.8 N/mm^2, for skin surface in compression and 64.5 N/mm^2 for skin surface in tension) when pooled together (span of 140 mm and 2 10 mm), loading on the skin surface in compression (SBT+STT) resulted in significantly higher MOR (104.2 N/mm^2) than skin surface in tension (SBB+STB) (9 1.2 N/mm^2).

In the case of MOE, position of the culm (base or top), mode of loading (skin surface in tension or compression) and span (140 mm or 2 10 mm) did not affect the results significantly.

Wall thickness was highly, negatively correlated with MOR, MOE and density (Table 12). Density was highly correlated with MOR and MOE. Multiple regression analyses showed that MOR and MOE can be predicted from density and wall thickness with a high level of confidence (Table 13).

Table 12.Correlation coefficients for the relationships between factors MOR, MOE, density and wall thickness of split specimens

Correlations	MOR	MOE	Density	Wall thickness
MOR	1.0000			
MOE	.8724**	1.0000		
Density	.7441**	.5981**	1.0000	
Wall thickness	-.7884**	-.7498**	-.8542 **	1.0000

** $p < .Ol$

Table 13. Multiple linear regression to predict dependent variables MOR and MOE of split specimens

Y	x_1	x_2	equation	R	R^2
MOR	density	wall thickness	$Y = .187x, - 1.739\ x_2$	.982	.964
MOE	density	wall thickness	$y = 20.720\ x_1 - 221.842\ x_2$	.966	.933

3.4 Comparisons among long, short and split specimens

The mean MOR and MOE values of long, short and split specimens are given in Table 14. In both MOR and MOE, there is significant difference among each other.

Table 14. Mean values of MOR and MOE (in N/mm^2) for long, short and split specimens

Type of specimen				MOR	MOE
Round,	Long		(RL)	72.6	17,608
Round,	Short,	Base	(RSB)	56.2	7,161
		TOP	(RST)	51.7	7,566
		Mean	(RS)	54.0	7,363
Split,	Base,	TOP	(SBT)	85.0	8,689
		Bottom	(SBB)	79.1	9,699
		Mean	(SB)	82.1	9,194
	Top,	Top	(STT)	122.8	12,335
		Bottom	(STB)	105.0	11,657
		Mean	(ST)	113.9	11,996

There was a high, positive correlation between MOE of long specimens (RL) and split specimens from the top (ST) (Table 15).

Table 16 gives the best fitting models arrived at by choosing the equation which had the lowest Furnival index (Fumival, 196 1). MOR of long specimens can be predicted from that of

Table 15. Correlation coefficients for relationships between factors MOR and MOE

Correlations	MOR l*	MOR 2	MOR 3	MOR 4	MOR 5	MOE 1	MOE 2	MOE 3	MOE 4	MOE 5
MOR 1	1.000									
MOR 2	.2587	1 .0000								
MOR 3	al894	a4679	1 .0000							
MOR 4	.5763	.4585	.3618	1.0000						
MOR 5	-. 1541	-.2878	· .4296	-, 1479	1.0000					
MOE 1	A510	.5679	a2858	.2033	-.6353	1.0000				
MOE 2	.5363	.7629*	.57 13	-.6827*	-. 1616	.3722	1.0000			
MOE 3	.2692	.2472	**.9132****	.3473	-.3876	.1870	.5022	1.0000		
MOE 4	.5052	.3333	,4179	**.9310****	-.2784	.1980	.6657*	.3975	1.0000	
MOE 5	-.2704	-.4472	-.3319	-.2517	.9550**	-.7352*	-.2816	-.2639	· .3242	1.0000

* 1 = RL (round, long) specimens: 2 = RSB (round, short, base); 3 = KST (round, short, top): 4 = SB (split, base): 5 = ST (split, top)

split specimens from the base with fair amount of confidence ($r^2 = .604$). Level of confidence is not very high ($r^2 = .643$) for predicting the MOE of long specimens from split specimens from the culm top.

Table 16. Best fitting models from regression analyses for the various relationships

Y	x	Equation	r	r^2
MOR 1*	MOR 4	$\ln y = 2.995 + .308 \ln x$	.777	.604
MOE 1	**MOE 5**	$Y = -128298.5 + 25.774 x - .0011 x^2$	.802	.643
MOR 2	MOE 2	$y = 3.339 + .000095 x$	,762	.581
MOR 3	MOE 3	$Y = .279 + .00895 x - .00000027 x^2$	.918	.842
MOR 4	MOE 4	$Y = -.389 + .016 x - .00000089 x^2$	.955	.911
MOR 5	MOE 5	$Y = 1.852 + .0092 x$	.955	.912

* 1 = RL (round, long) specimens; 2 = RSB (round, short,base); 3 = RST (round, short, top); 4 = SB (split, base) 5 = ST (split, top)

4. DISCUSSION

It can be seen from figure 7 that, in general, density increased from base to top of the culms. This is mainly because the amount of fibres increases and the number of vascular bundles decreases from base to top. Wall thickness, however, reduces from base to top. Most researchers take samples from three positions of the whole culm (base, middle and top) and report the average, but mean values may underestimate or overestimate the actual strength potential, depending on the species (see Shukla et al., 1988).

4.1 Round, long specimens

The MOR values of long specimens varied from 54.5 to 81.7 N/mm^2 and MOE, from 13,793 to 23,006 N/mm^2(Table 3). Interestingly, the highest MOR of 81.7 N/mm^2 was obtained for the specimen which had the lowest diameter, measured at mid-point, (69.7 mm) and the lowest MOR of 54.5 N/mm^2 was obtained for the specimen with the highest diameter (97.4 mm). This trend was observed by Espinosa (1930) also. However, the correlation coefficient obtained in this study between MOR and outer diameter (r = -.50) and between MOE and outer diameter (r = .22) is poor (Table 4). This is explainable, because the diameter is not a property of the material itself, and from mechanical principles we know that the E-modulus (MOE) is defined by the material, and not by the shape of the cross section. Besides, as shown by Arce (1993), the tapering of the culm affects, to a certain degree, the elastic curve of the beam.

Table 5 shows that density and outer diameter of bamboo culm can be used to predict MOR and MOE with high confidence (R^2 of .994 and .989 respectively) as the goodness of fit of the experimental data is very high. These predicted values will be applicable to a culm of 3 m. The values cannot be extrapolated too much as density and diameter vary along the culm.

4.2 Round, short specimens

The MOR and MOE values of short specimens were much lower compared to that of long specimens (Tables 6 and 14). The coefficients of variation were higher than that of long specimens. When span length is shortened, specimens tend to get crushed even at lower loads (Plate 2, Fig. 8) resulting in lower ultimate strength. Also they will be less elastic resulting in lower MOE. This clearly points out that results obtained bending tests with short span (in the order of 700 mm) do not reflect the actual potential of bamboo. The test specimens invariably fail due to crushing or shear even at lower loads. So, the failure is not due to the maximum transverse force. Therefore, testing round bamboo with short span under 3-point loading is not appropriate to be able to evaluate the strength potential of bamboo.

The MOR values decreased from base to top (significantly at p = .05) while MOE increased (though not significantly) (Table 7). This trend has been reported by many workers (Abd. Latif and Mohd. Zin, 1992; Sattar et al., 1992; Shukla et al., 1988; Espiloy, 1987; Janssen, 1981; Limaye, 1952).

When load was applied on node, MOR and MOE values were higher than when applied on internode (Table 7) even though the increase was not significant in the case of MOE. Similar results were reported by Abang Abdulla (1984): Sekhar and Bhartari (1960) and Limaye (1952). Limaye (1952) pointed out that disposition of nodes is the least important factor from a practical point of view. Prawirohatmodjo (1990) found that presence of nodes did not significantly affect bending strength.

Soeprayitno et al. (1990) reported a high correlation between MOR and density. However, Rajput et al. (1992) and, Abd.Latif and Mohd. Zin (1992) reported a poor relationship between MOR and density. This study also indicated a very poor relationship (Table 8).

Shukla et al. (1988) reported a very high correlation between average strength (MOR, MOE) and average external diameter of 11 different species. Sanyal et al. (1988) also indicated such a trend between MOE and outer diameter. However, Espiloy (1987) found a very poor relationship between strength and outer diameter. This study also showed that MOR of Guadua *amgustijolia* cannot be predicted by outer diameter, even though there was strong, negative relationship between MOE and outer diameter (Table 8).

Espiloy (1987) found significant, negative correlation between wall thickness and MOR for *Bambusa. blumeana* and between wall thickness and MOE for Gigantochloa levis. Abd. Latif and Mohd. Zin (1992) found a high, positive correlation between wall thickness and MOR, and a high, negative correlation between wall thickness and MOE. However, this study indicated a poor relationship between wall thickness and strength.

When a multiple regression was run with physical properties, very high R^2 values were obtained (Table 9). In the case of MOR, confidence level for prediction is 97.6% ($R^2 = .976$) and for MOE, 98.2% ($R^2 = .982$). These predicted values are applicable for only short lengths of the order of 700 mm. Here, results of specimens from base and top were pooled to arrive at the equation. So, depending on density and outer diameter of bamboo at any point, if the bamboo is to be used in short lengths, MOR and MOE values can be predicted using these equations.

4.3 Split specimens

The mean MOR and MOE values of split specimens from culm top were higher than that of base (Table 10). The increase in MOR was highly significant (p = .O 1), while in MOE it was not significant (Table 11). Li and Li (1983) also reported that MOR increased from base to top for split specimens. In the case of MOR, this trend is contrary to what was observed in round, short specimens. This makes it clear that bamboo behaves differently in round form and in split form. In split form, it behaves more like solid wood and both MOR and MOE are highly density dependent (Table 12). In contrast, the density dependence of round specimens was poor (Tables 4 and 8).

The mode of loading (whether skin surface in compression or tension) was significant in the case of MOR, when the samples were pooled; however, when the samples were segregated by the span length, only the 140 mm span proved to be significant (Table 11). While testing the specimens with skin surface in tension, the specimens tend to get crushed at the loading point (Plate 2, Fig. 9). Whereas when specimens were tested with skin surface in compression, mode of failure is similar for different thicknesses (Plate 2, Fig. 10). Atrops (1969) got a higher MOR value (142.5 N/mm^2) when he loaded the split bamboo on the skin side in compression than in tension (113.4 N/mm'). Espinosa (1930) also reported similar results. This trend has been noticed in this study also (MOR of 104.2 N/mm^2 and 91.2 N/mm^2 for loading skin surface in compression and tension respectively). However, a reverse trend was reported by Ueda (1980). When we look at the coefficient of variation (CV) values, variation while testing skin surface in compression is consistently lower (Table 10). This points out that it is good to adopt testing split specimens with skin surface in compression. This is in contrast to the suggestion of the Indian Standard (BIS, 1976).

Correlation coefficient value was higher for wall thickness than for density for their relationship with either MOR or MOE (Table 12). Even though the r-values are highly significant, to be able to predict MOR or MOE with high level of confidence, they are less than 0.9 (absolute value). However, in combination, both density and wall thickness were able to predict MOR and MOE with high level of confidence (Table 13). These two factors explain 96.4% of the total variation in MOR and 93.3% of the variation in MOE.

4.4 Comparisons among long, short and split specimens

The ultimate strength and MOE values obtained from the tests using three different types of specimens (round, long; round, short; split) are significantly different from each other (Table 14). In the case of MOR, split specimens yielded the highest values while the short specimens the lowest. In the case of MOE, the long specimens yielded the highest and the short specimens the lowest.

Shukla et al. (1988) compared the results of round, short specimens (span of 700 mm) with that of split specimens of three different species (Bambusa vulgar-is, *Dendrocahmus* giganteus and *D. humiltonii)* and found that MOR and MOE of split specimens were higher than that of round specimens. Similar results were obtained by Sekhar and Bhartari (1960) for D. stricti from Madhya Pradesh of India. This trend was confirmed in this study also for *Guadua.*

Atrops (1969) obtained lower MOR for full culms (with a free span of 3600 mm) than what was obtained for split specimens (span of 300 mm). The test species is not mentioned. This also conforms to the findings of this present study in the case of Guaducr.

The importance of testing bamboo in full size was emphasized by Meyer and Ekelund as early as 1924. Their comments are reproduced here: ". . . . . bamboo which must be accepted as it is naturally, should be tested in full sizes and in the same way as it is used in structures; when the shear in a long bamboo beam reaches 450 lb./sq.in. [about 3 N/mm^2] the beam simply collapses, thus rendering all the more or less erroneous small scale tests useless except for an academic analysis of the stress distribution." This study also has brought out this fact. If bamboo is to be used as long members, testing bamboo with 700 mm span will yield highly underestimated strength values, as this study has shown. This is because, in short-span testing, the specimens are not subjected to true bending.

As long-span four-point testing is quite cumbersome and most of the laboratories may not have this facility, it would be advantageous if the strength values of long culms could be predicted from short, clear specimens. The best fitting models show that MOR obtained from tests on split specimens from base, and the MOE obtained from tests on split specimens from top can be used to predict the MOR and MOE of long specimens respectively (Table 16). The level of confidence for predicting, however, is not high (60.4% and 64.3% respectively).

As can be seen from Table 16, there is a high correlation between MOR and MOE for split specimens both from base and top of the culm (r-value of .955). This shows that bamboo in split form, unlike in round form, behaves more like wood. Non-destructive testing, like stress grading machines, can be used to determine MOE and this can be used for predicting MOR of split specimens. However, use of bamboo in split form in structural applications is limited.

As this study has shown that density and outer diameter, in combination, can be successfully used in predicting the MOR and MOE of long specimens (R_2 values of .994 and .989 respectively), one should opt for this rather than trying to predict it from the strength values of split specimens. The predictability of MOR and MOE of long specimens using density and outer diameter should be verified and confirmed by carrying out tests on long specimens of different bamboo species of large, medium and small diameter. If this could be confirmed, carrying out cumbersome 4-point loading tests with long span can be eliminated. If such corifirmation is not forthcoming, unrealistic short span tests on round bamboo should not be carried out, as this study shows.

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