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Strength and elastic properties of bamboo elements used for housing

Jagadish Vengala[1], **R. Shruthi**[2] and **S. Raghunath**[2]
[1] *Products Application Division, IPIRTI, Bangalore – 560 022*
[2] *Department of Civil Engineering, BMS College of Engineering, Bull Temple Road, Bangalore – 560 019*

Abstract: This paper presents an investigation on the strength and elastic properties of *Bambusa bambos*, which is commonly used in the construction of bamboo houses in southern part of India, in particular Karnataka. Studies were carried out to examine the compressive strength, flexure strength and shear strength of the small specimens. The load carrying capacity of full-scale bamboo elements is also evaluated through experiments on single and double bamboo columns. Modulus of elasticity was obtained by carrying out flexural, vibration tests of bamboo beams. The compressive strength of bamboo specimen is in the range of 31MPa to 47 MPa. These are the values obtained from very short bamboo specimen (about 300 mm) long. These values agree with the codal provision. The modulus of elasticity of bamboo ranges from 20,000 MPa to 40,000 MPa. Modulus of elasticity in compression is lower than tension modulus, as expected. This was found from the flexural vibration test. These values were also in agreement with the codal provision. The shear strength ranges from 4 MPa to 11 MPa. The flexural strength is about 60 MPa with a strain capacity of 0.6 per cent. The average compressive strength of bamboo columns (single and double bamboo column) is as low as about 10 MPa. Full-scale bamboo columns fail due to crushing/splitting and local phenomenon rather than buckling.

Keywords: Bambusa bambos, compressive, shear and flexure strength of bamboo, modulus of elasticity, bamboo columns.

INTRODUCTION

Bamboo is the most versatile forest product and its potential can be harnessed in the service of the humble. There are about 75 genera and about 1250 species of bamboo. India's bamboo resources (both variety and distribution) are the second largest in the world, with the first being China. Bamboo species are generally hollow, but the size of the internal cavity depends upon the species, soil and climatic conditions. The outer skin of bamboo contains a small amount of silica, which improves its natural durability as well as the strength. Comparing the cost of bamboo and its behaviour under mechanical stresses, the choice of bamboo as a vernacular material for semi-

* To whom correspondence should be addressed; E-mail: jdvengala@yahoo.com,jdvengala@ipirti.gov.in

permanent rural houses is justified. Research carried out also has shown that bamboo is an earth quake resistant structural member. To facilitate proper designing in bamboo for different types of structural members like trusses, columns, rafters, *etc.* as well as for fabrication of various bamboo-based constructions economically, it is necessary to classify and grade different species of bamboo grown in India and determine their safe working stresses.

A programme of testing of bamboo for their physical and mechanical properties has been taken up at Forest Research Institute, Dehra Dun (Rajput *et al.*, 1992; Sanyal *et al.*, 1988) and methods of testing have been formulated and standardized for about of 20 important species of bamboos.

National Building Code of India (NBCI, 2005) has included a section for structural design of timber and bamboo. The code gives safe working stresses of bamboo for structural design. The safe working stresses for 16 species of bamboos are given in Table 1(NBCI, 2005). The code also mentions the factor of safety to be within 4-8 for bamboo based housing system. The code also includes that with the decrease in the moisture content, the strength of the bamboo specimen increases exponentially and bamboo has an intersection point (fiber saturation point) at around 25 per cent moisture content depending upon the species.

Table 1. Safe working stresses of bamboos for structural designing

Sl. No.	Species	Extreme fiber stress in bending (N/mm^2)	Modulus of elasticity (*10^3 N/mm^2)	Allowable compressive stress (N/mm^2)
1	*Bambusa glancescens*	20.7	3.28	15.4
2	*Dendrocalamus strictus*	18.4	2.66	10.3
3	*Oxytenanthera abyssinicia*	20.9	3.31	13.3
4	*Bambusa balcooa*	16.4	1.62	13.3
5	*B. pallida*	13.8	2.87	15.4
6	*B. nutans*	13.2	1.47	13.0
7	*B. tulda*	12.8	1.77	11.6
8	*B. auriculata*	16.3	3.34	10.5
9	*B. burmanica*	14.9	2.45	11.4
10	*Cephalostachyum pergracile*	13.2	2.48	10.5
11	*Melocanna baccifera*	13.3	2.53	15.4
12	*Thyrsotachys oliveri*	15.5	2.16	13.4
13	*Bambusa arundinacea*	14.6	1.32	10.1
14	*B. ventricosa*	8.5	0.75	10.3
15	*B. vulgaris*	10.4	0.64	11.0
16	*Dendrocalamus longispathus*	8.3	1.22	12.0

Note : The values given pertain to testing of bamboo in green condition

EXPERIMENTAL INVESTIGATION

The major objective of this investigation was to obtain the strength and the elastic properties of the elements in a typical bamboo-based housing system. A series of experiments were carried out to determine the various properties. Compression test, flexure test and shear test were conducted to obtain their respective strengths and elastic property. Later, free vibration test, under flexural vibration mode, was carried out to obtain modulus of elasticity.

Compression test

Essentially the load-carrying member is designed based on the compressive strength of bamboo specimen. Compressive strength of bamboo again depends on the size of the specimen and the way it is supported during test. Specimens during compression test mostly fail due to lateral strain, local buckling and splitting. Hence, this test forms as important component in designing of bamboo based housing system. Tests on ultimate compression stress of bamboo have been carried out by several authors. A summary is given in Table 2.

Three types of specimens were chosen for the purpose *viz.* (i) hollow specimens, (ii) node at either end of the specimen and (iii) node in between the specimen. Figure 1 shows the schematic diagram of the three types of specimens. Five specimens were tested from each type. The tests were carried out in accordance with IS 6874 (1973). Along with compression test an attempt was made to obtain stress strain relationship of bamboo under compression. To evaluate this, a compression strain gauge was used.

Table 2. Summary of compression test results by different authors on hollow specimen

Author	Species	Specimen (diameter, height in mm)	No. of tests	Ultimate compression stress N/mm^2	Remarks
Meyer and Ekelund (1922)	-	127, 127	4	44	Nodes at several places
Espinosa (1930)	*Bambosa spinosa*	61, 356	53	57	Node in between
Mc Clure (1938)	*B. tuldoides*	47, 305	21	35	Node in between
Glenn (1950)	*Phyll. bambusoides*	-, 153	11	13	-
Limaye (1952)	*D. strictus*	36,152	33	44 (@64%M.C.)	Node in between;
		36,152	33	71 (@ 9%M.C.)	2½ years old
Atrops (1969)	-	77, 308	36	40	Hollow;
		77, 308	36	43	Node in between
Sekhar (1961)	*D. strictus*	___	16	54	Hollow;3 years old

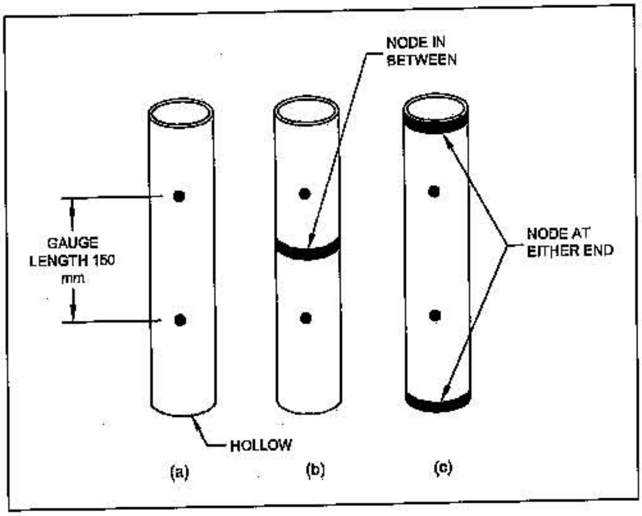


Figure 1. Schematic diagram of three types of specimen

All the bamboo specimens that were tested belonged to *B. bambos.* These specimens were cut at an age more than 3 years. The specimens were properly conditioned from bottom, middle and top of the culms. The specimen were cut into length varying between 300-320 mm as per IS standards. The outer and the inner diameter including the thickness of each specimen were measured using vernier calipers. Then finally the area of each specimen was calculated, as follows:

$$\text{Area} = \frac{\pi\,(d_1^2 - d_2^2)}{4}, d_2\text{- Outer diameter, } d_2\text{- inner diameter}$$

After this the studs were fixed to the specimen as per the gauge length. The specimen was then subjected to compression in the UTM @ a rate of 1N/s. at the same time strain was noted down using a digital dial gauge. The stress recorded in the dial gauge was used to obtain the stress strain relation. Ultimate load was noted down when the specimen failed to determine the ultimate compressive strength.

Shear test

As a material, bamboo has better shear strength than wood. Bamboo is not weakend by rays. The problem with shear in bamboo results from its shape. The interior part of wood cross section hardly contributes to the moment of inertia, but to shear area in the neutral layer. The purpose of test is to determine which factors are significant and which are not. The bamboo specimen was split in to two halves (specimen A and specimen B) for the purpose that as a whole it was strong enough to bend 10 mm steel rod. A slit was made through the specimen; through which a steel plate of 60x100x10 mm was placed. A small area was chipped at the top in line with the slot made. Supports were provided below the metal plate, and the load was applied at rate of $1N/mm^2/s$. The specimen was free to move down. It was observed that there was local compression at the junction of metal plate and the specimen. Figure 3 shows the schematic representation of the shear test setup. Plate 2 shows the experimental setup.

Free vibration tests to determine modulus of elasticity

Generally fibrous materials are known to exhibit an anisotropic behavior under tension and compression. Bamboo is also one such material whose tension and compression modulus may be different from each other. Obtaining a combined modulus may be more realistic from the consideration of using the values for deflection criterion. Flexural vibration test offers a way of obtaining the combined modulus of such materials.

The concept of free flexural vibration essentially involves setting up a specimen into "free vibration" by imparting an initial condition, such that the specimen vibrates in its fundamental natural frequency. Frequency can be easily measured using vibration recorders. Once the free vibration response is measured, the expression for fundamental natural frequency can be used to obtain the modulus of elasticity after extracting the fundamental natural frequency. Since during flexural vibrations, both tensile stresses and compression stress are excited, the modulus thus measured would be the combined modulus.

In the present case free vibration specimen were made as cantilevers. A bamboo specimen of length 800 mm was housed in concrete cubes of dimension 15 cmx15 cm x15 cm at one end. After requisite curing period of the cubes, the embedded end of the specimen was clamped in the compression-testing machine to achieve fixity. The other end was later gently tapped with a wooden pallet, to set the specimen into vibrations. Accelerometer was mounted on the tip of the specimen to record the response of the specimen. Figure 4 shows the schematic representation of free vibration test and Plate 4(a) and 4(b) show the experimental setup of vibration test.

Calculation of fundamental natural frequency

The analog signals were converted into digital signals using a high-speed data acquiring system. To obtain the natural frequency of the signal, a Fast Fourier Transformation (FFT) of digital data (time v/s acceleration) was carried out.

Calculation of combined modulus of elasticity

The expression for fundamental natural frequency of a cantilever is as follows:

$$\omega = \frac{(3.516\Pi\sqrt{EI})}{\sqrt{mL^4}} \text{ ,Where, w=2ðf}$$

f– Fundamental natural frequency in rad/sec, E –Combined modulus of elasticity (MPa)

I—Moment of inertia m ^{4}, m– Mass per unit length (2.95Kg/m), L—Length of the specimen (m).

From the compression test carried out modulus of elasticity in compression was obtained. Thus the Young's modulus of the specimen in tension can be obtained from the following expression $E = \frac{4(E)_t}{(1+\sqrt{E_t}/\sqrt{Ec})^2}$

Where, E—Combined modulus of elasticity (N/mm²), E_t—Tension modulus (N/mm²), E_c—Compression modulus (N/mm²).

Table 5 gives the results of free vibration test and modulus of elasticity values for both tension and compression

Flexural test

The test was carried out to determine the deflection pattern of the bamboo and also to obtain the moment curvature relationship and stress strain relationship. Seven specimens of length 750 mm were used for the purpose. After the initial dimensions were measured, the specimen was placed as a simply supported beam under the compression-testing machine. Two supports were provided at a distance of 250 mm from the center. A small aluminum plate was screwed at the center of the specimen. The plate was provided to monitor the deflection using a digital dial gauge. The magnetic dial gauge was used to measure the deflection of the specimen. The specimen was loaded at the center at a rate of 1kN/s.The deflection recorded in the dial gauge was used to plot at load v/s deflection curve and represented in Figure 6. Using the beam equation, a plot of moment v/s curvature was also generated (Figure 7), thus a plot of stress v/s strain was also generated.

Behaviour of bamboo columns

Bamboo members are the main load carrying members in bamboo based housing system. They not only transfer the vertical loads but also play an important role in resisting lateral loads that may occur during wind and seismic situations. Like in RC framed structures, bamboo columns are the basic skeletal members in withstanding the lateral stiffness. However, unlike RC columns, bamboo columns are significantly slender. These slender columns could be vulnerable to 'buckling'. However, lateral restraints in the form of beams and ties mitigate the problems of buckling significantly. Nevertheless there is a need to assess the axial load carrying capacity of bamboo columns, since there exists possibilities of loss of lateral restraints. There is also the problem of inherent eccentric loading, which may further reduce the load carrying capacity of the columns.

Two types of bamboo columns namely single and double bamboo columns were tested to check the behavior of the storey-high bamboo column subjected to axial loads. In the absence of the standard testing procedure for testing of the bamboo columns, the following procedure was adopted, albeit certain drawbacks. Initially the dimensions of each column were measured. The following dimensions such as outer diameter, inner diameter, length of the column, the length of the joints (in case of double column) were measured. A wooden plank of 15 mm thickness was bolted to the top and bottom of the bamboo column.

A concrete cube was first placed over which a loader of capacity 100 kN was placed. Over which 2 metal plates of thickness 20 mm was placed. No arrangements were made to prevent rotation of the specimen at the top and bottom. Hence the specimen can be assumed to be pinned at both the ends. Utmost precaution was taken to maintain the specimen as vertical as possible and to maintain the load axial.

The hydraulic jack was placed at the bottom, as the load carrying capacity of the bamboo column was much lower. Proving ring of 100 kN was placed over the hydraulic jack to obtain the divisions to further carry the ultimate load. Metal plates of thickness 40 mm was placed below the proving ring and 20 mm metal plate above was used, to avoid eccentric loads, as the surface of the bamboo column was not uniform. Figure 9 and Plate 6 shows the schematic representation of experimental setup of full scale column testing. Load was applied using a hydraulic jack. The division at which the specimen failed was noted down, to obtain the ultimate load and the strength of the single and double column. Plate 7 show the lateral deflection observed in both single and double columns during full scale column tests. Plate 8 shows the typical failure patterns observed in both cases.

RESULTS AND DISCUSSION

Plate 1 shows the typical failure patterns observed for all the three types of specimens during the test. Table 3 shows the summary of the compression test results, standard deviation and coefficient of variation for the three different types of specimens. Figure 2 shows the typical stress strain relationship of all the test specimens of each type.

Plate 3 shows the typical failure pattern of the test specimens. Table 4 gives the shear test results of the specimens and average shear strength. Figure 5 shows the typical vibration response obtained from the tip of the specimen. The first frequency corresponding to the fundamental mode generally has a relatively large peak. For each specimen signals from 6-8 repeated experiments were analyzed. During the experiment it was observed that there was also local compression at the point of application of load and when the load was realized the specimen regained its original shape. Figure 8 shows the stress v/s strain curve. Plate 5 shows the experimental set up and typical failure pattern observed during the test.

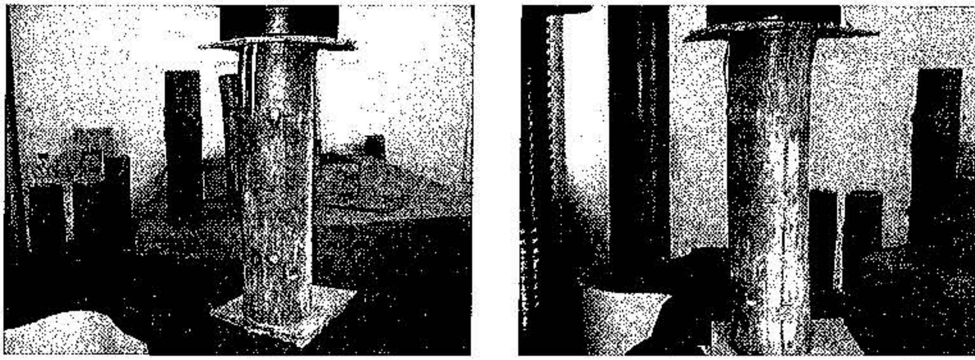


Plate 1 (a). Cracks and local crushing in hollow specimen

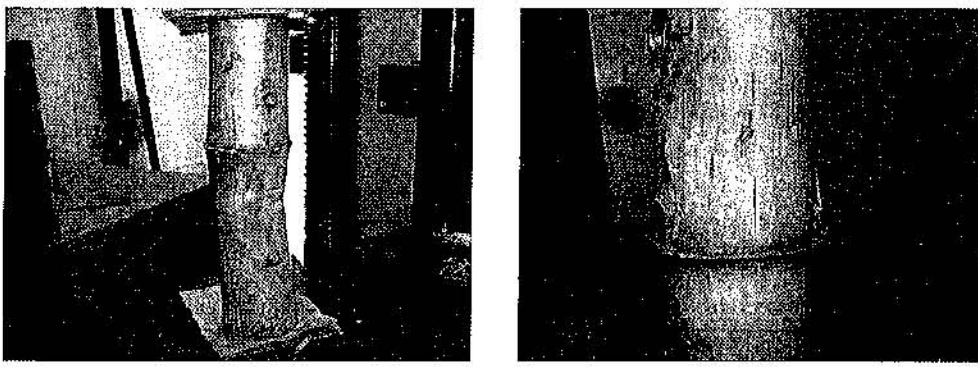


Plate 1 (b). Local buckling in node in between specimen

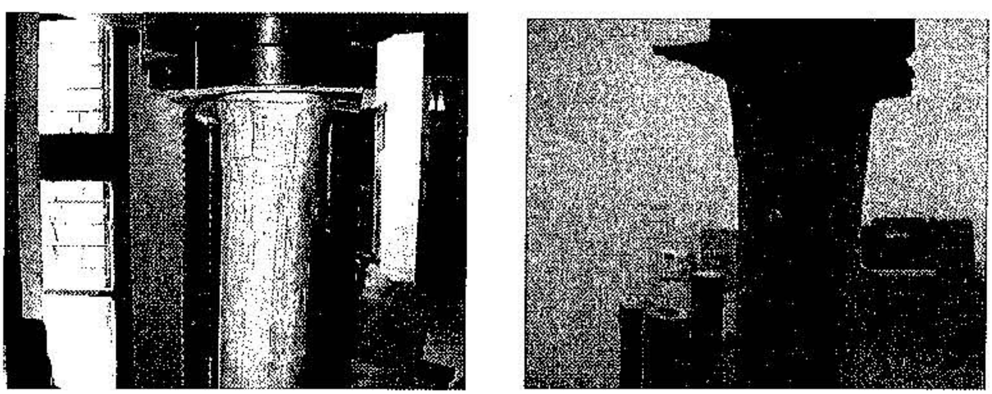


Plate 1 (c). Buckling at the node at either end of the specimen

Plate 1. Typical failure patterns observed

Table 6 and Table 7 give the results of the test carried out on single and double bamboo columns. A cursory glance indicates that none of the columns reached the Euler's critical load. It may be important to highlight here that classical buckling is a sudden failure phenomenon. This was not the case in the present investigation; the column gave clear indication of failures before reaching the ultimate loads. A careful observation of the failure pattern indicates that the failure was rather local in nature

Table 3. Summary of compression test results

Sl. No.	Specimen type	Compressive strength (N/mm^2)	Average compressive strength (N/mm^2)	Modulus of elasticity (N/mm^2)	Average modulus of elasticity (N/mm^2)
1	Hollow	42.93	33.7	29594	18419
2	specimens	32.77		10199	
3		23.45		26017	
4		38.66		18944	
5		30.88		13955	
	Standard deviation	7.48		8087	
	COV (%)	0.22		0.41	
1	Node at	28.60	30.2	20042	20968
2	either end	30.34		23049	
3		26.89		23067	
4		37.68		16777	
5		36.01		24057	
	Standard deviation	6.49		2991	
	COV (%)	0.21		0.14	
1	Node in	30.83	44.5	32075	27644
2	between	47.96		35781	
3		42.92		21265	
4		45.67		34998	
5		55.34		27352	
	Standard deviation	8.95		6033	
	COV (%)	0.20		0.20	

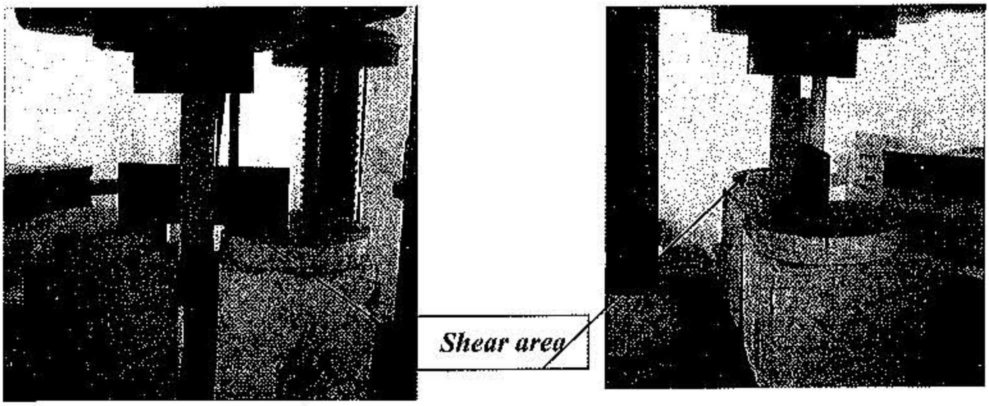


Plate 2. Experimental setup of shear test

by way of splitting and splitting at bolted joints (in case of double column). Probably the excessive bending of the specimen caused these. Perhaps this is due to the inherent eccentricity of loading or the inherent asymmetry of the bamboo specimen.

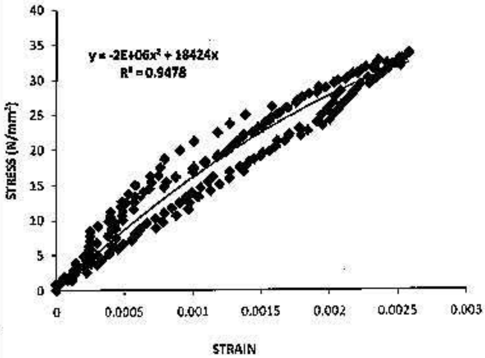


Figure 2(a). Hollow specimen

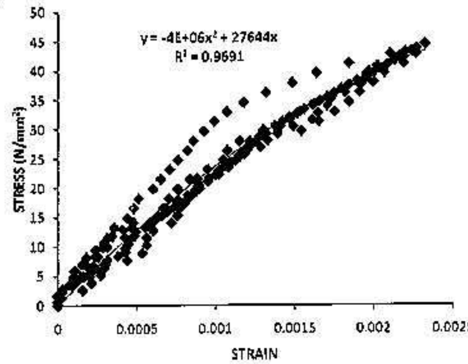


Figure 2(b). Node in between

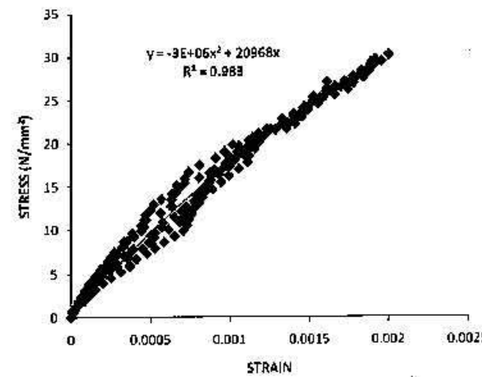


Figure 2(c). Node at either end of the specimen

Figure 2. Stress strain relationship of the specimens

Table 4. Summary of shear test results

Sl. No.	Specimen Number	Load (kN)	Shear area mm²	Shear strength N/mm²	Average shear strength N/mm²
1	A	8.0	1200	6.67	7.76
	B	10.0	1128	8.86	
2	A	10.0	1012	9.88	10.26
	B	11.5	1012	11.36	
3	A	10.0	1600	6.25	6.40
	B	10.5	1600	6.56	
4	A	9.5	1728	5.49	4.97
	B	8.0	1800	4.44	
5	A	10.2	990	10.30	11.14
	B	12.4	1034	11.99	
6	A	10.0	1620	6.79	6.72
	B	11.5	1728	6.65	
				AVG.	*7.87*
				Standard deviation	*2.38*
				COV (%)	*0.30*

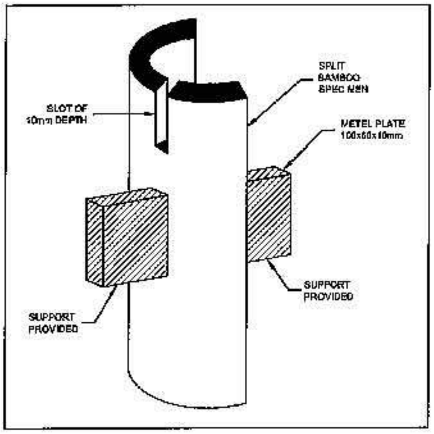


Figure 3. Schematic representation of shear test

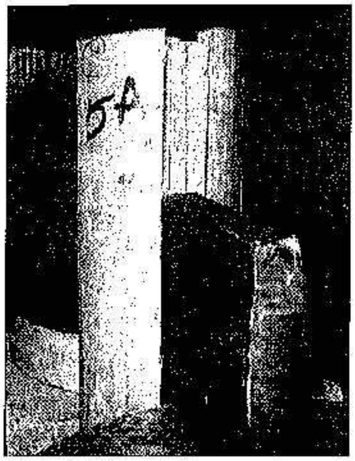


Plate 3(a) Vertical splitting

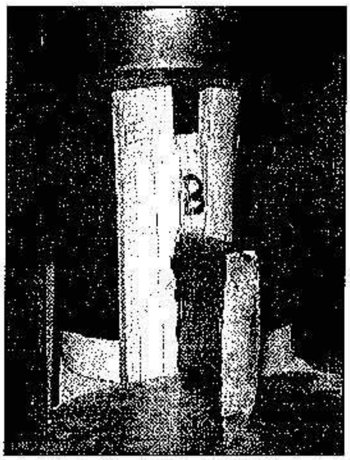


Plate 3(b) Shear areas gradually moved up

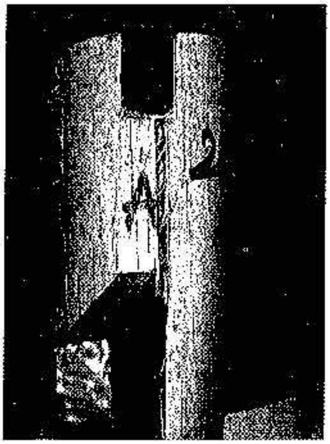


Plate 3(c) Full splitting at failure

Plate 3(d) Vertical splitting

Plate 3. Typical shear failure of the specimens

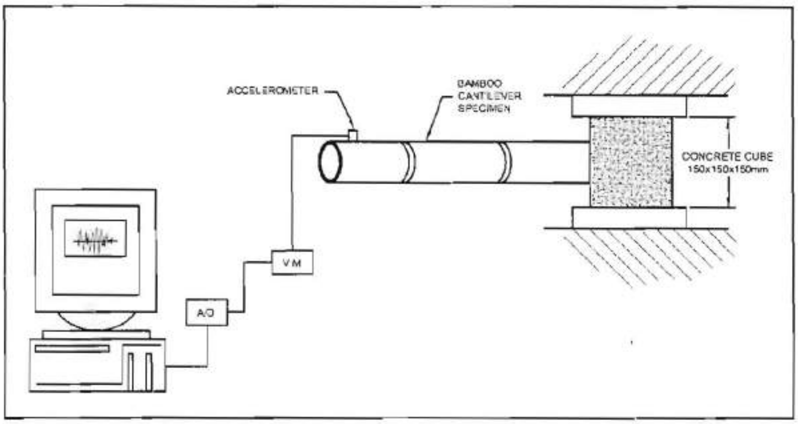


Figure 4. Schematic representation of free vibration test

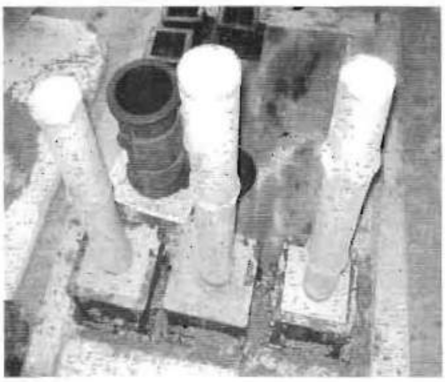


Plate 4(a) Bamboo culms housed in

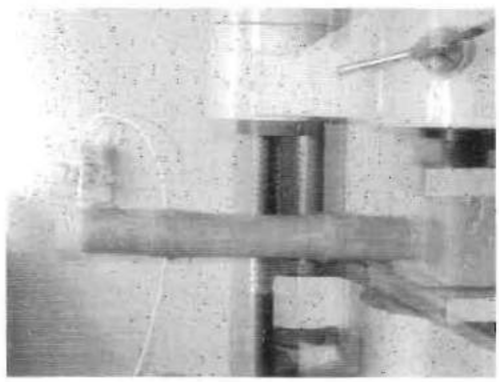


Plate 4(b) Accelerometer mounted on bamboo

Table 5. Results of free vibration test

Sl. No.	Fundamental natural frequency (Rad/Sec)	Modulus of elasticity (N/mm^2)		
		Combined modulus	Compression modulus	Tension modulus
1	110.27 118.50 109.26 111.52	20213.45	22343.67	18374.07
2	117.25 120.01 121.46 123.92	23325.40	22343.67	24373.45
3	133.25 119.56 122.30 125.06	24632.50	22343.67	27292.03

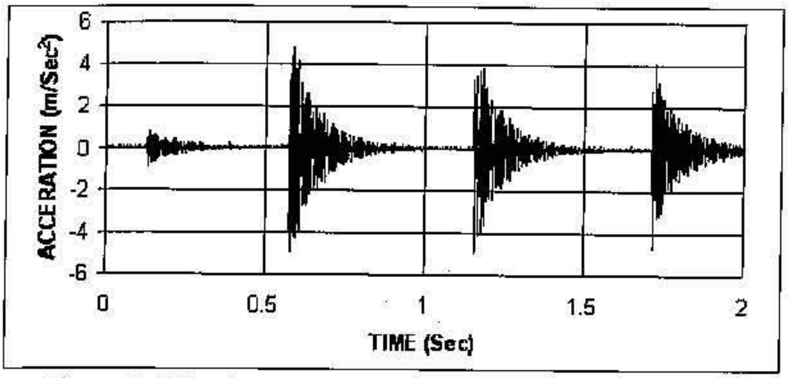


Figure 5. Vibration response obtained from the tip of the specimen

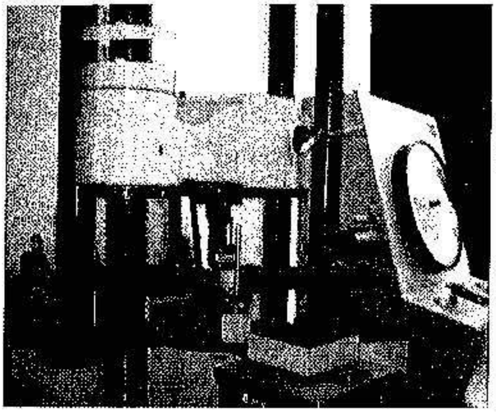


Plate 5(a) Experimental setup of flexural test

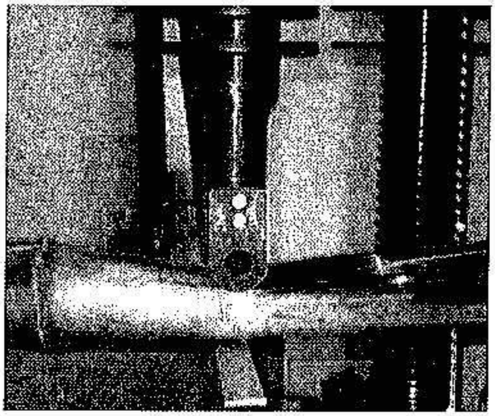


Plate 5(b) Local crushing observed

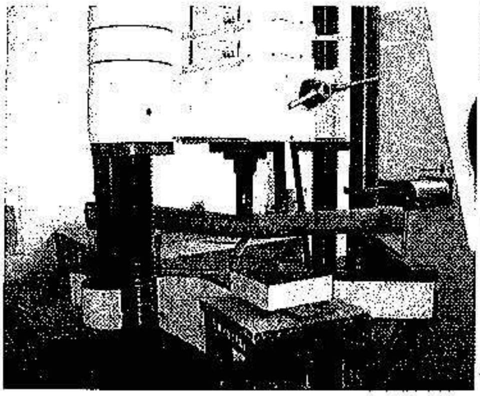


Plate 5 (c) Deflection observed

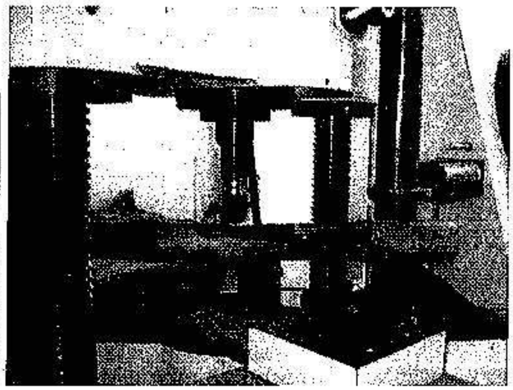


Plate 5(d) Specimen after the release of the load

Table 6. Test results of single bamboo columns

Sl. No.	Do (mm)	Di (mm)	Area (mm^2)	I_{min} (mm^4)	P_{cr} (kN)	P_{ult} (kN)	σ (MPa)	Remarks
1	83.45	39.38	4251.52	2262487.02	79.74	36.62	8.61	Splitting, local buckling
2	76.34	40.58	3283.79	1534052.21	54.07	30.34	9.23	Splitting, local shear and buckling
3	81.67	30.94	4041.55	2069809.5	72.95	31.60	8.54	Local buckling and splitting
					Average		*8.79*	
					Standard deviation		*0.38*	
					COV (%)		*0.04*	

Where, $_{Do}$ – outer diameter of the column (mm), $_{Di}$ - inner diameter of the column (mm),

I_{min} - moment of inertia (mm^4), $P_{cr} = \frac{\pi^2 EI}{L_{eff}^2}$ - Euler's buckling load (kN)

Where, **E**—Modulus of elasticity in compression (MPa), L_{eff} – Effective length of the column (m), P_{ult} - Ultimate load (KN),σ– Compressive strength of bamboo column (MPa)

Table 7. Test results of double bamboo columns

Sl. No.	Do (mm)	Di (mm)	Area (mm^2)	I_{min} (mm^4)	P_{cr} (kN)	P_{ult} (kN)	σ (N/mm^2)	Remarks
1	69.06 68.64	54.32 50.64	4164.66	1455991.60	51.32	54.36	11.57	Local buckling, crack near the joints
2	49.66 64.90	37.44 48.12	2616.62	809752.34	28.54	40.45	12.32	Local shear, local buckling
3	80.04 82.24	40.15 42.36	5279.55	3974478.95	14.00	25.28	7.56	Local buckling, crack near the joints
4	73.02 80.34	37.42 44.20	6690.12	3155242.06	11.12	29.07	9.45	Crack near the bolts, local buckling
5	66.51	30.28 59.67	6256.16 31.81	1494577.33	52.68	49.30	10.01	Local buckling, local deformation, crack at the joint
6	68.95 68.33	54.12 44.80	3439.99	1573085.12	55.44	39.19	8.02	Local buckling, cracks near the joints
					Average		*9.82*	
					Standard deviation		*1.88*	
					COV (%)		*0.19*	

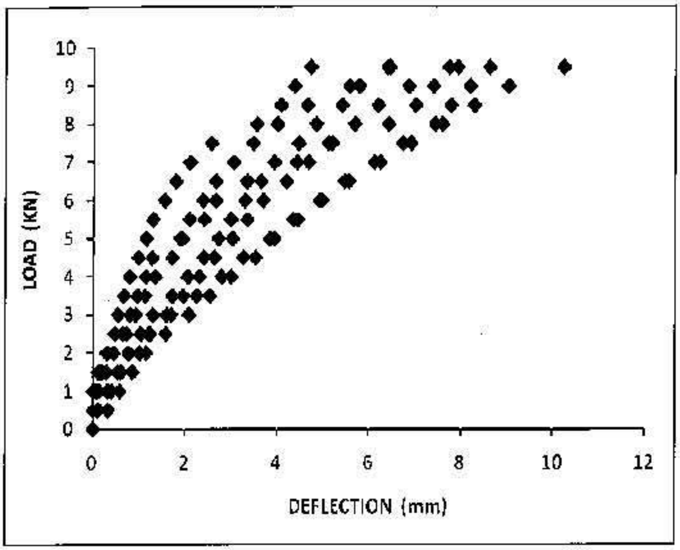


Figure 6. Load v/s deflection curve

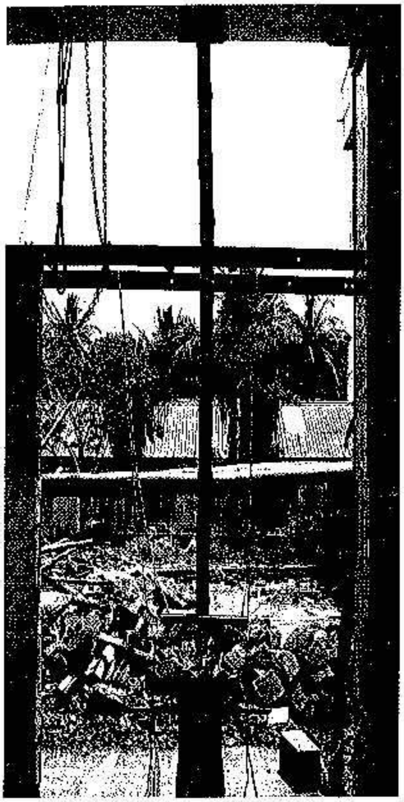


Plate 6 (a) Single bamboo column

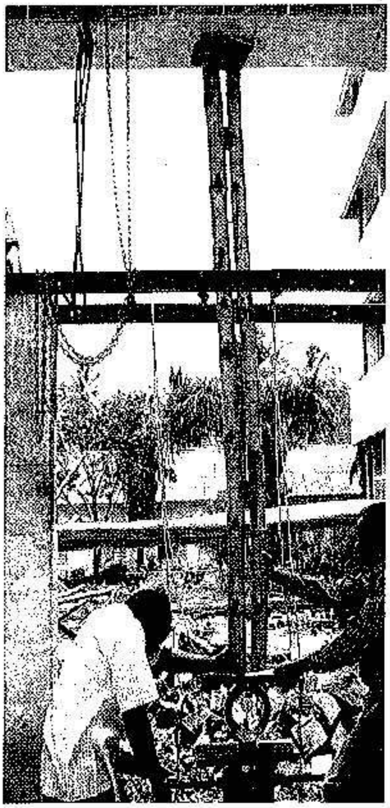


Plate 6 (b) Double bamboo column

Plate 6. Experimental setup of full scale column testing

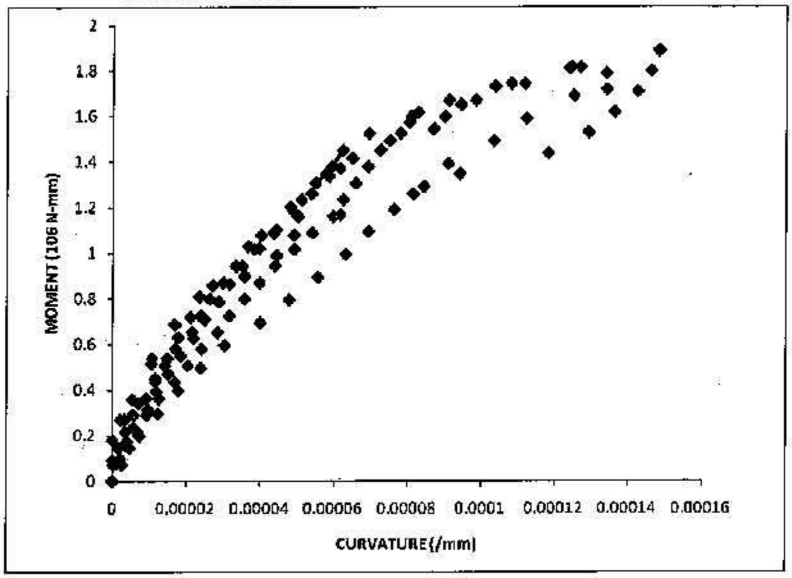


Figure 7. Moment-curvature relationship of test samples

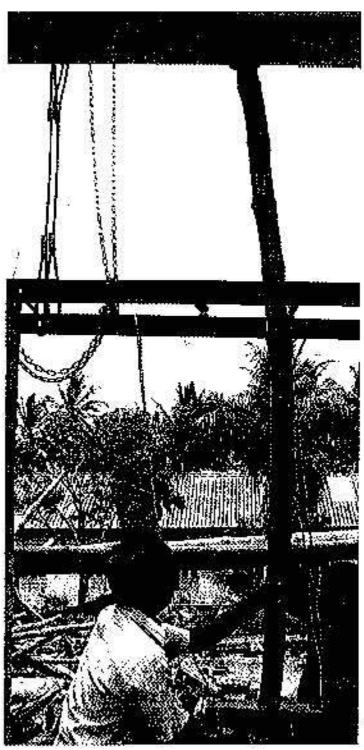


Plate 7 (a). Single bamboo column

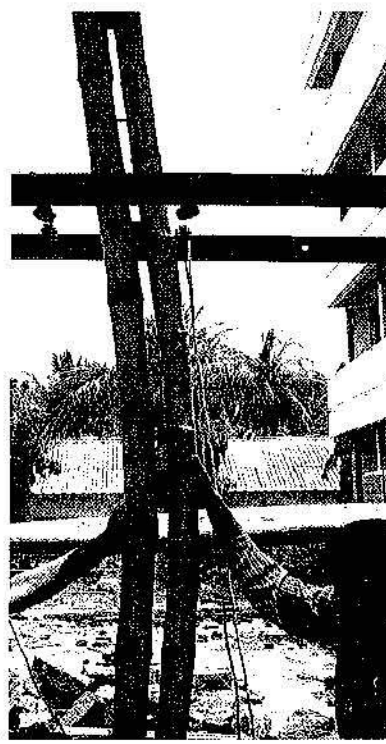


Plate 7(b). Double bamboo column

Plate 7. Lateral deflection observed during full scale column testing

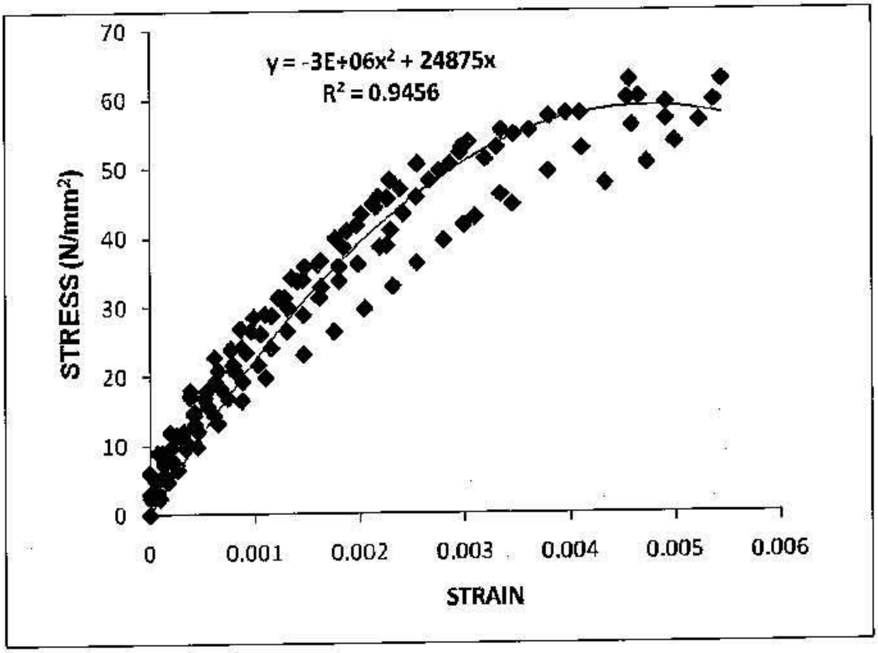


Figure 8. Stress-strain relationship

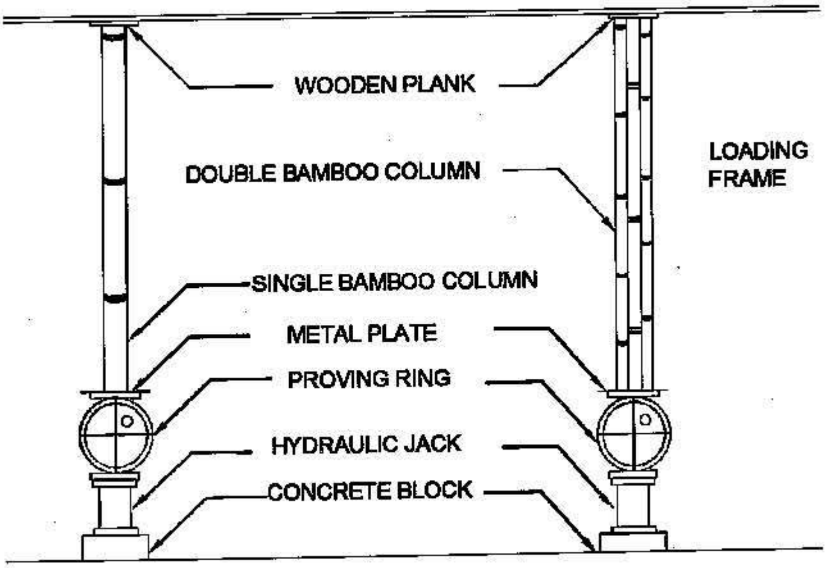
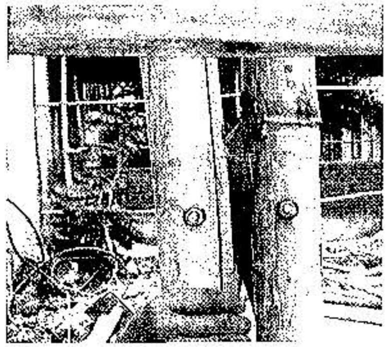


Figure 9. Schematic representation of experimental set up of full scale column testing



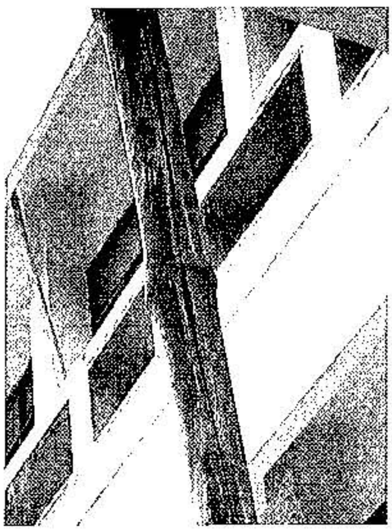


Plate 8 (a). Crack near the joint

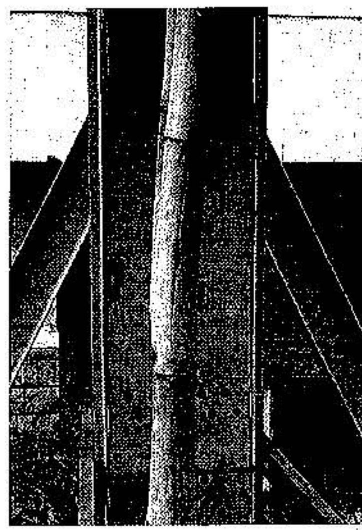


Plate 8 (c). Crack near the bolt

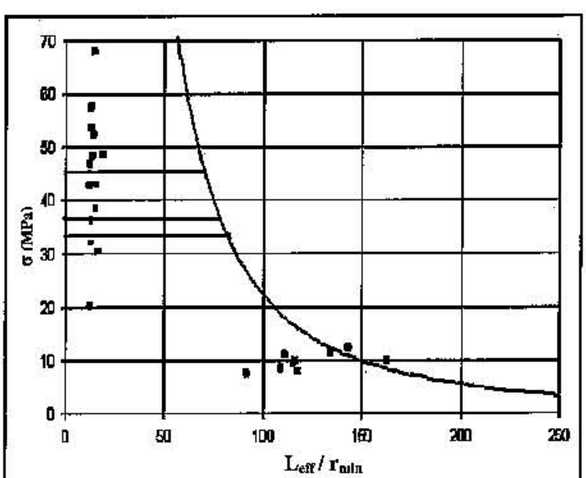


Figure 10. Stress v/s slenderness ratio of coloumns tested

The average ratio of P_{cr} and P_{ult} is an indication of the size effect of the specimen. An attempt has been made to plot a curve of stress v/s slenderness ratio, in an effort to identify whether the failure was close to buckling loads. Figure 10 shows the plot of stress v/s l_{eff}/ r_{min}. The bold line is the curve generated from Euler's formula. The points in the l_{eff}/r_{min} region of the 75 to175 are from the test on the columns. The points corresponding to l_{eff}/r_{min} lesser than 25 is from the test carried out on compression tests results the 3 types of specimens. It can be seen that storey high column tests specimen fall in the long column range.

It is clear that there is a need to test 'intermediate' column specimen as well. Also the experimental points are well within the upper band of the Euler's curve. Clearly, this indicates that failure of the long column (or even the short column) is mainly due to local effects such as splitting, local shearing, local deformation or even local buckling. There is a need to investigate this further.

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