Study on compression performance of laminated bamboo

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laminated bamboo

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1 Introduction

As resource availability declines and resource demands increase in today's modern industrialized world, it is becoming increasingly necessary to explore opportunities for new, sustainable building materials.

Both wood and bamboo have recently gained popularity in the green building community because of their environmentally beneficial characteristics: they are promoted as renewable, biodegradable, sequestering carbon from the atmosphere, low in embodied energy, and creating less pollution in production than steel or concrete.

Original bamboo building

Usable bamboo can be harvested in 3–4 years from the time of planting, as opposed to traditional timbers which need decades between planting and harvesting.

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Not only is bamboo fast-growing, but it is also highly efficient in comparison to other structural materials. Compared with other common building materials, bamboo is stronger than timber, and its strength-to-weight ratio is greater than that of common wood, cast iron, aluminum alloy, and structural steel.

Bamboo house in France

Original bamboo building

Finished by Elora Hardy and her team

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Original bamboo building

Green bamboo school, Bali Island, Indonesia

Bamboo tower, Venice, Italy

Original bamboo building

Bamboo vacation home, Taiwan, China

Bird shape arena, Hanoi, Vietnam

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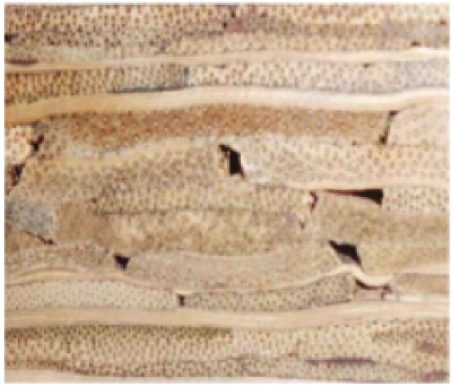
Although bamboo is a promising wood substitute, structural forms in which it can be used are limited by the diameter of the bamboo culm and the low rigidity of the bamboo.

Modern bamboo building materials



Glubam lumber

Parallel strand bamboo lumber

Laminated bamboo lumber

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2 Production process for the laminated bamboo

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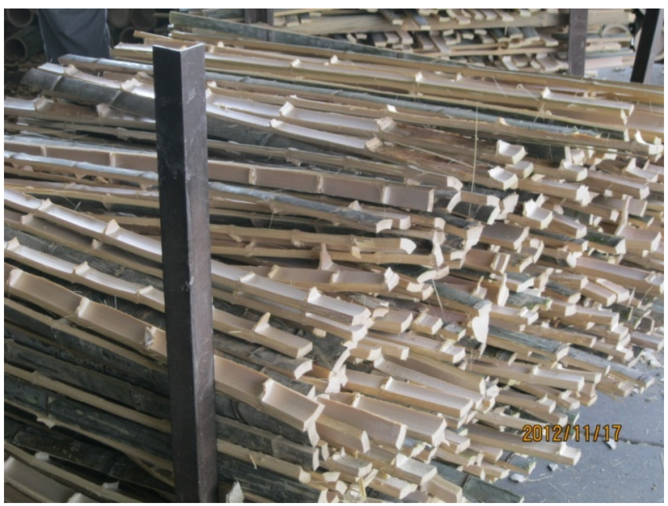
Laminated bamboo



The bamboo culm can be disassembled into thin flat laminae.

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The outer skin (epidermal) and inner cavity layer (pith peripheral) were removed using a planer.

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All the culm strips were then charred and dried.

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The bamboo strips were laminated together with adhesive to form certifiable structural members. Phenol glue was used to manufacture the laminated specimens. Single layers were made first, and these were then pressed together to form the blocks.

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A pressing temperature of 140±5ºC was used. A transverse compression of 1.82 MPa was applied for both the sheets and the blocks, and a confining pressure of 4.74 MPa was used when manufacturing the sheets.

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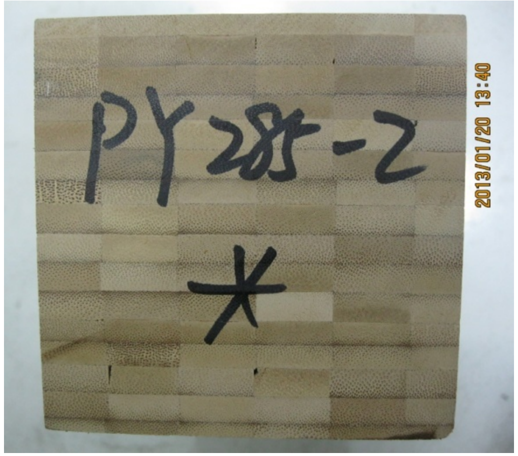

3 Axial compression performance of laminated bamboo column

Specimens

The source Moso bamboo was harvested at the age of 3–4 years. Bamboo strips from the lower, middle, and upper growth heights, respectively, of a 2100mm tall culm were selected.

The final moisture content was 8.26% and the density was 600 kg/m^3 for the laminate sourced from the lower portion, 645 kg/m^3 for the laminate sourced from the middle portion, and 647 kg/m^3 for the laminate sourced from the upper portion.

Each test specimen was constructed with the dimensions 100mm×100mm×300mm.

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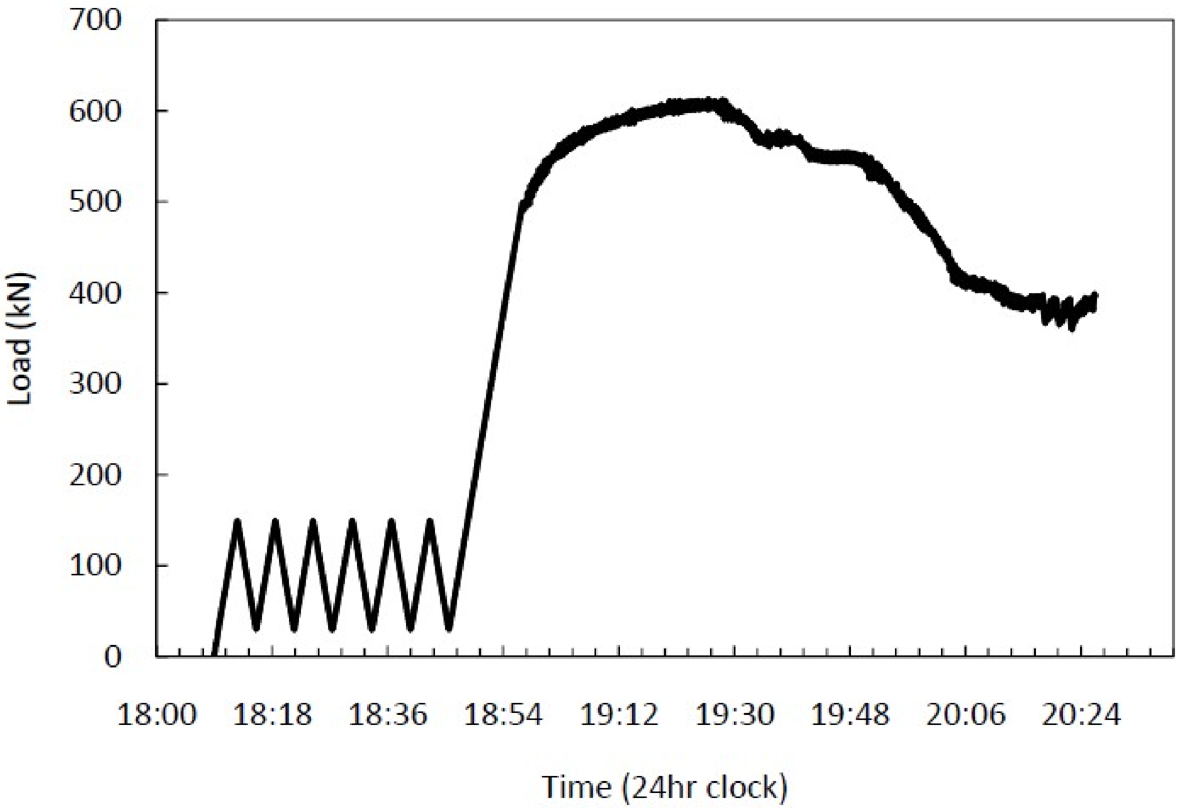
Experiment for
compression performance



Typical loading regime

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Lower growth portion group

The specimens exhibited a variety of failure mechanisms. The first specimen crushed at the bottom and split up the middle.

(a) Face A (b) Face B (c) Face C (d) Face D (e) Top surface (f) Bottom surface

Failure photos for specimen G300-1

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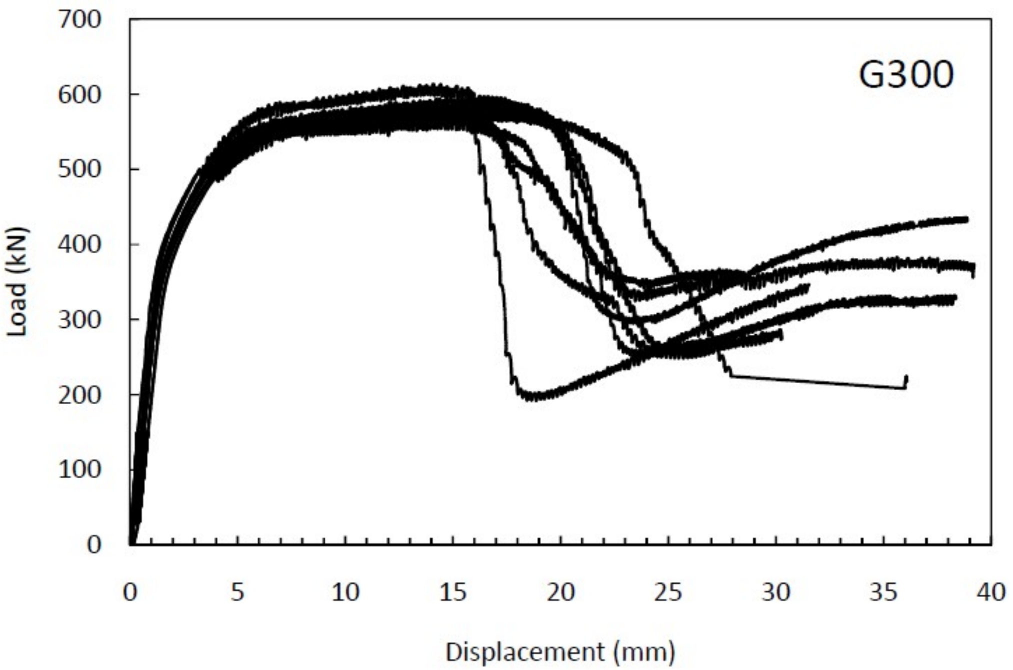
The eight tests are remarkably consistent up until a displacement of approximately 16 mm. Each test shows a clear elastic behaviour up to a load of approximately 350 kN, followed by non-linear behaviour until approximately 550 kN, after which there is a plastic plateau.



However, there is quite significant variation in the displacement at which unloading starts to commence, and behaviour during unloading also has a great deal of variation.

load against the displacement for the lower growth height specimens

Although there is some evidence of residual strength at high displacement, this residual strength is generally less than half the peak strength, and so is of no practical use in design.

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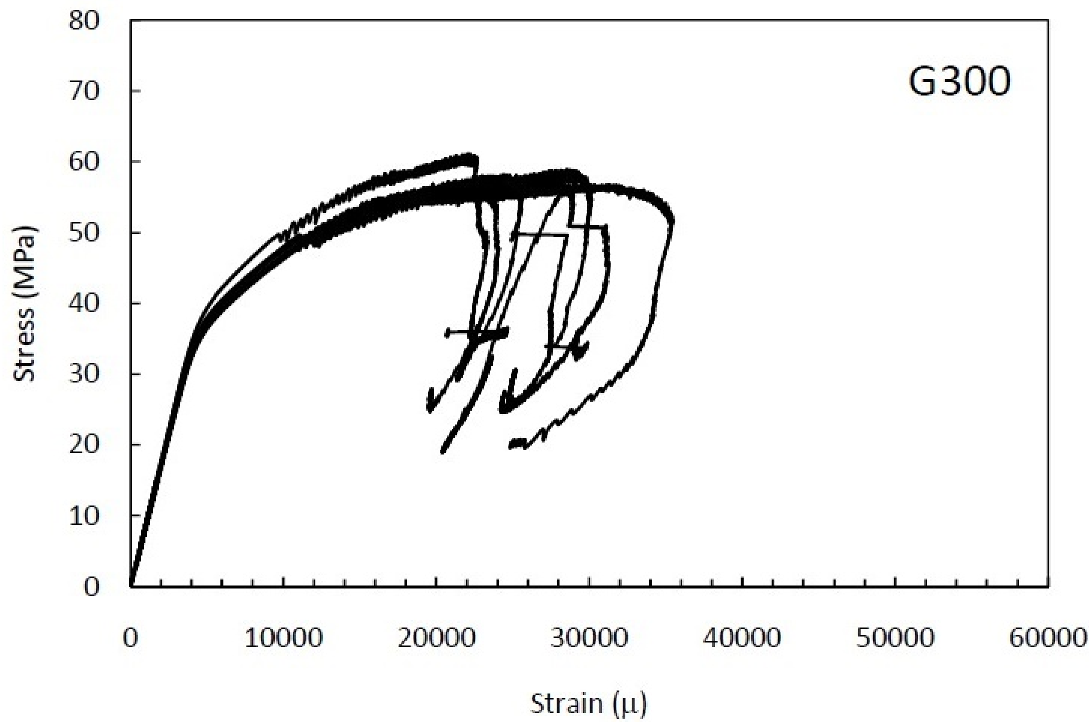
There is excellent consistency in the results, particularly in during elastic response. The six cycles of load between 50 and 150kN show so little variation that the cycling is not visible in the graph.



Stress vs Strain for the lower growth height specimens

The average elastic modulus is 8641 MPa with a standard deviation of only 196 MPa.

The average compressive strength of this group of specimens is 57.9 MPa, with a very low standard deviation of 1.5 MPa.

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Middle growth portion group

These specimens also exhibited a variety of failure mechanisms.

(a) Face A (b) Face B (c) Face C (d) Face D (e) Top surface (f) Bottom surface

Failure photos for specimen Z300-8

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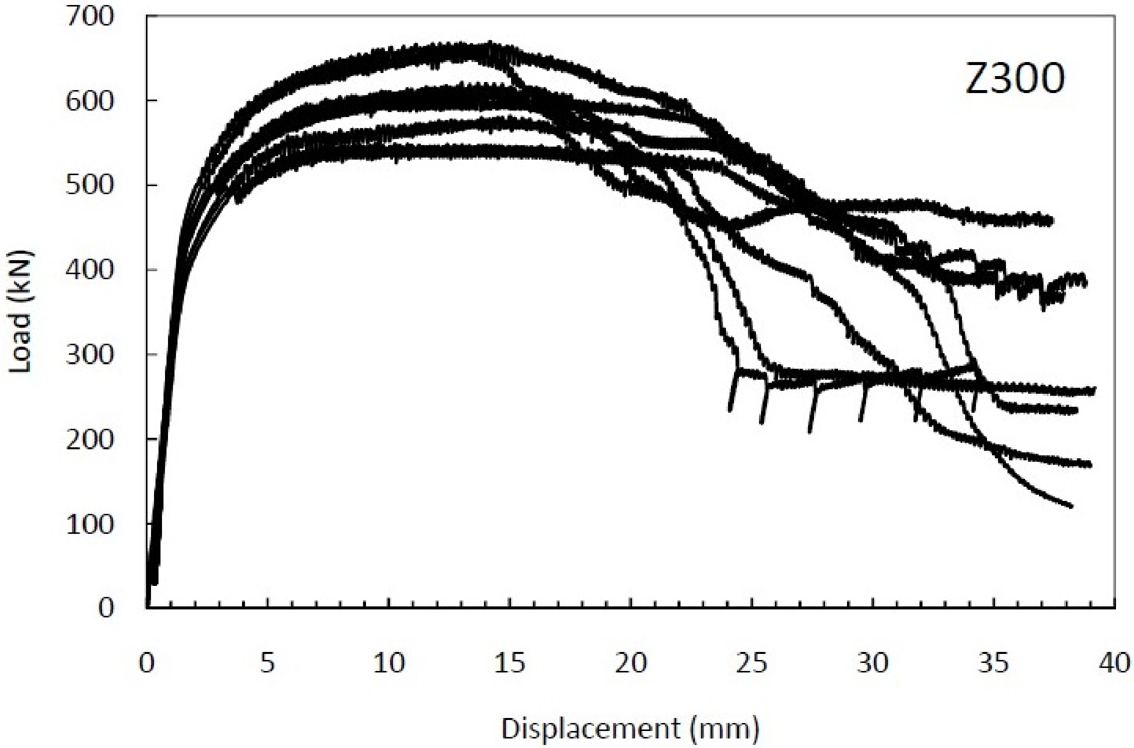
Like the first group, each test shows clear elastic behaviour up until a load of approximately 350 kN, followed by non-linear behaviour and a plastic plateau.

However, unlike the specimens from the lower growth portion, there is significant variation in the plateau load, ranging from 550 kN to 670 kN.



Load vs Displacement for the middle growth height specimens

The strongest two specimens do not exhibit a distinct plastic plateau, with the load increasing at a decreasing rate up to the maximum load and then decreasing at an increasing rate to a residual load.

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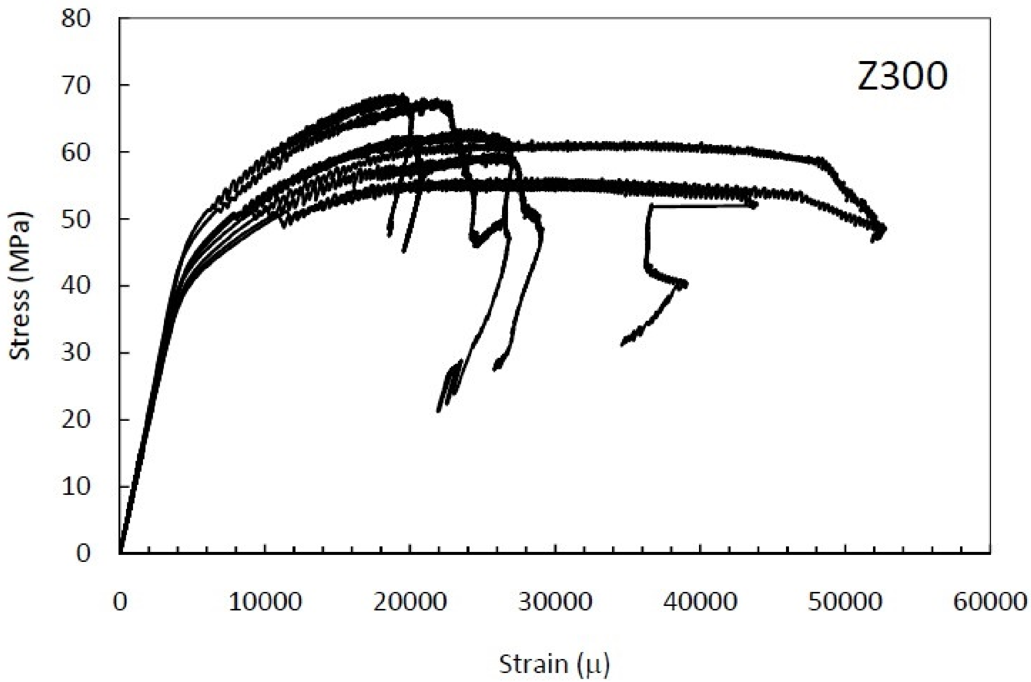
There is significantly more variation in the stress-strain between these specimens than was observed in the tests on the lower growth height specimens. However, the elastic behaviour is still quite consistent.

The average elastic modulus is 10,210 MPa with a standard deviation of 335 MPa, significantly higher than the average elastic modulus for the specimens sourced from the lower growth portion.

The average compressive strength of this group of specimens was 61.2 MPa with a standard deviation of 4.8 MPa.



Stress vs Strain for the middle growth height specimens

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Upper growth portion group

The sixth specimen in the series failed in shear through faces B and C, with bending and a central split on face A

(a) Face A (b) Face B (c) Face C (d) Face D (e) Top surface (f) Bottom surface

Failure photos for specimen S300-6

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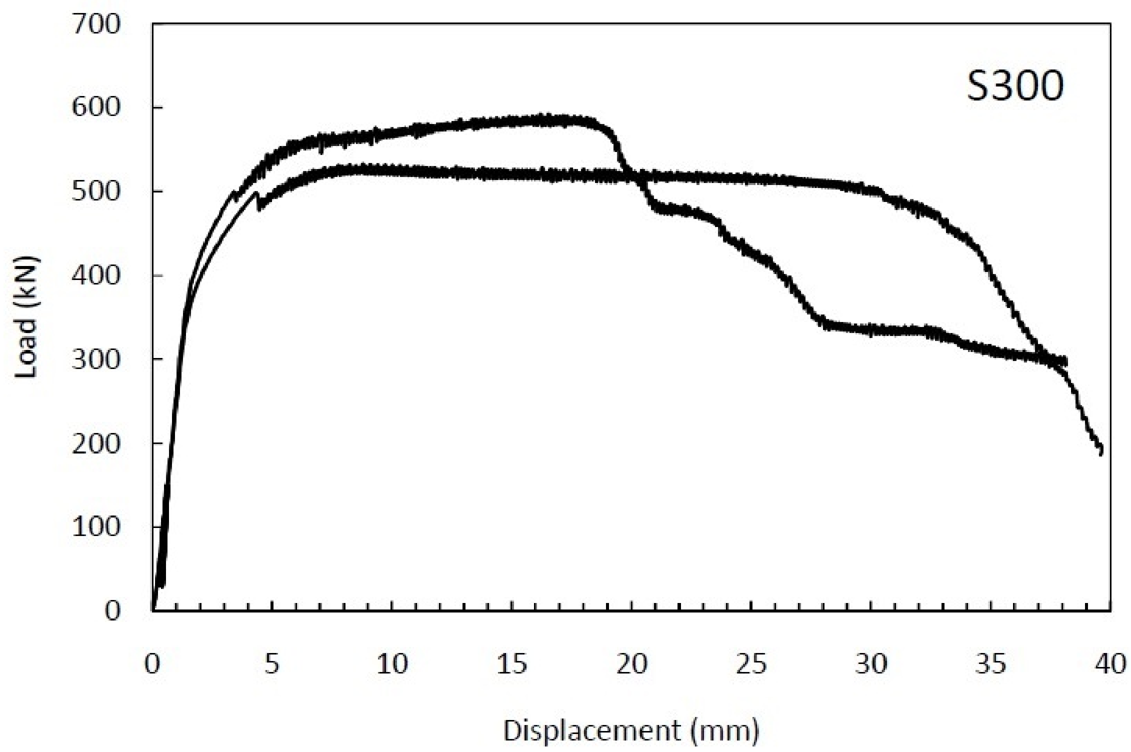
There is a significant different in the plateau loads of the two specimens, and also in the length of the plateau.



Load vs Displacement for the upper growth height specimens

Specimen S300-6 behaves plastically over a deformation of almost 22 mm, showing extreme ductility, while specimen S300-8 only behaves plastically over a deformation of 11mm.

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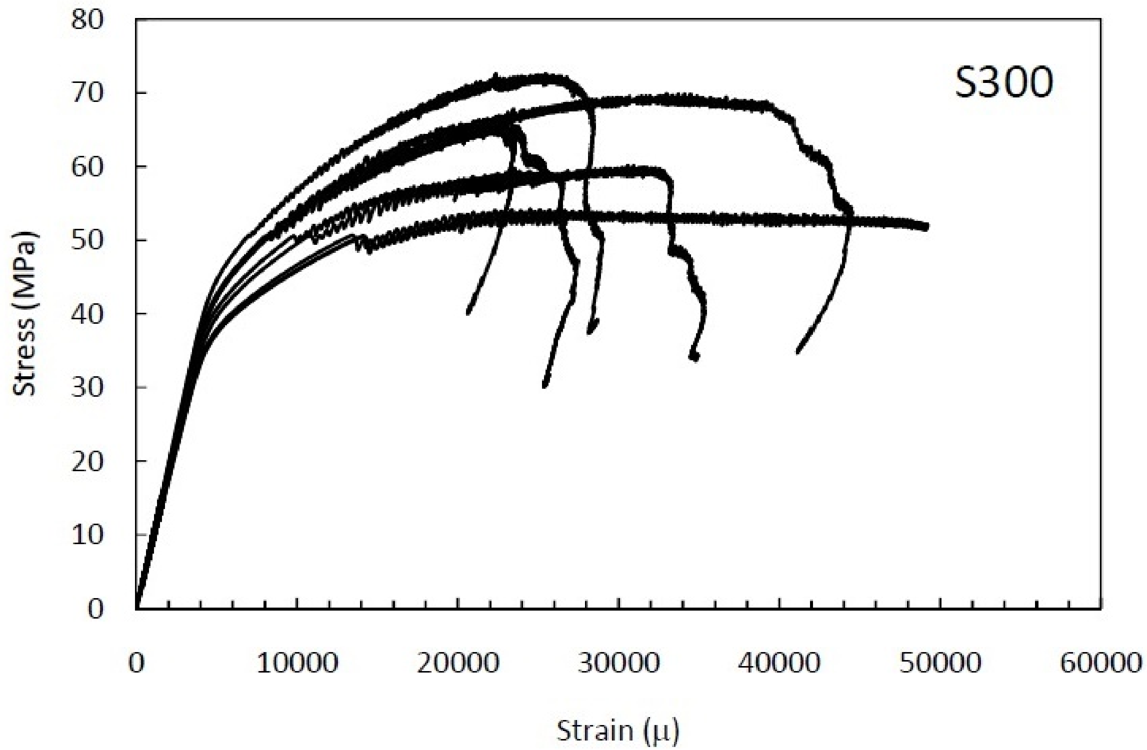
This group of specimens shows the biggest variation in terms of ultimate stress, although again the elastic behaviour is still consistent and the cycling between 50 and 150 kN does not result in plotable changes in the strains between cycles.

The average elastic modulus is 9322 MPa with a standard deviation of 362 MPa, somewhat lower than the average elastic modulus for the specimens sourced from the middle growth portion.

The average compressive strength of this group of specimens was 62.7 MPa with a standard deviation of 7.0 MPa.



Stress vs Strain for the upper growth height specimens

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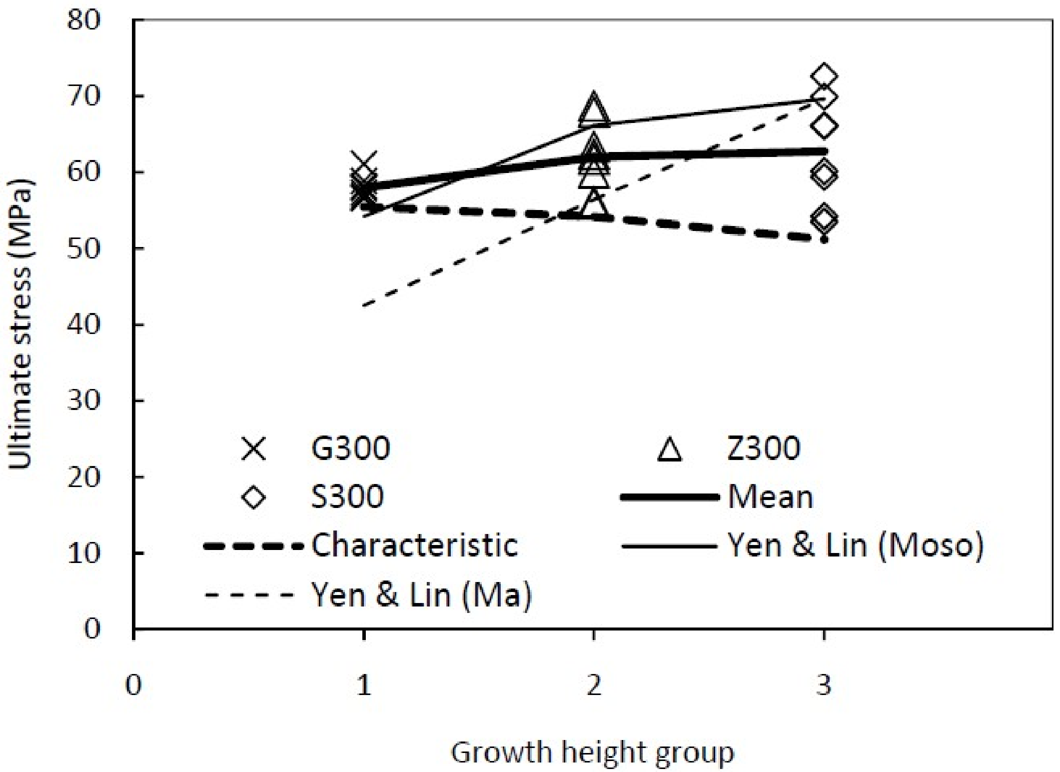
Effect of growth portion of source bamboo

This figure shows clearly that although the mean strength increases slightly with the source growth height, the variation in the test results also increases.

As a result, the characteristic strength decreases slightly with growth height, although this decrease is small compared with the variation in the test results.

The results of the current study suggest that, when assembled in larger sections, the increase in strength provided by source bamboo from the upper growth portion is (1) less significant than when assembled in smaller sections, and (2) offset completely by an increase in the variability of the test results, which results in the characteristic strength for design decreasing rather than increasing.



Effect of growth height on ultimate stress

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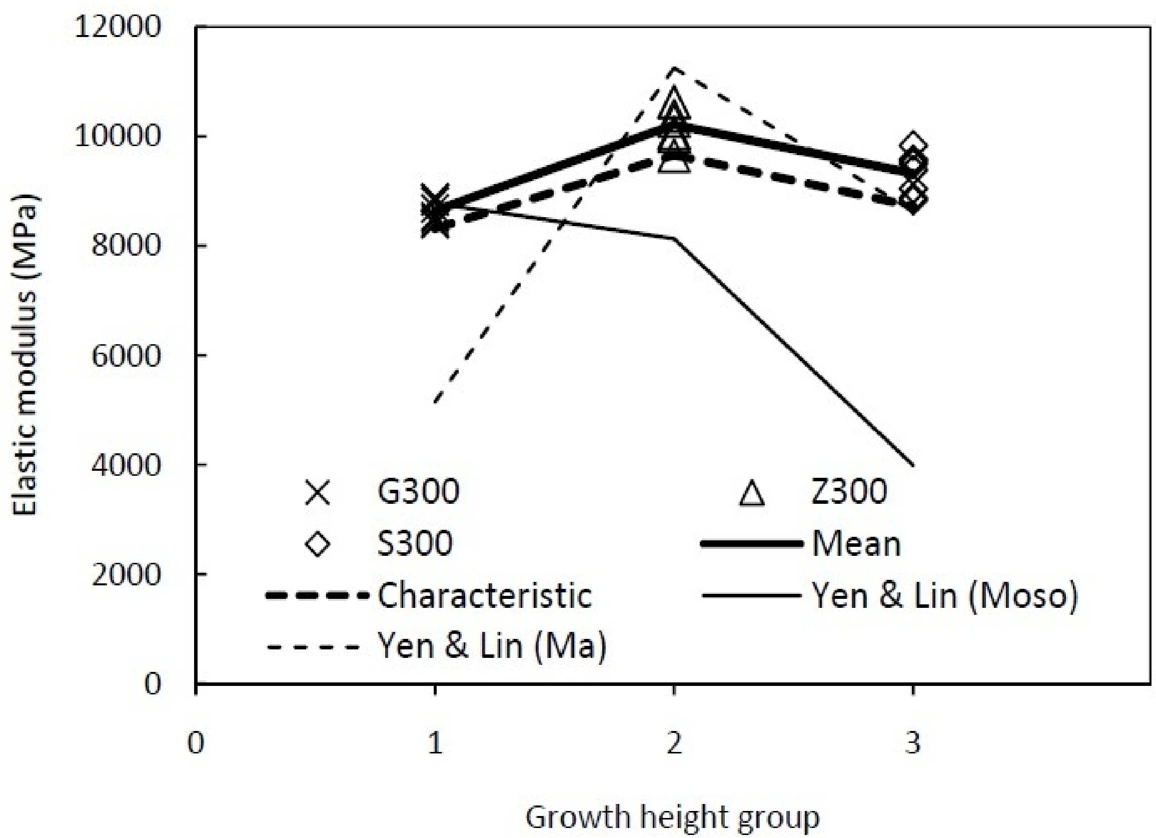
As with the ultimate strength results, the results for elastic modulus obtained by the current study suggest that assembling the laminated bamboo in larger cross-sections reduces the variability in stiffness resulting from sourcing bamboo from different growth heights.



Effect of growth height on elastic modulus

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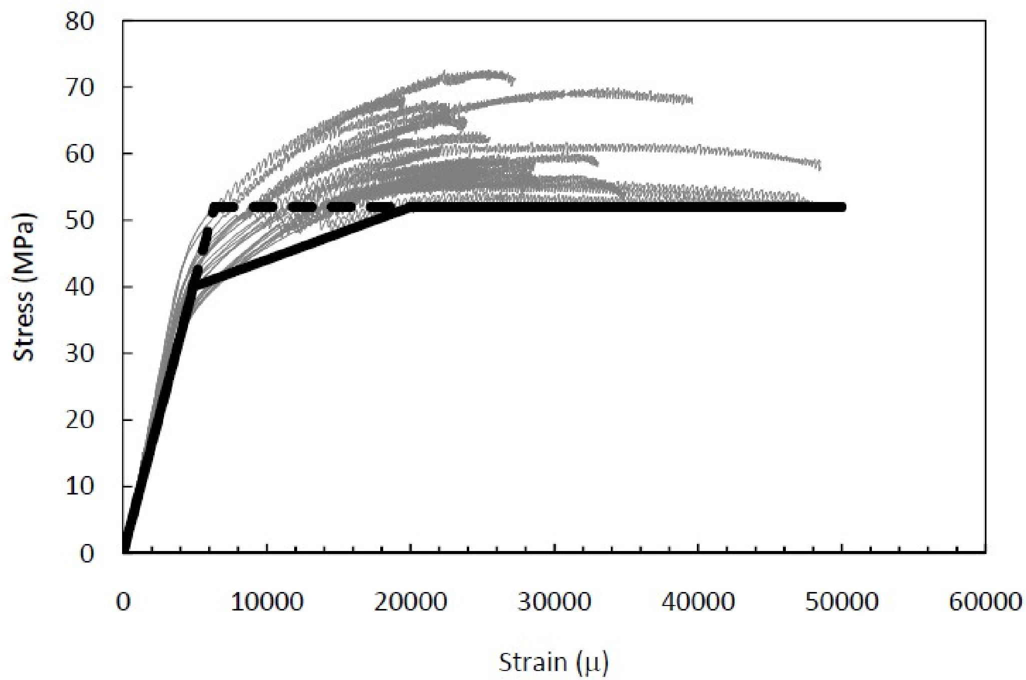
Combined results

Based on these 24 specimens, the characteristic compressive strength is 52 MPa. The characteristic elastic modulus for these specimens is 8200 Mpa.

The simplest possible model is a bi-linear elastic-perfectly plastic model. The initial slope of the model is 8200 MPa up to a stress of 52MPa, after which the material behaves plastically.



The elastic-perfectly plastic model will under predict the strains and hence displacements in the stress range between 40 MPa and 52 MPa, potentially significantly. To overcome this, a refined tri-linear model is proposed. In this model, elasticity is assumed up to a stress level of 40MPa, after which the modulus of the material reduces from 8200 MPa to about 800 MPa.

Recorded stress/strain behaviour compared with proposed models

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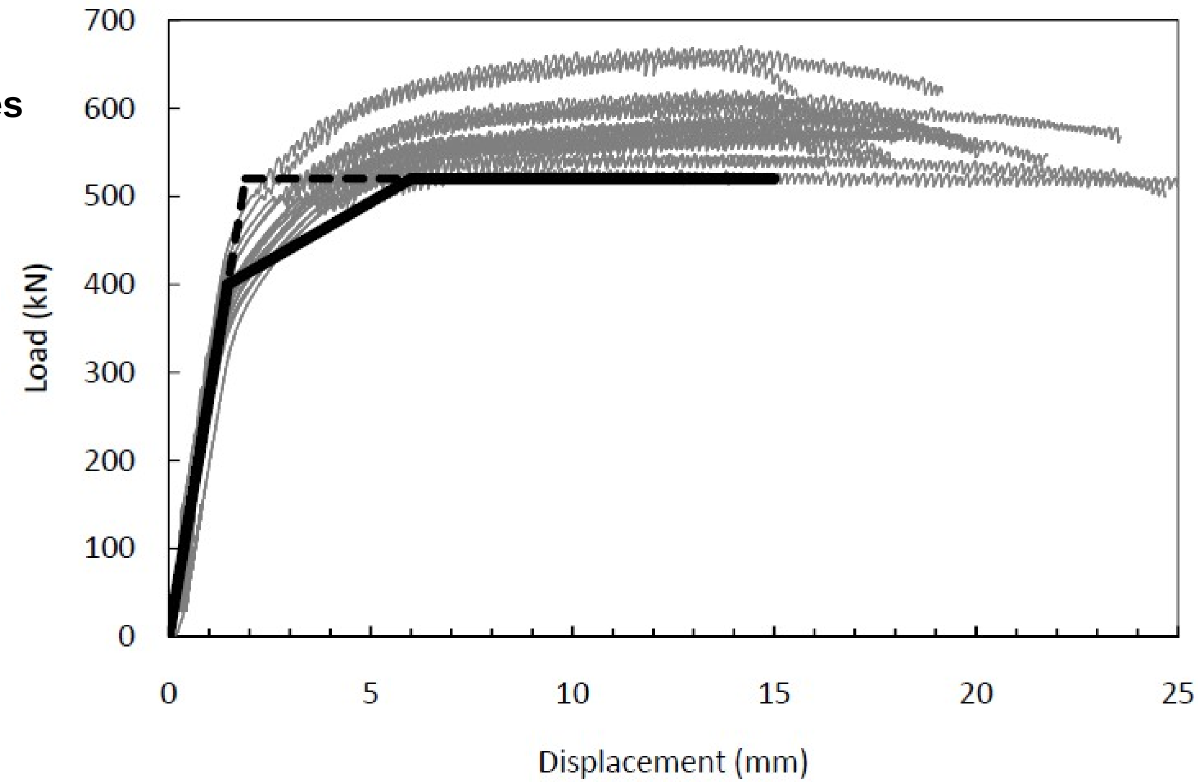
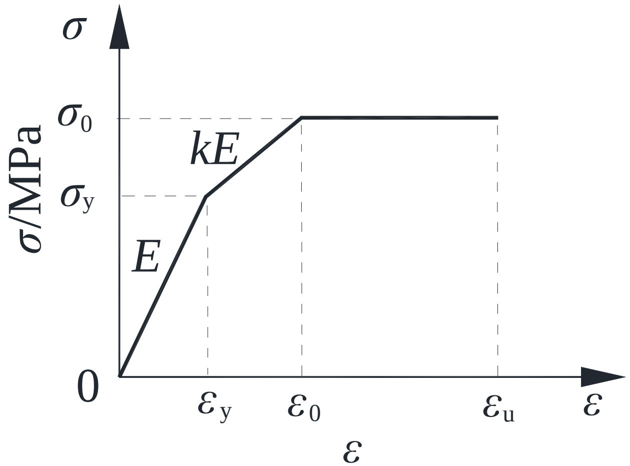
From a design point of view the proposed trilinear model captures the behaviour of the specimens extremely well.



Recorded load/displacement behaviour compared with proposed models

Strain-stress relationship mode study

Simplified Strain-stress relationship mode (trilinear model)



$$\sigma=\begin{cases} E\varepsilon & (0\le\varepsilon\le\varepsilon_{\mathrm{y}}) \\ \sigma_{\mathrm{y}}+kE(\varepsilon-\varepsilon_{\mathrm{y}}) & (\varepsilon_{\mathrm{y}}\le\varepsilon\le\varepsilon_{0}) \\ \sigma_{0} & (\varepsilon_{0}\le\varepsilon\le\varepsilon_{\mathrm{u}}) \end{cases}$$

$$k=\frac{\sigma_{\mathrm{c0}}-\sigma_{\mathrm{cy}}}{(\varepsilon_{\mathrm{c0}}-\varepsilon_{\mathrm{cy}})E}$$

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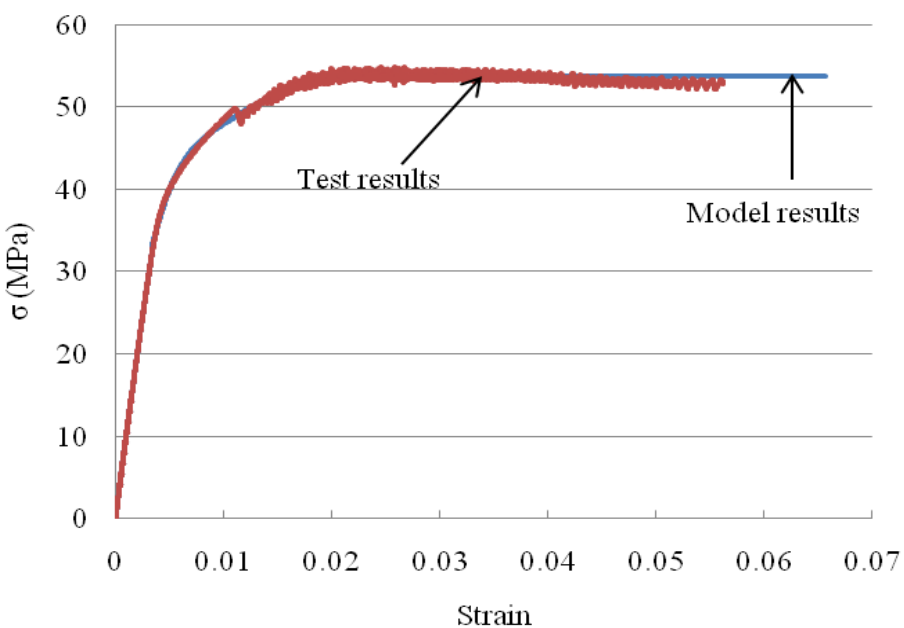
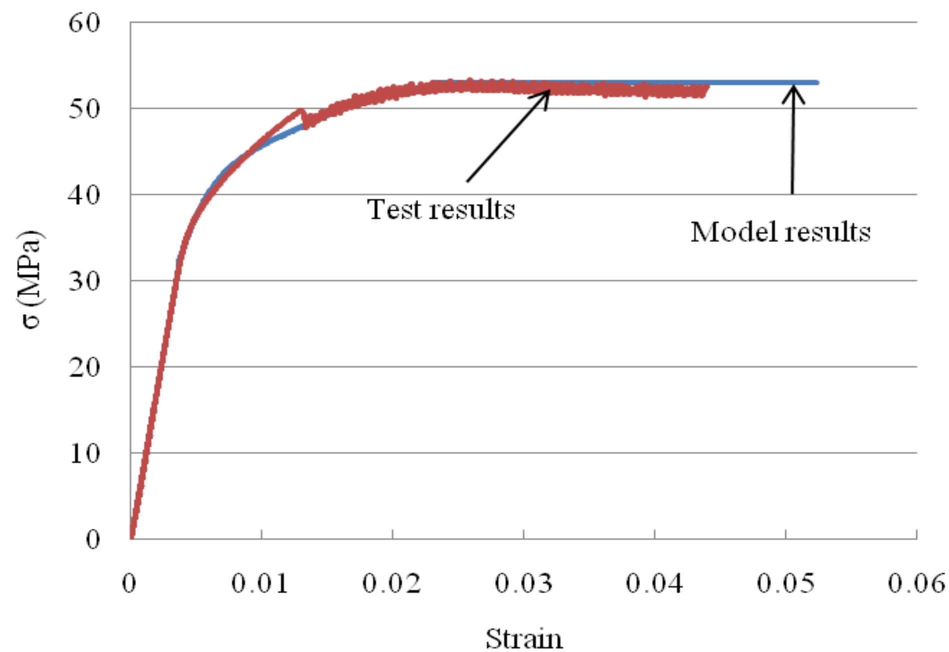
Refined Strain-stress relationship mode

$$\sigma=\begin{cases} =E\varepsilon & (\varepsilon \le \varepsilon_y) \\ =\sigma_0\left(7.3\dfrac{\varepsilon}{\varepsilon_0}-21.6\left(\dfrac{\varepsilon}{\varepsilon_0}\right)^2+33.39\left(\dfrac{\varepsilon}{\varepsilon_0}\right)^3-25.28\left(\dfrac{\varepsilon}{\varepsilon_0}\right)^4+7.4\left(\dfrac{\varepsilon}{\varepsilon_0}\right)^5-0.2045\right) & (\varepsilon_s \le \varepsilon \le \varepsilon_0) \\ =\alpha\sigma_0 & (\varepsilon_0 \le \varepsilon \le \varepsilon_u) \end{cases}$$



Specimen Z300-1



Specimen S300-6

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Comparison with other building materials

Materials		Compression strength /MPa	Elastic modulus /GPa	Density kg/m³	Compression strength / Density
Laminated bamboo	Fujian	80.43	9.69	640	0.1257
	Jiangxi	52.3	8.2	631	0.083
Wood	Larix gmelinii	57.6	14.5	517	0.111
	Fraxinus mandschurica	52.5	14.6	499	0.105
	China fir	32	9.3	289	0.111
Concrete	C30	20.1	30	2200-2400	0.0091-0.0084
	C40	23.4	31.5	2200-2400	0.0106-0.0098
Steel bar	HPB300	300	210	7850	0.038
	HRB335、HRBF335	335	200	7850	0.043
	HRB400、HRBF400、RRB400	400	200	7850	0.051
	HRB500、HRBF500	500	200	7850	0.064
Q235 steel	Less than 16mm	233	206	7850	0.03
	16-40mm	223	206	7850	0.028
Q345 steel	Less than 16mm	344	206	7850	0.044
	16-35mm	328	206	7850	0.042
fired common brick	MU10M10	3.02	4.84	1800-1900	0.0017-0.0016
	MU15M10	3.7	5.92	1800-1900	0.0021-0.0019
concrete solid brick	MU15Mb10	6.44	10.3	2200-2399	0.0029-0.0027
	MU15Mb15	7.38	11.81	2200-2400	0.0034-0.0031
Ordinary autoclaved fly ash brick	MU15M10	3.7	3.922	1400-1600	0.0026-0.0023
	MU15M15	4.46	4.73	1400-1600	0.0032-0.0028
Raw stone	MU20M5	3.43	4	2080-2480	0.0016-0.0014
	MU30M5	4.2	4	2080-2480	0.002-0.0017

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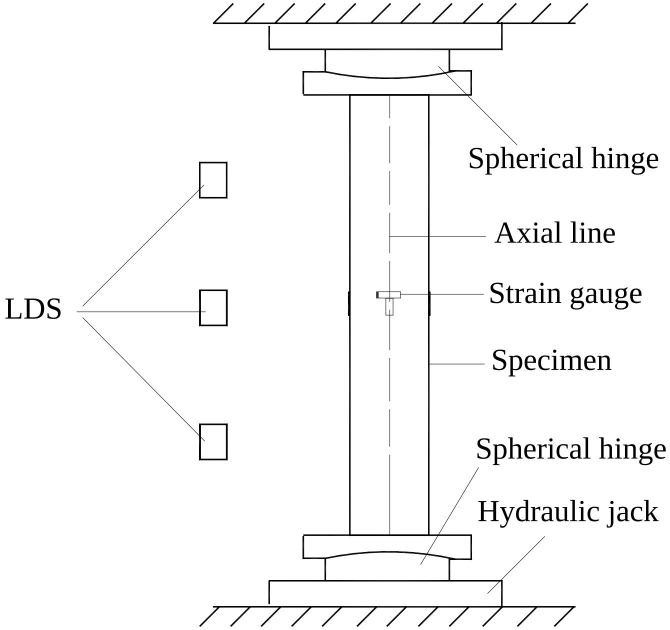
Columns with different lengths

Fifty groups of specimens were constructed with the same design cross section of 100 mm x 100 mm. Each group consisted of eight identical specimens. Specimens from the different groups are shown in the right Figure. The lengths ranged from 400 mm to 1800 mm with increments of 100 mm.

Test scheme



Two strain gauges were pasted on each middle side surface of the specimens.

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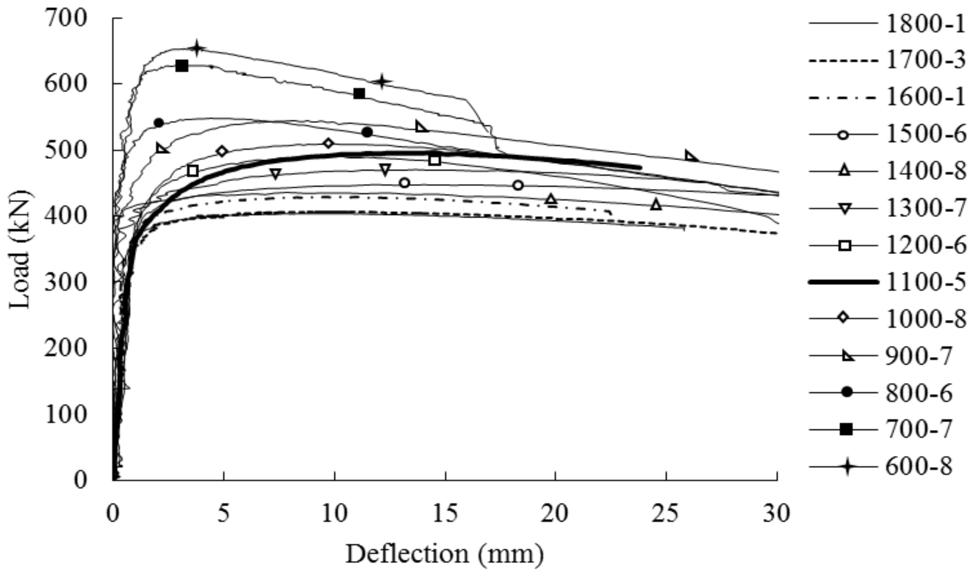
Influence of slenderness ratio upon deflection

In the initial phase the lateral deflection is very small, and increases linearly with axial load. After the peak load point, the lateral deflection increases suddenly. The load decreases while the lateral deflection keeps increasing until failure happens.



Load-middle lateral deflection curves for columns with various slenderness ratios

It can be seen from the figure that a horizontal section of the load-displacement curve is most obvious for the specimen with the biggest slenderness ratio, and the bigger the slenderness ratio, the more the failure resembles an ideal elastic buckling failure.

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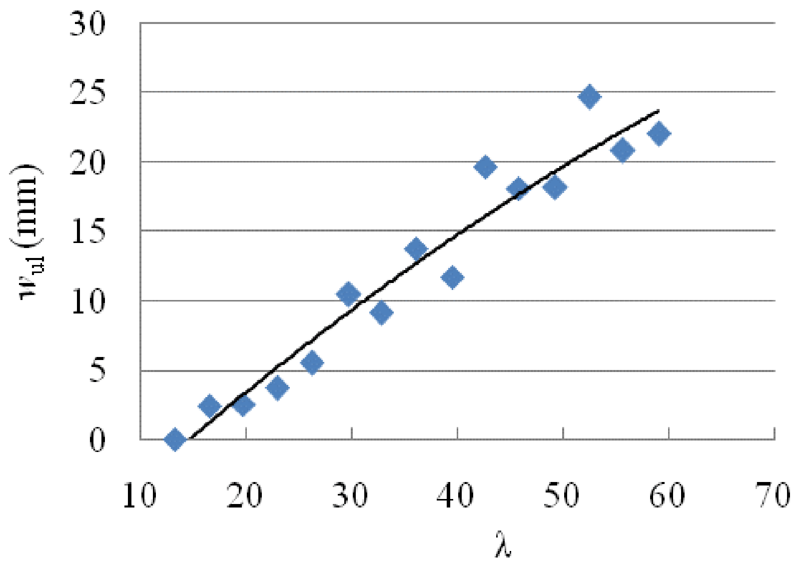
The ultimate lateral deflection becomes bigger and bigger with the increase of the slenderness ratio.

For the long columns, buckling failure occurs and the ultimate lateral deflection is significant.



Ultimate middle lateral deflection vs slenderness ratio

By statistical regression from the test results, the relationship between ultimate lateral deflection and slenderness ratio under the conditions described above can be expressed as

$$w_{ul} = 0.014\lambda^2 - 0.000002\lambda^4 - 2.461$$

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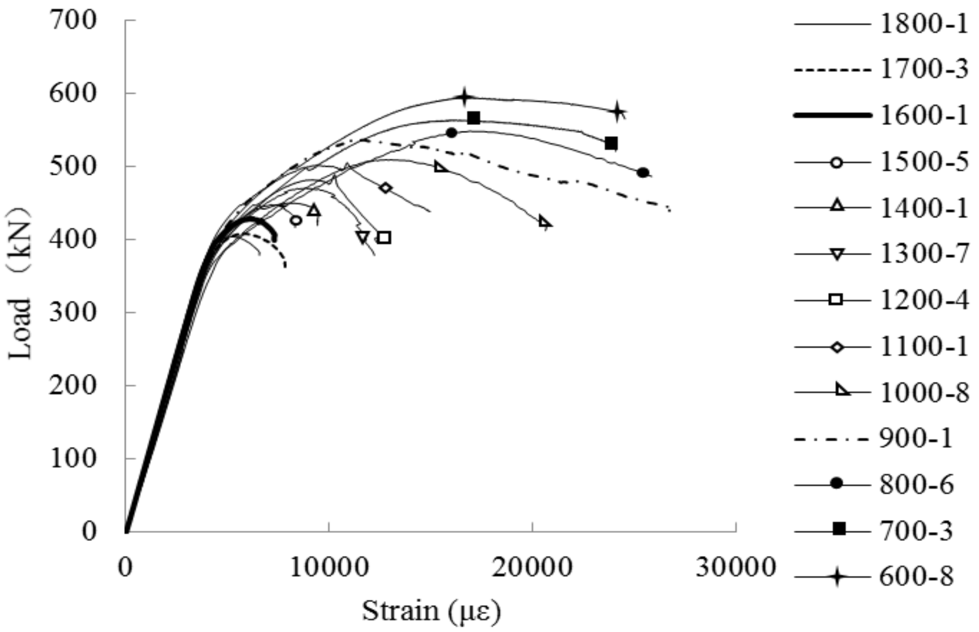
Influence of slenderness ratio upon the average longitudinal strain

Column specimens with a bigger slenderness ratio have a higher ultimate longitudinal strain on the whole.
The average longitudinal strain in the longer column specimens starts decrease earlier in the loading process than the shorter specimens.
Plastic deformation becomes more and more obvious with the decrease of the slenderness ratio. The material is brought closer to its full compressive strength for the short specimens than for the longer specimens.



Typical load vs average longitudinal strain for the mid-span cross-section

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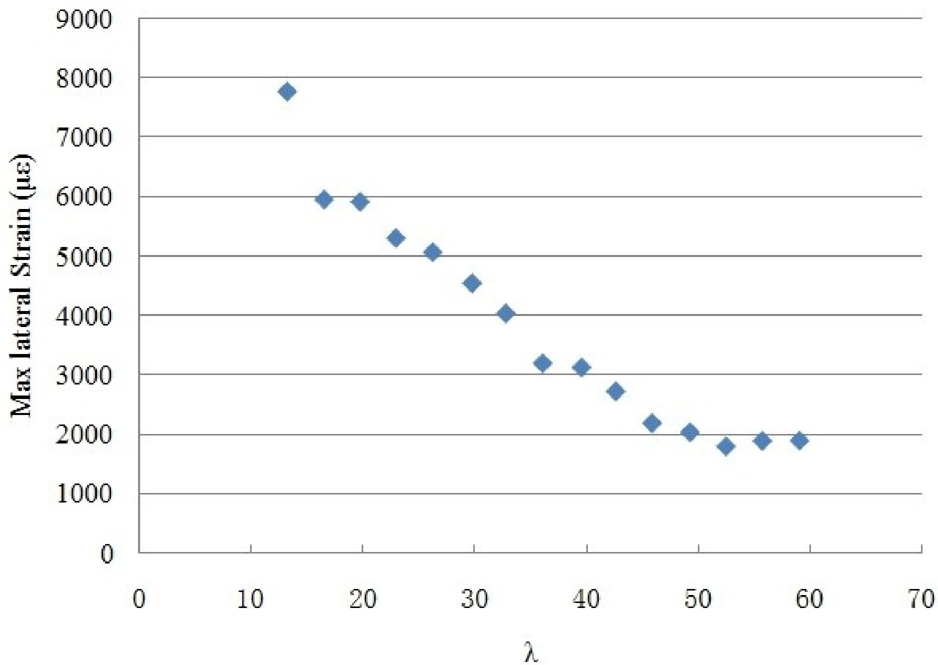
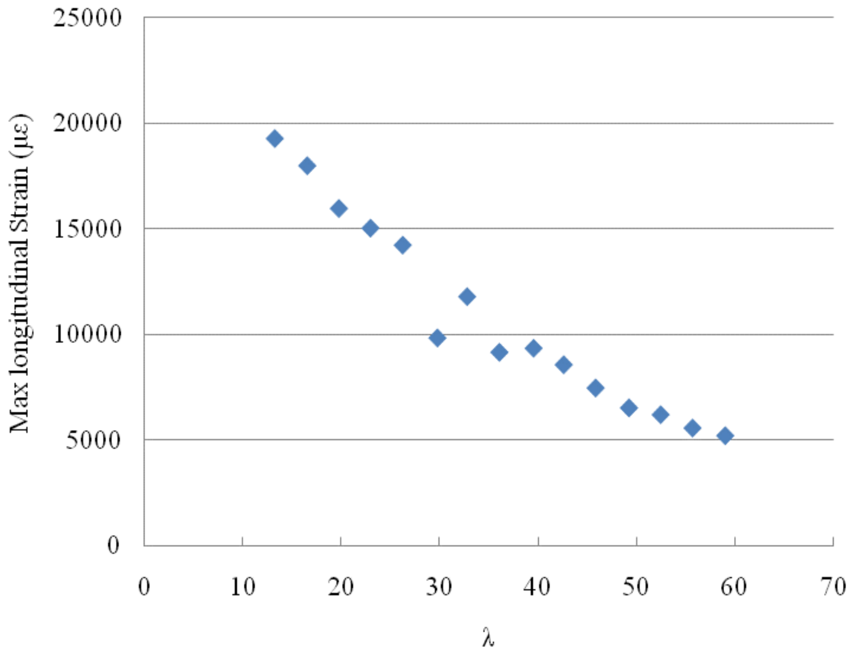
Influence of slenderness ratio upon the ultimate strain



Lateral strain vs slenderness ratio (λ)

$$\varepsilon_{\mathrm{ula}} = 8270 - 122.6\lambda^2$$



Longitudinal strain vs slenderness ratio (λ)

$$\varepsilon_{\mathrm{ulo}} = 16973 - 4.021\lambda^2$$

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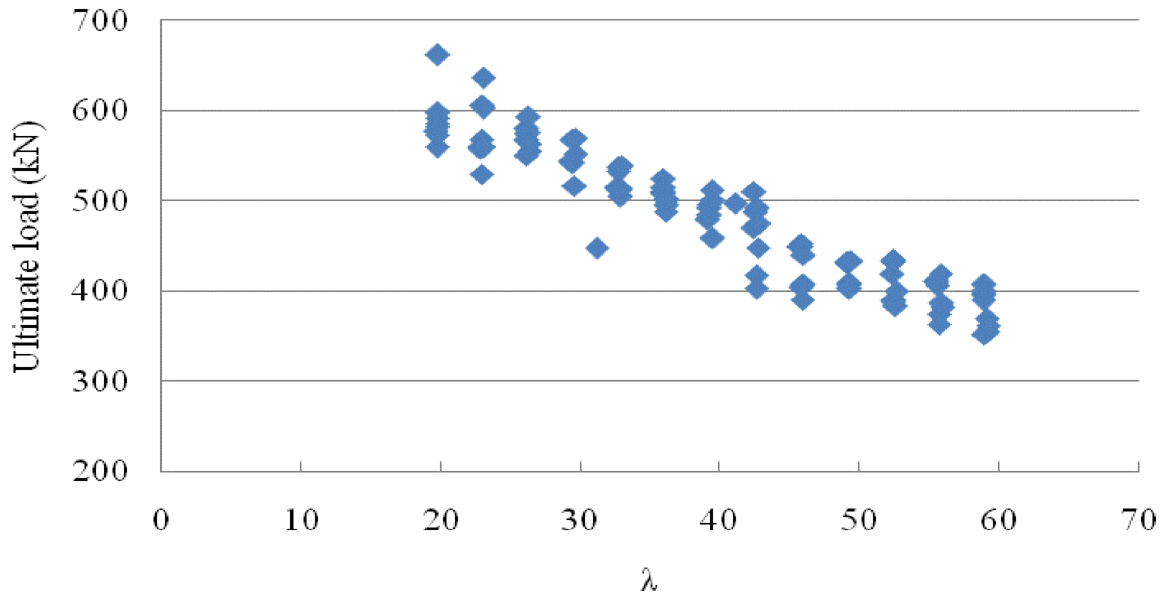
Influence of slenderness ratio upon load



Ultimate load vs slenderness ratio

An equation for calculating the stability coefficient of laminated bamboo columns can be expressed as

$$\varphi = 0.000106\left(l_0 / h\right)^2 - 0.0298\left(l_0 / h\right) + 1.1$$

$$N_{ul} = \varphi f_c A$$

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Comparison between the test results and calculation results

Group	Real test l_0 / h	Stability coefficient φ	Test results (kN)	Calculation results (kN)	Average value μ	Standard deviation	Coefficients of variation
600	5.69	0.934	580.5	586.7	0.99	0.021	0.022
700	6.62	0.907	568.5	570.1	1.00	0.048	0.048
800	7.57	0.881	569.4	553.2	1.03	0.025	0.024
900	8.52	0.854	548.0	536.5	1.02	0.036	0.035
1000	9.46	0.828	520.5	520.0	1.00	0.026	0.026
1100	10.4	0.801	505.5	503.5	1.00	0.022	0.022
1200	11.4	0.774	489.8	486.2	1.01	0.034	0.034
1300	12.3	0.75	462.5	471.0	0.98	0.080	0.081
1400	13.2	0.724	430.2	455.1	0.95	0.055	0.058
1500	14.2	0.698	420.7	438.6	0.96	0.032	0.033
1600	15.1	0.673	410.2	422.9	0.97	0.052	0.053
1700	16.1	0.649	393.8	407.6	0.97	0.050	0.051
1800	17.0	0.623	378.3	391.5	0.97	0.055	0.057

μ **stands for the average value of** N_u^t / N_u^c

4 Eccentric compression performance of laminated bamboo

11 groups of specimens were designed, with the eccentricity of 0mm, 10mm, 25mm, 40mm, 55mm, 70mm, 80mm, 90mm, 100mm, 110mm and 120mm respectively for each group. Each group contains 8 specimens and the total number is 88. The cross-section for the specimens is 100mm*100mm and the length for the specimens is 1200mm.

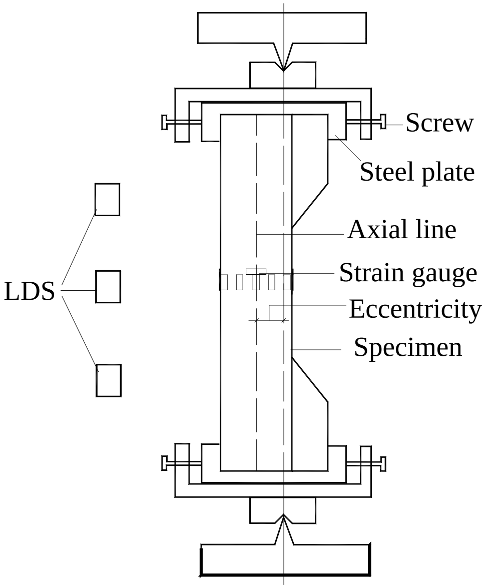

Fig. 4. Test scheme

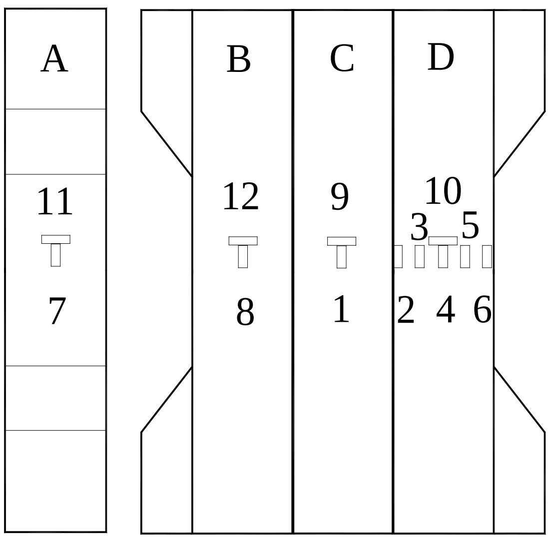

Fig. 5. Side surfaces

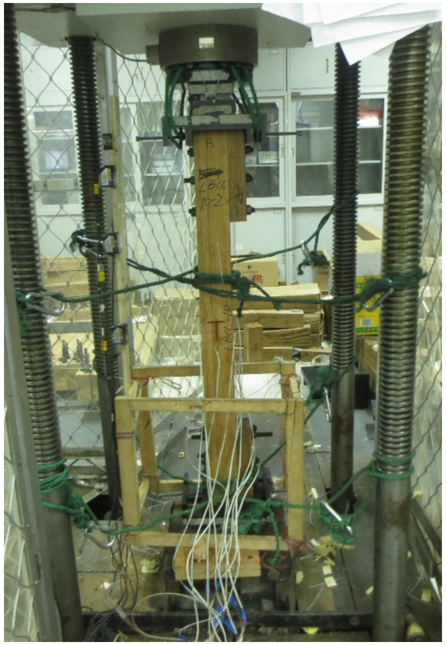

Fig. 6. Experiment for column specimen

The displacement for the quarter points, including the mid-span deflection, was measured using three laser displacement sensors.

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Each specimen behaved elastically at the beginning of loading. With increased loading, the specimens showed a small amount of plastic deformation, and the stiffness of the column decreased significantly.

Except for face A (bracket side), cracks can be seen clearly from the other three side surfaces. Bending failure occurred for the column specimens under eccentric compression.

Typical failure for the specimens

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Typical load strain curves can be seen in Fig. 8 and Fig. 9.

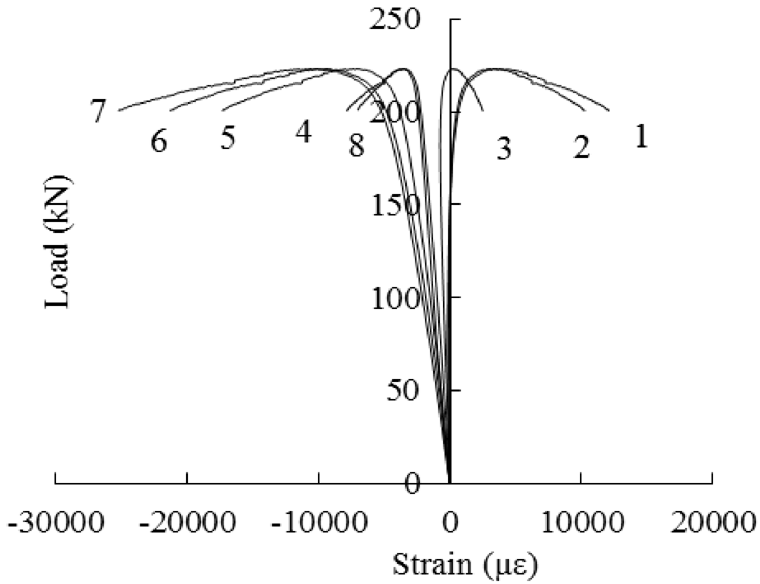

Fig. 8. Load-longitudinal strain curves for LBCC10-8

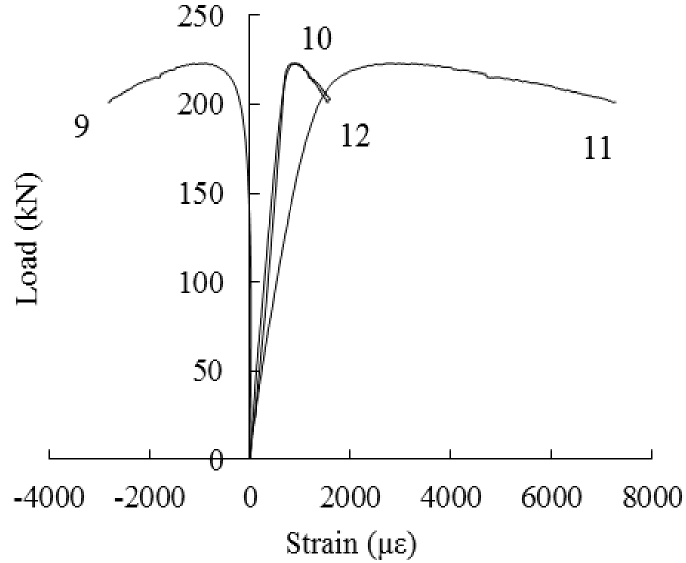

Fig. 9. Load-lateral strain curves for LBCC10-8

The ultimate longitudinal strain value on the compression surface (bracket side) of the specimen is the largest of the eight strains in Fig. 8, as is the ultimate lateral strain value on the compression surface among the four plotted in Fig. 9.
The tensile failure always happened earlier than the compression failure for laminated bamboo.
The main reason for this is that defects influenced the tensile strength more than compression strength.

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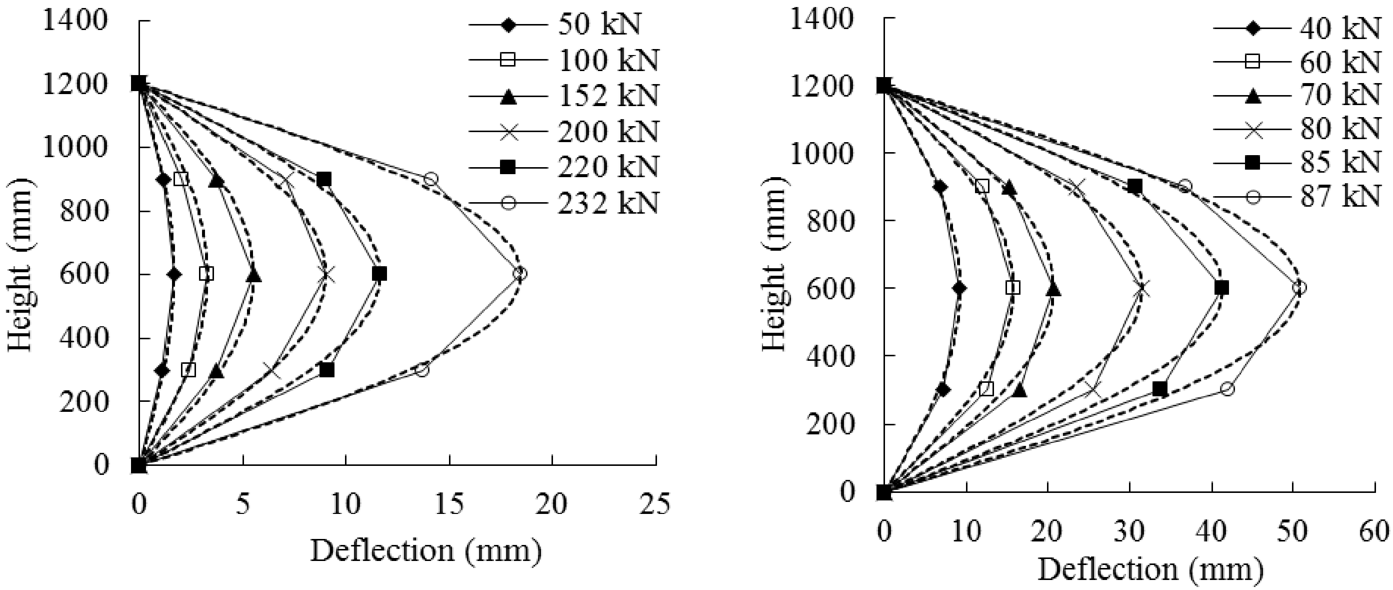

(a) Specimen LBCC10-8

(b) Specimen LBCC110-8

Fig. 10. Typical lateral deflection curves

The trends were similar for columns with both large and small eccentricity. Fitted sine half-wave curves were drawn using dotted lines in Fig. 10.
It can be seen clearly that the measured deflections are close to the sine line no matter what the eccentricity is. The equation of the deflection curve can be expressed as (Eq. 1):

$$w = w_{\mathrm{m}} \sin \frac{\pi H}{L}$$

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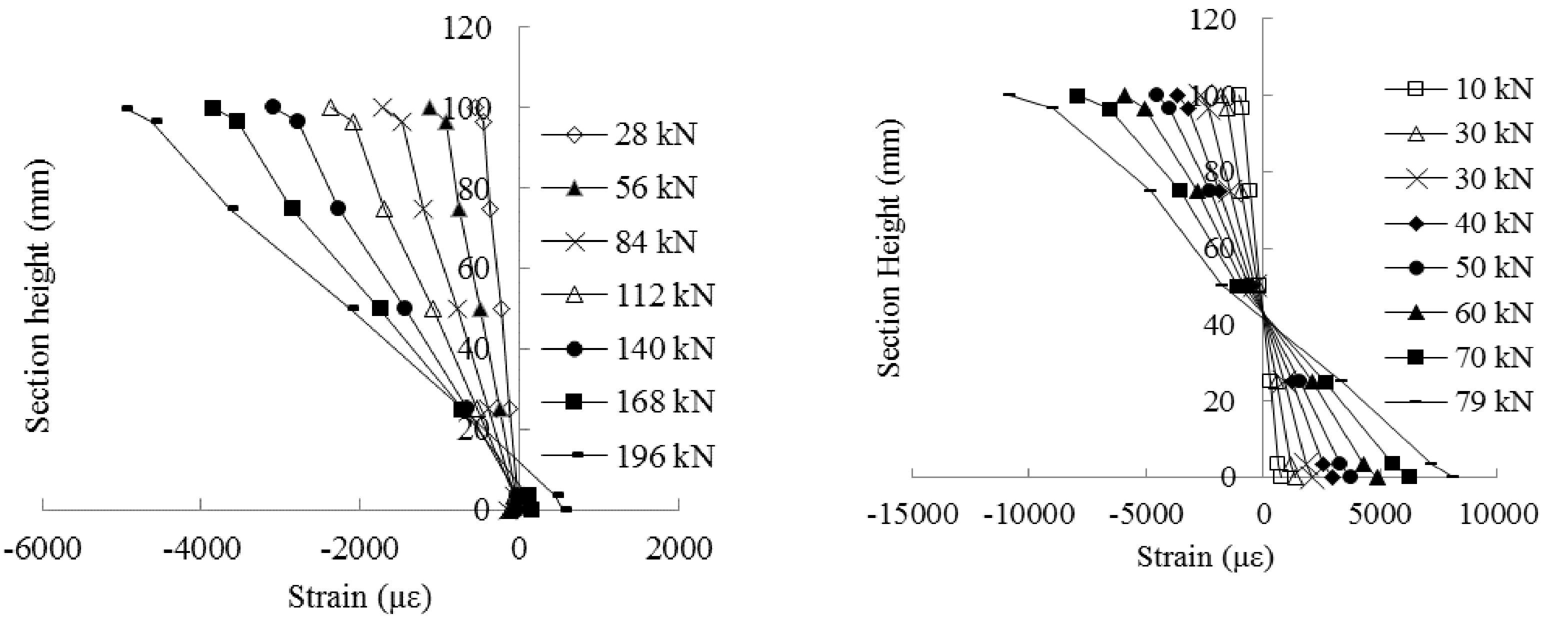
laminated bamboo

Plane cross-section assumption



(a) Specimen LBCC10-8 **(b) Specimen LBCC110-8**

Fig. 11. Typical strain profile development for the mid-span cross-section

Each test showed that the strain across the cross-section of the laminated bamboo column was basically linear throughout the loading process, following standard normal section bending theory.

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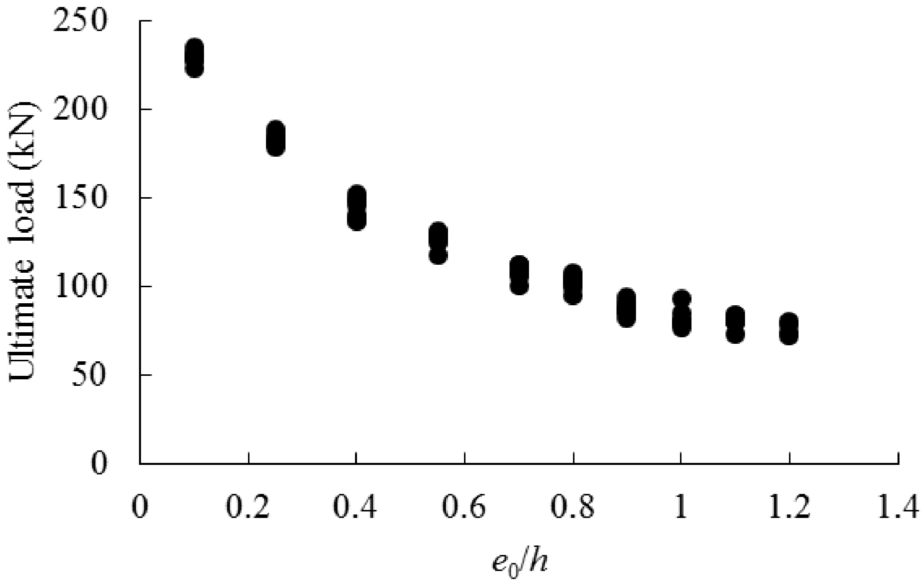

Fig. 13. Ultimate load comparison

The ultimate load values decreased with the increase of the eccentricity ratio.
The eccentricity ratio was the main influencing factor on the bearing capacity of the columns.

$$\varphi_e = N_{ul} / N_0 \qquad N_{ul} = \varphi_e N_0$$

N_{ul} **is the ultimate bearing capacity of laminated bamboo columns under eccentric compression**

N_0 **the ultimate bearing capacity of laminated bamboo columns under axial compression**

$$\varphi_e = \frac{1}{1.8 + 4.329 e_0 / h}$$

e_0 **is the eccentricity value of the laminated bamboo column**

h **is the height along the eccentric direction of the cross section**

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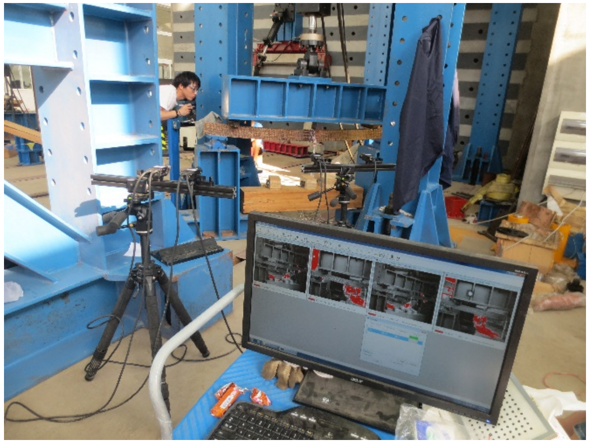
Comparison between the test results and calculation results

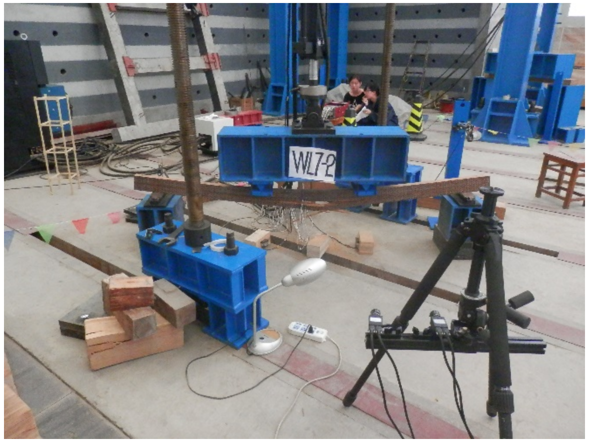
Group	Eccentricity ratio e_0 / h	Eccentricity influencing coefficient φ_e	Test results（kN） N_u^t	Calculation results （kN） N_u^c	Average value μ	Standard deviation	Coefficients of variation
LBCC10	0.1	0.356	229.3	232.1	0.988	0.012	0.013
LBCC25	0.25	0.283	182.7	179.8	1.016	0.016	0.016
LBCC40	0.4	0.235	143.6	146.8	0.978	0.036	0.037
LBCC55	0.55	0.201	126.8	124.0	1.022	0.031	0.030
LBCC70	0.7	0.176	108.2	107.4	1.008	0.034	0.034
LBCC80	0.8	0.162	102.2	98.55	1.037	0.035	0.034
LBCC90	0.9	0.151	87.9	91.06	0.966	0.036	0.037
LBCC100	1.0	0.14	81.9	84.6	0.968	0.054	0.055
LBCC110	1.1	0.132	80.5	79.1	1.018	0.036	0.035
LBCC120	1.2	0.124	76.2	74.2	1.027	0.052	0.050

μ **stands for the average value of** N_u^t / N_u^c

Other research and Application on laminated bamboo

Other research





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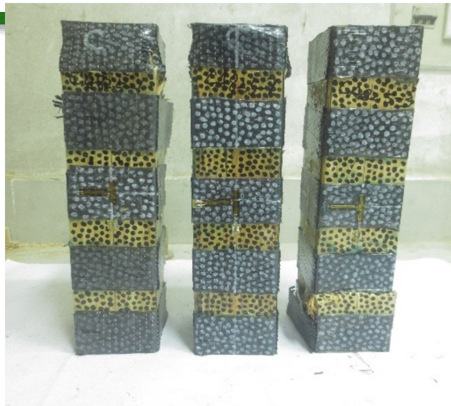

Carbon fiber

Glass Fiber Reinforced Polymer

Basalt Fiber

laminated bamboo Application

Precious bamboo co., LTD

Furnitures

laminated bamboo lumber building

Saudi Arabia

Precious bamboo co., LTD

laminated bamboo lumber building

Bamboo building

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Conclusions

(1) The mean compressive strength of the samples from higher growth heights was higher, although not to the same extent as has been observed in tests on smaller samples, suggesting that assembling bamboo into larger structural sections reduces the influence of growth height of the original bamboo.

(2) The variation of ultimate compressive strength increases with growth height. The results from this study show that the increase in variability more than counteracts the increase in mean compressive strength from a design point of view.

(3) The elastic modulus is largest for the bamboo laminate sourced from the middle growth section. However, there is not a great deal of variation of elastic modulus with growth height.

(4) From a design point of view, the variation in compressive strength resulting from source bamboo growth height can be neglected. A tri-linear model based on a characteristic elastic modulus of 8200 MPa up to a stress of 40 MPa, then a modulus of 800 MPa up to a stress of 52 MPa, followed by perfectly plastic deformation to an ultimate strain of 50,000 m was found to provide an appropriate structural design model for the average behaviour of the structural laminated bamboo tested.

laminated bamboo

(5) Typical failure for the short columns is a squashing or crushing failure. The material strength of the bamboo is brought into fuller play than occurs in longer columns. The bearing capacity of the short columns is determined by the compression bearing capacity of materials.

(6) Typical failure for the long columns is a buckling failure. The slenderness ratio is the main influencing factor on the bearing capacity of the columns. The ultimate load values decrease with the increase of the slenderness ratio. The failure mode for the long columns involves significant lateral deflection.

(7) An equation for calculating the stability coefficient of laminated bamboo columns is proposed. The load capacities calculated from the equations give good agreement with the test results.

(8) The eccentricity ratio of the load was the main influencing factors on the bearing capacity of the columns. The ultimate load values decreased with the increase of the eccentricity ratio.

(9) An equation for calculating the eccentricity influence coefficient of parallel bamboo strand lumber columns was proposed. The calculation results obtained from the equations agreed well with the test results.

Thank you!

By the way, besides teaching and research in Nanjing Forestry University, I also work as deputy director of administrative committee of New Energy Industrial Park, New District in Zhenjiang.
(镇江新区新能源产业园管委会副主任)
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Welcome to bring you company and business to Zhenjiang New District!
欢迎来镇江投资创业！欢迎把你们的公司或者公司分部设到镇江新区！

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Thank you!

Any questions?

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