ELSEVIER

Engineering Structures 24 (2002) 429–442

ENGINEERING STRUCTURES

www.elsevier.com/locate/engstruct

Mechanical properties of structural bamboo for bamboo scaffoldings

K.F. Chung *, W.K. Yu

Department of Civil and Structural Engineering, the Hong Kong Polytechnic University, Hung Hom,Kowloon, Hong Kong, China

Received 7 March 2001; received in revised form 14 September 2001; accepted 14 September 2001

Abstract

This paper presents an investigation on the mechanical properties of two bamboo species, namely *Bambusa Pervariabilis* (or Kao Jue) and *Phyllostachys Pubescens* (or Mao Jue), which are commonly used in access scaffoldings in the South East Asia, in particular, in Hong Kong and the Southern China. A pilot study was carried out to examine the variation of compressive strength against various physical properties along the length of bamboo culms for both bamboo species. Moreover, systematic test series with a large number of compression and bending tests were executed to establish characteristic values of both the strengths and the Young's moduli of each bamboo species for limit state structural design. It is shown that both Kao Jue and Mao Jue are good constructional materials with excellent mechanical properties against compression and bending. With a suitable choice of partial safety factors, structural engineers are able to design bamboo structures at a known level of confidence against failure.

Structural engineers are thus encouraged to take the advantage offered by bamboo to build light and strong structures to achieve enhanced economy and buildability. The effective use of structural bamboo as a substitute to structural timber will mitigate the pressures on the ever-shrinking natural forests in developing countries, and thus, facilitate the conservation of the global environment.

Keywords: Bamboo scaffoldings; Green construction; Structural bamboo; Qualification tests; Bamboo strength

1. Introduction

Timber is regarded as a good natural constructional material, and probably, one of the oldest known materials used in construction. A number of design recommendations [1–3] on structural timber are available, and traditionally, most of them employ permissible stress design. In a modern structural timber code [4], ultimate limit state design philosophy is adopted and structural adequacy is assessed with characteristic values of both loading and resistance using appropriate partial safety factors. Among many physical properties that affect the strength characteristics of structural timber, moisture content, density, slope of grain and defects are considered as the most important ones.

Bamboo is another natural constructional material and there are over 1500 different botanical species of bamboo in the world. Many of them have been used traditionally as structural members in low-rise houses, short span foot bridges, long span roofs and construction platforms in countries with plentiful bamboo resources. Studies have shown bamboo to be an ideal and safe structural material for many construction applications. In general, it is believed that the mechanical properties of bamboo are likely to be at least similar, if not superior, to those of structural timber. Furthermore, as bamboo grows very fast and usually takes 3–6 years to harvest, depending on the species and the plantation, there is a growing global interest in developing bamboo as a substitute of structural timber in construction. The effective use of structural bamboo will mitigate the pressures on the ever-shrinking natural forests in developing countries, and thus, facilitate the conservation of the global environment. However, a major constraint to the development of structural bamboo as a modern construction material is the lack of design standards on both mechanical properties and structural adequacy.

* Corresponding author. Tel.: +852-23346389.
E-mail address: cekchung@polyu.edu.hk (K.F. Chung).

0141-0296/02/$ - see front matter © 2002 Elsevier Science Ltd. All rights reserved.
PII: S0141-0296(01)00110-9

Nomenclature

A_m, Z_m, I_m are measured cross-sectional area, section modulus and second moment of area, respectively,
F_{test}, F_{design} are measured and design compressive force, respectively,
M_{test}, M_{design} are measured and design moment, respectively,
$f_{c,k}$, $f_{c,d}$ are characteristic and design compressive strengths, respectively,
$f_{b,k}$, $f_{b,d}$ are characteristic and design bending strengths, respectively,
$E_{c,d}$, $E_{b,d}$ are average Young's moduli under compression and bending, respectively,
ψ_c, ψ_b are model factors for compression test and bending test, respectively, and
γ_m is a partial safety factor for material strength.

1.1. Bamboo scaffoldings

Bamboo scaffoldings have been used in building construction in China for over a few thousand years. It is believed among Chinese that the first bamboo scaffolding was built some 5000 years ago while the basic framing systems and the erection methods were established through practice about 2000 years ago. In Hong Kong and other parts of the Southern China, bamboo scaffoldings are ones of the few traditional building systems which survive by self-improvement through practical experiences of scaffolding practitioners over generations. Nowadays, in spite of open competition with many metal scaffolding systems imported all over the world, bamboo scaffoldings remain to be one of the most preferred access scaffolding systems in building construction in Hong Kong and the neighbouring areas.

Bamboo scaffoldings are mainly built to provide workers access to different exposed locations to facilitate various construction and maintenance activities. Owing to their high adaptability and low construction cost, bamboo scaffoldings can be constructed in any layout to follow irregular architectural features of a building within a comparatively short period of time. Besides widely erected on construction sites, they are also used in signage erection, decoration work, demolition work and civil work.

Fig. 1 illustrates the typical application of bamboo scaffoldings in Hong Kong as a double layered bamboo access scaffoldings with safe working platforms for heavy duty work such as masonry work and installation of curtain walls. Primary vertical members, or posts, are typically placed 1.8–3 m apart with two to three secondary vertical members, or standards, in between while horizontal members, or ledgers, are placed 0.6–0.75 m apart. It is very important to provide sufficient lateral supports to the posts at regular intervals for structural adequacy of the bamboo scaffoldings. Moreover, diagonal members are also provided to form triangulated frameworks in order to increase the overall stability of the scaffoldings. Bamboo or plastic strips are used to form connections between the vertical and the horizontal members.

Typical usage of bamboo scaffoldings is widely reported to the community of structural engineers [5], and two complementary design guides [6,7] on erection and design of bamboo scaffoldings are compiled for the building construction industry in the South East Asia, in particular, Hong Kong. Moreover, industrial guides on safety of bamboo scaffolding are also available [8–10].

2. Recent research in structural bamboo

Structural bamboo have been used traditionally in China, Philippines, India, and Latin America for many hundred of years, but little research was reported in the past. Recent scientific investigations on bamboo as a construction material were reported by Au et al. in Hong Kong in 1978 [11] and also by Janssen in Holland in 1981 [12]. A large amount of data of the mechanical properties for various bamboo species all over the world were reported in 1991 [13]; however, only typical ranges of values were provided. More recently, a study was reported in the literature [14] where bamboo was classified as a smart natural composite material with optimized distribution of fibers and matrices, not just across cross sections but also along member lengths, in resisting environmental loads in nature.

A series of experimental studies on structural bamboo were reported by Arce-Villalobos in 1993 [15] and practical connection details for bamboo trusses and frames were also proposed and tested. Moreover, a recent study [16] on the traditional design and construction of bamboo in low-rise housing in Latin America is also available, and innovative applications of bamboo [17] in building construction in India is also reported. Furthermore, a theoretical study using advanced finite element analysis of one element per member was reported by Chan [18,19] to assess the load carrying capacities of bamboo scaffoldings. Moreover, a full-scale bamboo scaffolding was built in a construction site and tested to failure, providing data for calibration of the finite element model. Due to the slenderness of bamboo culms, it was recommended that non-linear analysis was often required to predict the buckling behaviour of bamboo scaffoldings accurately.

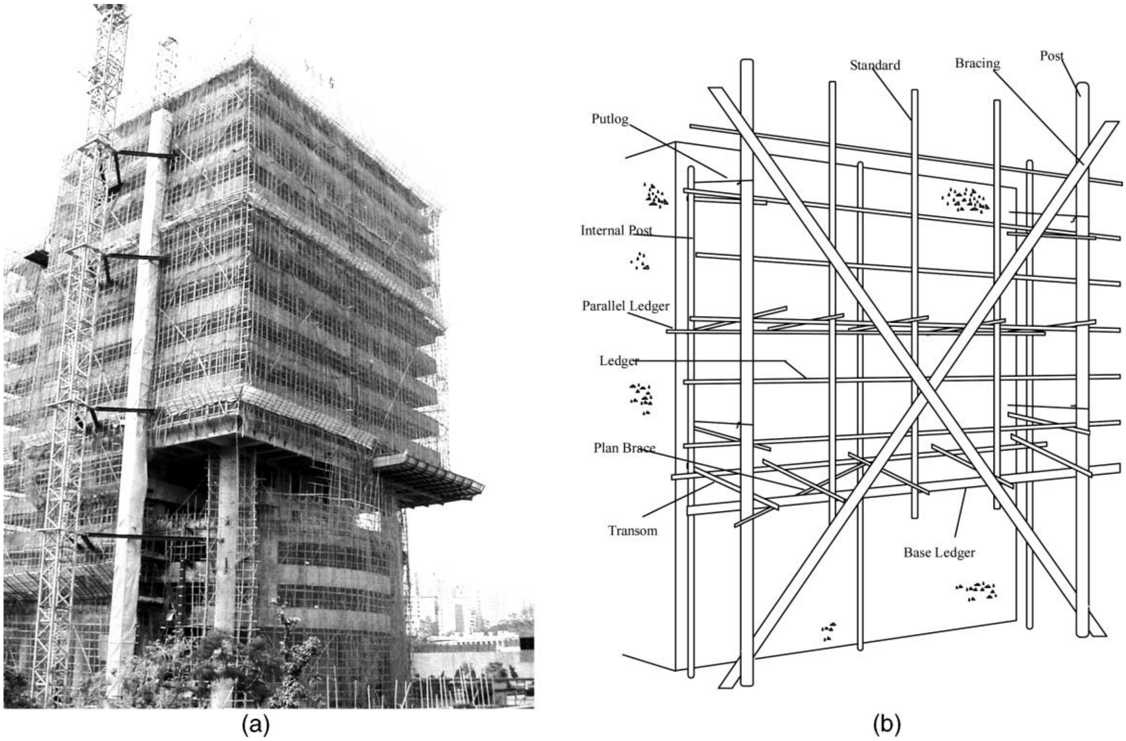

Fig. 1. Bamboo scaffoldings in Hong Kong. (a) Typical construction. (b) Diagrammatic illustration.

3. Scope of work

As natural non-homogenous organic materials, large variations of physical properties along the length of bamboo culms are apparent: external and internal diameters, dry density and moisture content. While engineers also expect variations in the mechanical properties of bamboo, they tend to accept that the mechanical properties of bamboo are likely to be more consistent when compared with those of concrete, probably similar to structural timber. Consequently, the project aims to establish characteristic values of the mechanical properties of two bamboo species, namely, *Bambusa Pervariabilis* (or Kao Jue) and *Phyllostachys Pubescens* (or Mao Jue), which are commonly used in Hong Kong and the Southern China in bamboo scaffoldings. The project [20,21] may be divided into the following parts of investigation:

Part I Pilot study
: A pilot study is first carried out to examine the variation of compressive strength against a number of physical properties along the length of bamboo culms of both bamboo species.

Part II Systematic tests
: A number of test series are then carried out to generate test data on the compressive and the bending strengths together with associated Young's moduli of both bamboo species. In each test series, a large number of compression and bending tests on bamboo culms are carried out over a wide range of physical properties against natural occurrence. Statistical analysis on the test data is then performed to establish the characteristic values of the mechanical properties of both bamboo species for limit state structural design.

The project forms part of a research and development programme to promote the effective use of structural bamboo in building construction. The programme aims to generate scientific design rules and data for the re-engineering of bamboo scaffoldings into modern green structures of high buildability through scientific investigation and technology transfer. Other aspects of bamboo scaffoldings such as column buckling and connections will be reported separately.

4. Pilot study

The primary physical properties of bamboo culms are:

- External diameter, D,
- Wall thickness, t, (and cross-sectional area, A)
- Dry density, ρ, and
- Moisture content, m.c.

Some of these physical parameters vary significantly along the length of bamboo culms, depending on the species. For structural application, it is important to establish safe mechanical properties of the bamboo culms, and also reliable co-relation between their physical and mechanical properties.

A preliminary study was carried out to examine the variation of the compressive strengths of both Kao Jue and Mao Jue along the length of bamboo culms against all the primary physical properties. For each species, three dry bamboo culms were tested, and all of them were mature with an age of at least 3 years old with no visual defect. The test specimens were prepared as follows:

- A length of 750 mm from both the top and the bottom ends of each bamboo culm was discarded.
- A number of test specimens were cut out from the bamboo culms at regular intervals, each marked with a label indicating its position from the bottom of the bamboo culm.
- The length of each test specimen was about twice the external diameter of the bamboo culms, but not larger than 150 mm.

All the physical properties of the test specimens were measured before and after the compression tests as appropriate.

4.1. Test procedure

Fig. 2 illustrates the general set-up of the compression tests, and both the applied loads and the axial shortening of the test specimens were measured during the tests. Details of the compression tests may be found in [22,23] while the data analysis procedure for compressive strength and Young's modulus is given in Appendix A.

4.2. Test results

Two failure modes, namely *End bearing* and *Splitting*, were identified, as shown in Fig. 2. It was found that most specimens failed in *End Bearing*, especially in those specimens with high moisture contents. As the moisture content decreased, cracks along fibers were often induced and caused *Splitting*. Typical load deflection curves of test specimens associated with both failure modes are also presented in Fig. 2.

After data analysis, Fig. 3 presents the variations of the physical properties along the length of the bamboo culms for both Kao Jue and Mao Jue. The failure loads, the ultimate compressive strengths and also the Young's modulus against compression are presented in Fig. 4.

4.3. Discussion on physical properties

(a) Kao Jue

In general, the physical properties of all three culms are found to be very similar among each other. It is shown that while the external diameter is fair uniform over the length of the bamboo culms with a typical value of 45 mm, the wall thickness varies from 8 mm at the bottom to 4 mm at the top of the culm. Consequently, the average cross-sectional area is 750 mm^2 with a variation of 250 mm^2 along the whole member length. However, both the dry density and the moisture content are fairly uniform with a value of 700 kg/m^3 and 12.5%, respectively along the whole member length.

(b) Mao Jue

On the contrary to Kao Jue, the physical properties of the three culms of Mao Jue are found to be significantly different among each other. From the bottom to the top of the culms, the external diameter is typically reduced from 80 mm to 50 mm. Moreover,

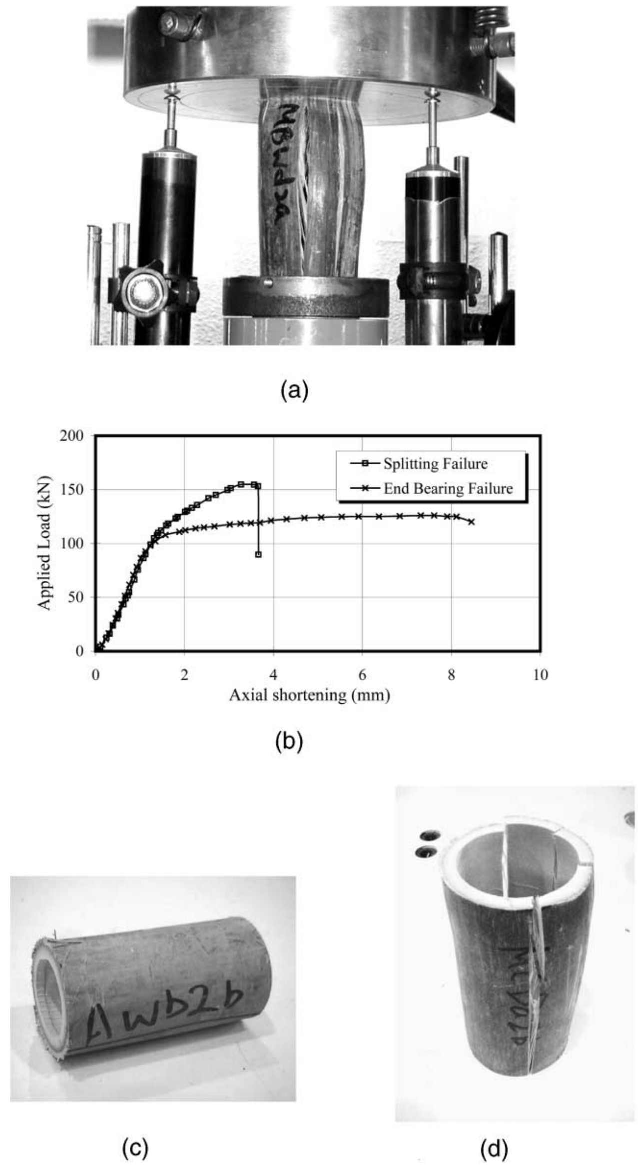

Fig. 2. Compression test. (a) General test set-up. (b) Load deflection curves. (c) Typical failure mode—end bearing. (d) Typical failure mode—splitting.

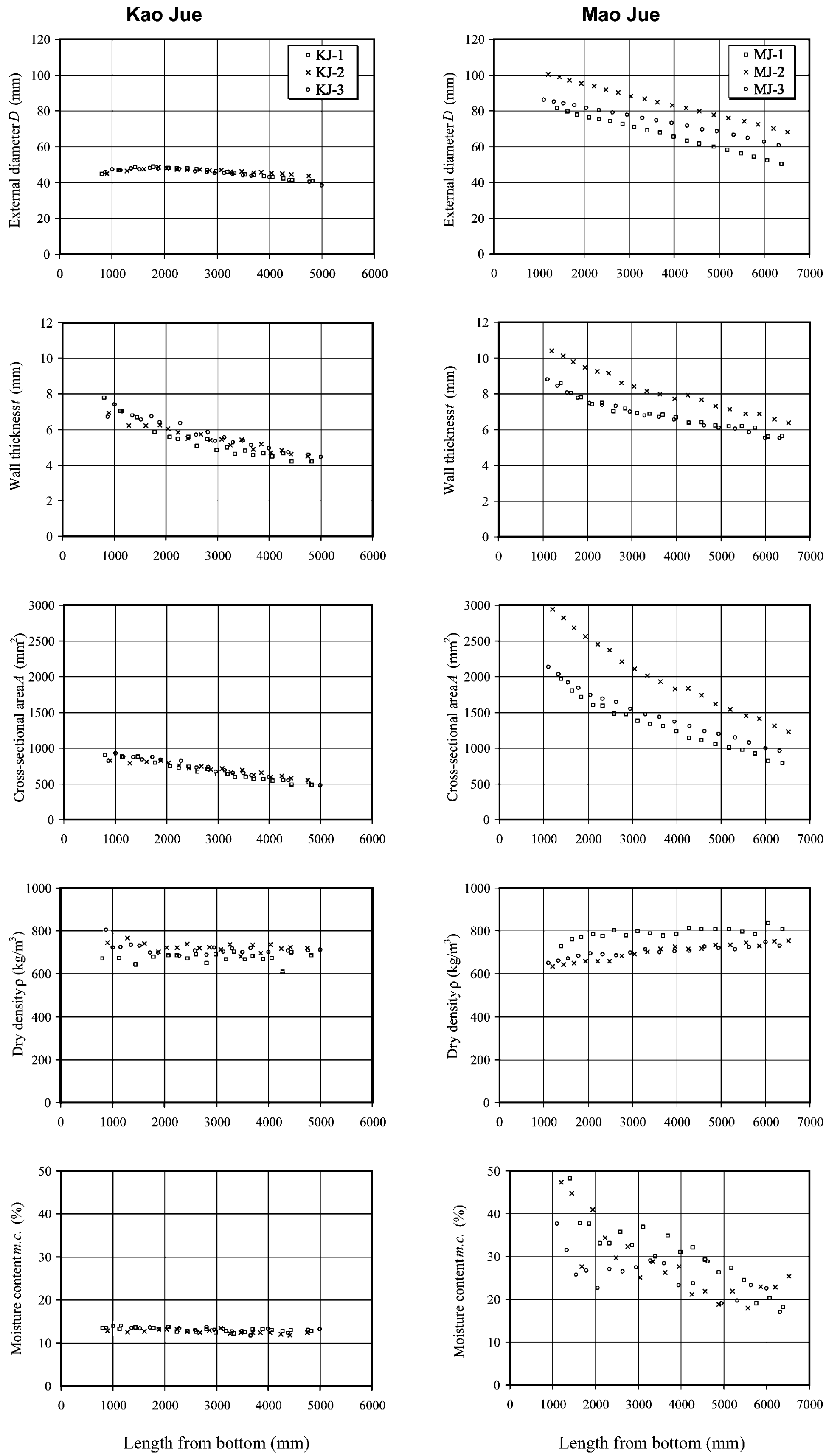

Fig. 3. Variation of physical properties along length of bamboo culms.

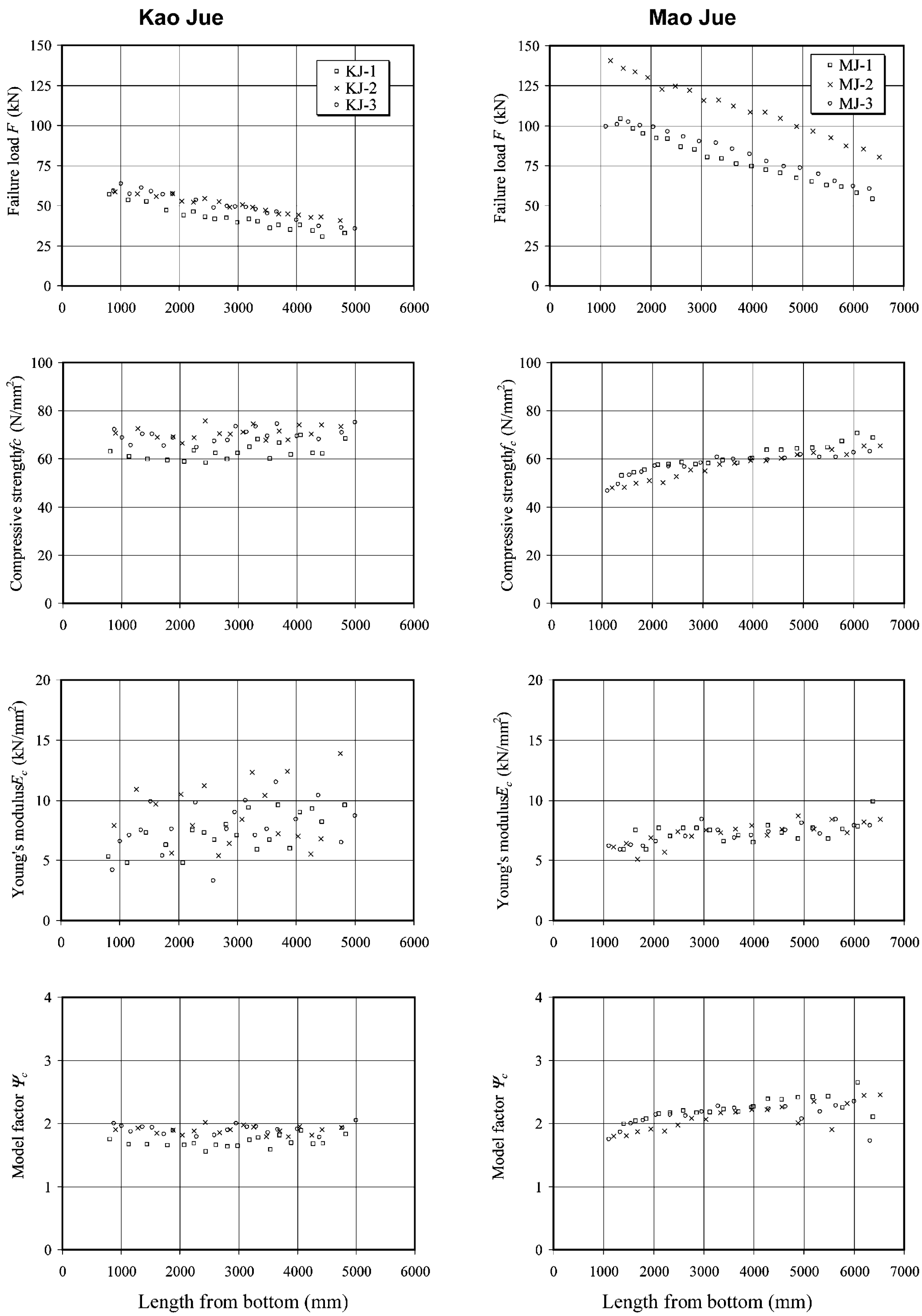

Fig. 4. Variation of mechanical properties along length of bamboo culms.

the wall thickness varies from 10 mm at the bottom to 6 mm at the top of the culms. Consequently, the average cross-sectional area is found to be 1750 mm^2 with a large variation of 1000 mm^2 along the whole member length. However, it is important to note that the dry density is somehow uniform with an average value of 700 kg/m^3 and a variation of 100 kg/m^3 along the whole member length. Moreover, large variation in the moisture content along the member length is also apparent, ranging from 40% at the bottom to 20% at the top of the culms.

4.4. Discussion on mechanical properties

(a) Kao Jue
The compression capacity is found to be at its maximum of about 60 kN at the bottom of the culm which is reduced steadily to about 30 kN at the top. After dividing with the cross-sectional areas, the compressive strength is found to vary from 60 to 80 N/mm^2 along the whole culm length. However, large variation in the Young's modulus against compression is apparent, scattering between 4 and 12 kN/mm^2 along the whole culm length.

(b) Mao Jue
Contrary to the physical properties, the mechanical properties of the three culms are found to be broadly similar. From the bottom to the top of the culms, the compression capacity is reduced steadily from 100 kN at the bottom of the culms to 50 kN at the top. After dividing with the cross-sectional areas, the compressive strength is found to be 50 N/mm^2 at the bottom of the culms which increases steadily to 70 N/mm^2 at the top. The Young's modulus against compression is found to vary steadily from 5 to 10 kN/mm^2 from the bottom to the top of the culms.

Consequently, it is shown that despite of the large variations in external diameter, wall thickness and dry density, representative values of mechanical properties may be obtained for both Kao Jue and Mao Jue. Among all the physical properties, it is found that moisture content is the most important one in governing the mechanical properties of the bamboo. Moreover, it may be acceptable to assume that all physical and mechanical properties are broadly constant along the culm lengths in Kao Jue. However, both the physical and the mechanical properties vary significantly along the culm lengths in Mao Jue, and thus, the non-uniformity should be incorporated when assessing their structural behaviour.

5. Systematic tests

In order to establish characteristic values of the compressive and the bending strengths together with associated Young's moduli of each bamboo species, a set of systematic test series, or a qualification test programme, was executed. In each test programme, a large number of compression and bending tests on bamboo specimens were carried out over a wide range of moisture contents as follows:

(a) Normal tests. The tests aimed to measure the compressive and the bending strengths of the test specimens in normal supply condition, i.e. *Green* (*G0*) and *Green+3 months* (*G3*). For each member position, six specimens were tested.

(b) Wet tests. The tests aimed to measure the compressive and the bending strengths of the test specimens with high moisture contents. For each member position, two specimens were immersed under water over different time periods.

(c) Dry tests. The tests aimed to measure the compressive and the bending strengths of the test specimens with low moisture contents. For each member position, two specimens were dried in oven at 105°C over different time periods.

The designation system for the test specimens is defined as follows:

Normal Tests—*G0*/*G3*	Wet tests—*W*	Dry tests—*D*
$\begin{Bmatrix}A\\B\\C\end{Bmatrix}X\{1,2,3,4,5,6\}$	$\begin{Bmatrix}A\\B\\C\end{Bmatrix}W\{a,b,c,d,e,f,g,h,i\}\begin{Bmatrix}1\\2\end{Bmatrix}$	$\begin{Bmatrix}A\\B\\C\end{Bmatrix}D\{a,b,c,d,e,f,g,h,i\}\begin{Bmatrix}1\\2\end{Bmatrix}$
No. of tests = 3×6×2 =36	No. of tests =3×9×2 =54	No. of tests =3×9×2 =54

where the time periods *a* to *i* are defined as follows:

a	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*
1 h	2 h	4 h	8 h	12 h	1 d	2 d	3 d	7 d

h= hour(s); d=day(s)

In general, the test specimens were selected and prepared as follows:

- All bamboo culms were about 6 m in length and of 3–6 years of age. They were air dry for at least 3 months before testing.
- A length of 750 mm from both the top and the bottom ends of the bamboo culms was discarded.
- Three specimens were cut out from the top, the middle and the bottom positions of the culm and marked with the letters *A*, *B*, and *C* respectively.
- The length of each specimen was about 1200 mm with acceptable out-of-straightness under visual inspection. The external diameters at the top and the bottom ends did not differ by more than 25 mm.

6. Test procedures

Two tests were carried out in the qualification test programmes as follows:

- Bending Tests
  Each bending test specimen was supported over a clear span of 1000 mm. The specimens were tested under single point load at mid-span until failure as shown in Fig. 5.
- Compression Tests

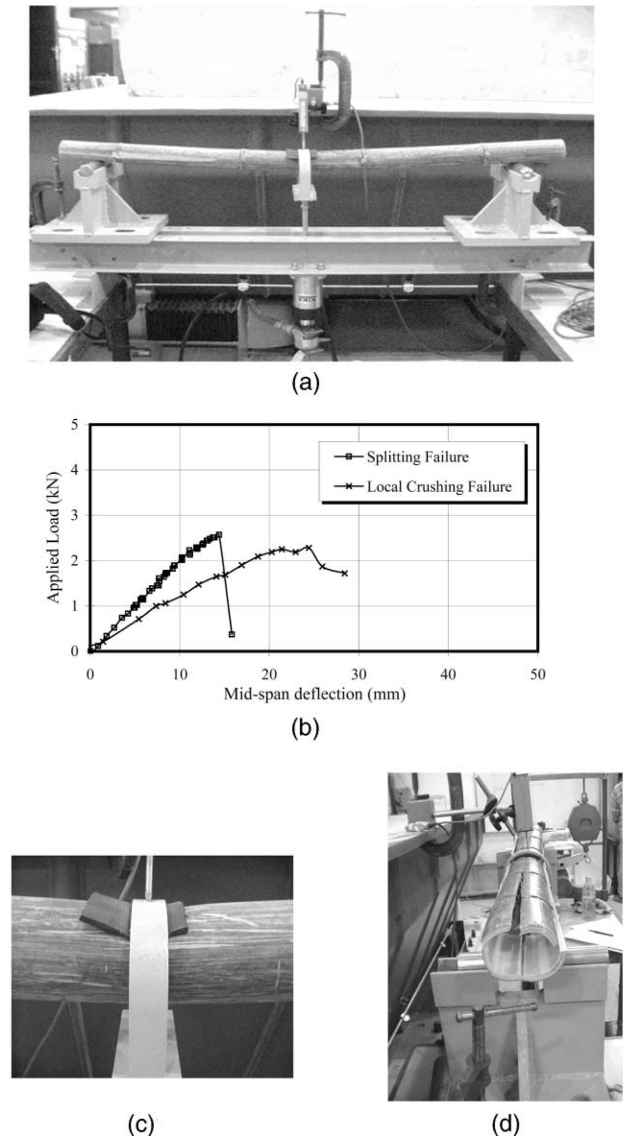

Fig. 5. Bending test. (a) General test set-up. (b) Load deflection curves. (c) Typical failure mode—local crushing. (d) Typical failure mode—splitting.

After each bending test, two compression test specimens were taken from the bending test specimen. The height of the compression test specimens was at least two times the external diameter of the bamboo culm, but not larger than 150 mm. The specimens were tested under axial compression until failure as shown in Fig. 2, similar to those compression tests in the pilot study.

Details of the compression and the bending tests may be found in [22,23] while the data analysis procedure for both bending and compressive strengths together with associated Young's moduli is given in Appendix A. It should be noted that in bamboo scaffoldings, the horizontal distance between the primary vertical members, or posts, typically ranges from 1800 to 3000 mm. Thus, the typical distance between points of inflection along a horizontal member, or a ledger, near internal supports is taken as 1000 mm. The bending tests are envisaged to provide data on the flexural behaviour of ledgers over internal supports under hogging moment.

6.1. Test results

- Compression tests

  Two failure modes, namely *End bearing* and *Splitting*, were identified, as shown in Fig. 2. It was found that most specimens failed in *End Bearing*, especially in those specimens with high moisture contents. As the moisture content decreased, cracks along fibers were often induced and caused *Splitting*. Typical load deflection curves of test specimens associated with both failure modes may be found in Fig. 2; they are similar to those obtained in the pilot study.
- Bending tests

  Two failure modes, namely, *Splitting* and *Local crushing* were identified, as shown in Fig. 5. Most specimens were found to be failed in *Splitting*, especially for those specimens with low moisture contents. For test specimens with high moisture contents, the specimens collapsed under combined bending and patch load, leading to *Local crushing*. Typical load deflection curves of test specimens associated with both failure modes may be found in Fig. 5.

A number of qualification test programmes [13,14] for both Kao Jue and Mao Jue have been executed for different batches of bamboo samples. Statistical analysis on all the test data was carried out to establish the characteristic values of the mechanical properties of the bamboo species for limit state structural design. Tables 1 and 2 summarizes the ranges of the measured mechanical properties obtained from the qualification test programmes. Moreover, the ranges of the physical properties covered in all the tests are also presented.

Based on a total of 364 compression tests and 91 bending tests, the variations of the compressive strength, f_c, and the bending strength, f_b, of Kao Jue against moisture contents are presented in Fig. 6(a) and (b), respectively. Similarly, based on a total of 213 compression tests and 128 bending tests, the variations of the compressive strength, f_c, and the bending strength, f_b, of Mao Jue against moisture contents are presented in Fig. 7(a) and (b), respectively. The Young's moduli under compression and bending for both Kao Jue and Mao Jue are plotted in Figs. 8 and 9 respectively.

It should be noted that

- Kao Jue

  Both the compressive and the bending strengths are

Table 1
Summary of physical and mechanical properties of *Bambusa pervariabilis* (Kao Jue)

	Nos.	Range	Maximum	Minimum	Average	Standard deviation	Characteristic value at fifth percentile
External diameter D (mm)	364	All specimens	57.6	23.9	40.7	5.9	31.1
Internal diameter d (mm)	364	All specimens	45.2	17.3	30.4	4.5	23.1
Wall thickness t (mm)	364	All specimens	10.7	2.9	5.2	1.4	2.9
Cross-sectional area A (mm^2)	364	All specimens	1375	213	589	207	–
Second moment area I (mm^4)	364	All specimens	37.3×10^4	1.16×10^4	10.4×10^4	6.01×10^4	–
Dry density ρ (kg/m^3)	364	All specimens	1731.6	522.0	708.8	87.02	–
Moisture content *m.c.* (%)	103	m.c.<5%	5.0	0.2	1.8	1.4	–
	136	m.c.=5–20%	19.3	5.4	13.4	2.3	–
	125	m.c.>20%	110.8	20.2	44.3	22.1	–
Compressive strength f_c (N/mm^2)	103	m.c.<5%	154	73	103	15	79
	136	m.c.=5–20%	99	44	69	12	48
	125	m.c.>20%	75	35	48	8	35
Young's modulus E_c (kN/mm^2)	70	m.c.<5%	15.8	4.9	10.3	2.4	–
	100	m.c.=5–20%	16.1	2.5	9.3	2.9	–
	90	m.c.>20%	14.2	2.2	6.8	2.2	–
Bending strength f_b (N/mm^2)	21	m.c.<5%	144	84	109	17	80
	53	m.c.=5–20%	118	48	82	17	54
	17	m.c.>20%	66	37	52	9	37
Young's modulus E_b (kN/mm^2)	21	m.c.<5%	35.3	14.3	22.0	5.0	–
	53	m.c.=5–20%	39.3	11.0	18.5	4.3	–
	17	m.c.>20%	28.5	11.0	16.4	4.7	–

Table 2
Summary of physical and mechanical properties of *Phyllostachya Pubescens* (Mao Jue)

	Nos.	Range	Maximum	Minimum	Average	Standard deviation	Characteristic value at fifth percentile
External diameter D (mm)	213	All specimens	95.4	39.4	68.6	11.6	49.5
Internal diameter d (mm)	213	All specimens	74.2	27.6	54.5	9.6	38.7
Wall thickness t (mm)	213	All specimens	11.0	4.7	7.1	1.3	5.0
Cross-sectional area A (mm^2)	213	All specimens	2831	578	1397	468	–
Second moment area I (mm^4)	213	All specimens	258×10^4	9.00×10^4	76.1×10^4	9.32×10^4	–
Dry density ρ (kg/m^3)	213	All specimens	1286.5	463.5	793.9	108.3	–
Moisture content *m.c.* (%)	9	m.c.<5%	3.0	0.9	1.5	0.7	–
	41	m.c.=5–30%	29.6	6.5	18.3	7.8	–
	163	m.c.>30%	59.1	30.1	43.4	7.0	–
Compressive strength f_c (N/mm^2)	9	m.c.<5%	152	122	134	10	117
	41	m.c.=5–30%	114	48	75	18	46
	163	m.c.>30%	81	37	57	8	44
Young's modulus E_c (kN/mm^2)	9	m.c.<5%	11.7	3.8	9.4	2.1	–
	41	m.c.=5–30%	11.0	3.6	7.8	1.9	–
	163	m.c.>30%	9.7	2.2	6.4	1.2	–
Bending strength f_b (N/mm^2)	15	m.c.<5%	124	56	85	21	51
	32	m.c.=5–30%	50	132	88	19	56
	81	m.c.>30%	118	49	76	13	55
Young's modulus E_b (kN/mm^2)	15	m.c.<5%	19.7	10.3	13.2	2.4	–
	32	m.c.=5–30%	18.2	7.1	11.4	2.8	–
	81	m.c.>30%	16.4	5.4	9.6	2.0	–

about 80 N/mm^2 in dry condition, i.e. m.c.<5%. In wet condition, i.e. m.c.>20%, both strengths are reduced roughly by half to 35 N/mm^2.
The average Young's moduli against compression and bending are 10.3 and 22.0 kN/mm^2, respectively in dry condition, and they are reduced roughly by one-third to 6.8 and 16.4 kN/mm^2 in wet conditions.

- Mao Jue
The compressive strength is 117 N/mm^2 in dry condition, i.e. m.c.<5%. However, in wet condition, i.e.

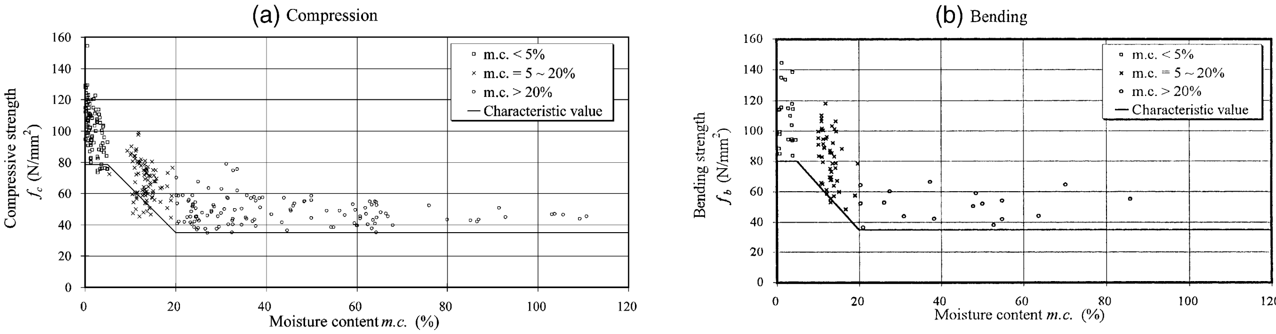

Fig. 6. Variation of mechanical properties of Kao Jue against moisture content.

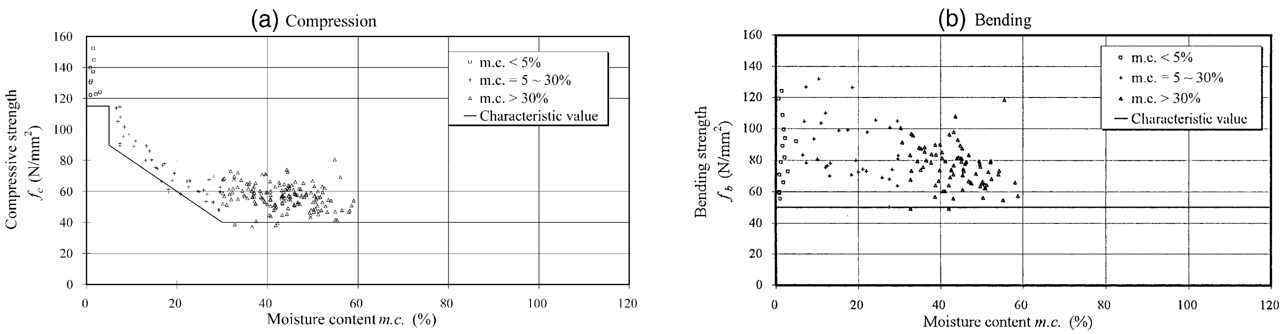

Fig. 7. Variation of mechanical properties of Mao Jue against moisture content.

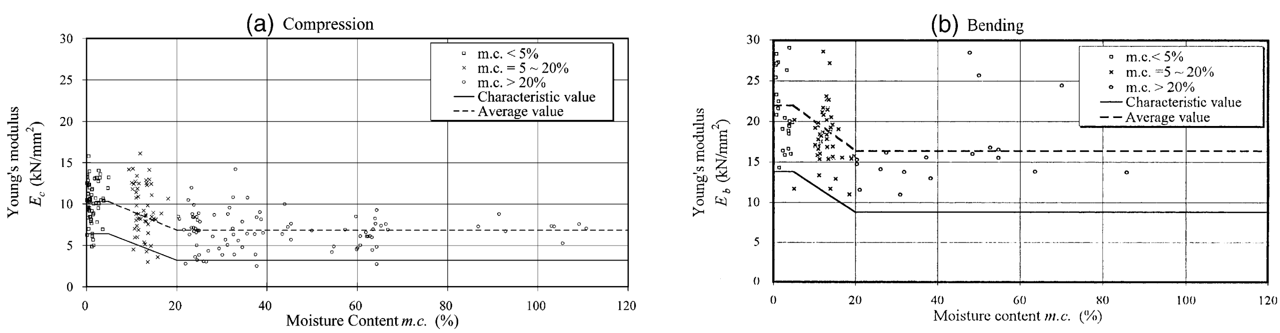

Fig. 8. Variation of mechanical properties of Kao Jue against moisture content.

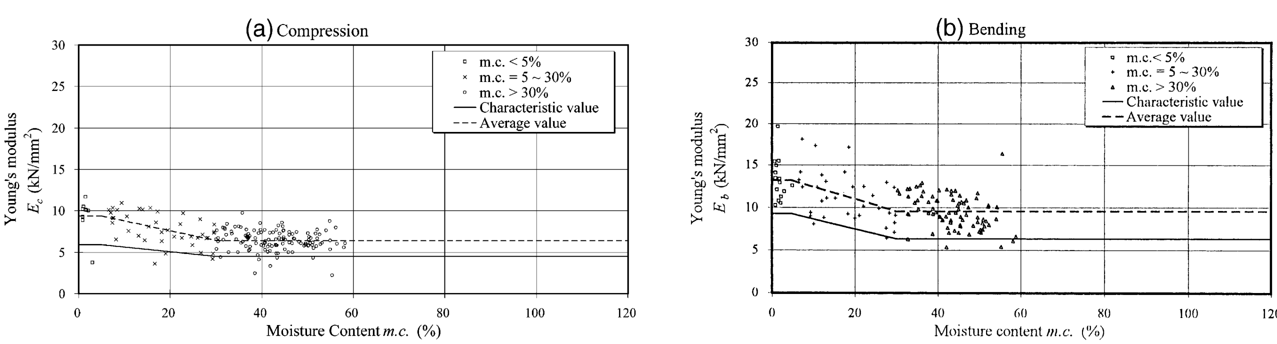

Fig. 9. Variation of mechanical properties of Mao Jue against moisture content.

m.c.>30%, the strength is reduced roughly to one-third of its original value to 44 N/mm^2. The bending strength may be taken at 50 N/mm^2, irrespective to the moisture content.

The average Young's moduli against compression and bending are 9.4 and 13.2 kN/mm^2, respectively in dry condition, and they are roughly reduced by one-third to 6.4 and 9.6 kN/mm^2, respectively in wet conditions.

7. Design data and design rules

In order to provide simple and effective design data, statistical analysis is carried out over three different ranges of moisture contents (*m.c.*) as shown in the pilot study:

Kao Jue

(a) m.c.<5%, (b) m.c.=5~20%, and (c) m.c.>20%.

Mao Jue

(a) m.c.<5%, (b) m.c.=5~30%, and (c) m.c.>30%.

Table 3 summarizes the proposed characteristic compression and bending strengths at fifth percentile values together with associated average Young's moduli. The material partial safety factor for bamboo, γ_m, is proposed to be 1.5. It should be noted that the characteristic values of the mechanical properties of both Kao Jue and Mao Jue are shown to be superior to common structural timber, and probably also to concrete.

Simple design rules for both compression and bending capacities of Kao Jue and Mao Jue are proposed as follows:

- Compression capacity: $F_{design} = f_{c,d} \times A_m$
- Bending capacity: $M_{design} = f_{b,d} \times Z_m$.

In order to assess the structural adequacy of the design rules, model factors ψ are established which are defined as follows:

- Compression capacity: $\psi_c = \frac{F_{test}}{F_{design}}$
- Bending capacity: $\psi_b = \frac{M_{test}}{M_{design}}$.

For the qualification test programmes, Figs. 10 and 11 plot the model factors of the design rules for both compression and bending capacities against moisture contents for both Kao Jue and Mao Jue respectively. The average model factors for compression are found to be 1.98 and 2.04 for Kao Jue and Mao Jue, respectively while the average model factors for bending are found to be 2.18 and 2.40 for Kao Jue and Mao Jue, respectively. Consequently, the proposed design rules are shown to be adequate over a wide range of physical properties.

It should also be noted that the model factors of the design rule for compression capacity against the position along the length of bamboo culms are presented in Fig. 4 for both Kao Jue and Mao Jue. The average model factors for compression are found to be 1.83 and 2.13 for Kao Jue and Mao Jue, respectively. Consequently, the proposed design rules are also shown to be adequate at any cross section along the length of bamboo culms.

8. Practical considerations

For structural design of bamboo scaffoldings in practice, the following should be noted:

(a) Moisture content

In general, the moisture contents at normal supply condition, i.e. air dry for three months after harvest, or *G3*, may be used to determine the design strengths

Table 3
Proposed mechanical properties[a] for *Bambusa pervariabilis* (Kao Jue) and *Phyllostachya pubescens* (Mao Jue)

Bamboo species		Characteristic strength (at fifth percentile)			Design strength (γ_m=1.5)			Design Young's modulus (Average value)		
			Dry	Wet		Dry	Wet		Dry	Wet
Bambusa pervariabilis (Kao Jue)	Compression	$f_{c,k}$ (N/mm^2)	79	35	$f_{c,d}$ (N/mm^2)	52	23	$E_{c,d}$ (kN/mm^2)	10.3	6.8
	Bending	$f_{b,k}$ (N/mm^2)	80	37	$f_{b,d}$ (N/mm^2)	54	24	$E_{b,d}$ (kN/mm^2)	22.0	16.4
Phyllostachya pubescens (Mao Jue)	Compression	$f_{c,k}$ (N/mm^2)	117	44	$f_{c,d}$ (N/mm^2)	78	29	$E_{c,d}$ (kN/mm^2)	9.4	6.4
	Bending	$f_{b,k}$ (N/mm^2)	51	55	$f_{b,d}$ (N/mm^2)	34	36	$E_{b,d}$ (kN/mm^2)	13.2	9.6

[a] Dry condition m.c.<5% for both Kao Jue and Mao Jue. Wet condition m.c.>20% for Kao Jue, and m.c.>30% for Mao Jue. Linear interpolation is permitted for mechanical properties with moisture contents between dry and wet conditions.

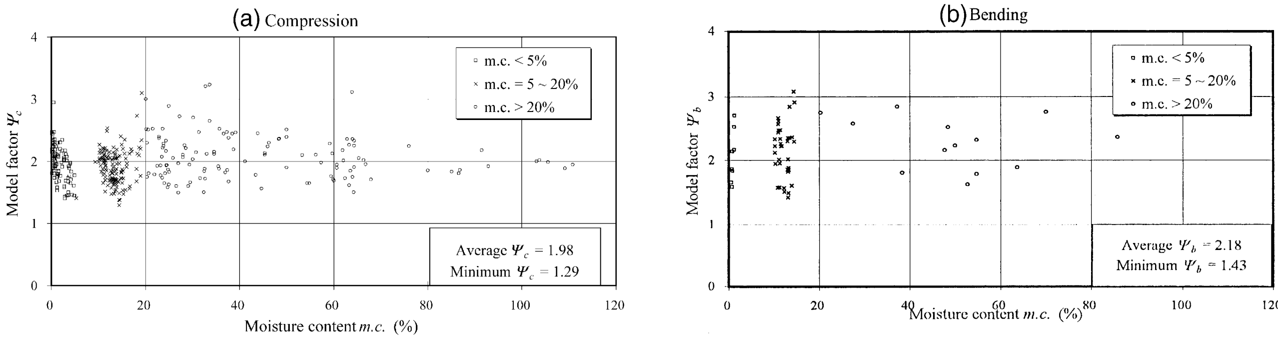

Fig. 10. Variation of model factors of Kao Jue against moisture content.

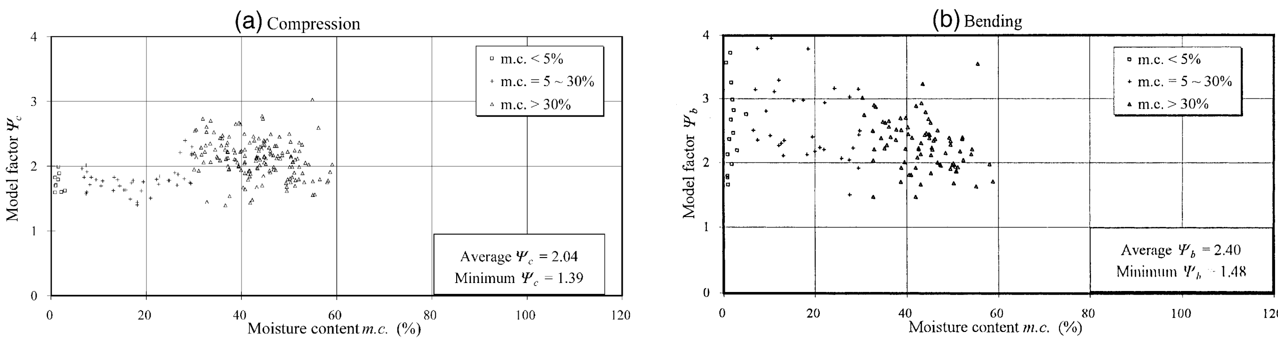

Fig. 11. Variation of model factors of Mao Jue against moisture content.

of exposed bamboo scaffoldings in dry seasons. Typical moisture contents for both Kao Jue and Mao Jue at *G3* are found to be 12.5% and 25%, respectively. For exposed bamboo scaffoldings with an intended life of usage over wet reasons, a conservative approach should be taken and all the mechanical properties should be evaluated at high moisture contents.

(b) Wall thickness of bamboo

It is necessary to provide the wall thicknesses of both Kao Jue and Mao Jue for structural design. Based on the data obtained in the present study, it is reasonable to adopt 5 and 7 mm as the nominal wall thicknesses of Kao Jue and Mao Jue respectively in the absence of measured data.

(c) Partial safety factors

For ultimate limit state design, a material factor of 1.5 should be used in general. However, the material factor may be reduced to 1.25 for those bamboo culms supplied under proper quality control. Moreover, it is recommended that the partial safe factor for construction load should be 2.0 in general. However, for construction sites with proper management and supervision on bamboo scaffoldings, the load factor may be reduced to 1.6 as appropriate. With a suitable choice of partial safety factors, structural engineers are thus able to design bamboo scaffoldings at a known level of confidence against failure.

(d) Column buckling

Due to the slenderness of the bamboo culms, column buckling is always critical in bamboo scaffoldings, especially in compression members with few lateral restraints. Furthermore, it is also important to incorporate the non-uniformity of flexural rigidity along the culm length as both the cross-sectional area and the Young's modulus vary significantly from the top to the bottom of a bamboo culm.

(e) Connections

In practice, all connections in bamboo scaffoldings are currently made up with plastic strips by hands, and they are considered as simple connections in design. Obviously, both the strength and the stiffness of the connections depend primarily on the workmanship of scaffolding practitioners. It is important to ensure that all the connections in bamboo scaffoldings are strong and reliable in both dry and wet conditions over prolonged periods.

9. Conclusions

A pilot study on two bamboo species was carried out to examine the variation of compressive strengths along the culm lengths. It was found that despite of large variations in external diameter, wall thickness and dry density, representative values of mechanical properties were obtained through systemic testing. Among all the physical properties, moisture content is found to be the most important one in governing the mechanical properties of bamboo. Furthermore, it may be acceptable to assume that all physical and mechanical properties are broadly constant along the culm lengths in Kao Jue. However, both the physical and the mechanical properties vary significantly along the culm lengths in Mao Jue, and thus, the non-uniformity should be incorporated when assessing their structural behaviour.

Moreover, a number of qualification test programmes were also executed to generate characteristic values of the mechanical properties of bamboo for limit state structural design. It was demonstrated that the characteristic values of the mechanical properties of the bamboo were superior to common structural timber. In order to qualify any bamboo species as a structural bamboo, qualification test programmes should be conducted to establish its mechanical properties.

Practical design data and simple design rules for compression and bending capacities are presented, and appropriate partial safety factors are also suggested. Structural engineers are thus encouraged to take the advantage offered by bamboo to build light and strong structures to achieve enhanced economy and buildability. The effective use of structural bamboo as a substitute to structural timber will mitigate the pressures on the ever-shrinking natural forests in developing countries, and thus, facilitate the conservation of the global environment.

Acknowledgements

The research project leading to the publication of this paper is supported by the International Network for Bamboo and Rattan (Project No. ZZ04), and also by the Research Committee of the Hong Kong Polytechnic University Research (Project No. G-V849). The authors would like to thank Professor J.M. Ko of the Hong Kong Polytechnic University and Professor J.J.A. Janssen of the Eindhoven University of Technology, co-chairmen of the Steering Committee of the INBAR project, for their general guidance and technical advice. Moreover, the authors would like to express their gratitude to Mr H.C. Ho, Mr K. Ying and Ms K.L. Chan, and also to the technicians of the Heavy Structure Laboratory for the execution of the tests. The test specimens were supplied by Wui Loong Scaffolding Works Co. Ltd.

Appendix A. Data analysis for compression tests and bending tests

A.1. Compression tests

The compressive strength is given by

$$f_c=\frac{F_{test}}{A_m}$$

while the Young's modulus in compression, E_c, is given by the initial slope of the load–deflection curve as follows:

$$\frac{P}{\Delta}=\frac{E_c A_m}{L}.$$

A.2. Bending tests

The bending strength is given by

$$f_b=\frac{M_{test}}{Z_m}$$

while the Young's modulus in bending, E_b, is given by the initial slope of the load–deflection curve as follows:

$$\frac{P}{\Delta}=\gamma\frac{E_b I_m}{L^3}$$

where γ=deflection coefficient which is equal to 48 for prismatic members, and equals 45 to 70 for Kao Jue and Mao Jue with non-uniform cross-sections along member length, depending on the ratios of the second moment of area at the top and the bottom of the member.

References

[1] American Forest and Paper Association. ANSI/NfoPA NDS-1991 national design specification for wood construction and supplement, revised 1991 eds., 1995.
[2] BS EN 384. Structural timber. Determination of characteristic values of mechanical properties and density. The British Standards Institution, 1995.
[3] BS5268. Structural use of timber. Part 2: Code of practice for permissible stress design, materials and workmanship. The British Standards Institution, 1996.
[4] DD ENV 1995-1-1. Eurocode 5: Design of timber structures, Part 1.1 General rules and rules for buildings, 1995.
[5] Fu WY. Bamboo scaffolding in Hong Kong. The Structural Engineer 1993;71(11):202–4.
[6] Chung KF, Siu YC. Bamboo scaffoldings in building construction: erection of bamboo scaffoldings. Joint Publication, the Hong Kong Polytechnic University and International Network for Bamboo and Rattan, in press.
[7] Chung KF, Chan SL. Bamboo scaffoldings in building construction: design of bamboo scaffoldings. Joint Publication, the Hong Kong Polytechnic University and International Network for Bamboo and Rattan, in press.
[8] Practice Guide for Bamboo Scaffolding Safety Management. Labour and Safety Committee, the Hong Kong Construction Association, 1995.
[9] So YS, Wong KW. Bamboo scaffolding development in Hong Kong—a critical review. In: Proceedings of the Symposium on "Bamboo and Metal Scaffolding". The Hong Kong Institution of Engineers, 1998:63–75.
[10] Wong KW. Bamboo scaffolding—Safety Management for the Building Industry in Hong Kong. Research Report, Department of Building and Real Estate, the Hong Kong Polytechnic University, 1998.

[11] Au F, Ginsburg KM, Poon YM, Shin FG. Report on study of bamboo as a construction material. The Hong Kong Polytechnic, 1978.
[12] Janssen JJA. Bamboo in building structures. PhD thesis, Eindhoven University of Technology, Holland, 1981.
[13] Janssen JJA. Mechanical properties of bamboo. Amsterdam: Kluwer Academic, 1991.
[14] Amada S, Munekata T, Nagase Y, Ichikawa Y, Kirigai A, Yang Z. The mechanical structures of bamboos in viewpoint of functionally gradient and composite materials. Journal of Composite Materials 1997;30(7):800–19.
[15] Arce-Villalobos OA. Fundamentals of the design of bamboo structures. PhD thesis, Eindhoven University of Technology, Holland, 1993.
[16] Gutierrez JA. Structural adequacy of traditional bamboo housing in Latin-America. Technical Report No. 321-98-519, Laboratorio Nacional de Materiales y Modelos Estructurales, Universidad de Costa Rica, Costa Rica, 1999.
[17] Society for Advancement of Renewable Materials and Energy Technologies. Technical Report on "Buildings with bamboo arch roof at Harita Ecological Institute—A review report and recommendations for design upgradation". International Network for Bamboo and Rattan, Beijing (China), 1999.
[18] Chan SL, Zhou ZH. Second-order analysis of frames using a single imperfect element per member. Journal of Structural Engineering, ASCE 1994;120(6):703–17.
[19] Chan SL, Wong KW, So YS, Poon SW. Empirical design and structural performance of bamboo scaffolding. In: Proceedings of the Symposium on Bamboo and Metal Scaffoldings, the Hong Kong Institution of Engineers, 1998.
[20] Yu WK, Chung KF. Qualification tests on Kao Jue under compression and bending. Technical Report, Research Centre for Advanced Technology in Structural Engineering, the Hong Kong Polytechnic University, 2000.
[21] Yu WK, Chung KF. Qualification tests on Mao Jue under compression and bending. Technical Report, Research Centre for Advanced Technology in Structural Engineering, the Hong Kong Polytechnic University, 2000.
[22] Janssen JJA. An international model building code for bamboo. The International Network for Bamboo and Rattan, draft document, 1999.
[23] Janssen JJA. INBAR standard for determination of physical and mechanical properties of bamboo. The International Network for Bamboo and Rattan, draft document, 1999.