THE HONG KONG POLYTECHNIC UNIVERSITY

PROCEEDINGS NO.8

Bamboo Scaffolds in Building Construction

K F Chung and S L Chan

INBAR

INTERNATIONAL NETWORK FOR BAMBOO AND RATTAN

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Financial support for INBAR's programs is provided by the Governments of China and the Netherlands, the International Development Research Center (IDRC) of Canada, and the United National International Fund for Agricultural Development (IFAD).

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The Research Centre of Advanced Technology in Structural Engineering (RCATISE) of the Hong Kong Polytechnic University was established in 1999 to provide a focused platform for research and development of advanced technologies in structural engineering in the South East Asia.

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Printed by : Colour Max Commercial Printing Company Limited.

ISBN : 962-367-368-x

Research Centre

for Advanced Technology in Structural Engineering

Proceedings of International Seminar

'Bamboo Scaffolds in Building Construction'

An Alternative and Supplement to Metal Scaffolds

11 May 2002, Hong Kong

Editors: **K. F. Chung and S. L. Chan**

Jointly organized by

Research Centre of Advanced Technology in Structural Engineering
The Hong Kong Polytechnic University

and

The International Network for Bamboo and Rattan

Supported by

Hong Kong Institution of Engineers

and

Hong Kong Institute of Steel Construction

Sponsored by

Wui Loong Scaffolding Works Co., Ltd.

Preface

Bamboo scaffolds have been used extensively in Hong Kong for many years. To us, people living in Hong Kong, they are important parts of our Chinese heritage of traditional building construction: light and slender bamboo members 'inter-woven' to form reliable grids and platforms for workers strolling at height, and climbing up and jumping around with little restriction.

Bamboo scaffolds are ones of the few traditional building systems which survive by self-improvement through practical experiences of scaffolding practitioners over generations. In spite of open competitions with many tubular metal scaffolding systems imported from countries all over the world, bamboo scaffolds are still being erected speedily in numerous construction sites in Hong Kong with new applications and innovations, readily serving the local construction industry.

In order to sustain the use of bamboo scaffolds in Hong Kong, and also to promote their use in countries with plentiful plantations across the globe, we believe it is important to formalize their design and construction technology through documentation and dissemination to all professionals in the construction industry. This International Seminar aims to provide a technical forum for researchers, engineers, contractors, and also regulatory agents to exchange basic design data, scientifically developed analysis and design methods, and established construction practices for safe and effective bamboo scaffolding. Furthermore, latest developments on both bamboo and metal scaffolds are reviewed while further developments are also proposed for general discussion.

We are very pleased to organize this International Seminar jointly with the International Network for Bamboo and Rattan (INBAR). Their support to our technological development on bamboo structures and associated activities is gratefully acknowledged.

Professor J.M. Ko

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MECHANICAL PROPERTIES AND ENGINEERING DATA OF STRUCTURAL BAMBOO

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ABSTRACT

Bamboo is a good natural structural material, and there are over 1500 different botanical species of bamboo in the world. Some of the bamboo species are very stiff and strong, suitable for many construction applications, such as low-rise houses, short span foot bridges, long span roofs and assess scaffolds. As natural non-homogenous organic materials, large variations of physical properties along the length of bamboo members are apparent: external and internal diameters, dry density and moisture content. While structural 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 than those of concrete, probably similar to structural timber.

This paper presents a series of experimental investigations on two structural bamboo species, namely *Bambusa Pervariabilis* (or Kao Jue) and *Phyllostachys Pubescens* (or Mao Jue). Both Kao Jue and Mao Jue are commonly used in access scaffolds in the South East Asia, in particular, in Hong Kong and the Southern China. Over 500 compression tests and 200 bending tests on both Kao Jue and Mao Jue with various moisture contents were performed and their basic capacities against compression and bending were obtained after statistical analysis. Moreover, a total of 72 column buckling tests on both Kao Jue and Mao Jue with various member lengths and moisture contents were also performed. Based on modern structural design philosophy, a design method is proposed for column buckling of both Kao Jue and Mao Jue in a limit state design format.

It is shown that both Kao Jue and Mao Jue are good constructional materials with excellent mechanical properties. With a suitable choice of partial safety factors, structural engineers are able to design bamboo structures at a known level of confidence against failure. Consequently, 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

Structural bamboo, basic mechanical properties, column buckling of bamboo, design development.

INTRODUCTION

Bamboo is a good natural structural material, and there are over 1500 different botanical species of bamboo in the world. Some of the bamboo species are considered to be effective structural materials for many construction applications such as structural members in low-rise houses, short span foot bridges, long span roofs and construction platforms in countries with plentiful bamboo resources. In general, it is considered 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 three to six years to harvest, depending on the species and the plantation, there is a growing global interest in developing bamboo as a substitute of timber in construction. It is generally expected that 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.

As natural non-homogenous organic materials, large variations of physical properties along the length of bamboo members are apparent: external and internal diameters, dry density and moisture content. While structural 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 than those of concrete, and probably similar to structural timber. Up to the presence, a major constraint to the development of bamboo as a modern construction material is the lack of mechanical properties and engineering data for structural bamboo. Moreover, there were only limited design rules available for the general design of structural bamboo, and further design development is highly desirable to provide guidance on the structural behaviour of bamboo members under practical loading and support conditions.

BAMBOO SCAFFOLDS

Bamboo scaffolds have been used in building construction in China for over a few thousand years. Nowadays, in spite of open competition with many metal scaffolding systems imported all over the world, bamboo scaffolds remain to be one of the most preferred systems for access in building construction in Hong Kong and the neighbouring areas, according to Fu (1993).

As reported by So and Wong (1998), bamboo scaffolds are commonly employed in building construction to provide temporary access, working platforms for construction workers and supervisory staff. Owing to their high adaptability and low construction cost, bamboo scaffolds can be constructed in any layout to follow various irregular architectural features of a building within a comparatively short period of time. Moreover, they are also erected to prevent construction debris from falling onto passers-by. In 1995, an industrial guide on safety of bamboo scaffolds is issued by the Hong Kong Construction Association (1995).

Typical usage of bamboo scaffolds in building construction in Hong Kong (Chung and Siu 2002) include:

- Single Layered Bamboo Scaffolds (SLBS) for light duty work, as shown in Figure 1. It is highly adaptable to site conditions with both easy erection and dismantling.

- Double Layered Bamboo Scaffolds (DLBS) with working platform for heavy duty work, as shown in Figure 2. It provides safe working platforms for construction activities to be carried out at heights.

Besides widely erected on construction sites, they are also used for signage erection, decoration work, demolition work and civil work (Tong 1998).

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.* (1978) in Hong Kong, and also by Janssen (1981) in Holland. A large amount of data of the mechanical properties for various bamboo species all over the world were also reported by Janssen (1991). While these sets of data provide typical values of compressive, bending and shear strengths of various bamboo species, no characteristic strengths for structural design were provided.

A series of experimental studies on structural bamboo were reported by Arce-Villalobos (1993) and practical connection details for bamboo trusses and frames were also proposed and tested. Moreover, a recent study conducted by Gutierrez (1999) on the traditional design and construction of bamboo in low-rise housing in Latin America was also available, and innovative applications of bamboo in building construction in India was also reported by INBAR (1999).

It is interesting to note that more recently, a study was reported by Amada *et. al.* (1997), where bamboo was classified as a smart natural composite material with optimized distribution of fibers and matrices, both across cross sections and along member lengths, in resisting environmental loads in nature.

EXPERIMENTAL INVESTIGATIONS

In order to establish the general use of structural bamboo, a series of experimental investigations on the mechanical properties and the structural behaviour of two bamboo species, namely, *Bambusa Pervariabilis* (or Kao Jue) and *Phyllostachys Pubescens* (or Mao Jue) were carried out. These two bamboo species are selected for study because they are commonly used in Hong Kong and the Southern China in bamboo scaffolds. The following experimental investigations for both Kao Jue and Mao Jue are carried out (Yu and Chung 2000a & 2000b, Yu *et. al.* 2002):

- Mechanical properties of structural bamboo

  It is necessary to establish basic design data, i.e. characteristic strength, for structural bamboo in order to evaluate their basic compression and bending capacities.

- Column buckling tests of structural bamboo

  In general, column buckling is considered to be one of the critical modes of failure in bamboo scaffolds, leading to overall structural collapse. After the determination of the basic compression and bending capacities of structural bamboo, it is necessary to investigate the buckling behaviour of long column members.

Due to the variations of physical properties in structural bamboo, it is necessary to carry out a large number of tests to assess the variations of the test results, and to provide engineering data after statistical analysis. For details of the testing procedures, please refer to the INBAR documents compiled by Janssen (1999a & 1999b).

PILOT STUDY ON SHORT BAMBOO MEMBERS UNDER COMPRESSION

A pilot study was carried out to examine the variation of compressive strength against the following physical properties of bamboo members:

- 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 members, and it is highly desirable to establish any co-relation between the physical and the mechanical properties of bamboo members. For each species, three dry bamboo members were tested, and all of them were mature with an age of at least three years old with no visual defect. The height to diameter ratio of the short bamboo members was kept approximately at two, and the maximum height of the short members was 150 mm.

Figure 3 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. Two failure modes, namely *End bearing* and *Splitting*, were identified, as also shown in Figure 3. 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*.

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

For Kao Jue, it should be noted that

- In general, the physical properties of all three members 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 members 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 members.

- The compression capacity is found to be at its maximum of about 60 kN at the bottom of the members 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 member length. However, large variation in the Young's modulus against compression is apparent, scattering between 4 kN/mm^2 and 12 kN/mm^2 along the whole member length.

For Mao Jue, it should be noted that

- On the contrary to Kao Jue, the physical properties of the three members are found to be significantly different among each other. From the bottom to the top of the members, the external diameter is typically reduced from 80 mm to 50 mm. Moreover, the wall thickness varies from 10 mm at the bottom to 6 mm at the top of the members.

- Contrary to the physical properties, the mechanical properties of the three members are found to be broadly similar. From the bottom to the top of the members, the compression capacity is reduced steadily from 100 kN at the bottom of the members 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 members which increases steadily to 70 N/mm^2 at the top. The Young's modulus against compression is found to vary steadily from 5 kN/mm^2 to 10 kN/mm^2 from the bottom to the top of the members.

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 through systemic testing on both Kao Jue and Mao Jue.

SYSTEMATIC TESTS FOR COMPRESSION AND BENDING STRENGTHS

In order to establish characteristic compressive and bending strengths together with associated Young's moduli of each bamboo species, a series of systematic tests, or a qualification test program, was executed by Yu and Chung (2000a & 2000b). Similar to structural timber, it is envisaged that among all the physical properties, moisture content is the most important one in defining the mechanical properties of the bamboo. Consequently, in each test program, a large number of destructive tests on bamboo members under compression and bending were carried out over a wide range of moisture contents as follows:

- Normal supply condition. The test specimens were in normal supply condition, i.e. they were air-dried for at least 3 months before testing.

- Wet condition. The moisture contents of the test specimens were high as they were immersed under water over different time periods.

- Dry condition. The moisture contents of the test specimens were low as they were dried in oven at 105°C over different time periods.

In general, all the test specimens were carefully selected from bamboo members which were about 6 metres in length and of 3 to 6 years of age. Three specimens were cut out from the top, the middle and the bottom positions of the bamboo members, and they were marked with the letters *A*, *B*, and *C* respectively.

Two sets of tests were carried out in the qualification test programs as follows:

- Bending Tests

  Bending tests on bamboo members under single point loads were carried out first. Each bending test specimen was supported over a clear span of 1200 mm, and the specimens were loaded at mid-span until failure, as shown in Figure 3.

- Compression Tests

  After each bending test, two compression test specimens were taken from the bending test specimen, and they were tested under axial compression until failure, as shown in Figure 3.

Typical Modes of Failure

For compression tests, two failure modes, namely *End bearing* and *Splitting*, were identified, as shown in Figure 3. 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*.

For bending tests, two failure modes, namely, *Splitting* and *Local crushing* were identified, as shown in Figure 3. It was found that most specimens 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*.

Test Results and Data Analyses of Systematic Tests

A number of qualification test programs on both Kao Jue and Mao Jue were executed with different batches of samples, and statistical analysis on all the test data were also carried out. Tables 1 and 2 summarize the ranges of both the measured physical and the measured mechanical properties from the qualification test programs.

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 illustrated in Figure 5. 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 also illustrated in Figure 5 for easy comparison.

It should be noted that (Yu and Chung 2001):

- For Kao Jue, both the compressive and the bending strengths are over 75 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.

- For Mao Jue, the compressive strength is over 115 N/mm^2 in dry condition, i.e. *m.c.* < 5 %. However, in wet condition, i.e. *m.c.* > 30 %, the strength is reduced roughly to one third of its original value, i.e. to 40 N/mm^2. The bending strength may be taken at 50 N/mm^2, irrespective to the moisture content.

DESIGN DATA AND DESIGN RULES FOR COMPRESSION AND BENDING

Table 3 summarizes the proposed characteristic compression and bending strengths together with associated Young's moduli at fifth percentile (Chung and Yu 2002). 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. The material partial safety factor for structural bamboo, γ_m , is proposed to be 1.5.

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

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

In order to assess the structural adequacy of the design rules, two model factors ψ_c and ψ_b are established for compression and bending respectively which are defined as follows:

- Compression : $\psi_c = \dfrac{F_{test}}{F_{design}}$
- Bending : $\psi_b = \dfrac{M_{test}}{M_{design}}$

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. Furthermore, it should also be noted that the average model factors of the design rules for compression against various positions along the bamboo members are found to be 1.83 and 2.13 for Kao Jue and Mao Jue respectively. Consequently, the proposed design rules are shown to be adequate over a wide range of moisture contents along the length of bamboo members.

COLUMN BUCKLING OF STRUCTURAL BAMBOO

In order to provide test data for the column buckling behaviour of structural bamboo over practical ranges of physical and mechanical properties, two test series for Kao Jue and Mao Jue were carried out by Yu *et. al.* (2002). In each test series, a total of 36 bamboo members were tested under two different conditions of moisture content, namely, natural and wet conditions. Moreover, three member lengths were tested, and they were 400, 600 and 800mm for Kao Jue while 1000, 1500 and 2000 mm for Mao Jue. The general set-up of the column buckling tests with pinned supports at both ends is illustrated in Figure 6. The applied load P, the axial shortening, w, and the horizontal displacements, u and v were measured continuously during the tests to provide load-deflection curves for data analysis, and the maximum applied load and the corresponding displacements at failure were obtained for each test.

After each buckling test, at least two short members were cut out from the test specimen and compression tests on the short members were carried out to evaluate the compressive strengths of the bamboo members. The moisture contents of the members were also obtained.

Typical Failure Modes

Two failure modes, namely *overall buckling* and *local buckling*, are identified among the tests, and they are shown in Figure 7. It is found that most Mao Jue members fail in overall buckling, especially for those long columns with high moisture contents. For wet and short columns of Kao Jue, local buckling is critical.

Test Results and Data Analysis of Column Buckling Tests

It is found that the load reduction due to column buckling of the test specimens were severe, and thus it is necessary to derive a suitable design method in order to assess the axial buckling resistances of long columns in typical applications.

COLUMN BUCKLING DESIGN FOR STRUCTURAL BAMBOO

Based on modern structural design philosophy, a design method is proposed (Chung and Chan 2002) for column buckling of both Kao Jue and Mao Jue in a limit state design format. The proposed design method follows closely to the column buckling methods of other constructional materials:

- Structural steel as given in the British steel code BS5950 (BSI 2000) and the European steel code Eurocode 3 (ECS 1993), and

- Structural timber as given in the European timber code Eurocode 5 (ECS 1995).

It should be noted that the formulation of the proposed design method adopts the use of a Perry-Robertson interaction formula to allow for the effects of both geometrical and material initial imperfections. In general, both the Perry factor and the Robertson coefficient may be chosen in such a way to fit a column buckling curve rationally into the relevant test data of columns with different cross-sections under different axes of buckling.

Moreover, as natural non-homogenous organic materials, large variations of physical properties along the length of bamboo members such as external and internal diameters are apparent. Thus, the non-prismatic effect is significant in the column buckling analysis, and this may be readily achieved by incorporating a non-prismatic parameter, α , to the elastic Euler buckling load of the bamboo member. The non-prismatic parameter α is a function of the change of the second moment of area along member length, and it may be evaluated through the minimum energy method. The proposed design method is presented as follows:

i) Basic section properties of a bamboo column are evaluated first:

Cross-sectional area: $A_1 = \left[\frac{\pi}{4}\left(D_e^{\,2} - D_i^{\,2}\right)\right]_1$

Second moment of area: $I_1 = \left[\frac{\pi}{64}\left(D_e^{\,4} - D_i^{\,4}\right)\right]_1$; $I_2 = \left[\frac{\pi}{64}\left(D_e^{\,4} - D_i^{\,4}\right)\right]_2$

Slenderness ratio: $\lambda_1 = \frac{L_E}{r_1}$ where $r_1 = \sqrt{\frac{I_1}{A_1}}$

where subscripts 1 and 2 denote the upper (smaller) cross-section and the lower (larger) cross-section respectively.

ii) The elastic critical buckling strength of the bamboo column, f_{cr} , is given by:

$$f_{cr} = \alpha \cdot \frac{\pi^2 E_{b,d}}{\lambda_1^{\,2}}$$

where the non-prismatic parameter, α , is the minimum root of the following cubic function,

$$g(\alpha) = c_3\alpha^3 + c_2\alpha^2 + c_1\alpha + c_0 \quad = 0$$

where

c_3 = -0.2880

c_2 = 2.016 (2 + ρ)

c_1 = -(14.11 + 14.11ρ + 3.098 ρ^2)

c_0 = 10.37 + 15.55ρ + 7.047ρ^2 + 0.932ρ^3

$\rho = \frac{I_2 - I_1}{I_1}$

If the value of ρ lies between 0 and 3, the value of α may be evaluated approximately as follows:

$\alpha = 1.005 + 0.4751\,\rho - 0.011\rho^2$ where α lies between 1.00 and 2.35.

iii) The compressive strength of the bamboo column, $f_{c,d}$, is given by:

$$f_{c,d} = \frac{f_{c,k}}{\gamma_m}$$

iv) The compressive buckling strength of the bamboo column, $f_{cc,d}$, is thus given by:

$$f_{cc,d} = \frac{f_{cr}\ f_{c,d}}{\phi + \left(\phi^2 - f_{cr}\ f_{c,d}\right)^{1/2}}$$

where

$$\phi = \frac{f_{c,d} + (1+\eta) f_{cr}}{2}$$

Perry factor, $\eta = 0.001\, a\left(\lambda_1 - \lambda_0\right)$

Robertson constant, a = 15 for Mao Jue, or
= 20 for Kao Jue.

Limiting slenderness ratio, $\lambda_0 = 0.2\ \pi \sqrt{\dfrac{E_{b,d}}{f_{c,d}}}$

A non-dimensionalized column buckling curve may be plotted using the following two non-dimensionalized quantities:

- Modified slenderness ratio, $\bar{\lambda} = \sqrt{\dfrac{f_{c,d}}{f_{cr}}}$
- Strength reduction factor, $\bar{\psi}_c = \dfrac{f_{cc,d}}{f_{c,d}}$

The compressive buckling strength of a bamboo member is thus obtained as a factor of the compressive strength.

Calibration of Column Buckling Curves

In order to calibrate the proposed design method, a back analysis against the test data was carried out where the measured dimensions of the test specimens and the measured compressive strengths of test specimens under natural and wet conditions were adopted. However, it should be noted that the design values of Young's moduli against bending of both Kao Jue and Mao Jue as given in Table 3 were used. Furthermore, all the partial safety factors were set to unity.

The results of the back analysis are summarized in Table 4 while Figures 8 and 9 present the proposed column buckling curves for both Kao Jue and Mao Jue respectively; all the test data are also plotted on the same graph for direct comparison.

For Kao Jue, it is found that due to the presence of large initial imperfections when compared with its diameter, the Robertson constant is selected to be 28 in order to yield safe design against all the test results. The measured modified slenderness ratios are found to range from 0.44 to 1.11 while the measured strength reduction ratios are found to range from 0.31 to 1.31.

For Mao Jue, the Robertson constant is selected to be 15 to allow for initial imperfections. The measured modified slenderness ratios are found to range from 0.66 to 2.22 and the measured strength reduction ratios are found to range from 0.23 to 0.93. In the present study, the value of non-prismatic parameter, α, is found to range from 1.00 to 1.28 for Kao Jue and from 1.04 to 2.11 for Mao Jue.

The model factors for the proposed design method of column buckling against the test data of both Kao Jue and Mao Jue are presented in Table 5. The distributions of the model factors for both Kao Jue and Mao Jue under different moisture conditions are also plotted in Figures 8 and 9 respectively for easy comparison. For Kao Jue, the average model factors are found to be 1.63 and 1.86 for natural and wet conditions respectively. Similarly, the average model factors for Mao Jue are found to be 1.48 and 1.67 for natural and wet conditions respectively. Consequently, the proposed design method is shown to be adequate, and the design procedure of a bamboo post using Mao Jue is fully presented in the Appendix.

CONCLUSIONS

A series of experimental investigations on both Kao Jue and Mao Jue was carried out to examine the variation of mechanical properties along the member lengths over a wide range of moisture contents. It was found that despite of large variations in external diameter, wall thickness, dry density and moisture contents, 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. Practical design data and simple design rules for compression and bending capacities are presented, and appropriate partial safety factors are also suggested.

Moreover, based on a systematic experimental investigation on the column buckling behaviour of bamboo members, a limit state design method for Kao Jue and Mao Jue is developed and calibrated against test data. It is shown that the proposed design method against column buckling of structural bamboo is reliable and yet simple in assessing the axial buckling resistances of both Kao Jue and Mao Jue, and thus it is suitable to be used in bamboo structures.

It is demonstrated that the characteristic values of the mechanical properties of structural bamboo are similar to those of structural timber. 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. It may be necessary to perform qualification test programs on various bamboo species in order to establish the mechanical properties of a bamboo species before qualifying them as structural bamboo and to be used in building construction.

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. All the test specimens were supplied by Wui Loong Scaffolding Works Co. Ltd..

NOTATIONS

A_m , Z_m	are measured cross-sectional area and section modulus respectively;
F_{design} , M_{design}	are design compressive force and moment capacity respectively;
F_{test} , M_{test}	are measured compressive force and moment capacity 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;
f_{cr}	is elastic critical buckling strength;
$f_{cc,d}$, $f_{cc,t}$	are design and measured compressive buckling strengths respectively;
ψ_c , ψ_b	are model factors for compression test and bending test respectively;
$\bar{\lambda}$	is the modified slenderness ratio defined as $\sqrt{\frac{f_{c,d}}{f_{cr}}}$;
$\bar{\psi}_c$, $\bar{\psi}_t$	are design and measured strength reduction factors for compressive buckling defined as $\frac{f_{cc,d}}{f_{c,d}}$ and $\frac{f_{cc,t}}{f_{c,d}}$ respectively with γ_m equal to 1.0 ;
γ_m	is a partial safety factor for material strength.

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Appendix: Worked Example. Design of a bamboo post using Mao Jue

Design Data

m.c. (%)	5	30	**20**
E_b (kN/mm^2)	13.2	9.6	**11.0**
$p_{c,k}$ (N/mm^2)	117	44	**73**

Member length
Effective length factor L = 2000 mm
Effective length k_E = 1.00
L_E = 2000 mm

	Cross section 1	Cross section 2
External diameter	D_e = 60 mm	D_e = 70 mm
Internal diameter	D_i = 48 mm	D_i = 56 mm
Cross-sectional area	$A_1 = \pi(D_e^2 - D_i^2)/4$	$A_2 = \pi(D_e^2 - D_i^2)/4$
	= 1018 mm^2	= 1385 mm^2
Second moment of area	$I_1 = \pi(D_e^4 - D_i^4)/64$	$I_2 = \pi(D_e^4 - D_i^4)/64$
	= 375600 mm^4	= 695800 mm^4

Radius of gyration
r_{y1} = $SQRT(I_1 / A_1)$
Slenderness ratio of section = 19.21 mm
$\lambda_1 = L_e / r_{y1}$
= 104.12

Ratio of section change
$\rho = (I_2 / I_1) - 1$
Non-prismatic parameter = 0.853
$\alpha = -0.011\,\rho^2 + 0.4751\,\rho + 1.005$
= 1.40

Young's Modulus against bending
Design compressive strength E_b = **11.0** kN/mm^2 γ_m = 1.0
p_c = **49** N/mm^2 γ_m = 1.5

Elastic critical buckling strength
$p_{cr} = \alpha\,(\pi^2 E_b / \lambda_1^2)$
= 14.1 N/mm^2

Column Buckling Curve
Robertson constant
Limiting slenderness a = 15
$\lambda_0 = SQRT(\pi^2 E_b / p_c)$
Perry factor = 47.3
$\eta = 0.001\,a\,(\lambda_1 - 0.2\,\lambda_o)$
= 1.42
$\phi = [p_c + (1 + \eta)\,p_{cr}] / 2$
Design compressive strength against column = 41.5 N/mm^2
buckling $p_{c,c} = p_{cr}\,p_c / [\phi + (\phi^2 - p_{cr}\,p_c)^{1/2}]$
= 9.3 N/mm^2

Modified slenderness
$\bar{\lambda} = SQRT(p_c / p_{cr})$
= 1.86

Modified strength
$\bar{\psi}_C = p_{c,c} / p_c$
= 0.19

Axial load resistance
$\boldsymbol{P} = p_{c,c}\,A_1$
= 9.52 kN

Note: If the Mao Jue is assumed to be prismatic with the external and the internal diameters at 60 and 48 mr respectively, the axial load resistance is 7.63 kN.

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

	Nos.	*Range*	*Maximum*	*Minimum*	*Average*	*Standard deviation*
External diameter D (mm)	364	All specimens	57.6	23.9	40.7	5.9
Internal diameter d (mm)	364	All specimens	45.2	17.3	30.4	4.5
Wall thickness t (mm)	364	All specimens	10.7	2.9	5.2	1.4
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
	136	$m.c.$ = 5 ~ 20%	99	44	69	12
	125	$m.c.$ > 20%	75	35	48	8
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
	53	$m.c.$ = 5 ~ 20%	118	48	82	17
	17	$m.c.$ > 20%	66	37	52	9
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 *Phyllostachys Pubescens* (Mao Jue)

	Nos.	*Range*	*Maximum*	*Minimum*	*Average*	*Standard deviation*
External diameter D (mm)	213	All specimens	95.4	39.4	68.6	11.6
Internal diameter d (mm)	213	All specimens	74.2	27.6	54.5	9.6
Wall thickness t (mm)	213	All specimens	11.0	4.7	7.1	1.3
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	108.33
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
	41	$m.c.$ = 5 ~ 30%	114	48	75	18
	163	$m.c.$ > 30%	81	37	57	8
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
	32	$m.c.$ = 5 ~ 30%	50	132	88	19
	81	$m.c.$ > 30%	118	49	76	13
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

Table 3 Proposed mechanical properties for structural bamboo

Bambusa Pervariabilis (Kao Jue)	Compression			Bending		
		Dry	Wet		Dry	Wet
Characteristic strength (N/mm^2) (at fifth percentile)	$f_{c,k}$	79	35	$f_{b,k}$	80	37
Design strength (N/mm^2) ($\gamma_m = 1.5$)	$f_{c,d}$	53	23	$f_{b,d}$	53	25
Design Young's modulus (kN/mm^2) (Average value)	$E_{c,d}$	10.3	6.8	$E_{b,d}$	22.0	16.4

Phyllostachys Pubescens (Mao Jue)	Compression			Bending		
		Dry	Wet		Dry	Wet
Characteristic strength (N/mm^2) (at fifth percentile)	$f_{c,k}$	117	44	$f_{b,k}$	51	55
Design strength (N/mm^2) ($\gamma_m = 1.5$)	$f_{c,d}$	78	29	$f_{b,d}$	34	37
Design Young's modulus (kN/mm^2) (Average value)	$E_{c,d}$	9.4	6.4	$E_{b,d}$	13.2	9.6

Notes: 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.

The shear strengths of both Kao Jue and Mao Jue are conservatively estimated as $0.25f_{c,d}$ but not less than $6N/mm^2$ and greater than $15N/mm^2$.

Table 4a   Summary of test results for Kao Jue

	Natural condition			Wet condition		
	Minimum	Maximum	Average	Minimum	Maximum	Average
λ	28.0	74.7	47.1	28.1	71.9	47.7
α	1.00	1.24	1.08	1.01	1.28	1.09
$f_{cc,\,t}$	17.6	73.6	43.0	14.8	49.3	34.2
$f_{cc,\,d}$	15.4	37.4	26.3	11.9	27.4	19.1
$\overline{\lambda}$	0.44	1.11	0.72	0.44	1.07	0.72
$\overline{\psi}_C$	0.28	0.67	0.47	0.29	0.67	0.47
$\overline{\psi}_T$	0.31	1.31	0.77	0.36	1.20	0.83

Table 4b   Summary of test results for Mao Jue

	Natural condition			Wet condition		
	Minimum	Maximum	Average	Minimum	Maximum	Average
λ	36.1	122.3	67.6	35.1	149.0	72.5
α	1.04	1.72	1.32	1.16	2.11	1.4
$f_{cc,\,t}$	12.6	42.0	27.0	10.2	41.0	25.6
$f_{cc,\,d}$	10.1	30.0	19.1	6.0	28.1	16.0
$\overline{\lambda}$	0.66	1.61	1.09	0.70	2.22	1.30
$\overline{\psi}_C$	0.22	0.65	0.42	0.14	0.64	0.36
$\overline{\psi}_T$	0.27	0.91	0.59	0.23	0.93	0.58

Table 5   Summary of model factors

	Model factor for columns under natural condition			Model factor for columns under wet condition		
	Minimum	Maximum	Average	Minimum	Maximum	Average
Kao Jue	1.08	2.35	1.63	1.01	2.76	1.86
Mao Jue	1.02	2.41	1.48	1.29	2.82	1.67

Figure 1 Single Layered Bamboo Scaffolds (SLBS)

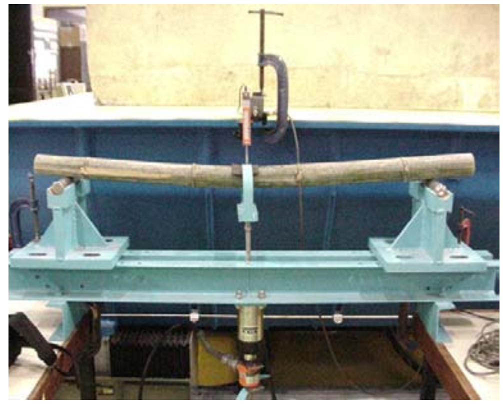
Figure 2 Double Layered Bamboo Scaffolds (DLBS)

i) General test set-up

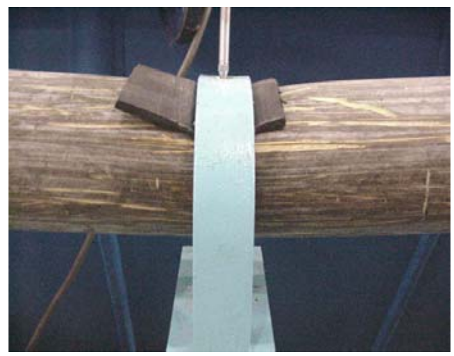
ii) Typical failure mode - End bearing

iii) Typical failure mode - Splitting

Figure 3a Compression test



i) General test set-up



ii) Typical failure mode - Local crushing

iii) Typical failure mode - Splitting

Figure 3b Bending test

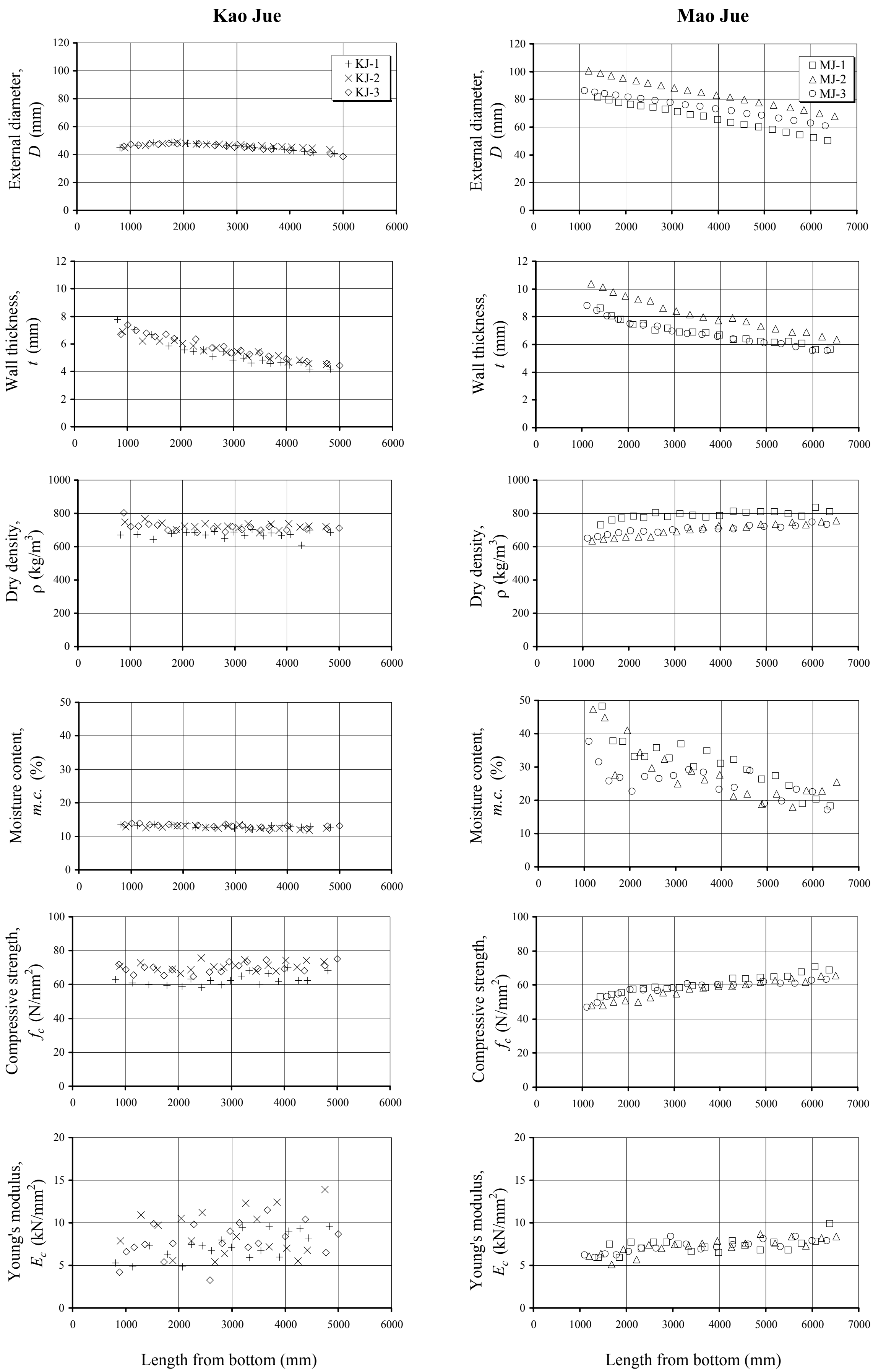


Figure 4 Variation of physical and mechanical properties along length of bamboo members

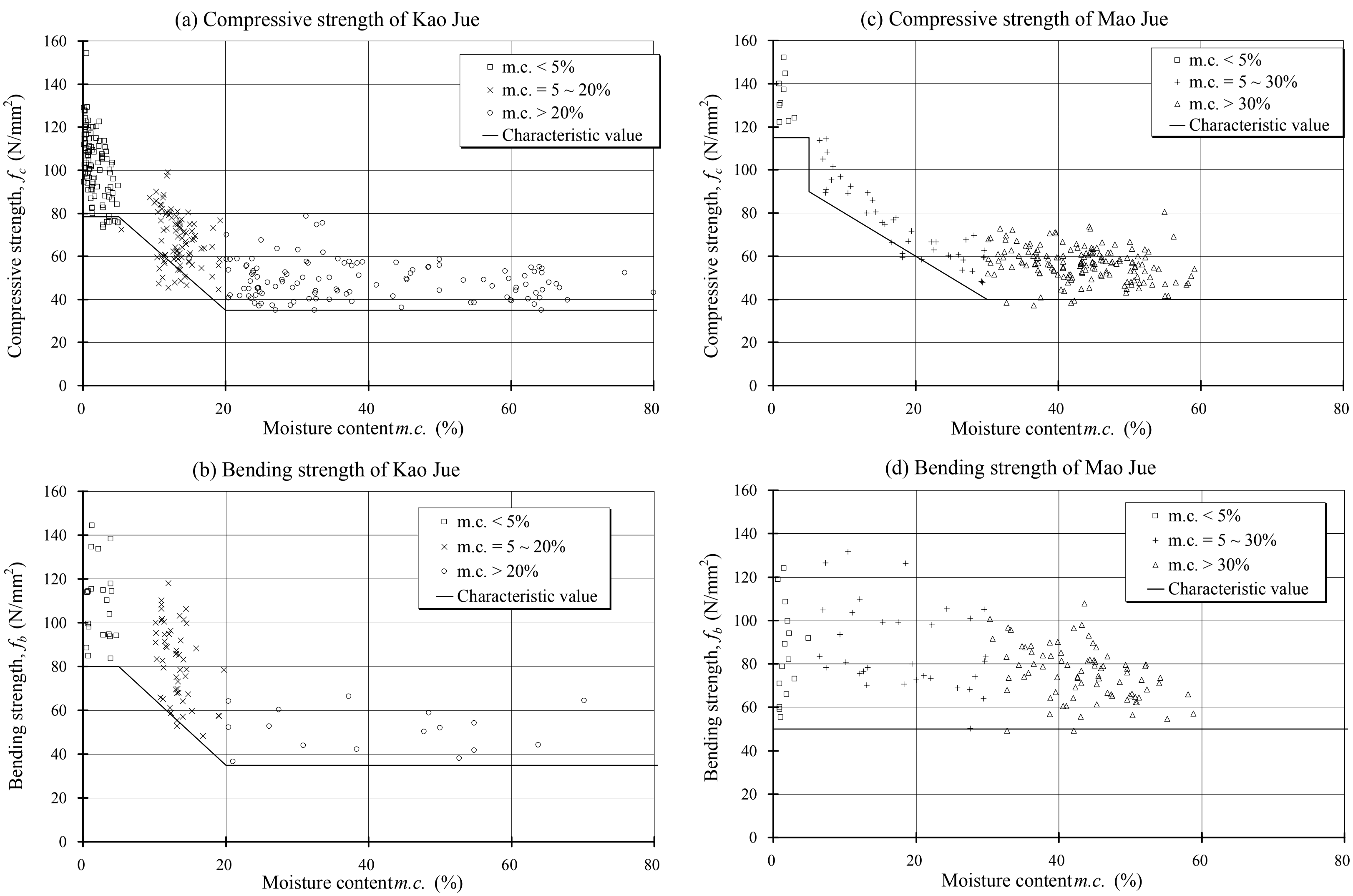
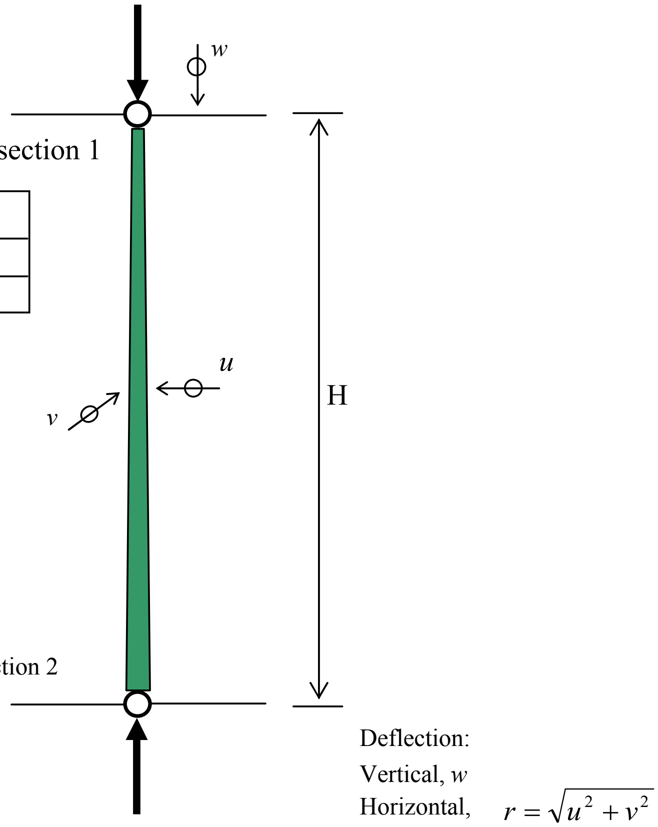
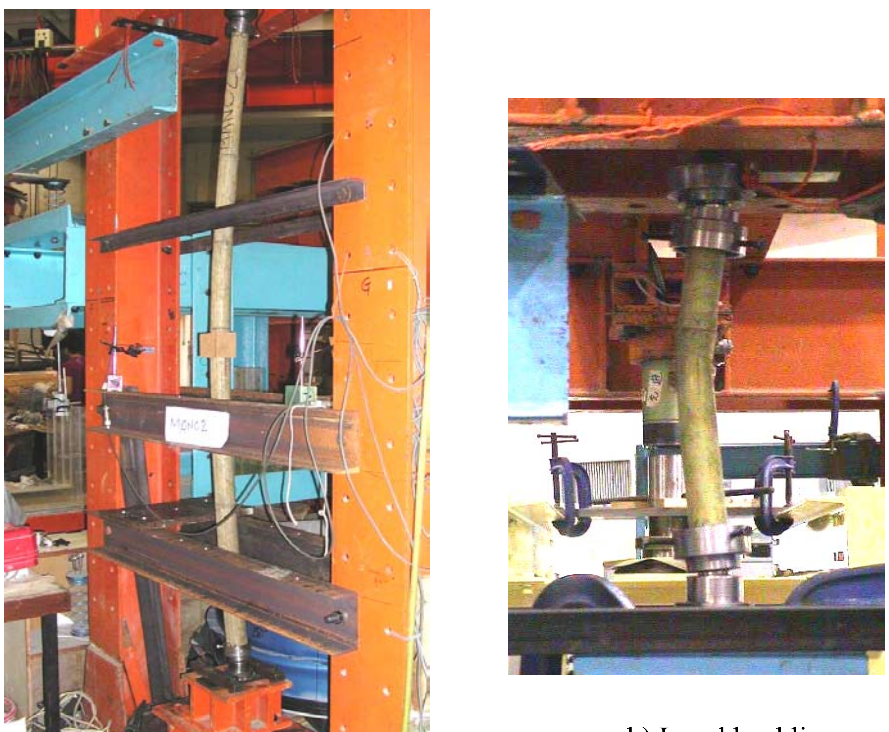


Figure 5 Variation of compressive and bending strengths of structural bamboo against moisture content



	H (mm)		
Kao Jue	400	600	800
Mao Jue	1000	1500	2000

Figure 6 General setup of column buckling tests



a) Overall buckling

b) Local buckling

Figure 7 Failure modes of bamboo column

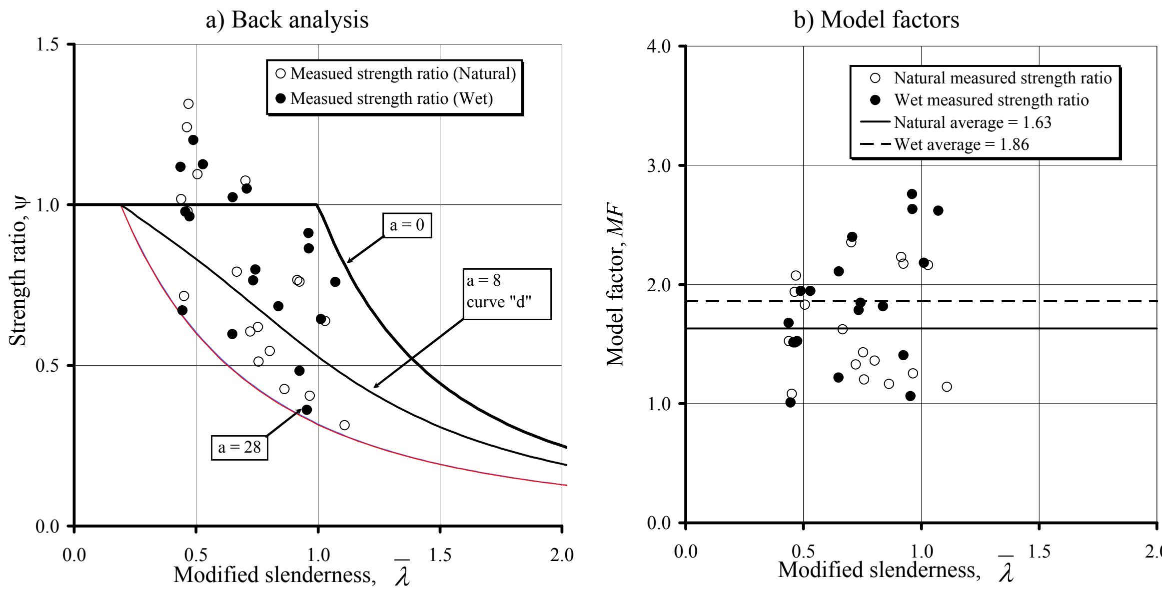


Figure 8 Column buckling analysis for Kao Jue

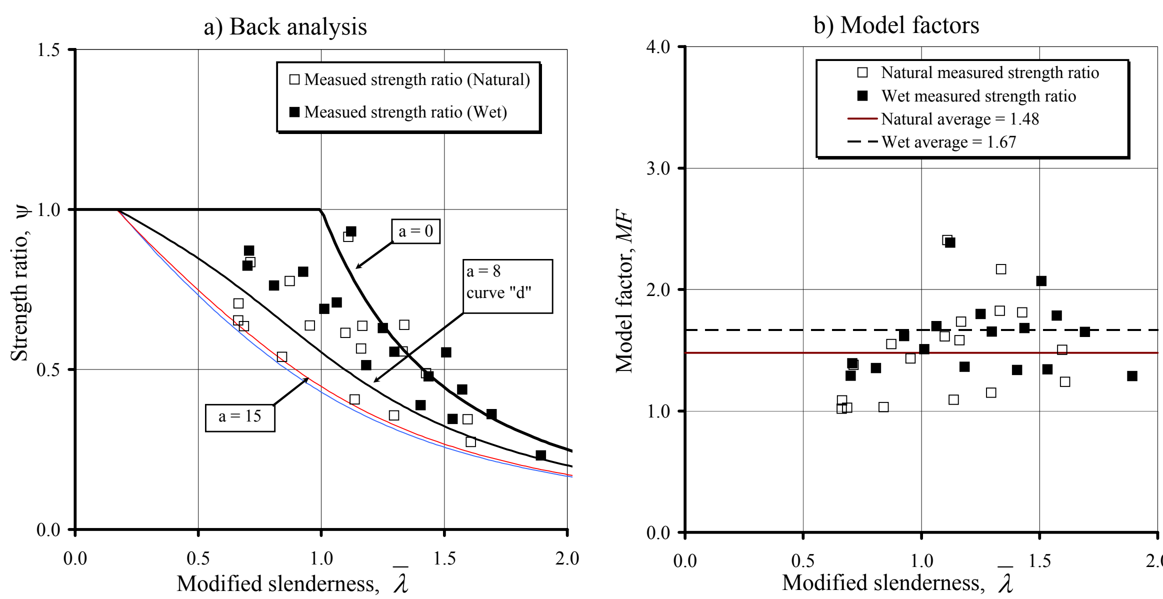


Figure 9 Column buckling analysis for Mao Jue

STRUCTURAL JOINTS IN BAMBOO

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ABSTRACT

This paper presents a background view on the design of structural joints in bamboo. First it will give a description of "joints" in general: next it will focus on joints in building structures. Gradually the scope will narrow itself towards bamboo and scaffolding. Constraints and strong points will be analysed, using a SWOT analysis (strength, weakness, opportunity and threat). From this analysis we will come to design rules for joints in bamboo scaffolding.

KEYWORDS

Joints, bamboo, scaffolding, structural design, SWOT-analysis.

INTRODUCTION

What in fact is a joint in general? Before we pay attention to our common interest in structural joints, it might be good to have a look at the meaning of this word itself. The Collins Cobuild Dictionary gives (among others) the next descriptions.

- Joint can mean: shared by or belonging to two or more people. Example: our interest in joints is a joint interest. A nice play on words!
- A part of your body such as your elbow or knee where two bones meet and are able to move together (good for us, but we do not like movement in our structures, except in hinges of doors and windows).
- The place where two things are fastened or fixed together (this is coming close to our business).
- A way of joining two pieces of wood together (this is even better than the previous one)
- A fairly large piece of meat which is suitable for roasting (out of our business, but too nice not to be mentioned).

Coming now to structural joints in building, the most simple joints can be seen in concrete, cast in situ: no problem at all! The next best is welded steel: the material itself is used to join two pieces together. In these two examples it is rather simple to design a joint which is as strong and stiff as the members on both sides. In timber we try to do the same by applying things like glue, nails, screws, bolts and the like. This list on its own shows already that a joint in timber is more complicated that one in cast concrete or welded steel. For prefabricated concrete and bolted steel we have similar lists. All these items have in common that the members on both sides are rectangular, which is a great advantage for any joints. The problems start as soon as we apply round timber: the round form makes any joint far more complicated. It is not without a good reason that we normally use sawn timber, taking into account the energy needed for the sawing process! This pays in the joints. But for bamboo we have to look for joints which are appropriate for round things.

In steel scaffolding we have tubes, which are round as well, but compared with bamboo these steel tubes are much more convenient: they are exactly round, and they are straight. Both are not true for bamboo: bamboo is not straight, it is not perfectly round, and moreover bamboo has nodes in irregular distances. These disadvantages request the most of our inventiveness, and our capacity to make a good design.

DESIGN OF JOINTS IN BAMBOO

A systematic approach of the design of bamboo joints should start with an objective function: The purpose of a joint is to achieve continuity between elements" (Arce 1993). He describes this as follows: "In modern construction technology, the concept of connection involves the search for mechanisms such that deformations can be kept largely under control, and that predictions are also possible. Structural continuity also conveys the idea of force transmission according to a certain prescribed and desirable manner. Perhaps the main role of the connection is indeed to safely transmit loads in a prescribed manner from element to element, and finally to the ground."

SWOT ANALYSIS (STRENGTH, WEAKNESS, OPPORTUNITY, THREAT)

We will apply this method first to bamboo in building, and next continue with bamboo in scaffolding. See Table 1.

This table is a mix from ideas by Arce (1993) and by participants in the meeting on October 25, 1999, in Hong Kong. We will explain the table into detail, as far as appropriate.

Strength.

The material bamboo is a complicated one: it is a unidirectionally reinforced composite, with comparatively little tangential capacity. Such a material is called anisotropic. Cellulose fibres run parallel to the axis of the culm, with weak material like lignin and pectin in between. For craftsmen making baskets and the like this is a great advantage but builders have other uses in mind.

The strength-weight ratio is a great advantage; steel and concrete are the losers and timber and bamboo the winners. The same goes for the price-weight ratio.

The production of bamboo is energy-friendly and environment-friendly. A comparison with steel shows these advantages for bamboo clearly, but these do not sell on the market until these items are taken into account for a complete calculation of costs.

TABLE 1
SWOT ANALYSIS

Strength	Weakness	Opportunity	Threat
BUILDING			
Reinforced composite	but unidirectional!	Availability	Other materials look better
Strength-weight ratio	Anisotropic material	Many structural forms	
Energy friendly	Little tangential capacity		
Environment friendly	Variability in size and shape		
Inexpensive	Joints difficult		
	Shrinkage, swelling		
	Durability		
SCAFFOLDING			
Light weight (transport)	Reuse limited		Competition with steel
Fast dismantling	Non-engineering		
Light and flexible > less labour	Non-modular		
Typhoon resistant	Lack of skilled labour		
Flexible in design	Lack of standards		

Weakness. Some weaknesses have been dealt with already.

The variability in size and shape is a difficult one. This exactly is one of the advantages of an industrial product like steel tubes. This makes the design of joints in bamboo difficult, together with the low tangential capacity mentioned earlier.

Threat.

Other materials look better. Especially in housing this is a problem. In many countries one can see how the people after a hurricane build houses with bamboo, but as soon as the economy allows they build again with bricks or some material like that, in spite of the proven unsafe behaviour.

Competition with steel is caused by some of the weaknesses: the joints, material properties, lack of skilled labour.

DESIGN RULES

Our task now is to derive design rules from all these data. The most important thing is to make it simple; if we should give the table to any designer he or she would look at it for one moment and then throw it in the paper basket. It is too complicated, it is not yet a help for the designer. What should we write down as design rules? (Arce 1993)

Like any other material, bamboo has a combination of good and bad material properties. Joints should be designed in such a way that we take full advantage of the material, to its full structural potential .

A good design is simple and effective, in terms of the amount of skill and equipment required for its production. The required goal should be reached with the least effort. A difference must be made between the production in the factory, and the work on the building site.
Stability is a must!

A modular design has many advantages: improved quality, mass production, lower costs, unskilled labour on site.

Strength and deformation must be predicted.

The solution must be cost effective.

From the table, only relevant items must be taken into account: the material properties are a must, but items like “energy friendly” do not matter any more for the designer of a joint.

This process helps the designer in developing a way of thinking, but it does not determine the design process completely nor does it determine the outcome. Let us take a view at two different designers. The first selects from the table some items which he or she thinks are important, as follows:

(1) the material is strong along the axis of the culm but weak in tangential direction,

(2) it is not exactly round, and we have nodes at irregular distances, and

(3) we prefer an industrial product which allows for unskilled labour on site.

Considering these items, the designer might choose to solve the tangential weakness, the not-round form and the node-problem by an infill in the open end. Paying attention also to our knowledge of timber joints, brings forward the complete design idea: fill the open end of the bamboo with a piece of round timber, glued inside, and add some holes for bolts. Do all this in the factory; on site we need only simple labour to fix the bolts and nuts. Stability, strength and deformation can be checked easily.

Another designer however could make a different choice; to cope with items (1) and (2) by not using an infill but by wrapping something around the bamboo, e.g. a band of metal, and fix these together to make the joint on site.

Both designers base their design on an analysis of the same items, but the outcome is completely different. This is the typical character of any design process. It shows the richness of the human imagination. This is a real strong property of us! We must be very glad we have this opportunity, to jump with our imagination to something unexpected. The analysis as shown in the table can only help to show us some way out of the problem, but it fact it is our imagination that does the job.

Evidently each design must be evaluated with the same table, leading to acceptance or to a new design process. Never we will reach the final solution. This is our richness and our fate at the same time. It is our fate because we will never find the best solution forever, and it is our richness because life would become very dull.

AND THE COMPUTER?

Certainly the computer with all its powerful software and hardware must be able to help us in solving all design problems. Sorry but this is impossible because the design problem is not well defined and only well defined problems can be tackled by any software program. Have a look at Table 1 and at the list of seven design rules: these look great but in fact both are vague and incomplete. The problem with any design is that the program only will be complete and clear as soon (and not earlier!) as the design is ready. This is due to the fact that each time the designer takes a decision, one specification is added to the program. This is an essential difference between making a design on one hand, and solving a mathematical or physical problem on the other hand. This type of problems is called “wicked problems”.

Please be sure software programs can be of considerable help to the designer. Examples are e.g. IDEF0 or Expert Rule Base. These are great tools to help the designer to keep an overview over all possibilities, and not to loose the way. One of my PhD candidates Fitri Mardjono from Indonesia, is working on bamboo housing design. He found for a connection in a bamboo wall a total of 8640 possibilities! This cannot be handled with manual methods any more, and proper software is a must. But the best software still is like a roadmap or a railway guide, and it is to the designer to decide which road or which train is the best way to a good design.

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Bamboo Scaffolding - Practical Application

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ABSTRACT

Bamboo Scaffold has been widely used in various areas in Hong Kong for many years. Because of its high flexibility and low construction cost, bamboo scaffolds can be constructed in different shapes to follow the irregular architectural features within a comparatively short period of time. Generally speaking, bamboo scaffolding is used to provide access of workers to different exposed locations to facilitate the carrying out of different construction and maintenance process. Besides being widely erected on construction sites, bamboo scaffolding are also being used in decoration work slope work, demolition work, graphic signage erection and even in Chinese Festivals decoration work.

This paper illustrates the basic structure of bamboo scaffolds and the respective practical applications. Some interesting trade practices of bamboo scaffolders in Hong Kong are also mentioned.

INTRODUCTION

Bamboo scaffolding is one of China's oldest construction craft skills. It is widely believed that Yau Chau Sze (有巢氏) extensively used bamboo scaffolding in his construction of the first "tree house" some 5000 years ago. Bamboo scaffolding has been used in Hong Kong in the construction industry since its very earliest days; it is still widely used and is regarded as the most economical and convenient method of gaining access to the exterior of a structure both under construction and after construction. It is one of the key trades offered by the Construction Industry Training Authority in its Basic Craft Training Courses for the purpose of training Hong Kong youngsters in joining the construction industry.

The sight of bamboo-scaffolding stretching several tens of meters high or stretching out from apparently no-where several tens of feet long is often regarded as one of the main tourist's wonders of Hong Kong. Many construction professionals from overseas are also perplexed by the use of bamboo scaffolding in the Hong Kong construction industry, they tend to be sceptical and apprehensive on the use of bamboo scaffolding on their first encounter of this ancient trade, but the majority of them would soon be converted into an advocator of bamboo scaffolding. I am positive that bamboo scaffolding is here to stay in the construction industry in Hong Kong for many decades to come.

ADVANTAGES OF BAMBOO SCAFFOLDING

Generally speaking, the use of bamboo has the advantages over other types of scaffolding in its flexibility, cost effectiveness and speediness in construction.

Bamboos can be cut and tailor-made easily to suit any contour of a construction structure. Bamboo scaffolding can also be securely constructed at the middle of a building stretching a few floors. This flexibility of bamboo scaffolding is specially advantageous in Hong Kong where buildings are tall and crowded to provide only limited space for access by scaffolding.

In view of the close proximity of Hong Kong with the few Chinese provinces which grow bamboo, bamboos suitable for scaffolding can easily be transported to Hong Kong and are available at a very reasonable price. Comparing the price, a typical piece of bamboo is only about 6% the cost of a similar length of steel scaffolding. This vast difference in price is one of the other key reasons why bamboo scaffolding is widely used here.

Bamboos are light-weighted material which can easily be manually handled, and the construction of bamboo scaffolding requires no machinery and no sophisticated hand tools; bamboo scaffolding can thus be constructed much quicker than other types of scaffolding. It is estimated that the erecting of bamboo scaffolding is about 6 times faster, and the dismantling of bamboo scaffolding about 12 times faster than other types of scaffolding, this speediness of construction is quite often the overwhelming factor favouring its continuing use in Hong Kong.

THE CONSTRUCTION OF A TYPICAL BAMBOO SCAFFOLDING USED IN THE CONSTRUCTION INDUSTRY

Single-row bamboo scaffoldings are constructed nowadays only for the provision of access, whilst double-row scaffoldings, which can provide a secure working platform, are normally constructed for construction purposes. The construction of a double-row bamboo scaffolding is described below:-

The double-row bamboo scaffolding consists of 2 layers. The inner layer, at about 150 – 300mm from the building face, is known as the finishing scaffolding (批盪架). The outer layer, at about 700mm from the inner layer, is called the working scaffolding (排柵). Working platforms (工作台) are erected between the inner and outer layers.

To start with the erection, scaffolders always erect two Mao Jue (茅竹) as the main vertical post (柱). Posts (柱) are the vertical members which rest on ground or steel brackets and are usually good quality and strong Mao Jue. They would then be connected with horizontal ledgers (牽) in order to fix their position. Then three Kao Jue (篙竹) will be erected in between the two Mao Jue as standards (針). Standards (針) are vertical members that overhung by the ledgers and would not rest on ground and brackets. Thus, a total of five bamboo poles now span over a distance of about 3m; so that the distance between two adjacent standards is about 750mm.

The vertical distance between two ledgers (i.e. distance between an upper ledger and a lower ledger) is also about 750mm (2.5 feet), that is why you may notice the bamboo scaffolding is in square form.

The inner layer, finishing scaffolding is erected in the same way. Transoms (陣) are erected to connect the inner and the outer layers. These transoms are used to support the working platform.

The integrity and lateral stability of bamboo scaffolding structure rely on the provision of bracing. For a large area of bamboo scaffolding, only Mao Jue may be used for bracing (斜撐). Each bracing section should consist of two pieces of bamboo which are fixed in an 'X' shape and usually in an angle between 60° - 70° over the section of bamboo scaffolding to be braced. Each bracing should also be tied to both the standards and the transoms of the scaffolding. In this way, the loading on the scaffolding can be distributed evenly.

Steel Bracket (狗肶架) are in a triangular shape and are used to support and transfer the loading from posts to the facade of a building. For multi-storey buildings, there is usually one set of steel brackets for every 10 storeys. Each post should rest on one steel bracket, and the horizontal distance between steel brackets is about 3m (10 feet).

Bamboo scaffoldings are tied to the facade of buildings by 6mm diameter mild steel bars 'putlogs' (拉搖) pre-fixed to concrete walls and they are required on every floor. They are often tied with each main standard (i.e. Mao Jue), and the distance of adjacent putlogs is about 3-4m.

After the tying of steel bars, a prop is installed between the building and the scaffolding. The mild steel bars are used to stop the scaffolding expelling away from the building and at the same time the prop can prevent leaning towards the building.

Working platforms are used to provide access for workers, and provide a leveled and safe working area for workers to carry out their construction work.

Working platforms may be covered by planks and are mainly used by plasterers and painters. According to the Code of Practice for Scaffolding Safety, side toe boards and end toe boards should be suitably fixed to all working platforms where a person may fall from a height of more than 2m. They should be of such a height that the gap between the top of the toe board and the guardrail does not exceed 700mm and have a minimum height of 200mm.

Catch fans are used to prevent debris falling from height which may endanger the public. Size and inclination of catch fans are usually determined according to actual site conditions.

Catch fans are usually required at 5 storey intervals and are connected with platforms which are covered with galvanized zinc sheets in order to have better performance for debris collection and removal. They are often connected to the outer layer of bamboo scaffolding. If a catch fan is too large, additional reinforcement such as hang pole (斜吊) and raker (斜挑) are required.

When the erection of catch fans is completed, nylon or galvanized zinc sheets will be laid on catch fans to prevent falling objects.

OTHER APPLICATIONS OF BAMBOO SCAFFOLDINGS

In view of its great advantages of flexibility, cost effectiveness and speed of construction, bamboo scaffolding have found many application outside its normal use in building construction. Some of these application widely adopted in Hong Kong are briefly described:-

Bamboo Scaffolding for Signage Work (招牌棚)

This type of scaffolding is usually a cantilever construction. Although no structural calculations are actually carried out for the scaffolding, it is the trade practice to have the cantilever length and height of the scaffolding in a 4:3 ratio i.e. if the cantilever length is 8m, the height of the scaffold should be 6m. The whole bamboo scaffold is supported by steel wires or hange pole connecting to the permanent structure. The bottom of the scaffold should be covered by timber board to provide working space for other tradesman. Moreover, attention has to be paid to the bottom clearance of the scaffold in order not to obstruct the passage of vehicles.

Truss-out Bamboo Scaffold (Single lift type)(懸空棚、吊棚)

This scaffold is used in locations where it is not practical to erect a scaffold from ground, i.e. for repairs of external drain pipes, spalling repairs to external facade etc. Since the duration of work is not long, the bamboo used will not be strong Mao Jue. The rakers or hang poles should also be supported from permanent structure of the building. When work is to be carried out on the scaffolding, ensure that loadings (working load, live load etc.) should never affect the stability of the scaffolding.

Bamboo Scaffolding on Slopes (斜坡棚架)

Generally speaking, there are 2 types of scaffolding used in slope works, namely, single lift scaffolding (山棚或排柵) and fir pole platform (杉台). Single lift scaffolding should not be treated as working platform for workers to carry out construction work. It should only be used to provide access for workers and supervisors to the some required locations. If construction work has to be carried out on slope, double row scaffolding or single lift scaffold with platform would normally be used.

For slope protection works such as shotcreting and soil anchor works, double row scaffolding is used. The working platform is formed by transoms covered with planks in about 1.5m wide. Usually, platforms are provided at every 2m interval along the hillslope.

For heavier construction work, fir pole is erected to provide stronger working platform to support the operation of construction plant, i.e. site investigation drilling machine, bore piling machines etc. Large diameter Chinese fir pole would therefore be used to support the platform in firm position. As the stability of the platform is very important, settlement monitoring will be carried out at regular intervals.

Bamboo Scaffolding for Demolition Work

Bamboo scaffolding is also used in building demolition work. The whole bamboo scaffolding would be covered by canvas in order to stop dust and debris flying everywhere. However, with the canvas covering, the whole scaffolding would suffer a heavy wind load. It would thus be recommended to remove the canvas portion by portion immediately after the building demolition.

During erection of bamboo scaffolding in demolition work, bamboo scaffolder will drill a hole through the facade wall and penetrate with steel wire. The wire will then tied up the scaffolding firmly to the facade wall.

Another point worth to mentioned is that the ledger is fixed at outside elevation of the scaffolding, which is the reverse in bamboo scaffolding for construction work. With the ledger outside, canvas can be easily tied at the ledger and workers can climb the scaffold inside.

***Scaffolding in Lift Shaft* (軳胆棚)**

There are 2 types of scaffolding which will be erected according to detail drawing, i.e. the scaffolding for temporary performance stage and the scaffolding in lift shaft. The dimension for all installation work in the lift shaft has very little tolerance and the lift shaft scaffold should be erected strictly in accordance with the drawing.

During lift guard rail installation, workers sometimes may damage part of the bamboo scaffold. So experienced bamboo scaffolder will erect raker (斜挑) at certain floors interval such that this damage of the bamboo members will not affect the scaffold stability.

Unlike other types of bamboo scaffolding, bamboo has to be distributed to each floors before erection of the scaffolding. After erection, it is very difficult to pass bamboo to higher levels.

Bamboo Scaffold for Temporary Performance Stage

As mentioned before, this type of scaffold would be erected according to design drawings. Unlike other scaffolding erection, scaffolders will carry out erection work even under rainy days. The performance stage has to be completed within the required period of time and no extension of time will be entertained as the festival celebration will by no means be postponed.

Since a lot of visitors will stay in the performance stage, the bamboo scaffolding has to be inspected by Fire Service Department after completion. Adequate means of escape and fire extinguisher should also be provided.

Although the appearance of this scaffolding is very much different to other bamboo scaffolding structure, the basic bamboo members and erection techniques are same as construction bamboo scaffolding. The whole stage will consist of posts, standards, ledgers, rakers and hang poles. However, the larger the span of the stage, the more difficult to erect the scaffolding stage.

Scaffolds with bamboo and steel members（竹鋼混合棚）

Recently, a new type of scaffolding mixed with steel tubes and bamboo poles has been used in the local construction industry. This type of scaffold has a similar structure to traditional bamboo scaffold. It comprises post, standard, base ledger, horizontal ledger, bracing, parallel ledger, transom and working platform etc and the whole structure will also be secured by a putlog system. In this steel/bamboo mixed structure, load bearing members of the scaffolds（e.g. the post, base ledger and bracing）are steel tubes or fibre reinforced plastic tubes, coupled by metal couplers at intersection points. For those non-load bearing members (e.g. ledger, standard) Kao Jue 篙竹 bamboo poles will be used. Similar to traditional bamboo scaffolding structures, these Kao Jue bamboo poles are secured by nylon ties at intersections between bamboo members or bamboo/steel members.

This type of mixed structure has both the advantages of bamboo scaffolds and metal scaffolds. Structurally, as the load bearing members are steel tubes, it will be more durable and not vulnerable to accidental damage by workers. It will also maintain the high flexibility of bamboo scaffolds and can suit most of the irregular architectural features in building construction. The erection and dismantling time of this mixed structure will be much less than that required by metal scaffolding.

However, as this type of scaffold comprises both bamboo and steel elements, the skill requirement for scaffolders will be much higher. They should be familiar with both skills in bamboo scaffolding and metal scaffolding erection. Regarding to cost, this type of mixed scaffold will be, to certain extent, higher than traditional bamboo scaffold as bamboo poles and nylon ties are much cheaper than steel tubes and couplers. Roughly speaking, the cost ratio of bamboo scaffold, bamboo-steel scaffold and steel scaffold is about 1:3:6 for one construction project. But since the maintenance costs for these 3 types of scaffolds are just in the reverse ratio and the steel tubes can be reused for many times, the cost difference will be levelled out when more and more projects are taken into consideration.

CONCLUSIONS

In concluding, I wish to reiterate my firm belief that, unless the supply of bamboo to Hong Kong is hintered, bamboo scaffolding is here to stay for many decades to come. We, at the Construction Industry Training Authority have been conducting a Basic Craft course in bamboo scaffolding for the past 20 years for the training of youngsters to master this constructional skill and currently have 60 training places per year. This CITA training course is conducted **NOT** for the purpose of reserving an ancient China artististical skill, **BUT** solely to meet the genuine needs of the construction industry.

In concluding, I would also like to clarify the general misconception that bamboo scaffolding is a very dangerous trade; in fact bamboo scaffolding is relatively a safe construction trade, there is rarely any accident on construction sites involving injury or fatal death of bamboo scaffolders. The safety to users of bamboo scaffolding is of course a complex issue necessitating detailed discussion. I only wish to acclaim here that, should bamboo scaffolding be properly maintained by scaffolders and are not willfully or unknowingly damaged or infringed by other tradesmen, bamboo scaffolding should at least be as safe as any other types of scaffolding used on construction sites.

Double layered scaffolds

Double layered scaffolds

Signage scaffolds

Truss-out bamboo scaffolds

Truss-out Bamboo scaffolds

Bamboo scaffolds on slope

Bamboo scaffolds for
Demolition Work

Bamboo scaffolds for
demolition work

Bamboo scaffolds for
temporary performance stage

Bamboo scaffolds for
temporary performance stage

Bamboo and metal scaffolds

Bamboo and metal scaffolds

Double layered bamboo scaffolds on slope

Closer view on transom platforms

Single layered bamboo scaffolds on slope

BAMBOO IN CONSTRUCTION

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ABSTRACT

Bamboo is one of the oldest and most versatile building materials with many applications in the field of construction, particularly in developing countries. It is strong and lightweight and can often be used without processing or finishing. Bamboo constructions are easy to build, resilient to wind and even earthquake forces, and readily repairable in the event of damage. Associated products such as bamboo based panels and bamboo reinforced concrete also find applications in the construction process. In spite of these clear advantages, the use of bamboo has been largely restricted to temporary structures and lower grade buildings due to limited natural durability, difficulties in jointing, a lack of structural design data and exclusion from building codes. The diminishing wood resource and restrictions imposed on felling in natural forests, particularly in the tropics, have focused world attention on the need to identify a substitute material which should be renewable, environmentally friendly and widely available. In view of its rapid growth, a ready adaptability to most climatic and edaphic conditions and properties superior to most juvenile fast growing wood, bamboo emerges as a very suitable alternative. However, in order to exploit fully the potential of bamboo as a construction material, development effort should be directed at the key areas of preservation, jointing, structural design and codification.

KEYWORDS

bamboo, construction, durability, jointing

INTRODUCTION

Bamboo has a long and well established tradition as a building material throughout the world's tropical and sub-tropical regions. It is widely used for many forms of construction, in particular for housing in rural areas. Bamboo is a renewable and versatile resource, characterised by high strength and low weight, and is easily worked using simple tools. As such, bamboo constructions are easy to build, resilient to wind and even earthquake forces (given the correct detailing) and readily repairable in the event of damage. Associated products (bamboo based panels and bamboo reinforced concrete, for example) also find applications in the construction process.

There are however a number of important considerations which currently limit the use of bamboo as a universally applicable construction material:

- ***Durability***: bamboo is subject to attack by fungi and insects. For this reason, untreated bamboo structures are viewed as temporary with an expected life of no more than five years.
- ***Jointing***: although many traditional joint types exist, their structural efficiency is low (Herbert *et al.* 1979). Considerable research has been directed at the development of more effective jointing methods.
- ***Flammability***: bamboo structures do not behave well in fires, and the cost of treatment, where available, is relatively high.
- ***Lack of design guidance and standardisation***: the engineering design of bamboo structures has not yet been fully addressed.

The majority of bamboo construction relates to rural community needs in developing countries. As such, domestic housing predominates and, in accordance with their rural origins, these buildings are often simple in design and construction relying on a living tradition of local skills and methods. Other common types of construction include farm and school buildings and bridges. Further applications of bamboo relevant to construction include its use as scaffolding, water piping, and as shuttering and reinforcement for concrete. In addition, the potential number of construction applications has been increased by the recent development of a variety of bamboo based panels.

BAMBOO BUILDINGS

Bamboo can be used to make all the components of small buildings, both structural and non-structural, with the exception of fireplaces and chimneys. It is, however, often used in conjunction with other materials.

Bamboo building construction is characterised by a structural frame approach similar to that applied in timber frame construction. In this case, the floor, wall and roof elements are interconnected and often one dependent on the other for overall stability. There is a need to control lateral deformations in some traditional forms of building in particular.

The adequacy and suitability of the building for occupancy will also depend to a large extent on good detailing, for example to help prevent water and moisture ingress, fungal attack and vermin infestation.

All of the above features are dealt with in the following sections.

Foundations

The types of bamboo foundation in common use are:

- Bamboo in direct ground contact
- Bamboo on rock or preformed concrete footings
- Bamboo incorporated into concrete footings (Figure 1)
- Bamboo on steel shoes (Figure 1)
- Bamboo reinforced concrete

In general, it is best to keep bamboo clear of the ground, since untreated material can decay very quickly in ground contact.

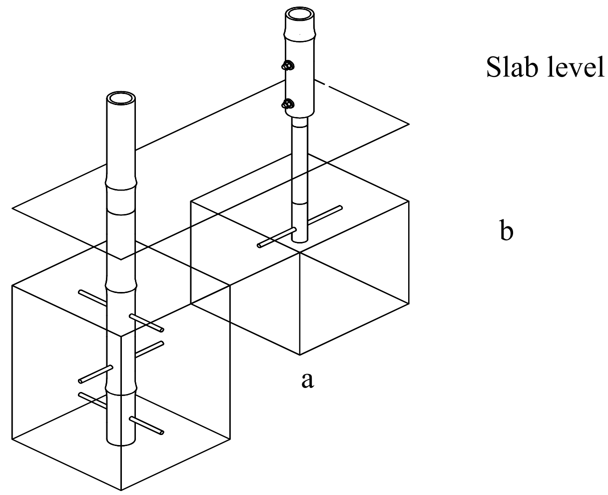


Figure 1: Examples of columns set a) in concrete footing and b) on steel shoe

Floors

The floor of a bamboo building may be at ground level, and therefore consist only of compacted earth, with or without a covering of bamboo matting. However, the preferred solution is to raise the floor above the ground creating a stilt type of construction. This improves comfort and hygiene and can provide a covered storage area below the floor. When the floor is elevated, it becomes an integral part of the structural framework of the building. The floor comprises:

- structural bamboo elements
- bamboo decking

Floor structure

Bamboo floors normally consist of bamboo beams fixed to strip footings or to foundation posts. The beams therefore run around the perimeter of the building. Where the beams are fixed to posts, careful attention to jointing is required. Beams and columns are generally around 100mm in diameter.

Bamboo joists then span in the shortest direction across the perimeter beams. The joists are often laid on the beams without fixing, but some form of mechanical connection is recommended. Depending on the form of floor decking, secondary joists, often taking the form of split culms, may be required. Joist diameters are in the order of 70mm. Joist centres are typically 300 to 400mm, or up to 500mm if secondary joists are used.

Floor decking

Bamboo floor decking can take one of the following forms:

- Small bamboo culms
- Split bamboo
- Flattened bamboo (bamboo boards)

- Bamboo mats
- Bamboo panels, laminates or parquettes

Walls

The most extensive use of bamboo in construction is for walls and partitions. The major elements of a bamboo wall generally constitute part of the structural framework. As such they are required to carry the building self-weight and loadings imposed by the occupants, the weather and earthquakes.

An infill between framing members is required to complete the wall. The purpose of the infill is to protect against rain, wind and animals, to offer privacy and to provide in-plane bracing to ensure the overall stability of the structure when subjected to horizontal forces. The infill should also be designed to allow for light and ventilation. Not least is its architectural and aesthetic function. This infill can take many forms:

- Whole or halved vertical or horizontal bamboo culms, with or without bamboo mats
- Split or flattened bamboo, with mats and/or plaster
- Bajareque
- Wattle (wattle and daub, lath and plaster, quincha)
- Woven bamboo, or bamboo grids, with or without plaster (see Figure 2)
- Bamboo panels

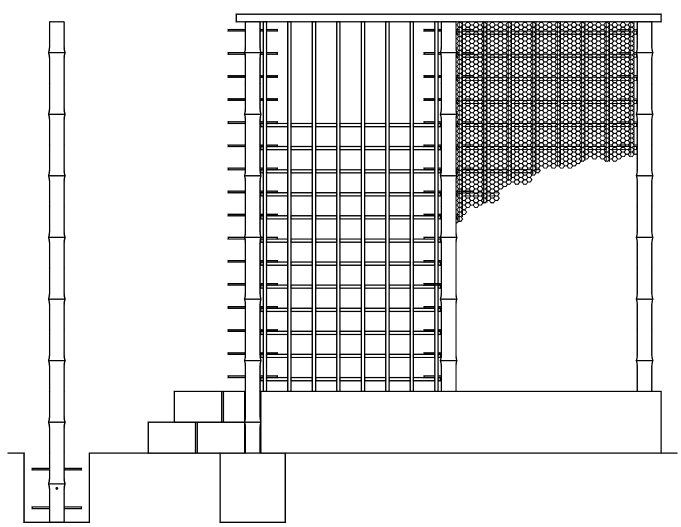


Figure 2: Wall construction using plastered bamboo grid

Roofs

The roof of a building is required to offer protection against extremes of weather including rain, sun and wind, and to provide clear, usable space beneath its canopy. Above all, it must be strong enough to resist the considerable forces generated by wind and roof coverings. In this respect bamboo is ideal as a roofing material - it is strong, resilient and light-weight.

The bamboo structure of a roof can comprise "cut" components - purlins, rafters and laths or battens, or triangulated (trussed) assemblies. Bamboo, in a variety of forms, is also used as a roof covering and for ceilings.

Roof covering

Bamboo roof coverings can form an integral part of the structure, as in the case of overlapping halved culms. More often, they are non-structural in function. Examples include:

- Bamboo tiles
- Bamboo shingles
- Bamboo mats
- Bamboo mat board
- Plastered bamboo

Corrugated sheet made from bamboo mats, currently under development at IPIRTI in India, shows great potential as a roof covering. It is light, strong and resilient, waterproof and impermeable with low thermal conductivity and good fire resistance.

Doors and windows

In traditional types of bamboo building, doors and windows are usually very simple in form and operation. Bamboo doors can be side hinged or sliding, comprising a bamboo frame with an infill of woven bamboo or small diameter culms.

Bamboo windows are generally left unglazed and can have bamboo bars, or a sash with woven bamboo infill. The sash can be side hinged or sliding , or, more commonly, top hinged to keep out direct sunlight and rain. At night, windows are closed to protect against insects and animals. Hinges are formed from simple bindings, or connecting bamboo elements.

PROTECTION OF BAMBOO COMPONENTS

Bamboo is non-durable in its natural state. It provides a ready food source for insects and fungi, and can decay in less than a year in direct ground contact. Protection is therefore essential to ensure the longest possible life for the material, and the building in which it is used.

Protection does not necessarily mean chemical treatment. The first line of defence (post-harvesting) is good design.

Protection by design

Protection by design involves 4 basic principles:

- Keeping the bamboo dry
- Keeping the bamboo out of ground contact
- Ensuring good air circulation
- Ensuring good visibility

Large roof overhangs prevent direct wetting of walls in heavy and driving rain, and drainage channels and/or gutters can be used to discharge water a safe distance from the building. The risk of more general flooding can be reduced by building on a graded or slightly sloping site, and using raised masonry or concrete footings.

The effects of water inside the building should not be overlooked. Simple provision can be made to drain away washing and cooking water, avoiding the hazards of prolonged wetting (see Figure 3).

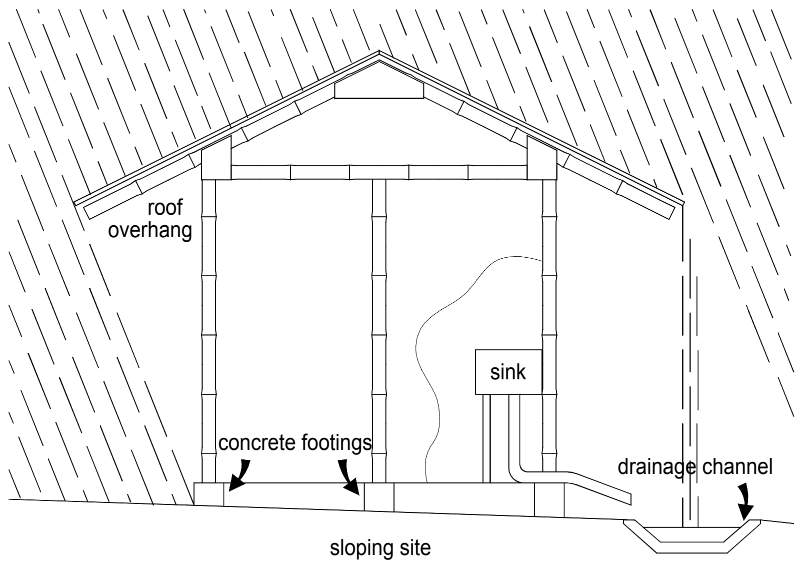


Figure 3: Protection by design

Raising bamboo columns or wall panels clear of the ground also reduces the risk of termite infestation, and improves visibility, making inspection easier. Termite shields can be used between the footings and walls, if the risk is considered high. Where possible, the roof space should be left exposed to improve both visibility and airflow, and aid routine maintenance.

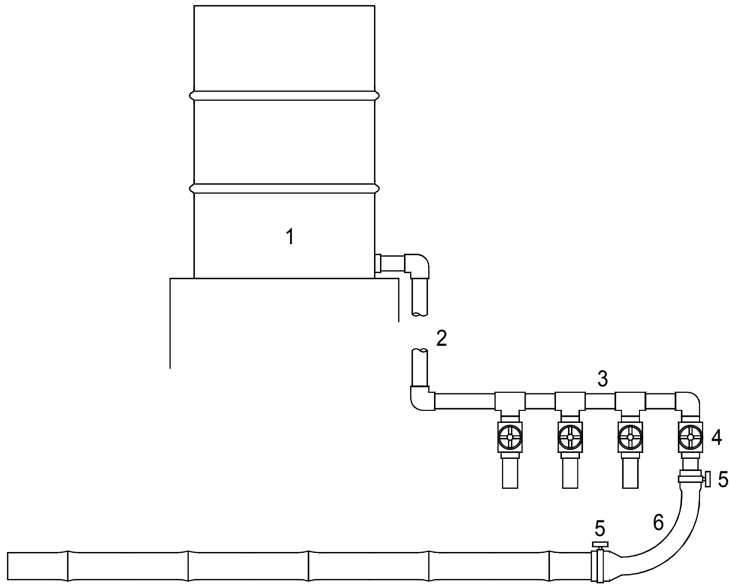
Bamboo constructions can also provide ideal nesting areas for rodents and other pests. In general, open culm ends should be plugged and cavity construction should be avoided.

Protection by preservation

In general, the natural durability of bamboo can be enhanced by the application of preservative compounds which help to prevent insect and fungal attack. A wide range of preservatives is available, including oil based, oil soluble, water soluble and water soluble “fixed” types. However, chemicals over which there are environmental and health and safety concerns should be discounted. Tar oil and boron based chemicals are relatively safe options, and are often available locally. Four treatment methods are ideally suited to site or workshop application:

- internodal injection of creosote oil
- dip diffusion with boric acid and borax
- hot and cold creosote method
- the Boucherie method (see Figure 4) using boric acid and borax

Preservative treatment is covered in detail in the book by Jayanetti and Follett (1998).



1. Tank containing preservative, located at high level
2. Connection pipework
3. Distribution manifold
4. Valve
5. Tube clamp
6. Flexible rubber tubing

Figure 4: Arrangement for Boucherie treatment process

OTHER TYPES OF CONSTRUCTION AND CONSTRUCTION APPLICATIONS

Bridges

A bridge can be defined as an elevated structure supported at intervals for carrying traffic across obstacles (valleys and rivers, for example). In general terms, therefore, the range of types, spans and capacities is almost infinite. Bamboo bridges, however, are generally of trestle construction and of limited span for carrying only light (usually pedestrian) traffic. Simple trussed constructions have also been built and have been shown capable of supporting substantial loads.

Scaffolding

Bamboo scaffolding is widely used throughout South and South East Asia and also South America as a temporary structure for supporting working platforms in building construction and maintenance. The main advantages of bamboo scaffolding when compared with steel are its lightness and low cost. It is also readily tailored to suit the shape of a building. However, problems such as lack of durability, and non-standardised jointing currently limit its wider application.

Bamboo reinforced concrete

The use of bamboo as concrete reinforcement is one of the more broadly covered topics relating to bamboo in construction. There are several good reasons why bamboo might be considered as reinforcement for concrete:

- It is of low cost compared with steel
- It is readily available
- Its strength to weight ratio compares favourably with steel

However, bamboo exhibits certain characteristics which limit its effectiveness as concrete reinforcement, and considerable research effort continues to be directed at this subject.

Bamboo based panels

The earliest bamboo panel was made in China during the First World War. To date, many different panel types have been developed, mostly in Asia, but investigations into construction applications have only recently been carried out (Ganapathy *et al.* 1995). Bamboo based panels have proved suitable for structural as well as non-structural applications, in both low and high grade building work. Specific end uses include floors, walls, partitions, doors, ceilings and roofs, and by virtue of their inherent rigidity and enhanced durability (through preservative treatment), such panels can offer significant advantages over the use of bamboo in its natural state. The various types of panel product can be broadly classified as follows:

- Processed strips, laths or slivers
- Processed, peeled veneers
- Strands, particles or fibres reconstituted into panels
- Combinations of one or more of the above
- Combinations of one or more of the above with wood, other lignocellulosic materials and inorganic substances

The two most common panel types, for which product standards have been formulated in countries where they are commercially produced, are:

- Bamboo mat board (bamboo mat plywood)
- Bamboo strip board (bamboo strip plywood)

JOINTING TECHNIQUES

Effective jointing is fundamental to the structural integrity of a framed construction. Furthermore, the suitability of a material for use in framing is largely dependent upon the ease with which joints can be formed.

Because of its round, tubular form, jointing of two or more bamboo members requires a different approach to that adopted for, say, solid timber. Despite its relatively high strength, bamboo is susceptible to crushing, particularly of open ends. It is also characterised by a tendency to split; the use of nails, pegs, notches or mortises can therefore result in considerable reductions in strength. Connections must also cope with variations in diameter, wall thickness and straightness.

Clearly, these limitations have not presented an obstacle to the use of bamboo in traditional forms of construction. However, the building of structurally efficient, more durable and possibly larger and more economical bamboo structures will depend to a large extent on improvements and developments in jointing technology.

Traditional joints

Traditional jointing methods rely principally on lashing or tying, with or without pegs or dowels. The basic joint types are:

- Spliced joints
- Orthogonal joints
- Angled joints
- Through joints

Improved traditional joints

The mechanical performance of traditional bamboo joints can be improved by the adoption of the following procedures:

- *Form joints at or near nodes*: nodes are more resistant to splitting than internodes. It is therefore good practice to make joints as close to nodes as possible. For example, in the simple saddle joint, the saddle should be formed directly above a node.
- *Minimise on holes*: it is generally accepted that holes, cuts and notches will reduce the ultimate strength of a bamboo culm. If a hole is made in a culm (for a peg, dowel, mortise, inset support or insert) this should be as close as possible to the node, paying particular attention to the direction of the applied force. Furthermore, whenever possible holes should be round or radiused rather than square cut as these are less likely to propagate splits.
- *Use seasoned culms*: seasoned rather than green bamboo should be used for two reasons. Firstly, bamboo shrinks on drying and this will generally cause joints to loosen. Secondly, drying splits can form which could further weaken the assembly (Narayanamurty *et al.* 1972).
- *Reinforce against splitting and crushing*: tight binding, especially with wire, can in itself offer good resistance to splitting. In trusses, the use of quarter-round bamboo bearing plates reduces the risk of crushing of the chords by the compression webs (Janssen, 1995).
- *Improve durability*: preservative treatment of the bamboo and protection from wetting by good detailing will increase the life of the joint. The use of wire is in many cases preferable to bamboo lashings or rope as it is not subject to insect attack.

Recent developments

By building on traditional methods and exploiting the strengths and advantages of bamboo, a number of jointing techniques have been developed which offer more structurally efficient solutions to jointing problems. However, their adoption and suitability will depend to a large extent on the cost and availability of materials, equipment and skilled labour. Recent examples include:

- Gusset plates
- ITCR joint
- Arce joint
- Filled joint

- Das clamp
- Herbert shear pin connector
- Gutierrez joint
- Steel or plastic insert connectors

DESIGN CONSIDERATIONS

The use of bamboo as an engineering material is limited from the point of view of design by two major considerations:

- The formulation of structural design guidance is governed to a large extent by practical, engineering experience. In the case of bamboo, information from this source is somewhat limited.
- Basic mechanical properties have been dealt with by many authors, but, unlike timber, bamboo properties do not relate well to species because of the dependency on other factors, such as geographical location and age (Arce, 1993).

Considerable effort continues to be directed at the derivation of mechanical properties, but perhaps with insufficient regard to applications in the field. Janssen (1995), however, has shown that a relationship exists between density and permissible stress which forms the basis of Table 1 below:

TABLE 1
ALLOWABLE LONG-TERM STRESS (N/MM^2) PER UNIT VOLUME (KG/M^3)

	Axial compression (no buckling)	Bending	Shear
Air dry	0.013	0.020	0.003
Green	0.011	0.015	-

For example, if green bamboo has a density of $600kg/m^3$, the allowable stress in bending would be 0.015 x 600 = $9N/mm^2$. As these are long-term stresses, Janssen suggests they may be increased by 25% for live, or medium-term loading, and by 50% for short-term loading.

Other studies relate to specific species, or groups of species. Rajput *et. al.* (1994) considered sixteen species and derived minimum long-term safe working stresses for the green condition as summarised in Table 2 below:

TABLE 2
SAFE LONG-TERM GREEN WORKING STRESS (N/MM^2)

	Bending	**Stiffness**	**Compression**
Group A	17.2	1,960	9.8
Group B	12.3	1,370	8.3
Group C	7.4	680	6.9

Group A	*Bambusa glaucescenes (*syn. *B. nana), Dendrocalamus strictus, Oxytenanthera abyssinica*
Group B	*Bambusa balcooa, B. pallida, B. nutans, B. tulds, B auriculata, B. burmanica, Cephalostachyum pergracile, Melocanna baccifera, Thyrosostachys oliveri*
Group C	*Bambusa ventricosa, B. vulgaris, B. bambos (*syn. *B. arundinaceae), Dendrocalamus longispathus*

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STABILITY DESIGN OF HOLLOW TIMBER SECTION – BAMBOO

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ABSTRACT

In steel structures, hollow sections such as circular hollow section (CHS) and rectangular hollow sections (RHS) are commonly used because of their torsional rigidity and structural efficiency. In plant, there exists a similar type of hollow sections, bamboo, which is also widely used in scaffolding in Hong Kong and part of China. This paper describes the structural design and analysis of bamboo structures by a stability analysis computer software, NAF-Nida, developed in Hong Kong.

INTRODUCTION

Nearly all structures in building construction can be designed and analyzed for checking the safety of a structure. However, due to lack of standardization and research, bamboo structures can hardly be designed by engineers. In fact, research on the engineering properties of bamboo has been conducted quite extensively in the past few decades. As bamboo skeleton is slender, buckling is an important check for its safety. For an economical design of slender frames, buckling check is complicated, even for steel material which is relatively more homogeneous than bamboo in both material properties and geometry. Opposed to what engineers may think that second-order is too advanced for practical uses, Dobson[1] highlighted the following in the professional journal The Structural Engineer as follows.

Possibly the biggest shock to UK engineers in the Eurocodes is in realising that the use of second-order analysis is the norm for all building structures, whilst the use of first order analysis is only by exception.

This paper describes the application of the second-order analysis and design to practical design of bamboo scaffolds of 24m high and used successfully in Hong Kong.

BACKGROUND ON THE CURRENT DESIGN METHODS AGAINST BUCKLING

In a linear analysis, either by hand calculation or by most commercial software, the axial shortening of a column is proportional to the applied axial force. This assumption is only true when the axial force is small and the column is short. When the axial force is large and the column is of medium to high slenderness, the column buckles before it can be shortened to reach its yield or failure stress.

Second-order analysis is a structural analysis and design method to cater for the second-order, buckling or instability effect of a structure. The term second-order does not imply the effect is of secondary importance, it only refers to the terms as second derivative in the equilibrium equation which becomes larger than the first order term near buckling. In the BS5950[2], clause 2.4.2. and appendices E and F deal with the problem of system instability for steel structures. The buckling load factor λ_{cr}, defined as the factor multiplied to the design load to cause the eigen buckling of the frame, is calculated to determine whether or not a structure is sway or non-sway.

For example, if the factored design load on a column (F) is 100kN, and the elastic buckling load (*i.e.* $P_{cr} = \frac{\pi^2 EI}{L_e^2}$ *in which* P_{cr} *is the elastic buckling load,* π *is a constant equal to 3.142,* L_e *is the effective length of the column, E is the Young's modulus of elasticity and I is the second moment of area*) is 500 kN, the buckling load factor is then equal to 500/100 or 5. When λ_{cr} is larger than 10, the building is considered as non-sway otherwise it is classified as sway-sensitive frame.

If we know the value of λ_{cr}, a more reliable method for determination of effective length can then be applied in the above equation as,

$$L_e = \sqrt{\frac{\pi^2 EI}{P_{cr}}} == \sqrt{\frac{\pi^2 EI}{\lambda_{cr} F}} \tag{1}$$

BS5950[2] suggests simplified method for sway frames through the determination of deflections from the linear elastic analysis (see Appendix F.2.1, BS5950[2]). The method for computation of effective length in Equation 1 is considered as a much more reliable method than by "*guess*" commonly used and it should be followed whenever possible to prevent buckling collapse for slender frames.

This empirical method, however, may not be applicable to design of bamboo structures and resort is therefore made to the use of the second-order analysis for automatic consideration of effective length.

The advantage of this method is that we only need the geometry of a structure and its material properties such as Young's and shear moduli of elasticity and yield stress. The design charts and tables for buckling checks are not needed. Initially, the buckling strength curves are compared and fit for consideration of statistical member imperfection (Yu, Chung and Chan[4]), and residual stress, if applicable. Because of this, design of structures made of new materials is especially convenient by the second-order analysis.

If we limit the design load to the formation of first plastic hinge, the computed load is then a lower bound solution to the load carrying capacity. Further, the approach is found to be only slightly conservative since bamboo members fail by buckling and not by plastic collapse. Most importantly, it is the method used in practice for design of steel structures in Hong Kong and many other places. The full plastic analysis and design allowing for formation of a series of plastic hinges is only used occasionally in design of portal frames or seismic structural analysis for ductility check. Chan and Zhou[5] terms this analysis and design method as **nonlinear integrated design and analysis** and a computer software, NAF-Nida (2001) is developed along this line of thought.

Figure 1 shows graphically the relationship between the linear, eigen-value buckling analysis, plastic analysis and second-order analysis with and without first plastic hinge limitation. For a more complete description of various methods of analysis, Chan[3] should be referred.

PROPOSED DESIGN METHOD USING NIDA

NIDA (Nonlinear integrated design and analysis) is a software developed along the philosophy of simulating the response of a structure by proper modeling of buckling and material yielding effects and other characteristics of a real structure like imperfections so that design can be directly based on the computed structural response. Under the design load, every member in a structure should satisfy the section capacity check to various design codes as follows.

$$\frac{P}{Ap_y} + \frac{M_x + P(\delta_x + \Delta_x)}{Z_x p_x} + \frac{M_y + P(\delta_y + \Delta_y)}{Z_y p_y} = \chi \geq 1 \qquad (2)$$

in which P is the internal force, M_x and M_y are the moments acting on any section along a member being considered, A is the cross sectional area, Z_x and Z_y are the elastic sectional modulus about the principal axes and p_y is the design strength taken as material failure stress, δ and Δ are the small and large delta effects referring to the system and member geometrical changes. χ is a parameter for checking the consumption of strength by external loads. When it is very much below 1, a small portion of the strength of a member is utilised, implying an over-conservative or uneconomical design. On the other hand, when χ is larger than 1, the member does not satisfy the code requirement for buckling strength when the interactive formula in clause 4.8.3 in BS5950[2] is used.

It has been demonstrated by Chan and Zhou[5] that for cases where the effective length can be assumed accurately, such as a pin-fixed, pin-pin or fix-fix column, NIDA gives the same result as the design code. This indicates the compliance of NIDA with the design code and NIDA assists us to consider the effect of effective length through a second-order analysis procedure, which leads to a substantial saving in material, ensuring safety and in improving the efficiency in design. From previous test results (Chan and Xian[6], Chung and Yu[7]), the compressive strength and the Young's modulus of elasticity for quality bamboo of species Bambusa Pervaiabius (or Kao Jue) and Phyllostachys Pubescens (or Mao Jue) can be taken conservatively as 40 N/mm^2 and 12 kN/mm^2 respectively.

The argument that the method is not too conservative is due to the fact that the load capacity is usually below the elastic buckling load by a small percentage for most bamboo columns under full factored design load. The use of, say, higher yield stress does not increase significantly the load capacity which is dominated by Young's modulus affecting the P-δ and P-Δ effects. Most important of all, the procedure follows the current design practice that its output can be directly used by engineers.

ILLUSTRATIVE EXAMPLE FOR DESIGN OF A SIMPLE PORTAL FRAME

The simple portal frame is under a pair of point loads of 5,000 kN each at its columns. All members of the frames are made of 305x305x137UC (Area=174cm^2, Ix=32,770cm^4, Zx=2,048cm^3, r=13.7cm) and grade 50 or S355 steel with design strength 355 N/mm^2. The columns are pinned at base and rigidly connected to the horizontal beam at top. The problem here is to determine the effective length and the load capacity of the columns.

When using the deflection method in F.2.1. in Appendix F of BS5950[2], the buckling load factor, λ_{cr} is calculated as follows:

$$\phi = \frac{\delta}{h} = \frac{0.01495}{4} = 0.00374$$
$$\lambda = \frac{1}{200\phi} = 1.34 \tag{3}$$

The effective length can be determined as follows:

$$L_e = \sqrt{\frac{\pi^2 EI}{\lambda F}} = \sqrt{\frac{\pi^2 x2.05x10^5 x3.277x10^8}{1.34x5000x10^3}} = 9.95m \tag{4}$$

Slenderness ratio is obtained as follows:

$$\frac{L_e}{r} = \frac{9950}{137} = 72.6 \tag{5}$$

The permissible buckling stress, pc from Table 4.14 is then 261N/mm^2 and the design load capacity for the column is 4,540 kN.

When using eigen-buckling function in NIDA, λ_{cr} below is computed as 1.27.

$$| K_L + \lambda_{cr} K_G | = 0 \tag{6}$$

When using second-order analysis function in NIDA with 0.5% notional force in horizontal direction, the structure is loaded incrementally and the section capacity check is violated at a load factor of 0.86 where the column axial force or its design load capacity is 4,300 kN.

Both the design codes and the computer results gave a result with 5% discrepancy that the structure is under-designed and increase of column size is needed for taking the same loads.

It is interesting to note that when one of the columns is also pinned at top, the design strength for the structure drops to 1,883 kN, which is significantly less than the above value of 4,540 kN. This is called the leaning column effect that is detrimental to a scaffolding system and must be avoided on site. The corresponding eigen-buckling load factor is 0.452 which is less than half of the above.

When using some commercial software where the effective length is defaulted as unity or 1, the slenderness ratio is 4m/0.137m = 29.2. From Table 4.13 (BS5950[2]) and then Table 4.14, the buckling stress is 344.8 N/mm^2 and the column load capacity is calculated as 5,994 kN. This shows the incorrect calculated load capacity of the column when using a defaulted effective ratio of 1, which is a quite common practice in Hong Kong.

Even though the slenderness ratio for the frame here is not high and of 72.9, the error is already quite significant. For common cases of columns with slenderness ratio in excess of 100, the over-estimation of design load capacity can be catastrophic.

DESIGN OF A 24 M HIGH ACCESS BAMBOO SCAFFOLD

The 24 m high bamboo scaffolding system was designed for a construction project in Hong Kong. The ledgers, posts and transoms are all made bamboo of minimum size of 40 mm outer diameter and 5 mm thick. The vertical posts rest on steel bracket supports cast onto concrete wall and the two diagonal bracing members crossing the complete scaffold are of minimum 100 mm diameter and 5 mm thick. In cases where the posts of this size are not available, they can be replaced by metal hollow sections.

According to the present design rule for loading in temporary structures, the top two levels are loaded by a uniform pressure load of 0.75 kPa and half of this load is present at all other levels. A live load factor of 1.6 is used but wind load on scaffold with covering cloth is not considered because (1) the scaffold is analyzed to be unable to resist such a severe wind load and (2) the covering cloth is expected to be dismantled during typhoon. The imposed load intensity is for light duty such as workers polishing the external facades and walls. The scaffold is assumed simply supported on the steel brackets fixed to concrete walls. It is assumed that any bamboo members less than these dimensions are used as non-structural elements such as the lapping portions. The geometry of the scaffold is shown in Figure 3.

A total of 20 increments of load with each incremental load of 10% of the design load are applied to the scaffold. The load level causing the failure of section capacity check for any of the members is taken as the design failure load. For horizontal members, the plastic modulus is used for horizontal members taking mainly bending moment whereas elastic modulus is used for vertical members under predominant axial force.

It can be seen in the analysis output that the vertical posts reach their buckling strength above the factored design load. Using this method, we can check the safety of the structure under design load, as well as determining the loading capacity and then the safety margin by observing the design strength which is taken as the load factor causing the attainment of first plastic hinge under moment and axial force action. The result can be seen graphically in

Figure 4, with the member in red indicates it has violated the buckling strength check in Equation 2. This approach follows the design philosophy commonly used in structural design by an elastic analysis limiting the formation of the first plastic hinge.

When using the eigenvalue buckling analysis, the elastic eigen load factor is calculated as 7.9 with mode shape shown in Figure 5. This implies that the frame will buckle elastically when the load is increased by this eigen buckling load factor. However, this buckling load factor cannot be used directly for design since it does not consider material strength nor large deflection effects.

Provided that the design parameters used in the analysis are consistent with those on site, the design output is believed to provide us a reasonable estimation of the load capacity of the structure.

CONCLUSIONS

A computer method for design of bamboo scaffolds is presented. The buckling and material yielding effects are fully considered in the analysis which is considered as a norm for design of skeletal structures in the European, the American code and the British codes. The method computes accurately the buckling strength of a structure without manual guess of effective length and buckling load factor, which may lead to a gross error in the calculated load capacity of a structure. The defaulted use of the effective length factor of 1 has been also demonstrated to produce an unsafe design in a simple portal frame against the method in design code and by a second-order computer analysis.

ACKNOWLEDGEMENT

The authors acknowledge the financial support of INBAR in the research and development project entitled ‘Bamboo Scaffolds in Building Construction’.

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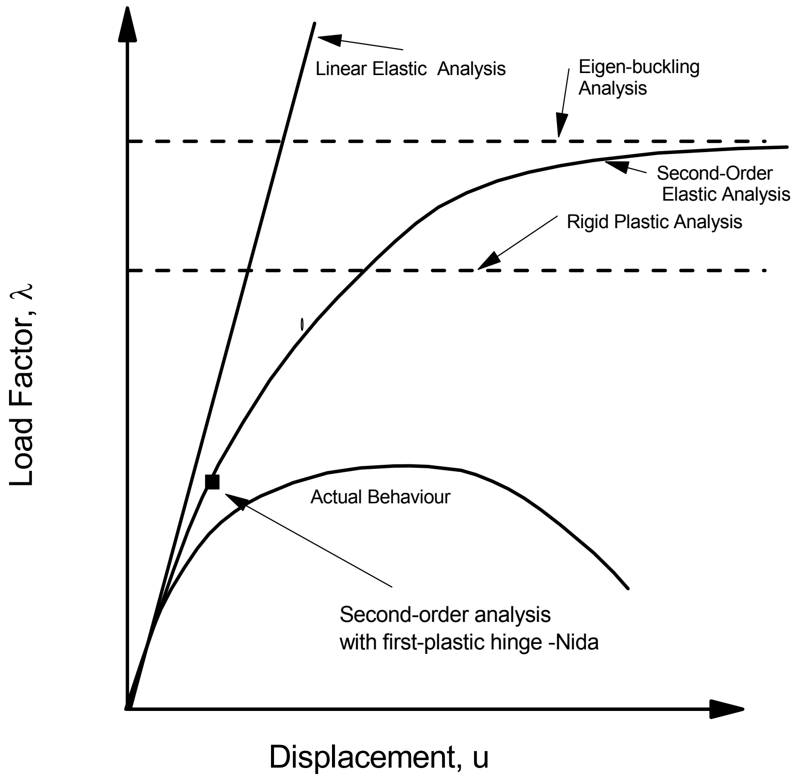

Figure 1 Relationships between several types of analyses

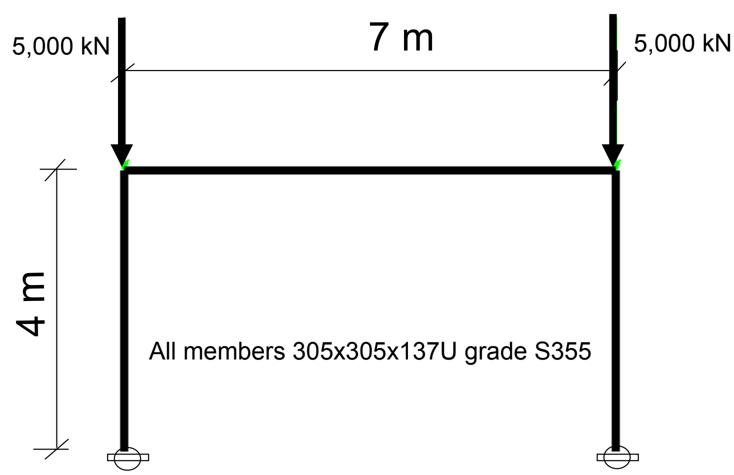

Figure 2 The 3 member simple portal frame for demonstration of the results of analysis by different methods

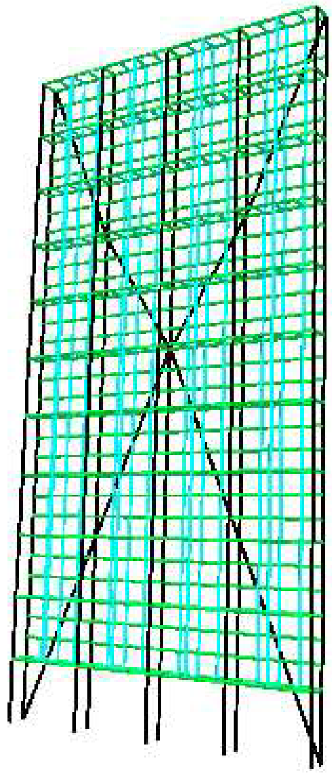

Figure 3 The perspective view of the 24 m high bamboo scaffold modeled by NIDA

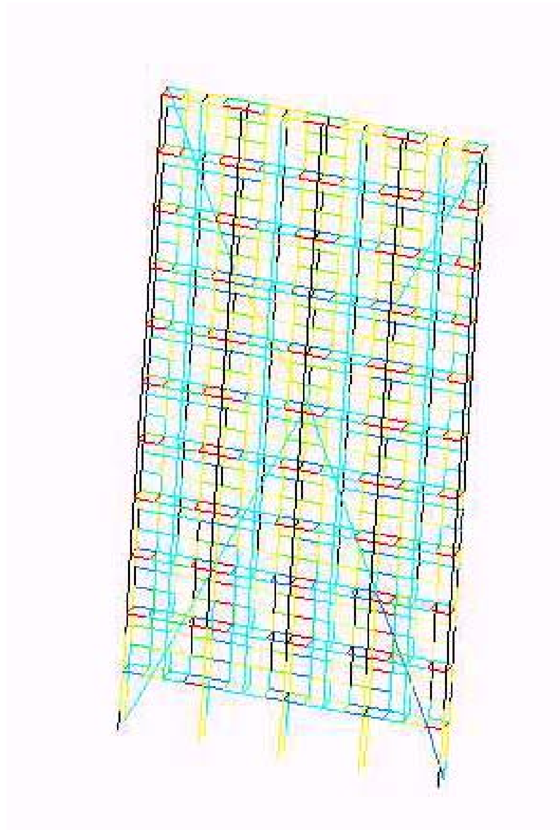

Figure 4 The second-order analysis of the scaffold with member in red violating the buckling strength check in Equation 2

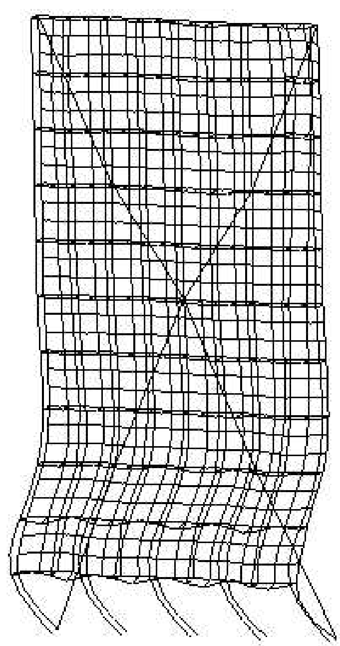

Figure 5 The eigenvalue buckled mode shape of the 24m bamboo scaffold by NIDA

PRACTICAL DESIGN OF BAMBOO SCAFFOLDS

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ABSTRACT

Bamboo scaffolds have been used in building construction in China for over a few thousand years. It is believed among Chinese that the first bamboo scaffold was built some 5000 years ago while the basic framing systems and the erection methods were established through practice about two thousand years ago. Bamboo scaffolds provide temporary access, working platforms for construction workers and supervisory staff, and also prevents construction debris from falling onto passers-by. In Hong Kong and other parts of the Southern China, bamboo scaffolds are ones of the few traditional building systems which survive by self-improvement through practical experiences of scaffolding practitioners over generations.

This paper presents the general design principles of bamboo scaffolds together with the basic design data for both Kao Jue and Mao Jue. Moreover, the basic configurations of typical bamboo scaffolds using both Kao Jue and Mao Jue are presented: Single Layered Bamboo Scaffolds (**SLBS**) and Double Layered Bamboo Scaffolds (**DLBS**). In order to provide guidance on the design of bamboo scaffolds with different practical arrangements of lateral restraints, a parametric study using advanced non-linear analysis on the structural behaviour of bamboo scaffolds were executed. Recommendations on the effective length coefficients for posts in both SLBS and DLBS with different arrangements of lateral restraints are thus provided for practical design.

It is envisaged that through rational design and erection of bamboo scaffolds, the safety of workers in construction sites will be greatly improved. Moreover, through the use of scientifically developed design rules, structural engineers are able to design not only bamboo scaffolds of new configurations but also bamboo structures for new applications.

KEYWORDS

Bamboo scaffolds, design development, effective length, column buckling, practical design.

INTRODUCTION

Bamboo scaffolds have been used in building construction in China for over a few thousand years. It is believed among Chinese that the first bamboo scaffold was built some 5000 years ago while the basic framing systems and the erection methods were established through practice about two thousand years ago (Tong 1998). Bamboo scaffolds provide temporary access, working platforms for construction workers and supervisory staff, and also prevents construction debris from falling onto passers-by. The major advantages of bamboo (Au *et. al.* 1978 and Janssen 1981) as a constructional material are high strength-to-weight ratio, simple erection, and easy adaptability to building forms and site conditions.

In Hong Kong and other parts of the Southern China, bamboo scaffolds are ones of the few traditional building systems which survive by self-improvement through practical experiences of scaffolding practitioners over generations (Fu 1993). Nowadays, in spite of open competition with many metal scaffolding systems imported all over the world, bamboo scaffolds remain to be one of the most preferred systems for access in building construction in Hong Kong and the neighbouring areas. At present, the typical height of bamboo scaffolds is 15 m and the installation of steel bracket supports at regular intervals allow full coverage of building height.

Bamboo scaffolds are traditionally erected by specialized scaffolding practitioners, and thus the safety and effectiveness of the bamboo scaffolds depend primarily on the individual skills of the practitioners. This knowledge is passed on younger workers through an apprentice system, mostly through on-the-job learning. Bamboo members used for both the standards (vertical members) and the ledgers (horizontal members) in scaffolds range from 40 to 100 mm in diameters and 6 to 8 m in length, and they are light enough for one person to easily handle a single member at a time. Due to the ease of handling, bamboo scaffolds are easily and efficiently erected and dismantled; compared to steel scaffolds, where installation and dismantling take the same amount of time, bamboo scaffolds can be dismantled in one tenth of the time it takes to install. No machinery, power-driven tools and tightening equipment are necessary as only simple hand tools and nylon or wire ties are required to erect bamboo scaffolds.

For the research work on bamboo scaffolds, a theoretical study (Chan *et. al.* 1998) using an advanced finite element analysis with one element per member was carried out in Hong Kong to assess the load carrying capacities of bamboo scaffolds. Moreover, a full-scale bamboo scaffold was built in a construction site and tested to failure in order to provide data for calibration of the finite element model. Due to the slenderness of bamboo members, it was found that non-linear analysis was often required to predict the buckling behaviour of bamboo scaffolds accurately. More recently, four full-scale tests on bamboo scaffolds were carried out with the assistance from the Construction Industry Training Authority to provide test data for design development against buckling behaviour of bamboo scaffolds (Chung *et. al.* 2002b).

TYPICAL APPLICATIONS IN CONSTRUCTION

The applications of bamboo scaffolds in building construction are numerous while typical applications are:

- Single layered scaffolds
- Double layered scaffolds
- Demolition scaffolds
- Truss-out scaffolds
- Cantilever scaffolds or signage scaffolds
- Platform scaffolds
- Foot-bridge scaffolds
- Civil engineering scaffolds

Typical applications of bamboo scaffolds are fully presented in a practical document entitled '*Bamboo Scaffolds in Building Construction. Erection of Bamboo Scaffolds*' compiled by Chung and Siu (2002). As most of the scaffolds are generated from the basic scaffolding systems, namely, the Single Layered Bamboo Scaffolds (**SLBS**) as shown in Figure 1, and the Double Layered Bamboo Scaffolds (**DLBS**) as shown in Figure 2, only those two systems are discussed in details. The load requirements for bamboo scaffolds are summarized in Table 1.

GENERAL DESIGN PRINCIPLES

Bamboo scaffolds are tubular frameworks with high degree of structural redundancy. In typical bamboo scaffolds, most of the members such as the posts are under compression while some of them such as the base or the main ledgers are under bending. Overall stability of bamboo scaffolds are achieved through rational provision of vertical supports and lateral restraints.

In additional to primary structural members for direct load bearing, many secondary members such as standards, ledgers, and diagonals are also installed to share loads and to provide restraints to the primary members. The presence of all these secondary or bracing members ensures effective load distribution within the scaffolds, thus improving their structural performance significantly. Furthermore, in the event of local failure, effective load-redistribution within the scaffolds may readily be achieved without major adverse effects on the scaffolds.

As most of the ledgers are connected onto the posts with bamboo or plastic strips, all the connections may be considered to be pinned, i.e. the ledgers are allowed to rotate freely from the posts. However, due to the continuity of the ledgers over the post-ledger connections, the ledgers should be designed as continuous beams with simple supports, i.e. no moment is transferred to the posts. This situation is different from conventional structural design of both reinforced concrete and steel building structures.

In order to present simple design methods of bamboo scaffolds, it is recommended to firstly establish the minimum configuration of the scaffolds for overall stability and structural adequacy. This allows simple and clear identification of primary load paths within the scaffolds, and thus, the design of both compression and bending members may be readily achieved. Secondly, bracing members may then be introduced to provide secondary load paths within the scaffolds in order to enhance the structural behaviour of the scaffolds.

STANDARD DIMENSIONS OF KAO JUE AND MAO JUE

In structural design, the following dimensions of Kao Jue and Mao Jue may be adopted for general application:

- For Kao Jue, the external and the internal diameters are 40 and 30 mm respectively and they are considered to be constant along the length of the bamboo; the wall thickness is 5 mm.

- For Mao Jue, the external and the internal diameters at the top cross-section are 60 and 48 mm respectively and they are considered to increase linearly down to the bottom cross-section to 90 and 72 mm respectively over a length of 6 m. The wall thickness increases linearly from 6 mm at the top cross-section to 9 mm at the bottom cross-section.

The dimensions of Kao Jue and Mao Jue are illustrated in Figure 3. These design data are considered to be conservative and should be adopted in the absence of measured and statistically corrected data.

PRACTICAL CONSIDERATIONS

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

- Mechanical properties

  The proposed mechanical properties of both Kao Jue and Mao Jue are presented in Table 2 with appropriate characteristic values for design over practical ranges of moisture contents. Typical mechanical properties of various bamboo species may be found in the literature (Janssen 1991).

  It should be noted that for structural bamboo in bamboo scaffolds, shear force is comparatively less critical when compared with bending and column buckling. Nevertheless, design guidance on the shear strength of both Kao Jue and Mao Jue is provided in a simple and conservative manner. The shear strengths of various bamboo species are found to range typically from 6 to 15 N/mm^2, and they are broadly proportional to the compressive strengths of the bamboo species (Janssen 1991).

  Consequently, it is recommended that the shear strength may be conservatively estimated as 25 % of the compressive strength for all bamboo species for practical design.

- Moisture content

  In general, the moisture contents at normal supply condition, i.e. air-dried for three months after harvest, or *G3*, may be used to determine the design strengths of exposed bamboo scaffolds in dry seasons. Typical moisture contents for both Kao Jue and Mao Jue at *G3* are found to be 12.5 % and 20 % respectively. For exposed bamboo scaffolds with an intended life of usage over wet seasons, a conservative approach should be taken and all the mechanical properties should be evaluated at high moisture contents.

- 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 members supplied under proper quality control. Moreover, it is recommended that the partial safety factor for construction load should be 2.0 in general. However, for construction sites with proper management and supervision on bamboo scaffolds, 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 scaffolds at a known level of confidence against failure.

- Connections

  In general, all connections in bamboo scaffolds are 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 scaffolds are strong and reliable in both dry and wet conditions over prolonged periods.

  The basic characteristic resistance for each fastening (or knot) in both ledger-to-post connections and post-to-post connections may be taken at 1.10 kN, and this may be conservatively applied to all connections between members of Kao Jue and Mao Jue (Chung *et. al.* 2002a, Chung and Chan 2002). A partial safety factor of 1.1 to 1.25 may be used, depending on the quality of workmenship.

BASIC CONFIGURATION OF SLBS

The usage of SLBS is to provide access for workers on site, and thus workers should not carry out any construction activity from the SLBS. The design is usually controlled by the own weight of the workers, i.e. 80 kg (unfactored) x 1.6 per person or 1.25 kN (factored) per person. Typical height of the SLBS is about 6 to 9 m. Figure 4 presents the configuration of the proposed SLBS systems; the member sizes are summarized in Table 3.

SLBS with Kao Jue

Figure 4 presents the configuration of the proposed SLBS systems using mainly Kao Jue as follows:

Primary members

Both the main posts and the main ledgers are considered as primary structural members and carry construction loads; their structural performance should be checked in structural design. Typical configurations are as follows:

- Main posts at a spacing of 1.2 to 1.8 m in the horizontal direction.

- Main ledgers at a spacing of 1.8 to 2.25 m in the vertical direction.

All main posts are properly supported against gravity loads.

Bracing members

In order to enhance the structural behaviour of SLBS, additional members are also provided as bracing members as follows:

- Standards at a horizontal spacing of 0.60 m, i.e. one or two standards in between every two posts.

- Ledgers at a vertical spacing of 0.6 to 0.75 m, i.e. two ledgers in between every two main ledgers.

In general, no supports may be provided to the standards due to site constraints, and the standards are attached to the base ledger. Additional Kao Jue is also installed as cross diagonals to increase the lateral stability of the structure. Furthermore, additional ledgers may also be provided to improve load distributions throughout the SLBS together with the standards and the diagonals. Some of the ledgers may be required to be load-bearing.

Supports

Lateral restraints are provided to the scaffolds at the post - main ledger connections, i.e. at the post spacing of 1.2 to 1.8 m in the horizontal direction and 1.8 to 2.25 m in the vertical direction. Due to site constraints, some lateral restraints may not be provided. In such cases, the load capacities of the scaffolds will be reduced significantly, and caution should be exercised in their usage.

Steel brackets are provided at the bottom of the posts as supports against gravity loading whenever necessary.

SLBS with Mao Jue

Figure 4 also presents the configuration of the proposed SLBS systems using mainly Mao Jue as follows:

Primary members

Both the main posts and the main ledgers are considered as primary structural members and carry construction loads; their structural performance should be checked in structural design. Typical configurations are as follows:

- Main posts at a spacing of 1.5 to 2.4 m in the horizontal direction.
- Main ledgers at a spacing of 1.8 to 2.25 m in the vertical direction.

All main posts are properly supported against gravity loads.

Bracing members

In order to enhance the structural behaviour of SLBS, additional members are also provided as bracing members as follows:

- Standards at a horizontal spacing of 0.5 to 0.6 m, i.e. two to three standards in between every two posts.
- Ledgers at a vertical spacing of 0.6 to 0.75 m, i.e. two ledgers in between every two main ledgers.

In general, no supports may be provided to the standards due to site constraints, and the standards are attached to the base ledger. Additional Mao Jue is also installed as cross diagonals to increase the lateral stability of the structure. Furthermore, additional ledgers are also provided to improve load distributions throughout the SLBS together with the standards and the diagonals. Some of the ledgers may be required to be load-bearing.

Supports

Lateral restraints are provided to the scaffolds at the post – main ledger connections, i.e. at the post spacing of 1.5 to 2.4 m in the horizontal direction and 1.8 to 2.25 m in the vertical direction. Due to site constraints, some lateral restraints may not be provided. In such cases, the load capacities of the scaffolds will be reduced significantly, and caution should be exercised in their usage.

Steel brackets are provided at the bottom of the posts as supports against gravity loading when necessary.

BASIC CONFIGURATION OF DLBS

The usage of DLBS is to provide access and safe working platform to workers on site, and thus, the workers are allowed to carry out 'light-duty' construction activity from the DLBS. The design is usually controlled by the construction loads at a typical value of 1.5 kPa. Typical height of the DLBS is about 10 to 15 m. Figure 4 presents the configuration of the proposed DLBS Systems while the member sizes are summarized in Table 3.

Primary Members

Outer layer

Mao Jue is used for both the posts and the base ledger together with Kao Jue as main ledgers as follows:

- Main posts at a spacing of 1.5 to 2.4 m in the horizontal direction.
- Main ledgers at a spacing of 1.8 to 2.25 m in the vertical direction.

All main posts are properly supported against gravity loads.

Inner layer

Kao Jue is used for both the posts and the main ledgers as follows:

- Main posts at a spacing of 0.75 to 1.2 m in the horizontal direction, i.e. half of those in the outer layer.
- Main ledgers at a spacing of 1.8 to 2.25 m in the vertical direction, i.e. same as those in the outer layer.

All main posts are properly supported against gravity loads.

Bracing Members

Outer layer

Additional Kao Jue is also installed as follows:

- Three standards in between every two posts, i.e. at a horizontal spacing of 0.375 to 0.6 m.
- Ledgers at a vertical spacing of 0.6 to 0.75 m, i.e. two ledgers in between every two main ledgers.

In general, no supports may be provided to the standards due to site constraints, and the standards are attached to the base ledger instead. Additional Mao Jue is also installed as cross diagonals to increase the lateral stability of the structure. Furthermore, additional ledgers are also provided to improve load distributions throughout the DLBS together with the standards and the diagonals. Some of the ledgers may be required to be load-bearing.

Inner layer

No bracing members are provided in the inner layer.

Linking outer and inner layers

In order to support construction loads from working platforms, short poles of Kao Jue are installed as transoms at the post - main ledger connections, i.e. at a spacing of 1.5 to 2.4 m in the horizontal direction and 1.8 to 2.25 m in the vertical direction. Additional transoms may also be provided along the main ledgers of both the outer and the inner layers. All construction loads acting onto the working platforms are applied through the transoms, the ledgers and then to the posts. Typical distance between the outer and the inner layers ranges from 600 to 750 mm.

Supports

Lateral restraints are provided to the outer layer at a spacing of 1.5 to 2.4 m in the horizontal direction and 1.8 to 2.25 m in the vertical direction. Due to site constraints, some lateral restraints may not be provided. In such cases, the load capacities of the scaffolds will be reduced significantly, and caution should be exercised in their usage.

Steel brackets are provided as supports at the bottom of the main posts in both the outer and the inner layers against gravity loading when necessary.

ARRANGEMENT OF LATERAL RESTRAINTS

In order to achieve overall structural stability of the bamboo scaffolds with high structural efficiency, lateral restraints should be provided at close intervals whenever feasible. However, due to site restrictions such as availability of strong supports in proximity, it may not be practical or even impossible to provide lateral restraints in every main post – main ledger connection of the bamboo scaffolds. In the absence of sufficient lateral restraints, the effective length of bamboo columns will be larger than their member lengths between ledgers, and the axial buckling resistance of the bamboo columns may be reduced significantly. Thus, it is necessary to provide design guidance on practical arrangements of lateral restraints.

An advanced non-linear finite element analysis using NIDA was carried out to investigate the column buckling behaviour of bamboo scaffolds (Chung and Chan 2002) based on high performance beam-column elements using the one-element-per-member formulation (Chan and Zhou 1994). Both SLBS and DLBS with various practical arrangements of lateral restraints are examined as follows:

- Typical distance between lateral restraints, H , is assigned to be 2.0 h, 2.667 h and 3.0 h in various arrangements where h is the height of a platform, or the vertical distance between two platforms.

- For each value of H, the lateral restraints are provided either at regular intervals or in a staggered manner.

The configurations of the systems are presented in Figures 5 to 7 while the details of the member sizes are summarized in Table 3.

Through advanced non-linear analyses, both the local buckling of bamboo posts between ledgers and the global instability of the entire scaffolds with regular and staggered lateral restraints are accurately incorporated. In all cases, out-of-plane buckling of the posts is critical, and the deformed shapes of SLBS and DLBS are also presented in Figures 5 to 7. The predicted failure loads are the applied loads at first yield of the posts in the presence of initial geometrical imperfections under combined compression and bending.

It should be noted that for simplicity, diagonal members and secondary members such as standards and ledgers have not been included in the model. The lateral restraints provided in the model are sufficiently less than those in typical SLBS and DLBS in practice, and consequently, the predicted load resistances of the posts are conservative. Table 4 summarizes the load resistances of the posts in SLBS and DLBS under various practical arrangements of lateral restraints. It should be noted that for simplicity, Mao Jue is modelled conservatively as a prismatic member with the external and the internal diameters at 60 and 48 mm respectively.

Design Rules for SLBS

As shown in Table 4, the basic effective length of the posts, h_e , for SLBS with **regular lateral restraints** is found to range from 0.885 H to 0.956 H where H is the system length between lateral restraints. The reduction in the effective length depends on the member configurations of SLBS, and also the relative slenderness of the posts and the ledgers. Furthermore, for SLBS with **staggered lateral restraints**, the effective length, h_e , of the posts is found to range from 0.434 H to 0.561 H due to the restraining effects provided by the ledgers attached. Consequently, it is recommended that the effective length of a post, h_e , may conservatively be taken as as follows:

$$h_e = k_e \times H$$

where

k_e is the effective length coefficient

= 1.0 for SLBS with **regular lateral restraints** with H = 1.0 h to 3.0 h

= 0.7 for SLBS with **staggered lateral restraints** with H = 2.0 h to 3.0 h

H is the system length between lateral restraints

h is the height of a platform, or the vertical distance between two platforms.

Based on the predicted structural performance of SLBS from the non-linear analysis, the maximum value of H should not exceed 3.0 h in practice.

Design Rules for DLBS

As shown in Table 4, it is found that due to the presence of bracing members in the posts of the outer layer, i.e. Mao Jue, it is always the posts of the inner layer, i.e. Kao Jue, that fails first. However, it should be noted that the effective length of Kao Jue actually depends on the lateral restraints provided to Mao Jue as follows:

- The basic effective length of Kao Jue, h_e , for DLBS with regular lateral restraints to the outer layer at H = h is considered to be 1.0.

- For DLBS with **regular lateral restraints** to the outer layer at H = 2.667 h, the effective length of Kao Jue is found to be 1.460, i.e. an increase less than 50%.

- For DLBS with **staggered lateral restraints** to the outer layer at H = 2.667 h, the effective length of Kao Jue is found to be 1.077, i.e. an increase less than 10%.

Consequently, it is recommended that the effective length of the post in DLBS, h_e, may conservatively be taken as as follows:

<u>Inner layer</u>

$h_e \quad = \quad k_e \times h$

where

k_e is the effective length coefficient

$= \quad k_i \times k_b$

$k_i \quad =$ secondary effective length coefficient which depends on the restraint arrangement provided at the posts of the outer layer as follows:

H / h	1.0	1.5	2.0	2.667	3.0
k_i	1.0	1.10	1.25	1.50	1.75

$k_b \quad =$ 1.0 for DLBS with regular lateral restraints, or

$=$ 0.7 for DLBS with staggered lateral restraints

H is the system length between lateral restraints

h is the height of a platform, or the vertical distance between two platforms.

<u>Outer layer</u>

$h_e \quad = \quad k_e \times H$

where

k_e is the effective length coefficient

$= \quad k_o \times k_b$

$k_o \quad =$ 0.7 for DLBS with H = 1.0 h to 2.667 h

$k_b \quad =$ 1.0 for DLBS with **regular lateral restraints**

$=$ 0.7 for DLBS with **staggered lateral restraints**

H is the system length between lateral restraints

h is the height of a platform, or the vertical distance between two platforms.

Based on the predicted structural performance of DLBS from the non-linear analysis, the maximum value of H should not exceed 2.667 h in practice. For further details of the parametric studies, refer to the design document entitled '*Bamboo Scaffolds in Building Construction. Design of Bamboo Scaffolds*' compiled by Chung and Chan (2002).

WORKED EXAMPLES

The design procedures of a number of typical structural bamboo members and scaffolding systems are fully presented through worked examples in the design document (Chung and Chan 2002) as follows:

Worked Examples 1 and 2

The design of a bamboo post using a standard Kao Jue and a bamboo post using a standard Mao Jue are presented.

Worked Example 3

The design of a simply supported bamboo transom using a standard Kao Jue under uniformly distributed load is presented. Moreover, the design of a continuous bamboo ledger using a standard Kao Jue under single point load is also presented.

Worked Examples 4 and 5

The design of a short span SLBS is presented where a standard Kao Jue is used as bamboo posts and ledgers. Moreover, the design of a long span SLBS is also presented where a standard Mao Jue is used as bamboo posts and the base ledger. Kao Jue is also provided as additional secondary ledgers. Through the use of effective length coefficients on bamboo posts, the effects of various lateral restraint arrangements are incorporated in the design of SLBS.

Worked Example 6

As shown in Figure 8, the design of a DLBS is presented with the following configuration:

Outer layer

- Mao Jue is used as the main posts and the base of the outer layer.
- Kao Jue is used as the main ledgers of the outer layers.
- Mao Jue is also as the diagonals of the outer layer.
- Additional secondary ledgers of Kao Jue are also provided.

Inner layer

- Kao Jue is used as the main posts of the inner layer.
- Kao Jue is used as the main ledgers of the inner layers.

Through the use of effective length coefficients on bamboo posts, the effects of staggered lateral restraints on the axial buckling resistances of the posts in both the inner and the outer layers are incorporated. This Worked Example presents the typical configuration of a DLBS commonly used in Hong Kong.

CONCLUSIONS

This paper presents the general design principles of typical bamboo scaffolds commonly used in Hong Kong. Detailed configurations of both Single Layered Bamboo Scaffolds (**SLBS**) and Double Layered Bamboo Scaffolds (**DLBS**) are also presented. Furthermore, recommendations on the effective length coefficients for posts in both SLBS and DLBS with different arrangements of lateral restraints are also provided for practical design.

It is envisaged that through rational design and erection of bamboo scaffolds, the safety of workers in construction sites will be improved significantly. Moreover, through the use of scientifically developed design rules, structural engineers are able to design not only bamboo scaffolds of new configurations but also bamboo structures for new applications.

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.

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Table 1 General load requirements for bamboo scaffolds

BS 5973: 1993: Table 1 Access and working scaffolds					
Duty	Use of platform	Distributed load on platforms (kN/m^2)	Maximum number of platforms	Commonly used widths using 225 mm boards	Maximum bay length (m)
Inspection and very light duty	Inspection, painting, stone cleaning, light cleaning and access	0.75	1 working platform	3 boards	2.7
Light duty	Plastering, painting, stone cleaning, glazing and pointing	1.50	2 working platforms	4 boards	2.4
General purpose	General building work including brickwork, window and mullion fixing, rendering, plastering	2.00	2 working platforms + 1 at very light duty	5 boards or 4 boards + 1 inside	2.1
Heavy duty	Blockwork, brickwork, heavy cladding	2.50	2 working platforms + 1 at very light duty	5 boards or 5 boards + 1 inside or 4 boards + 1 inside	2.0
Masonry or special duty	Masonry work, concrete blockwork, and very heavy cladding	3.00	1 working platform + 1 at very light duty	6 to 8 boards	1.8

Table 2 Proposed mechanical properties for structural bamboo

***Bambusa Pervariabilis* (Kao Jue)**	Compression			Bending		
		Dry	Wet		Dry	Wet
Characteristic strength (N/mm^2) (at fifth percentile)	$f_{c,k}$	79	35	$f_{b,k}$	80	37
Design strength (N/mm^2) ($\gamma_m = 1.5$)	$f_{c,d}$	53	23	$f_{b,d}$	53	25
Design Young's modulus (kN/mm^2) (Average value)	$E_{c,d}$	10.3	6.8	$E_{b,d}$	22.0	16.4

***Phyllostachys Pubescens* (Mao Jue)**	Compression			Bending		
		Dry	Wet		Dry	Wet
Characteristic strength (N/mm^2) (at fifth percentile)	$f_{c,k}$	117	44	$f_{b,k}$	51	55
Design strength (N/mm^2) ($\gamma_m = 1.5$)	$f_{c,d}$	78	29	$f_{b,d}$	34	37
Design Young's modulus (kN/mm^2) (Average value)	$E_{c,d}$	9.4	6.4	$E_{b,d}$	13.2	9.6

Notes: 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.

The shear strengths of both Kao Jue and Mao Jue are conservatively estimated as $0.25 f_{c,d}$ but not less than $6N/mm^2$ and greater than $15N/mm^2$.

Table 3 Material specifications for SLBS and DLBS

SLBS	SLBS with Kao Jue		SLBS with Mao Jue	
	Member type	Member diameter (mm)	Member type	Member diameter (mm)
Main post	Kao Jue	40/30	Mao Jue	60~90/48~72
Base ledger	Kao Jue	40/30	Mao Jue	60~90/48~72
Standard	Kao Jue	40/30	Kao Jue	40/30
Ledger	Kao Jue	40/30	Kao Jue	40/30
Diagonal	Kao Jue	40/30	Mao Jue	60~90/48~72

DLBS	**Outer layer**		**Inner layer**	
	Member type	Member diameter (mm)	Member type	Member diameter (mm)
Main post	Mao Jue	60~90/48~72	Kao Jue	40/30
Base ledger	Mao Jue	60~90/48~72	Kao Jue	40/30
Standard	Kao Jue	40/30	Kao Jue	40/30
Ledger	Kao Jue	40/30	Kao Jue	40/30
Diagonal	Mao Jue	60~90/48~72	-	-
Transom	Kao Jue	40/30	Kao Jue	40/30

Table 4 Load resistances and effective length coefficients of SLBS and DLBS derived from NIDA

SLBS with Kao Jue							
Distance between Lateral restraints H (mm)		Regular restraints			Staggered restraints		
		P_c (kN)	h_e (mm)	k_e	P_c (kN)	h_e (mm)	k_e
h	2000	2.156	2000	1.000	-	-	-
2 h	4000	0.776	3796	0.949	2.655	1736	0.434
2.667 h	5333	0.535	4720	0.885	1.521	2512	0.471
3 h	6000	0.380	5736	0.956	1.068	3132	0.522

SLBS with Mao Jue							
Distance between lateral restraints H (mm)		Regular restraints			Staggered restraints		
		P_c (kN)	h_e (mm)	k_e	P_c (kN)	h_e (mm)	k_e
h	2000	7.605	2000	1.000	-	-	-
2 h	4000	2.405	3816	0.954	8.348	1892	0.473
2.667 h	5333	1.545	4837	0.907	3.876	2938	0.551
3 h	6000	1.135	5694	0.949	3.029	3366	0.561

DLBS with Mao Jue							
Distance between lateral restraints H (mm)		Regular restraints			Staggered restraints		
		P_c (kN)	h_e (mm)	k_e	P_c (kN)	h_e (mm)	k_e
h	2000	2.156	2000	1.000	-	-	-
1.5 h	3000	1.970	2124	1.062	2.313	1908	0.954
2 h	4000	1.581	2451	1.226	2.285	1924	0.962
2.667 h	5333	1.196	2921	1.460	1.929	2154	1.077
3 h	6000	0.923	3424	1.712	1.766	2283	1.141

Figure 1 Single Layered Bamboo Scaffolds (SLBS)

Figure 2 Double Layered Bamboo Scaffolds (DLBS)

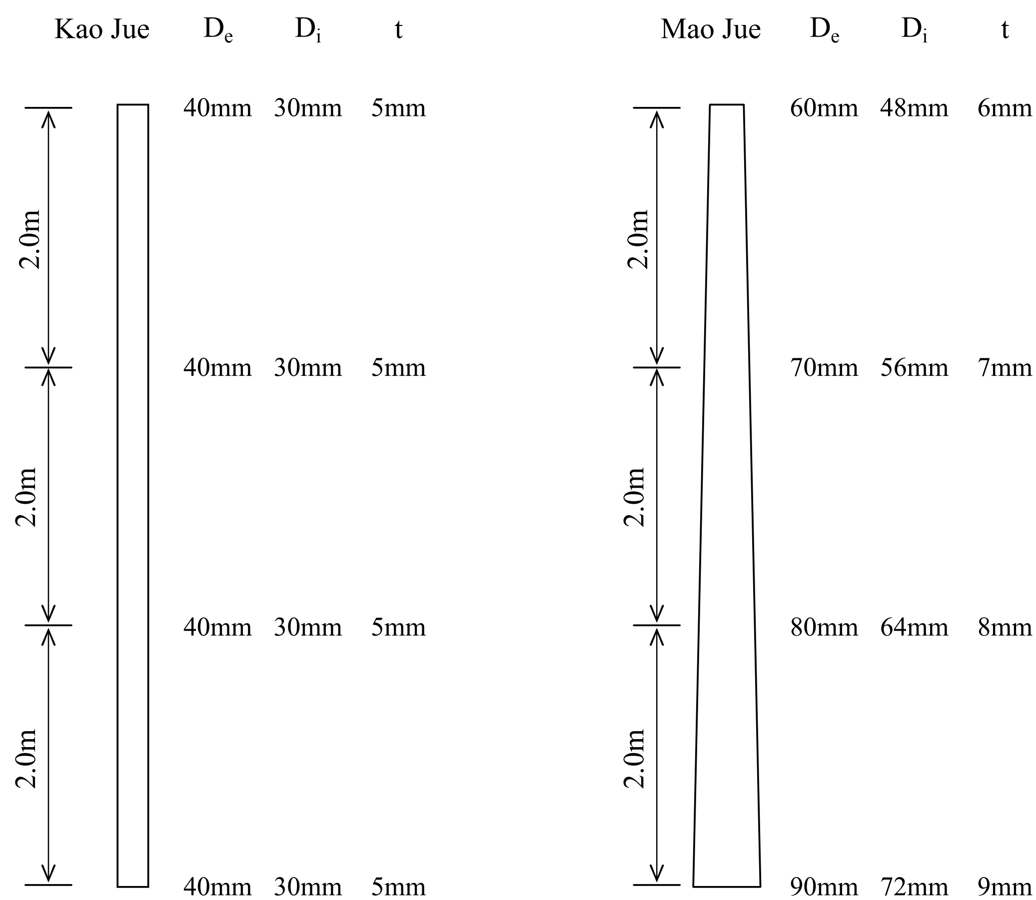
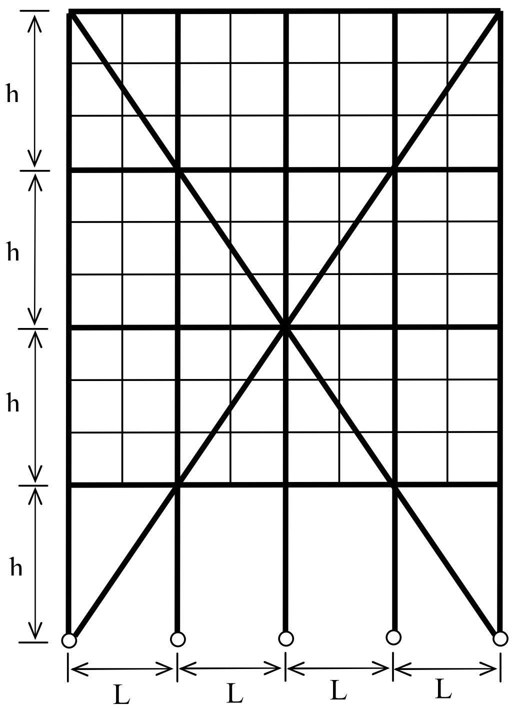


Figure 3 Design data of the dimensions of Kao Jue and Mao Jue

a) SLBS using Kao Jue

L = 1.2m ~ 1.8m
h = 1.8m ~ 2.25m



b) SLBS using Mao Jue

L = 1.5m ~ 2.4m
h = 1.8m ~ 2.25m

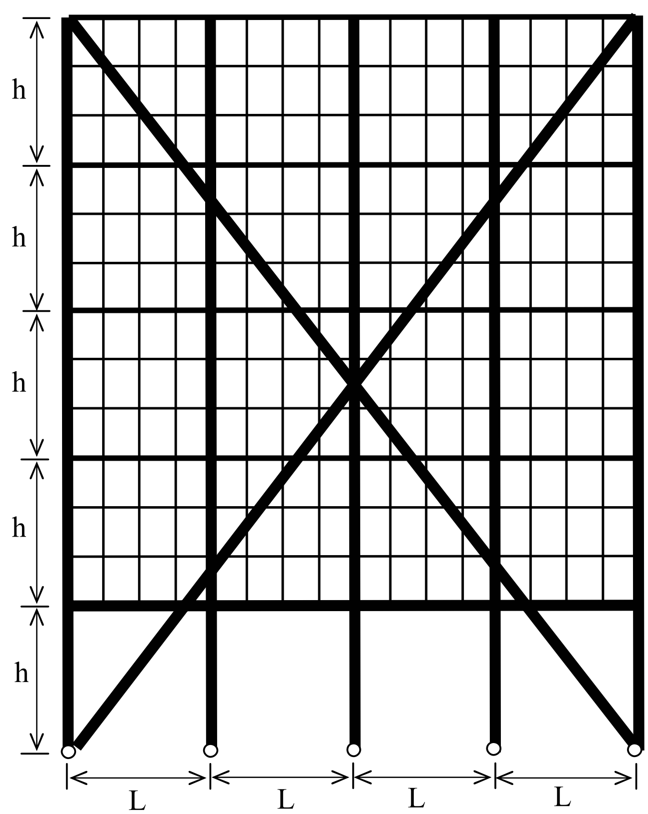
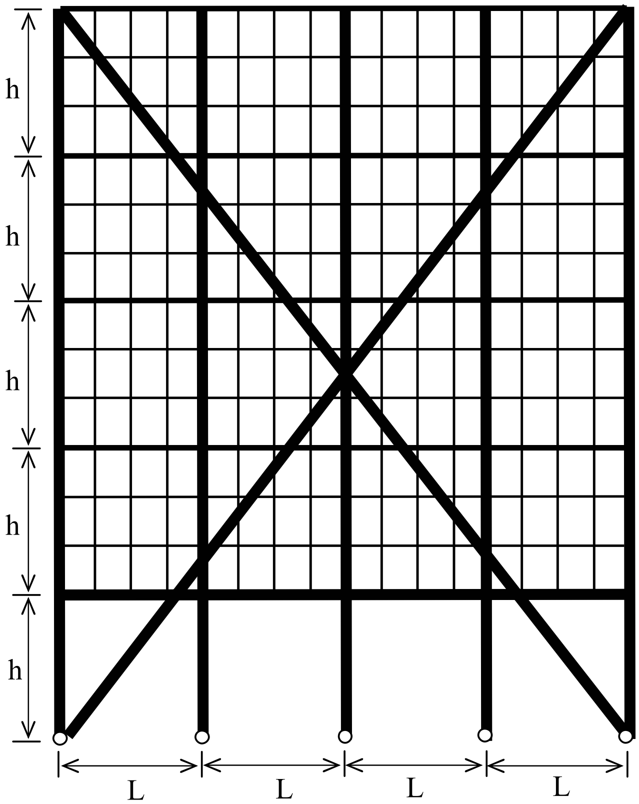


Figure 4   Typical configuration of SLBS and DLBS

c) DLBS with Mao Jue and Kao Jue

Outer layer

L = 1.5m ~ 2.4m
h = 1.8m ~ 2.25m



Inner layer

L = 1.5m ~ 2.4m
h = 1.8m ~ 2.25m

lateral restraints connected to main posts of outer layer.

lateral restraints connected to ledgers.

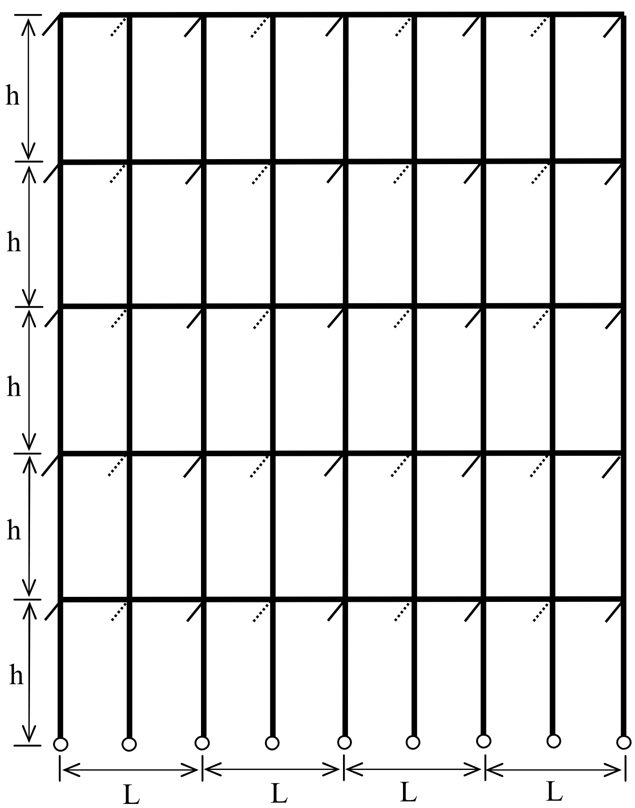


Figure 4 Typical configuration of SLBS and DLBS

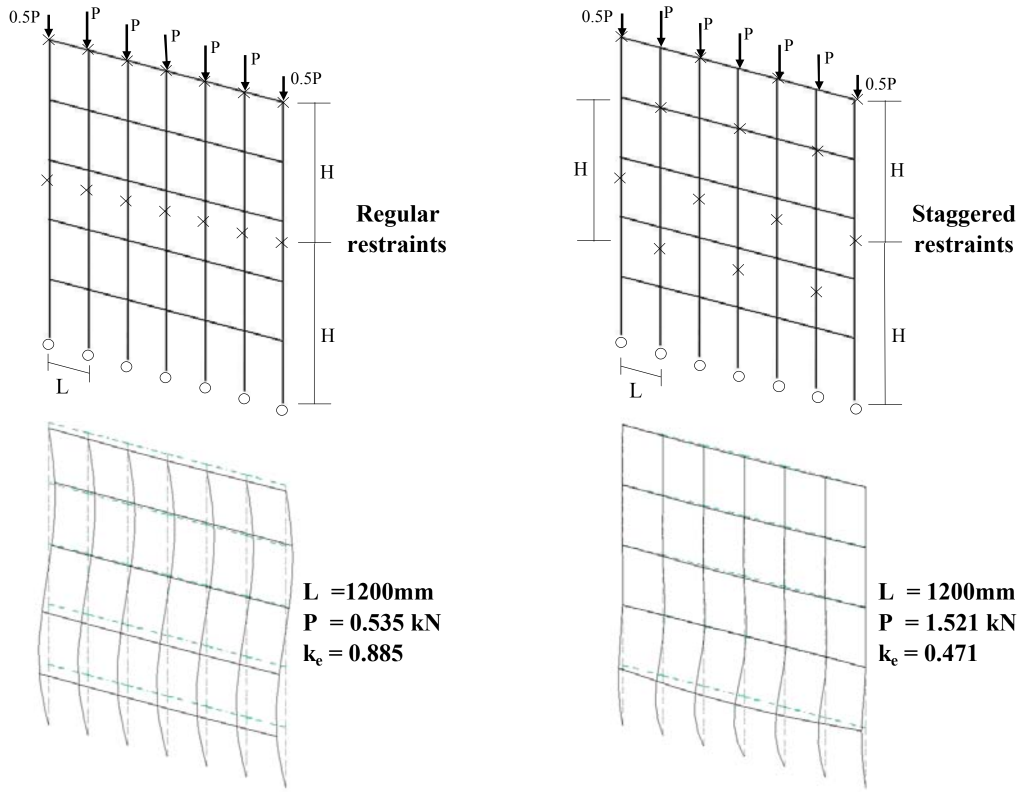
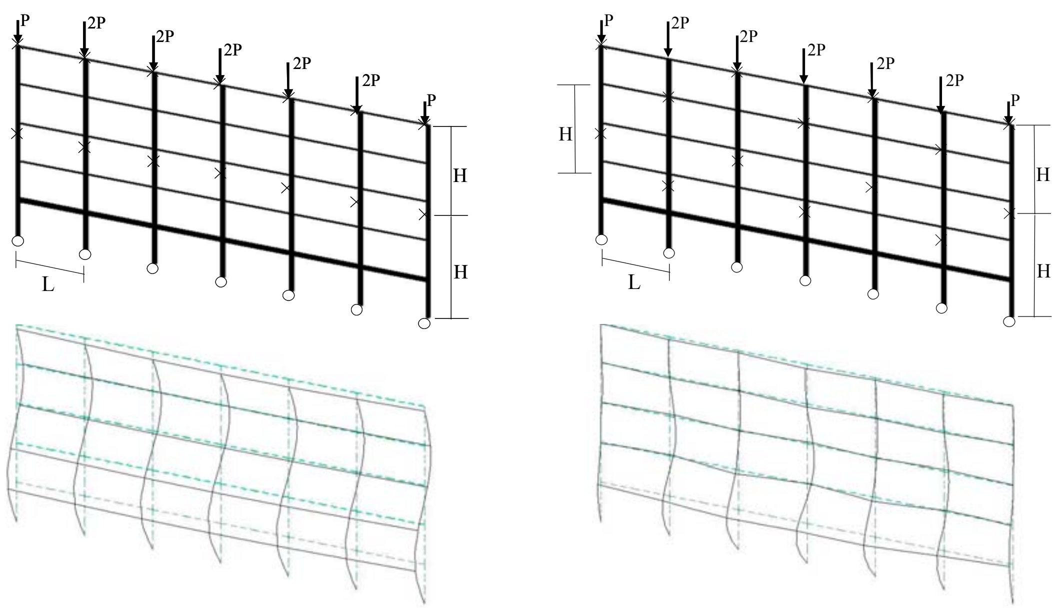


Figure 5 Results of SLBS with Kao Jue at H equal to 2.667 h



Regular restraints
L = 1800mm
P = 1.545 kN
k_e = 0.907

Staggered restraints
L = 1800mm
P = 3.876 kN
k_e = 0.551

Figure 6 Results of SLBS with Mao Jue at H equal to 2.667 h

Notes: Diagonals and bracing members and also the inner layer are not included in analysis.
×– Lateral restraints $h_e = k_e H$
H = 2.667 h or 5333 mm

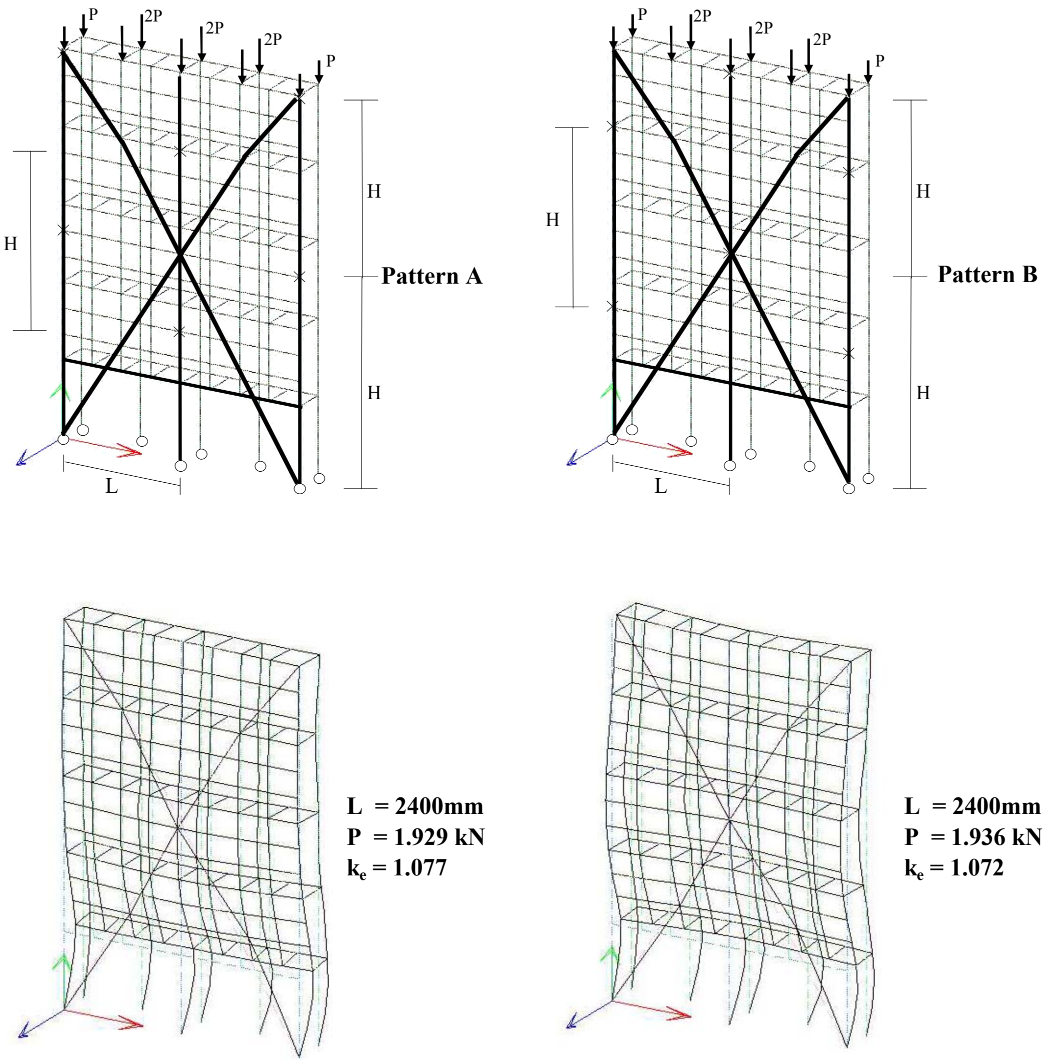


Figure 7 Results of DLBS at H equal to 2.667 h with staggered restraints

Notes: Diagonals and bracing members and also the inner layer are not included in analysis.

× – Lateral restraints

H = 2.667 h or 5333 mm

$h_e = k_e H$

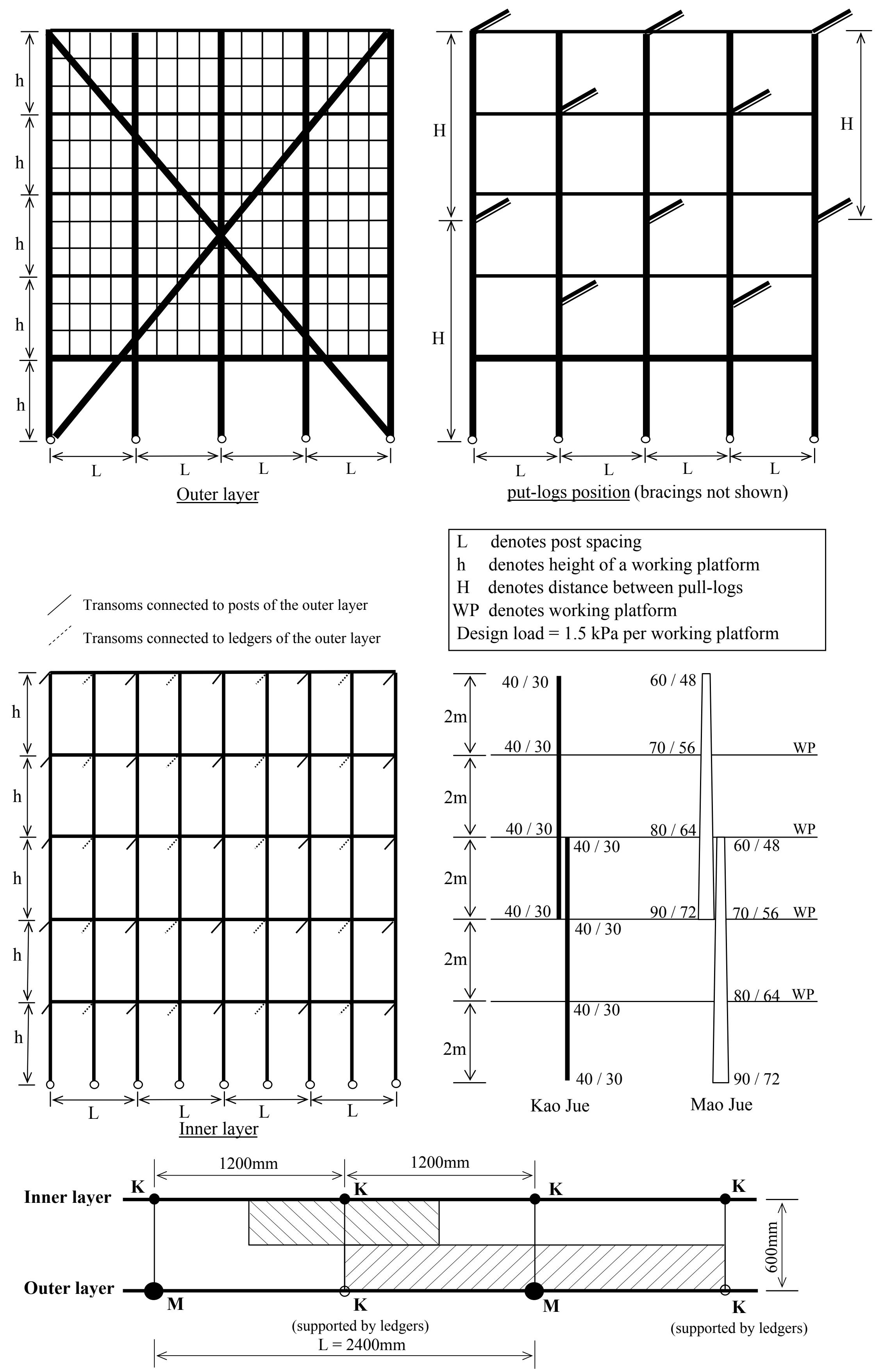


Figure 8 Worked Example 6: Design of a Double Layered Bamboo Scaffold (DLBS)

TRADE PRACTICE OF BAMBOO SCAFFOLDS AND MIXED METAL-BAMBOO SCAFFOLDS

Francis Y. S. So

Wui Loong Scaffolding Works Co., Ltd.

ABSRACT

To gain safety access to height above 2 meters depends on the reliability of provisional working platform. Scaffolding has been used extensively for this purpose in the construction industry in Hong Kong. The type of scaffolding evolved from bamboo scaffolds which was almost the only type of working platform being used from thousands of years ago in South-east Asia countries (including Hong Kong and China), until mixed metal-bamboo scaffold are commonly recognized as an alternative option in the market due to its high durability and overwhelming success over its safety and cost –saving concerns as compared to traditional bamboo scaffolds and heavy duty metal scaffolds.

TRADITIONAL BAMBOO SCAFFOLD

Bamboo scaffold has been chosen as temporary working platform by the majority of building contractors in Hong Kong because it is easier to fabricate, light so that load on supports like steel brackets can be smaller and more economical. Two common types of bamboo used for scaffold are Mao Jue (academic term phyllostachys edulis) and Gao Jue (academic term bambusa pervaribilis). The structure of bamboo scaffold relies on the strength and quality of each piece, due to the variation in size and its mature lifetime, or even the checking of stability can be carried out from time to time, the maximum buckling strength may not be assured. In addition, the following factors are also critical in regard to the potential problems of bamboo scaffold.

Failures of Bamboo Scaffold

Collapse of bamboo scaffold due to bamboo failure is mostly caused by the degradation of bamboo itself and by strong wind such as strong monsoon or typhoon signal.

Moreover, sustained high moisture level in Hong Kong is the key factor that affects the quality of bamboo significantly, hence shortening the useful life of bamboo pieces.

External destruction of Bamboo Scaffold

Owing to its advantages of flexibility and method of securing the complete set of bamboo scaffold, intentional destruction by other trades' workers are very common, in particular the plasters and workers from water pipe installation. They usually damage the connection of R6 wires between external wall of building and the double layer bamboo scaffold to facilitate their completion of works.

In addition, un-necessary and non-professional modifications of bamboo scaffold by cutting individual bamboo into pieces such as to create openings for transferring construction materials by those workers always underestimate both the short-term and long-term effects leading to various extent of structural deformation.

Most of the collapse cases of bamboo scaffold involve either part of the above scenario or the combination of all situations due to the above-mentioned irresponsible behaviour done by other workers during the construction period.

Apart from both self-failure and external destruction of bamboo scaffold, the putlog pattern is also the major determinants of the stability of bamboo scaffold. As we carried out the structural analysis with 'NAF-NIDA' computer program for geometrically non-linear analysis, the stress level of the bamboo member can be demonstrated by the following data. The results from table 1 and 2 showed that both increasing the distance between horizontal level and vertical level for putlogs layout would accelerate the buckling process and increase the stress level of the bamboo member by more than 30% or more.

TABLE 1

EFFECT OF STRESS LEVEL UNDER SHORTER WIDTH AGAINST DIFFERENT PUTLOGS PATTERN

Layout of putlogs pattern with 3 meter width basis	Stress level of the bamboo member
3 m (W) x 2 (m) (L)	0.509
3 m (W) x 4 (m) (L)	0.601
3 m (W) x 8 (m) (L)	Buckling occurs

TABLE 2

EFFECT OF STRESS LEVEL UNDER LONGER WIDTH AGAINST DIFFERENT SIZE OF PUTLOGS PATTERN

Layout of putlogs pattern with 3 meter width basis	Stress level of the bamboo member
6 m (W) x 2 m (L)	0.815
6 m (W) x 4 m (L)	0.846
6 m (W) x 8 m (L)	Buckling occurs

Hence, shorter distance in both horizontal level and vertical of putlog installation can provide more stability to prevent the possibility of buckling of bamboo scaffold.

INNOVATIVE PATENTED SYSTEM OF MIXED METAL-BAMBOO SCAFFOLDS

Over the years in Hong Kong, workers working at height relied on bamboo scaffold. With the advantages of flexibility, efficiency and cost-effectiveness, bamboo scaffold is still preferred for most of commercial application. However, some bamboo structural members may not be able to resist the applied loads because of various reasons. To circumvent the problem of medium duty scaffolding design, the highly loaded structural members resting on ground or brackets can be made of steel or other metallic elements. At present, the innovative patented scaffolding system is made partly by bamboo (60%) and (40%) of steel.

In the design of mixed metal-bamboo scaffold, only metal tubes are used for the structural members. Therefore, any cases of bamboo failure due to self-deterioration would not affect the overall structure. Furthermore, metal tube is a much stronger material than bamboo, modifications or intentional damages by other parties are not easy to achieve. The stability of mixed metal-bamboo scaffold can be shown by the installation of “L’ shape steel bar putlog, which is fixed to the wall by an anchor bolt. Unlike the R6 wire using in bamboo scaffold, external destruction of mixed-metal bamboo scaffold can be minimized to maintain good conditions of scaffold at all times.

Secure ‘L’ shape steel bar putlog

Mixed metal-bamboo system applied in West Rail Station construction

CONTINUOUS DEVELOPMENT OF MIXED METAL-BAMBOO SCAFFOLDS

Further research on mixed metal-bamboo system has been made by replacement of material of both vertical post and horizontal ledger members to analyse how alternate mixed metal-bamboo system can perform in terms of stress level. Indeed, lower value of the readings reflected higher stability because less stress or loading can be transferred to scaffolding member causing buckling or collapse. Apart from the readings of each material that we can take considerations, the value of the support reaction can also affect the type of brackets used together with the operation cost in our consideration of possible development of new scaffolding system in the future.

TABLE 3

EFFECT OF STRESS LEVEL AGAINST VARIOUS COMBINATION OF MIXED SYSTEM SCAFFOLDING

Mixed system	Steel	Aluminium	Bamboo	Support reaction
Patented Layout	0.598		0.249	17 kN
Layout 1		0.558	0.312	13 kN
Layout 2	0.426	0.230	0.247	15.5 kN
Layout 3	0.286	0.542	0.242	14 kN
Layout 4	0.456	0.867	0.548	23 kN

Remarks: Layout 1 - Aluminium –Bamboo mixed system
Layout 2 - posts make of Aluminium ; ledgers make of Steel
Layout 3 - posts make of Steel ; Ledgers make of Aluminium
Layout 4 - posts make of Aluminium or Steel in alternate position ; Ledgers make of Steel

The design of mixed metal-bamboo system is based on well-proven technology to comply with safety standard. It provides reasonable flexibility which can be applied on any design or shape of building up to 45 meters high for every layer of steel supporting brackets. Each job is designed, calculated and documented with drawings with the approval from the registered professional engineers to ensure safety. With all of the scientific results from our research, we strive to provide most suitable working platform to our clients to cater for their construction need in an effective way.

EXAMPLES OF TRADE PRACTICES OF BAMBOO SCAFFOLDING

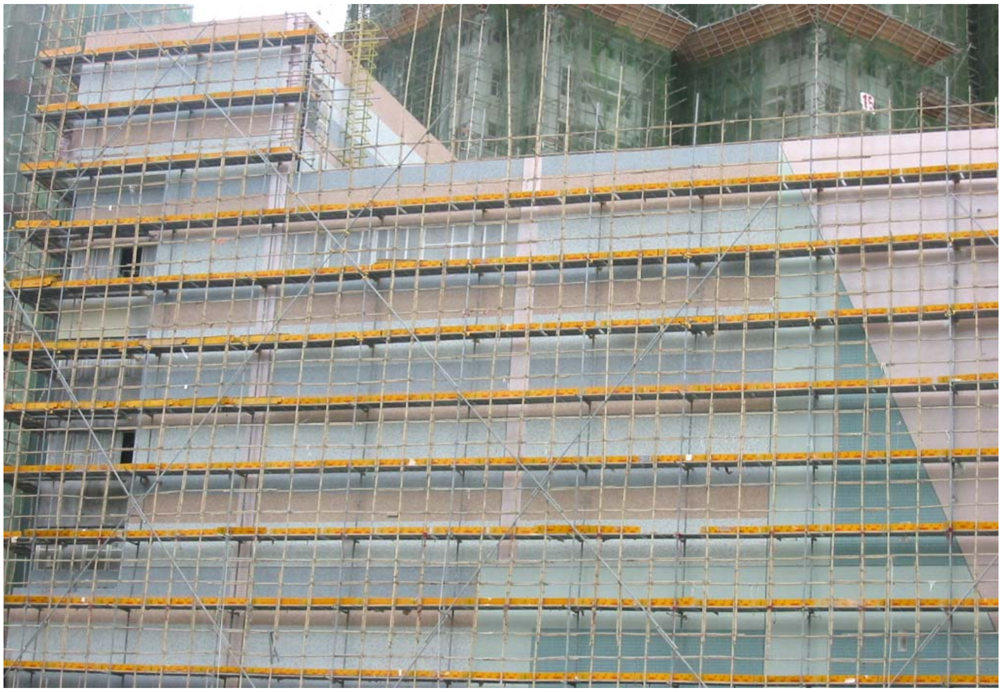
Scaffolding applied in hotel development project

Scaffolding for signage work

Majority of renovation works employ bamboo scaffolding

Scaffolding for repair of external walls

EXAMPLES OF TRADE PRACTICES OF MIXED METAL-BAMBOO SCAFFOLDING



Mixed System Scaffolding used for car-park development

Mixed System Scaffolding used for West Rail Station construction

PERFORMANCE OF METAL SCAFFOLDING USED IN SLOPEWORKS

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ABSTRACT

Metal scaffolding has recently become more popular for erection on slopes to provide the access as well as a working platform for various slopeworks such as the installation of soil nails and rock dowels.. However, the guidelines available for design and construction of metal scaffolding including the latest code of practice are largely building construction oriented and in many cases inapplicable to slopeworks environment. A study was undertaken to assess the performance characteristics of scaffolding materials. This paper presents the test results of metal tubes generally used for erection of working platforms in slopeworks.

KEYWORDS

Metal scaffolding, working platform, slopeworks, metal tubes, load tests, performance

INTRODUCTION

Mostly in the past and occasionally nowadays, bamboo scaffolding has been erected on slopes mainly to provide the access for inspection purposes. In view of the high loads encountered such as during the installation of soil nails which are commonly required in the landslip preventive measures, metal scaffolding has recently become more popular to be erected on slopes. Although metal scaffolding is more difficult to erect on an undulating and inclined surface and requires more manpower to do so, it has a greater strength and robustness, and a higher reliability in resisting the loads. Further, metal components can be made to meet standard specifications. Thus, the design process and the performance of metal scaffolding as a working platform in resisting the loads can be more predictable.

GUIDANCE AND REGULATIONS

Currently the erection and maintenance of the metal scaffolding are being guided or controlled under various regulations as well as appropriate codes of practices in Hong Kong. Nevertheless most of these guidelines, including the Code of Practice for Metal Scaffolding Safety issued recently by the Labour Department are building works oriented. In many instances, their recommendations are practically inapplicable in the slopeworks environment.

Unlike building works, most slopeworks are carried out in very restricted site conditions under which the use of mechanical plant is not viable. The majority of the materials and equipment are transported by manual labour on the slope surface. Thus the use of lighter materials such as the thinner steel tubes in forming the scaffolding would be essential for the safety of workers and the productivity of the works.

One requirement as stipulated in the Code of Practice for Metal Scaffolding Safety in Section 5.2 is that 'A tube made of steel should have a yield stress not less than 235N/mm^2, and should have an outside diameter of 48.3 mm and a wall thickness of 4 mm. As mentioned above, due to the logistic consideration for manoeuvring metal scaffold components in difficult slope topography, most of the tubular materials used in scaffolding erection on slopes though comply with BS1139 but are lighter in weight. They are usually thinner than 4mm and quite often they are of a diameter less than 48.3 mm.

Also it has been noticed from the sloping sites in Hong Kong that a large variety of metal scaffolding practices exist among different contractors. These include variation in the scaffold materials, components, layout and degree of safety of the scaffolding system.

REVIEW OF GEO GUIDANCE NOTES

It is anticipated that a total of 2,500 government slopes would have been upgraded during the ten-year period starting from 2000. It is vital to ensure a safe metal scaffolding system be available and adopted by all contractors involved in slopeworks.

The Guidance Notes prepared by the Geotechnical Engineering Office in 1997 provide the schematic configuration of a working platform for soil nailing works on slopes, along with supporting calculations (Figure 1). In general the setup has been proved to be adequate for most slopeworks. However, there are areas where the Guidance Notes do not cater for sufficiently such as:

1. Tubes thinner than 2.9mm
2. Horizontal reaction from drilling rig
3. Slopes greater than forty-five degrees

In practice the tubes can be as thin as 2.2mm thick. The design calculation needs to be revised and it has been proved that the system is still adequate by considering a lower dead weight of the rig.

It is estimated that the reaction from the drilling force can be as high as 10kN. Such a high force which is acting near to the horizontal is evident by the fact that the whole platform shifts when drilling is in progress. This force can be taken up by one or both of the following ways:

- Counteracted by the moment from the dead load of the rig and the platform.
- Dissipated through the planar action of the working platform to the two sides.

In some cases, existing slopes up to sixty degrees are upgraded with the installation of soil nails. To build a working platform in accordance with the Guidance Notes would require the use of longer vertical members of metal tubes and proper sitting of vertical members on the slope surface can be difficult. Furthermore, such a platform tends to be less stable while the drilling rig is working. Collapse of the platform in the form of toppling would become likely when vertical members buckle. To overcome these difficulties, the following improvements are proposed:

- All vertical members should be diagonally braced in addition to the requirements stipulated in the Guidance Notes.
- Wire ropes to support the working platform should be installed from above at regular intervals to guard against the collapse of the working platform.

COMPRESSION TESTS

Compression tests of metal tubes commonly used in slopeworks were carried out in 2000. Results of the tests for metal tubes of different wall thickness and from four different suppliers are shown in Figures 2 and 3. The unbraced lengths tested vary between 1.5m and 3m which are typical for platform erection on slopes. Theoretical buckling stresses against the slenderness ratios are also plotted in the figures. It can be seen that the actual buckling stresses are in the order of two times the theoretical stresses and hence the design is on the conservative side.

The reasons contributing to the higher buckling stress observed are as follows:

- the actual yield stress of the metal was higher than assumed; and .
- the actual end conditions were not perfect pin joints.

All metal tubes for the buckling tests were of new and good condition, and are ready for use on site. Allowing for some imperfection or possibly slight bending in the metal tubes, the theoretical buckling stresses should be adopted in the design.

In practice most metal tubes used for platform erection in slopeworks are of light duty category for the ease of handling and erection purposes. Therefore the design calculations should be based on the characteristics of the light duty metal tubes.

FIELD TESTS

Two field tests will be carried out on site to ascertain the performance of metal scaffolding used as a working platform.

- Test 1
  The first test is to measure the horizontal reaction force exerted by soil nail drilling rig on

the scaffolding platform when drilling into different subsoil materials. Results of this test will be used for the estimation of the most adverse load combination exerted on the metal scaffolding platform.

- Test 2
  The second test is to determine the confidence on the use of the refined metal scaffold working platform layout by loading such platform until failure on site and to establish the mode of failure. The safety margin of the scaffold structure can be worked out and the failure mode of the platform can be examined and studied.

CONCLUSIONS

Although there are codes of practice governing the use of metal scaffolding, they are not totally applicable to the erection of metal scaffolding in slopeworks. The common metal tubes, which are extensively used in Hong Kong, do not comply with all regulation requirements. In general they are smaller in diameter and are thinner. However, they have a greater loadbearing capacity when compared with the theoretical strengths. It is anticipated that the field tests to be undertaken can be used to assess the magnitude of loads encountered and establish the safety margin of the typical layout of the metal scaffolding used in slopeworks.

ACKNOWLEDGEMENT

The support received from the Committee on Research and Conference Grants, The University of Hong Kong, which made this study possible, is gratefully acknowledged.

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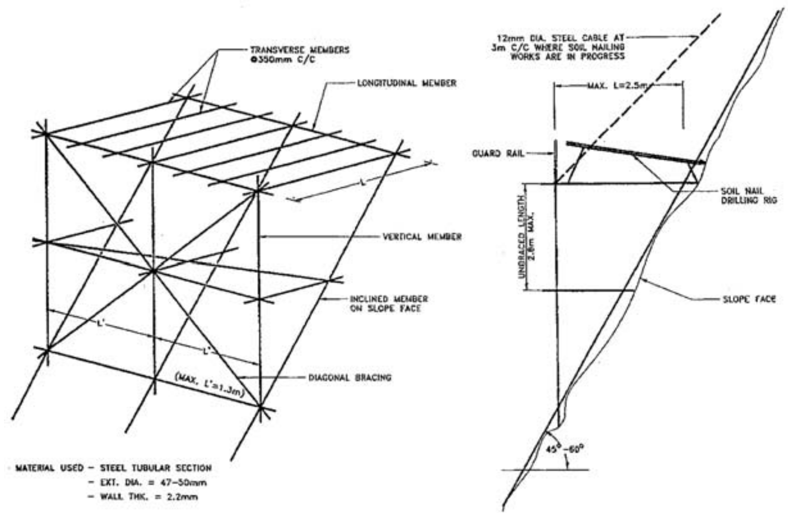

Figure 1 Working Platform For Soil Nailing Works on 45° - 60° Slopes

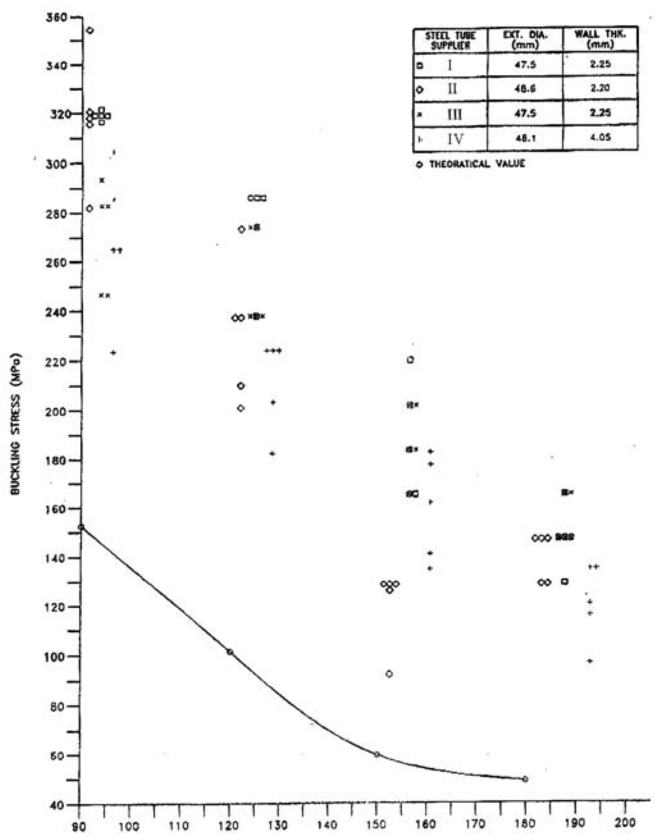

Figure 2 Buckling Stresses Vs Slenderness Ratios For Steel Tubes From Various Suppliers

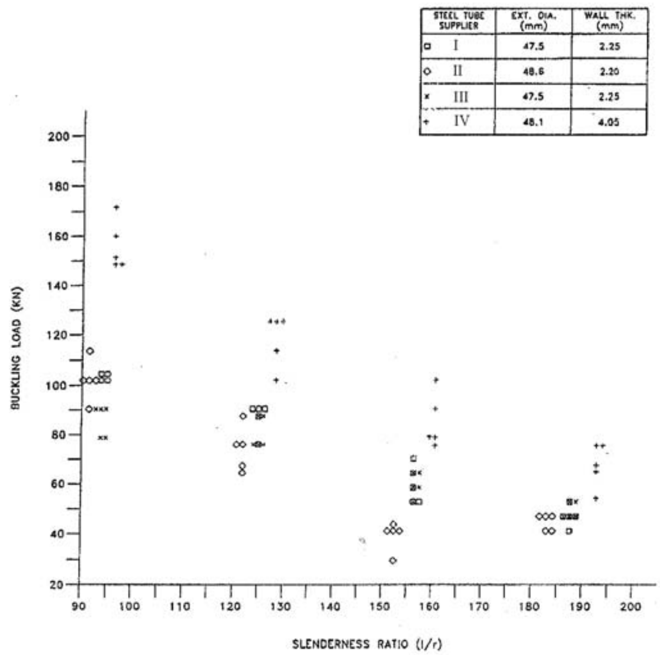

Figure 3   Buckling Loads Vs Slenderness Ratios For Steel Tubes From Various Suppliers

BAMBOO SCAFFOLDING - PAST, PRESENT AND FUTURE - A SAFETY PRACTITIONER'S VIEW

LEE Hung-kwong

H.K. Lee & Associates Limited

ABSTRACT

The aim of this paper is to share the views of a safety practitioner with legal responsibility for promoting safety on construction sites in general and bamboo scaffolding in particular.

KEYWORDS

Safety practitioner, bamboo scaffolding.

INTRODUCTION

First, I am not an engineer, a professor, a scientist or a research fellow. I am a registered safety officer under Hong Kong law and have been a safety practitioner for 35 years, with most of my time spent on promoting safety in the construction industry. I spent 20 years in the Hong Kong Government and the last 15 years in the private sector.

Now I would like to share with you my views concerning the safe use of bamboo as a scaffolding material. The prime objective is to increase the value of bamboo and focus on its use as a construction material with enhanced safety in mind. In order to do this, it is important to generate a road map for the future. By that, I mean we need a carefully thought out agenda for the application of science and technology to the use of bamboo as a construction material. What do we have to do? Who is going to finance such projects? Who are the stakeholders? I hope that, through the discussion today, such a road map can be drawn up. Perhaps this will be one of the outcomes of today's seminar. Without a road map, there will just be disorganized, fragmented studies and no accelerated progress in the use of bamboo scaffolding. The future of the use of bamboo depends on what we plan to and actually do.

THE PAST

In the past, bamboo scaffolding was not only used for construction but also for sheltering bombs, during wartime. I do not have the technical details, but I came across a newspaper article about it.

THE PRESENT

In the 1980s a study was conducted on falls of persons from height. This was the period that recorded the highest number of deaths from falling. There are lessons that we should learn. Let me highlight the results of the study:

- Of the 173 falls recorded in 1981-1987, 48 were from bamboo scaffolding or platforms on scaffold. This represents about 28% of all the deaths.

- Of the falls recorded, 26 were scaffold erectors. This represents about 15% of all the deaths.

- 56 of the dead were general workers/labourers working on construction sites. This represents 32% of all the deaths.

- 26 of the dead were scaffold erectors. This represents 15% of all the deaths.

- The contributing factors to the 173 falls, in descending order, were: (1) loss of balance - 88 cases; (2) collapse of platform, ladder or scaffold in whole or in part due to the failure of construction members - 35 cases; (3) collapse of platform, ladder or scaffold in whole or in part due to insecure fixing - 16 cases; and (4) taking the wrong step - 6 cases.

The study shows us why people have concerns about the safety of bamboo scaffolding and do not regard bamboo scaffolding to be as safe as metal scaffolding. These are lessons that we should examine.

THE FUTURE

First and foremost is the training of bamboo scaffolders. The Construction Industry Training Authority will touch on this subject during the seminar. The authority conducts courses. My view is that bamboo scaffolders perform highly skilled tasks and should be required to register under a system designed to recognise those who have attended the relevant courses, the purpose being to differentiate levels of skill and experience. As a bamboo scaffolder advances in skill, he/she will be able to perform more challenging tasks. I understand that this kind of differentiation does not exist at present. Do we need a registration system to address such differentiation?

The second area that needs attention is the strength of bamboo members and the tying and fixing arrangements. Studies may have been carried out in the past. If that is the case, how can the conclusions of these studies be applied on site? Can a checklist be developed for safety officers to follow?

The third area is the use of bamboo members to secure safety belts for workers. Do we need studies to find out exactly how safe this practice is?

The regulatory body of the Hong Kong SAR Government does not ban the use of bamboo as a scaffolding material. In fact, its use is governed by a Code issued by the Occupational Safety & Health Branch of the Labour Department under section 7A of the Factories and Industrial Undertakings Ordinance, Cap 59, with particular reference to sections 6A and 6B of the Ordinance and the Construction Sites (Safety) Regulations. The Code has been in place since 16 March 2001 and replaces one that was issued in 1995. The Code has a legal effect as defined under section 41(2)(a) of the Occupational Safety and Health Ordinance, Cap 509.

Despite the presence of a Code of Practice for Bamboo Scaffolding Safety, I think there is a need in Hong Kong and probably elsewhere to obtain scientific and technical data on bamboo scaffolding with an emphasis on safety. The studies, among other things, should cover:

- The kind of bamboo species that can be used as bamboo scaffolding.
- The application of biotechnology to the identification of such species.
- Use of bamboo frame as an anchorage for safety belts.
- Strength of bamboo members, strength depreciation through wear and tear.
- Maintenance, replacement and inspection of bamboo scaffolding.
- Wind effects on the stability of bamboo scaffoldings and precautions before and after typhoon.
- Size and stability of platform for work or storage purposes.
- Loading characteristics of bamboo scaffolding.
- Can a coating be developed for bamboo so that it does not burn so easily?

We should carry out the studies that are comparable to those covering metal scaffoldings, if we are to acquire sufficient information regarding the safe use of bamboo scaffolding.

As a safety practitioner, how do I view the use of bamboo scaffolding in construction? The answer depends on a number of important factors. The business world of today is different from that of yesteryear. Trust is no longer enough; people look for proof in everything nowadays. In terms of bamboo scaffolding, this means the material must be demonstrated to be safe. Unless it can be demonstrated that bamboo scaffoldings are safe and seen to be so, its potential for development will be limited. That is why some form of bamboo scaffolding standard is needed.

One final point I would like to make is that I do not see any competition between metal and bamboo scaffoldings. I think the construction industry is capable of making the best use of the two material and derive benefits from both, but safety must be a priority.

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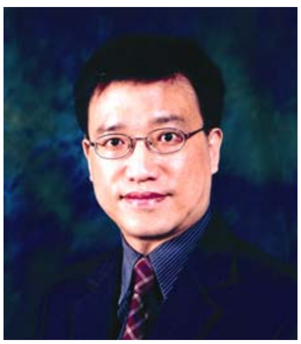
Biographies of Speakers

Professor S. L. CHAN is a professor of Department of Civil and Structural Engineering of the Hong Kong Polytechnic University. Currently he is the chief editor of the *Steel and Composite Structures - an International Journal* and the Asian regional editor of *International Journal of Applied Mechanics and Engineering*. He also serves as a member of editorial boards in 4 other journals, of ad-hoc committees in drafting guides for design of steel and glass structures in Hong Kong and of glass structures for the IStructE, of which he is also a member of the Research Panel. Professor Chan is also the founding President of the Hong Kong Institute of Steel Construction which promotes technological advances in steel related construction.

Professor Chan's research interests include the stability analysis and design of steel, glass and slender skeletal structures, scaffolding and pre-tensioned steel structures. Together with his academic colleagues at the Hong Kong Polytechnic University, he has published a number of technical reports and papers on the stability behaviour of bamboo columns and the advanced non-linear analyses of bamboo and metal scaffolds.



Dr. K.F. CHUNG is an Associate Professor in the Department of Civil and Structural Engineering of the Hong Kong Polytechnic University. He is a chartered structural engineer with established expertise in steel and composite design and construction in both UK and Hong Kong. Dr Chung has published a number of research papers on steel and composite construction in both research and professional journals together with four SCI design guides. Currently, he is also Vice President of the Hong Kong Institute of Steel Construction which promotes technological advances in steel related construction.

Between 1999 and 2001, Dr Chung has executed a research and development project titled '*Bamboo Scaffolds in Building Construction*' under the financial support of the International Network for Bamboo and Rattan. The major objective of the project is to promote the effective use of bamboo scaffolding in building construction through advancement and dissemination of structural bamboo technology. Dr Chung has published extensively on the structural use of bamboo, and the design and construction of bamboo scaffolds.

Professor Jules JANSSEN (1935) devoted his life since 1974 to research in bamboo as a building and engineering material, for poverty alleviation for lower income groups in tropical countries when he was an Assistant Professor at the Eindhoven University of Technology, The Netherlands. Highlights are his Ph.D. thesis *Bamboo in building structures* (1981), his numerous visits to projects in several countries, and his publications. At present, he has retired from the University, but keeps on working for **INBAR**, mainly as Editor-in-chief of the *Journal of Bamboo and Rattan*, and for **ISO** standards on bamboo.

Lionel JAYANETTI, Head of TRADA International based in UK, is a chartered civil engineer with a post graduate degree in timber engineering. His work has been mostly in developing countries dealing with projects involving the efficient use of timber including bamboo. In addition to construction, his experience consists of timber processing, timber drying and preservation. His present projects are mostly to provide solutions to affordable shelters to the poorest of the poor in developing countries. He is an author of many books including FAO wood preservation manual, Bamboo in construction and Timber pole construction. Before joining TRADA he has been a staff member of FAO of the United Nations and the Commonwealth Secretariat.

LEE Hung-kwong obtained his Bachelor of Science (Hons) degree in Civil Engineering from Loughborough University, a Post-graduate Certificate in Occupational Safety and Hygiene from Aston-in-Birmingham University, and also a Master of Science degree in Industrial Engineering from the University of Hong Kong. He has served for 20 years in the Safety Inspectorate of the Hong Kong Government. After that, he worked for 10 years as a corporate Health, Safety and Environment Manager for Shell Companies in the North East Asia, and then, two years with Lloyd's' Register. He is currently the Managing Director of H. K. Lee & Associates Limited, a registered safety officer and also a registered safety auditor.

Mr Lee is an author of five books relating to health, safety and environment. He was also the founding president of the *Society of Registered Safety Officers* in Hong Kong.

Ir S.W. POON is an Assistant Professor in the Department of Real Estate and Construction, the University of Hong Kong. He had taught at the National University of Singapore and the Hong Kong Polytechnic University before taking up the present appointment. His research interests include project management, quality and safety management and construction failures.

He is currently a Senior Member of the Professional Committee of Construction Safety, the China Association of Construction Industry, Beijing, China. He was the Chairman (2000-2001) of Safety Specialist Group of the Hong Kong Institution of Engineers.

SO Yu-shing Francis graduated from the University of Hong Kong in 1976. He worked for the Labour Department of the Hong Kong Government for 15 years before assuming the position of the Managing Director of Wui Loong Scaffolding Works Co., Ltd. in 1991. Mr So has also obtained a Master of Science Degree in engineering business management from the Warwick University, U. K.

In 2001, Mr So obtained a patent in the *Metal-Bamboo Matrix System Scaffolding (MBMSS)*, and in the same year, his company *WLS Holdings Limited* was successfully listed on the Growth Enterprise Market of the Hong Kong Stock Exchange.

Ir Tong Yat-chu, a veteran engineer, is Fellow Members of numerous professional engineering, science and technology institutions; he also has a M.Sc. degree from the Manchester University, U.K. Ir Tong is currently the Executive Director of the Construction Industry Training Authority and has had over thirty years' experience in the provision of technical education and industrial training to the local youngsters.

Ir Tong has extensive experience in the administration and development of the education and training requirement of craftsman, operatives, technicians and technologists, as well as in the provision of CPD for these different levels of personnel.

THE HONG KONG POLYTECHNIC UNIVERSITY

PROCEEDINGS NO.8

Bamboo scaffolds have been widely used in construction applications in South East Asia, in particular, Hong Kong for many years. Because of their high adaptability and low construction cost, bamboo scaffolds can be constructed in different shapes to follow any irregular architectural features of a building within a comparatively short period of time. In general, bamboo scaffolds are mainly used to provide access of workers to different exposed locations to facilitate various construction and maintenance process. Besides widely erected on construction sites, bamboo scaffolds are also used in signage erection, decoration work, demolition work and civil work.

This International Seminar aims to provide a technical forum for researchers, engineers, contractors, and also regulatory agents to exchange basic design data, scientifically developed analysis and design methods, and established construction practices for safe and effective bamboo scaffolding. Furthermore, latest developments on both bamboo and metal scaffolds are reviewed while further developments are also proposed for general discussion.

INBAR