Interactive buckling of structural local bamboo in Malaysia

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Abstract. Bamboo is a naturally available construction material and one of the fastest growing plant compared with the tree, which increases its suitability to be used as a sustainable source for wood industry, especially in construction works. Due to the lack of understanding on bamboo properties and lack of design standard, the utilization of bamboo in construction has always been neglected. This paper presents an investigation on the buckling behaviour of three species treated bamboos that are available in Malaysia, which included Bambusa Vulgaris, Dendrocalamus Asper, and Gigantochloa Scortechinii. Furthermore, a design method based on Perry-Robertson formula was proposed for compressive buckling of the bamboo. The experimental compressive buckling on 15 columns was conducted to investigate the buckling behaviours and the design procedure was developed by using the test data results. It was shown that for Dendrocalamus Asper, the model factors of the proposed design method was 1.16 while Bambusa Vulgaris was 1.15 and Gigantochloa Scortechinii was also 1.15. As result, the proposed design method was shown to be adequate and also was successfully calibrated against the test data. Thus, the advantages of bamboo in the structural application should be fully utilized to build light, strong bamboo structure.

1. Introduction

Being classified as a grass member of a larger grass family [1], bamboo can be easily found in tropical and some temperate areas of the world. Bamboo has a nature form comprising a cylindrical pole with jointed stem known as a culm. There are over 1500 identified bamboo species in the world [2]. As one of the fastest growing plants, bamboo can reach a full height ranging from 15-30m in a period of two to four months [3]. The thickness of a bamboo decreases along the height of the culm, while the fibres density increases from the bamboo culm’s inner wall to outer wall. The strength of bamboos also depends on age ranges and species, which determines their suitability to be used in construction when they reach maturity age of around 3-4 years. Bamboo needs to be treated in order to increase the durability and to resist fungus attack. The durability of untreated bamboo usually depends on the age, species and storage method [4]. In addition, the lifespan of treated bamboo will last for over 3-4 years
if placed outdoor but the lifespan of the bamboo structure will last over 50 years if placed under roof and not directly contact with the rain and sunlight.

This paper presents a research for structural bamboo where the buckling behaviour of bamboo column were investigated. A total of 15 column with typical dimension and properties were tested and a limit state design method for buckling of bamboo column based on modified slenderness was proposed for general design after carefully calibrated against test data.

![Figure 1. Application of bamboo as scaffolding and main structure in building.](image1)

1.1. Current research on bamboo structure
Bamboo have been used extensively in traditional ways for structural purposes especially in China, Indonesia, India and Latin America for many hundreds of years. Unfortunately, there was small research and information regarding the structural bamboo. Current scientific research on bamboo as construction materials were reported by Janssen [6] in Holland and also Au et al. [7] in Hong Kong. Janssen [8] also had reported that there was large amount of data of the mechanical properties for various bamboo species all over the world. Meanwhile, most of previous research focusing on typical testing of compressive, bending and shear strengths of assorted bamboo species but no characteristic strengths for contemporary structural design were provided.

Compare with a conventional material such as concrete, steel and timber, the understanding of the structural behaviour of full culm bamboo can be considered poor which results in less utilization or being neglected in construction. One of the most important structural elements is a column. Just like other material such as steel and timber, the main problem of the column is buckling due to its slenderness. Buckling is the failure when there is uncontrolled lateral displacement of columns at which no additional load can be supported especially compressive stress. The structures experience large deformation and lose stability to carry the load when reaching the critical load value.

A research on critical buckling of Guadua species was conducted by Arce-Villalobos in 1993 where a critical buckling load equation was developed for a variable Young’s modulus and tapered cross-section of bamboo. As a recommendation, Arce-Villalobos suggest an equation using average properties of Young’s modulus (E) and moment of inertia (I). This is because the buckling load is affected by the changing of the cross-section dimensions and the modulus along the height of the bamboo [9].

In general, many researchers have studied the buckling behaviour of non-prismatic columns such as non-prismatic columns of wide flange I-sections, box sections, and solid sections with different support conditions. Gere and Carter [10] presented both exact and approximate solutions for the critical buckling loads of non-prismatic columns, but no solutions for non-prismatic tubular columns were given.

In order to promote the effective use of structural bamboo in building construction, it is essential to provide basic design data of mechanical properties and design rules against various modes of failure in
accordance with modern design philosophy. Previously, a pilot study was carried out to examine the variation of compressive strength against various physical properties along the length of bamboo culms for Dendrocalamus Asper, Bambusa Vulgaris and Gigantochloa Scortechinii. Moreover, systematic test series with a large number of compression test were executed to establish characteristic values of both the strengths and the Young's modulus of each bamboo species for limit state structural design.

2. Materials and methods

2.1. Preparation of the bamboo
Three species of bamboo are involved in column test which known as Dendrocalamus Asper, Bambusa Vulgaris and Gigantochloa Scortechinii. They were subsequently treated in order to increase their durability and ability against fungus attack. Combination of boric acid and borax in a ratio of 1:1.5 form an alkaline salt where this salt was obtained in ready mixed powder form. This powder was poured and mixed with water in the special rectangular tank and the bamboo was immersed into the tank for about 1 week before they were left to dry. A total of 15 specimens were prepared which consist of 5 specimens from each species with different length. All the culm specimens were cut to length and the measurements were taken along the culm for wall thickness, culm diameter and internodes length. Based on the average wall thickness (t) and diameter (D) that measured at each internode and gross section dimensions, the value of the cross sectional area (A_{culm}) and second moment of area (I_{culm}) were determined.

![Figure 2. Schematic diagram of bamboo column test set-up.](image)

2.2. Propose design method
All basic section properties of the bamboo column are assessed by using standard equations required for buckling [11]:

\[ A = \frac{\pi}{4} [D^2 - (D - 2t)^2] \]  

(1)
Second moment of area, \( I = \frac{\pi}{64} [D^4 - (D - 2t)^4] \) \( (2) \)

Slenderness ratio, \( \lambda = \frac{L_e}{r} \) \( (3) \)

Radius of gyration, \( r = \left( \frac{I}{A} \right)^{\frac{1}{2}} \) \( (4) \)

The design elastic critical buckling load of a column, \( P_{cr} \), from classical energy method is given by:

\[
P_{cr} = \frac{\pi E I}{L_e^2}
\]

The elastic critical buckling strength, \( f_{cr} \), is given by dividing the design critical load with the cross-sectional area, \( A \) as shown below:

\[
f_{cr} = \pi^2 E \frac{1}{\left( \frac{L_e}{r} \right)^2}
\]

\[
f_{cr} = \pi^2 E \frac{1}{\lambda^2}
\]

By adopting Perry-Robertson interaction formula:

\[(f_{cr} - f_{cc,d})(f_{c,d} - f_{cc,d}) = \eta f_{cr} f_{cc,d}\] \( (7) \)

The design compressive buckling strength, \( f_{cc,d} \), of a column is given by:

\[
f_{cc} = \frac{(f_{cr})(f_{cd})}{\phi + \sqrt{\phi^2 - f_{cr}f_{cd}}}
\]

Where,

\[
\phi = \frac{f_{cd} + (1 + \eta)f_{cr}}{2}
\]

\[
\eta = 0.001a(\lambda - \lambda_o)
\]

Limiting slenderness, \( \lambda_o = 0.2 \pi \left( \frac{E}{f_{cd}} \right)^{\frac{1}{2}} \)

A non-dimensionalized column buckling curve can be plotted by using the following non-dimensionalized quantities:

\[
\text{Modified slenderness ratio, } \bar{\lambda} = \frac{E}{f_{cd}}
\]

\[
\text{Strength reduction factor, } \Psi_c = \frac{f_{cc}d}{f_{cd}}
\]
Table 1. Proposed mechanical properties of bamboo based on compressive test.

| Bamboo species          | Designation | Compression (N/mm²) |
|------------------------|-------------|---------------------|
| Dendrocalamus Asper    |             |                     |
| Characteristic strength (average value) | fₖₜ | 55.32               |
| Design strength (γₘ = 1.5) | fₖₜ,d | 36.88               |
| Design Young’s modulus  | Eₖₜ,d | 6810                |
| Bambusa Vulgaris       |             |                     |
| Characteristic strength | fₖₜ | 49.95               |
| Design strength (γₘ = 1.5) | fₖₜ,d | 33.3                |
| Design Young’s modulus  | Eₖₜ,d | 10420               |
| Gigantochloa Scortechinii |         |                     |
| Characteristic strength | fₖₜ | 50.67               |
| Design strength (γₘ = 1.5) | fₖₜ,d | 33.78               |
| Design Young’s modulus  | Eₖₜ,d | 7800                |

3. Results and discussions

3.1. Buckling test results
All measured data were summarized in Table 2. It was found that the measured compressive buckling strength for all specimens decreased with the increased of length. Dendrocalamus Asper shows the highest compressive buckling strength, followed by Bambusa Vulgaris and Gigantochloa Scortechinii. The measured strength reduction ratio of Dendrocalamus Asper ranging from 0.80-1.11 while Bambusa Vulgaris ranging from 0.77-1.16 and Gigantochloa Scortechinii ranging from 0.39-0.81.

Table 2. Result of bamboo column specimens.

| Sample  | D (mm)  | t (mm) | L (mm) | Load (kN) | fₑₑ (N/mm²) | Ψₑₑ |
|---------|---------|--------|--------|-----------|-------------|-----|
| DA1     | 108.93  | 12.03  | 1400   | 150.20    | 41.01       | 1.11|
| DA2     | 108.22  | 10.94  | 1800   | 136.20    | 40.74       | 1.10|
| DA3     | 110.04  | 11.67  | 2200   | 106.00    | 29.39       | 0.80|
| DA4     | 106.62  | 12.39  | 2600   | 104.00    | 28.35       | 0.77|
| DA5     | 107.14  | 12.10  | 2600   | 106.2     | 29.40       | 0.80|
| BV1     | 79.42   | 7.04   | 1400   | 62.10     | 38.79       | 1.16|
| BV2     | 77.16   | 7.84   | 1800   | 57.40     | 33.62       | 1.01|
| BV3     | 75.32   | 8.02   | 2200   | 47.20     | 27.84       | 0.84|
| BV4     | 76.41   | 7.20   | 2600   | 40.30     | 25.74       | 0.77|
| BV5     | 77.07   | 7.05   | 2600   | 49.30     | 31.79       | 0.95|
| GS1     | 68.22   | 7.76   | 1400   | 40.30     | 27.34       | 0.81|
| GS2     | 65.71   | 8.10   | 1800   | 34.10     | 23.26       | 0.69|
| GS3     | 65.64   | 7.42   | 2200   | 31.3      | 23.06       | 0.68|
| GS4     | 59.32   | 7.00   | 2600   | 16.00     | 13.91       | 0.41|
| GS5     | 59.52   | 6.93   | 2600   | 15.50     | 13.28       | 0.39|

D = outer diameter, L = length, fₑₑ = Measured compressive buckling strength

Figure 3 shows the graph of the load against displacement for all bamboo column specimens. It is understood that most of the specimen experience large displacement in the horizontal direction.
3.2. Calibration of design method

A back analysis by using the test data was carried out with all partial safety factors equal in unity in order to calibrate the proposed design method. All the specimens dimension measured in the test were used and all measured compressive strengths of test specimens also were adopted. The value of Young’s modulus in compression was used in the back analysis. The result of the back analysis was shown in Figure 4, Table 3 and Table 4. As shown in Figure 4, the Robertson constant for Dendrocalamus Asper was selected to be 6 because it was found that the presence of small initial imperfection when compared with the external diameter.

The measured strength reduction ratios were found to range from 0.80-1.11, compared with the calculated design strength reduction ratios that range from 0.69-0.91. Meanwhile, the modified slenderness ratios were found to range from 0.5-0.95. For Bambusa Vulgaris, the value of Robertson was selected to be 2.5 due to smallest initial imperfection when compared with its external diameter. The measured strength reduction ratios were found to be range from 0.77-1.16, compared with the calculated design strength reduction ratios that range from 0.72-0.94. The modified slenderness ratios were found to be 0.52-1.00.

**Figure 3.** Load vs displacement graph of all bamboo column specimens.
a) Column buckling analysis for Dendrocalamus Asper

b) Column buckling analysis for Bambusa Vulgaris

c) Column buckling analysis for Gigantochloa Scortechinii

**Figure 4.** Graph of bamboo column buckling analysis.

Different with Gigantochloa Scortechinii, the presence of large initial imperfection when compared with external diameter, the Robertson constant was selected to be 9.5 in order to give a safe design for all test data. The measured strength reduction ratios were found to be range from 0.39-0.81, compared with the calculated design strength reduction ratios that range from 0.39-0.73 while the modified slenderness ratios are found to be range from 0.72-1.54. The Robertson constant for all species involves in this test were chosen differently from each other to fit test data in column buckling. Bambusa Vulgaris has the smallest Robertson constant as this species naturally possesses almost similar dimension and less taper condition which contribute to small initial imperfection. Differ with Gigantochloa Scortechinii that having high Robertson constant value due to excessive taper condition when compared with other species in this study.
Table 3. Result of back analysis of bamboo column specimens.

| Sample | λ  | \( f_{cr} \) (N/mm²) | \( \eta \) | \( f_{ccd} \) (N/mm²) | \( \Psi_{design} \) |
|--------|----|-----------------------|-------|----------------------|------------------|
| DA1    | 21.32 | 147.92               | 0.08  | 33.55               | 0.91             |
| DA2    | 27.41 | 89.48                | 0.11  | 31.40               | 0.85             |
| DA3    | 33.50 | 59.90                | 0.15  | 28.65               | 0.78             |
| DA4    | 39.59 | 42.89                | 0.19  | 25.34               | 0.69             |
| DA5    | 39.59 | 42.89                | 0.19  | 25.34               | 0.69             |
| BV1    | 29.84 | 115.47               | 0.05  | 31.29               | 0.94             |
| BV2    | 38.37 | 69.85                | 0.07  | 29.77               | 0.89             |
| BV3    | 46.90 | 46.76                | 0.09  | 27.39               | 0.82             |
| BV4    | 55.42 | 33.48                | 0.11  | 23.96               | 0.72             |
| BV5    | 55.42 | 33.48                | 0.11  | 23.96               | 0.72             |
| GS1    | 33.76 | 67.53                | 0.23  | 24.77               | 0.73             |
| GS2    | 43.40 | 40.85                | 0.32  | 20.52               | 0.61             |
| GS3    | 53.06 | 27.35                | 0.41  | 16.52               | 0.48             |
| GS4    | 62.70 | 19.58                | 0.50  | 13.22               | 0.39             |
| GS5    | 62.70 | 19.58                | 0.50  | 13.22               | 0.39             |

\( f_{cr} \) = Critical buckling strength, \( \eta \) = Perry factor, \( f_{ccd} \) = Design compressive buckling strength

Based on Table 4, the model factor of Dendrocalamus Asper specimens were found to range from 1.03-1.29 while Bambusa Vulgaris range from 1.02-1.32. Last but not least, the model factor for Gigantochloa Scortechinii were ranged from 1.05-1.41. It should be noted that the model factor needs to be higher or equal to one, \( MF \geq 1 \), as the design of compressive buckling need to be lower than measured compressive buckling strength in order to avoid the structural column from ‘under design’ problems. Based on the previous study on Bambusa Pervariabilis and Phyllostachys Pubescent, the average model factor for both species was found to be 1.63 and 1.48 while the proposed Robertson constant was found to be 28 and 15 based on the same proposed design method in this study [12].

Table 4. Model factor of column bamboo specimens.

| Sample | Modified slenderness, \( \lambda \) | Design strength reduction ratio, \( \Psi_{design} \) | Measured strength reduction ratio, \( \Psi_{test} \) | Model factor, MF | Average model factor, \( MF_{avg} \) |
|--------|-----------------------------------|---------------------------------|---------------------|-------------------|---------------------|
| DA1    | 0.50                              | 0.91                            | 1.11                | 1.22              | 1.16                |
| DA2    | 0.64                              | 0.85                            | 1.10                | 1.29              |                     |
| DA3    | 0.78                              | 0.78                            | 0.80                | 1.03              |                     |
| DA4    | 0.95                              | 0.69                            | 0.77                | 1.12              |                     |
| DA5    | 0.95                              | 0.69                            | 0.80                | 1.16              |                     |
| BV1    | 0.52                              | 0.94                            | 1.16                | 1.23              | 1.15                |
| BV2    | 0.69                              | 0.89                            | 1.01                | 1.13              |                     |
| BV3    | 0.87                              | 0.82                            | 0.84                | 1.02              |                     |
| BV4    | 1.00                              | 0.72                            | 0.77                | 1.07              |                     |
| BV5    | 0.99                              | 0.72                            | 0.95                | 1.32              |                     |
| GS1    | 0.72                              | 0.73                            | 0.81                | 1.11              | 1.15                |
| GS2    | 0.97                              | 0.61                            | 0.69                | 1.13              |                     |
| GS3    | 1.17                              | 0.48                            | 0.68                | 1.41              |                     |
| GS4    | 1.54                              | 0.39                            | 0.41                | 1.05              |                     |
| GS5    | 1.53                              | 0.39                            | 0.39                | 1.05              |                     |

\( \Psi_{design} = f_{ccd} / f_{cd} \), \( \Psi_{test} = f_{ct} / f_{cd} \). MF denotes the model factor \( \Psi_{test} / \Psi_{design} \)
3.3. Mode of failures
There are two modes of failure identified in bamboo column buckling test which known as overall buckling and local buckling. An observation was made during the load applied and all the specimens were noticed to buckle over the entire of their length. It is found that most of the column sample exhibits overall buckling before failing especially for those possess long span. Figure 5 shows some sample of Dendrocalamus Asper, Bambusa Vulgaris and Gigantochloa Scortechinii experienced overall buckling during the test.

Longitudinal splitting was noticed occurred at the top part of the specimen where at this part, the thickness of the culm wall is at the smallest. This longitudinal splitting failure was continued to the middle part of. In the case of splitting of column specimens, the flexure induced by buckling resulting shear split where the specimens were splits into a few pieces along culm.

4. Conclusion
Understanding the behaviour of structural bamboo is needed as the bamboo has a lot of potentials to be used in the construction field. The main purpose of this chapter was to present the buckling behaviour of single culm of different species of bamboo and to proposed design method accordance with modern structural design philosophy.

Based on the extensive experimental testing on the buckling behaviour of the bamboo column, a design method for column buckling of structural bamboo based on the modified slenderness was proposed and developed. The proposed design method also was shown to be structurally adequate. Furthermore, the proposed design method has been calibrated successfully against test data for Dendrocalamus Asper, Bambusa Vulgaris and Gigantochloa Scortechinii based on the proposed buckling curve for bamboo specimens. The proposed Robertson constant for Dendrocalamus Asper was found to be 6 while Bambusa Vulgaris was 2.5 and Gigantochloa Scortechinii was 9.5.

Figure 5. Overall buckling and longitudinal splitting of bamboo column.
Moreover, the cross-section area of Dendrocalamus Asper and Bambusa Vulgaris may be considered uniform throughout the length since there was the only small difference in dimensions and taper conditions. Thus, all bamboo specimens in this study may be considered to be homogeneous in terms of mechanical properties to be used in design purpose. Thus, the proposed design method of column buckling of structural bamboo may be used effectively in developing bamboo as a modern construction material.

5. References
[1] Q. Xu, K. Harries, X. Li, Q. Liu, and J. Gottron 2014 Mechanical properties of structural bamboo following immersion in water. Eng. Struct. 81 pp 230–239.
[2] K. F. Chung and W. K. Yu 2002 Mechanical properties of structural bamboo for bamboo scaffoldings. Eng. Struct. 24 pp 429–442.
[3] W. Liese 1987 Research on bamboo. Wood Sci. Technol. 21 pp 189–209.
[4] K. Ghavami 2008 Bamboo: Low cost and energy saving construction materials. Int. Conf. Mod. Bamboo Struct.
[5] A. Syeda, B. Shrujal, and J. Kumar 2014 A case study on bamboo as green building material. International Journal of Engineering and Advanced Technology 4 pp. 78–82.
[6] Janssen JJA 1981 Bamboo in building structures. PhD thesis, Eindhoven University of Technology, Holland.
[7] Au F, Ginsburg KM, Poon YM, Shin FG 1978 Report on study of bamboo as a construction material. The Hong Kong Polytechnic.
[8] Janssen, J.J.A 1985 The mechanical properties of bamboo. Recent Research in Bamboo. Proceeding of the International Bamboo Workshop Hangshou, China. Oct. pp 6-14.
[9] Arce-Villalobos OA 1993 Fundamentals of the design of bamboo structures. PhD thesis, Eindhoven University of Technology, Holland.
[10] Gere JM, Carter WO 1963 Critical buckling loads for tapered columns. Journal of the Structural Division; 128(II) pp 736–54.
[11] British Standard Institution 2000 B.S. 5950. Structural use of steelwork in building. Part 1: Code of practice for design - Rolled and welded section.
[12] W. K. Yu and K. F. Chung 2003 Column buckling of structural bamboo. Eng. Struct. 25 pp. 755-768.

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