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Development of Load Tables for Design of Full-Culm Bamboo

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Abstract

Design aids in the form of load tables or span tables are well known to engineers and are commonly used in timber and steel design. Such tables reduce the need for repetitive calculation and allow for easy 'what-if' queries during design. They also permit rapid communication of minimum design requirements. This paper demonstrates an approach for developing design load tables for full culm bamboo elements for compression and flexure. The design tables are based on the provisions of ISO 22156:2021 and are most easily developed based upon an established grading procedure as described by ISO 19624:2018. Prior to the synthesis of these two standards, generation of such load tables for bamboo was not practical. The development of archetypal column axial load tables and beam flexural span load tables are demonstrated. Examples of their use are illustrated demonstrating how alternate designs are easily established and compared. Such load tables are most appropriate for bespoke in-house design aides or as "national annexes" appended to ISO 22156:2021 upon its adoption by a jurisdiction.

Keywords

bamboo, structural design, compression, flexure, design aids

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1 ISO 22156 Bamboo Structural Design

In June 2021, the International Organization for Standards published *ISO 22156:2021 – Bamboo Structures – Bamboo Culms - Structural Design*. This standard significantly revises and replaces the 2004 edition, *ISO 22156:2004 – Bamboo – Structural Design*. The 2004 first edition was ground breaking; it was the first international attempt to develop a design standard for full-culm bamboo. The first edition was an 'intent-signifying' document; prescribed design was "by calculation" or based on experiment. Little specific guidance was provided in either case. One could not design a structure using ISO 22156:2004, one could only ensure that a design met the intent of the document. Efforts to revise ISO 22156 began in 2016 and were made feasible by the parallel development of *ISO 19624:2018 – Bamboo structures – Grading of bamboo culms* which provided the framework around which a load-bearing capacity-based design approach could be developed.

The scope of ISO 22156:2021 is limited to one- and two-storey residential, small commercial or institutional and light industrial buildings not exceeding 7 m in height whose primary load bearing structure is made of full-culm (i.e. round pole) bamboo. ISO 22156 also describes composite bamboo shear wall systems in which the framing members are made from round bamboo, although these are not discussed in this paper.

Although ISO 22156 does not limit culm dimensions that may be employed, the intent, expressed in ISO 22156:2021 Annex A, is that 50 mm is a practical minimum diameter for a structural load-bearing element. Exceptions may be in bundled multiple-culm compressive load carrying members such as columns, arches and truss chords, however buckling of individual small culms in such assemblies must be addressed.

Full culm bamboo used in load bearing structural applications will typically have a diameter-to-wall thickness ratio (D/t) less than 12 (ISO 22156:2021 Annex A; Harries et al. 2017). Above this threshold, local buckling of the culm walls, particularly in the compression regions of members in bending, becomes a concern. Additionally, by applying a limit of $D/t \leq 12$, the calculation of culm shear properties can be simplified as described in this paper.

2 Mechanical Properties of Bamboo Culms

The nature of full-culm bamboo construction and the inherent natural variation of both geometric and material properties make full-culm bamboo uniquely suited to an allowable load bearing capacity-based design (ACD) approach rather than (or in addition to) an allowable stress-based design (ASD) approach. ISO 22156:2021 specifically permits either approach referring to capacity determined from component "capacity" or member "strength", independently.

Strength is an intensive property of the bamboo material whereas capacity results from the combination of material properties and member geometry (i.e. an extensive property). Taking the example of a flexural member (Figure 1): the modulus of rupture or bending strength (f_m) is the stress at the extreme fibre at failure and is expressed in units of force per unit area (e.g., MPa). The flexural moment capacity (units of N·m) of the cross section of the member is $M = S \cdot f_m$, where S is the elastic section modulus, a geometric property of the culm. Similarly, the bamboo material has an elastic modulus (E) and the member has a flexural stiffness $E \cdot I$, where I is the section moment of inertia.

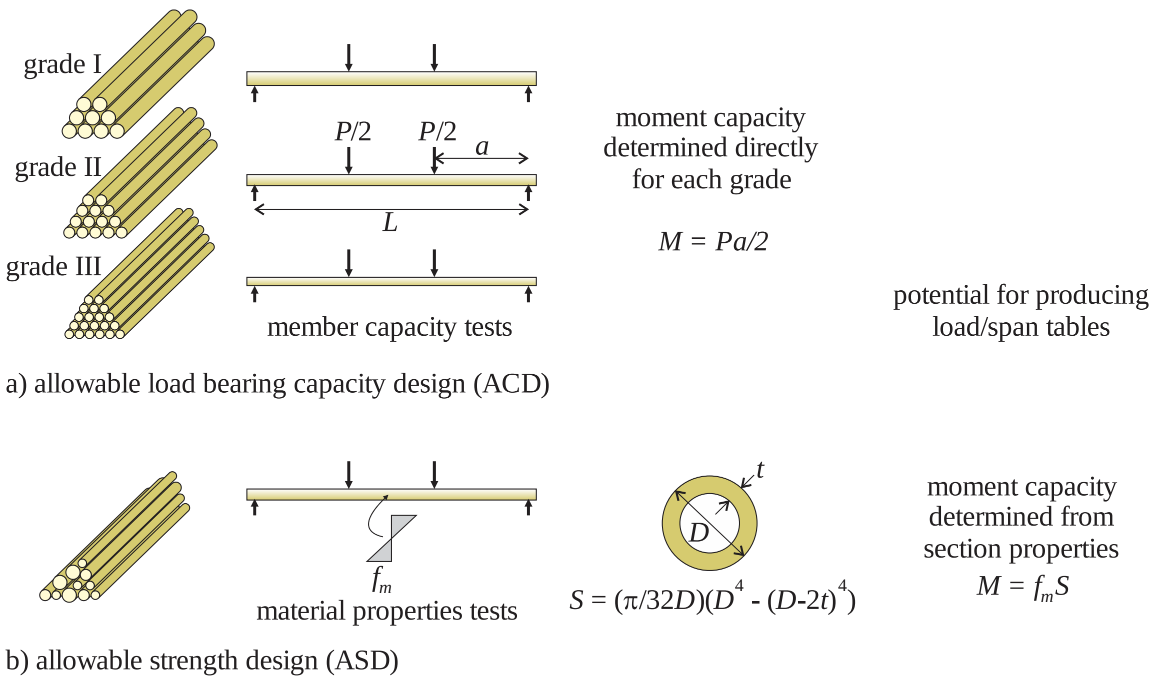

Figure 1 Representation of ACD and ASD determination of flexural capacity.

Therefore, member capacity is expressed directly in units of load-bearing capacity; that is: Newtons (N) for axial load (N_t) and shear (V), and Newton-metres (N·m) for moment (M) capacity. Member flexural stiffness (EI) is defined in units of N·m^2. Member capacity is determined directly from component tests – that is tests that are representative in terms of cross section of the bamboo being used – and may be a grade-determining property (ISO 19624:2018). Strength is determined from standard materials tests and is defined independent of bamboo section geometry. Strengths determined using ISO 22157-defined material tests are compression (f_c), tension (f_t), bending (f_m) and shear (f_v) strength parallel to fibres, and tension (f_{t90}) and bending (f_{m90}) strength perpendicular to fibres. All are expressed as stresses (e.g., N/mm^2). Similarly, the bamboo elastic modulus (E) is determined from tension or compression tests. Geometric properties are determined based on cylinder having an average diameter, D, and wall thickness, t.

An advantage of using ACD over ASD is that the former is able to explicitly capture the anisotropic nature of bamboo and the often complex interactions between actions that may result from this (Akinbade et al. 2019 and 2021; Richard 2015). Consider, for example the interaction between shear and flexure in a member subject to bending. A strength design approach correlates strength with capacity through a variety of assumptions of fundamental mechanics. Due to the complex morphology and highly anisotropic nature of bamboo, some of these assumptions may not hold true in all cases. Examples include the assumption of strain compatibility in flexure. While ISO 22156:2021 goes to great lengths to ensure longitudinal splitting does not affect culm bending tests, the strain compatibility assumption inherent in Bernoulli beam theory has been observed to degrade before splitting occurs in bamboo (Richard et al. 2017). Furthermore, in the same culm subject to bending, improved prediction of mechanical behaviour is achieved when it is considered as a bimodulus material – that is the tension and compression moduli in bending are different (Lorenzo et al. 2020). ISO 22156:2021 does not address the bimodulus behaviour in ASD, although the affect is implicitly considered in the ACD approach. Another advantage of ACD, is that experimental determination of material strength requires approximations; for example in terms of the effect that the taper (e.g., Harries et al. 2017; Nugroho and Bahtiar 2013). This approximation, is then repeated (compounded) at the calculation of load bearing capacity. Few, if any, bamboo species have undergone a systematic geometric characterisation; engineers tend to assume the geometric characteristics of the bamboo culms. This process introduces an unquantified uncertainty.

Member capacity will typically be prescribed by grading. Member capacity should not, however, be confused with “design by testing”, also permitted by ISO 22156:2021. The latter is intended for structural systems whose design or analysis differs from those described in ISO 22156. Design by testing is intended for unique design situations and requires additional rigour and conformance of tests to the case being designed.

Characteristic values of both member capacity and strength are defined by ISO 22156 as the 5th percentile value determined from testing expressed with 75% confidence. Modulus values used in design are defined as the mean value determined from testing expressed with 75% confidence. These are the typical definitions also used in timber design.

3 Allowable Capacity or Material Strength for Design

Characteristic capacities or material strengths are used for design. Factors are subsequently applied to these in order to determine an allowable design capacity or strength – a value that cannot be exceeded in design. In ISO 22156:2021, the allowable member capacity is given as:

$$X = x_k \frac{C_R \times C_{DF} \times C_T}{FS} \quad \text{Eq. 1}$$

Where x_k is the characteristic member strength or capacity obtained from testing. The following modification factors are prescribed in ISO 22156:2021.

C_R is a modification factor intended to encourage the use of redundant structural details. C_R = 1.1 for redundant members; C_R = 0.9 for nonredundant members; and, C_R =1.0 otherwise. In the context of the present work, ISO 22156:2021 defines multiple culm members comprising fewer than four culms as being non-redundant. This addresses the loss of capacity of a multiple culm member resulting from the failure of one culm or the need to remove and replace a culm at some point in the member's life.

C_{DF} is a modification factor accounting for anticipated in-service equilibrium moisture content of the bamboo (defined by "Service Classes") and the expected duration of load. This factor is similar to that used in timber design. Like timber, bamboo is susceptible to creep under sustained or permanent loading conditions and exhibits a degree of resiliency when subject to instantaneously applied loads such as wind and seismic loads. This behaviour is affected by the moisture content of the bamboo.

C_T is a modification factor for service temperature above 38°C. When heated, the strength and stiffness of bamboo decrease (Gutierrez Gonzalez 2020). The effects of elevated temperature are immediate and their magnitude varies depending on the moisture content of the bamboo. Up to 65ºC, the immediate effect is reversible upon cooling. ISO 22156:2021 does not permit bamboo structural members to experience prolonged exposure to temperatures greater than 50ºC or short term exposure to temperatures greater than 65ºC.

FS is the component factor of safety. *FS* = 2 for load or force actions dominated by the longitudinal behaviour of the bamboo: compression, tension and bending of the culm. For actions dominated by the more brittle splitting behaviour, *FS* = 4.

Under indoor, air-conditioned conditions (Service Class 1), the combination of factors $C_D \cdot C_{DF} \cdot C_T / FS$ is calibrated to be equal to 0.30 for permanent loads, 0.38 for transient loads and 0.50 for instantaneous loads (half these values for shear). This is reduced for both conditions of greater equilibrium moisture content and/or higher ambient temperature.

The modulus of elasticity used for design is given as:

$$E_d = E_k \times C_{DE} \times C_T \quad \text{Eq. 2}$$

Where E_k is the characteristic modulus. C_T is the same modification described for strength. C_{DE} is a modification factor accounting for Service Class and the expected duration of load. For calculations requiring modulus, creep is the dominant effect. For Service Class 1, C_{DE} = 1 for instantaneous and transient loads and C_{DE} = 0.5 for sustained loads causing creep (Gottron et al. 2014). A factor of safety (*FS*) is not applied to calculations requiring modulus.

3.1 Non-composite Behaviour of Multiple-Culm Members

ISO 22156:2021 addresses the design of single and multiple-culm members, although does not permit an assumption of composite behaviour for multiple-culm members. The capacity of multiple-culm members is determined as the sum of the capacities of the individual members comprising the member. This will generally be a conservative assumption (Correal and Echeverry 2016), however no general approach for addressing composite, or indeed partially composite behaviour, of multiple-culm bamboo has been proposed.

4 Potential for Design Load Tables

Design aids in the form of load tables or span tables are well known to engineers and are commonly used in timber and steel design. Such tables facilitate the rapid design of well-known and commonly used structural elements subject to common loading conditions. Design tables, however, are predicated upon a number of fundamental assumptions, not the least of which is known material properties and geometries. With the acceptance of ACD for bamboo, coupled with methods of grading, sufficient basis for the development of design load tables is possible.

The following sections describe the design and development of design load tables for full culm bamboo elements for compression and flexure. These are fundamental. At this time, only concentric axial load is considered for column load tables and only uniformly distributed loads are considered for flexural elements. ISO 22156:2021 Clause 9.5 provides requirements for determining the capacity of members for which axial load and flexure interact.

The tables developed rely on an established grading system being in place. In developing the example tables, it is assumed that grading is species-specific and addresses culm diameter, wall thickness, compressive strength and modulus, and flexure and shear strength. These may be combinations of dependent and grade-determining properties (ISO 19624:2018) provided that they are known. In this work, the example load tables were generated using an Excel spreadsheet. Following the development of load tables, a simple example is presented to demonstrate their use.

5 Design of Bamboo Members Resisting Axial Load

Bamboo culms may be used as both columns and as compression or tension members in truss or braced frame structures. When used in tension, it is unlikely that the member behaviour will govern design. Few connections will be able to develop the tension capacity of a culm; which, in any case, is determined based on a simple least cross section capacity. Thus, this paper focuses on culms and multiple culm members loaded in concentric compression.

Considering the manner in which bamboo grows, internode geometry and spacing is such that buckling of the thin bamboo culm wall is unlikely (Harries et al. 2017). Nonetheless, structural load bearing bamboo should have a diameter-to-wall thickness ratio (D/t) less than 12 helping to ensure that wall buckling is not a design limit state. For most applications, compression behaviour will be governed by lateral instability of the bamboo culm over its length. Although this is referred to as member or global ‘buckling’, for bamboo the behaviour is more complex (Richard 2013). For relatively long culms, conventional elastic buckling behaviour (i.e. Euler column buckling) is observed. For shorter members, as may be used in a truss, elastic lateral behaviour is observed at moderate load levels. However, as the axial load is increased, a behaviour characterised by the interaction of local culm wall crippling, longitudinal splitting of the culm and global culm buckling – referred to as ‘kinking’ – is observed (Richard 2012).

For most practical structures, multiple-culm columns are commonly required. These permit larger loads to be carried and facilitate simple concentric connections. Although full composite behaviour cannot be achieved, culms in multiple-culm columns must be ‘stitched’ together at intervals along their length not exceeding 10 times the smallest culm diameter comprising the member (ISO 22156:2021). Providing such stitching mitigates uncontrolled compression failure of the individual culms comprising the column although does not make the column act as a composite element (Richard and Harries 2012). ISO 22156:2021 requires that multiple-culm compression members be symmetric about two axes or radially symmetric; equilateral triangular arrangements are also permitted. The individual culms in a multiple-culm member must not be separated by a clear distance of more than the average culm diameter comprising the member. ISO 22156:2021 prescribes additional requirements for multiple-culm compression members primarily intended to ensure the member behaves as a single, albeit non-composite, member. Most importantly is the determination of redundancy. While all single culm compression members are non-redundant by definition, multiple-culm members – especially members having a small number of culms – may also be non-redundant. If the removal of any single culm from a multiple-culm member results in failure of the member, the member is non-redundant and the redundancy factor, $C_R = 0.90$.

5.1 Compression Capacity

ISO 22156:2021 adopts the member compression capacity promulgated by Ylinen (1956). This approach has been used in North American (AWS 2018) timber design practice since 1991 and shown to be effective at predicting the behaviour of *G. angustofia* (Bahtiar et al. 2021). The Ylinen equation, given here as Equation 3, presents column capacity (N_{cr}) as a continuous function of slenderness which inherently accounts for the interaction between crushing and global buckling failure modes. This interaction, according to Zahn (1992) “is caused by any departure from the assumptions of elementary elastic-plastic theory, that is, by nonlinear stress-strain behaviour, inhomogeneity, crookedness, and accidental eccentricity"; all factors common to bamboo construction.

$$N_{cr} = \frac{P_c + P_e}{2c} - \sqrt{\left(\frac{P_c + P_e}{2c}\right)^2 - \frac{P_c P_e}{c}}$$ Eq. 3

In which, P_c is the crushing capacity of the compression member and P_e is the buckling capacity given by Equations 4 and 5, respectively. The Ylinen coefficient, prescribed by ISO 22156:2021 as $c = 0.80$, models the degree of interaction between crushing and buckling.

$$P_c = f_c \times \sum A$$ Eq. 4

$$P_e = \frac{n\pi^2 EIC_{bow}}{(KL)^2}$$ Eq. 5

Where f_c is the compression strength of the bamboo and ΣA is the sum of the areas of the n culms comprising the member. Moment of inertia (I) or flexural stiffness (EI) are taken as the minimum such value for all n culms comprising the member. In a multiple-culm member, the 'weakest' culm will buckle first and the residual capacity of the member will be reduced and rely on the remaining culms. The effective length of a bamboo compression member, KL, is the product of the member length between points of restraint, L, and the effective length factor, K, given by ISO 22156:2021.

The reduction factor, C_{bow}, accounts for the initial bow (b_o) of the culm:

$$C_{bow} = 1 - b_o/0.02$$ Eq. 6

Where bow, b_o, describes the curvature or 'sweep' of a culm. Implicit in Eq. 6, and specified by ISO 22516, is that bow cannot exceed 0.02. Bow is determined as the ratio of the maximum perpendicular distance (b_{max}) from the centre of the culm cross section to the chord drawn from the centres at either end of the reference length (L_{ref}): $b_o = b_{max}/L_{ref}$. Bow may be determined over any length, although, most typically, the reference length will be taken as the member length (L). The effect of C_{bow} in Equation Eq. 6 is perhaps more pronounced than elastic buckling theory would predict, however it is intended to enforce the use of straight culms having the smallest value of b_o possible. For this reason, b_o, may be an appropriate grading property for compression members.

Because of the reliance of buckling behaviour on a range of factors, especially the *in situ* length and restraint conditions, ISO 22156:2021 does not include provisions for member load-bearing capacity-based design for compression members. However, using the 'design by testing provisions' of

ISO 22156:2021, a load-bearing capacity approach could be adopted for very specific design scenarios. An example may be the mass production of bamboo frame or truss elements using a well-established material source. In such an instance, members having specified length and end conditions may be ubiquitous making a capacity-based grading scheme justifiably appropriate.

5.2 Establishing Compression Capacity Tables

Table 1 summarises the steps required to construct the archetypal axial load table shown in Table 2. Such tables will necessarily be very specific in terms of their parameters and will likely correspond to bamboo grades. ISO 22156:2021 prescribes the use of load duration factor to address long-term behaviour of bamboo under the effects of sustained load (due to the reduction in strength with time that bamboo, like timber, exhibits). It is therefore necessary to define the portion of load that is permanent and that which is transient (step 4, below). Typically, 100% of dead load and a portion of live load is taken as being permanent. Bamboo structures will typically be light, with their design dominated by live load effects; in this example, permanent load is taken as 30% of the total applied load, making $\alpha = 0.30$ in the calculation of the load duration factor C_{DF}:

$$C_{DF} = \alpha C_{DF,permanent} + (1 - \alpha) C_{DF,transient} \quad \text{Eq. 7}$$

Where $C_{DF,permanent}$ and $C_{DF,transient}$ are those values tabulated in ISO 22156:2021.

The material properties used in the example are representative of *P.edulis* or *G. angustafolia* bamboo (species commonly used in China and South/Central America, respectively).

Table 1 Steps for preparing compression load table.

Step		Assumptions used in constructing Table 2
1	Determine geometric properties of bamboo: *D, t, A, I*	D = 75, 100, 125, 150 mm D/t = 10
2	Determine characteristic material properties of bamboo: f_{ck}, E_k	f_{ck} = 40 MPa E_k = 12,000 MPa
3	Define Service Class	Service Classes 1 and 2
4	Proportion of total load that is 'permanent'	30%; α = 0.30
5	Calculate allowable stress from Equation 1: $f_c = f_{ck}C_R[\alpha C_{DFpermanent} + (1-\alpha)C_{DFtransient}]C_T/FS_m$ Service Class 1: f_c = 40 x 1.0 x [(0.30 x 0.60)+(0.70 x 0.75)] x 1.0 / 2 = 14.1 MPa Service Class 2: f_c = 40 x 1.0 x [(0.30 x 0.55)+(0.70 x 0.65)] x 1.0 / 2 = 12.4 MPa	C_R = 1.0 T < 38°C; C_T = 1 f_c = 14 MPa (Service 1) f_c = 12 MPa (Service 2)
6	Calculate design modulus of elasticity from Equation 2: $E_d = E_k[\alpha C_{DEpermanent} + (1-\alpha)C_{DEtransient}]C_T$ Service Class 1: E_d = 12000 x [(0.30 x 0.50)+(0.70 x 1.0)] x 1.0 = 10,200 MPa Service Class 2: E_d = 12000 x [(0.30 x 0.45)+(0.70 x 95)] x 1.0 = 9,600 MPa	T < 38°C; C_T = 1 E_d = 10,200 MPa (Service 1) E_d = 9,600 MPa (Service 2)
7	Calculate $C_{bow} = 1 - b_o/0.02$	b_o = 0 → C_{bow} = 1.0 b_o = 0.005 → C_{bow} = 0.75
8	Calculate P_c, P_e and N_{cr} for **single** culm from Equation 3	$\Sigma A = A$ and n = 1 0 m < KL < 6 m
9	For multiple-culm columns, multiply tabulated values as follows to obtain column capacity: number of culms, n < 4; multiply by 0.9n (nonredundant member) number of culms, $n \geq 4$; multiply by n	

From Table 2, a single 100 mm diameter culm having KL = 4.5 m and a bow of 0.005, has an axial capacity of 10.1 kN for Service Class 1 exposure. A column comprised of a bundle of nine such culms has a capacity of 90.9 kN while a single-culm would have a capacity of 0.9 x 10.1 = 9.1 kN accounting for the lack of redundancy (i.e. C_R = 0.9).

Table 2 Example tabulation of compressive capacities.

Axial compression capacity of **single** culm (kN) proportion of load that is permanent = 30%							f_{ck} = 40 MPa E_k = 12,000 MPa D/t = 10 C_R = 1.0 C_T = 1.0 ($T \leq 38^oC$)	
D (mm)	75		100		125		150	
b_o	0	0.005	0	0.005	0	0.005	0	0.005
KL (m)	SERVICE CLASS 1						f_c = 14 MPa E_d = 10,200 MPa	
0	22.3	22.3	39.6	39.6	61.9	61.9	89.1	89.1
0.5	22.0	21.9	39.3	39.2	61.6	61.5	88.8	88.7
1.0	21.0	20.5	38.4	38.0	60.7	60.3	88.0	87.6
1.5	19.0	17.6	36.7	35.5	59.1	58.1	86.4	85.5
2.0	15.7	13.3	33.8	31.3	56.6	54.4	84.1	82.1
2.5	12.0	9.6	29.5	25.6	52.8	48.8	80.7	77.2
3.0	9.0	7.0	24.5	20.1	47.5	41.8	76.0	70.3
3.5	6.9	5.3	19.8	15.8	41.4	34.7	69.8	62.0
4.0	5.4	4.1	16.0	12.5	35.2	28.5	62.6	53.3
4.5	4.3	3.3	13.1	10.1	29.7	23.5	55.1	45.3
5.0	3.6	2.7	10.9	8.3	25.1	19.6	47.9	38.5
5.5	3.0	2.2	9.1	6.9	21.3	16.5	41.6	32.8
6.0	2.5	1.9	7.7	5.9	18.3	14.0	36.1	28.2
KL (m)	SERVICE CLASS 2						f_c = 12 MPa E_d = 9,600 MPa	
0	19.1	19.1	33.9	33.9	53.0	53.0	76.3	76.3
0.5	18.9	18.8	33.7	33.6	52.8	52.7	76.1	76.1
1.0	18.1	17.8	33.0	32.7	52.1	51.8	75.5	75.2
1.5	16.6	15.5	31.7	30.8	50.9	50.1	74.3	73.6
2.0	14.0	12.1	29.5	27.6	49.0	47.3	72.5	71.0
2.5	11.0	8.9	26.2	23.1	46.1	43.1	69.9	67.3
3.0	8.4	6.6	22.2	18.5	42.1	37.6	66.3	62.0
3.5	6.4	5.0	18.2	14.6	37.2	31.7	61.7	55.5
4.0	5.1	3.9	14.9	11.7	32.1	26.3	56.0	48.4
4.5	4.1	3.1	12.2	9.4	27.3	21.8	49.9	41.6
5.0	3.3	2.5	10.1	7.8	23.2	18.2	43.8	35.5
5.5	2.8	2.1	8.5	6.5	19.8	15.4	38.3	30.4
6.0	2.3	1.8	7.2	5.5	17.0	13.1	33.4	26.2

6 Design of Bamboo Flexural Members

Bamboo culms and assemblies of culms are regularly used to carrying bending loads – most often when supporting floor systems. Because bamboo typically exhibits a relative high ratio of flexural strength to modulus of elasticity (i.e., f_m/E), it is flexible and flexural design will be governed by allowable deflections (Correal 2020). Allowable deflections are not prescribed by ISO 22156:2021; rather these fall into the jurisdiction of local or national building codes, or client requirements. Typical values for allowable deflections of floors are: L/360 for the application of live load only and L/240 for the combination of dead and live loads (ICC 2020).

6.1 Geometric Limitations on Flexural Members

Flexural members bent about their strong axis are susceptible to buckling – so-called 'lateral torsional buckling' or 'flexural torsional buckling' – about their weak axes. Because of the lack of reliable composite behaviour in multiple-culm flexural members, the permitted geometry of such members is limited by ISO 22156:2021. The overall depth-to-overall width ratio of multiple-culm members is limited to 3. Additionally, members must be symmetric about the centreline of their cross section. Triangular shaped members are permitted provided they are oriented such that a flat side of the triangle is located along the compression flange. For this reason, triangular members can only be used in regions of single curvature (i.e., simply supported beams). Because composite behaviour is not accounted for, wide shallow flexural members are equally as efficient as deeper sections having the same number of culms. Additionally, shallow members are less susceptible to shear deformations, do not require lateral bracing and result in lower localised bearing demands on the members at their supports. Figure 2 shows a variety of acceptable multiple-culm flexural member geometries.

Typically, the individual culms in a multiple culm flexural member will be in contact with each other, constrained by the stitch connections. Nonetheless, in order to accommodate the intersection of transverse members, ISO 22156 permits culms in a flexural member to be separated by a distance no greater than the average diameter of the culms comprising the member.

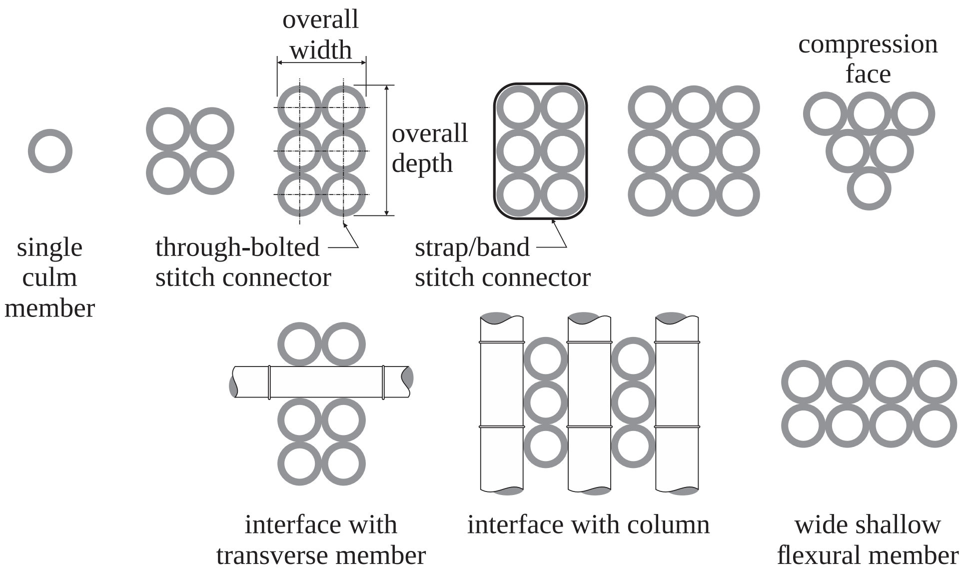

Figure 2 Examples of permitted bamboo flexural member geometry.

6.2 Flexural Capacity

Once again, since composite behaviour is not permitted, the flexural capacity (M_r) of a multiple-culm bending member is determined as the sum of the constituent culm capacities (ΣM_i) or from the sum of the constituent culm elastic section moduli (ΣS_i), that is:

$$M_r = \sum M_i \qquad \text{[ACD]} \qquad \text{Eq. 8a}$$

$$M_r = f_m \times \sum S_i \qquad \text{[ASD]} \qquad \text{Eq. 8b}$$

Where f_m is the modulus of rupture of the bamboo.

Deflections are similarly determined from the sum of the culm stiffnesses ($\Sigma(EI)_i$) or moments of inertia (ΣI_i):

$$EI = \sum (EI)_i \times C_V \qquad \text{[ACD]} \qquad \text{Eq. 9a}$$

$$EI = E_d \times \sum I_i \times C_V \qquad \text{[ASD]} \qquad \text{Eq. 9b}$$

ISO 22156:2021 includes a number of provisions intended to ensure longitudinal splitting does not affect culm bending behaviour. Nonetheless, the highly anisotropic nature of bamboo results in a measurable ‘softening’ of the flexural behaviour in the presence of shear (Richard et al. 2017). This effect is predicted by beam theory (Timoshenko 1921) but is typically neglected in most materials except over very short spans. The modification factor for shear deformations, C_V, given by ISO 22156:2021, reduces the bending stiffness for members having a shear span-to-culm diameter ratio (*a/D*) less than 10:

$$C_v = 0.50 + 0.05\left(\frac{a}{D}\right) \leq 1.0 \qquad \text{Eq. 10}$$

The shear span, a, is the shortest distance between a location of maximum moment and the nearest point of inflection (zero moment). For a simple span beam subject to uniformly distributed load, the shear span is equal to one half the span. The introduction of the modification factor is intended to incentivise flexure-dominant members having spans longer than 20D.

Using ACD, however, ISO 22156:2021 permits the allowable flexural design capacity of a multiple-culm member to be used explicitly. This would require a testing protocol suitable for determining such a characteristic capacity. Similar to compression members, taking such an approach may be beneficial when fabricating flexural members on an industrial scale; using such an approach, the extent of partial composite behaviour that can be developed is implicit in the resulting characteristic or design capacity.

Although composite behaviour in bending is difficult to achieve in practice and is not permitted in ISO 22156:2021, culms in multiple-culm flexural members (like columns) must be 'stitched' together at intervals no greater than 10 times the smallest culm diameter comprising the member. The stitch connections force all culms in the multi-culm member to deflect in the same direction, help to distribute load internally in the member and help to limit buckling of culms placed in compression. The stitch, however does not make the member act in a fully composite manner.

An important implication of ISO 22156:2021 not accounting for composite behaviour is that, since forces are not transferred between culms, bamboo flexural members must be prismatic; that is the number of culms in the cross section cannot vary along the length of the member. Nevertheless, such tapered members can be designed using a corbelling or hammer-beam approach to the changing section depth rather than considering the member as a single tapered beam.

6.3 Shear Capacity

Bamboo is susceptible to shear-dominated behaviour. Where practical, members subject to transverse loading should be designed to mitigate shear modes of failure although this is not always possible. As such, design for flexure using an ACD approach should account for shear and the length of such members prescribed such that shear is not critical. Using strength-based design, the shear capacity of a member in flexure is determined as the sum of the shear capacities of the culms comprising the member.

ISO 22156:2021 defines the shear capacity of a bamboo culm based on fundamental mechanics which places the maximum shear at the neutral axis of the single culm cross section. The shear capacity, V_r, is derived from the equations for shear flow at this longitudinal section:

$$V_r = f_v \times \sum \frac{3\pi t}{8} \frac{D^4-(D-2t)^4}{D^3-(D-2t)^3} \quad \text{Eq. 11}$$

Where f_v is the shear strength parallel to the fibres of the bamboo. The term in the summation is the shear area (A_v) of the cross section. Applying the fundamental mechanics solution for shear in a thin-walled pipe (Timoshenko 1921), this term may be approximated as $A_v = A/2$, where A is the area of the culm. Such a simplification is marginally conservative resulting in a 2.6% underestimation of Equation 11 when $D/t = 6$ and a 0.8% underestimation for $D/t = 10$.

6.4 Establishing Flexural Capacity Span Tables

Table 3 summarises the steps required to construct the archetypal flexural capacity load tables shown in Tables 5 and 6. Such tables will be very specific in terms of their parameters and will likely correspond to bamboo grades. The same material properties and sustained load ratio (i.e., α = 0.30) as used to develop compression capacity tables are used for the flexural capacity tables. Table 4 summarises the equations for moment, shear and deflection of uniformly loaded beams having simple and multiple continuous span arrangements. In developing Tables 5 and 6, only three configurations are used: simple span, two span, and 3+ spans. Using the design values for 3+ spans, design values for beams having four or more spans are marginally conservative.

In the resulting span tables, two values are given for each case. $w(f)$ is the uniformly applied load corresponding the achieving the lesser of the flexural (Eq. 8) and shear (Eq. 11) capacities. When the value is given in bold font, it is a shear capacity indicating the member is not flexure critical. $w(\Delta)$ is the uniformly applied load corresponding to achieving the prescribed deflection limit ($\Delta = L/240$ for the example shown; see step 10 in Table 3). The tabulated values are uniform loads applied along the length of the flexural member reported in units of kN/m. To obtain an allowable uniformly distributed load (ρ in units of kN/m^2), the reported values are divided by the spacing of the flexural members; i.e.:

$\rho = w/spacing$. Thus, the span tables are equivalent to reporting uniformly distributed loads in units of kPa for the case in which flexural member spacing is 1 m.

From Table 5, a single 9 m long, 100 mm diameter culm that is continuous over three spans (i.e., L = 3 m), has a flexural load carrying capacity of 0.96 kN/m (w) for Service Class 1 exposure. If deflection is limited to L/240, the capacity is 0.70 kN/m (Δ). The culm is flexure critical. If such single culms spaced at 0.5 m comprise a floor system, the load carrying capacity is 0.96/0.5 = 1.92 kPa and deflection-limited capacity is 1.4 kPa.

Table 3 Steps for preparing flexural capacity span tables.

	Step	Assumptions used in constructing Tables 6 and 7
1	Determine geometric properties of bamboo: *D, t, A, I, S*	D = 75, 100, 125, 150 mm D/t = 10
2	Determine characteristic material properties of bamboo: f_{mk}, f_{vk}, E_k	f_{mk} = 45 MPa; f_{vk} = 8 MPa E_k = 12,000 MPa
3	Define Service Class	Service Classes 1 and 2
4	Proportion of total load that is 'permanent'	30%; α = 0.30
5	Calculate allowable stress from Equation 1: $f_c = f_{ck}C_R[\alpha C_{DFpermanent} + (1\text{-}\alpha)C_{DFtransient}]C_T/FS_m$ Service Class 1: f_m = 45 x 1.0 x [(0.30 x 0.60)+(0.70 x 0.75)] x 1.0 / 2 = 15.8 MPa f_v = 8 x 1.0 x [(0.30 x 0.60)+(0.70 x 0.75)] x 1.0 / 4 = 1.4 MPa Service Class 2: f_m = 45 x 1.0 x [(0.30 x 0.55)+(0.70 x 0.65)] x 1.0 / 2 = 14.0 MPa f_v = 8 x 1.0 x [(0.30 x 0.55)+(0.70 x 0.65)] x 1.0 / 4 = 1.2 MPa	C_R = 1.0 T < 38°C; C_T = 1 f_m = 16 MPa (Service 1) f_v = 1.4 MPa (Service 1) f_m = 14 MPa (Service 2) f_v = 1.2 MPa (Service 2)
6	Calculate design modulus of elasticity from Equation 2: $E_d = E_k[\alpha C_{DEpermanent} + (1\text{-}\alpha)C_{DEtransient}]C_T$ Service Class 1: E_d = 12000 x [(0.30 x 0.50)+(0.70 x 1.0)] x 1.0 = 10,200 MPa Service Class 2: E_d = 12000 x [(0.30 x 0.45)+(0.70 x 95)] x 1.0 = 9,600 MPa	T < 38°C; C_T = 1 E_d = 10,200 MPa (Service 1) E_d = 9,600 MPa (Service 2)
7	Identify support configuration as shown in Table 5	see Table 5
8	Calculate values of *M* and *V* for **single** culm from Equations 8 and 11, respectively	$\Sigma A = A$ and $\Sigma S = S$
9	Using the moment and shear equations given in Table 4, calculate *w(f)* for a range of spans, *L*; tabulate the **lesser** of the values determined for moment and shear capacity. Identify those cases in which shear capacity controls design.	0 m < *L* < 6 m
9	Calculate from Equation 10: $C_v = 0.5 + 0.05(a/D) \leq 1.00$	$a = L/2$
10	Using the deflection equations given in Table 4, calculate *w(Δ)* to cause specified deflection.	$\Delta = L/240$ 0 m < *L* < 6 m
11	For multiple-culm members, multiply tabulated values as follows to obtain beam capacity: number of culms, $n < 4$; multiply by 0.9*n* (nonredundant member) number of culms, $n \geq 4$; multiply by *n*	

Table 4 Design forces and deflections for beams having uniformly distributed load across all spans.

	Moment	Shear	Deflection
simple span	$M_r = 0.125wL^2$	$V_r = 0.500wL$	$\Delta = 0.0130wL^4/EI$
two span continuous	$M_r = 0.125wL^2$	$V_r = 0.600wL$	$\Delta = 0.0054wL^4/EI$
three span continuous	$M_r = 0.100wL^2$	$V_r = 0.600wL$	$\Delta = 0.0069wL^4/EI$
four or more spans	$M_r = 0.107wL^2$	$V_r = 0.607wL$	$\Delta = 0.0065wL^4/EI$

$w = \rho$ x *spacing of flexural members* = uniformly distributed load (kN/m) along flexural member.
L = length of individual span; all continuous spans are of equal length
ρ = uniform design load (kPa)

Table 5 Example tabulation of flexural capacities (Service Class 1).

Uniform load bearing capacity of **single** culm (kN/m) proportion of load that is permanent = 30% *w(f)* = uniform load capacity based on strength values in ***bold*** are controlled by shear capacity of culm *w(Δ)* = uniform load to cause maximum deflection = L/240											f_{mk} = 45 MPa f_{vk} = 8 MPa E_k = 12,000 MPa *D/t* = 10 C_R = 1.0 C_T = 1.0 (T ≤ 38°C)		
D (mm)		75			100			125			150		
SERVICE CLASS 1											f_m = 16 MPa f_v = 1.4 MPa E_d = 10,200 MPa		
M (Nm)		391			927			1811			3130		
V (N)		1113			1979			3093			4453		
spans		1	2	3+	1	2	3+	1	2	3+	1	2	3+
L (m)													
0.5	*w(f)*	***4.45***	***3.56***	***3.67***	***7.92***	***6.33***	***6.52***	***12.4***	***9.90***	***10.2***	***17.8***	***14.2***	***14.7***
	w(Δ)	16.0	38.5	32.0	47.4	114	94.8	111	267	222	224	539	448
1	*w(f)*	***2.23***	***1.78***	***1.83***	***3.96***	***3.17***	***3.26***	***6.19***	***4.95***	***5.09***	***8.91***	***7.13***	***7.34***
	w(Δ)	2.50	6.01	5.00	7.11	17.1	14.2	16.2	39.0	32.4	32.0	77.0	64.0
1.5	*w(f)*	1.39	***1.19***	***1.22***	***2.64***	***2.11***	***2.17***	***4.12***	***3.30***	***3.40***	***5.94***	***4.75***	***4.89***
	w(Δ)	0.89	2.14	1.78	2.46	5.91	4.91	5.48	13.2	11.0	10.7	25.7	21.3
2	*w(f)*	0.78	0.78	0.91	1.85	***1.58***	***1.63***	***3.09***	***2.47***	***2.55***	***4.45***	***3.56***	***3.67***
	w(Δ)	0.37	0.90	0.75	1.18	2.85	2.37	2.60	6.26	5.20	5.00	12.0	9.99
2.5	*w(f)*	0.50	0.50	0.59	1.19	1.19	***1.30***	2.32	***1.98***	***2.04***	***3.56***	***2.85***	***2.93***
	w(Δ)	0.19	0.46	0.38	0.61	1.46	1.21	1.48	3.56	2.96	2.81	6.77	5.63
3	*w(f)*	0.35	0.35	0.41	0.82	0.82	0.96	1.61	1.61	***1.70***	2.78	***2.38***	***2.45***
	w(Δ)	0.11	0.27	0.22	0.35	0.84	0.70	0.86	2.06	1.71	1.78	4.28	3.55
3.5	*w(f)*	0.26	0.26	0.30	0.61	0.61	0.71	1.18	1.18	1.38	2.04	***2.04***	***2.10***
	w(Δ)	0.07	0.17	0.14	0.22	0.53	0.44	0.54	1.30	1.08	1.12	2.69	2.24
4	*w(f)*	0.20	0.20	0.23	0.46	0.46	0.54	0.91	0.91	1.06	1.56	1.56	1.83
	w(Δ)	0.05	0.11	0.09	0.15	0.36	0.30	0.36	0.87	0.72	0.75	1.80	1.50
4.5	*w(f)*	0.15	0.15	0.18	0.37	0.37	0.43	0.72	0.72	0.84	1.24	1.24	1.44
	w(Δ)	0.03	0.08	0.07	0.10	0.25	0.21	0.25	0.61	0.51	0.53	1.27	1.05
5	*w(f)*	0.13	0.13	0.15	0.30	0.30	0.35	0.58	0.58	0.68	1.00	1.00	1.17
	w(Δ)	0.02	0.06	0.05	0.08	0.18	0.15	0.19	0.45	0.37	0.38	0.92	0.77
5.5	*w(f)*	0.10	0.10	0.12	0.25	0.25	0.29	0.48	0.48	0.56	0.83	0.83	0.97
	w(Δ)	0.02	0.04	0.04	0.06	0.14	0.11	0.14	0.33	0.28	0.29	0.69	0.58
6	*w(f)*	0.09	0.09	0.10	0.21	0.21	0.24	0.40	0.40	0.47	0.70	0.70	0.81
	w(Δ)	0.01	0.03	0.03	0.04	0.11	0.09	0.11	0.26	0.21	0.22	0.53	0.44

Table 6 Example tabulation of flexural capacities (Service Class 2).

Uniform load bearing capacity of **single** culm (kN/m) proportion of load that is permanent = 30% *w(f)* = uniform load capacity based on strength values in ***bold*** are controlled by shear capacity of culm *w(Δ)* = uniform load to cause maximum deflection = L/240											f_{mk} = 45 MPa f_{vk} = 8 MPa E_k = 12,000 MPa D/t = 10 C_R = 1.0 C_T = 1.0 (T ≤ 38ºC)		
D (mm)		75			100			125			150		
SERVICE CLASS 2											f_m = 14 MPa f_v = 1.2 MPa E_d = 9,600 MPa		
M (Nm)		342			811			1585			2739		
V (N)		954			1693			2651			3817		
spans		1	2	3+	1	2	3+	1	2	3+	1	2	3+
L (m)													
0.5	*w(f)*	***3.82***	***3.05***	***3.14***	***6.79***	***5.43***	***5.59***	***10.6***	***8.48***	***8.73***	***15.3***	***12.2***	***12.6***
	w(Δ)	15.0	36.2	30.1	44.6	107	89.2	104	252	209	211	507	421
1	*w(f)*	***1.91***	***1.53***	***1.57***	***3.39***	***2.71***	***2.79***	***5.30***	***4.24***	***4.37***	***7.63***	***6.11***	***6.29***
	w(Δ)	2.35	5.66	4.70	6.69	16.1	13.4	15.2	36.7	30.5	30.1	72.4	60.2
1.5	*w(f)*	1.22	***1.02***	***1.05***	***2.26***	***1.81***	***1.86***	***3.53***	***2.83***	***2.91***	***5.09***	***4.07***	***4.19***
	w(Δ)	0.84	2.01	1.67	2.31	5.57	4.62	5.16	12.4	10.3	10.0	24.2	20.1
2	*w(f)*	0.68	0.68	***0.79***	1.62	***1.36***	***1.40***	***2.65***	***2.12***	***2.18***	***3.82***	***3.05***	***3.14***
	w(Δ)	0.35	0.85	0.71	1.11	2.68	2.23	2.45	5.90	4.90	4.70	11.3	9.40
2.5	*w(f)*	0.44	0.44	0.51	1.04	1.04	***1.12***	2.03	***1.70***	***1.75***	***3.05***	***2.44***	***2.52***
	w(Δ)	0.18	0.43	0.36	0.57	1.37	1.14	1.39	3.35	2.79	2.65	6.38	5.30
3	*w(f)*	0.30	0.30	0.36	0.72	0.72	0.84	1.41	1.41	***1.46***	2.43	***2.04***	***2.10***
	w(Δ)	0.10	0.25	0.21	0.33	0.80	0.66	0.81	1.94	1.61	1.67	4.03	3.34
3.5	*w(f)*	0.22	0.22	0.26	0.53	0.53	0.62	1.04	1.04	1.21	1.79	***1.74***	***1.80***
	w(Δ)	0.07	0.16	0.13	0.21	0.50	0.42	0.51	1.22	1.02	1.05	2.53	2.11
4	*w(f)*	0.17	0.17	0.20	0.41	0.41	0.47	0.79	0.79	0.93	1.37	1.37	**1.57**
	w(Δ)	0.04	0.11	0.09	0.14	0.34	0.28	0.34	0.82	0.68	0.71	1.70	1.41
4.5	*w(f)*	0.14	0.14	0.16	0.32	0.32	0.37	0.63	0.63	0.73	1.08	1.08	1.26
	w(Δ)	0.03	0.07	0.06	0.10	0.24	0.20	0.24	0.58	0.48	0.50	1.19	0.99
5	*w(f)*	0.11	0.11	0.13	0.26	0.26	0.30	0.51	0.51	0.59	0.88	0.88	1.02
	w(Δ)	0.02	0.05	0.05	0.07	0.17	0.14	0.17	0.42	0.35	0.36	0.87	0.72
5.5	*w(f)*	0.09	0.09	0.11	0.21	0.21	0.25	0.42	0.42	0.49	0.72	0.72	0.85
	w(Δ)	0.02	0.04	0.03	0.05	0.13	0.11	0.13	0.32	0.26	0.27	0.65	0.54
6	*w(f)*	0.08	0.08	0.09	0.18	0.18	0.21	0.35	0.35	0.41	0.61	0.61	0.71
	w(Δ)	0.01	0.03	0.03	0.04	0.10	0.08	0.10	0.24	0.20	0.21	0.50	0.42

7 Design Examples Using Tables

The following examples are intended to be sufficiently simple to be illustrative of the use of the design tables developed in the previous sections. In these examples, two ‘grades’ – defined by their diameter in this instance – of *P. edulis* bamboo culms are assumed to be available (Table 7); these correspond to the materials presented in Tables 2, 5 and 6, and are representative of typically-reported properties (Chung and Yu 2002; Gauss et al. 2019; Zhou et al. 2021).

Table 7 Grade properties of bamboo (determined from ISO 22157) used for examples.

D	D/t	f_{ck}	f_{mk}	f_{vk}	E_k	ρ	w	b_o	available length
mm		MPa	MPa	MPa	MPa	kg/m^3	kg/m		m
75	10	40	45	8	12000	790	1.3	< 0.005	12
125	10	40	45	8	12000	790	3.5	< 0.005	12

The basis of the design examples is a prototype two storey, 3 x 3 bay, residential structure having bay sizes 4 m x 3.5 m and 3.2 m storey height. The prototype is shown schematically in Figure 3. For the sake of the examples presented, only the gravity loads reported in Table 8 are considered. 30% of the total load is assumed to be permanent (i.e., 0.9 kPa). Floor deflections are limited to $L/240$ under the effects of the total load.

Table 8 Uniformly-distributed gravity loads assumed for examples.

	dead load (DL)	live load (LL)	total load
roof	0.3 kPa	0.5 kPa	0.8 kPa
first floor	0.3 kPa	1.9 kPa	2.2 kPa

The structure is designed for Service Class 2: “characterised by an equilibrium moisture content in the bamboo not exceeding 20%.”[5] and the service temperature is below 38°C.

7.1 Interior Ground Floor Column

Load on interior ground floor column B2 = 4 m x 3.5 m x [2.2 kPa + 0.8 kPa] = 42 kN

Assume column is pin-ended and laterally restrained[6]; K = 1.1; KL = 3.2 x 1.1 = 3.5 m

Enter the lower portion (Service Class 2) of Table 2 using KL = 3.5 and b_o = 0.005 and determine suitable multi-culm column design:

[5] ISO 22156:2021 §5.6.2
[6] ISO 22156:2021 §9.2

From Table 2, the capacity of a single 75 mm culm = 5.0 kN; therefore, a nine-culm column, having a capacity of 45 kN is required. This requires 144 – 6.4 m long 75 mm diameter culms (1200 kg) for the entire prototype structure. Similarly, the capacity of a single 125 mm culm = 31.7 kN. For a two culm column, C_R = 0.9 making the capacity 57 kN. This requires 32 – 6.4 m long 125 mm diameter culms (720 kg) for the structure.

7.2 Floor Joist Design

Using Table 6 (Service Class 2), determine the capacity of a single culm for the various span options (length and continuity) consistent with the structure; potential designs are summarised in Table 9. Shorter, 3.5 m span lengths are used when the joists are oriented in the N-S direction (Figure 3), whereas 4 m spans result when spanning the E-W direction. In order to permit[7] C_R = 1.1, joists must be continuous over at least two spans and have a spacing not exceeding 600 mm.

Table 9 Example joist designs.

span length	m	3.5				4.0			
span arrangement		1 span		3 span		1 span		3 span	
C_R		1.0	1.0	1.1	1.1	1.0	1.0	1.1	1.1
culm diameter	mm	75	125	75	125	75	125	75	125
Table 6 *w(f)*	kN/m	0.22	1.04	0.26	1.21	0.17	0.79	0.20	0.93
Table 6 *w(Δ)*	kN/m	0.07	0.51	0.13	1.02	0.04	0.34	0.09	0.68
culms required: 2.2 kPa/(C_R x [min *w(f)*, *w(Δ)*])	culms/m	32	4.3	16	2	55	6.5	23	3
single culm spacing	mm	-	230	-	500	-	150	-	325
double culm spacing	mm	-	460	-	1000[4]	-	300	-	600
four culm spacing	mm	-	1000	250	2000[8]	-	600	-	1200[4]

For the spans considered, 75 mm diameter culm joists are shown to be impractical. When feasible, single culm joists are easiest to erect and since design is deflection controlled, continuous joists are most efficient and preferable. Two alternate designs result: 1) 125 mm culms at 500 mm spacing spanning continuously over three 3.5 m spans; or, 2) 125 mm culms spaced at 325 mm (or pairs of culms at 600 mm) spanning continuously over three 4 m spans.

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[7] ISO 22156:2021 §5.4
[8] C_R = 1.0 since spacing > 600 mm

7.3 Alternate Primary Beam Designs

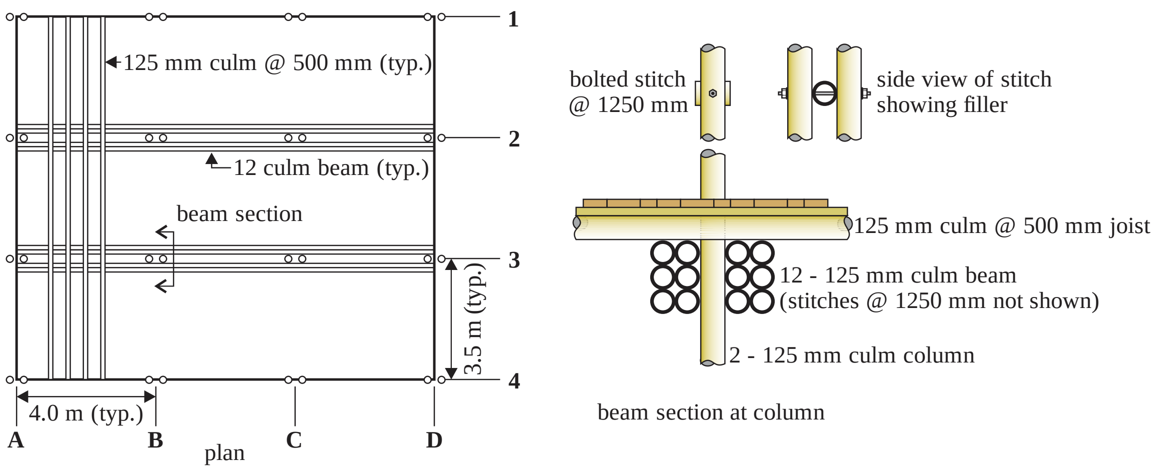
Using the two joist alternates, supporting primary beams (girders) are designed in the same manner as the joists as described in Table 10.

Table 10 Primary beam designs for two alternate joist arrangements.

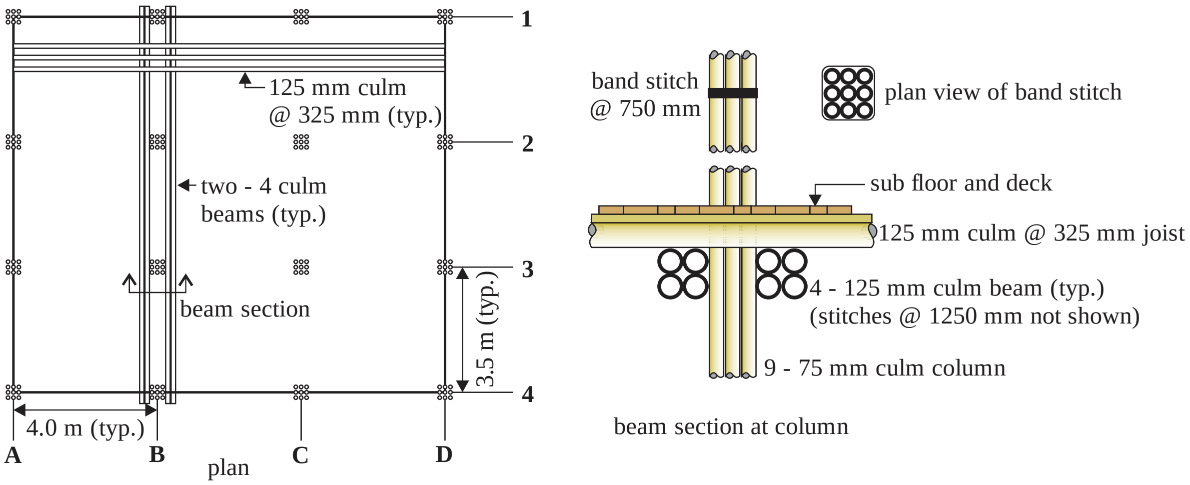
		Alternate 1		Alternate 2	
joist selection		125 mm culms @ 500 mm 3 – 3.5 m span continuous		125 mm culms @ 325 mm 3 – 4.0 m span continuous	
primary beam span length	m	4.0		3.5	
primary beam line load		2.2 kPa x 3.5 m = 7.7 kN/m		2.2 kPa x 4.0 m = 8.8 kN/m	
span arrangement		1 span	3 span	1 span	3 span
C_R		1.0	1.1	1.0	1.1
culm diameter	mm	125	125	125	125
Table 6 *w(f)*	kN/m	0.79	0.93	1.04	1.21
Table 6 *w(Δ)*	kN/m	0.34	0.68	0.51	1.02
culms required: 7.7 kN/m/(C_R x [min *w(f)*, *w(Δ)*])	culms	23	11	18	8
resulting beam (depth x width)	mm	4 x 6 culm (500 x 750)	3 x 4 culm (375 x 500)	3 x 6 culm (375 x 750)	2 x 4 culm (250 x 500)
125 mm culms required for floor system (12 m each)		121 (5100 kg)	73 (3100 kg)	106 (4500 kg)	66 (2800 kg)

Multiple culm members require stitches (see Figure 2) located at intervals along their length not exceeding 10 times the smallest culm diameter comprising the member (ISO 22156:2021). Thus, in Alternate 1, stitches are required over the height of the columns at no greater than 1250 mm spacing; these stitches will require a ‘filler’ element as shown in the detail of Figure 3a. Stitches are required for the beams of Alternative 1 also at a spacing not exceeding 1250 mm. Similarly, stitches are required at spacings not exceeding 750 mm and 1250 mm for the columns and beams of Alternate 2. Stitches are not required for the floor joists since attachment of the sub floor will provide the necessary connection. For clarity, only column stitches are shown in Figure 3.

Schematic representations of both alternate designs at a typical interior column are shown in Figure 3. Figure 3a shows two – 125 mm culm columns whereas Figure 3b shows nine – 75 mm culm columns. Although the designs are quite similar (as expected for an essentially uniform structure), using beam span tables illustrates how simple ‘what if’ scenarios can be assessed and alternate designs quickly generated. In this case, the economy (in terms of bamboo material required) of Alternate 2 having 75 mm columns (requiring only about 3500 kg of bamboo) over Alternate 1 (4300 kg) and all other options is apparent.



a) Alternate 1 with 125 mm culm columns; beams span 4 m direction; joists span 3.5 m direction



a) Alternate 2 with 75 mm culm columns; beams span 3.5 m direction; joists span 4 m direction

Figure 3 Example prototype structure and resulting alternate designs.

8 Conclusions

This paper demonstrates an approach for developing design load tables for full culm bamboo elements for compression and flexure. The specific tables presented in this paper are illustrative and are not intended to be used directly. The approach for developing design tables presented is based on provisions of ISO 22156:2021 and is compatible with a material strength grading procedure as described by ISO 19624:2018. In developing example tables, it is assumed that grading is species-specific and addresses culm diameter, wall thickness, compressive strength and modulus, and flexure and shear strength. These may be combinations of dependent and grade-determining properties (ISO 19624:2018) provided that they are known. Simple examples of the use of the design load tables is demonstrated.

Prior to the synthesis of these two standards, generation of such load tables was not be practical. Such load tables can be developed for a range of bamboo properties and are most appropriate for "national annexes" appended to ISO 22156:2021 upon its adoption by a jurisdiction. Load tables can also be developed as bespoke in-house design aides based on specific properties. Load tables are familiar to engineers, reduce the need for repetitive calculation and allow for easy 'what-if' queries during design. They also permit rapid communication of minimum design requirements if applied using standard-prescribed minimum material properties.

The example tables developed in this paper were created using Excel spreadsheet software; a copy is available from the corresponding author.

Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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