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Low-cost bamboo lattice towers for small wind turbines

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ABSTRACT

We investigate the feasibility of using bamboo in triangular lattice towers, to be used with small wind turbines. To examine the feasibility, experimental tests on bamboo's material properties and design analysis of a 12 m high bamboo tower for a 500 W wind turbine have been carried out. Essential material properties of a typical bamboo species for structural analysis of the tower have been experimentally determined. Analytical and finite element methods have been used in the analysis. The result of this study demonstrates the feasibility of designing bamboo lattice towers for small wind turbines, which shows promising cost reduction potential for small wind turbine towers in developing countries.

Introduction

Small wind turbines can offer an economic option for electricity generation in off-grid remote regions of developing countries. Small wind turbines are categorized by their rated power being less than 50 kW (IEC Standard 61400-3, 2006; Wood, 2011). Most of these turbines are installed on steel monopole towers, which are often difficult to transport to remote locations. Clifton-Smith and Wood (2010) reported that the manufacturing cost of monopole towers can be 30–40% of the installation cost. Moreover, the cost of transportation to remote areas can be very high where there are no roads for transportation. In order to minimize the costs of manufacture, transportation, and utilize natural and sustainable materials, we investigate the feasibility of using bamboo in triangular lattice towers.

For bamboo to be used in small towers, a suitable tower design must be selected. Until now, very few studies have focused on design aspects of small wind turbine towers. Wood (2011) analyzed monopole and lattice towers based on the safety requirements of (IEC Standard 61400-3, 2006). Clifton-Smith and Wood (2010) presented a numerical optimization procedure for self-supporting octagonal monopole towers. Clausen et al. (2011) studied the design of self-supporting triangular and square lattice towers using finite element analysis (FEA). Adhikari et al. (2014) developed a design procedure for triangular and rectangular steel lattice towers and showed that avoiding buckling in the downwind leg is a crucial design requirement. These studies have suggested that self-supporting lattice towers are cheaper than the monopoles. Moreover, lattice towers can be manufactured using simple technology and with minimum workmanship. In this paper, we investigate the feasibility of self-supporting bamboo lattice towers to be used with small wind turbines. Because bamboo has naturally tubular sections, it should be ideal for tubular lattice towers provided it is sufficiently strong. As an example, we present a design analysis of a 12 m high triangular lattice tower considering the load cases of a 500 W wind turbine. After establishing the necessary material properties through experimental tests, we use the analytical and FEA techniques to examine the structural behavior of the bamboo tower. The context of this work is a number of renewable energy projects the authors are working on in Nepal, so we consider only the material properties of the *Bambusa Arundinacea* species of bamboo, which is commonly available in that country. It is demonstrated that bamboo is a feasible material for the 12 m tower for a 500 W turbine.

The triangular lattice tower

Triangular lattice towers consist of three legs positioned at the corners of an equilateral triangle, which are braced at regular intervals by horizontal- and cross-bracings as shown in Fig. 1. It is possible to design lattice towers with different bracing configurations; however, we consider only the horizontal and cross-bracing configuration shown in Fig. 1. In the design of lattice towers, the tower-top width should be kept as small as possible to allow adequate clearance between the blades and tower. Assuming that the tower-top width is small compared to the base distance between the legs and removing the horizontal- and cross-bracings, the triangular lattice tower can be modeled as a tripod consisting of three legs as its main load carrying structural elements as shown in Fig. 2. This allows calculation of approximate stress on tower legs as well as tower deflection based on the analysis developed in Ref. (Adhikari et al., 2014).

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Nomenclature

A	cross-sectional area of tower legs
b	base distance between tower legs (m)
C_d	drag coefficient
D	external diameter of tower legs (mm)
E	modulus of elasticity of bamboo (GPa)
F	thrust on turbine blades at extreme wind speed (N)
h	height of tower (m)
I	moment of inertia of bamboo columns (m^4)
$I(y)$	moment of inertia of the tower section (m^4)
l	length of leg section (m)
$M(y)$	bending moment (Nm)
q	drag force per unit length on tower members (N/m)
R_1	internal radius of bamboo section, tower legs (mm)
R_2	external radius of bamboo section, tower legs (mm)
t	thickness of bamboo section (mm)
U	extreme wind speed (m/s)
v	Poisson ratio of bamboo
$v(y)$	deflection of tower (mm)
W	weight of turbine (N)
W_t	weight of tower (N)
ρ	density of air (1.225 kg/m^3)
σ_a	axial stress (N/m^2)
σ_b	bending stress (N/m^2)
σ_{cb}	characteristic buckling strength (N/m^2)

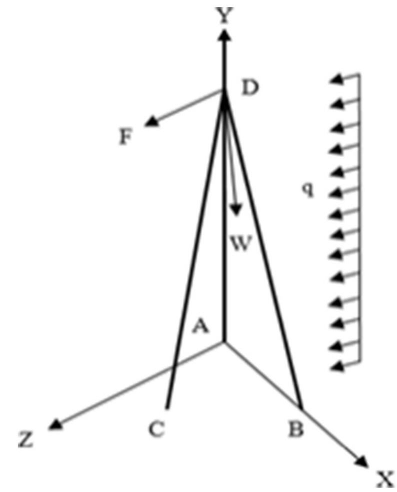

Fig. 2. Free body diagram (FBD) of the tripod model. The legs are denoted by AD, BD, and CD. The turbine is mounted at point D. The arrows indicate the direction of forces.

Bamboo as a material for lattice towers

The predominant materials for wind turbine towers are steel and concrete. Very recently, timber has been investigated for large wind turbine towers, and a prototype has been built for a 1.5 MW wind turbine in Germany (Prototype Timber Tower). Ultra high performance reinforced concrete (UPHRC) was investigated in Francois-Xavier (2009) and is used by some current large wind turbine manufacturers. In this study, we investigate the feasibility of using bamboo as a structural material in triangular lattice towers for small wind turbines. Use of bamboo has several benefits; it is a cheap, renewable, and sustainable material that grows quickly and easily in many developing countries. Because of its low cost and good tensile, compressive and buckling properties, it is a promising natural material that shows its suitability in lattice towers. Presently, bamboo is widely used for scaffolding (Yu et al., 2003), and many other temporary structures (Janssen, 1981), particularly in developing countries.

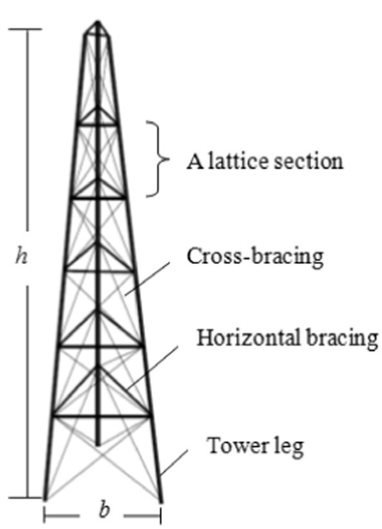

Fig. 1. Structural model of the triangular lattice tower.

As a natural material, bamboo grows as a hollow cylindrical structure with repeating solid diaphragms along the length. Bamboo's tubular structure makes it suitable for lattice tower, which would not require any structural modifications. It possesses a fiber-composite structure, in which cellulose fibers are reinforced longitudinally in the lignin matrix (Ghavami et al., 2003; Amada, 1997).The composite structure of the wall combined with its hollow tubular structure and periodic diaphragms provides high buckling strength, which is a very important property for lattice tower members. Ghavami et al. (2003) and Amada (1997) studied bamboo structure through digital image analysis and found more densely packed fibers towards outer wall. This gradient structure exhibits excellent tensile, compressive, and buckling strengths and stiffness properties in the longitudinal direction (Ghavami et al., 2003; Tan et al., 2011; Silva et al., 2006), despite the much lower transverse strength. Silva et al. (2006) used finite element methods to determine the mechanical properties by assuming the composite structure was a homogenized material. Bamboo has tensile strength of 135–357 MPa in the longitudinal direction (Adhikari, 2013). Similarly, compressive strengths are reported in the range of 44–117 MPa depending upon the species and moisture content (Adhikari, 2013). Elastic modulus and Poisson ratio are reported in the range of 13–23 GPa and 0.3–0.35 respectively (Adhikari, 2013). More information on composite structure and basic mechanical properties of bamboo can be found in Adhikari (2013).

If bamboo is to be used in lattice towers, it should meet design requirements, such as the avoidance of buckling at extreme wind loads (Wood, 2011; Clausen et al., 2011; Adhikari et al., 2014), as determined by the international standard for small wind turbine safety (IEC Standard 61400-3, 2006). Therefore, the buckling strength of bamboo columns must be characterized. Another important design consideration is the strength of joints connecting the tower members. We propose a method of joining bamboo sections that prevents splitting as well as weathering. This is essential to preserve the strength of bamboo sections over the design life-span of the tower, which ideally is 20 years. The prime candidate is a cylindrical steel cap system, described in the section on Joining techniques, to hold two vertical members coaxially. A single cap design can be used for the whole tower. Detailed joint design and surface coating are not considered in this study which concentrates on establishing the feasibility of bamboo in terms of strength on the grounds that joints and weathering should be considered only if bamboo is likely to be sufficiently strong.

Experimental tests on bamboo

As the dominant mode of failure in lattice towers is by buckling of tower legs (Wood, 2011; Clausen et al., 2011; Hau, 2006), we carried out experimental tests to characterize the buckling strength of bamboo columns, and to determine the elastic modulus, Poisson's ratio, and maximum compressive strength.

Materials

The bamboo species used in the experiments was *Bambusa Arundinacea*, which is commonly known as tama bamboo in Nepal. This species is one of the strongest available in Nepal and it grows in most parts of the country. Straight bamboo culms were obtained from plantations of about 3–4 years of age as specified by the test protocol (ISO, 2004). To prepare the test specimens, straight sections of the culms, from bottom to top sections of bamboo plant, were cut into different lengths ranging from 700 to 1500 mm, having typical diameters between 45 and 70 mm. Only straight sections of bamboo were used for the test specimens; straightness was decided by visual inspection. The specimens for the compression and buckling tests were obtained from the same bamboo sections. Since mechanical properties of bamboo depend upon moisture content (Yu et al., 2003; Janssen, 1981), the specimens were dried for one and half months until the moisture content was reduced below 20% before testing. Yu et al. (2003) showed that bamboo possesses good mechanical properties below 20% moisture content and more importantly, consistent mechanical properties could be obtained from the experimental tests.

Experimental methods

Two machines were used in the tests; one has a load rating 100 tons and data logging capability of 20 kg/division, while the other one, shown in Fig. 3, is rated at 10 tons with load–deflection recording capability at 1 mm/min. For the buckling tests, the specimens were aligned vertically in the test machine (Fig. 3) and an axial compressive load was then applied. No rotation or translation of the specimens was allowed, to simulate the fixed end connections of tower members. The load was recorded after the buckling failure was observed in the test specimen. A typical indication of buckling failure was a small notch-like crack or indentation at around middle section of the column.

To determine the elastic modulus and Poisson ratio, compressive testing was carried out. The specimens were prepared according to the test protocol (ISO, 2004), which requires that the length of the specimen must be between *D* and 2*D*. In the compression test, load, deformation and strains were measured. Two strain gauges were fixed at mid-heights on diagonally opposite sides of the specimen to measure the strains in the specimens (Fig. 4). Under compression loading, two

Fig. 3. Buckling mode of the bamboo column during the buckling test.

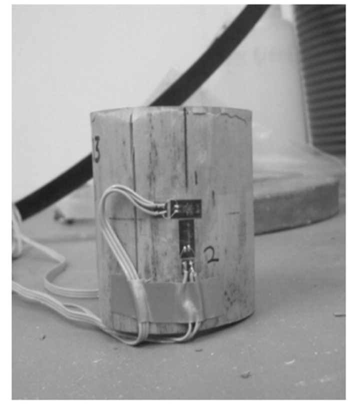

Fig. 4. Specimens with strain gauges for the compression tests.

strain gauges measured the longitudinal strains (labeled 2 in Fig. 4) and the other two measured circumferential strains (labeled 1 in the Fig. 4). Thin rubber pads were placed at each end of the specimens to ensure uniform loading in the specimen during compression loading, as required by the test protocol for bamboo (ISO, 2004). The loads and deformations were recorded until the splitting failure was observed in the specimen.

Experimental results

Using Euler's column theory, the buckling strength of bamboo columns is characterized in terms of slenderness ratio:

$$\sigma_{cb} = \pi^2 E/\lambda^2 \quad (1)$$

where σ_{cb} is the characteristic buckling strength of the column, E is the elastic modulus and λ is the slenderness ratio which is defined as the ratio of the length of column to its radius of gyration. Since cross-sectional dimensions of bamboo columns vary along the longitudinal axis, compressive strength was calculated using the minimum cross-sectional area of the column and the moment of inertia. In addition, the bamboo columns were assumed to be hollow circular pipes. Characteristic load deflection curves for two specimens are shown in Fig. 5. Despite the variability between the specimens, each load–deflection curve is approximately linear for a wide range of loads which allows E to be determined. σ_{cb} is taken as the maximum compressive load. Fig. 6 plots the buckling stress from all the tests, along with the predictions from Eq. (1) using the average E. The buckling strength does not vary considerably as λ increases from 40 to 110 and Eq. (1) will clearly

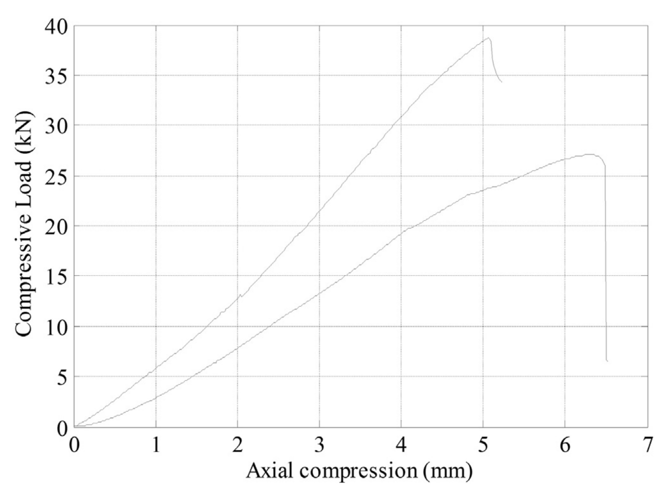

Fig. 5. Load–deflection behavior of bamboo column under buckling.

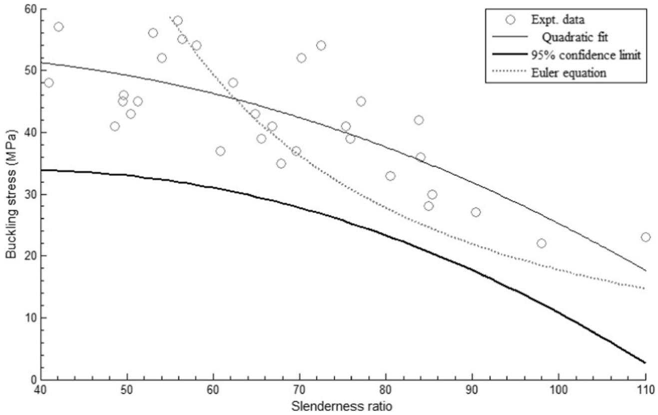

Fig. 6. Relationship between buckling strength and slenderness ratio for bamboo columns.

over-estimate the strength at λ < 50. As an alternative, a quadratic equation was fitted into the data using least squares:

$$\sigma_{cb} = -0.0061\lambda^2 + 0.47\lambda + 24.77. \tag{2}$$

The IEC Standard 61400-3 (2006) mandates the use of material properties at the 95% confidence level. This limit on buckling strength is also plotted in Fig. 6. The results of buckling tests compare reasonably well with the results obtained by Yu et al. (2003) for the *Kao Jue* and *Mao Jue* species of bamboo. From the stress–strain curve, E was calculated as 18 GPa at 95% confidence level. Similarly v was determined as 0.35 at 95% confidence level. These values compare reasonably well with the results reported by various authors for other species of bamboo (Yu et al., 2003; Janssen, 1981).

Compression tests were made on ten samples, all similar to the one shown in Fig. 4. The mean maximum compressive strength was 44 MPa at 95% confidence, which is a reasonable extrapolation to zero slenderness in Fig. 6.

Structural modeling of lattice tower

Load modeling

The main loads acting on wind turbine towers are the aerodynamic thrust on turbine blades, the drag on tower members, and the gravity load of the turbine and tower (Fig. 7) (Adhikari et al., 2014). This section provides the necessary details from Adhikari et al. (2014). The IEC Standard 61400-3 (2006) for class III wind turbines requires that the turbine thrust and drag forces on tower should be calculated using the 50-year 3 s, gust wind speed, which is 52.5 m/s (IEC Standard 61400-3, 2006). To be consistent with the load analysis presented in Wood (2011), we assumed the extreme wind speed of 50 m/s to calculate the turbine thrust and drag on tower. This wind load is also consistent with measurements of high wind speeds in Nepal, where this research was primarily focused. The aerodynamic thrust, F, on turbine blades is determined by:

$$F = \frac{C_T \rho A U^2}{2} \tag{3}$$

where C_T is the thrust coefficient, ρ is the air density (1.225 kg/m^3), A is the swept area of the rotor, and U is the extreme wind speed (50 m/s). Using load case H of the "simple load model (SLM)" described in IEC Standard 61400-3 (2006), the thrust is calculated as 1592 N. The turbine weighs 30 kg. The drag on tower was determined by assuming the bamboo sections to be circular cylinders and the wind speed of 50 m/s acts uniformly throughout the tower height. For typical bamboo diameters (60–70 mm), the Reynolds number of the wind flow based on the diameter of the tower members at this wind speed is subcritical, so the drag coefficient C_d for circular cylinders is taken as 1.3 (IEC Standard 61400-3, 2006; Wood, 2011). The drag force per unit length of tower members is

$$q = \frac{C_d \rho D U^2}{2} \tag{4}$$

where q is the drag force per unit length, and D is the diameter of tower members. The total bending moment at the tower base due to F and q on the tower was determined by assuming that the tower was a cantilevered beam of three legs and no bracing (Fig. 6). The total bending moment at the tower section y due to turbine thrust and drag is

$$M(y) = F\,(h-y) + \frac{3q(h-y)^2}{2} \tag{5}$$

where $M(y)$ is the bending moment and h is the height of tower.

Structural analysis

In practical tower designs, the key design variables for the triangular lattice tower are: the loads acting on the tower, the base distance between the legs, the diameter and thickness of the tower members, and the buckling strength of leg sections. In order to determine the stress on tower legs, the free body diagram (FBD) shown in Fig. 2 will be used along with the further details given in Figs. 7 and 8. As mentioned above, lattice towers generally fail by buckling. So we consider the worst case of buckling, which occurs when the wind blows in the direction shown in Fig. 8.

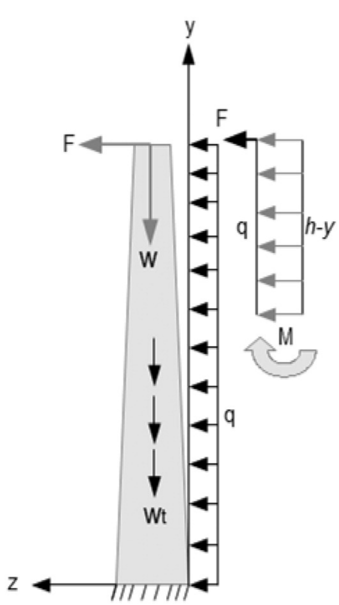

Fig. 7. Lattice tower as a cantilever beam.

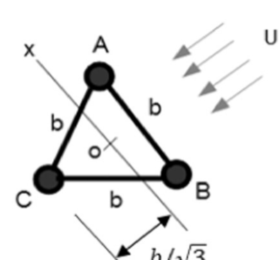

Fig. 8. Cross-section of the triangular lattice tower as a composite beam of legs and bracings for the worst case of buckling.

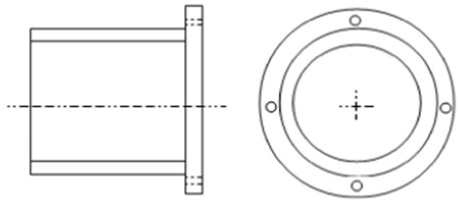

Fig. 9. Schematic of the steel cylindrical-cap.

Assuming that three legs share equally the gravity loads due to turbine and tower mass, the axial compressive stress in each leg is:

$$\sigma_a = \frac{w + \rho g \Sigma A_i l_i}{3A}. \tag{6}$$

Similarly, the compressive stress due to bending loads is given by:

$$\sigma_b = \frac{M(y).z}{I(y)} \tag{7}$$

where z is the distance of the leg from the centroidal axis and $I(y)$ is the second moment of inertia of the composite section. Considering bamboo as circular hollow tubes of constant diameters, $I(y)$ at the base of the tower can be expressed by (Adhikari et al., 2014):

$$\begin{aligned} I(y) &= 2A\left(b/2\sqrt{3}\right)^2 + A\left(b/\sqrt{3}\right)^2 + 3A\left({R_1}^2 + {R_2}^2\right)/2 \\ &= Ab^2/2 + 3A\left({R_1}^2 + {R_2}^2\right)/2. \end{aligned} \tag{8}$$

A similar analysis for the moment of inertia of the triangular mast is found in Gantes et al. (1997). Since the maximum stress occurs at the bottom section of the back leg (Fig. 8), the compressive stress in that leg is calculated by combining the axial and bending stresses using

$$\frac{\sigma_a}{F_a} + \frac{\sigma_b}{F_b} \le 1 \tag{9}$$

where F_a is the allowable axial stress and F_b is the allowable bending stress (Wood, 2011). In assessing the buckling strength of the tower leg, the combined compressive stress should be less than the allowable buckling stress of the bamboo column. By using Eqs. (3)–(9), it is possible to determine the optimum b and D of bamboo columns for the preliminary design of the bamboo tower. According to the IEC Standard 61400-3 (2006), we use the load safety factors of 1.1 and 1.35 for the gravity and wind loads respectively while using Eq. (9) or Eqs. (3), (4), and (6).

During extreme winds, the tower should remain in the linear elastic region with minimum tower top deflection. However, IEC Standard 61400-3 (2006) does not specify any limiting value for the maximum tower-top deflection. Clifton-Smith and Wood (2010) optimized an octagonal tower for a 5 kW wind turbine based on buckling strength and concluded that tower top deflection might not be the “critical factor” in tower design. It was recommended that maximum tower-top deflection of 5% of the tower height would be satisfactory for the design of small towers. This limiting value is used here as the maximum allowable deflection. The tower-top deflection can be approximately determined by assuming the tower as a composite beam of three legs as illustrated in Fig. 8 (Adhikari et al., 2014; Gantes et al., 1997). The tower deflection, $v(y)$, is determined by solving the moment–curvature relationship for an Euler–Bernoulli beam:

$$\frac{d^2 v}{dy^2} = \frac{M(y)}{E\,I(y)}. \tag{10}$$

Integrating the Eq. (10) twice and applying the boundary conditions that the slope and deflection are both zero at the tower base ($y = 0$), one can find the tower deflection $v(y)$. The derivation for $v(y)$ is given in Ref. (Adhikari et al., 2014). The tower-top deflection is

$$\begin{aligned} v(h) = \frac{h^3}{12EA_{cs}(b-D)^4\sqrt{{R_1}^2-{R_2}^2}} \Big[& 3\sqrt{{R_2}^2+{R_1}^2}[2(b-D)(4bF-4DF)+15bhq-3Dhq) \\ & -4b[-DF+b(F+3hq)]log\left[2b^2+3\left({R_2}^2+{R_1}^2\right)\right]+\left[4bDF-2b^2(2F+3hq)\right. \\ & \left.+9hq\left({R_2}^2+{R_1}^2\right)\right]log\left[h^2\left(2b^2+3\left({R_2}^2+{R_1}^2\right)\right]+4b[-DF+b(F+3hq)]\right]log\left[2D^2\right. \\ & \left.+3\left({R_2}^2+{R_1}^2\right)\right]+\left[\left[-4DF+b^2(4F+6hq)-9hq\right]\right. \\ & \left.-9hq\left({R_2}^2+{R_1}^2\right)\right]log\left[h^2\left(2D^2+3\left({R_2}^2+{R_1}^2\right)\right]\Big]. \end{aligned} \tag{11}$$

The MATLAB program listed in Adhikari (2013) was modified to determine the tower-top deflection numerically by solving the Eq. (10). The above analytical solutions for the buckling stress and tower deflection have been validated with the FEA results for tubular rectangular and triangular lattice towers in Adhikari et al. (2014).

Joining techniques

The most effective joining practice is to use lashing, as is common for scaffolding (Yu et al., 2003) and various other temporary structures (Janssen, 1981). After establishing that bamboo is sufficiently strong to be used for wind turbine towers, the design of a cheap, strong, and reliable joint needs to be addressed. The inherent limitations of bamboo are that the sections cannot be joined by welding or be machined to a desired shape, and use of mechanical fasteners leads to splitting. In addition, water ingression could further degrade the strength of joints. Further, bamboo has short durability (3–5 years) when unprotected from weather (Janssen, 1981), but longevity could be improved if protective coatings are applied. Considering the nominal 20 years lifespan of wind turbines, we assume that the tower members could be replaced periodically, say every 4–5 years. It is important to note that the proposed replacement would not hinder bamboo's potential for lattice towers because bamboo is extremely cheap, easily available, and can be worked with little workmanship. Considering these design factors, we propose a bamboo–steel adhesive joint combined with conventional lashing. The design is modular; so that tower members could be replaced easily. In this design, the bamboo ends are encased inside steel cylindrical caps as illustrated in Figs. 9 and 10. Then the bamboo sections can be easily connected to build the tripod structure. Strength is enhanced by applying conventional lashings, which have long been

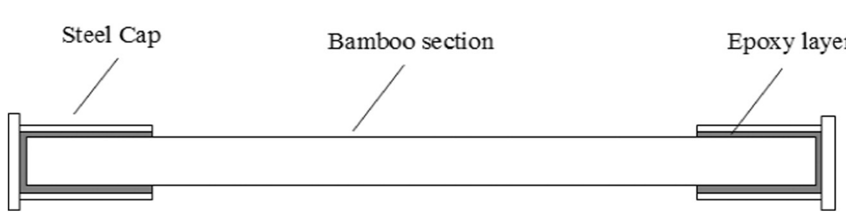

Fig. 10. Connection of leg sections using steel caps.

Table 1
Results of pull-out test.

Test number	Dia. of bamboo, left end (mm)	Dia. of bamboo, right end (mm)	Dia. of steel cap (mm)	Joint length (mm)	Pull-out resistance (kN)
TS1	64.7	64.4	68.6	46	21.46
TS2	64.1	64.3	68.6	46	22.45
TS3	62.8	62.6	68.6	46	23.23
TS4	63.4	63.3	68.6	46	22.91
TS5	63.4	63.3	68.6	46	22.58

Table 2
Design specifications for the bamboo tower.

No of lattice sections	8
Thickness of leg sections (mm)	6
Turbine capacity (W)	500
Mass of turbine and steel connectors (kg)	60
Turbine thrust (N)	2150
Extreme wind speed (m/s)	50
Maximum compressive strength (MPa)	44

proven very effective in housings and scaffoldings. However, the horizontal and cross-bracings are joined to the leg sections by using lashings only.

To the authors' knowledge, steel–bamboo joints have not been studied. However, strength of polyvinyl chloride (PVC) and bamboo adhesive joints was experimentally investigated by Albermani et al. (2007). In their work, the bamboo ends were encased inside the cylindrical connector made of PVC using a megapoxy grouting material. Similarly, we investigated a steel–bamboo adhesive joint (Fig. 9), considering 65 mm diameter bamboo, which is a commonly available size. Epoxy was used to join the bamboo and steel cap. Detailed design procedures were not developed in this study, however, a preliminary design procedure can be found in Adhikari (2013). The specifications of the specimens and the results of the experimental tests are given in Table 1. The average pull-out resistance of the joint was obtained as 20.32 kN at 95% confidence level. This value is close to the resistance of 18 kN obtained by Albermani et al. (2007) for the bamboo–PVC joints of the 61 mm diameter bamboo.

Finite element analysis (FEA)

The structural analysis presented above gives only approximate analytical solutions for the buckling stress and tower top deflection. Preliminary design optimization is possible with those solutions. Optimization of b and D is not possible when cross bracings are included in the tower. In order to examine the accuracy of the analytical solutions for the buckling stress and tower top deflection, finite element modeling of the tower was performed using ANSYS APDL (ANSYS®, 2014). In addition, FEA was used to further develop the tower design.

For finite element modeling, the tower legs and bracings can be treated as one-dimensional beams using homogeneous isotropic beam elements subjected to axial and bending loads. This treatment is particularly valid for lattice tower members because the tower members are subjected to axial and bending loads and the strength in the longitudinal axis is critical. Two-nodes with the 188 beam element available in ANSYS was utilized for the tower members. This beam element is a linear, quadratic or cubic two-nodes beam element that can accurately model “slender and moderately thick beam” structures (ANSYS®, 2014). Each node has six or seven degrees of freedom, which includes translation and rotation in or about three co-ordinate directions. The material properties required in the FEA are E, and v, which were experimentally determined as 18 GPa and 0.35 respectively. Because the tower is uniformly loaded by the wind, the drag was applied at each nodal point. The ends of tower members were assumed to be fixed. The criteria of tower failure are the buckling of legs and tensile strength of adhesive joints.

Results and discussion

To examine the feasibility of bamboo tower design, an example 12 m high bamboo tower for a 500 W wind turbine is presented. The schematic of the tower configuration is shown in Fig. 11. The main design parameters for the tower are b, D, σ_c, joint strength, and the tower top deflection. These design parameters determine the configuration of the tower. The design procedure involves minimizing b and D under allowable σ_c and tower top deflection (Adhikari et al., 2014). The design specifications for the tower are given in Table 2.

Initially, the turbine thrust and mass are known, but not the tower mass and the drag forces because they depend on D of tower legs, which we treat as a variable. As discussed before, the buckling strength depends upon the diameter of the bamboo column. As bamboo is a light weight material, the mass of the tower would change only slightly even with considerable change in diameter of the legs. We assume that the mass of turbine and steel caps is 60 kg and the mass of the bamboo sections is 45 kg for a typical bamboo size of 65 mm diameter and 6 mm thickness. This size of bamboo is the commonly available for the species considered.

Eqs. (2) and (4)–(9) were used to determine the minimum D of bamboo columns that is safe against buckling at various b (Fig. 12). It was assumed that maximum tensile stress, which occurs when the wind blows in the opposite direction than that of the maximum compressive stress condition, was always less than the maximum compressive stress and

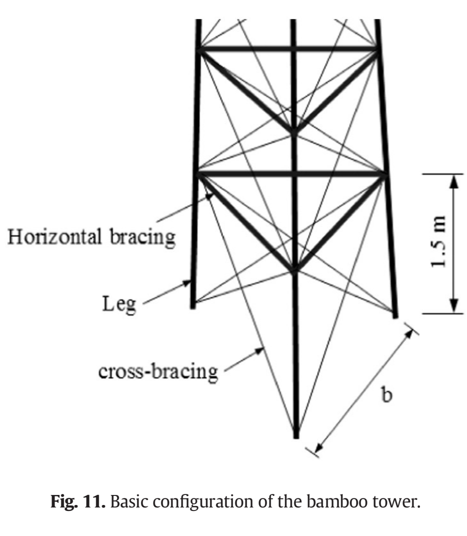

Fig. 11. Basic configuration of the bamboo tower.

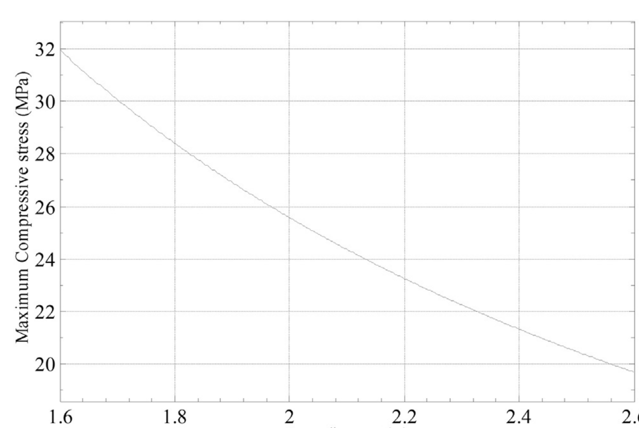

Fig. 12. Variation of maximum compressive stress with base distance.

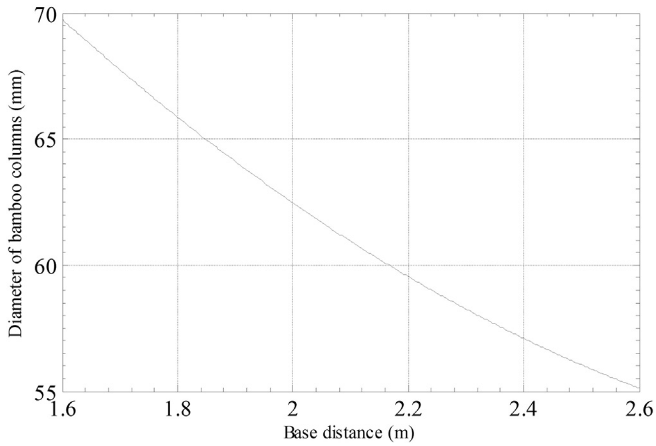

Fig. 13. Minimum diameters of bamboo columns for tower legs (1.5 m long, 6 mm thickness) that are safe against buckling obtained from analytical method.

would not exceed the strength of the steel–bamboo adhesive joint combined with lashings. The minimum deflection criterion is not required to be included in this simple optimization because the maximum tower deflection determined was well below the allowable deflection 600 mm (5% of the tower height). It can be observed from Fig. 12 that the maximum compressive stresses in tower legs decreased as b is increased for $D = 65$ mm and $t = 6$ mm. The minimum D of bamboo that is safe against compressive loads for different b is obtained from Eq. (9), which is shown in Fig. 13. Considering the typical bamboo size of $D = 65$ mm and $t = 6$ mm, the tower with $b = 1.85$ m would not buckle.

To check the accuracy of the analytical procedure presented above, FEA was carried out for the tripod configurations with specific values of b and D. The results of analytical method and FEA for different tower configurations are shown in Table 3. FEA results were slightly lower than the analytical solutions for the maximum compressive stress and slightly higher for the tower top deflection. It is found that the analytical solutions are accurate in determining the tower dimensions.

A tower with $b = 1.85$ m and $D = 65$ mm was designed with horizontal bracings of the same diameter. This is the optimal b and D obtained from the analytical solution (Fig. 13). Fig. 14 shows the tower top deflection and distribution of compressive stresses in tower legs obtained from the FEA. Maximum compressive stress of 24.17 MPa was obtained in the back leg when the wind direction for the worst case of buckling was considered. By including the horizontal bracings, the tower top deflection was reduced to 193 mm. This indicates the suitability of the linear-static model as required by IEC. Similarly, the load factors of 1.1 and 1.35 for gravity and wind loads respectively make the tower safe in extreme wind loads.

The effect of including the cross-bracings was also investigated in FEA by considering different sizes of cross-bracing members for the same tower. In practical situations, it may not be possible to get bamboo columns of the desired length having D less than 20–25 mm. We modeled the tower with cross-bracings having 25 mm and 6 mm thickness bamboo columns. The cross-bracings can be rigidly joined to leg sections of the tower using lashing. From the FEA, it was found that the maximum compressive stress in the leg increased to 27 MPa from 24.1 MPa (Fig. 14). The corresponding maximum compressive stress as determined by the analytical solution is 26.8 MPa (Eq. (9) and Fig. 12). However, in this case the tower deflection decreased considerably to 94 mm. Nevertheless, it would be possible to minimize the leg size or D that would reduce the tower drag while using cross-bracings, but this would require extensive FEA. It is evident that drag forces on the cross-bracings lead to an increase in the compressive stress in tower legs. Also, tower deflection was not shown to be a critical factor for the tower with horizontal bracings even if cross-bracings are not used. Consequently, bamboo cross-bracings are not recommended. However, smaller round sections, such as solid steel rods having diameters of 10–12 mm, such as used (Wood, 2011), may be used. However, the effect of such bracing on compressive stress and stiffness was not investigated in this study.

Conclusions

In this paper, we investigated bamboo's feasibility for use in triangular lattice towers for small wind turbines. In order to assess the structural behavior of the towers, material properties of bamboo and strength of a steel–bamboo adhesive joint were experimentally determined. The Nepalese bamboo species *Bambusa Arundinacea* was used for this purpose. The buckling strength of bamboo columns has been characterized in terms of slenderness ratio, and the compressive strength and Young's modulus determined, along with the adhesive strength of a bamboo–steel connection.

A design example of a 12 m high triangular lattice tower was investigated considering the load cases of a 500 W wind turbine at extreme wind speed as required by the International Electrotechnical Commission (IEC) safety standard for small wind turbines. The main design parameters considered in the tower analysis are the base distance between the tower leg sections, the buckling strength of legs and the strength of the joints connecting the leg sections. For connecting leg sections in the tower, steel–bamboo adhesive joint combined with conventional lashings has been proposed. Analytical solutions for the buckling stress and tower top deflection, which allow preliminary design optimization, have been formulated to determine the maximum compressive and tensile loads or stresses on tower legs. This can be used to optimize the base distance and the size of tower legs.

To assess the validity of the method and the effect of including the cross-bracings in the tower, a detailed finite element analysis was performed. Of the several base distances considered for a typical bamboo size of 65 mm and 6 mm thickness, the optimum tower configuration was obtained for the tower base distance of 1.85 m without using cross-bracings. Analytical solutions for the buckling stress are in good agreement with those from finite element analysis of the tower without cross-bracings. This confirms the validity of analytical solutions for the tower design and optimization. The results of finite element analysis for the tower with cross-bracings of smallest possible diameter of 25 mm showed that the maximum compressive and tensile stresses exceeded the allowable stresses in the tower legs. It was concluded that drag on tower is critical if optimum size for the legs is considered and cross-bracings are used. Therefore, towers with only horizontal bracings are recommended. The best tower design had a 1.85 m base

Table 3
Comparison of analytical, numerical, and FEA results for the tripod tower.

Base distance, b (m)	1.85 ($D = 65$ mm)	2.18 ($D = 60$ mm)	2.6 ($D = 55$ mm)
Compressive stress (MPa), analytical	26.8	24.4	19.6
Compressive stress (MPa), FEA	24.1	23.3	19.2
Tower-top deflection (mm), analytical	216.4	163.4	113.1
Tower-top deflection (mm), numerical	216.3	163.8	112.3
Tower-top deflection (mm), FEA	213.5	167.7	116.3

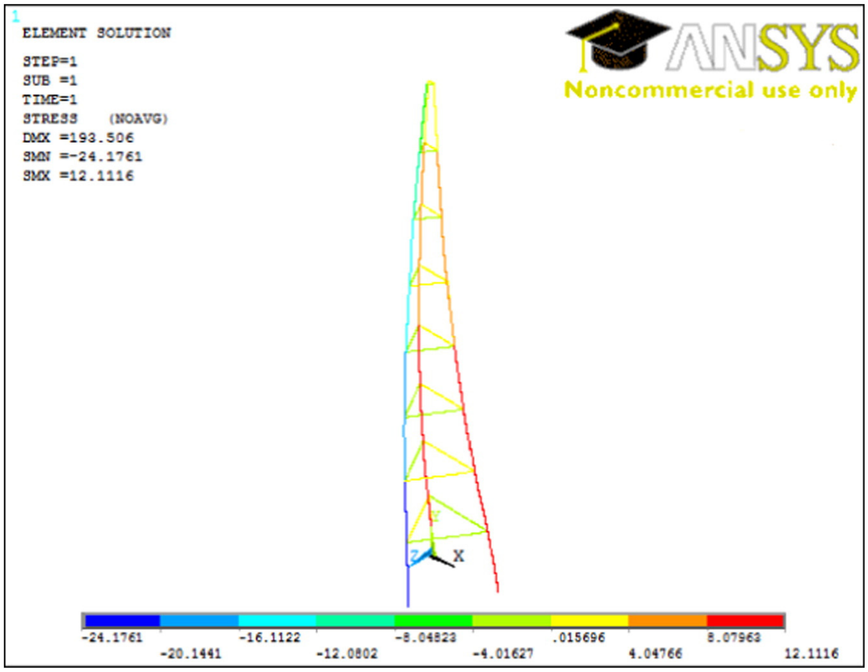

Fig. 14. Maximum compressive stress in tower legs for $b = 1.85$, $D = 65$ mm and $t = 6$ mm. The color scale gives the stress in kPa.

distance and 1.51 m long leg sections having 65 mm diameter and 6 mm thickness.

In order to address the issue of longevity, periodic replacement of tower members after every 4–5 years is recommended. The detailed practical aspects of installations and maintenance were not considered; however, the design procedure adopted in this work validates the feasibility of designing small bamboo towers for practical applications. Nevertheless, further investigations on joints and longevity would help to build confidence on practical applications of bamboo towers. It is concluded that the designed bamboo tower can meet the safety requirements of IEC standards for small wind turbine and hence the bamboo towers are practically feasible for wind turbines of 500 W or lesser capacity. This is particularly promising in developing clusters of small wind turbines to generate electricity in remote areas of the developing countries, where bamboo resources are available or can be grown easily.

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References

Adhikari RC. Low-cost triangular lattice towers for small wind turbines [MSc thesis] Canada: University of Calgary; 2013.
Adhikari RC, Wood DH, Sudak L. Design procedures for tubular lattice towers for small wind turbines. Wind Eng 2014;38:359–76.
Albermani F, Goh GY, Chan SL. Lightweight bamboo double layer grid system. Eng Struct 2007;vol. 29:1499–506.
Amada S. The mechanical structures of bamboos in viewpoint of functionally gradient and composite materials. J Compos Mater 1997;30(7):800–19.
ANSYS®. Academic Research, release 14.0, ANSYS, Inc; 2014.
Clausen PD, Peterson P, Wilson SVR, Wood DH. Designing an easily-made lattice tower for a small wind turbine. International Workshop on Small Scale Wind Energy for Developing Countries, Nepal; 2011.
Clifton-Smith MJ, Wood DH. Optimisation of self-supporting towers for small wind turbines. Wind Eng 2010;34(5):561–78.
Francois-Xavier Jammes. Design of wind turbine towers with ultra-high performance concrete (UHPC) [M.Sc thesis] USA: Massachusetts Institute of Technology; 2009.
Gantes C, Khoury R, Konner JJ, Pauangar C. Modeling, loading, and preliminary design considerations for tall guyed towers. Compos Struct 1997;49(5):797–805.
Ghavami K, Rodrigues CS, Paciomik S. Bamboo: functionally graded composite material. Asian J Civ Eng Build Hous 2003;4(1):1–10.
Hau E. Wind turbines: fundamentals, technologies, application, economics. New York: Springer-Verlag; 2006. http://dx.doi.org/10.1007/3-540-29284-5.
IEC Standard 61400-3. Design requirements for small wind turbines. International Electrotechnical Commission; 2006.
ISO. 22157-1: bamboo—determination of physical and mechanical properties—part I: requirements. Geneva, Switzerland: International Standards Organization; 2004.
Janssen JA. Bamboo in building structures [Ph.D. thesis] Eindhoven, Netherlands: Eindhoven University of Technology; 1981.
Prototype timber tower. Prototype timber tower. source: http://www.timbertower.de/en/projects/100m-prototype-hannover/. [accessed on 24 September, 2013].
Silva ECN, Matthew CW, Paulino GH. Modelling bamboo as a functionally graded material: lessons for the analysis of affordable materials. J Mater Sci 2006;41:6991–7004.
Tan T, Rahbar N, Allameh SM, Kwofie S, Dissmore D, Ghavami K, et al. Mechanical properties of functionally graded hierarchical bamboo structures. Acta Biomater 2011;7(10):3796–803.
Wood DH. Small wind turbines: analysis, design and application. London: Springer; 2011.
Yu WK, Chung KF, Chan SL. Column buckling of structural bamboo. Eng Struct 2003;25(6):755–68.