Energy for Sustainable Development 28 (2015) 21–28

Contents lists available at ScienceDirect

Energy for Sustainable Development

Low-cost bamboo lattice towers for small wind turbines

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ARTICLE INFO

Article history:
Received 4 July 2014
Revised 15 June 2015
Accepted 16 June 2015
Available online xxxx

Keywords:
Bamboo
Buckling strength
Bamboo tower
Finite element modeling
Small wind turbines

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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http://dx.doi.org/10.1016/j.esd.2015.06.006
0973-0826/

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)

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.

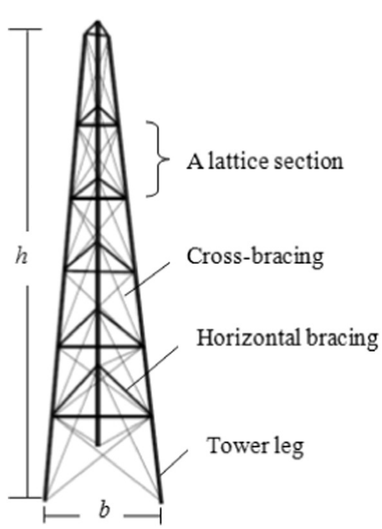

Fig. 1. Structural model of the triangular lattice tower.

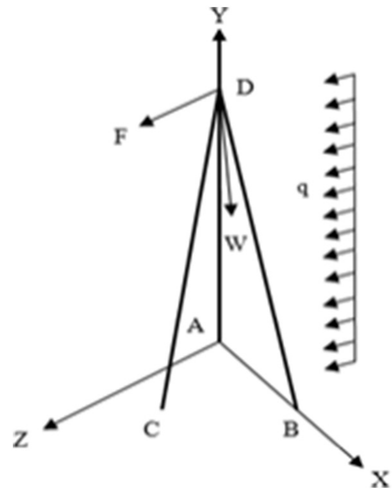

Fig. 2. Free body diagram (FBD) of the tripod model. The legs are denoted by AD, BD, and CD. The turbine is mounted at point D. The arrows indicate the direction of forces.

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.