Structural and Life-Cycle Economic Feasibility of Rooftop Low-Height Bamboo Telecom Tower Considering a Case Study from Bangladesh

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Abstract: In this paper, structural adequacy and life-cycle economic feasibility of bamboo as primary construction material for a rooftop low-height telecommunication tower is examined. For this, a relatively strong locally cultivated bamboo species in Bangladesh named Bambusa tulda has been selected for the project. A joint system with transverse steel bolts, with steel plates attached to these bolts, has been proposed as a mechanism to transfer a load between different bamboo members of the tower. Bamboo samples have been tested using this joint system to ascertain the characteristic compressive (40.5 MPa), tensile (53.4 MPa), and bending strength (73.1 MPa) and also the corresponding modulus of elasticity. A 5-m high bamboo lattice tower has been modeled in the three-dimensional finite-element software SAP2000. The analysis results have showed that maximum axial and bending stresses developed in bamboo members of a 5-m high tower is much less than the allowable stresses of bamboo. The top deflection of the bamboo tower has been checked and is found to be within the acceptable limit. An analysis considering a 15-year life-cycle has showed that the bamboo tower is 18% less expensive than a galvanized iron (GI) pipe tower of an equivalent height, which it intends to replace. This proves that a low-height rooftop telecommunication tower may be economically constructed using bamboo. **DOI:** **10.1061/(ASCE)SC.1943-5576.0000492.** *© 2020 American Society of Civil Engineers.*

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Introduction

The expansion of network coverage and capacity for mobile telephone operators through the construction of telecommunication infrastructure is a capital-intensive endeavor. Mobile phone companies all over the world invest a large share of their capital into developing network infrastructure. In recent years, in Bangladesh, stiff competition among operators has resulted in a reduced user rate and a corresponding reduction in revenue. Consequently, mobile phone operators are aggressively looking toward cost reduction in every aspect of their operation, including the construction of new infrastructure. Relatively inexpensive and easily available bamboo as an alternative to galvanized iron (GI) pipe for low-height rooftop telecommunication towers may provide a solution toward cost reduction. As bamboo is a natural and renewable product, it may also bring about more sustainability in civil construction related operation in the telecommunications sector.

Lattice, guyed, and monopole are the usual three types of telecommunication towers that are used for holding antennas. Bamboo with natural tubular sections having nodes at regular intervals that contains solid transvers diaphragms make it particularly suitable for the lattice-type configuration and has previously been used for constructing lattice towers. Low-cost, three-legged bamboo lattice towers are in operations in Nepal for small wind turbines (Adhikari et al. 2015). Apart from this, there are many applications of bamboo as structural material, such as the framing system of a house or foot bridges. Bamboo scaffolding is widely used in construction in South East Asia and Southern China (Chung and Yu 2002). Many innovative uses of bamboo in construction, e.g., strengthening the embankment of highways (Ye and Fu 2018), are being explored as it is a green and environmentally friendly material. Bamboo has a tensile and compressive strength of 135–357 MPa and 44–117 MPa, respectively, in the longitudinal direction, depending upon species and moisture content (Adhikari 2013), whereas, the elastic modulus and Poisson's ratio are reported to be in the range of 13–23 GPa and 0.3–0.35, respectively (Adhikari 2013). These excellent mechanical properties make it a potentially promising material for telecommunication structures. Hence, a comprehensive project was undertaken to design and construct a low-height (5 m) rooftop bamboo telecommunication tower at Bangladesh University of Engineering and Technology in Dhaka, Bangladesh, with collaboration from edotco (Edotcogroup 2019), a large telecommunications infrastructure company. From this project, the first bamboo tower (Fig. 1) using locally grown bamboo species named Bambusa tulda, was constructed and installed over a 6-story building in Dhaka, Bangladesh, in 2017 (Telecomlead 2017; Materia 2017; Thedailystar 2017). Except slight fading of the external enamel paint, no deterioration was observed from this bamboo tower for the last 2 1/2 years at the time of writing this paper. Following an acceptable performance, as many as 12 bamboo towers were installed all over Dhaka, Bangladesh, by edotco (Edotcogroup 2019) in recent months.

For bamboo to be used in a telecommunications structure, it should be able to withstand compressive and tensile stresses generated from antenna and other associated loads. Another important design criterion is that the joints should have adequate strength to transfer loads among different bamboo members and ultimately to

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Fig. 1. Bamboo tower placed over rooftop at Dhaka, Bangladesh. (Image by Md. Shahrior Alam.)

the foundation of the tower. Therefore, a suitable joining technique must also be devised for a bamboo telecommunication tower. This paper describes a bamboo tower configuration, proposed joining technique, testing scheme of the selected bamboo specimen to determine its mechanical properties, and a structural analysis of the bamboo tower that demonstrate the feasibility of bamboo as a primary structural material for a low-height rooftop telecommunication tower. Further, a life-cycle economic analysis comparing a bamboo tower with an equivalent height GI pipe tower is also presented to validate cost reduction aspects of such a tower.

Bamboo Tower and Joint Configuration

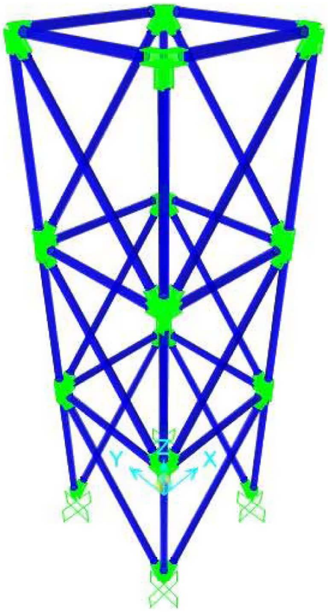
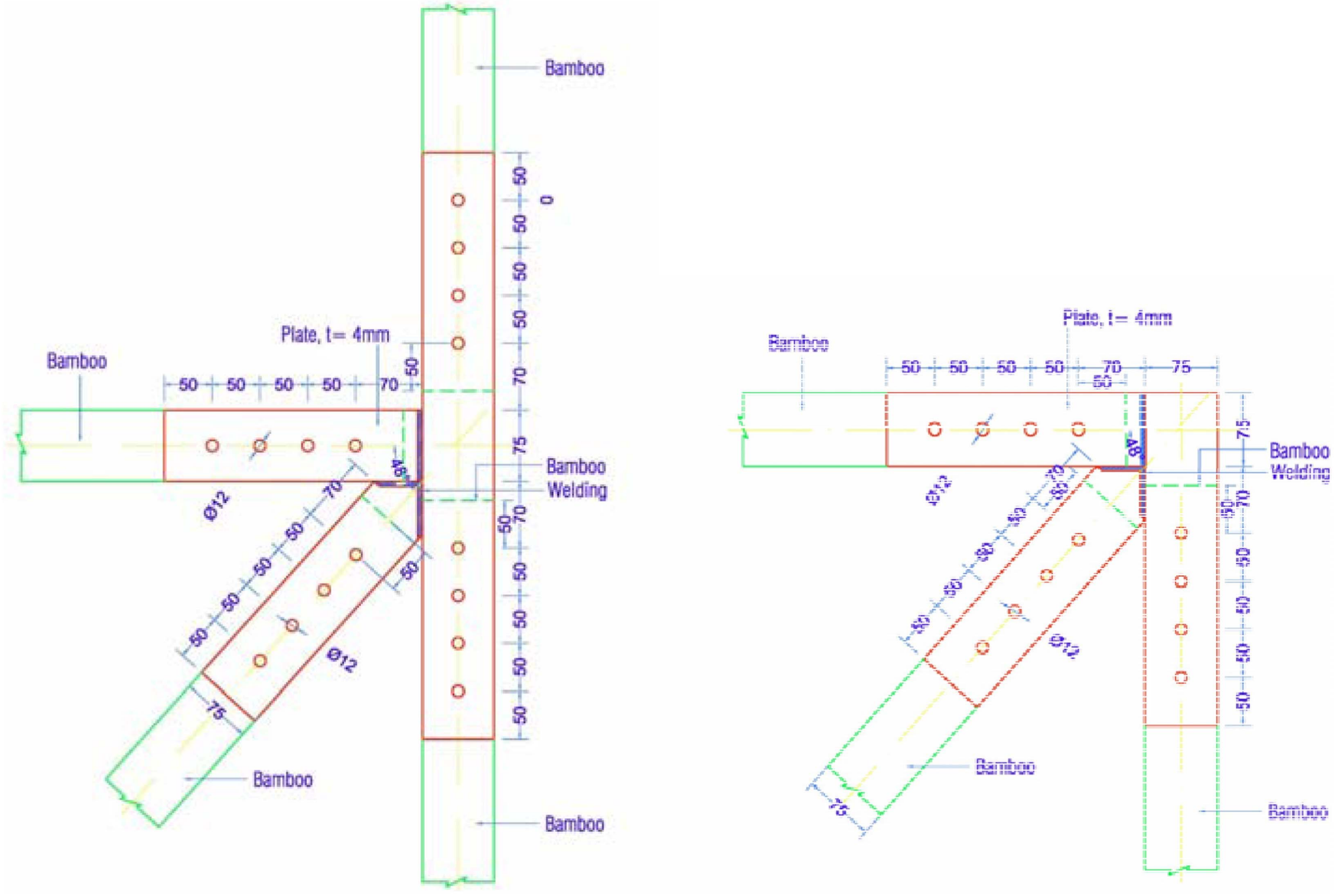


Fig. 2. Schematic model of four-legged bamboo lattice tower.

Fig. 3. Drilling holes at bamboo end for inserting 12-mm bolts.

In this work, a four-legged square telecommunication tower of a 5-m height with a base width of 1.5 m was designed and constructed using bamboo. Vertically, the tower was divided into three equal height panels of 1.67-m. A 1.5-m long horizontal bamboo member connected the top joints of each panel. Apart from these, there was also a diagonal bracing at each face of each panel (Fig. 2). The length of these diagonal panels were approximately 2.25 m. Joint or connectors in any bamboo structure are the most important and complicated part. As bamboo has a hollow tubular cross-sectional profile, it was difficult to join two or more bamboo meeting in a point from different angles in the tower. For this, different available joint systems traditionally used were explored. Arce (1993) and Janssen (1981) investigated different types of connectors used in bamboo structures. Laroque (2007) categorize bamboo joints as two types: traditional and innovative, including bolt connections. Trujillo and Malkowska (2018) examined different parameters of bolt combined with mortar fill joints for Guadua bamboo. Adhikari et al. (2015) used steel caps attached to bamboo ends using epoxy along with traditional lashing for their bamboo lattice tower for wind turbine. In this project, a dowel-type mechanical joint used through bolts connected to steel plates was used as connector. This was a modified version of a bolt connection used in the bamboo structures of Columbia (Trujillo 2007). For this, four holes were drilled in the transverse direction at each end of the bamboos (Fig. 3). Circular steel bolts of a 12-mm diameter were passed through these holes, which were then attached to a steel plate with a 4 mm thickness. Loads from one bamboo member to another member and ultimately to the foundation were in effect transferred through these two steel plates, which were laterally restrained by four bolts attached to the bamboo ends. Fig. 4 shows a schematic representation of typical joint configurations used in the tower. One of the main benefits of this joint was that any or all bamboo members of the tower could easily be replaced, keeping the steel joint intact. Also, this type of joint could accommodate variations in diameters of bamboo, as there may be a 6% variation in the diameter due of variations of ambient moisture (Laroque 2007).



(a) (b)

Fig. 4. Typical schematic drawings of typical steel joints used in the tower: (a) intermediate joint; and (b) corner joint.

Experimental Program

Materials

Of the 26 bamboo species that are available in Bangladesh (Banglapedia 2019), Bambusa tulda, also known as Indian timber bamboo or Bengal bamboo, was selected for this project. This is one of the strongest species available in Bangladesh and is extensively used for scaffolding, temporary ladders, and other construction purposes. Typically, culms of Bambusa Tulda are 6–20 m high having diameter of about 5–10 cm with prominent nodes (Useful Tropical Plants 2019). The outer diameter (D_o) and wall thickness (t_w) are usually highest at the bottom and reduce toward the top of the bamboo culm. On the other hand, the distance between the nodes (internode) increases toward the top. Several samples, having straight and similar cross-sectional properties, were carefully selected from the bottom part of the bamboo culm for testing the physical and mechanical properties (Fig. 5). These specimens were preserved in green conditions under water for at least 10 days. This is called *leaching bamboo*, a traditional method of preserving bamboo in many parts of the world (Kaur et al. 2013). Through this process, the starch content of bamboo was subjected to a leaching process that decreased the starch level and increased the durability of the bamboo. Then, the bamboo samples were dried for one month so that its moisture content (MC) was reduced to below 20%. This was a very important criterion as Yu et al. (2003) had reported that bamboo specimen exhibits consistent and better mechanical properties when its MC is below 20%. Mitch et al. (2010) had also stated that dry bamboo exhibits greater consistency in the measurement and prediction of mechanical properties. Next, a termite control pesticide was applied in four layers to protect the bamboo members from degradation. Each layer is applied within four hours of the previous application. Subsequently, physical properties such as the dimensions, density, and moisture content of the bamboo samples were measured, as per ISO 22157 (ISO 2019). Table 1 shows the typical range of physical properties of the Bambusa tulda measured in the entire experimental scheme of this project.

Test on Bamboo Specimen

The compressive and tensile strength with a corresponding modulus of elasticity of the bamboo was measured next. The maximum length of the bamboo member in the tower was 2.25 m long (bracing). Hence, to be on the conservative side, a 2.25-m long bamboo specimen was considered for testing compression and tension strength. Bamboo, having a length shorter than 2.25 m, would understandably possess better mechanical properties. Afterward, an appropriate end joint system was essential to facilitate the grip between the testing machine and the bamboo sample. For that, a conceptually similar joint configuration that was used in the tower was applied in the bamboo samples for testing. For this, four holes were drilled in the transverse direction at each end of the bamboos. Circular steel bolts of a 12 mm diameter are passed through these

Fig. 5. Selection of Bambusa tulda samples.

holes, which were then attached to a steel plate (75 mm width and 4 mm thickness), as shown in Fig. 6. This arrangement was then placed in a universal testing machine (Fig. 7) followed by a direct application of compressive or tensile loads to measure the corresponding strength.

Compression Capacity

A compressive load was applied in the deflection control scheme with a rate of 0.01 mm/s, as per ISO 22157 (ISO 2019). Fig. 8 shows the characteristic load deflection behavior of bamboo in compression, which was approximately linear up until close to the ultimate load. This was similar to the load deflection pattern observed by previous researchers (Adhikari et al. 2015; Yu et al. 2003). Failure was sudden and abrupt and was found to initiate

Table 1. Physical properties of Bambusa tulda samples

Properties	Values
Outer diameter (D_o) (mm)	73.4–82.5
Wall thickness (t_w) (mm)	16.2–12.4
Internode length (mm)	190–225
Average density (air dry condition) (kg/m^3)	822–856
Moisture content (%)	9.7–13.3

Fig. 6. Mild steel joint system attached to bamboo ends.

Fig. 7. Bamboo sample in universal testing machine.

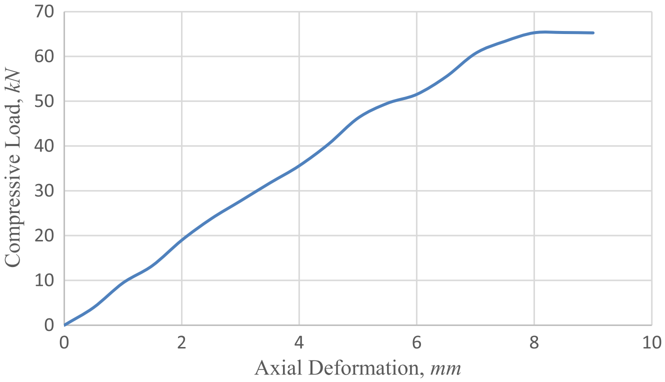


Fig. 8. Load deflection behavior of bamboo specimen under compressive load.

through longitudinal splitting that always started at the joint holes (Fig. 9). Corresponding stress and strain values were computed from a load deflection curve considering the cross-sectional area and sample length between the centerline of the supports. The modulus of elasticity in compression was calculated as a linear slope of the stress–strain curve between 20% and 80% of the ultimate load, as per ISO 22157 (ISO 2019). Table 2 shows the outer diameter (D_o), wall thickness (t_w), ultimate compressive load (P_c), compressive strength (F_c), MC, and modulus of elasticity in compression (E_c) of 24 samples of the Bambusa tulda. Cross sectional dimensions were measured at both the top and bottom, and average values are reported in Table 2. The cross sectional area was calculated using following equation:

$$A = \pi[D_o^2 - (D_0 - t_w)^2]/4 \tag{1}$$

Fig. 9. Longitudinal splitting of bamboo at joints under compressive load.

From Table 2, the compressive strength of the Bambusa tulda was found in the range of 36–46 MPa, which gave a characteristic compressive strength of 40.5 MPa at the 95% confidence level. The modulus of elasticity (MoE) on the other hand was found to vary between 7.9 and 11.1 GPa. The characteristic value of the MoE at a 95% confidence level was found to be 9.1 GPa. The compressive strength of the bamboo found from this testing scheme compared reasonably well with the results obtained by various authors for other species of bamboo of similar lengths (Janssen 1981; Yu et al. 2003; Adhikari et al. 2015; Xu et al. 2014). The MoE, on the other hand, was similar to those obtained for the Mao Jue bamboo (Chung and Yu 2002). These were higher than those obtained for the Moso bamboo (Xu et al. 2014) but lower than that of Bambusa arundinacea (Adhikari et al. 2015).

Tension Capacity

Table 3 shows tensile test results of the 24 specimens of Bambusa tulda. Except for the loading direction, all other standards, measuring, and calculation procedures were similar to the compression testing scheme. In the case of tension, failure occured due to the tearing of the bamboo through a line along the holes, as shown in Fig. 10. Therefore, in effect, this was a failure in the joint region and not the true tensile capacity of the bamboo material. However, this was the closest simulation of tensile behavior of a bamboo member in the actual tower. Fig. 11 shows a characteristic load deflection behavior in tension, which displayed large post peak deformation before failure.

From Table 3, the tensile strength of the Bambusa tulda, considering the joint configuration adopted in this research, was found to be in the range of 46.3–62.4 MPa, which gave a characteristic tensile strength of 53.7 MPa at a 95% confidence level. The MoE in tension was found to vary between 13.4 and 17 GPa, which provided a characteristic MoE of 14.6 GPa at the 95% confidence level.

Table 2. Behavior of Bambusa tulda under compressive load

No.	Length (L_o)	MC (%)	Outer dia (D_o)	Wall thickness (t_w), mm	Cross sectional area, A, mm^2	Ultimate load, P_c	$F_c = P_c/A$, MPa	MoE in compression (E_c), GPa
C01	2.25	11.9	81.4	14.4	1,678	67.3	40.12	9.25
C02	2.25	11.6	79.7	13.2	1,515	62.5	41.26	8.85
C03	2.25	11.0	74.5	13.4	1,426	62.8	44.03	10.7
C04	2.25	11.2	78	13.5	1,510	66.2	43.84	10.3
C05	2.25	10.9	79.4	13.2	1,509	65.6	43.48	8.27
C06	2.25	11.3	76.3	13.4	1,464	58.1	39.68	9.47
C07	2.25	12.1	79.2	12.8	1,463	61.8	42.24	9.68
C08	2.25	11.8	78.5	14.4	1,612	66.8	41.44	8.15
C09	2.25	10.4	75.6	13.6	1,469	62.2	42.34	7.95
C10	2.25	9.9	77.4	14.1	1,557	65.4	41.99	9.44
C11	2.25	12.2	82.5	16.2	1,892	68.5	36.20	10.4
C12	2.25	11.9	77.2	13.4	1,483	59.1	39.85	9.57
C13	2.25	11.4	77.8	14.2	1,576	67.3	42.70	8.52
C14	2.25	11.1	79.5	13.6	1,552	62.5	40.26	9.23
C15	2.25	12.7	73.7	13.7	1,438	62.8	43.68	10.2
C16	2.25	11.7	81.1	14.8	1,712	68.1	39.77	9.68
C17	2.25	11.5	74.4	13.5	1,367	65.6	45.75	11.1
C18	2.25	10.9	76.2	13.4	1,462	58.1	39.74	9.26
C19	2.25	10.6	79.3	14.1	1,599	61.8	38.64	8.96
C20	2.25	11.2	74.1	14.7	1,541	58.7	38.10	9.44
C21	2.25	9.7	77.2	13.6	1,503	62	41.25	10.2
C22	2.25	11.4	76.9	11.9	1,326	58.9	44.43	8.9
C23	2.25	11.5	79.1	12.4	1,419	64.8	45.66	8.85
C24	2.25	10.6	74.9	13.4	1,435	59.1	41.19	9.91

Table 3. Behavior of Bambusa tulda under tensile load

No.	Length (L_o), m	MC (%)	Outer dia (D_o), mm	Wall thickness (t_w), mm	Cross sectional area, A, mm^2	P_c	$F_t = P_t/A$, MPa	MoE for tension (E_t), GPa
T01	2.25	11.2	77.2	13.2	1,463	87.1	59.53	14.3
T02	2.25	12.1	77.7	13.7	1,524	90.2	59.19	13.7
T03	2.25	10.9	76.4	13.3	1,456	83.7	57.47	16.4
T04	2.25	9.8	80.7	14.1	1,630	88.6	54.34	15.8
T05	2.25	10.2	81.2	15.9	1,829	92.3	50.48	13.9
T06	2.25	9.7	78.4	13.4	1,508	87.2	57.81	14.6
T07	2.25	11.7	75.4	13.2	1,426	86	60.32	14.9
T08	2.25	11.2	74.3	12.9	1,374	85.8	62.44	16.4
T09	2.25	12.0	77.2	13.7	1,513	78.4	51.81	13.4
T10	2.25	12.4	81.4	15.1	1,751	83	47.41	14.6
T11	2.25	9.9	76.8	14.4	1,574	86.9	55.23	15.8
T12	2.25	10.2	80.1	15.6	1,771	82.1	46.36	14.8
T13	2.25	11.4	74.8	13.9	1,481	86.5	58.42	15.1
T14	2.25	10.4	78.3	14.3	1,597	84.7	53.02	14.3
T15	2.25	10.6	77.2	13.6	1,503	78.1	51.96	15.7
T16	2.25	12.9	80.2	14.3	1,640	83.1	50.67	14.9
T17	2.25	12.9	78.8	13.4	1,517	87.6	57.75	17.0
T18	2.25	12.7	77.2	13.5	1,493	82.1	54.98	14.3
T19	2.25	11.9	79.3	14.2	1,610	92	57.16	13.9
T20	2.25	11.8	76.5	13.8	1,508	90.8	60.21	14.6
T21	2.25	12.8	74.3	13.2	1,403	83.7	59.66	15.7
T22	2.25	11.8	79.5	14.9	1,685	88.4	52.45	14.7
T23	2.25	11.7	73.4	12.4	1,308	84.8	64.82	15.6
T24	2.25	12.8	77.4	14.8	1,627	87.1	53.55	15.3

Bending Strength

The flexural strength and corresponding MoE for Bambusa tulda was estimated following the four-point loading procedures, as per ISO 22157 (ISO 2019). A total sample length of bamboo was 2.8 m, whereas the free length between the supports was 2.4 m. Fig. 12 shows a bamboo specimen being tested for flexural strength. From the test, the load deflection behavior in the bending, ultimate load, F (N), and corresponding deflection, δ (mm), were measured. Fig. 13 shows a typical load deflection behavior in bending. The failure initiated within the middle third zone of the bamboo in the form of splitting, which propagated toward the ends with the increase of the load. Table 4 shows the ultimate bending strength,

Fig. 10. Tension failure due to tearing through a line along the holes of joints.

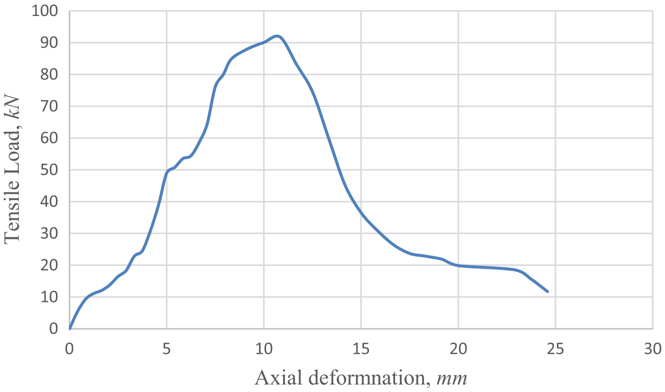


Fig. 11. Load deflection curve for bamboo specimen under tensile load.

σ_{ult} (MPa), and bending MoE, E_b (MPa), of the 24 samples of Bambusa tulda, which were calculated as per the following equations:

$$\sigma_{\text{ult}} = F \times L \times D/12 \times I_B \tag{2}$$

where L and D = clear span and outer diameter in mm, respectively; and I_B (mm^4) = second moment of inertia (MoI) of the bamboo cross sectional area

$$E_b = 23 \times F \times L^3 \times \delta/I_B/1296 \tag{3}$$

From Table 4, the bending strength of the Bambusa tulda was found to be in the range of 57.8–96.2 MPa, which gives a characteristic bending strength of 73.1 MPa at a 95% confidence level. The bending MoE (E_b) was found to vary between 12.2 and 21.7 GPa, which gives a characteristic MoE of 15.7 GPa at a 95% confidence level. These values were found to be comparable to those of the Mao Jue bamboo (Chung and Yu 2002).

Safety Factor and Allowable Stresses

For the ultimate limit state design, a material safety factor of 1.5 should be used and may be reduced to 1.25 if the bamboo is selected under proper quality control (Chung and Yu 2002). Bamboo for tower construction would be selected as defect free, straight, and having the recommended cross-sectional properties under a strict quality control regime. The MC of the selected bamboo would also be closely monitored so as to keep it under 12%, as mechanical and durability properties of bamboo depends on it. Also, it has previously been observed in two different species that the fatigue failure of bamboo does not occur when it is loaded parallel to its axis (Keogh et al. 2015). However, the tower would be subjected to constantly changing environmental parameters, such as temperature and moisture content, for a long period of time. Hence, a safety factor of 2.0 was considered in this work. Consequently, allowable stresses were 50% of that of the characteristic strength of corresponding properties. These allowable stresses were compared with the stresses generated in the bamboo member of the tower due to the factored ultimate load to ensure adequate safety in the design.

Fig. 12. Bambusa tulda sample being tested for bending strength.

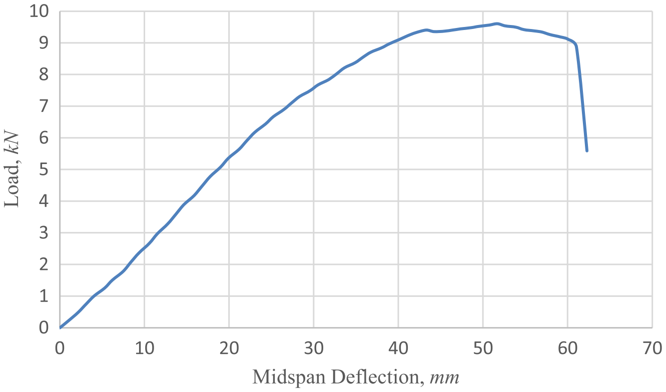


Fig. 13. Load deflection curve for bamboo specimen under bending load.

Structural Modeling and Analysis of Bamboo Tower

Material and Sectional Dimension

For actual tower construction, it was recommended that the outer diameter and wall thickness of the selected bamboo not be less than

Table 4. Behavior of Bambusa tulda under bending load

No.	Free span, L (m)	MC (%)	Outer dia (mm)	Wall thickness (mm)	Cross sectional area, A (mm^2)	MoI, I_B (mm^4) × 10^5	Ultimate load, F, kN	Deflection at ultimate load, δ (mm)	Ultimate bending strength, σ_{ult} (MPa)	Bending MoE (GPa)
B01	2.4	12.6	75.3	13.1	1,414	129	6.41	64.8	74.7	18.8
B02	2.4	10.9	74.4	13.0	1,386	123	5.95	70.2	71.7	16.8
B03	2.4	12.2	77.3	13.8	1,525	145	6.28	56.7	66.8	18.7
B04	2.4	11.4	81.3	15.0	1,738	180	7.44	72.9	67.0	13.9
B05	2.4	12.8	76.7	14.3	1,561	144	6.82	67.5	72.9	17.3
B06	2.4	13.3	80.0	15.6	1,768	173	6.26	64.4	57.8	13.8
B07	2.4	14.1	74.8	14.0	1,490	130	6.18	75.6	71.1	15.4
B08	2.4	12.9	78.2	14.3	1,595	154	7.35	76.7	74.7	15.3
B09	2.4	13.5	80.4	14.7	1,686	172	8.16	67.5	76.3	17.3
B10	2.4	12.1	74.4	13.5	1,434	126	7.65	91.8	90.6	16.3
B11	2.4	11.4	76.2	13.4	1,462	136	7.49	62.1	83.8	21.7
B12	2.4	11.7	79.2	14.2	1,607	160	8.08	62.1	79.8	19.9
B13	2.4	10.8	74.2	14.0	1,477	126	7.68	78.3	90.1	19.0
B14	2.4	11.9	77.2	13.5	1,493	143	8.92	86.4	96.2	17.7
B15	2.4	12.2	77.0	13.3	1,469	141	7.15	72.9	78.2	17.1
B16	2.4	12.8	74.3	12.9	1,374	122	7.45	78.3	90.4	19.1
B17	2.4	13.1	77.2	13.8	1,523	145	6.84	78.3	73.0	14.8
B18	2.4	11.6	81.2	15.0	1,736	180	8.34	83.7	75.4	13.6
B19	2.4	12.1	76.8	14.4	1,574	145	7.63	86.4	81.0	15.0
B20	2.4	11.2	80.2	15.5	1,763	174	7.25	83.7	66.7	12.2
B21	2.4	11.5	74.8	13.9	1,481	130	6.96	81	80.3	16.3
B22	2.4	12.4	78.3	14.4	1,607	155	6.72	75.6	67.9	14.1
B23	2.4	12.5	77.3	13.7	1,515	145	7.63	72.9	81.4	17.7
B24	2.4	11.7	80.1	14.4	1,648	168	8.38	64.8	79.9	18.9

80 and 13 mm, respectively. To be on the conservative side, the bamboo section considered in the analysis and modeling was a tubular hollow section with an outer diameter and thickness of 75 and 12 mm, respectively. A characteristic compressive, tensile, and bending strength, as well as the corresponding MoE of the Bambusa tulda found from the testing scheme, were considered in the analysis.

Table 5. Telecommunication antennas considered in bamboo tower

Antenna type	No. of antennas attached to tower	Dimension (m)	Weight (kg)	Wind load for (210 km/h) (kN)
Microwave	1	0.6 D	15	0.9
GSM	4	2.6H × 0.26W	22	1.4

Load Modeling

The predominant loads acting on the bamboo tower are those generated due to wind thrust on the telecommunication antennas, drag forces on the bamboo members, and the gravity load of the tower and antennas. The lateral load generated due to an earthquake also acts on the bamboo tower. Because the tower was to be placed in Dhaka, Bangladesh, the wind speed of 210 km/h was considered, as per the Bangladesh National Building Code (BNBC) (BNBC 1993), with the surrounding considered as the urban terrain zone. It was also considered that the tower had been placed over an 18-m-high building. Two types of antennas are usually used for mobile network coverage. A parabolic microwave (MW) antenna is used for linking the adjacent base transceiver station (BTS). The panel type global system for mobile (GSM) antennas provide connection with customers in the area covered by that particular BTS. Four GSM and one MW are the usual antenna configurations for small BTS. Accordingly, a bamboo tower was considered to be subjected to wind load from four GSM antennas and one MW antenna. Several factors, including the drag coefficient, aspect ratio, cross-sectional area of the antenna, and air density and velocity, influence the wind load on antennas. Table 5 shows the antenna wind load calculated according to a standard procedure (Ferris 2009). Considering the height, exposure condition, and gust factor, the wind force on the bamboo members was estimated as 1.8 kN/m^2 of the projected area, as per the BNBC, which gave a value of 0.14 kN per linear meter of bamboo, considering a conservative diameter of 80 mm (projection width). An equivalent static earthquake load was generated by SAP2000 from the input parameters based on the BNBC recommendations for the Dhaka, Bangladesh, region.

Structural Modeling and Analysis of Bamboo Tower

To check the adequacy of different bamboo members against the applied load, a three-dimensional finite-element model of the bamboo tower was developed in the structural analysis software SAP2000 (CSI 2015) (Fig. 1). Joints were modeled using steel plates with a 4 mm thickness. There were four bolts at each end, so no rotation was possible between the bamboo member and steel joint at the ends. Again, due to four bolts at the foundation joint, no rotation of the bamboo member was possible at those joints as well. Hence, rotational fixity was ensured between the steel joint and bamboo member end and at the foundation joints of the model. Fig. 14 shows the applied wind load due to the GSM and microwave antenna, whereas Fig. 15 shows distributed wind load on the bamboo members. The forces shown in Figs. 14 and 15 are due to wind acting at a perpendicular direction (90°) to a tower face. Apart from 90°, wind can act on this tower from any direction. Hence, an analysis was also performed considering the wind load acting at 77.5° and 45° (Fig. 16) with respect to the tower face to account for the variability in the wind direction. As the bamboo tower is square and symmetric in plan, these three cases were sufficient to cover all critical wind directions. In a similar fashion, the

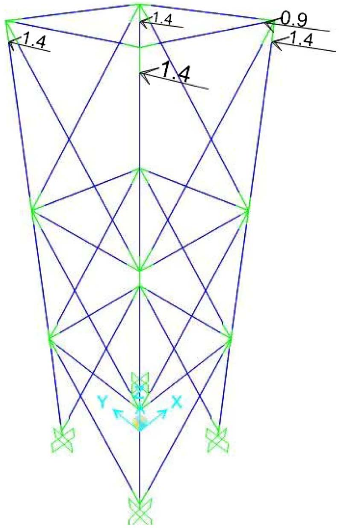


Fig. 14. Wind load on bamboo tower due to antennas.

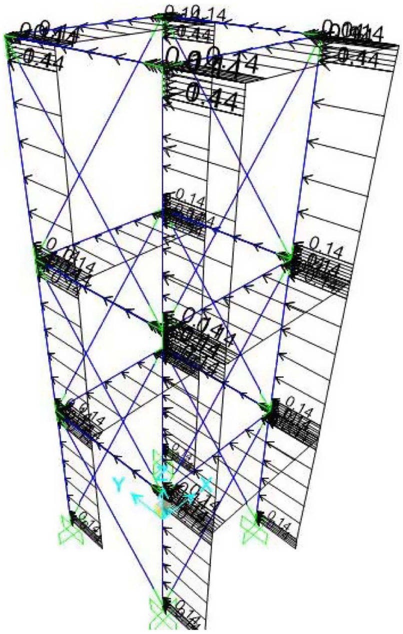


Fig. 15. Wind load acting on bamboo member.

earthquake load was applied to the bamboo tower from these critical directions.

Results and Discussions

The model developed in SAP2000 (CSI 2015) was analyzed, and the stresses in the bamboo were evaluated as per the BNBC load combinations. For each member, both axial (compressive and tensile) and bending stresses were measured and compared with their respective allowable stresses. Also, for a bamboo member to be safe, a combination of bending and axial stresses must satisfy the following equation:

$$\frac{\sigma_a}{F_a} + \frac{\sigma_b}{F_b} \leq 1 \tag{4}$$

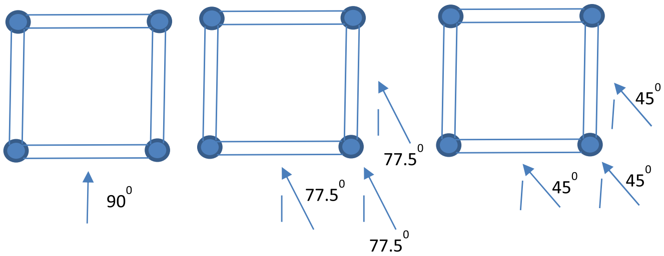


Fig. 16. Different directions of wind load on bamboo tower.

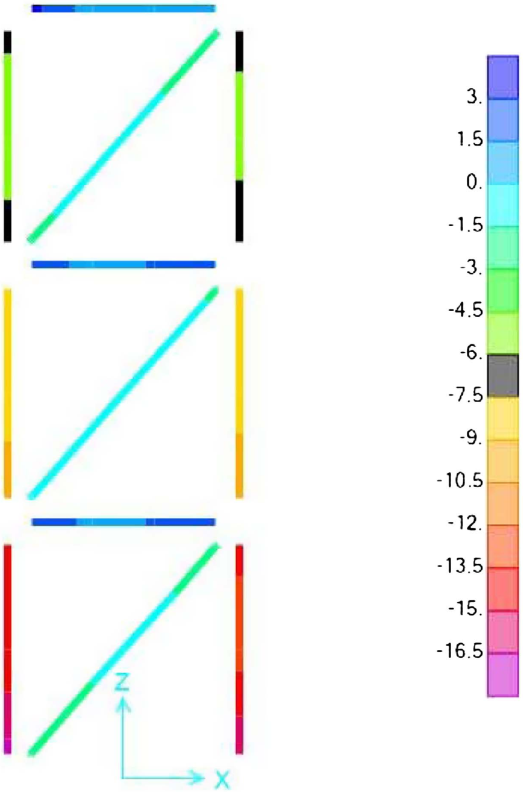


Fig. 17. Compressive stresses (MPa) in bamboo member.

where σ_a and σ_b = axial and bending stresses due to loads, respectively; and F_a and F_b = allowable axial and bending stresses, respectively. It was observed for all critical directions that forces and moments in bamboo members of the tower were much higher for the wind load than for the earthquake load. Figs. 17 and 18 show maximum axial compressive and tensile stresses developed in the bamboo member, respectively. For simplicity, steel joint stresses are omitted in these figures. Explicably, the maximum compressive and tensile force were developed at the bottom part of the vertical member and on opposite sides, respectively. Both maximum compressive (16.5 MPa) and tensile (12.0 MPa) stresses were much less than the allowable stresses (20.2 and 26.8 MPa, respectively) established from the testing scheme after allowing a material safety factor of 2.0. The maximum bending moments, found from the analysis, are shown in Fig. 19. As can be seen from this figure, and due to lattice configuration of the tower, the generated moment value was small compared to the axial load and corresponding axial stresses. The resultant bending stresses were also very low, and Eq. (4) could easily be satisfied.

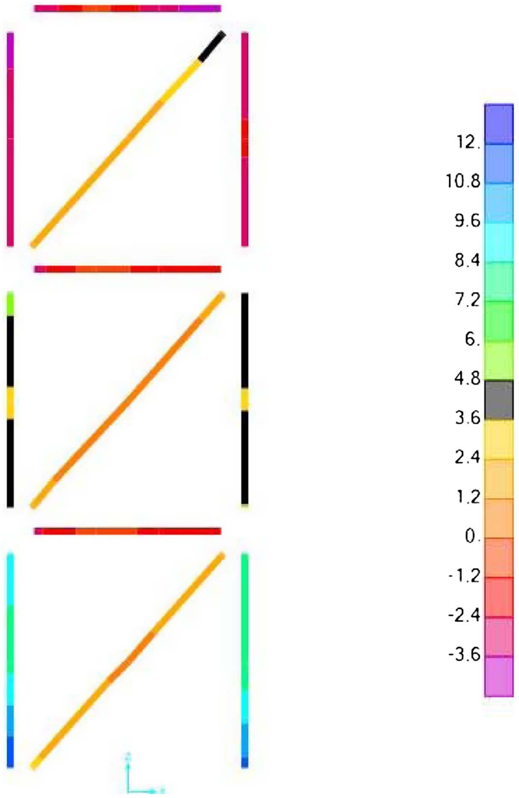


Fig. 18. Tensile stresses (MPa) in bamboo tower member.

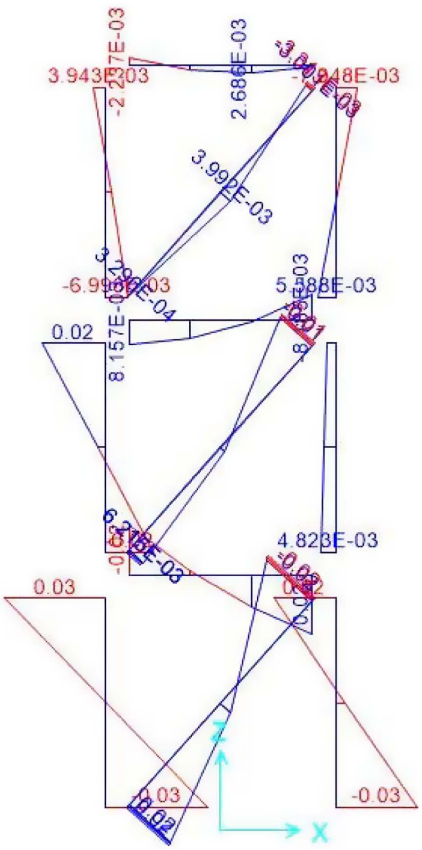


Fig. 19. Bending moment (kN-m) in bamboo tower member.

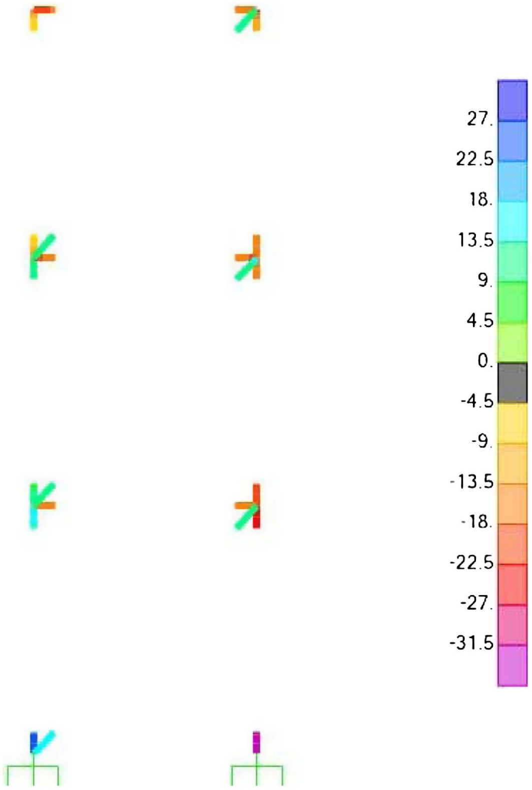


Fig. 20. Stresses developed in the steel joint (kN-m).

Stresses at joints were also checked for adequacy and safety (Fig. 20). It was found that 4 mm steel plates were adequate for the joints because the maximum stresses developed in the joints were found to be 63 MPa, which is much less than the yield stress of 350 MPa for steel. Hence, 4-mm thick steel plates may be considered as adequate.

The maximum compressive and uplift reaction force at the base of the tower was found to be 33 and 32 kN, respectively. To transmit this load to the concrete foundation over which the tower is installed, the joints at the foundation level were attached to a 300-mm square steel base plate with a 6-mm thickness through which six 12-mm diameter foundation bolts were inserted 350 mm into the concrete base. A calculation shows that both the base plate and foundation bolt dimensions are adequate to transmit the reaction loads.

Fig. 21 shows a deflected pattern of the tower while the maximum top deflection of 19 mm was observed at the service load stage. This corresponds to a rotation of 0.2°, much less than allowable deflection of 1° considered by edotco (Edotcogroup 2019). Considering these results, it may be concluded that a bamboo tower possesses sufficient strength and stiffness to meet the service load and ultimate load criteria.

Economic Performance of the Bamboo Tower

The economic performance of the bamboo tower was evaluated and compared with a GI pipe tower of an equivalent height, considering the life-cycle cost assessment. This assessment was based on themes specified in ISO 15686 (ISO 2008) and included the cost of three items: construction cost, maintenance cost, and disposal cost. Telecommunication structures are typically constructed for a design life of 15 years, and hence, all calculations have been based on that period. The construction cost included that for materials, transportation, fabrication, and workforce. Maintenance included periodic costs for paints and chemical retreatments. In this work, it was assumed that bamboo would be replaced at the end of each 5-year period after installation. This is in line with Adhikari et al. (2015) who suggested the replacement of bamboo after 4–5 years for bamboo wind turbine. Therefore, the purchase cost of the replaced bamboo, including its treatment and disposal of discarded bamboo, was also included in the total cost comparison. At the end of the service life, demolition and removal cost was added to the total life-cycle cost. To allow for currency fluctuation, all future costs were converted to the present value using the following equation (ISO 2008):

$$PV = \sum_{t=0}^{t_{L-1}} \frac{C_t}{(1+d)^t} \tag{5}$$

where PV = time adjusted total cost at the present value; C_t = sum of all costs incurred in a year t; tL = effective service life of the tower in years; and d = discount rate. The discount rate depends on several factors and may vary from year to year. ISO 15686-5 (ISO 2008) proposes that the discount rate may be between 0 to 4%, and a rate of 4% was used in this work. Table 6 shows the construction cost difference between a bamboo tower and conventional GI pipe. Table 7 shows the maintenance cost difference in the present value for a lifespan of 15 years. Table 7 also includes the salvage value at the end of dismantling and the total life-cycle comparison between bamboo and GI pipe tower. The basic cost values for construction and other items listed in Tables 6 and 7 were provided by edotco (Edotcogroup 2019), which were then processed and rounded, as per Eq. (5). From the total life-cycle cost, as shown in Table 7, it can be seen that a savings of about 18% could be achieved if a bamboo tower is constructed instead of a GI pipe tower. Also, the initial investment of $1,045 for the bamboo tower was about 46% less than the $1,970 required for installing a GI pipe tower.

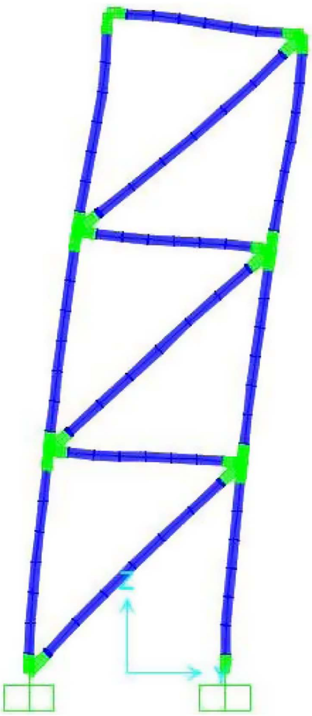


Fig. 21. Deflection pattern of the tower.

Table 6. Construction cost comparison between bamboo and equivalent GI pipe tower

Item description	Bamboo tower (in USD)	GI pipe tower (in USD)
Material cost (main member and joint) including transportation	320	1,380
Installation cost	425	440
Beautification and treatment	150	0
Tower foundation part	150	150
Total construction cost (A)	1,045	1,970

Conclusion

In this paper, the design of a 5-m-high rooftop telecommunication tower using bamboo has been described in detail. Bambusa tulda, also known as Indian timber bamboo or Bengal bamboo, was used to design and construct the tower using a joint system that can transfer forces between bamboo members. An experimental investigation on the bamboo sample showed that the characteristic compressive strength of a 2.25-m-long bamboo was 40.5 MPa, whereas, the characteristic tensile and bending strength was 53.4 and 73.1 MPa, respectively. To assess the structural adequacy of the bamboo tower, a three-dimensional model of a 5-m-high bamboo telecommunication tower was developed in the finite-element software SAP2000 (CSI 2015), considering material properties evaluated from the testing scheme. The analysis results showed that member stresses are much less than the allowable compressive, tensile, and bending capacity of bamboo. The durability of the bamboo tower was ensured through appropriate treatment against insects and other environmental parameters. The life-cycle cost comparison showed that the bamboo tower was 18% less expensive than the

Table 7. Maintenance cost comparison between bamboo and equivalent GI pipe tower

	Bamboo tower (in USD)			GI pipe tower (in USD)		
Item description	Frequency in 15 years	Unit cost	Total cost	Frequency in 15 years	Unit cost	Subtotal
Purchase of main member of the tower and disposal of old bamboo	2	75	150	0	0	0
Reinstallation of main members	2	95	190	0	0	0
Chemical retreatment	2	50	100	0	0	0
Paint	5	40	200	1	80	80
Dismantle cost after 15 years	1	45	45	1	180	180
Total maintenance cost (B)	705			260		
Salvage value (C)	20			150		
Total life-cycle cost (A + B − C)	1,730			2,080		

GI pipe tower of an equivalent height. Also, an initial investment was found to be 46% less in the bamboo tower. Hence, considering the bamboo species named Bambusa tulda, the environmental condition, and the loading criteria of Dhaka, Bangladesh, it may be concluded that bamboo may be used to construct low-height rooftop telecommunication towers, which would bring about economic and environmental benefits in the telecommunications sector. Also, for a developing country such as Bangladesh where bamboo is locally cultivated, its use as a primary construction material for a telecommunication tower would benefit the local economy as opposed to constructing a tower with imported iron or steel. Based on the current research findings, future research endeavors will focus on developing accurate life-cycle prediction models for bamboo exposed to different environmental conditions. The feasibility of constructing medium height telecommunication towers (10–15 m) with bamboo will also be explored in the future.

Data Availability Statement

Additional photographs, software models, and raw test data that support the findings of this study are available from the corresponding author upon reasonable request.

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