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Design and Optimization of a Laser-Welded Corrugated-Core Steel Structure for Monopoles

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ABSTRACT

Designing lighter structures which are resistant to environmental forces, such as wind, is of major importance as there is less usage of material. A lightweight structure is more cost effective and enables innovation in design. In this study, a laser-welded corrugated-core steel sandwich structure is designed and optimized to reduce the amount of material used for manufacturing monopoles. A model of an existing tower, designed to resist cyclonic wind forces in Mauritius, is obtained from industry and the optimization process is carried out following a parametric study whereby several design variables are introduced. The weight of the structure is taken as the objective function for minimization. The design constraints are set as per the structural standard ANSI/TIA/EIA-222F and the limitations in manufacturing of the structure. To choose the optimum model, the reduced mass and the structural performance of the corrugated structure are compared to those of an existing tower. Once the optimum model is selected, a finite element analysis is carried out whereby the displacements and stresses developed are analyzed. Ultimately, a mass reduction of 26.1 % is achieved and the results show a safe structure.

Keywords: Monopoles; Parametric Study; Optimization; Structural Efficiency; FEM; CFM.

1. INTRODUCTION

Over the last two decades, the telecommunication industry has encountered a considerable growth in the wireless sector. With the increasing use of mobile phones and wireless technologies all over the world, construction of telecommunication towers is being given more importance than ever before. These towers exist in various forms notably lattice towers, monopole towers, self-supporting towers and guyed towers. Compared to the other types of tower, monopoles create an unobstructed environment as minimal land perimeter is needed for their erection. However, the weight and cost of monopoles are much higher than those of lattice towers because of the huge amount of steel used, which is at least five times more [1]. Monopole towers are tapered steel tubular structures and are designed as per ANSI/TIA/EIA-222F, which is the structural standard for antenna supporting structures. Most monopole towers have heights in the range of 20 m to 45 m and consist of segments which are either joined by flanges, collars or are welded together. There are cut-outs in the structure in the form of doors, with stiffeners to strengthen the tower at the lower extremity, as can be seen in Figure 1. The bottom diameter is above 1000 mm and the top diameter is 900 mm. The thickness of a steel segment is at least 6 mm.

Engineering practice often focusses on the need to reduce the mass of a structure while maintaining enough stiffness and resistance to environmental forces. The traditional way of tackling this problem is to use another material exhibiting superior properties. For instance, composite materials are known to be highly effective in applications requiring high strength-to-weight ratio [2]. However, this solution is not often worthwhile due to the high cost of these sophisticated materials. An innovative way of reducing the mass of a structure while upholding its performance (in terms of strength and stiffness) is to make use of sandwich panel structures. According to Li and Wang [3], sandwich panels, also known as lightweight structures, are made from two stiff and strong skins separated by a core usually made of a polymeric foam or in the form of a corrugated or honeycomb structure. The skins of the sandwich structure provide structural stiffness and guard the core against weathering and damage. When a force is applied on the sandwich panel, the face sheets take tensile and compressive loads while the core converts shear loads between the skins and provides high bending stiffness. Nowadays, thin shells are also widely used in state-of-the-art structures, having shown impressive structural resistance [4].

In this study, a laser-welded corrugated-core steel sandwich structure was designed and optimised for monopoles, with the intent of minimising material usage and yet providing a safe structure which is resistant to wind loads. To do so, a structural analysis was initially carried out on a 20-m tall existing tower made of a S355 steel structure, whereby the bending stiffness, static deflection and stresses developed were analysed. Following this analysis, the corrugated structure was modelled and optimised by means of a parametric study, which enabled determination of the optimum model.

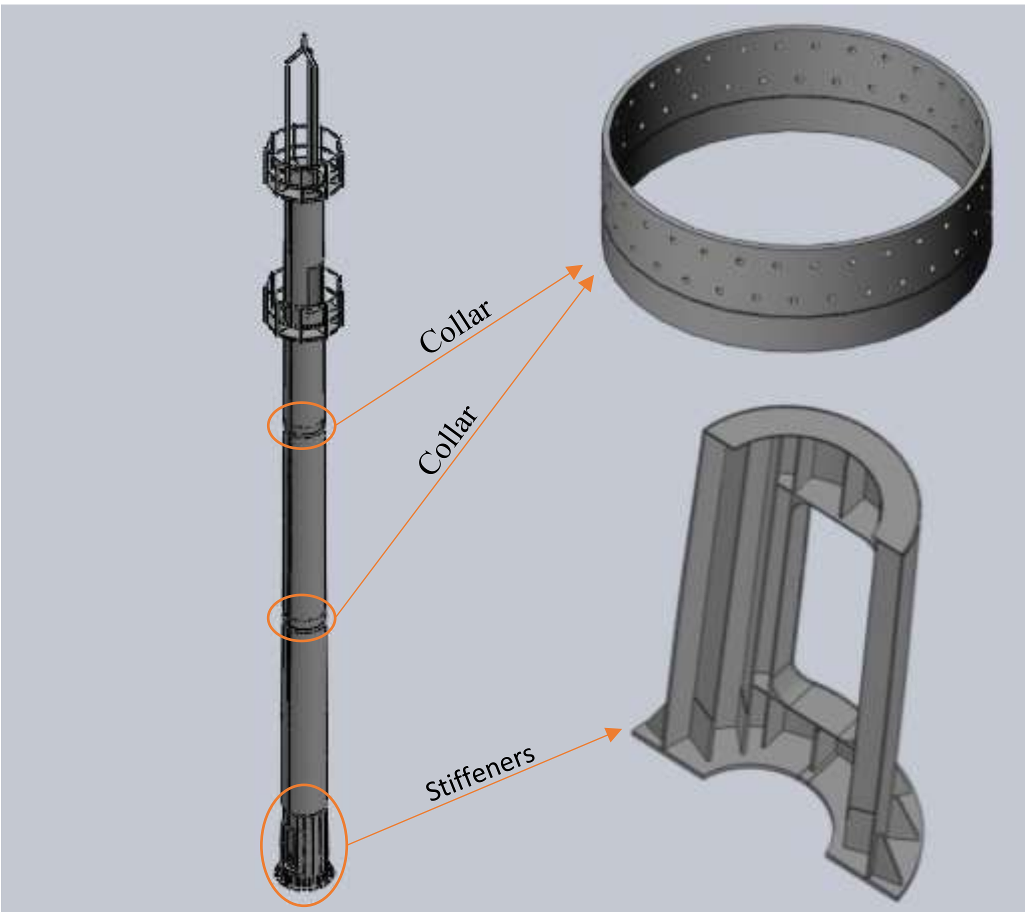

Figure 1. Existing Tower

2. LITERATURE REVIEW

2.1 Monopole Tower Analysis

Masmoudi et al. [5] built a 12-m high experimental model of a pole structure and used ADINA as a finite element analysis tool to determine the maximum deflection under wind load. A ratio between 0.97 and 1.05 was achieved between the experimental model and the finite element model. Sangasuri et al. [6] developed an analytical model and a finite element model in ANSYS Workbench to investigate the static deflection of a 10-kW wind turbine tower under wind action and a difference of 15 % in the static deflection was achieved. ANSYS Workbench was also used in other studies of monopole towers to determine the static deflection under specific wind pressures [7, 8].

2.2 Optimization

According to Ahuja and Hazra [9], optimization is an exercise performed to find an optimal solution satisfying a given number of constraints. An optimization process consists of the following components: design objective, design variables and design constraints. An optimization algorithm is formulated whereby feedback is given to it and a new design solution is calculated by means of a mathematical program. This process is iterative in nature and is repeated until the objective function is minimal. Using an optimization procedure, Sakurada et al. [10] achieved a 17.5 % weight reduction without altering the stiffness of a thin plate hollow cantilevered structure. Cicconi et al. [11] carried out a two-phase weight optimization on a steel structure and showed that using a two-stage approach was 30 % less time consuming and a mass reduction of 15 % was successfully achieved.

2.3 Sandwich Structure

Sandwich panels are used in applications requiring high stiffness to weight ratio because, for a given weight, the structure has a higher moment of inertia compared to solid [12]. With its material reduction capabilities, sandwich structures accomplish the desired function of a system with optimal utilization of resources [13]. According to Kujala et al. [14], steel sandwich panels can offer 30-50% weight savings compared to conventional steel structures. The mechanical behaviour of the sandwich structures depends on the geometry of the skins, the material used and more importantly the design of the core topology. Li and Wang [3] argued that the sandwich effect is lost if the core does not have enough shear properties to prevent the skins from sliding during bending. Meifeng et al. [15] revealed that maximum flexural rigidity and bending strength is achieved if the weight of the core is between 50-66.7%. Zeng et al. [16] showed that composite lattice cores have superior mechanical properties than metallic cores when the structures are subjected to out of plane compression loading.

As far as the manufacture of sandwich structures is concerned, Rejab et al. [17] used a hot press molding for composite cores and bonded the skins using epoxy adhesives. Fan et al. [18] developed an interlacing method to produce sandwich composites with pyramidal cores made up of carbon fiber via additive manufacturing. Xiong et al. [19] made a composite pyramidal truss core using a hot-press method through molding. However, the advancement of technologies has enabled use of laser welding as a new joining technique, by many industries, to produce sandwich structures in large amount [20]. According to Kananen et al. [21], a corrugated core can be manufactured either by mechanical rolling incorporated with a gear press or using a press brake machine. The quality of the core is very crucial to have an effective laser welding. Katayama [22] stated that there should be an air gap of less than 0.2 mm in overlap joints to have a weldable surface. Nilson et al. [23] explained that laser welded cores can provide robust and continuous connection for thicknesses over 10 mm. According to Kujala et al. [20], the investment cost of laser welding is relatively high, and the price of the steel panels is correlated to the volume of production. Nevertheless, as the cost of material is much lesser due to decreased weight, the price of sandwich panels per unit area is about the same magnitude as conventional steel plates joined by traditional welding. Poirier at al. [24] argued that laser welding consumes huge amount of energy. However, taking the speed of welding into consideration, the magnitude of energy consumption compared to conventional welding is the same. Lamsa et al. [25] showed that laser welding is 40 times faster compared to manual TIG welding.

3. CONCEPTUAL DESIGN

3.1 Concept Generation

The new tower to be considered as a replacement for existing monopoles should have a lighter structure and also be resistant to cyclonic wind forces. Figure 2 shows concepts of lightweight tower structures which were generated taking into consideration the economic viability and manufacturability of the new structure.

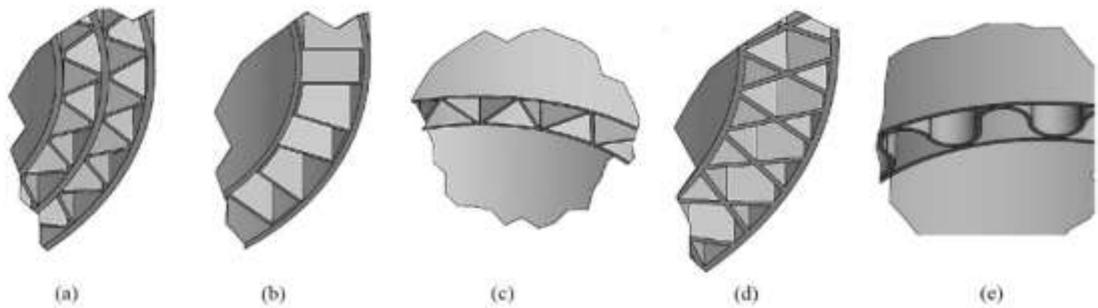

Figure 2. Concepts: (a) Dual Layer (b) Square-Corrugation (c) Single Layer (d) X-corrugation (e) Round-Corrugation.

3.2 Concept Selection

3.2.1 Selection of criteria

The criteria considered for evaluation of the set of concepts are listed and explained as follows:

- Lightweight Structure - This is one of the most significant criteria as it is within the scope of the study, which is weight minimisation.
- Stiffness and Strength - This criterion depends on the type of corrugation between the skins. Basically, an increase in the number of corrugations leads to a stiffer structure.
- Stability - The stability of the structure depends on its capability to transmit the wind loadings safely to the ground.
- Aesthetics - Based on the principle of architectural design, the new structure should be more focused on its functionality rather than aesthetics. However, an aesthetically pleasing sandwich structure allows innovation in the design.
- Ease of manufacture - This criterion deals with the complexity of manufacturing the corrugated structure.
- Manufacturing cost - The cost is estimated by judging the type of corrugation and the amount of material needed to manufacture the structure.

3.2.2 Weighting the criteria

The index weights of the criteria were evaluated on a scale of 1 to 3, with the least important factor being 1 and the most important one being 3. Table 1 shows the weighted criteria based on the design requirements.

3.2.3 Rating of concepts

To rate the different concepts, a scale of 1-5 was used as follows:

1 – Poor
2 – Fair
3 – Good
4 – Very Good
5 – Excellent

Following assignment of the relevant rating to each concept against a datum, the raw score was calculated by summing the ratings, as shown in Table 1.

3.2.4 Ranking and Selection

The concepts were ranked in order of their respective weighted scores. The latter were calculated using Equation (1).

$$\text{Weighted score} = \sum(\text{Individual rating given to criteria x Index weight}) \quad (1)$$

The one with the largest score is ranked first and is selected for further development. As shown in Table 1, the best concept is the single layer corrugated structure.

Table 1. Concept Selection table

	Criteria						Results		
Weights	3	2.4	2.1	2	1.7	1			
Concepts	Lightweight	Stability	Ease of Manufacture	Stiffness and Strength	Manufacturing Cost	Aesthetics	Raw Score	Weighted Score	Rank
1 – Multi layer	4	5	1	5	2	3	20	43	4
2 – Square	5	3	4	3	3	3	21	45	3
3 – Single layer (Datum)	**5**	**4**	**4**	**4**	**3**	**3**	**23**	**49**	**1**
4 – X-core	4	5	4	5	1	4	20	42	4
5 - Round	5	3	4	3	3	4	22	46	2

4. MODELLING & ANALYSIS OF EXISTING TOWER STRUCTURE

4.1 Determination of the Mass of the Existing Tower

The mass of the existing tower was calculated from Equation (2).

$$m_e = \rho_s \ x \ V_e \quad (2)$$

Where, m_e is the mass of the existing tower structure (kg), ρ_s is the density of S355 steel (7850 kgm^{-3}) and V_e is the volume of the existing tower structure (m^3).

Since the thickness of the monopole varies from one segment to another, as can be seen in Figure 3, the volume for each segment was calculated separately using Equation (3) and then added together. To account for the taper, an average radius was considered for each segment.

$$V_s=\pi(R^2-r^2)\times l \quad (3)$$

Where, V_s is the volume of a tower segment, R is the outer radius of a tower segment, r is the inner radius of a tower segment and l is the length of a tower segment.

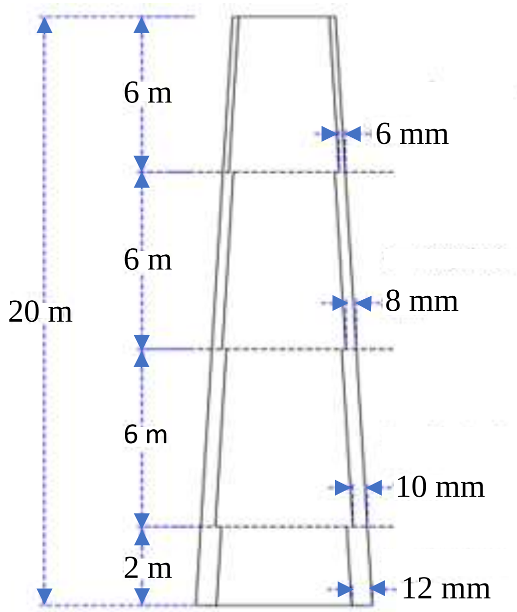

Figure 3. Schematic of the tower structure with varying thicknesses.

4.2 Calculation of Wind Forces

The wind force acting on the structure was determined using Equation (4) as per BS EN 1991-1-4:2005+A1:2010 [26].

$$F_w=c_s c_d c_f q_p(z_e) A_{ref} \quad (4)$$

Where, F_w is the wind force, $c_s c_d$ is the structural factor, c_f is the force coefficient, $q_p(z_e)$ is the peak velocity pressure at reference height z_e above the ground and A_{ref} is the projected area of the cylindrical section of the structure being considered.

The recommended value of $c_s c_d$ for structures having circular cross section and height less than 60 m is 1.00.

The peak velocity pressure $q_p(z_e)$ is found using Equation (5).

$$q_p(z_e)=\left(1+7.I_v(z_e)\right).\frac{1}{2}.\rho.v_m(z_e)^2 \quad (5)$$

Where, $I_v(z_e)$ is the wind turbulence, ρ is the density of air and the recommended value is 1.25 kg/m^3, $v_m(z_e)$ is the mean wind velocity and is given by Equation (6).

$$v_m(z_e)=c_r(z_e).c_0(z_e).v_b \quad (6)$$

Where, $c_r(z_e)$ is the terrain roughness, $c_o(z_e)$ is the orograhy factor and v_b is the basic wind speed considered for the design.

The recommended value of $c_o(z_e)$ is 1.00,

Terrain category III (areas with regular cover of buildings and vegetation) was considered for the calculation of the wind pressure as most monopoles are erected in places where space is an issue. A basic wind speed of 84 ms^{-1} with a safety factor of 1.5, which is generally used for design purposes in Mauritius, was considered. Wind pressures were calculated at different heights as shown in Table 2.

Table 2. Wind forces acting on the existing tower

Reference Height Z_e (m)	**Factored Force F_W×1.5 (N)**	**Effective Pressure $(F_W\times1.5)/A_{ref}$ (Pa)**
5	25171	4576
6.5	7500	4762
8	8089	5211
9.5	8561	5596
11	8932	5925
12.5	9250	6229
14	9512	6505
15.5	9733	6759
17	9916	6994
18.5	10064	7214
20	10185	7421

4.3 Formulation of a Closed Form Model (CFM)

The static deflection of the tower was found using the Castigliano's theorem [27], for which the following assumptions were made:

- The model is assumed to be a tapered cantilevered beam without considering the jointed connections at each segment;
- The material used is homogenous, linearly elastic and isotropic;
- Secondary effects such as axial loads and shear deformations are neglected.

As per BS EN 1991-1-4 +A1:2010 [26], the total wind force acting on the structure (F_{wT}) may be expressed as a vectorial summation of the forces over the individual structural elements using Equation (7).

$$F_{wT}=c_s c_d \sum c_f q_p(z_e) A_{ref} \tag{7}$$

The summation of forces of all the structural elements is equal to 116913 N. Basically, when a force acting on a body is replaced by another force such that the resulting rigid-body effects remain unchanged, the two systems are considered to be statically equivalent. To find the static deflection, the wind force acting midway of the structure is replaced by an equivalent force at the top of the tower. To generate the same base overturning moment, the force that need to be applied at the tip of the monopole (F_{top}) is 58457 N.

According to Kalaga [28], an equivalent pole can be devised to analyse tapered poles. For a tapered pole subjected to a single point force at the free end, an equivalent cylindrical structure with an equivalent second moment of area (I_{eq}) can be considered. Since the existing monopole has varying thicknesses along its length (L_e), an average value of 9 mm was considered for the thickness of the equivalent cylinder. The diameter of the equivalent cylinder was obtained by averaging the top and bottom diameter of the tapered pole. From the Castigliano's theorem [27], the tip deflection (y_A) was calculated using Equation (8).

$$y_A = \frac{PL_e^3}{3E_{steel}I_{eq}} \tag{8}$$

Where, E_{steel} (modulus of elasticity of S355 steel) = 210×10^9 Pa, $L_e = 20$ m, $I_{eq} = 0.00344\ m^4$ and $P = F_{top} = 58.5$ kN.

The Bending Stiffness (S) was then calculated using Equation (9).

$$S = \frac{F_{top}}{y_A} \tag{9}$$

4.4 Finite Element Analysis (FEA)

A Finite Element Model (FEM) of the existing tower was created in the ANSYS Workbench software to analyse the displacements and stresses developed under cyclonic wind conditions. The masses of the antennas and microwave dishes were applied as distributed masses at the top of the tower and the surfaces of holes for foundation bolts in the base plate were set as fixed supports. Regarding meshing, the sweep mesh method was used whereby a combination of tetrahedral and hexagonal elements was generated. The structure was considered as several segments, allowing a varying pressure to be applied along the height of the tower.

5. MODELLING AND ANALYSIS OF CORRUGATED-CORE STRUCTURE

The mass of the corrugated structure (m_c) was determined by assuming its cross section to consist of several parallelograms and two annuli, as shown in Figure 4. The cross-sectional area (A) is given by Equation (9).

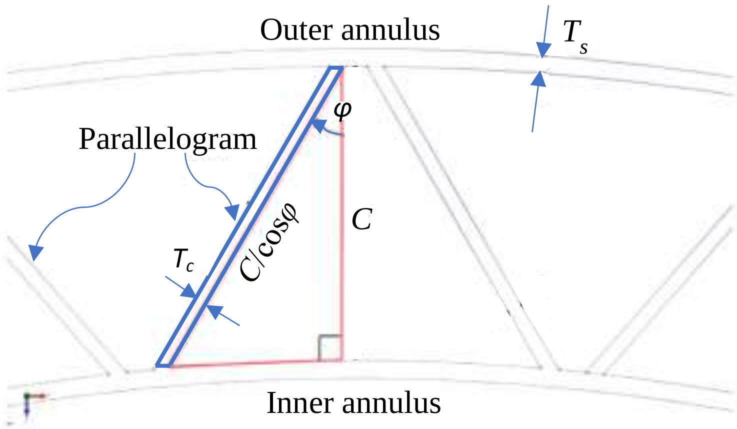

Figure 4. Parameters involved in determining the mass of the structure.

$$A = N \times A_p + A_i + A_0 \tag{9}$$

Where, N is the number of parallelograms, A_p is the area of one parallelogram, A_i is the area of the inner annulus, A_o is the area of the outer annulus.

From Figure 4, the total area of the parallelograms (A_{pT}) is calculated using Equation (10).

$$A_{pT} = N \times A_p \times T_C = N \times (C/\cos\varphi) \times T_C \tag{10}$$

To account for the taper of the tower, Equation (11) was used to calculate the diameter (D_{avg}) of an equivalent cylinder, equal to the average of the top diameter (D_A) and bottom diameter (D_B) of the structure.

$$D_{avg} = \frac{D_A + D_B}{2} \tag{11}$$

From Figure 4, D_{avg} was then used to calculate the area of the inner and outer annuli, as shown by Equations (12) and (13).

$$A_o = \pi\left[\left(\frac{D_{avg}}{2}\right)^2 - \left(\frac{D_{avg}}{2} - T_s\right)^2\right] \tag{12}$$

$$A_i = \pi\left[\left(\frac{D_{avg}}{2} - T_S - C\right)^2 - \left(\frac{D_{avg}}{2} - 2T_S - C\right)^2\right] \tag{13}$$

The area of the cross section was calculated using Equation (14) and then replaced in Equation (15) to obtain the mass of the corrugated tower of length (L_c) 20 m and made of S355 steel of density (ρ) 7850 kgm^{-3}.

$$A = A_p + A_o + A_i \tag{14}$$

$$m_c = \rho \times A \times L_c \tag{15}$$

6. OPTIMISATION

The optimisation process had as design objective to reduce the mass of the structure without compromising on structural efficiency. The latter was evaluated in terms of the bending stiffness to mass (*S/m*) ratio.

A web angle greater than 308 does not increase the efficiency of the section and there is no substantial change in the modulus of the section [29]. If the web angle is less than 308, although the structural performance increases, the efficiency of the material decreases for a given modulus. Thus, for the optimization process, the web angle was kept constant at 30°. A parametric study was performed with D_A, D_B, T_s, C and T_c as design variables as shown in Table 3. The reason for not reducing D_A further than 810 mm was due to a fixed ladder safety cage inside the tower. As per ANSI/TIA/EIA–222F-1996 [30], the diameter of the cage should be 600 mm. Thus, to allow for suitable clearances between the safety cage and the structure, the diameter was not further reduced.

The whole optimisation procedure is described through an optimisation flowchart (Figure 5). In a first phase of the optimisation process, T_s was reduced from 3 mm to 2.5 mm, with T_c constant. The optimum model from this first phase was then further optimised by reducing T_c. The effect of reducing the thickness of the core on the structural efficiency of the corrugated structure was investigated. The thickness was reduced to a minimum of 1.8 mm because of the inefficiency of a rolling machine to press thinner metal sheets.

Table 3. Design Table

Model Name	Diameter (mm)	T_s (mm)	T_c (mm)	C (mm)
A	D_A = 900 D_B = 1100	3	2.5	40
B				45
C				50
D		2.5	2.5	40
E				45
F				50
G	D_A = 855 D_B = 1045	3	2.5	40
H				45
I				50
J		2.5	2.5	40
K				45
L				50
M	D_A = 810 D_B = 990	3	2.5	40
N				45
O				50
P		2.5	2.5	40
Q				45
R				50

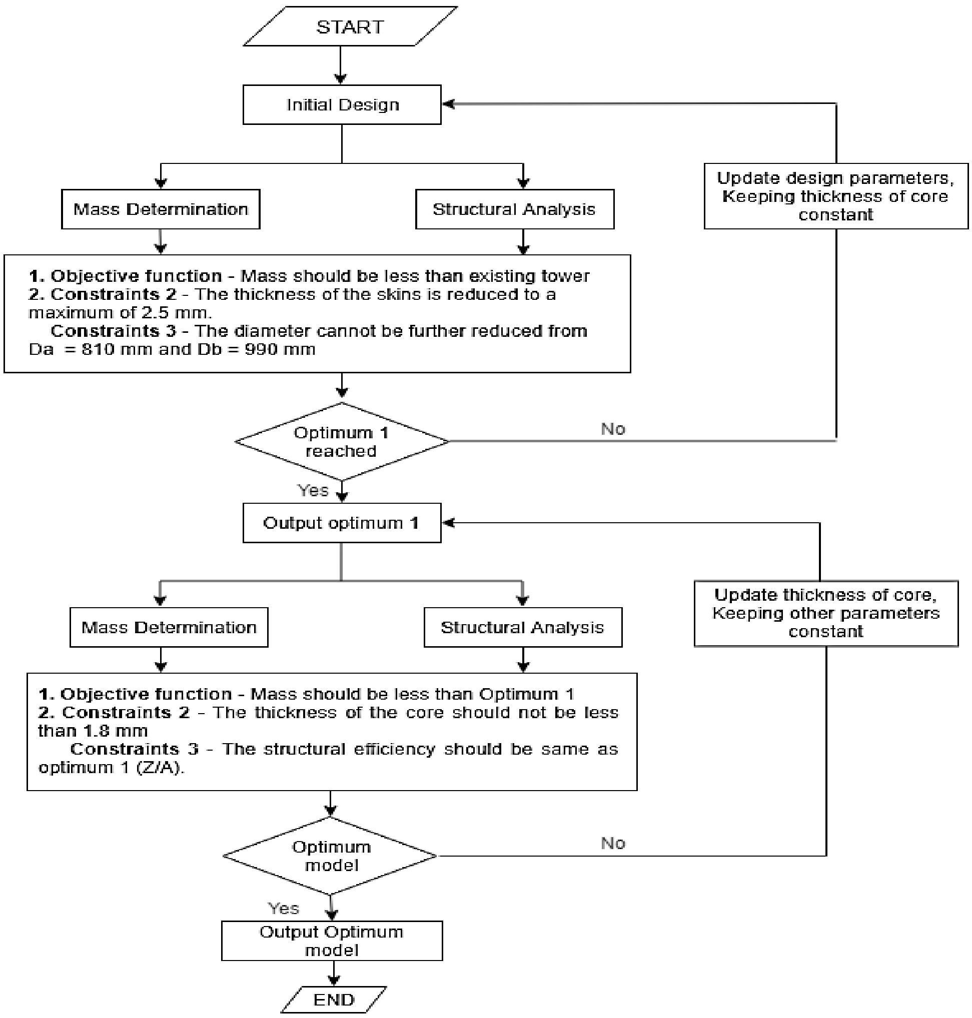

Figure 5. Optimization Flowchart

As shown in Figure 6, a program in C++ programming language was written to evaluate the mass of each parametric model just by inputting the values of the relevant parameters.

```
/*
* Program to calculate mass
*/
#include<iostream>
using namespace std;
int main ()
{
    float Mass,p,Tc,Ts,N,c,Db,Da,L,Ap,Ac,Ai,x,y,r,q,AvgDia;  // Defining the parameters involved for the mass calculation
    cout<<"Enter p=";                                        // Enter a value for the density of the material
    cin>>p;                                                  // Reading the input from the keyboard
    cout<<"Enter Tc=";                                       // Enter a value for the thickness of core
    cin>>Tc;                                                 // Reading the input from the keyboard
    cout<<"Enter Ts=";                                       // Enter a value for thickness of skin
    cin>>Ts;                                                 // Reading the input from the keyboard
    cout<<"Enter N=";                                        // Enter a value for the number of corrugation
    cin>>N;                                                  // Reading the input from the keyboard
    cout<<"Enter c=";                                        // Enter a value for the core depth
    cin>>c;                                                  // Reading the input from the keyboard
    cout<<"Enter Db=";                                       // Enter a value for the butt diameter
    cin>>Db;                                                 // Reading the input from the keyboard
    cout<<"Enter Da=";                                       // Enter a value for the top diameter
    cin>>Da;                                                 // Reading the input from the keyboard
    cout<<"Enter L=";                                        // Enter a value for the length of the tower
    cin>>L;                                                  // Reading the input from the keyboard
    AvgDia=(Da+Db)/2;
    x=AvgDia/2;                                              // Perform arithmetic operations
    y=(AvgDia/2)-Ts;                                         // Perform arithmetic operations
    r=(AvgDia/2)-Ts-c;                                       // Perform arithmetic operations
    q=(AvgDia/2)-Ts-Ts-c;                                    // Perform arithmetic operations
    Ap=(2*Tc*N*c)/1.732050808;                               // Perform arithmetic operations
    Ac=3.142*((x*x)-(y*y));                                  // Perform arithmetic operations
    Ai=3.142*((r*r)-(q*q));                                  // Perform arithmetic operations
    Mass=p*(Ap+Ac+Ai)*L;                                     // Perform arithmetic operations
    cout<<"Mass="<<Mass;                                     // Output Mass
    return 0;
}
```

Figure 6. Mathematical program to find the mass of the parametric models

For determination of the static deflection of each parametric model, the Mc Cutcheon method (Equation 16) was used. McCutcheon [31] derived an equation to calculate the deflections of circular tapered poles subjected to different types of loadings.

The following assumptions were made: (1) uniform taper from tip to butt, (2) negligible shear deformations and no axial loadings, (3) constant modulus of elasticity. In a cantilevered beam, the maximum deflection is always at the tip. To find the deflection, the real load being applied on the structure was replaced by a force acting at the tip. Based on the BS EN 1993-3-2:2006 [32], the static deflection should be within the ratio of the height of the structure divided by 50.

Since Diameter is a design parameter, the wind pressures were calculated at varying diameters (Table 4). The same methodology described in sections 4.2 and 4.3 was used to calculate the effective pressures and F_{top}.

$$y_A = \frac{PL^3}{3EI_A} \cdot \frac{1}{r^3} \tag{16}$$

Where, y_A is the tip deflection (m), P is the bending moment due to real load (Nm), L is the length of pole (m), E is the modulus of elasticity (Pa), I_A is the moment of inertia at tip (m^4) and r is the ratio of butt diameter to tip diameter.

Table 4. Wind pressures at varying diameters

Reference Height Z_e (m)	Effective pressure with safety factor of 1.5 (Pa)		
	D_B = 1100 mm, D_A = 900 mm	D_B = 1045 mm, D_A = 855 mm	D_B = 990 mm, D_A = 810 mm
5	4576	4593	4610
6.5	4762	4789	4808
8	5211	5231	5260
9.5	5596	5617	5640
11	5925	5958	5982
12.5	6229	6254	6289
14	6505	6531	6557
15.5	6759	6786	6813
17	6994	7011	7050
18.5	7214	7231	7260
20	7421	7439	7468

7. RESULTS AND DISCUSSIONS

7.1 Analysis of Existing Tower Structure

For the Finite Element Model (FEM), the maximum deflection of the tower was 0.207 m and the maximum stress developed was 425 MPa, as can be seen in the Figures 7 and 8. The maximum stress occurred at the collar joining the upper and middle segment of the tower.

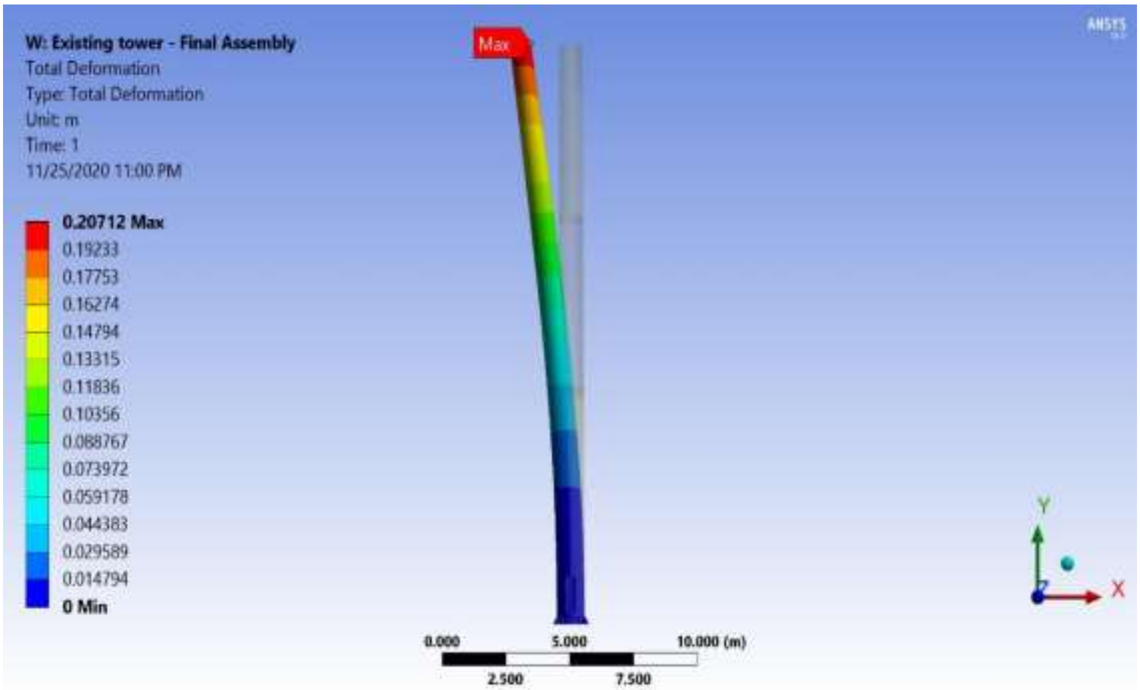

Figure 7. Displacement plot of the existing tower

The value for the stress generated shows that the collar yielded. This high stress was developed because of the variable wind pressure which acts on the tower. At the top, the forces are higher, and this tends to uplift the top segment and thereby inducing high stresses on the collar. Besides, the difference in pressures on the two segments creates a moment action on the collar.

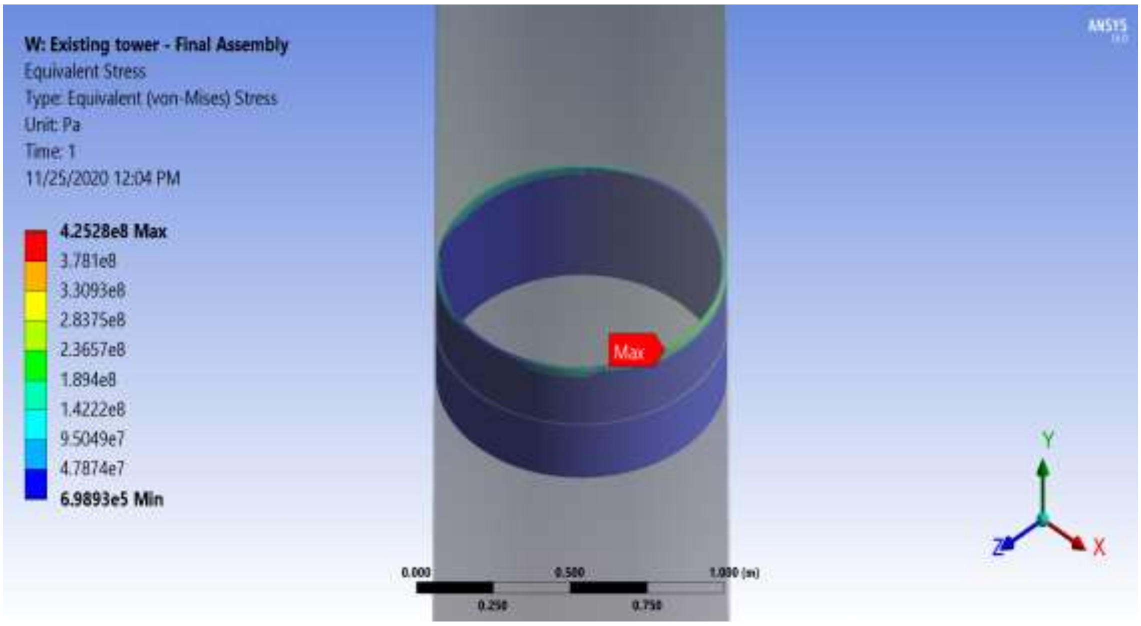

Figure 8. Stress plot of the existing tower showing collar

As per the Closed Form Model (CFM), the bending stiffness (*S*) of the structure of the existing tower and the bending stiffness to mass (*S/m*) ratio, calculated using Equations (8) and (9), were found to be 263 kNm^{-1} and 63.2 respectively. From Table 5, it can be observed that the mass of structure calculated from the CFM using Equation (2) is very close to the mass obtained from the FEM. The deflections obtained from both the closed form solution and finite element analysis are within the serviceability limit state. However, the analytically predicted deflection (CFM) is 7.2 % higher. This is because the CFM is being assumed as a single entity without any stiffeners, doors and collars.

Table 5: Comparison between FEM and CFM

	Mass of structure (kg)	Deflection (m)
CFM	4160	0.222
FEM	4155	0.207
Ratio (FEM/Analytical Model)	0.999	1.02

7.2 Optimisation of the Corrugated-Core Structure

7.2.1 Optimisation phase 1

To choose the optimum model from this first optimisation process, the structural performance and mass reduction of each model were analysed from Table 6. The model with a mass reduction greater than 10 % is given priority over the other models. Besides, the structural performance should be better than or same as the existing tower.

The *S/m* ratio of model P is 63.5 which indicates a better structural performance than the existing tower of *S/m* ratio equal to 63.2. Besides, it provides a good mass reduction of 17.1 %. Thus, model P was selected for use in the second optimisation process.

Table 6: Results of the first optimisation process

Model Name	**m (kg)**	**I-Value / m^4**	**y_A (m)**	**Weight Reduction (%)**	**S/m**
A	4274		-	$m_c > m_e$	-
B	4318		-	$m_c > m_e$	-
C	4335		-	$m_c > m_e$	-
D	3951	0.00216	0.188	5	78.7
E	3893	0.00213	0.191	6.4	78.6
F	3871	0.00209	0.195	7	77.5
G	4126		-	0.8 (not significant)	-
H	4088		-	1.7 (not significant)	-
I	4051		-	2.6 (not significant)	-
J	3682	0.00182	0.213	11	71.2
K	3647	0.00178	0.217	12	70.5
L	3612	0.00174	0.222	13	69.5
M	3869	0.00169	0.218	7	62.8
N	3859	0.00166	0.222	7.2	61.9
O	3812	0.00163	0.226	8.4	61.6
P	3450	0.00152	0.242	17.1	63.5
Q	3443	0.00150	0.280	17.2	62.7
R	3444	0.00148	0.284	17.2	61.8

7.2.2 Optimisation phase 2

As observed in Table 7, reducing the thickness of the core (T_c) decreases the mass and at the same time increases the tip deflection. However, it can be observed that there was a very small or no change in the *S/m* ratio of the structure when T_c was decreased i.e. no change in the structural efficiency of the corrugated structure. The result obtained was in conformity with a study carried out by Knox et al. [29], whereby the influence of various parameters of the core and skins on structural efficiency on a sandwich panel was evaluated.

Since decreasing the thickness of the core reduces the mass of the structure whilst maintaining a good structural performance, the model P’’ in Table 7 was selected as the final optimum model. The *S/m* ratio was the same as that of the existing tower and it gave a mass reduction of 26.1 % compared to model P which gave only 17.1%.

Table 7. Results of the second optimisation process

Model Name	**T_c / mm**	**m / kg**	**I-Value / m^4**	**Deflection / m**	**Mass reduction (%)**	***S/m* ratio**
P	2.5	3450	0.00152	0.242	17.1	63.5
P`	2.0	3182	0.00140	0.263	23.5	63.5
P``	1.8	3075	0.00135	0.273	26	63.2

7.3 Static Structural Analysis of the Final Optimum Model

FEA was carried out using ANSYS Workbench software, with the 3D model created using Solidworks software, as shown in Figure 9.

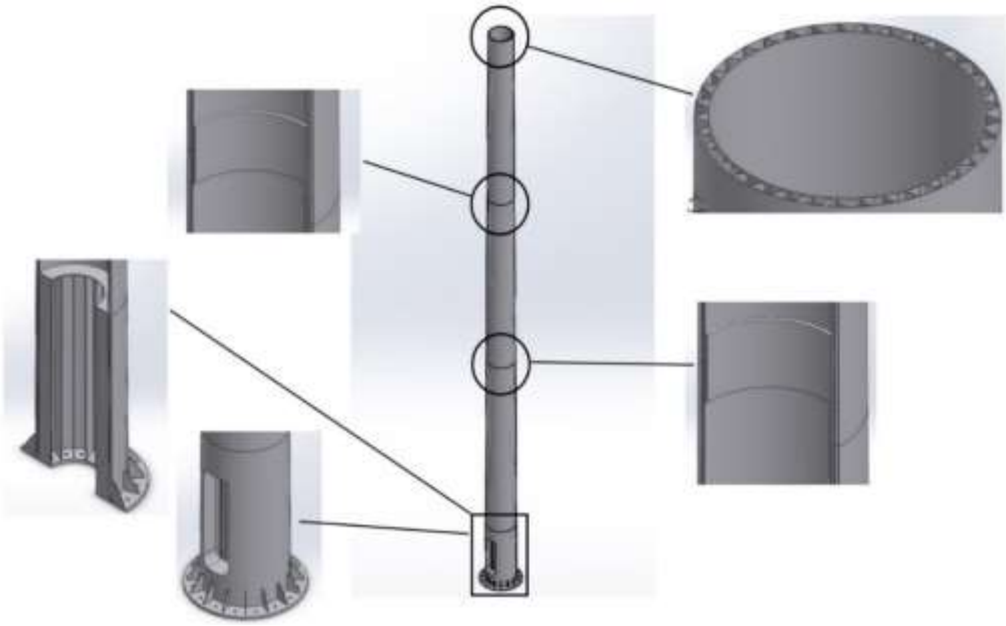

Figure 9. Final model of the corrugated structure

The boundary conditions were the same as those used for the existing tower and the masses of the antennas and the dishes were placed as distributed masses on top of the structure. A maximum tip deflection of 0.307 m was obtained which lies within the serviceability limit state. The maximum stress developed was found to be at the bottom part of the top segment, near the collar, as shown in Figure 10. The corresponding stress value revealed that the yield strength of S355 steel was not exceeded since maximum stress was less than 355 MPa. Figure 11 shows the stresses developed in other regions of the corrugated-core tower structure.

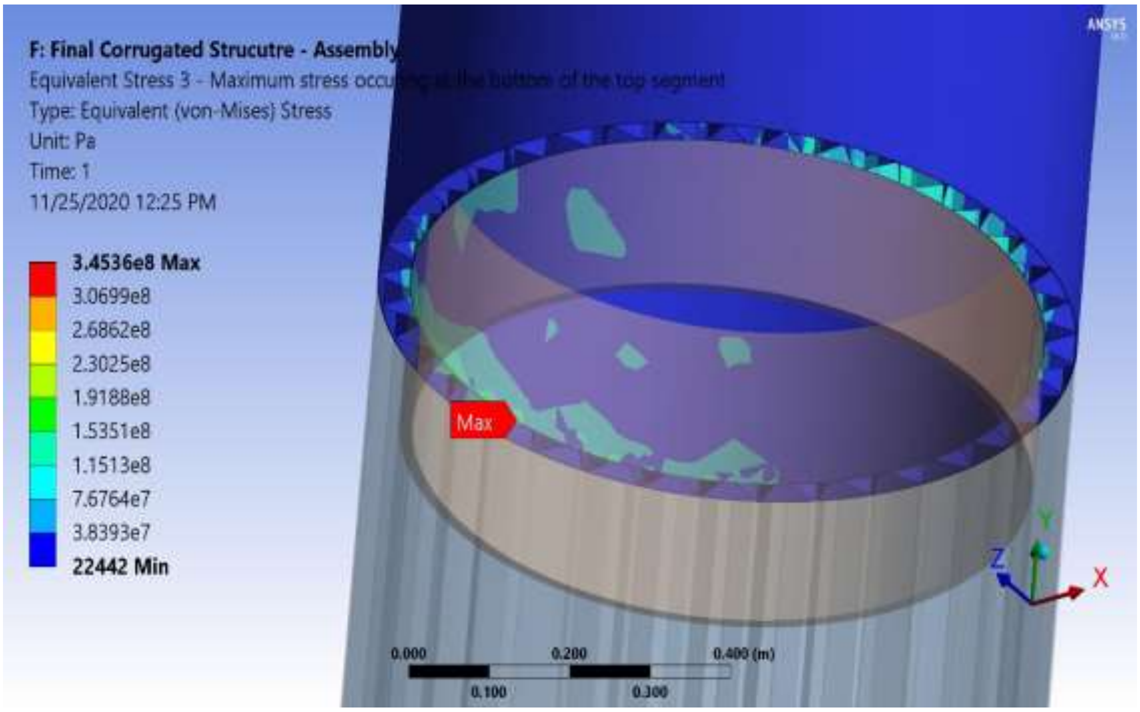

Figure 10. Stress plot showing bottom part of the top segment

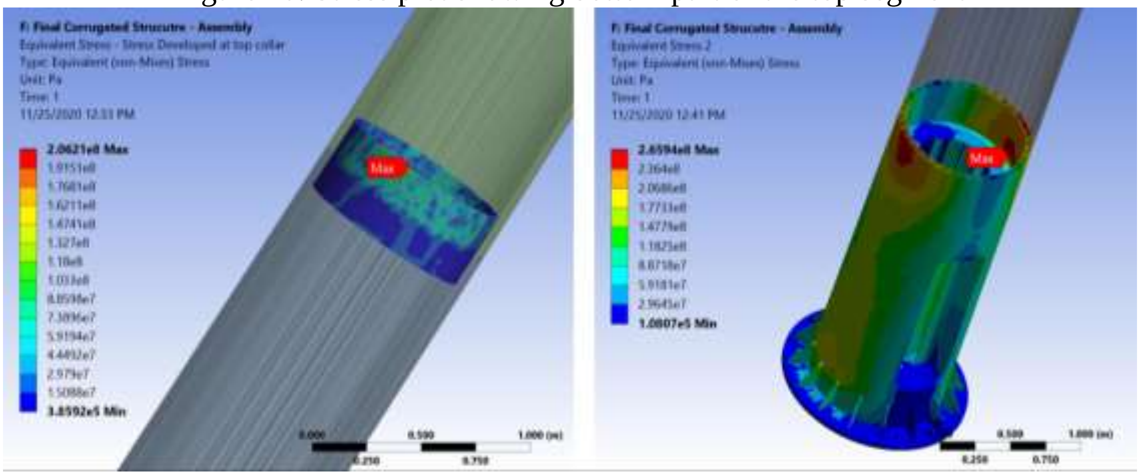

Figure 11. Stress plots showing upper collar (left) and base (right)

To validate the results, the static deflection was compared to the results obtained using the Mc Cutcheon method. The analytically predicted deflection was lower than the FEA value by 12.4 %. The reason for this deviation is because of the assumptions made using the Mc Cutcheon method. For instance the structure was assumed to be perfectly circular. However, with the inclusion of the door and the collars, this assumption is violated.

8. CONCLUSION AND RECOMMENDATIONS

The results showed that corrugated core sandwich panels can be used as an alternative to the existing tower structures. The optimum design achieved in this study had the same structural performance with reduced mass. The static deflection of the tower was within the serviceability limit state, which indicates efficient signal transmission even in cyclonic wind conditions. Moreover, the stress analysis conducted on the corrugated model showed that the structure is stiff enough to prevent high stresses developing on the collars and therefore prevents yielding.

As far as monopoles are concerned, most of them are erected in regions where space availability is an issue. In this study, Terrain category III was considered as per BS EN 1991-1-4:2005+A1:2010, and the results show the effectiveness of the corrugated-core structure. However, in the worst terrain category, the wind pressures would be much higher due to the absence of buildings and trees. Thus, the corrugated structure should be investigated in such terrain to show its survival.

In this paper, the effects of orography were neglected. Orography effect arises in regions such as hills and cliffs where the wind velocities increase by more than 5%. Wind blowing on uphill slope tends to increase the acceleration of the wind and ultimately increase the wind pressures. However, the safety factor considered in this study was assumed to compensate for the orography effects. Furthermore, the addition of the concealments such as fake leaves would increase the mass of the structure and lower the natural frequency. This shows the need to evaluate the vibration modes as well.

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CONFLICT OF INTERESTS

The authors would like to confirm that there is no conflict of interests associated with this publication and there is no financial fund for this work that can affect the research outcomes.

REFERENCES

[1] Bhagat S. Right of Way for Monopoles, http://www.powertoday.in/News.aspx?nId=n+Nme40jz7jicvGdpwNGEA (accessed 31 January 2017).

[2] Wani S.B. Analytical Study on the Influence of Rib Beams on the Stability of RCC Dome Structures. *International Journal of Innovative Technology and Interdisciplinary Sciences*, 2020; 3(3); 480-489.

[3] Li T. and Wang L. Bending behaviour of sandwich composite structures with tunable 3D-printed core materials. *Composite Structures*, 2017; 175; 46-57.

[4] Pramono A., Sulaiman F., Alfirano., Alhamidi, A. A. and Milandia, A.. Fabrication of the Ti/SiC Based Composites by Self-Propagating High Temperature Synthesis. *International Journal of Innovative Technology and Interdisciplinary Sciences*, 2020; 3(4); 513-520.

[5] Masmoudi R., Mohamed H. and Metiche S. Finite Element Modelling for Deflection and Bending Responses of GFRP Poles. *Journal of Reinforced Plastics and Composites*, 2008; 27(6); 639-658.

[6] Sangasuri S., Srikanth L. and Savanur R. Design and Analysis of 10 kW Wind Turbine Tower. *International Journal of Mechanical and Production Engineering*, 2017; 5(12); 93-96.

[7] Varghese J., and Joseph R. Analysis of Monopole Communication Tower. *International Journal of Engineering Studies and Technical Approach*, 2015; 1(11); 23-34.

[8] Patel H. and Ramani S. Finite Element Analysis of Monopole Tower for Domestic Wind Turbine. *Journal of Emerging Technologies and Innovative Research*, 2017; 4(4): 129-133.

[9] Ahuja V. and Hazra S. Application of Optimization Techniques in Reducing the Weight of Engine Mounting Bracket. *HTC*, 2012; 1-8.

[10] Sakurada M., Nagasawa O. and Oshino M. Application of Optimization Techniques to Weight Reduction of Automobile Bodies. *JSAE Review*, 1994; 15; 21-26.

[11] Ciconni P, Germani M, Bondi S, et al. A Design Methodology to Support Optimisation of Steel Structures. *Procedia CIRP*, 2016; 50; 58-64.

[12] Lindstrom A. (2007) *Strength of Sandwich Panels Loaded In-plane Compression*. Licientiate thesis, KTH Engineering Sciences, Sweden.

[13] Miltenovic A., Banic M. and Miltenovic V. Role and Importance of Lightweight Design in the Product Development. In: *Conference on Mechanical Engineering Technologies and Applications*, Sarajevo 2014, p. 529-538.

[14] Kujala P. and Klanac A. Steel sandwich panels in marine applications. *BRODOGRADNJA*, 2005; 56(4); 305-314.

[15] Meifeng H., and Wenbin H. A Study on Composite Honeycomb Sandwich Panel Structure. *Materials and Design*, 2008; 29; 709-713.

[16] Zeng T., Fang D.N., Yan S, et al. Compressive properties of carbon epoxy composite sandwich panels with pyramidal truss core. In: *Joint-Symposium on Mechanics of Advanced Materials & Structures.* Harbin 2010, p. 1-15.

[17] Rejab M.R.M. and Cantwell W.J. The mechanical behaviour of corrugated core sandwich panel. *Composites Part B: Engineering*, 2013; 47; 267-277.

[18] Fan H. and Yang W. The Equivalent Continuum Method of Lattice Structures. *Acta Mechanica Solida Sinica*, 2006; 19(2); 103-113.

[19] Xiong J., Ma L., Wu L.Z., et al. Fabrication and crushing behavior of low density carbon fiber composite pyramidal truss structures. *Compos. Struct.*, 2010; 92; 2695–2702.

[20] Kujala P. and Salminen A. Optimum solutions for laser welded all steel sandwich panels. In: *ICALEO'99: Proceedings of the Laser Materials Processing Conference*, San Diego 1999, p. 110-119.

[21] Kananen M., Mantyjarvi K., Keskitalo M., et al. Laser Welded Corrugated Steel Panels in Industrial Applications. *Physics Procedia*, 2015; 78; 202-209.

[22] Katayama S. (2013) *Handbook of Laser Welding Technologies*. 1st ed. Cambridge: Woodhead Publishing Ltd.

[23] Nilsson P., Al-Emrani M. and Atashipoyr S. Transverse shear stiffness of corrugated core steel sandwich panels with dual weld lines. *Thin Walled Structures*, 2017; 117; 98-112.

[24] Poirier J., Vel S. and Caccese V. Multiobjective Optimisation of Laser Welded Steel Sandwich Panels for Static Loads Using a Genetic Algorithm. *Engineering Structures*, 2013; 49; 508-524.

[25] Lämsä J, Järvenpää A and Mäntyjärvi K. Designing and Manufacturing of a Flexible Longitudinally Laminated Sandwich Panel Forming Tool. *Key Engineering Materials*, 2014; 611; 786-793.

[26] BS EN 1991-1-4:2005+A1: 2010. Eurocode 1: Action on Structures – Part 1-4: Wind Actions.

[27] MATHalino, Strain Energy Method (Castigliano's Theorem)|Beam Deflection, https://www.mathalino.com/reviewer/strength-materials/beam-deflection-strain-energy-method-castigliano-s-theorem (accessed 17 March 2018).

[28] Kalaga S. Equivalent pole concept for tapered power poles. *Journal of Structural Engineering*, 2012; 38(6); 507-518.

[29] Knox E, Cowling M, Winkle I. Adhesively bonded steel corrugated core sandwich construction for marine applications. *Marine Structures*, 1998; 11; 185-204.

[30] ANSI/TIA/EIA–222F: 1996. Structural Standards for Steel Antenna Towers and Antenna Supporting Structures.

[31] McCutcheon J. Deflections and Stresses in Circular Tapered Beams and Poles. *Civil Engineering for Practicing and Design Engineers* 1983; 2: 207-233.

[32] BS EN 1993-3-2: 2006. Eurocode 3: Design of Steel Structures – Part 3-2: Tower, Masts and Chimneys – Chimneys.