

# Design and analysis of darrieus vertical axis wind turbines towers

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## ABSTRACT

*In the present situation and considering the dangers that affect human life and the environment, it is necessary to expand the use of renewable energy that is available in all geographical areas. Environmental pollution caused by urban life has attracted researchers' attention to the use of renewable energy such as vertical axis wind turbines (VAWTs) with the aim of urban application. Because of their unique features, these turbines can provide the electricity needed for the targets, but to date, less attention has been paid to their tower structure. A wind turbine tower is one of the main and costliest components of wind systems. In this paper, based on the standards of turbine design and its structure, an algorithm was presented to create more resistance and strength in the tower structure and control the tower's deflection caused by incoming loads. Different models of simple monopole towers, variable cross-section monopole towers, monopole towers with channel beam control, and monopole towers with lateral restraint in the case study of Iran were simulated. Results show that models with lateral restraint have the lowest deflection of about 3 to 5 cm and, in addition to passing all design standards, the members' stress ratio is allowed within the limit.*

**Keywords:** Wind Energy, Darrieus, Monopole Tower, VAWT, Deflection.

## 1. Introduction

In recent years, attention to renewable energy has increased due to climate change and environmental pollution. Wind's popularity as a renewable source is growing rapidly, so the world's installed wind energy capacity has reached 792 gigawatts by 2020, compared to just 198 gigawatts in 2010. Modern wind turbines are divided into horizontal and vertical axis turbines based on the type of generator axis and rotor rotation or operation based on lift and drag force.

Vertical axis wind turbines (VAWTs) have advantages such as low wind speed operation, urban application, wind independence, less noise, and easy installation and maintenance compared to horizontal axis turbines [1]. Darrieus turbine has attracted more attention among VAWTs due to its higher power. The tower is one of the main components of wind turbines responsible for connecting and maintaining rotors, generators, and other equipment. There are various towers such as tubular or conic steel structures, lattices, concrete towers, guyed towers, and monopoles [2]. Choosing the suitable tower depends on factors, such as the natural frequency of vibrations, deflection, bending, fatigue, wind resources, beauty, and installation location. Wind turbine towers are prone to deflection and bending

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due to their loads and forces. These forces are essentially caused by the interaction between the rotor and the structure of the turbine tower with environmental conditions, the forces resulting from the turbine's regular performance, and the rotor's rotation. Therefore, it is essential to recognize and predict the response of tower structures against external forces [3]. Most of the previous research on horizontal and vertical axis wind turbines has focused on aerodynamics and rotor performance, and few studies have been conducted on turbine towers. Dagli et al. [4] studied the effects of environmental forces and earthquake load on marine wind turbines using the Rayleigh model and finite element model. Their results show the Rayleigh model can be used as an alternative method with acceptable accuracy for wind turbine tower analysis. Ferroudji et al. [5] analyzed a 10-kW vertical axis wind turbine tower (VAWTT) with heights of 12, 14, 16, and 18 meters and different diameters under aerodynamic and gravitational forces by numerical simulation. All models showed maximum stress less than the yield stress and also the 18-meter tower meets the normal frequency requirements. Feliciano et al. [6] analyzed and simulated the angular deflection and displacement of NREL's 5-MW wind turbine tower. Their results suggest that displacement deviation increases with increasing turbulence and mass imbalance due to the rotational effect of blades having a minor effect on tower deflection. Uys et al. [7] have developed a procedure to calculate the least cost design of a slightly conical steel wind turbine tower that meets the structural requirements of slender structures, predominantly loaded by bending due to dynamic loads. The results show that the minimum cost solution corresponds to the minimum number of ring-stiffeners. Hulio and Jiang [8] have investigated the impact of wind classes 3 and 7 on wind turbine life and its components. Their results indicate that increasing wind loads increases tangential loads and decreases the life of the wind turbine. Also, a wind turbine should be designed according to a site-specific wind environment for maximum energy generation and to lower the wind loads on the drive train component. Stavridou et al. [9] have investigated the effect of replacing the pipe tower with a lattice tower to minimize the structure's weight by maintaining its capacity. The results showed the lattice tower reduced the total cost of initial construction by 15%, in addition to being 40% lighter. The advantages that a lattice tower

offers in terms of transportation and construction, combined with the flexibility of its configuration, may lead to significant changes and usefulness in configuring the wind turbine tower design. The results of Jiqui et al. [10] research show that the structural-fluid interaction field of VAWTT has little effect on modal vibration mode and has a great impact on its natural frequency and maximum deformation. Four different algorithms are tested by Ghoshal et al. [11] for detected damage on wind turbine blades. These are the transmittance function, resonant comparison, operational deflection shape, and wave propagation methods. These experiments indicate the feasibility of using piezoceramic patches for excitation and a SLDV or piezoceramic patches to measure vibration to detect damage. Quilligan et al. [12] studied the relative structural performance of steel and prestressed concrete wind turbine towers of 88 m to 120 m in height. For all cases it was seen that the steel towers exhibited significantly higher probabilities of limit state exceedance. Rafiee et al. [13] examined wind turbine blade aeroelasticity through FSI coupling. Analysis of their results show that the vibration of turbine blades has a negative effect on the rated and cut-out wind speed of the turbine and reduces the nominal power output.

This paper investigates the maximum deflection of different tower models for constructing a 2-kW VAWTT in Sirjan city. The designed and constructed tower introduced in this article shown in Fig. 1.

### Nomenclature

$VAWTs$	Vertical axis wind turbines
$VAWTT$	Vertical axis wind turbine tower
$F_{T_r}$	Aerodynamic loads on the rotor
$F_{T_t}$	Wind loads on the tower
$F_g$	Gravitational loads
$NWC$	Normal wind conditions
$EW C$	Extreme wind conditions
$V_{ave}$	Average wind speed
$v(z)$	Wind profile
$V_{e50}$	50-year-old extreme wind speeds
$V_{e1}$	1-year extreme wind speeds
$z_{hub}$	Height of the hub



Fig. 1. A view of the designed and built tower in Sirjan

$DMST$	Double multiple stream tube
$C_T$	Thrust force coefficient
$A$	Rotor swept area
$\sigma_{max}$	The maximum stress of the tower
$A_b$	The cross-section of the tower
$M$	The flexural torque
$\delta_t$	Deflection of the tower
$\delta_r$	Deflection of the rotor

## 2. Structural design of wind turbine

According to the IEC61400-2 standard [14], the design of a small-size wind turbine includes four parts, external conditions, conceptual design, aerodynamic design, and structural design. In the structural design of a wind turbine, it should be noted that, in addition to identifying the types of loads that enter the turbine, the resources and effects of these loads should also be identified [15]. Load sources include aerodynamic resources, gravitational resources, mechanical control resources such as stopping turbines by applying brakes, and dynamic interaction sources. In turn, interactions caused by aerodynamic and gravitational forces induce loads on other parts of the turbine.

### 2. 1. Type of the Loads

Generally, the forces on the wind turbine are divided into five categories having steady loads that do not change over a relatively long period, cyclic loads that arise as a result of factors such as the weight of the blades and the shear flow of the wind, transient or non-uniform loads that change with time and arise in response to some temporary external events, stochastic loads caused by turbulence in the wind and induced resonance loads. Resonance-induced loads are cyclic loads caused by the dynamic response of part of the wind turbine, which is excited at one of its natural frequencies and may reach high quantities. This type of occurrence should be avoided at any time.

Considering the load sources, as shown in Fig. 2, it is possible to summarize the classification of the mentioned loads on a VAWT into three categories of loads, including aerodynamic loads on the rotor ( $F_{T_r}$ ), wind loads on the tower ( $F_{T_t}$ ) and gravitational loads ( $F_g$ ). Of course, it should be noted that if the conditions of turbine installation are different, other loads, such as earthquake and wave loads, can be considered.

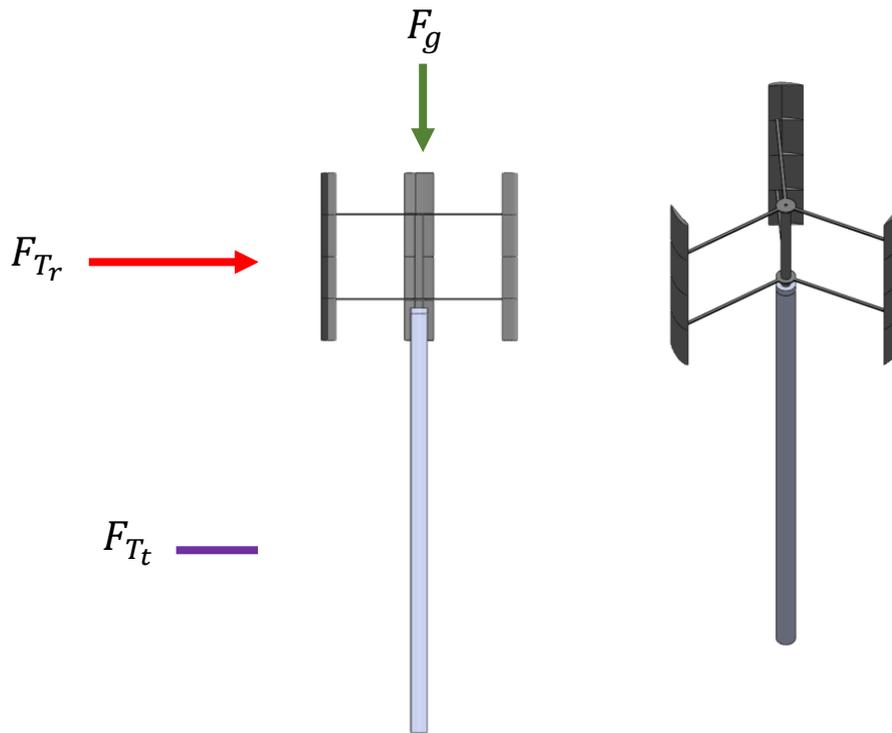


Fig. 2. Distribution of loads on wind turbines

### 2.1.1. Aerodynamic Loads

One of the first things to be examined in the design of wind turbines is the assessment of wind energy, and the first step to the assessment of wind energy is to receive meteorological data and process them [16]. The wind regime for load and safety considerations is divided into normal wind conditions (NWC) that frequently occur during normal wind turbine operation and extreme wind conditions (EWC) defined as a 1-50-year period [14].

#### 2.1.1.1. Normal wind conditions

The distribution of wind speed is important for the design of a small-size wind turbine, as it determines the frequency of the occurrence of individual load conditions. In IEC standard small-size wind turbine classes, the average wind speed value over a 10-minute period is assumed as the Rayleigh distribution for design load calculations. Cumulative probability distribution at hub height is introduced by

$$P_R(V_{hub}) = 1 - e^{\left[-\pi(V_{hub}/2V_{ave})^2\right]} \quad (1)$$

Wind profile  $v(z)$  shows the average wind speed as a function of height. With standard

wind turbine classes, normal wind speed profiles are provided by the Power law as

$$V(z) = V_{hub} \left( \frac{z}{z_{hub}} \right)^\alpha \quad (2)$$

In the Power law, the  $\alpha$  must be assumed to be equal to 0.2. The assumed wind profile defines the shear speed of the average wind across the rotor's swept area.

#### 2.1.1.2. Extreme wind conditions

Extreme wind conditions determine extreme wind loads on small-size wind turbines. These conditions include peak wind speed due to storms and rapid changes in wind speed and direction. These extreme conditions include the potential effects of wind turbulence, so only definitive effects should be considered in design calculations.

50-year-old extreme wind speeds ( $V_{e50}$ ) and 1-year extreme wind speeds ( $V_{e1}$ ) are used to calculate the maximum wind speed that may occur. Based on the reference wind speed, these two parameters can be calculated using

$$V_{e50}(z) = 1.4V_{ref} \left( \frac{z}{z_{hub}} \right)^{0.11} \quad (3)$$

$$V_{e1} = 0.75V_{e50} \quad (4)$$

where the  $z_{hub}$  is the height of the hub and the 1.4 value is the coefficient of the wind gust factor at the height of the hub.

When the wind flow hits the rotor or turbine blades, it causes aerodynamic forces that are the source of the rotor rotation. The VAWT aerodynamic forces can be calculated from theoretical models, such as DMST, Vortex models, Cascade models, or numerical simulation methods. Thrust force is the most important aerodynamic force on the wind turbine rotor that affects the dynamic interaction of the turbine tower and rotor. This force can be checked in 3 modes: rotating rotor, fixed rotor, and variable pitch angle [17]. However, according to the design standard of small-size wind turbines, the maximum amount of thrust force applied to the turbine can be calculated from

$$F_{T_r} = \frac{1}{2} C_T \rho (2.5 \times V_{ave})^2 A \quad (5)$$

where the  $F_{T_r}$  is the thrust force on the rotor,  $C_T$  is the thrust force coefficient equal to 0.5,  $V_{ave}$  is the average wind speed, and  $A$  is the swept area by the rotor.

#### 2.1.2. Wind loads on the tower

The wind loads on the wind turbine tower can be uniform or non-uniform. Considering the uniform distribution of wind on the turbine tower, the resulting thrust force can be calculated from

$$F_{T_t} = \frac{1}{2} C_{T_t} \rho V_{e50}^2 A \quad (6)$$

where the  $F_{T_t}$  is the thrust force on the tower,  $C_{T_t}$  is the thrust force coefficient,  $V_{e50}$  is the extreme wind speed is 50 years, and  $A$  is the area of the tower.

#### 2.1.3. Gravitational Loads

Gravitational loads or dead loads result from the structure's weight, i.e., the tower, the rotor, and its components.

### 3. Stress and structural deflection analysis of wind turbine tower

Wind turbine towers should be designed to withstand stresses such as bending, deflection, vibrations, and noise. Also, the material used in the tower must have the ability to resist fatigue in addition to high strength.

#### 3.1. Structural stress analysis of wind turbine

As shown in Eq. (7), the tower's stress is expressed by the weight of the structure and the bending torque applied by the wind on the rotor and the tower.

$$\sigma_{max} = \frac{F_g}{A_b} \pm \frac{My}{I} \quad (7)$$

where the  $F_g$  is the weight of the structure,  $A_b$  is the cross-section of the tower,  $M$  is the flexural torque,  $y$  is the distance from the neutral axis, and  $I$  is the moment of inertia.

#### 3.2. Analysis of wind turbine structure deflection

According to the TIA-222-G standard [18], the amount of deflection allowed due to the forces caused by the wind and the weight of the structure is equal to one percent of the tower's height. The base of the tower is not deviant because of the foundation and the maximum deviation and deflection created at the top of the tower. The wind speed profiles applied to the turbine tower and rotor are non-uniform. Considering the linear profiles, the deflection of the tower ( $\delta_t$ ) and the rotor ( $\delta_r$ ) can be calculated from

$$\delta_r = \frac{F_{T_r} L^3}{3EI} \quad (8)$$

$$\delta_t = \frac{5F_{T_t} L^3}{48EI} \quad (9)$$

### 4. Design of wind turbine tower structure

In the design of a product, various aspects, such as safety, time, economic costs, beauty, feasibility, and applicability must be considered. Engineering design has a set of steps that must be followed by engineers for the final design and production of the product, and

these steps have a repetitive process to achieve the desired result. According to the conditions of each project, the number of repetitions is different. This paper aims to design a suitable VAWTT in the case study of Sirjan City. Table 1 presents the technical specifications of a 3-kW turbine. The diameter and height of the rotor are equal to 2.2m and 2m, respectively. According to Table 2, wind turbine towers in four groups have been analyzed by ETABS software: simple monopole, variable cross-section monopole, monopole with channel beam, and monopole with lateral restraint. For many years, TABS and ETABS software have covered all international standards in the analysis, design, and mathematical model of structures and consequently create the model of a structure graphically. By the actual map, this software is used to evaluate the performance of the desired design in seismic, modeling, and analysis. The software provides visual and integrated features of applications from the practical level to the implementation process. Also, the most crucial feature of this software is the final analysis of structures. Since implementing a secure structure is one of the most prominent objectives of the project, the ETABS has a very high efficiency in checking the behavior of

structures in real terms with precise details to create security for the structure.

**Table 1.** Specifications of Darrieus VAWT

Parameter	Value
Rated power (kW)	3
Rotor diameter (m)	2.2
Rotor height (m)	3
Rotor weight (kg)	60
Cut-in speed (m/s)	3
Cut-out speed (m/s)	50

To design the suitable tower, the designed flowchart is displayed in Fig. 3. According to the flowchart, the specifications of the introduced wind turbine are determined first. Then, according to the characteristics of the wind turbine and its specifications, the tower model is selected from the four models presented in Table 2. By choosing the tower model, its dimensional characteristics, such as diameter and thickness, are determined by initial guess. Thus, the initial calculations of the forces on the tower structure and wind turbine can be performed. To determine the loads on the structure and turbine, wind energy potential and characteristics such as 50-year wind speed and wind speed profiles are initially investigated in the case study of Sirjan.

**Table 2.** Vertical axis wind turbine tower models

a) Variable cross-section monopole	b) Simple monopole	c) Monopole with channel beam	d) Monopole with lateral restraint
			



Fig. 3. Flowchart of the design of an optimum tower for a VAWT

In the next step, structural, aerodynamic design, and thrust force on the tower and turbine can be determined according to the proposed algorithm. It should be noted that due to the small cross-section of the structure, the load of snow and rain has been neglected. Also, because of the geographical location of the case study, flood load and ice weight load have been ignored. By calculating the loads on the tower and wind turbine, it is possible to analyze the stress and deflection of the tower. Also, the analysis of the failure and stresses on the structural components has been evaluated according to the static deterioration criteria of soft materials, such as the Von Mises criterion. If the design factor of safety is calculated as greater than or equal to one, it is in the safe range. The design should be done from point A and with the next guess of the geometric specifications of the tower. In the next step, the deflection of the tower is evaluated using the TIA-222-G standard. According to the standard, if the deflection of the tower is less than 1% of the tower's height, the tower can be introduced to select the optimum VAWTT. Otherwise, the design should be repeated from point B, and this time by changing the model of the tower, the rest of the steps should be done. This process is repeated until the appropriate design factor of safety and the amount of permissible deflection is achieved.

## 5. Results

### 5.1. Case study

The case study focuses on the Golgohar Tourism Area located in Sirjan city, with geographic coordinates  $29^{\circ}15'45.4''\text{N}$  and  $55^{\circ}32'39.6''\text{E}$ . Based on the data presented in Fig. 4, the average monthly wind speed over the past 15 years was recorded at 3.1 m/s, and the prevailing wind direction at this location is from the southwest.

### 5.2. Tower Analysis

The purpose of this section is to introduce the appropriate VAWTT by analyzing the stress ratio and deflection of the structure. To do this, all four groups of tower models (Table 2), using Etabs software and force calculations, were analyzed and checked. In accordance with Sirjan city's wind energy assessment, wind speed is equal to 130 km/h, wind load equivalent to 100 kg, and dead load 180 kg considered in VAWTT design. The VAWT was modeled as a rectangular plane with dimensions  $3 \times 2 \text{ m}^2$  on the maximum tower height point. The modeled load on the turbine equals 1020 N, and the wind torque is considered 153,000 N.m.

Figure 5 shows three tower models with different sections that were analyzed, and their results are presented below.

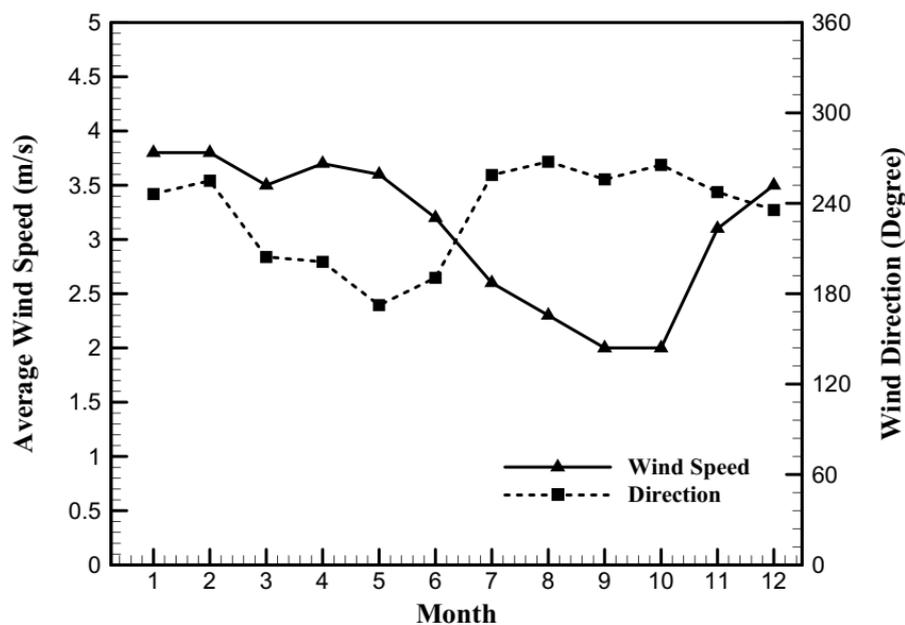


Fig. 4. Average monthly wind speed and direction for the last 15 years

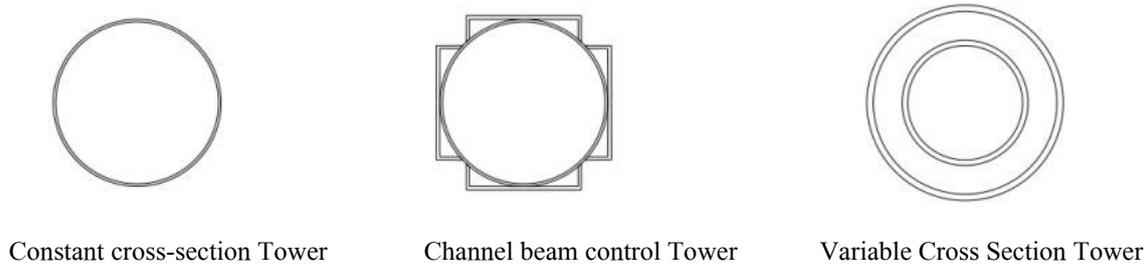


Fig. 5. Different sections of the tower

### 5.2.1. Tower analysis with a variable cross-section

The first modeling was conducted as a Monopole with a variable section (Table 2-a). This model, with a height of 10 meters, consists of two parts, each measuring 5 meters. The diameter of the lower and upper parts is 355 mm and 219 mm, respectively, with both parts having a thickness of 6 mm. Due to the wind gust observed in the case study, the tower's deflection was calculated to be 30.87 cm. The upper part of the tower, which had a smaller cross-section, exhibited stress levels within the critical range. To reduce both the deflection and stress ratio, the upper part of the tower was replaced with a 355 mm diameter and a thickness of 6 mm. The results of this analysis are presented in the next section.

### 5.2.2. Tower analysis with constant cross-section

As mentioned in the previous section, constant cross-section tower was modeled (Table 2-b) to inhibit the tower tip's deflection and control the allowable stress ratio. The results indicate that the stress ratio falls within the acceptable range, and the deflection measures 19.45 cm. Compared with the first model, the deflection is reduced by 37%. However, it still exceeds the TIA-222-G standard by 9.45 cm.

### 5.2.3. Tower analysis with channel beam control

As the variable and constant cross-section models from the previous sections did not meet the allowable deflection and stress ratio, the tower was further modeled and analyzed using channel beam control (Table 2-c). In this approach, the UNP series of channel beams, produced under the European DIN standard and listed in Table 3, were employed to regulate the tower tip's deflection and allowable stress. The results indicate that by using UNP160 to UNP260 channel beams, the deflection meets the TIA-222-G standards. Specifically, the tower featuring UNP260 channel beam exhibits a remarkable 73% improvement in deflection compared to the constant-section tower.

Table 4 compares the three sections of the tower. The modeling results show that the tower with variable and constant cross-sections is unsuccessful in controlling the deflection, and the stress in the structural components exceeds the allowed limits. On the other hand, using the UNP series channel beam has significantly reduced the deflection, keeping it within the authorized range of TIA-222-G. Additionally, it effectively improves the stress ratio. However, it comes with the drawback of being considerably heavier and economically inappropriate.

Table 3. UNP channel beam

UNP	Height H (mm)	Width W(mm)	Weight (kg/m)	Thickness $t_f$ (mm)	Thickness $t_w$ (mm)	Surface Area ( $m^2/m$ )
140	140	60	16.3	10	7	0.487
160	160	65	19.2	10.5	7.5	0.545
180	180	70	22.4	11	8	0.603
200	200	75	25.7	11.5	8.5	0.660
220	220	80	30.0	12.5	9	0.718
240	240	85	33.8	13	9.5	0.776
260	260	90	38.6	14	10	0.833
280	280	95	42.7	15	10	0.891

**Table 4.** Deflection comparison of variable cross-sections, Constant sections, and channel beam control monopole towers.

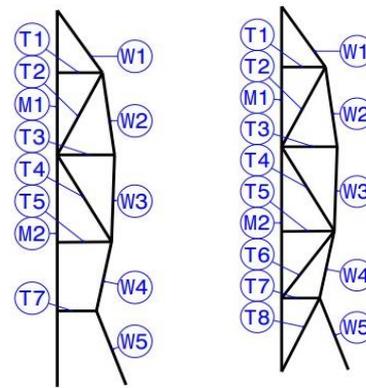
	Monopole with variable cross-section	Monopole with constant cross-section	Monopole with unp160	Monopole with unp260
Diameter (mm)	355, 219	355	355	355
Weight (kg)	535	575	1340	2120
Deflection (cm)	30.87	19.45	9.28	5.21

#### 5.2.4. Tower Analysis with lateral restraint

According to the Sirjan case study, in terms of tourist and visitor attendance, the wind turbine tower was designed architecturally to be appropriate for the tourist destination. To control the deflection rate according to the TIA-222-G standard and maintain the allowable stress ratio, the constant cross-section tower with a diameter of 355 mm and a thickness of 6 mm was restrained by pipe fittings on all four sides. In an effort to minimize deflection and achieve the allowable stress ratio while reducing the weight of lateral members, pipe fittings with various thicknesses and diameters were thoroughly investigated. The analysis includes three tower models with lateral restraints, and the results will be presented. Additionally, the optimal vertical wind turbine tower design will be introduced.

##### Model 1.

In the first phase of tower design with lateral restraint, the thickness for each structural component was carefully selected to ensure that the stress ratio and deflection are within allowable limits, thereby reducing the tower's weight. All the members of the tower are labeled in Fig. 6, with M representing the middle pipe, T as the central member, and W indicating the side member. As shown in Table 5, Model 1 was investigated under three conditions. However, as evident from the stress distribution in Fig. 7 for Model 1, the central member of T4 and the lateral members of W4 and W5 exhibit critical stress ratios, exceeding the permissible limits. As a result, this tower design has been rejected. The deflection in Model 1-1 measures 4.99 cm.



Model 1 - Model 2

Model 3

**Fig. 6.** Naming the members of the tower

##### Model 2.

Considering the high weight of the middle member M in Model 1, its thickness was reduced, leading to the design of Model 2. The results in Table 5 and Fig. 7 indicate that the stress on the lateral members W4 and W5 and the middle member T4 is critical in this new design. Additionally, the middle pipe M bears a higher stress ratio compared to Model 1. However, the deflection in this model measures 4.34 cm, which is less than the previous one.

##### Model 3.

T6 and T8 were added to the lower part of the tower to control deflection and increase strength. Finally, the latest design was simulated. According to Table 5 and Fig. 7, this model was introduced as a suitable tower for the Darrieus VAWT due to its compliance with the allowable stress ratios and deflection limits. The deflection value of this model is lower than all simulated models, measuring 3.19 cm.

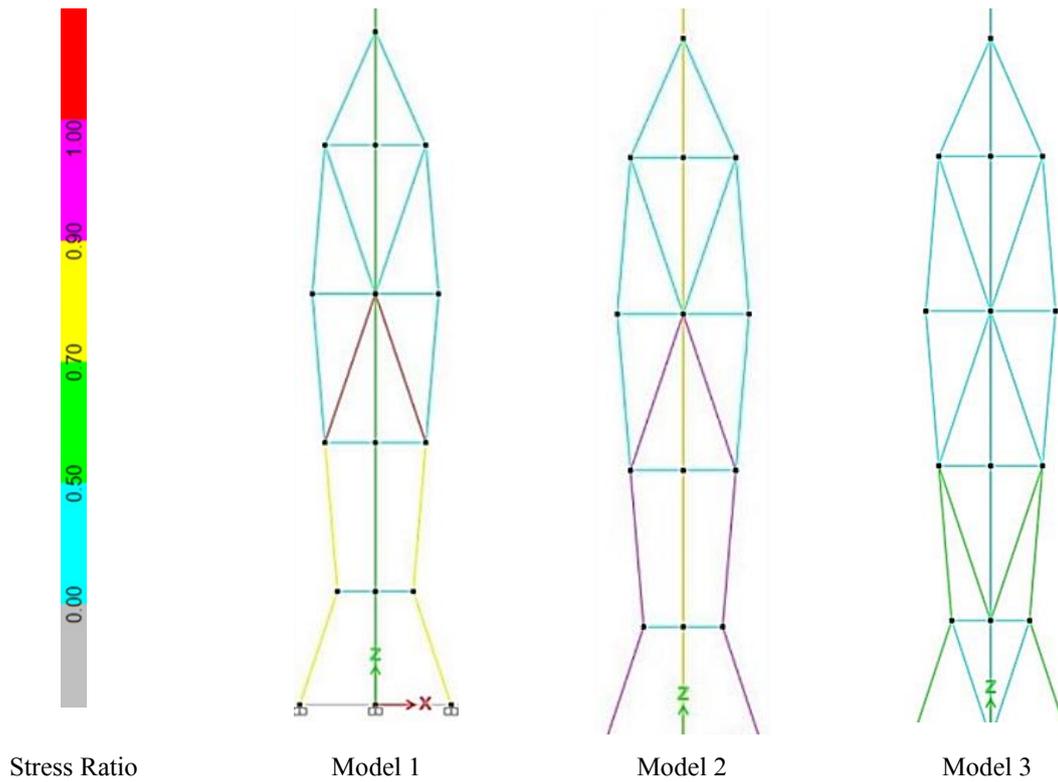


Fig. 7. Stress ratio of models

Table 5. Stress ratio in different models

	Model 1						Model 2		Model 3	
	Model 1-1		Model 1-2		Model 1-3		D (mm)	t (mm)	D (mm)	t (mm)
	D (mm)	t (mm)	D (mm)	t (mm)	D (mm)	t (mm)				
M1	355	6	355	6	355	6	355	4	355	4
M2	355	6	355	6	355	6	355	4	355	4
T1	2	3	2	3	3	2	3	2	3	2
T2	2	3	2	3	3	2	3	2	3	2
T3	2	3	2	3	3	2	3	2	3	2
T4	2	3	4	3	3	2	3	2	4	3
T5	2	3	2	3	3	2	4	3	4	3
T6	-	-	-	-	-	-	-	-	4	3
T7	2	3	2	3	3	2	4	3	4	3
T8	-	-	-	-	-	-	-	-	4	3
W1	4	3	4	3	4	3	4	3	4	3
W2	4	3	4	3	4	3	4	3	4	3
W3	4	3	4	3	4	3	4	3	4	3
W4	4	3	4	3	4	3	4	3	5	4
W5	4	3	4	3	4	3	4	3	5	4

According to Table 5, the green range is optimal for structural strength, and the yellow range is more cost-effective for construction. Other colors are not recommended in terms of both structural strength and cost-effectiveness.

Figure 8 presents the changes in tower

deflection and weight for the studied models. As seen, Model 3 exhibits the lowest deflection compared to the other models. The addition of new members has increased the weight of this model, but this issue has been successfully addressed with a proper foundation design.

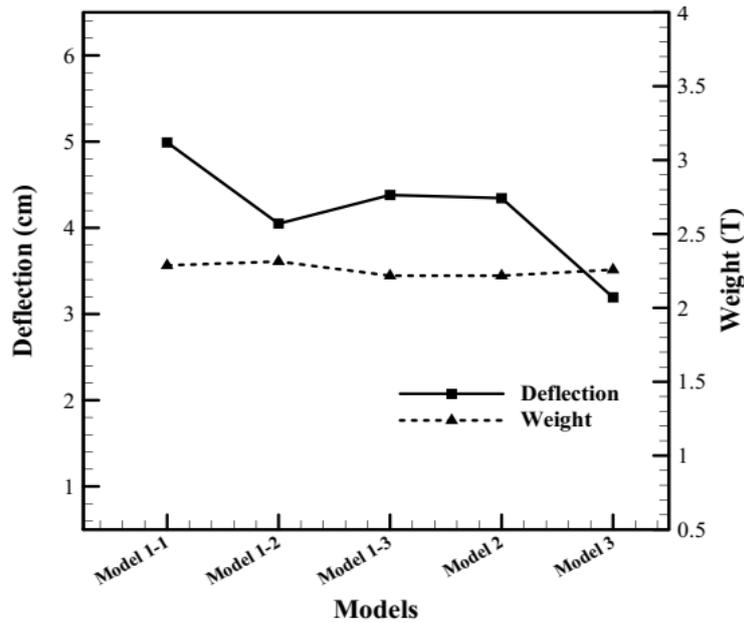


Fig. 8. Diagram of changes in deflection and weight of structures

## 6. Conclusions

In this paper, based on the design algorithm of the optimum vertical axis wind turbine tower, various towers with different cross-sections and constraints were investigated within the context of a case study in Iran. Based on the algorithms and standards of wind turbine and tower design, the tower structure is suitable for vertical axis turbines, which is to control the stress on the structure members, the deflection of the tower is within the permissible limits. The results of the analysis of different models of the tower show that:

- **Tower model with a variable cross-section:** The tower has a height of 10 meters and is composed of two sections, each measuring 5 meters in length, with diameters of 355mm and 219mm, respectively. However, this model falls within the critical range in terms of stress ratio, and its deflection measures 30.87 cm, which exceeds the permissible limits.
- **Tower model with a constant cross-section:** The tower has a height of 10 meters and a diameter of 355 mm. Its deflection measures 19.45 cm, which is a 37% improvement compared to the tower model with a variable cross-section.
- **Tower model with channel beam control:** The tower has a height of 10 meters, and the channel beams used range from

UNP160 to UNP260, all of which fall within the permissible deflection range. The tower's deflection with UNP260 channel beams improved by 73% compared to a constant cross-section tower.

- **Tower model with lateral restraint:** The models with lateral restraint were designed to achieve the lowest deflection and allowable stress ratio of structural members while also considering architectural aesthetics. Among the designed towers, model 3 has the lowest deflection of 3.19 cm and successfully meets all design standards, with the members' stress ratio falling within the allowed limit.

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