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Wind loads for stadium lighting towers according to Eurocode 1

Zeki Karaca [a], Hasan Tahsin Öztürk [b], Erdem Türkeli [c,*]

[a] *Department of Civil Engineering, Ondokuz Mayıs University, 55139 Samsun, Turkey*
[b] *Department of Civil Engineering, Of Technology Faculty, Karadeniz Technical University, 61830 Trabzon, Turkey*
[c] *Ordu Provincial Organization of Ministry of Environment and Urban Planning, 52100 Ordu, Turkey*

ABSTRACT

The determination of actions on structures is an important step of in the design process. In nature, so many outer and inner actions are acting on structures continuously. The two most important ones of those actions are the earthquake and wind actions. For some structures, i.e. towers, high chimneys or lighting towers, the priority of these two severe actions can change. Wind forces can become a governing force on the design of these structures. Therefore, the determination of wind forces for these tall, slender and wind-sensitive structures becomes very important. Also, these tall and slender structures have a high ratio of height to least diameter that makes them more slender and wind-sensitive than any other structures. In this study, the determination of wind loads for a selected and modeled stadium lighting tower was given according to Eurocode 1 which is an international well-known standard. This study showed that it is difficult to calculate wind loads of stadium lighting towers according to Eurocode 1 because of the complexity of the document, insufficient explanation of some formulas like resonant response factor and unclear graph sections for the reader. This study is believed to enlighten the way of the users of Eurocode 1.

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1. Introduction

Stadium lighting towers are generally used for lighting of the sport stages at dark during sport events. Four stadium lighting towers lighting a stadium during a football match were shown in Fig. 1.

The characteristic natural properties of these structures are: lightweight when compared to other structures, easily erectable, high cost efficiency, high aspect ratio (ratio of total length to least diameter), slender and wind sensitive (Chien and Jang, 2010). Also, it was stated by Abdullah (2011) that tall, slender and flexible structures such as towers, chimneys, masts are prone to wind action. In recent years, several failures of HMS towers have brought to light the need for a better understanding of the complex behavior of these structures (Warpinski et al., 2010). Collapse of these tall steel cantilever structures showed the importance of the right determination of wind loads acting to them. In Fig. 2, the base of a collapsed lighting tower due to wind loads was shown (Repetto and Solari, 2010).

Structural properties i.e. total height of the lighting tower, the strength of materials used for the construction, number of lighting bulbs used are different for different stadiums in different countries of the world. Lighting bulbs are mounted on top of the tower. Angle of lighting bulbs with the vertical, number and brightness of lighting bulbs are determined according to the needs of the stadium.

The objective of this paper is to determine the along-wind loads for stadium lighting towers according to Eurocode 1. For this purpose, a stadium lighting tower that has 20 meters height (Fig. 3) was modeled in SAP2000 (Wilson, 2000) and wind loads acting to this structure were calculated.

2. Calculation of Along-Wind Forces according to Eurocode 1 (CEN, 2004)

Eurocode 1 (CEN, 2004) deals with buildings and civil engineering works with heights up to 200 m. There are

* *Corresponding author.* Tel.: +90-452-2339588 ; Fax: +90-452-2332508 ; E-mail address: erdem18turkeli@hotmail.com (E. Türkeli)
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so many tables, formulas and figures in the wind load calculation procedure for the use of people using this standard in their calculations. Moreover, mean wind speed is not taken from a table or a chart. It is calculated from the basic wind velocity and the fundamental value of the basic wind velocity.

Fig. 1. Four stadium lighting towers (Bajaj Electricals, 2013).

Fig. 2. Base of collapsed steel lighting tower (Repetto and Solari, 2010).

In this part of the study, it is aimed to give only brief information about the procedure used in the calculation of along-wind loads according to Eurocode 1. The across-wind forces are not in the scope of this paper. Eurocode 1 is open to the use of the public. Therefore, there is no need to give detailed calculation procedures of the standard for the purpose of the volume limitation of the study.

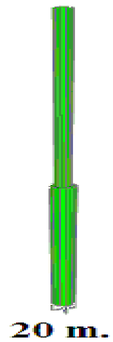

Fig. 3. SAP2000 model of 20 meters high stadium lighting tower (Wilson, 2000).

Total wind load which is shown in Eq. (1) is the combination of structural factor, the force coefficient, peak velocity pressure and the reference area for the structure. This standard also deals with the turbulence intensity in the calculation of peak velocity pressure. The most difficult parameter to calculate in the wind load formula is the structural factor because it contains the resonant part and the resonant part has so many parameters in it. Another difference used in this standard is the use of Reynolds number in the determination of force parameter. Moreover, tables and figures are used for the selection of relevant information.

$$F_w = c_s c_d \cdot c_f \cdot q_p(Z_e) \cdot A_{ref} \,. \tag{1}$$

The detailed procedure for calculating the structural factor $c_s c_d$ is given in Eq. (2);

$$C_s C_d = \frac{1+2 \cdot k_p \cdot I_v(z_e) \cdot \sqrt{B^2+R^2}}{1+7 \cdot I_v(z_e)} \,. \tag{2}$$

In Eq. (2), z_e is expressing the reference height, k_p is expressing the peak factor defined as the ratio of the maximum value of the fluctuating part of the response to its standard deviation, I_v is expressing the turbulence intensity, B^2 is expressing the background factor and R^2 is expressing the resonance response factor (Handa, 2006) given in Eq. (3). It is on the safe side to use $B^2 = 1$.

$$R^2 = \frac{2 \cdot \pi . F . \varphi_b \cdot \varphi_h}{\delta_s + \delta_a} \,. \tag{3}$$

In Eq. (3), F is expressing Wind Energy Spectrum, $\emptyset_b$ is expressing the size effect (breadth of the building), $\emptyset_h$ is expressing size effect (height of the building), δ_s is expressing the structural damping expressed by the logarithmic decrement and δ_a is expressing aerodynamic damping. The force coefficient c_f for a finite circular cylinder should be determined from Eq. (4);

$$c_f = c_{f,0} \cdot \psi_\lambda \,. \tag{4}$$

In Eq. (4), $c_{f,0}$ is expressing the force coefficient of cylinders without free-end flow and ψ_λ is expressing end-effect factor. The parameter $c_{f,0}$ given in Eq.(4) can be found by using the graph given in Eurocode 1. Also, peak velocity pressure $q_p(z)$ can be calculated by using Eq. (5);

$$q_p(z) = [1 + 7 \cdot I_V(z)] \cdot \frac{1}{2} \cdot p \cdot V_m^2(z)\,. \qquad (5)$$

ρ, $V_m(z)$ and $I_v(z)$ are impending air density, mean wind velocity and turbulence intensity, respectively.

3. General Structural and Mechanical Information about the Stadium Lighting Tower

A 20 meters high stadium lighting tower was constituted from 10 meters high pole sections with section splices. The finite element model (FEM) of the tower (Fig. 3) was created in Structural Analysis Program SAP2000. By using the structural information given in Table 1, two dimensional linear dynamic analyses were carried out.

The FEM model of 20 meters high stadium lighting tower was developed from non-prismatic circle sectioned steel bars. Steel has unit mass, unit weight, the module of elasticity and Poisson ratio, 7.849 kN.s²/m⁴, 76.973 kN/m³, 200,000 MPa and 0.3 respectively. During SAP2000 dynamic analyses, some assumptions were made: all splice points have three degree of freedoms namely 2 translational and 1 rotational, base was fixed to the ground, effect of earthquakes and lighting bulbs and relevant equipment ignored, tower was constructed on sea or coastal area exposed to open sea, no effect of other structures to the direction of wind, no holes on outer or inner surfaces of the tower.

Table 1. Structural information of 20 meters high stadium lighting tower.

Section No	Section No	Outside Diameter (mm)	Wall Thickness (mm)	Inside Diameter (mm)
	Height (m)	20	20	20
0	0	1200	5	1190
1	10	800	5	790
2	20	400	4	392

4. Calculation of Along-Wind Loads for 20 meters high Stadium Lighting Tower according to Eurocode 1

The fundamental value of the basic wind velocity according to logarithmic law for 20 meters high tower was given in Table 2.

In Table 2, the fundamental value of the basic wind velocity was selected as 36.00 m/s. The value of basic wind velocity was given in Table 3. In Table 3, directional & seasonal factors were given as 1.0.

The terrain factor used in the calculation of roughness factor was given in Table 4. In Table 4, according to Eurocode 1, z_0 and $z_{0,11}$ values were selected as 0.003 and 0.050, respectively. Also, in Table 5, the roughness factor was calculated depending on the terrain factor.

After calculation of basic wind velocity and the roughness factor, the mean wind velocity was calculated in Table 6.

The turbulence intensity was calculated in Table 7. Also, the size effects for breadth and height of the 20 meters high lighting tower were given in Table 8 and 9, respectively.

The value of the non-dimensional frequency was given in Table 10 and the value of the wind-energy spectrum according to non-dimensional frequency was given as Table 11. The value of peak velocity pressure was calculated and given in Table 12.

Table 2. The fundamental value of the basic wind velocity according to logarithmic law.

Section No	Height from Ground (m)	H_0 (m)	z_0 (m)	$\ln(H/z_0)$	$\ln(H_0/z_0)$	$\frac{\ln(H/z_0)}{\ln(H_0/z_0)}$	V_0 (m/s)	$V_{b,0}$ (m/s)
0	0	10.000	0.003	0.000	8.112	0.000	36.000	0.000
1	10	10.000	0.003	8.112	8.112	1.000	36.000	36.000
2	20	10.000	0.003	8.805	8.112	1.085	36.000	39.076

Table 3. The value of the basic wind velocity.

Section No	Height from Ground (m)	$V_{b,0}$ (m/s)	C_{dir}	C_{season}	V_b (m/s)
0	0	0.000	1.000	1.000	0.000
1	10	36.000	1.000	1.000	36.000
2	20	39.076	1.000	1.000	39.076

Table 4. The terrain factor.

z_0 (m)	$z_{0,11}$ (m)	$0{,}19*(z_0/z_{0,11})^{0{,}07}$	k_r
0.003	0.050	0.156	0.156

Table 5. The roughness factor.

Section No	Height from Ground (m)	z_0 (m)	$\ln(z/z_0)$	k_r	$C_r(z)$
0	0	0.003	5.809	0.156	0.906
1	10	0.003	8.112	0.156	1.266
2	20	0.003	8.805	0.156	1.374

Table 6. The mean wind velocity.

Section No	Height from Ground (m)	$C_r(z)$	$C_0(z)$	V_b (m/s)	$V_m(z)$ (m/s)
0	0	0.906	1.000	0.000	0.000
1	10	1.266	1.000	36.000	45.566
2	20	1.374	1.000	39.076	53.686

Table 7. The turbulence intensity.

Section No	Height from Ground (m)	k_I	$C_0(z)$	$\ln(z/z_0)$	$I_v(z)$
0	0	1.000	1.000	5.809	0.172
1	10	1.000	1.000	8.112	0.123
2	20	1.000	1.000	8.805	0.114

Table 8. The size effect for breadth of the structure.

Outer Diameter at top of the Tower (m)	First Mode Natural Frequency (Hz)	Mean Wind Speed at top (m/s)	$\varnothing_b$
0.400	2.618007	53.686	0.941

Table 9. The size effect for height of the structure.

Height of the Lighting Tower (m)	First Mode Natural Frequency (Hz)	Mean Wind Speed at top (m/s)	$\varnothing_h$
20.000	2.618007	53.686	0.339

Table 10. The value of non-dimensional frequency.

Section No	Height From Ground (m)	Reference Length Scale (m)	Reference Height (m)	α	Turbulence Length Scale (m)	First Mode Natural Frequency (Hz)	Mean Wind Speed at top (m/s)	C
0	0	300	200	0.380	40.159	2.618	53.686	1.958
1	10	300	200	0.380	96.233	2.618	53.686	4.693
2	20	300	200	0.380	125.193	2.618	53.686	6.105

Table 11. The wind-energy spectrum.

Section No	Height from Ground (m)	C	F
0	0	1.958	0.073
1	10	4.693	0.041
2	20	6.105	0.034

Table 12. Peak velocity pressure.

Section No	Height from Ground (m)	$I_v(z)$	ρ (kg/m³)	$V_m(z)$ (m/s)	$q_p(z)$ (kg/m.s²)
0	0	0.172	1.250	0.000	0.000
1	10	0.123	1.250	45.566	2417.469
2	20	0.114	1.250	53.686	3233.459

The value of peak velocity pressure in Table 12 was dependent on turbulence intensity given in Table 7, density of air (taken as 1.25 kg/m^3) and mean wind velocity given in Table 6. Also, the Reynolds number for circular cylinders was given in Table 13. In Table 13, z_e is the reference height which is 60% of the total height given in Eurocode 1. Also, the kinematic viscosity in Eurocode 1 was given as 0.000015 m^2/s.

The force coefficient dependent on Reynolds number and k/b ratio was given in Table 14. Also, end-effect factor can be selected from the figure given in Eurocode 1 by using solidity ratio and effective slenderness. The end-effect factor was given in Table 15.

In Table 15, the effective slenderness from the interpolation was found as 40. Also, the solidity ratio for the steel cantilever structure was found as 1.00 because there is no spacing on the body of the structure. The force coefficient dependent on the force coefficient of cylinders without free-end flow given in Table 14 and end-effect factor given in Table 15 was calculated in Table 16.

The equivalent mass per unit length for the upper third of the 20 meters high stadium lighting tower was given in Table 17. From the definition m_e, it may be approximated by the average value of m over the upper third of the structure.

By using the equivalent mass per unit length given in Table 17, the logarithmic decrement of aerodynamic damping was given in Table 18. Also, the resonant response part was calculated in Table 19. Structural damping was given as 0.05 for steel structures. Also, the up-crossing frequency for peak factor and the peak factor dependent on up-crossing frequency was given in Table 20 and 21, respectively.

Peak factor, k_p was selected as the greater of the values given in grey color in Table 21. Also, the structural factor was given in Table 22. In Table 22, the background factor B^2 is recommended to use as 1.0.

The total along-wind loading per unit length on 20 meters high HMS lighting tower was calculated in Table 23. The reference areas were calculated as the projection of the areas swept by the wind. This area is a trapezoid.

Table 13. Reynolds number for circular cylinders.

Section No	Height from Ground (m)	Diameter of the Section (m)	$V_m(z_e)$ (m/s)	N (m²/s)	Re
0	0	1.200	46.590	0.000015	$3.7*10^6$
1	10	0.800	46.590	0.000015	$2.4*10^6$
2	20	0.400	46.590	0.000015	$1.2*10^6$

Table 14. The force coefficient of cylinders without free-end flow.

Section No	Height from Ground (m)	Diameter of the Section (m)	Equivalent Roughness (mm)	k/b	Re	$C_{f,0}$
0	0	1.200	0.200	0.0001666667	$3.7*10^6$	*0.000*
1	10	0.800	0.200	0.0002500000	$2.4*10^6$	*0.796*
2	20	0.400	0.200	0.0005000000	$1.2*10^6$	*0.801*

Table 15. The end-effect factor.

Section No	Height From Ground (m)	l	b	$0,7*l/b$	λ	$\lambda_{interpolation}$	A	A_c	$\varphi=A/A_c$	ψ_λ
0	0	20.000	0.400	35.000	70.000	40.000	...	...	0.000	0.000
1	10	20.000	0.400	35.000	70.000	40.000	10.000	10.000	1.000	0.830
2	20	20.000	0.400	35.000	70.000	40.000	6.000	6.000	1.000	0.830

Table 16. The force coefficient.

Section No	Height from Ground (m)	$C_{f,0}$	ψ_λ	C_f
0	0	0.000	0.000	0.000
1	10	0.796	0.830	0.660
2	20	0.801	0.830	0.665

Table 17. The equivalent mass per unit length.

Section No	Height From Ground (m)	Outside Diameter of the Section (m)	Inside Diameter of the Section (m)	Wall Thickness of the Section (mm)	Volume of the Section (m^3)	Mass Per Unit Volume (kg/m^3) (steel)	Mass of the Section (kg)	m_e (kg/m)
0	0	1.200	1.190	5.000	...	800.000	0.000	...
1	14	0.640	0.630	5.000	...	800.000	0.000	...
2	20	0.400	0.392	4.000	0.044	800.000	35.570	5.928

Table 18. The logarithmic decrement of aerodynamic damping.

Section No	Height From Ground (m)	C_f	ρ (kg/m^3)	Top Mean Wind Speed (m/s)	Outer Diameter at top (m)	m_e (kg/m)	1st Mode Natural Frequency (Hz)	δ_a
0	0	0.000	1.250	53.686	0.400	5.928	2.618007	0.000
1	10	0.660	1.250	53.686	0.400	5.928	2.618007	1.142
2	20	0.665	1.250	53.686	0.400	5.928	2.618007	1.150

Table 19. The resonant response part.

Section No	Height From Ground (m)	F	$\varnothing_b$	$\varnothing_h$	δ_s	δ_a	R^2
0	0	0.073	0.941	0.339	0.050	0.000	...
1	10	0.041	0.941	0.339	0.050	1.142	0.069
2	20	0.034	0.941	0.339	0.050	1.150	0.057

Table 20. The up-crossing frequency.

Section No	Height from Ground (m)	B^2	R^2	First Mode Natural Frequency (Hz)	ν
0	0	1.000	...	2.618007	...
1	10	1.000	0.069	2.618007	0.664
2	20	1.000	0.057	2.618007	0.610

Table 21. The peak factor.

Section No	Height from Ground (m)	v	k_p	k_p
0	0	...	3.000	...
1	10	0.664	3.000	3.628
2	20	0.610	3.000	3.605

Table 22. The structural factor.

Section No	Height from Ground (m)	k_p	$I_v(z_e)$	R^2	B^2	c_sc_d
0	0	...	0.118	...	1.000	...
1	10	3.628	0.118	0.069	1.000	1.032
2	20	3.605	0.118	0.057	1.000	1.027

Table 23. The total along-wind load on 20 meters high stadium lighting tower.

Section No	Height from Ground (m)	c_sc_d	C_f	$q_p(z)$	A_{ref}	F_w (kN/m)
0	0	...	0.000	0.000	...	0.000
1	10	1.032	0.660	2417.469	10.000	1.648
2	20	1.027	0.665	3233.459	6.000	1.324

5. Conclusions

In this study, along-wind forces acting on 20 meters high stadium lighting tower according to Eurocode 1 were calculated. The FEM of 20 meters high stadium lighting tower was developed in SAP2000 and the wind loading calculations were performed step by step in tabular form. Due to the fact that Eurocode 1 is open to the use of public and the volume limitation of this study, there is no need to provide all detailed along-wind calculation procedures given in Eurocode 1. Therefore, only the relevant equations were given in the preceding parts of the study. Some of the results, discussions and suggestions deducted from the study were given as follows:

From Table 23, it can be clearly seen that although wind speed increases with height, the wind loading on the stadium lighting tower is not increasing with the increase in height due to decreasing wind affected area because of their trapezoidal (projection) geometry. The calculation of resonant response factor in Eurocode 1 is so complex and difficult. Therefore, in this study, an explanatory additional equation was provided for resonant response factor. In Eurocode 1, the calculation of force coefficient is dependent on a graph (not given in this study due to the volume limitation) which is constructed from two different equations. It is very difficult and time consuming for the users to directly select the value from the graph due to illegible closer values. Also, directly usage of these two different equations is time consuming. Therefore, the graph for the calculation of force coefficient should be enhanced and clarified for the users. Moreover, end-effect factor given in Table 15 was determined by using the graph (not given in this study due to the volume limitation) in Eurocode 1. There is no scale or any other provided intermediate values on this graph. Therefore, the obtained values for end-effect factor are depending on the ability of the user. Even for the same values of solidity ratio and effective slenderness, different users can find different values of end-effect factor. This phenomenon leads wind loads to differ from each other. A research study can be made to clarify the use of this graph.

This study is only dealt with the along-wind loading calculation of a 20 meters high stadium lighting tower according to Eurocode 1. The effect of earthquakes, across-wind forces (wind induced forces), divergence or flutter, galloping, wake buffeting are not considered and not taken into account. In the design of stadium lighting towers, it is advised to determine all of governing forces in order to design and construct safer stadium lighting towers.

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