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WIND LOADS ON STRUCTURES: SOFTWARE APPLICATION
II. TOWERS

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Abstract. The paper presents a design example for the computation of wind forces on lattice towers using a software application designed and implemented by the author. The purpose of the software is to evaluate wind loads on typical structures such as: multistory buildings, industrial buildings and steel lattice towers based on the Romanian wind code CR 1-1-4/2012. The field of application of CR 1-1-4 is limited to buildings and structures with a height less than 200 m and bridges with a length up to 200 m and does not consider lattice towers with non-parallel legs. For such structures, the code states that reference should be made to SR EN 1993-3-1, the software application making use of the therein procedure to evaluate force coefficients for lattice towers.

Key words: wind software; wind codes; lattice towers; wind action.

1. Introduction

Wind action on buildings and structures as well as wind-induced dynamic response are dealt with by means of random vibration theory and

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modal analysis (Ghiocel & Lungu, 1975; Simiu & Schanlan,1986). One of the most widely used analytical methods to evaluate the wind-induced dynamic response is the Gust Factor Technique, first introduced by Davenport (1967) and lately generalized as Gust Effect Factor technique by Solari and Piccardo (2002). Alternatively, wind action on structures as well as the corresponding dynamic response can be evaluated by means of experimental studies (Glanville & Kwok, 1995). Results of analytical and experimental research have been incorporated into design codes and standards.

A previous paper (Calotescu, 2012) introduced the software application created by the author based on the Romanian wind code CR 1-1-4/2012 for the computation of wind action on multistory buildings, industrial buildings and lattice towers. The layout of the software application along with a design example for multistory buildings was described. This paper presents a practical example for the computation of wind forces on freestanding lattice towers using the previously introduced software application.

2. Wind Loading On Lattice Towers: Design Example

The structure under examination is a 90 m high freestanding lattice tower with triangular in-plane shape. The side length at the base is equal to 12 m and it varies linearly up to z = 75.0 m. From this level to the top, the side length is equal to 3.00 m. The tower's legs are constituted of circular-section members whereas all the diagonals and the horizontal members have angle cross-sections.

2.1. Wind Velocity And Velocity Pressure

The *Wind* window (Fig. 1) contains the wind and terrain related input parameters. The user must select the type of structure, the importance-exposure class of the structure, the terrain category and the basic values of the wind velocity and wind pressure.

For the tower under analysis, a site corresponding to category III terrain, characterized by a roughness length equal to z_0 = 0.30 m and a reference wind velocity pressure v_b=30.0 m/s is selected. The reference velocity pressure results q_b=0.562 kPa. The building is assumed to belong to the importance-exposure Class I, resulting γ_{Iw}=1.15.

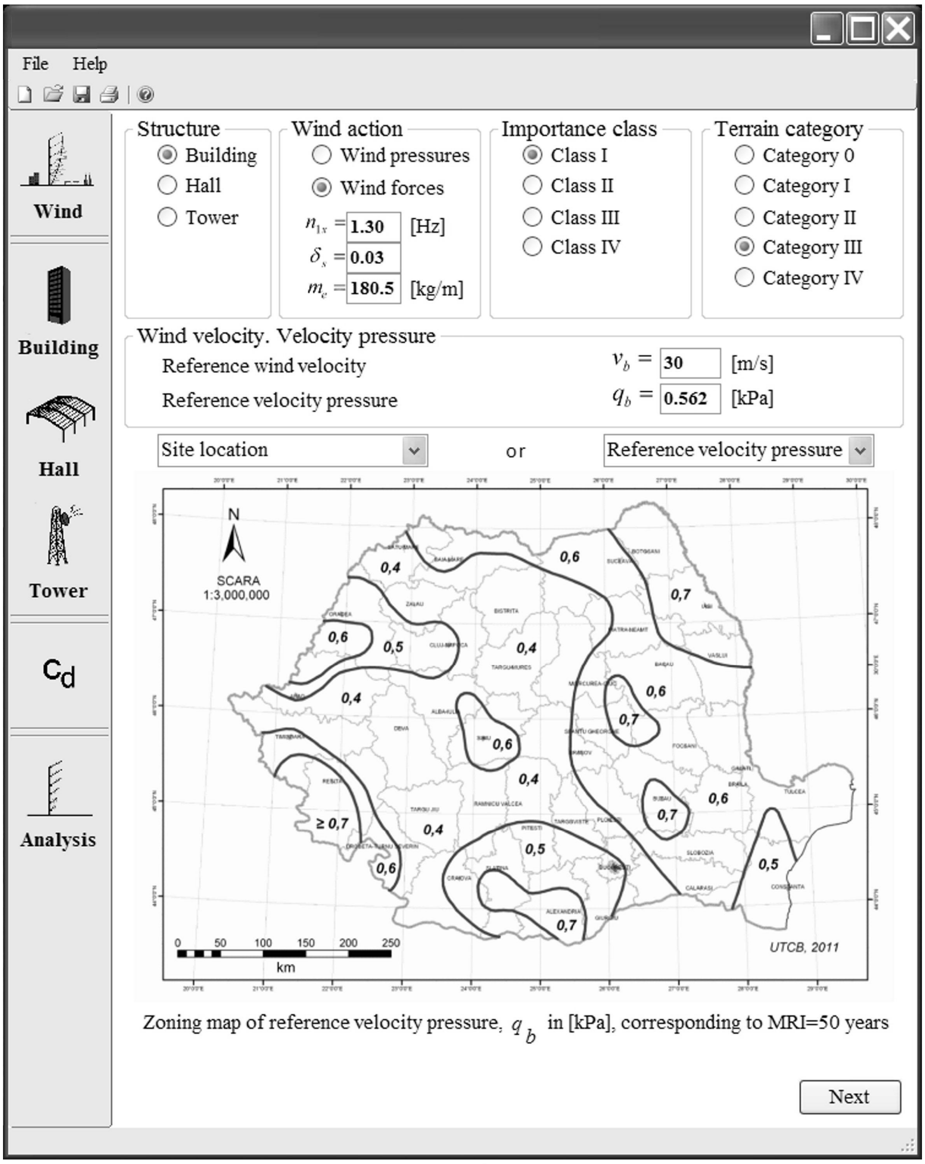


Fig. 1 – *Wind* window.

2.2. Wind Force Coefficients

The force coefficient for a steel lattice tower depends on the solidity ratio, φ, defined as the ratio of the solid area to the area of a panel as if it was full.

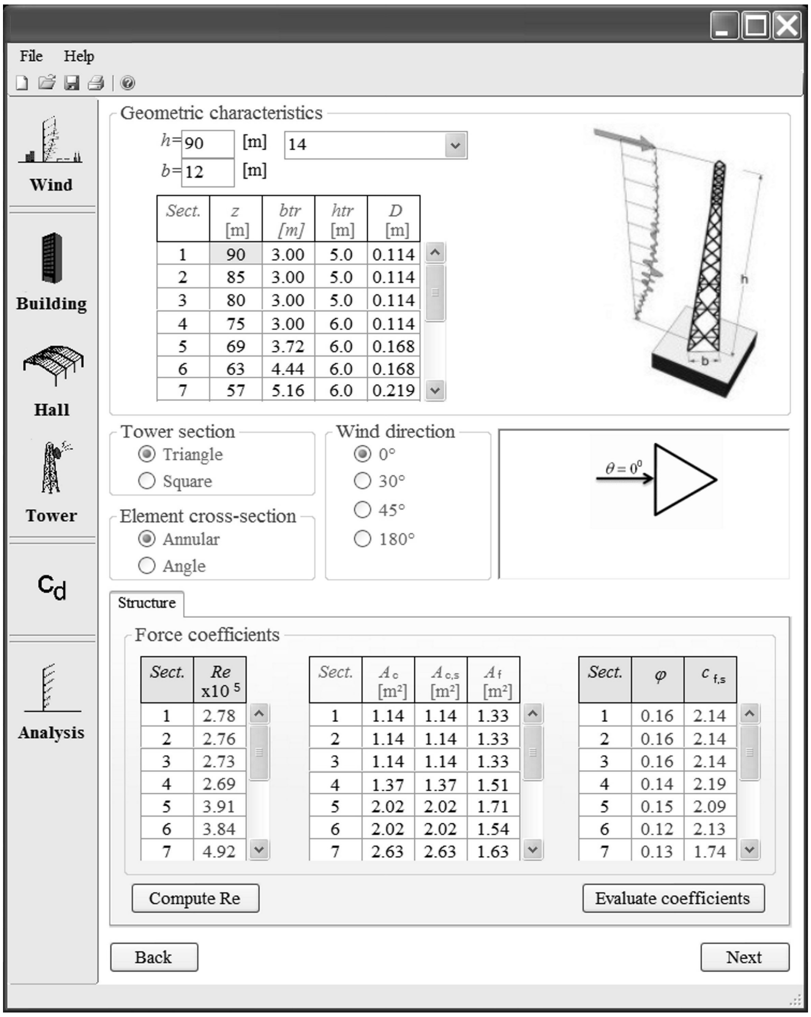


Fig. 2 – *Tower* window.

According to SR EN 1993-3-1, the total wind force coefficient in the direction of the wind over a section of the tower can be taken as

$$c_f = c_{f,s} + c_{f,A}, \tag{1}$$

where: $c_{f,A}$ is the wind force coefficient of the ancillaries and $c_{f,s}$ – the wind force coefficient of the bare structure section. The software application does not take into ancillaries. The wind force coefficient of the bare structure section is given by:

$$c_{f,s} = K_\theta c_{f,s,0}, \tag{2}$$

where: K_θ is the wind incidence factor and $c_{f,s,0}$ – the overall normal force coefficient applicable to a tower panel composed of both flat-sided and circular-section members given by:

$$c_{f,s,0,j} = c_{f,0,f} \frac{A_f}{A_s} + c_{f,0,c} \frac{A_c}{A_s} + c_{f,0,c,\sup} \frac{A_{c,\sup}}{A_s}, \quad (3)$$

where: A_f is the total projected area of the flat sided section members on a plane perpendicular to the wind direction, A_c – the total projected area of the circular section members in the sub critical regimes on a plane perpendicular to the wind direction, $A_{c,\sup}$ – the total projected area of the circular section members in the super critical regimes on a plane perpendicular to the wind direction.

For steel lattice towers with equilateral triangular in-plane shape, the wind provides maximum drag when normal to a face (Sachs, 1978). A zero angle of attack, *i.e.* wind normal to the face of the tower (θ = 0°) will be considered in this analysis.

For the analysed structure the Reynolds number, the solidity ratio and the force coefficients corresponding to each tower section as obtained from the software application are presented in Fig. 2. The results obtained with an independent analysis from the software are presented in Table 1.

Table 1
Reynolds Number, Solidity Ratio qnd Force Coefficients

Section	z, [m]	$\Re e$	φ	c_f
1	90.0	2.78E+05	0.16	2.14
2	85.0	2.76E+05	0.16	2.14
3	80.0	2.73E+05	0.16	2.14
4	75.0	2.69E+05	0.14	2.19
5	69.0	3.91E+05	0.15	2.09
6	63.0	3.84E+05	0.12	2.13
7	57.0	4.92E+05	0.13	1.74
8	51.0	4.81E+05	0.12	1.79
9	45.0	5.25E+05	0.11	1.75
10	39.0	5.10E+05	0.11	1.87
11	33.0	5.49E+05	0.10	1.77
12	25.5	5.19E+05	0.11	1.89
13	18.0	5.68E+05	0.10	1.78
14	9.0	4.72E+05	0.10	1.89

2.3. Dynamic Factor for Gust Response

The *cd* window (Fig. 3) evaluates the dynamic response factor for the analysed tower. The dynamic parameters of the tower were obtained using a finite element model. The first mode of vibration is a lateral displacements with frequency n_1 = 1.30 Hz and the logarithmic decrement of the structural damping was assumed δ = 0.03. This value is recommended in CR 1-1-4, similar values being given by (ESDU, 1991).

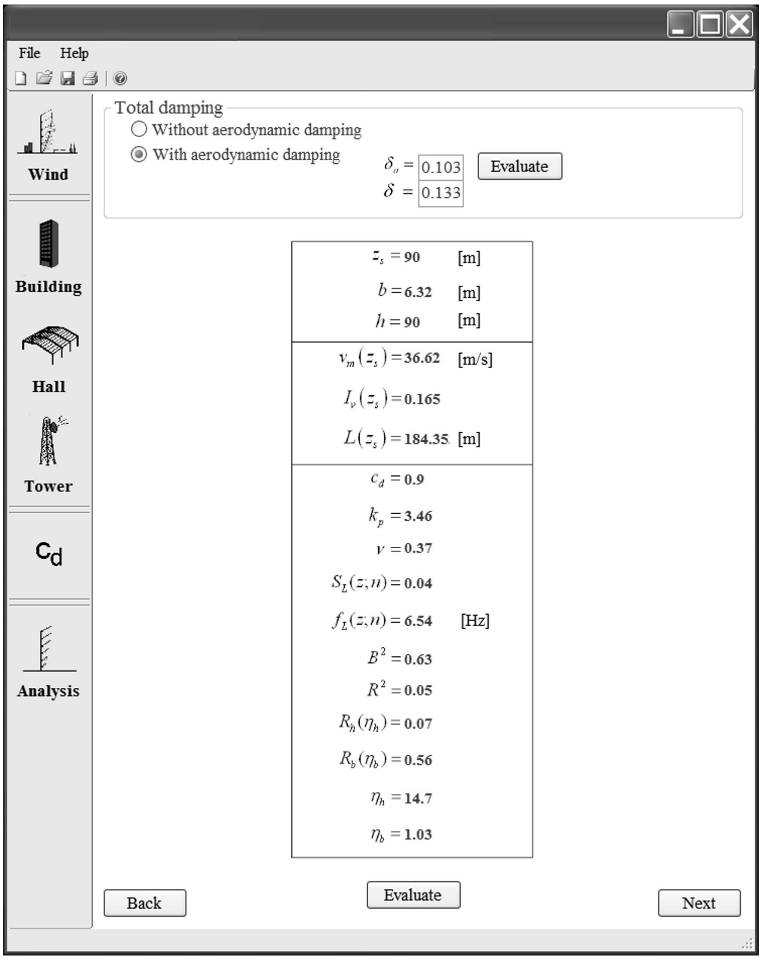


Fig. 3 – *cd* window.

The aerodynamic damping is the damping caused by the relative velocity of the structure to that of the air flow. For along-wind direction, the aerodynamic damping is essential and, for low mass structures such as lattice towers is usually larger than structural damping (Holmes, 1996). The software takes into account both structural as well as aerodynamic damping.

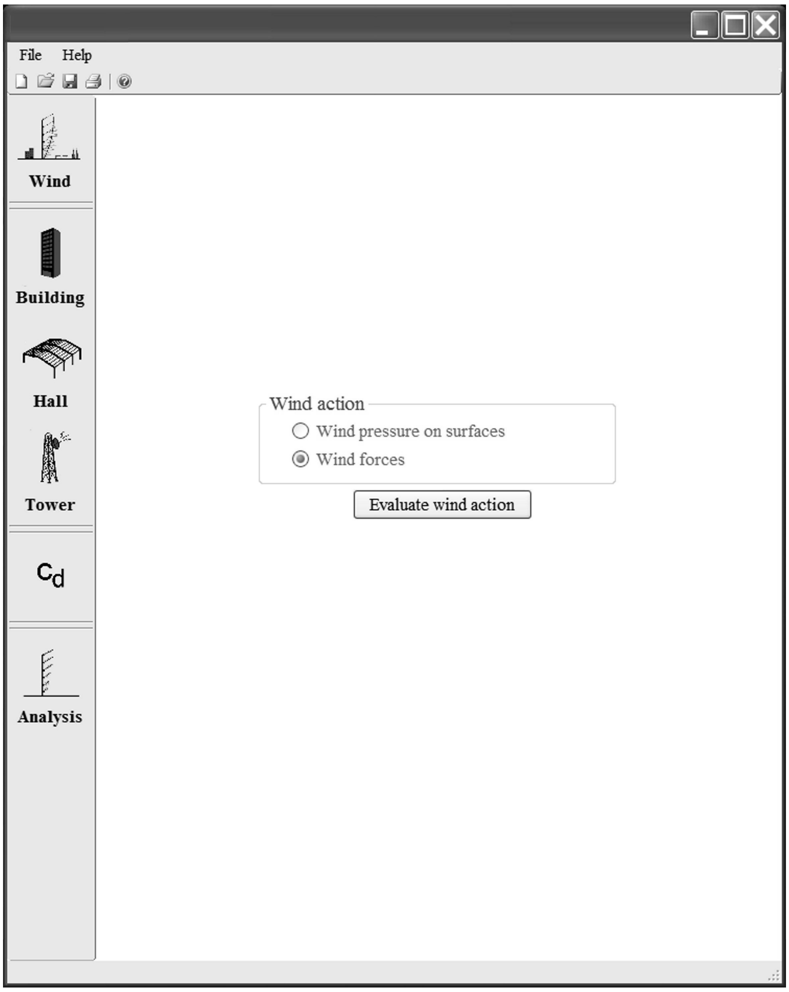


Fig. 4 – *Analysis* window.

The logarithmic decrement of aerodynamic damping may be estimated by

$$\delta_a = \frac{c_f \rho b v_m(z_s)}{2 n_1 m_e}, \tag{4}$$

where: c_f is the force coefficient, b – the reference width of the structure v_m – the mean wind velocity evaluated at reference height z_s and m_e – the equivalent mass depending on the fundamental mode shape of vibration. For the analysed tower, the logarithmic decrement of aerodynamic damping is δ_a = 0.103, the total logarithmic decrement resulting δ = 0.133.

The dynamic response factor evaluated at a reference height z_s is given by

$$c_d = \frac{1 + 2k_p I_v(z_s)\sqrt{B^2 + R^2}}{1 + 7I_v(z_s)}, \tag{5}$$

where I_v is the turbulence intensity, k_p – the along-wind peak factor, B^2 – the background factor and R^2 – the resonant response factor

Table 2 presents the values of the main parameters involved in the computation of the dynamic response factor obtained independently from the software application. The results coincide with the values given in Fig. 3.

Table 2
Dynamic Response Coefficient

z_s, [m]	I_v, [m]	B^2	R_D^2	k_p	c_d
90.0	0.165	0.63	0.05	3.46	0.90

The *Analysis* window (Fig. 4) lunches the result page containing the computation of wind forces corresponding to the sections of the analysed tower.

2.3. Wind Forces

The wind force acting on a structure or a structural component may be determined using the expression:

$$F_w(z) = \gamma_{Iw} c_d c_f(z) q_p(z) A_{\text{ref}}, \tag{6}$$

where: γ_{Iw} is the importance-exposure factor, c_d – the dynamic response factor, c_f – the force coefficient, A_{ref} – the reference oriented perpendicular to the wind direction and q_p – the peak velocity pressure given by

$$q_p(z) = c_{pq}(z) q_m(z) = \left[1 + 7I_v(z)\right] c_0^2 k_r^2(z_0) \left[\ln\left(\frac{z}{z_0}\right)\right]^2 \frac{1}{2}\rho v_b^2, \tag{7}$$

where: c_{pq} is the pressure gust factor, q_m – the mean wind pressure, I_v – the turbu-lence intensity, c_0 – the orography factor, z_0 – the roughness length and v_b – the reference wind velocity.

The result window for towers (Figs. 5 *a*, 5 *b* and 5 *c*) is structured into three main panels. The first panel contains information related to the geometric characteristics of the tower under analysis. The second panel presents the theoretical background related to the wind velocity and wind pressure, such as reference values for wind velocity and pressure, characteristics of terrain roughness, analytical expressions for the mean wind velocity and mean wind pressure as well as for turbulence intensity, gust factor, exposure coefficient and peak wind velocity and pressure.

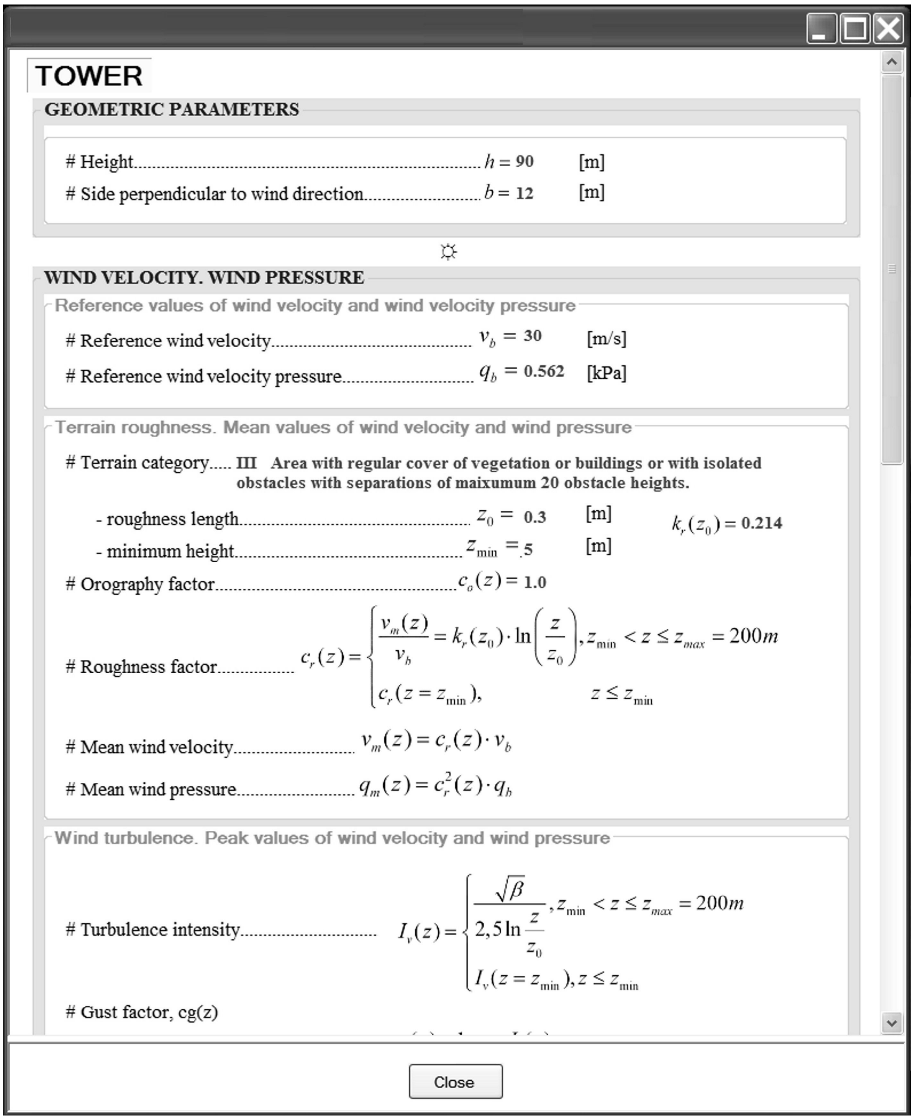


Fig. 5 *a* – Results window.

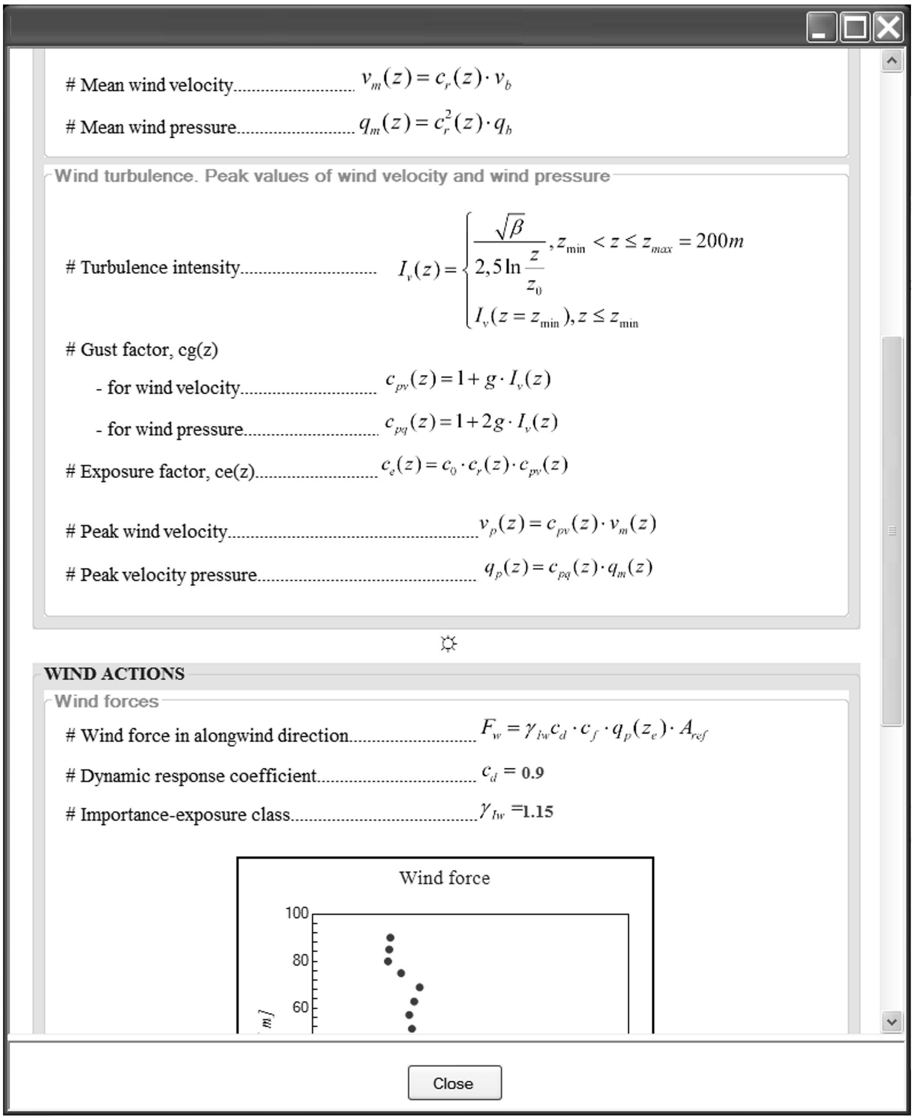


Fig. 5 *b* – Results window (continuation).

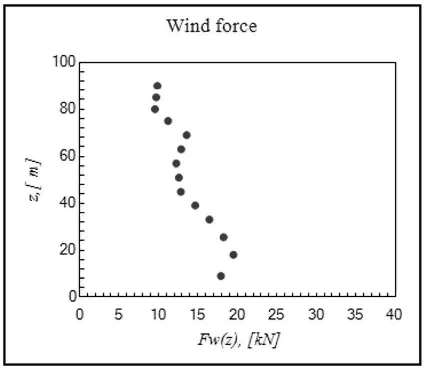
The third panel contains the analytical expressions of the wind force as well as the values for the dynamic response coefficient and the importance-exposure factor. It also contains a figure representing the variation of the wind force with height.

The results are presented in tabulated form and indicate the level, z, the turbulence intensity, I_v, the mean wind velocity, v_m, the peak wind velocity, v_p, the mean wind velocity pressure q_m, the peak wind velocity pressure q_p, the reference area A_{ref}, the force coefficient c_f and the total wind force F_w corresponding to each tower section.

Table 3 shows the results obtained from an independent computation and it can be seen that they are similar to the results obtained with the software application.

Dynamic response coefficient.................................. $c_d = 0.9$

Importance-exposure class.. $\gamma_{Iw} = 1.15$



Wind forces on the tower sections

Sect.	z [m]	I_v	v_m [m/s]	v_p [m/s]	q_m [kPa]	q_p [kPa]	A_{ref} [m²]	c_f	F_w [kN]
1	90	0.16	36.62	57.76	0.84	1.8	2.47	2.14	9.87
2	85	0.17	36.25	57.39	0.82	1.78	2.47	2.14	9.72
3	80	0.17	35.86	57	0.8	1.75	2.47	2.14	9.57
4	75	0.17	35.45	56.59	0.78	1.72	2.88	2.19	11.23
5	69	0.17	34.91	56.05	0.76	1.68	3.73	2.09	13.58
6	63	0.18	34.33	55.47	0.74	1.64	3.56	2.13	12.89
7	57	0.18	33.69	54.82	0.71	1.6	4.26	1.74	12.26
8	51	0.18	32.97	54.11	0.68	1.55	4.39	1.79	12.6
9	45	0.19	32.17	53.31	0.65	1.5	4.74	1.75	12.84
10	39	0.19	31.25	52.39	0.61	1.43	5.28	1.87	14.66
11	33	0.2	30.18	51.31	0.57	1.37	6.58	1.77	16.46
12	25.5	0.21	28.52	49.66	0.51	1.26	7.4	1.89	18.25
13	18	0.23	26.29	47.42	0.43	1.13	9.41	1.78	19.51
14	9	0.28	21.84	42.97	0.3	0.87	10.48	1.89	17.92

Close

Fig. 5 *c* – Results window (cont.).

Table 3
Wind Pressure Action on External and Internal Surfaces

Section	z m	I_v	v_m m/s	v_p m/s	q_m kPa	q_p kPa	F_w kN
1	90.0	0.165	36.62	57.76	0.84	1.81	9.88
2	85.0	0.167	36.25	57.39	0.82	1.78	9.74
3	80.0	0.168	35.86	57.00	0.80	1.75	9.58
4	75.0	0.170	35.45	56.59	0.79	1.72	11.22
5	69.0	0.173	34.91	56.05	0.76	1.68	13.55
6	63.0	0.176	34.33	55.47	0.74	1.64	12.91
7	57.0	0.179	33.69	54.82	0.71	1.60	12.26
8	51.0	0.183	32.97	54.11	0.68	1.55	12.59
9	45.0	0.188	32.17	53.31	0.65	1.50	12.86
10	39.0	0.193	31.25	52.39	0.61	1.44	14.61
11	33.0	0.200	30.18	51.31	0.57	1.37	16.40
12	25.5	0.212	28.52	49.66	0.51	1.26	18.22
13	18.0	0.230	26.29	47.42	0.43	1.13	19.44
14	9.0	0.277	21.84	42.97	0.30	0.87	17.90

3. Conclusions

The paper presents a practical design example for the evaluation of wind forces on steel lattice towers using a software application designed by the author.

In order to validate the software application, a comparison is made between results obtained from the software and from a computation performed independently. The results are identical except for some differences related to the rounding of decimals.

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SOFTWARE PENTRU EVALUAREA ACȚIUNII VÂNTULUI PE CONTRUCȚII
II: Turnuri

(Rezumat)

Se prezintă un exemplu de calcul pentru evaluarea forțelor din vânt pe turnuri cu zăbrele utilizând o aplicație software creată şi implementată de autor. Scopul aplicației este de a evalua acțiunea vântului pe o serie de structuri şi anume clădiri multietajate, hale industriale şi turnuri metalice conform codului românesc de vânt CR 1-1-4/2012. Codul CR 1-1-4 este aplicabil structurilor şi clădirilor cu înălțimi de cel mult 200 m şi podurilor cu deschiderea mai mică de 200 m, evaluarea acțiunii vântului pe turnuri cu zăbrele cu tălpi neparalele nefiind considerată. Ca atare, pentru calculul coeficienților de forță ai acestor structuri, aplicația software utilizează metoda prezentată în SR EN 1993-3-1.