WIND LOADS ON STRUCTURES: SOFTWARE APPLICATION
PART I: BUILDINGS

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Abstract. The evaluation of wind loading on typical buildings and structures is performed according to the regulations provided in wind standards. The evolution of wind codes follows the evolution of analytical and experimental research which leads to the development of the mathematical formulation in wind engineering. Thus wind codes have become less intuitive and more inclined towards automatic computation. In this context, there is a need for design examples and software applications in order to ease the use of wind standards and to offer a better understanding of the wind loading computation process. The paper introduces a software application created and implemented by the author for the computation of wind loads on structures based on the Romanian wind code NP 082-2004 (revised in 2011). The purpose of the software is to evaluate wind loads on typical structures such as multistory buildings, industrial buildings and steel lattice towers.

Key words: wind software; wind codes; multistory buildings; wind action.

1. Introduction

Recent advances in wind engineering are synthesized in wind codes in order to provide principles and rules of application for the evaluation of wind

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actions on buildings and structures. In some cases, codes are accompanied by commentaries, design examples and guidelines (Cook, 1985; Simiu, 2011) for designers in order to make the methods accessible for the practicing engineer. Code comparisons also provide useful information about the methodologies used in various standards (Lungu & Van Gelder, 1997; Holmes *et al.*, 2009). The latest versions of wind loading standards are based on probabilistic principles (Ghiocel & Lungu, 1975) that are better suited for automatic computation and, even if some codes have already been implemented in software applications such as MECAWind for ASCE/SEI 7-10, for many standards such software are yet unavailable. In this paper a software application based on the Romanian wind code NP 082-2004 (revised in 2011) for the computation of wind action on multistory buildings, industrial buildings and lattice towers is introduced.

2. Software Design Description

The user interface is structured into nine windows, six for data input and three for results. The input data windows are entitled: *Wind*, *Building*, *Hall*, *Tower*, *cd* and *Analysis*. Results windows are displayed at the end of the computation process, and can be lunched only from the *Analysis* window.

Wind window contains the input parameters for wind velocity and velocity pressure as well as terrain categories and importance-exposure classes.

Building, *Hall* and *Tower* windows include the geometric characteristics of the structures and compute the corresponding aerodynamic coefficients.

The *cd* window evaluates the dynamic response coefficients for the buildings and structures based on the detailed procedure presented in the code.

The *Analysis* window contains two radio buttons corresponding to the analysis type, *i.e.* evaluation of wind pressures and evaluation of wind forces. The computation of wind pressure on surfaces is appropriate for multistory and industrial buildings whereas the computation of wind forces should be selected for lattice towers.

3. Wind Loading on Multistory Buildings: Design Example

In order to validate the results obtained with the software application, a typical design example is considered, *i.e.* evaluation of external and internal overall wind pressure on vertical walls of a multistory building.

The building under examination is a 84.1 m high steel building and has a rectangular plan (32.2 m × 20.65 m).

The analysis proceeds in four stages. First, the terrain category and importance-exposure class are selected and the value for the wind velocity pressure corresponding to the site location is chosen from the hazard map. The

second stage consists in evaluating the external and internal pressure coefficients for the vertical walls of the building. The third stage estimates the dynamic parameters of the building and evaluates the dynamic response factor for along-wind gustiness. Finally, the overall wind pressure acting on the structure is calculated.

3.1. Wind Velocity and Velocity Pressure

The reference wind velocity corresponding to a given site is determined based on the value of the reference velocity pressure selected from the wind hazard map and it is given by relation

$$v_b = \sqrt{\frac{2q_b}{\rho}} \,, \tag{1}$$

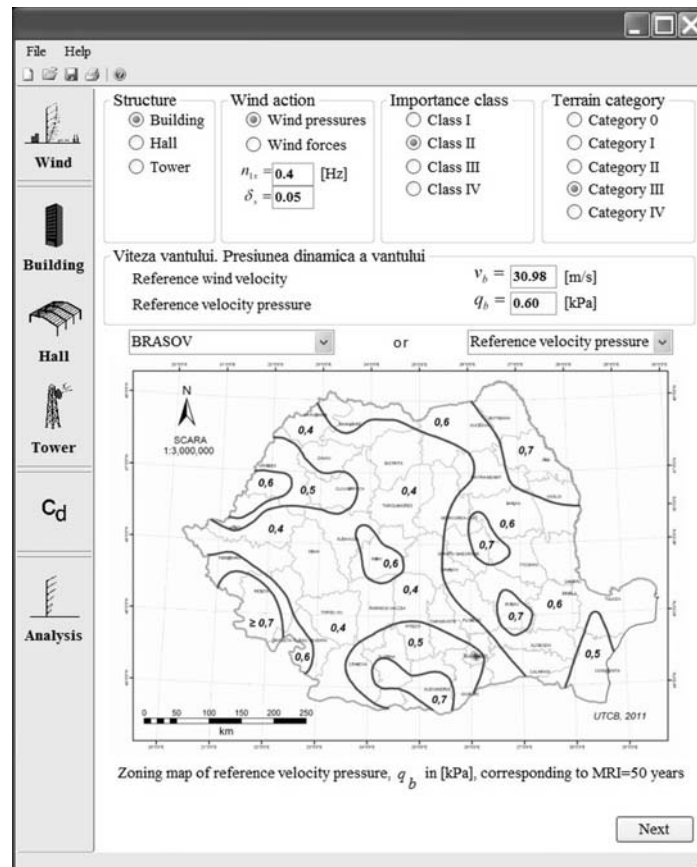where: q_b is the reference velocity pressure and ρ – the air density.

Fig. 1 – *Wind* window.

The terrain category is characterized by the roughness length, z_0, which is a measure of the size of a characteristic vortex formed at the ground surface due to the friction forces.

The importance-exposure category is accounted for by means of the importance-exposure coefficient, γ_{Iw}, which amplifies the wind forces for building and structures considered essential for society or buildings and structures that can produce, in case of damage, major hazard for human life.

The *Wind* window (Fig. 1) contains the wind and terrain related input parameters. For the analysed building, located in Braşov, a site corresponding to terrain category III, characterized by a roughness length equal to $z_0 = 0.30$ m and a reference velocity pressure $q_b = 0.6$ kPa is selected. The building is assumed to belong to the importance-exposure Class II, resulting $\gamma_{Iw} = 1.15$.

3.2. Pressure Coefficients for Vertical Walls

In order to evaluate wind-induced pressures on buildings, the distribution of external and internal pressure coefficients are needed.

External pressure coefficients for vertical walls, c_{pe}, are evaluated by interpolation of local pressure coefficients, $c_{pe,1}$, and overall pressure coefficients, $c_{pe,10}$. The values of the external pressure coefficients depend on the positions of the walls, defined by zones A, B, C, D and E, D corresponding to the windward wall, E to the leeward wall and A, B and C, respectively, to zones located on the side walls.

The internal pressure coefficients, c_{pi}, depend of the size and distribution of the openings in the building envelope. They are evaluated based on the existence of a dominant face. If a building has a dominant face, then the internal pressure should be taken as a fraction of the external pressure at the openings of the dominant face. For buildings without a dominant face, the internal pressure coefficient may be taken +0.2 or –0.3, and the highest resulting wind pressures should be considered.

For the analysed structure the external pressure coefficients obtained from a computation independent from the software applications are given in Table 1. The internal pressure coefficients were evaluated considering that the building does not have a dominant face and were taken conservatively as +0.2.

Table 1
External Pressure Coefficients

h/d	A	B	C	D	E
4.073	1.2	–0.8	–	0.8	–0.654

Fig. 2 presents the *Building* window corresponding to the multistory building considered in this paper. It can be seen from Fig. 2 and Table 1 that

the values of external and internal pressure coefficients obtained form the software coincide with the values obtained from the independent computation.

Fig. 2 – *Building* window.

3.3. Dynamic Factor for Gust Response

The dynamic response factor is defined as the ratio of the response gust factor to the pressure gust factor. A gust factor is a dimensionless coefficient which amplifies the mean value of the response in order obtain its mean maximum value. The gust factor technique was first introduced by Davenport (1967) and it defines a non-dimensional parameter termed displacement gust factor that is used to evaluate the mean maximum displacement in the along-wind direction. The method was further generalized by Piccardo and Solari (2002) to define non-dimensional quantities, called *gust effect factors*, in order

to determine the mean maximum values of the considered effect associated with 3-D wind-excited response, at any height of a cantilever vertical structure.

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

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

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. The background factor takes into account the lack of full correlation of pressure on the structure surface whereas the resonance response factor takes into account the frequency content of wind turbulence in quasi-resonance with the structure fundamental frequency.

Fig. 3 – cd window.

The dynamic response coefficient can be smaller, larger or equal to 1. Values less than unity correspond to large, stiff and highly damped structures, whereas values greater than 1 are representative of small, flexible or low damped structures (Solari & Tubino, 2007).

The *cd* window (Fig. 3) evaluates the dynamic response coefficient for the analysed building.

The building vibrates in the fundamental mode with a frequency $n_{1,x} =$ = 0.4 Hz and the logarithmic decrement of the structural damping was assumed $\delta = 0.05$.

Table 2 presents the values of the main parameters involved in the computation of the dynamic response factor obtained independently from the software application. It can be seen that the results coincide with those obtained with the software application (Fig. 3).

Table 2

Dynamic Response Coefficient

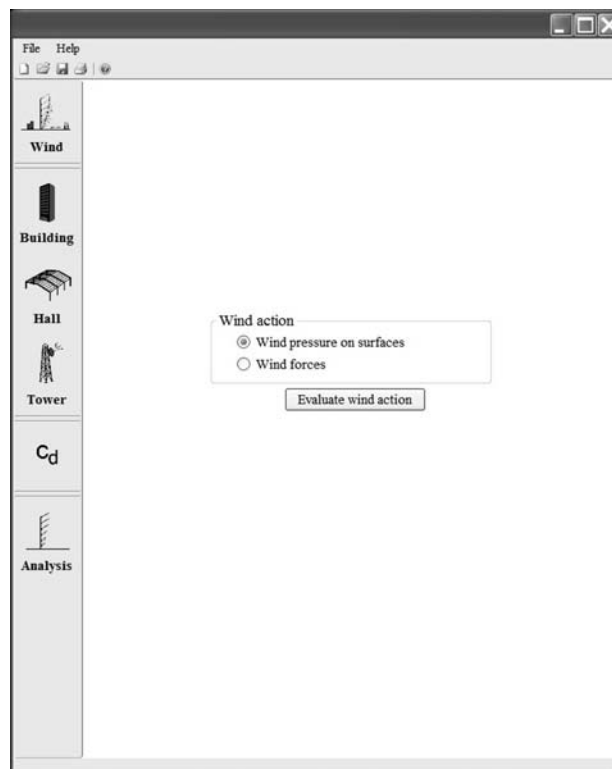| z_s, [m]	I_v, [m]	B^2	R_D^2	ν	k_p	c_d
50.46	0.184	0.54	0.77	0.31	3.41	1.064

Fig. 4 – *Analysis* window.

The *Analysis* window (Fig. 4) launches the result page containing the computation of the external and internal pressures on the vertical walls of the multistory building.

3.3. Wind Pressure on Surfaces

The wind pressures on the external, w_e, and internal, w_i, surfaces are given by

$$w_e = q_p(z_e)c_{pe},\tag{3}$$

$$w_i = q_p(z_i)c_{pi},\tag{4}$$

where: z_e, z_i are the reference heights for external and internal pressure, respectively, c_{pe} – the external pressure coefficient, c_{pi} – the internal pressure coefficient and q_p – the peak velocity pressure.

The result window for buildings (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 building 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.

The third panel contains the analytical expressions of the wind external and internal pressures as well as the values for the dynamic response coefficient and the importance-exposure factor. For tall buildings the software divides the vertical walls into six zones, for medium height buildings there are two zone considered and for short buildings one zone.

The results are presented in tabulated form and indicate the reference height, peak wind pressure, external wind pressure and internal wind pressure corresponding to each zone. Table 3 shows the obtained results from an independent computation and it can be seen that they are similar to the results obtained with the software application except for some differences related to the rounding of decimals.

Table 3
Wind Pressure Action on External and Internal Surfaces

z, [m]	q_p, [kPa]	w_e, [kPa]				w_i, [kPa]			
		A	B	D	E	A	B	D	E
84.1	1.89	−2.61	−1.74	1.74	−1.42	0.435	0.435	0.435	0.435
51.9	1.66	−2.29	−1.53	1.53	−1.25	0.382	0.382	0.382	0.382
47.0	1.62	−2.23	−1.49	1.49	−1.21	0.372	0.372	0.372	0.372
42.1	1.57	−2.16	−1.44	1.44	−1.18	0.360	0.360	0.360	0.360
37.1	1.51	−2.08	−1.39	1.39	−1.13	0.347	0.347	0.347	0.347
32.2	1.45	−2.00	−1.33	1.33	−1.09	0.333	0.333	0.333	0.333

BUILDINGS

GEOMETRIC PARAMETERS

Height...$h = 84.1$ [m]

Side perpendicular to wind direction..........................$b = 32.2$ [m]

Side parallel to wind direction....................................$d = 20.65$ [m]

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WIND VELOCITY. WIND PRESSURE

Reference values of wind velocity and wind velocity pressure

Reference wind velocity...$v_b = 30.98$ [m/s]

Reference wind velocity pressure..............................$q_b = 0.6$ [kPa]

Terrain roughness. Mean values of wind velocity and wind pressure

Terrain category..... **III** Area with regular cover of vegetation or buildings or with isolated obstacles with separations of maixumum 20 obstacle heights.

- roughness length...$z_0 = 0.3$ [m] $k_r(z_0) = 0.214$

- minimum height...$z_{min} = .5$ [m]

Orography factor..$c_o(z) = 1.0$

Roughness factor..................$c_r(z) = \begin{cases} \dfrac{v_m(z)}{v_b} = k_r(z_0) \cdot \ln\left(\dfrac{z}{z_0}\right), z_{min} < z \le z_{max} = 200m \\ c_r(z = z_{min}), \qquad\qquad z \le z_{min} \end{cases}$

Mean wind velocity...........................$v_m(z) = c_r(z) \cdot v_b$

Mean wind pressure...........................$q_m(z) = c_r^2(z) \cdot q_b$

Wind turbulence. Peak values of wind velocity and wind pressure

Turbulence intensity...............................$I_v(z) = \begin{cases} \dfrac{\sqrt{\beta}}{2{,}5 \ln \dfrac{z}{z_0}}, z_{min} < z \le z_{max} = 200m \\ I_v(z = z_{min}), z \le z_{min} \end{cases}$

Close

Fig. 5 *a* – Results window.

Mean wind velocity................................ $v_m(z) = c_r(z) \cdot v_b$

Mean wind pressure................................ $q_m(z) = c_r^2(z) \cdot q_b$

Wind turbulence. Peak values of wind velocity and wind pressure

Turbulence intensity............................... $I_v(z) = \begin{cases} \dfrac{\sqrt{\beta}}{2,5\ln\dfrac{z}{z_0}}, z_{min} < z \le z_{max} = 200m \\ I_v(z = z_{min}), z \le z_{min} \end{cases}$

Gust factor, cg(z)
   - for wind velocity.............................. $c_{pv}(z) = 1 + g \cdot I_v(z)$

   - for wind pressure............................. $c_{pq}(z) = 1 + 2g \cdot I_v(z)$

Exposure factor, ce(z).......................... $c_e(z) = c_0 \cdot c_r(z) \cdot c_{pv}(z)$

Peak wind velocity............................... $v_p(z) = c_{pv}(z) \cdot v_m(z)$

Peak velocity pressure......................... $q_p(z) = c_{pq}(z) \cdot q_m(z)$

Introduce height $z =$	50	[m]					Evaluate	
I_v	$c_r(z)$	v_m	$c_{pv}(z)$	v_p	$c_r^2(z)$	q_m	$c_{pq}(z)$	q_p
0.18	1.09	33.92	1.64	55.75	1.2	0.72	2.29	1.65

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WIND ACTION

Wind pressure on surfaces

Wind pressure acting on external surfaces................ $w_e = c_{pe} \cdot q_p(z_e)$

Wind pressure acting on internal surfaces................ $w_i = c_{pi} \cdot q_p(z_i)$

Dynamic response coefficient...................... $c_d = 1.07$

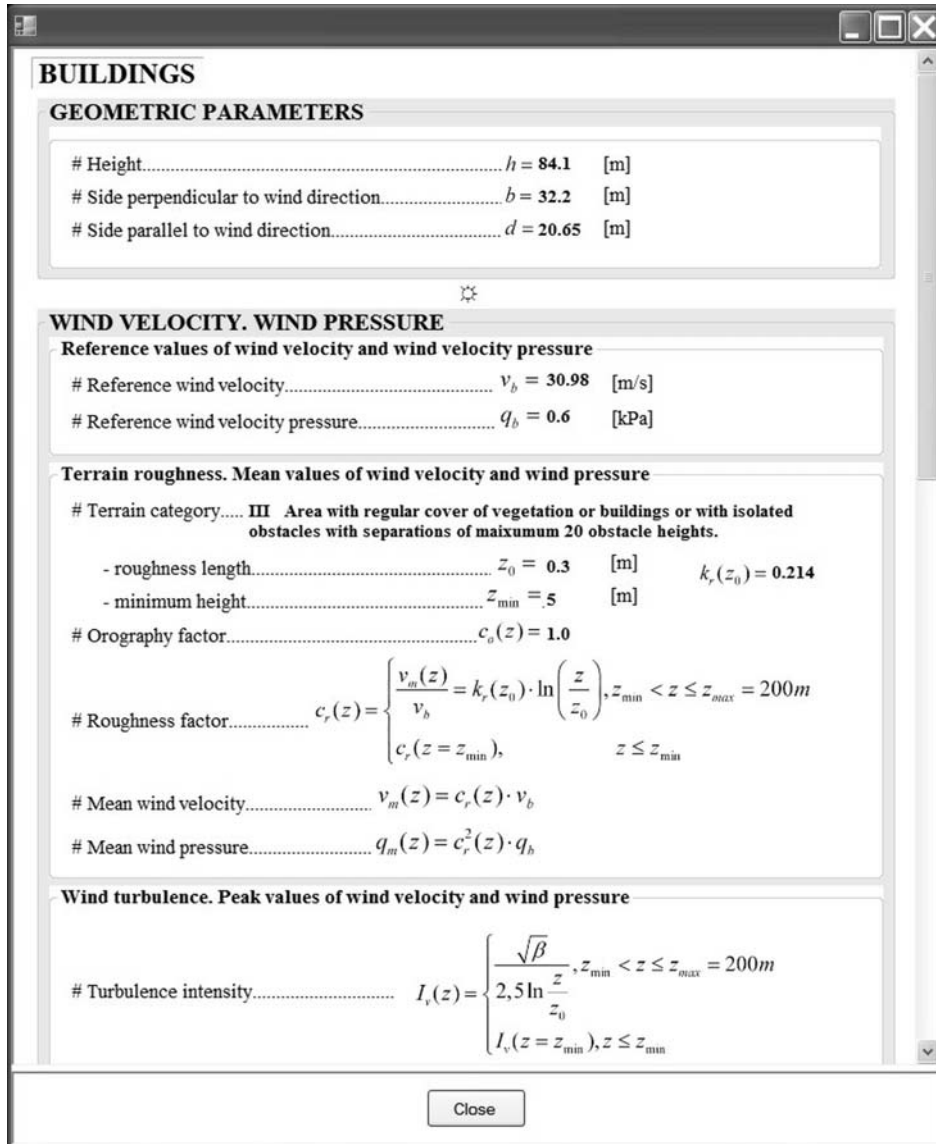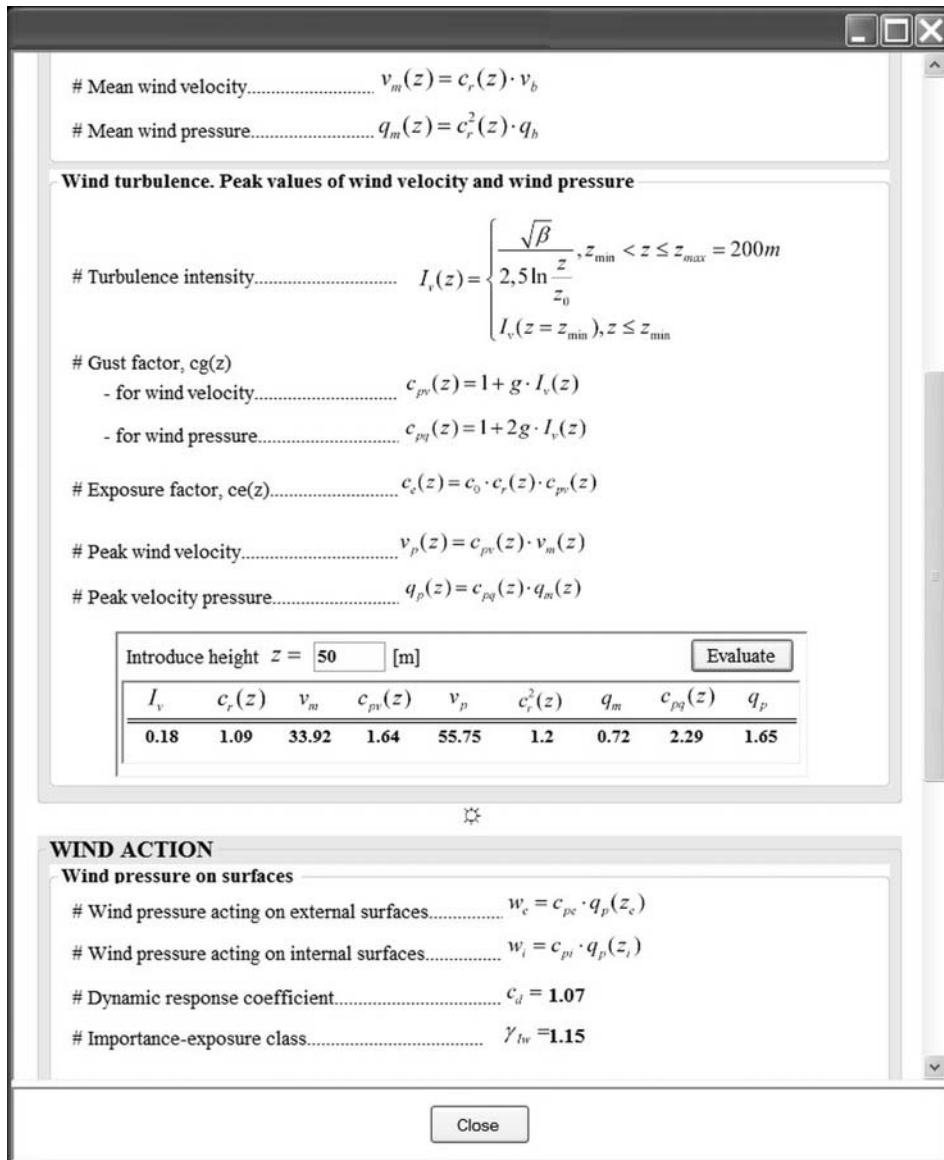# Importance-exposure class........................ $\gamma_{Iw} = 1.15$
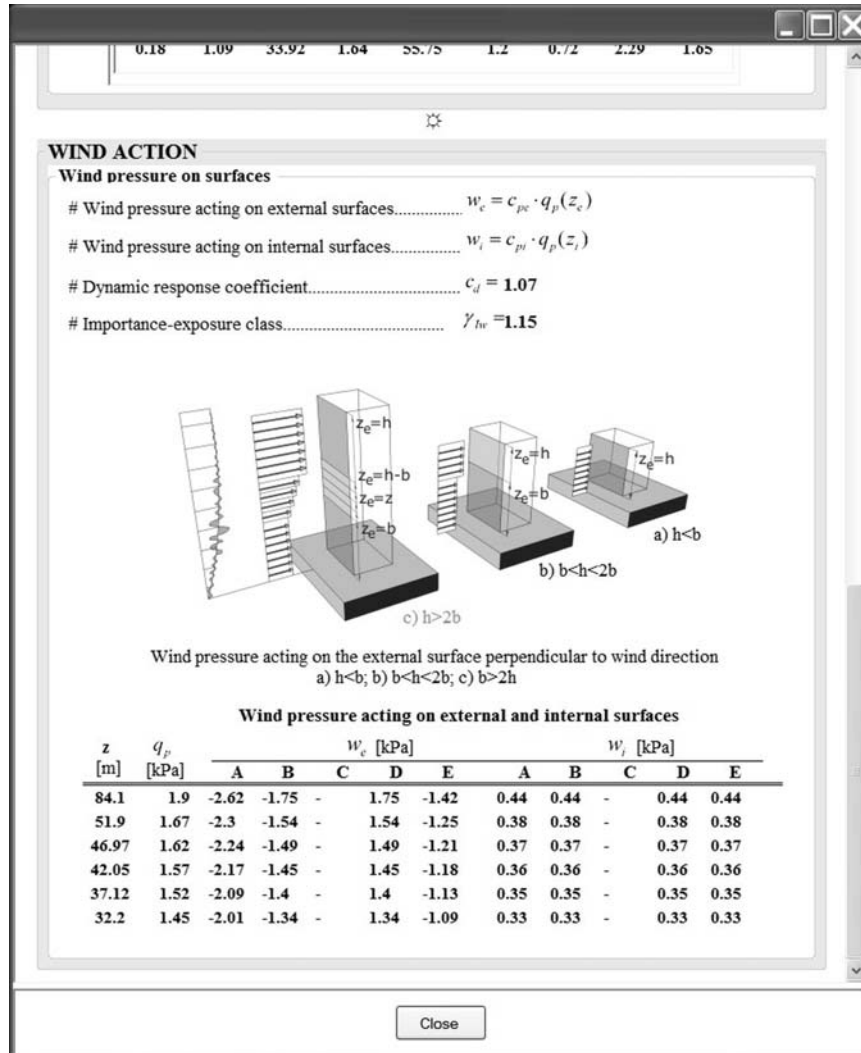
Close

Fig. 5 *b* – Results window (cont.).

Fig. 5 *c* – Results window (cont.)

4. Conclusions

In this paper a software application created and implemented by the author based on the Romanian wind code NP 082-2004 (revised in 2011) was introduced. The software computes the wind external and internal pressures on vertical walls of multistory and industrial buildings, wind pressures on roofs of industrial buildings and wind forces on steel lattice towers. Such applications are needed in order to render more accessible to the practicing engineer the method of computation of wind actions on buildings and structures comprised

in wind loading standards. The paper presents a practical design example for the evaluation of wind pressure on multistory buildings.

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SOFTWARE PENTRU EVALUAREA ACŢIUNII VÂNTULUI PE CONTRUCŢII
Partea I: Clădiri

(Rezumat)

Pentru construcţiile tipice inginereşti evaluarea acţiunii vântului se realizează respectând regulile incluse în codurile de proiectare la vânt. Prescripţiile de proiectare la vânt au evoluat de-a lungul timpului, această evoluţie fiind în concordanţă cu cercetările

analitice şi experimentale, cu creşterea numărului de înregistrări şi, totodată, cu dezvoltarea din punct de vedere al formulării matematice de care s-a bucurat domeniul ingineriei vântului în ultimele decenii. Prin urmare, au devenit mai puţin intuitive şi mai orientate către calculul automat. În aceste condiţii, în proiectarea curentă este nevoie de exemple de calcul precum şi de programe software specializate menite să uşureze aplicabilitatea metodelor de calcul utilizate în codurile de vânt.

        Se prezintă o aplicaţie software, creată şi implementată de către autor, pentru calculul la vânt al construcţiilor bazată pe codul românesc de vânt NP 082-2004 (revizuire 2011). Scopul aplicaţiei este de a evalua acţiunea vântului pe o serie de structuri, şi anume clădiri multietajate, hale industriale şi turnuri metalice cu zăbrele.