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REVEALING THE INFLUENCE OF WIND VORTEX SHEDDING ON THE STRESSED-STRAINED STATE OF STEEL TOWER STRUCTURES WITH SOLID CROSS-SECTION

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This work investigated the effect of vortex shedding during the action of wind on tower structures with a solid cross-section. Failure to take into account this influence, together with the manifestation of the phenomena of physical wear of structures during long-term operation, can lead to building accidents. The object of the research are tower structures with a solid cross-section, which are widely used in modern infrastructure – advertising pylons with a transparent advertising structure with a height of about 12, 22, 25 m, and a flagpole with a height of 48 m. The most frequent manifestations of oscillations according to the first natural frequency and shape have been considered, which occur even with moderate winds and when a large number of oscillation cycles occur. In this work, the number of oscillating cycles per year was determined and estimated based on the archive of meteorological observations. It was found that the number of oscillating cycles due to the action of wind excitation for the example of the structures under study is from 2.6 to 14.4 million per year, which requires the mandatory limitation of stresses in the parts of structures during the design to enable their durability. The magnitude of forces from vortex shedding for the studied structures ranges from 2.9 to 43.5 % of the forces caused by the influence of the frontal wind, depending on the height of the structure. Thus, it was found that the influence of vortex shedding is very insignificant for structures up to 12–15 m high and increases for structures 20 m and higher. Rational forms of the cross-sections of structures were established to reduce the influence of vortex shedding – these are cross-sections of a circular and a cross-section close to it. In a general formulation, these are sections for which peak stresses relative to forces in one plane fall into the neutral zone for stresses from forces in another plane. Recommendations have been also given on the simultaneous consideration of forces from the action of frontal wind on the structure and vortex shedding since both manifestations of wind action on tower structures cannot be separated

Keywords: tower structures, wind dynamics, vortex shedding, endurance calculation, natural frequency

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1. Introduction

The general tasks for ensuring structural safety of steel structures can be represented by the following directions:

a) loss of stability of structural systems taking into account the physical and geometric non-linear operation of both individual elements and systems as a whole [1–3];

b) peculiarities in the operation of supporting steel structures during earthquakes, taking into account possible additional effects from fires [4, 5]. Considering such phenomena as stress concentration, fatigue of steel under the action of long-term dynamic loads, researchers face urgent problems related to devising methods for assessing the safety of steel structures for various purposes, including nuclear power plants [5, 6].

An excitation vortex is a side phenomenon that occurs under the action of a frontal wind and involves the evolution of inertial oscillations of the structure in the direction transverse to the action of the wind. The development of this phenomenon is typical for tower structures, cylindrical, square, and similar cross-sections, in which the width and depth of the cross-section along the wind are the same. The paradox is that from the very beginning of the formation in the 1960s of modern scientific thought, theories, calculation models and schemes for calculating the wind load of buildings, the influence of the maximum frontal wind on buildings and structures was considered. The phenomenon of vortex shedding, which necessarily always appears simultaneously with the action of frontal wind in tower structures, was investigated and finally formulated in calculation models only in the early 2000s. Many tower structures were erected without taking into account vortex shedding and the influence of multi-cycle oscillations, and as a result, in recent years, there have been accidents on a local scale of chimneys with a height of 100...120 m, which were erected in the 1960s and 1970s. There are also accidents of smaller structures during operation under strong winds, which may indicate fatigue accumulation phenomena.

Therefore, determining the effect of wind loads and the conditions for the occurrence of vortex shedding is among the most urgent tasks of scientific research for vertical structural steel systems from the point of view of preventing the creation of conditions for their collapsing destruction.

2. Literature review and problem statement

The study of vortex shedding took place in parallel with the formation of the theory of calculation of structures for frontal wind, but the analytical methods of calculation were formulated relatively later. All studies were carried out on models in wind tunnels and involved determining the properties of the systems regarding their self-oscillations in the direction transverse to the action of the wind flow. The amplitude value of the deviations of the upper point of the system during the manifestations of various natural forms of oscillations was determined. After that, the differential equations of oscillation of the elastic axis of the rod at the corresponding natural frequencies were derived and solved for the given conditions. The history of research is given in work [7], on the basis of which calculation analytical methods were developed, implemented in Eurocode ENV 1991-2-4. In particular, in ENV 1991-2-4, two basic methods of calculation for vortex shedding are implemented – for tower structures of solid section and lattice, which are used both for design and for scientific research.

Modern theoretical research continues. For example, in [8], the results of the study of the oscillation of cylindrical rods in the wind flow with parameters different from those previously studied are reported. The authors studied systems with a height-to-diameter ratio of 10 in the Reynolds number ranges from 3.6×10^4 to 3.26×10^5, which often correspond in terms of parameters to the resistances of wind power plants. Models made of propylene were tested using the method of blowing in a wind tunnel with the detection of the effect of nonlinearity in the parameters of amplitude deviations. However, the research is still theoretical and needs development for implementation for real structures. In work [9], research is conducted on the mutual influence of two adjacent structures with a height of 570 m on the manifestation of wind flows and the development of vortex shedding. A positive effect of mutual interference and quenching of wind flows was found when the relative distance between buildings is less than 1.0 and the mutual influence of vortex shedding is dampened. When the relative distance increases to 2.0, the interference effect disappears, and each structure works on the wind load as a separate one. The disadvantage is that it is difficult or almost impossible to confirm this in practice due to the scale of analytically studied structures.

There are also applied studies on the influence of vortex shedding aimed at calculating and predicting the safe operation of specific, often individual, and unique buildings and structures.

Thus, in [10], the support nodes of electric lighting masts were studied for durability by the finite element method, namely, the variable parameters were the thickness of the wall of the body of the structure and the support base, the optimal indicators of the ratio of thicknesses were found, and the durability assessment was carried out according to Eurocode methods. The effect of changing the thickness of building elements on endurance is indicated in the work, but the cross-section not reinforced with ribs at the connection point with the base of the columns is considered, and the problem of the distribution of the stress level and the number of oscillation cycles during the life of the building remains unsolved. In [11], the results of research on the support of a power transmission line with a cylindrical cross-section in a wind tunnel in different wind directions and in the presence of an angle of support to the wind are given. It was found that when the structure is tilted to the direction of the wind, the effect of the vortex shedding disappears. It was confirmed that the effect of the wind on the amplitude of oscillations in the direction transverse to the wind is greater than the frontal dynamic response of the structure to the wind. It was found that at slopes higher than 10°, the intensity of the effect of vortex shedding fades, thus the effect of vortex shedding was clarified for structures inclined to the wind. In [12], a study of the endurance of the unique 88 m Lotus tower in the capital of Sri Lanka was carried out with by blowing its model in a wind tunnel. An assessment of the formation of cracks in its reinforced concrete structures was performed and recommendations for further safe operation were compiled. The simultaneous effect of frontal wind and vortex shedding was taken into account. But from the point of view of the influence of wind load, the problem of the real spectrum of winds acting on the structure remains unsolved, and calculations are made with approximation. In work [13], fatigue assessment of structures of a telecommunications 200 m lattice tower of variable cross-section height based on Eurocode methods was performed. Critical zones for lattice structures of this form under the action of vortex shedding were determined. The critical elements in which fatigue can occur for a given shape of the structure when oscillations from vortex shedding occur at the first natural frequency were determined, and the number of endurance cycles for these elements was determined. At the same time, the method of determining endurance over time in relation to specific climatic conditions remains unresolved. Paper [14] examines the effect of vortex shedding on the fatigue of structures of wind power plants of a rational form from the point of view of minimizing the effects of vortex shedding fatigue on them and features associated with various wind conditions. Effective forms of wind power structures are proposed in order to minimize the effect of vortex shedding. In work [15], calculations are carried out on the vortex shedding and fatigue of the parts of the solid-film lighting support of the stadium with a height of 37.9 m, implemented in Germany. The calculation of vortex shedding according to the first and second natural form of oscillations according to the Eurocode method, which can be manifested in the climatic conditions of the location of the building, is given. Calculations confirm that oscillations from vortex shedding by the second form of natural oscillations cause the appearance of resonant maximum forces. The maximum number of oscillating cycles, which causes fatigue of building elements from vortex shedding, is also determined. At the same time, the simultaneous influence of vortex shedding and frontal wind is not taken into account, and the potential number of oscillation cycles during the life of the structure under the real conditions of the construction site is not determined. Work [16] provides an overview of the use of devices for extinguishing vortex breakdowns on structures that reduce or prevent the influence of this factor. Such devices include propeller blades and petals fixed to the structure, which prevent the breakdown of vortices, but at the same time increase the aerodynamic resistance of the structure. The disadvantage of the available research results is that individual designs were previously studied in a liquid stream and their effectiveness is reduced in air. The authors draw attention to the fact that research is ongoing, and these devices should be especially effective for wind energy installations. In work [17], the effect of vortex shedding on a 96-m blade of wind turbines from a turbulent flow, which includes not only the action of the external wind, but also the effect of wind turbulence from the rotation of the turbine blades, is studied by the method of mathematical modeling. Rational criteria for the shape and angle of rotation of the blade in relation to the action of the wind have been established, however, the question of how far the results of these studies can be applied to similar structures with other geometric dimensions has not been resolved.

Therefore, most modern research is of applied nature for specific unique structures and their details. The nature of change in the effect of vortex shedding on buildings with increasing height remains undetermined. This especially applies to structures of relatively low height up to 10...20 m, which are widely used in modern infrastructure and were often designed earlier without taking into account the effect of vortex shedding. In addition, the problem of determining the number of oscillating cycles from vortex shedding and the actual quantitative distribution of the stress spectrum in the building elements as a whole during operation for the purpose of calculating their endurance has not been solved.

3. The aim and objectives of the study

The purpose of our study is to identify patterns of the stressed-strained state in the structural elements under the simultaneous action of the frontal wind, taking into account the dynamic response and vortex shedding for tower structures of solid section of different heights and stiffness. This will make it possible to compile recommendations for the design of tower structures taking into account the effective shape of the cross-section to absorb forces from the simultaneous action of frontal wind and vortex shedding.

In order to fulfill the purpose of the research, it is necessary to solve the following tasks:

– to determine the natural frequencies, critical speeds, and forms of natural oscillations of structures;

– to perform dynamic calculation of structures for frontal wind and for structure oscillations due to vortex shedding according to available methods and schemes and to conduct an analysis of the nature of the effect of vortex shedding on structures of different heights;

– to analyze the archive of meteorological data from available sources and perform a sample for the year regarding the distribution of wind speed and their duration. This will make it possible to determine the approximate number of oscillation cycles per year, during the life cycle, to establish the main criteria for calculating structures for endurance;

– to establish criteria for rational shaping of cross-sections and nodes and parts of structures, which make it possible to minimize the influence of vortex shedding.

4. The study materials and methods

There is no direct and unequivocal relationship between the parameters that affect the nature of the manifestation of vortex shedding, which prevents the creation of a certain idealized model. Therefore, it was decided to consider four implemented designs and try to make a generalization. Four tower structures that are widely used in modern infrastructure were chosen as the objects of the study – these are three «MacDonald's» advertising pylons with a corporate sign with a total height of 11,355, 22, 25,572 m, and a flagpole with a height of 48 m. All structures have been implemented.

Structure 1. Pylon with a total height of 11.355 mm. It is depicted in Fig. 1. The structure is single-section, consists of pipes of round section 325×6, height 9.04 m, on which there is a company sign with illumination weighing about 0.5 T.

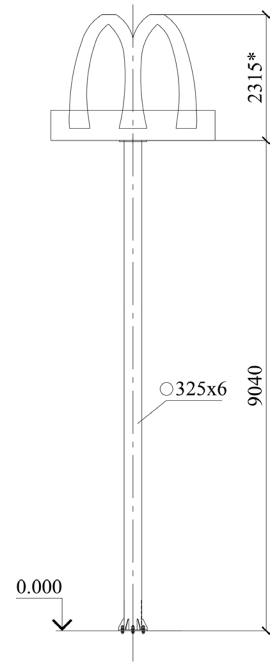

Fig. 1. Structure 1 — a pylon with a height of 11.355 m

Structure 2. A pylon with a total height of 22 mm. It is depicted in Fig. 2. The building is structurally two-sectioned, assembled on flanges with bolts, but has three levels of stiffness. The lower part with a height of 7.5 m is a 530×8 steel pipe, reinforced with four 24 channels, the middle part is a 530×8 pipe, the upper part is a 325×6 pipe from 12 m to the brand mark. The height to the structure of the trademark is 18.365 m. The weight of the trademark is 1 ton.

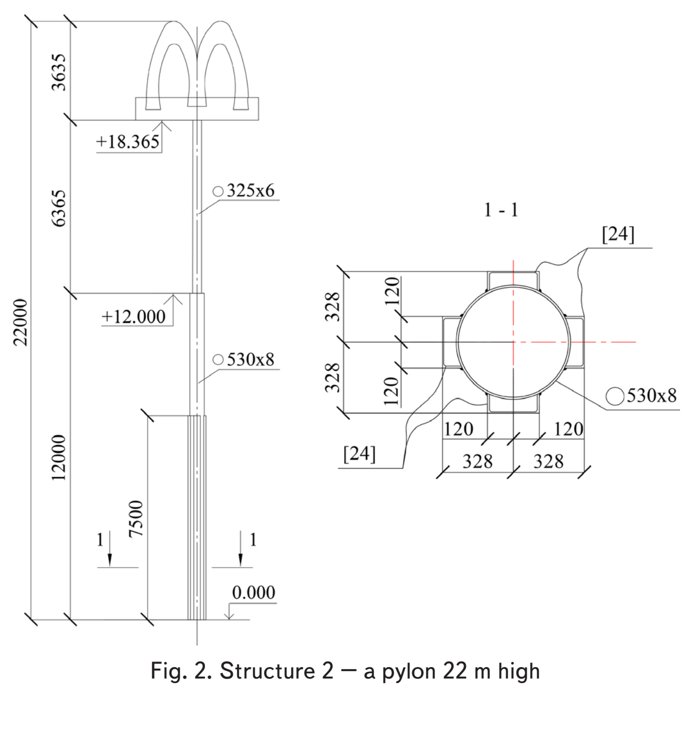

Fig. 2. Structure 2 — a pylon 22 m high

Structure 3. A pylon with a total height of 25 m. It consists of two sections of a folded cross-section. The lower section with a height of 12.046 m consists of a steel pipe 530×8 reinforced with four channels 24, the upper section consists of channels 30 on slats reinforced with channels 24 (Fig. 3). The height to the structure of the trademark is 21.0 m. The weight of the trademark is 1 T.

Structure 4. The flagpole with a height of 48 m, located in the center of the composition of the «Stars and Constellations» fountain, was built in 1964 in Kyiv as part of the landscaping composition of the Palace of Children and Youth. The structure of variable section, consisting of three welded brands, is lined with an aluminum facade system. The structural scheme is shown in Fig. 4.

Since the oscillations from vortex shedding are inertial in nature, the main hypothesis of the research assumes that the influence of vortex shedding will increase with the height of the building. At the same time, the frequencies of natural oscillations change, the mass increases according to the length and stiffness of the structure, and the arm of the center of mass of the entire structure increases. In addition, the manifestation of vortex shedding most often occurs according to the first eigenform of oscillations with a very large number of cycles.

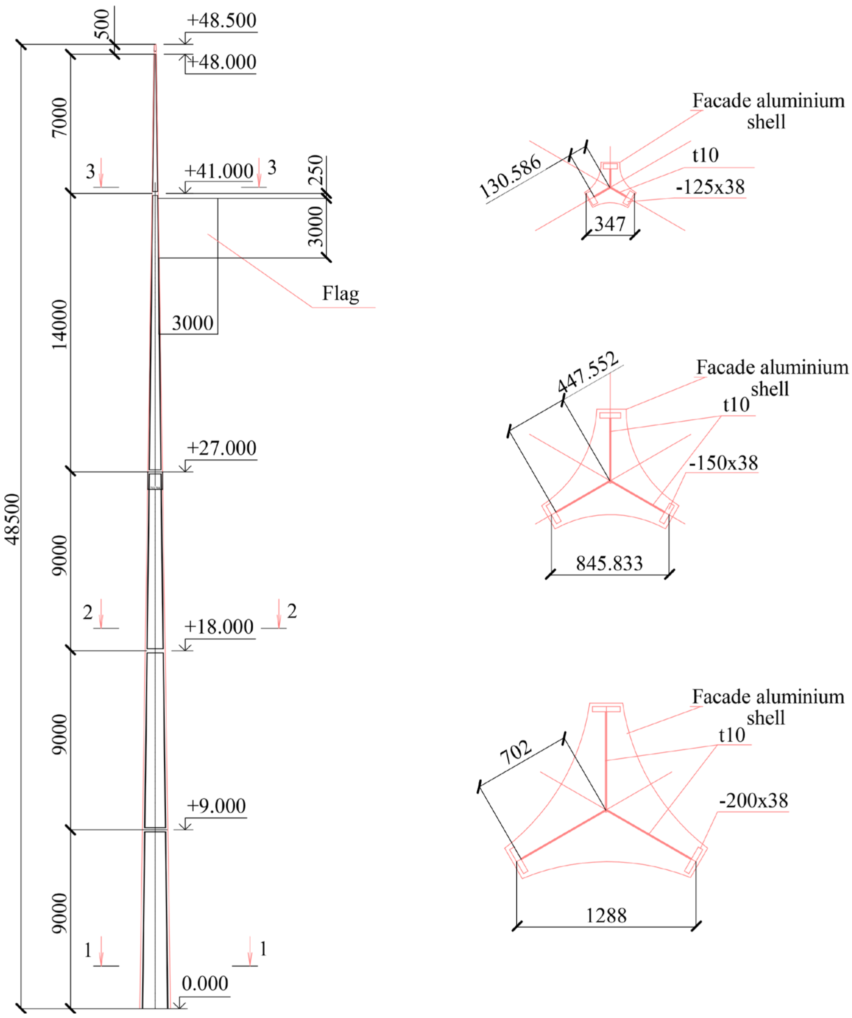

Fig. 4. Flagpole design — structure 4

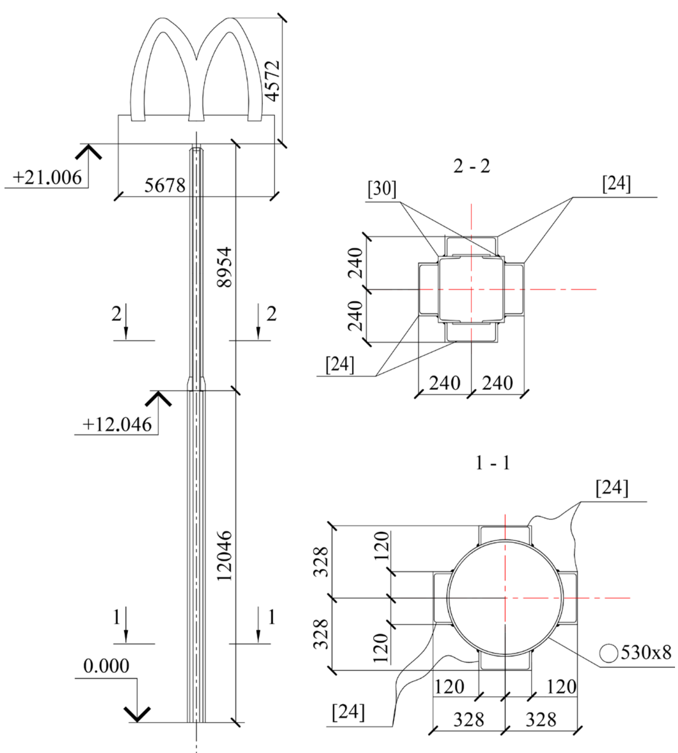

Fig. 3. Structure 3 — a 25 m high pylon

Also, the manifestation of vortex shedding always occurs simultaneously with the manifestation of frontal wind action. It is necessary to establish criteria regarding the need to limit the ultimate stresses in structural elements under conditions of endurance under multi-cyclic dynamic wind action or perform a fatigue calculation taking into account various stress spectra acting in structural elements. This will make it possible to analyze the endurance of existing structures in operation.

All tower structures of the type of pylons with a company sign and flagpoles have three main characteristic forms of natural oscillations (Fig. 5).

During the study, the critical speeds and, accordingly, the forms of oscillations during vortex shedding were determined for each of the studied structures, which are real in the city of Kyiv.

Determination of natural frequencies of oscillations was carried out by modal analysis using the SCAD software package (License No. 19782, transferred to the Kyiv National University of Civil Engineering and Architecture on 05/13/2024).

In general, in the study, more attention was paid to oscillations according to the first form, which do not give maximum effort, but according to the previous hypothesis, they have a very high repeatability, which was proven in the study.

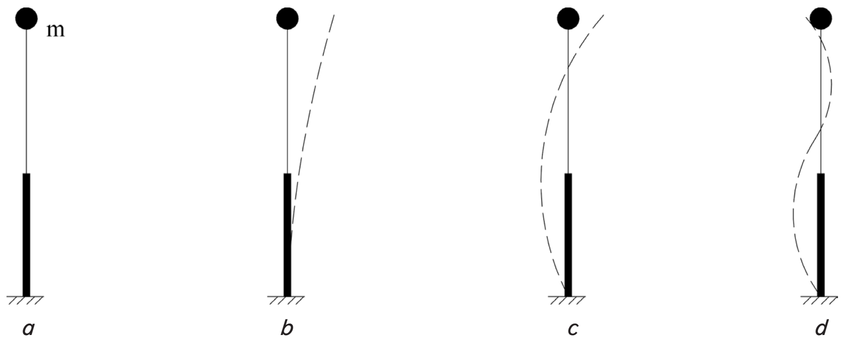

Fig. 5. Calculation scheme and forms of self-oscillations of tower structures: *a* – calculation scheme of the structure; *b* – the first form of self-oscillations; *c* – the second form of self-oscillations; *d* – the third form of self-oscillations

The critical speed at which the phenomenon of vortex shedding begins (Fig. 6) is determined from the formula:

$$V_{cr,i} = \frac{n_i d}{s_t}, \quad (1)$$

where n_i is the natural vibration frequency of the structure, *d* is the width of the structure, S_t is the Strouhal number.

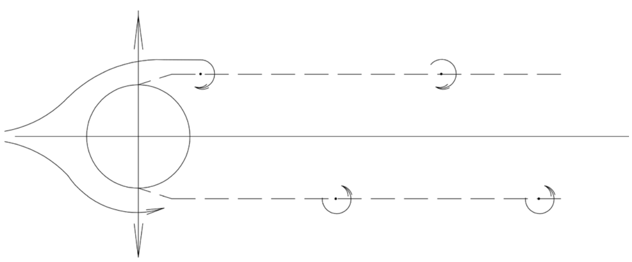

Fig. 6. Scheme of formation of vortex shedding and Karman track

Calculation of structures for frontal wind was carried out according to the Eurocode for the city of Kyiv.

The calculation of vortex shedding was performed according to the equivalent calculation schemes of EN 1991-1-4:2005. So, first, the amplitude of aeroelastic deviations of the upper point of the structure is determined according to the specified procedure:

$$\frac{y_{F,\max}}{b} = \frac{1}{St^2} \cdot \frac{1}{S_c} \cdot K \cdot K_w \cdot C_{lat}, \quad (2)$$

where $y_{F,\max}$ is the amplitude of transverse oscillations in the air flow; S_t is the Strouhal number; S_c is the Scruton number, which determines the tendency and contribution of the structure to oscillation in an aeroelastic environment; *B* is the width of the structure exposed to the wind; *K* is the tabular coefficient of the form of oscillations, which is taken depending on the form of oscillations. In particular, for the first form, it is accepted as 0.13; K_w is the correlation coefficient determined by geometric parameters according to the formulas from Appendix E of EN 1991-1-4:2005; C_{lat} is the coefficient of action of the lateral force, which for round sections is taken according to the Reynolds number charts, for rectangular – 1.1.

Subsequently, the calculation is performed according to simplified schemes with the determination of the linear force:

$$F_w(s) = m(s) \cdot (2 \cdot \pi \cdot n_{i,y})^2 \cdot \Phi_{i,y}(s) \cdot y_{F,\max}, \quad (3)$$

$m(s)$ is the distributed mass of the structure; $n_{i,y}$ – natural frequency of oscillations; $\Phi_{i,y(s)}$ is a function of the shape of natural oscillations.

Analysis of wind speeds and duration of action was taken from the website of the weather bot archive [18], which contains shorthand wind speeds with an interval of 30 minutes from 2011 to 2023. The year 2011 was taken for analysis in order to establish the primary qualitative distribution of wind speeds and duration of their action. The direction of the wind for vortex shedding is of secondary importance since the wind action is distributed on the main planes of the building with oscillations relative to the main axes of inertia. Oscillations from vortex shedding have a steady character, provided that the wind speed exceeds the critical one for this form of oscillations. The number of oscillation cycles for each structure can be determined from the following formula:

$$N_i = \frac{\sum t}{T_i}, \quad (4)$$

where N_i is the number of oscillation cycles at the *i*-th natural frequency of oscillations, $\sum t$ is the total time of winds with a speed exceeding the critical one for the *i*-th form, T_i is the period of oscillations at the *i*-th natural frequency.

Based on the obtained data, an analysis is performed to determine the stress limit when calculating structures for endurance in the event that the number of oscillation cycles during the life cycle of the structure exceeds 10^5 according to the national standards of Ukraine or $2 \cdot 10^6$ according to the Eurocode.

For the analysis of the effect of vortex shedding on the structure, the maximum forces from the frontal wind were taken as a comparative basis. The frontal wind calculation is performed according to EN 1991-1-4:2005 for terrain with a maximum average wind of 25 m/s. Structures 1, 2, 3 were calculated for area III, and structure 4 for area IV according to real conditions.

All calculation schemes with actual stiffnesses were set as rod systems using the finite element method in SCAD, in which the dynamic characteristics of structures were determined – natural frequencies, centers of mass, internal forces. The bending moment in the resistance of each structure from the frontal wind and vortex shedding was taken as the main determining value.

Analysis of the effect of vortex shedding on the stressed state of the main supporting cross-section of the structure was carried out according to the formula of normal stresses from the theory of elasticity:

$$\sigma = -\frac{N}{A} \pm \frac{M_x}{I_x} y \pm \frac{M_y}{I_y} x, \quad (5)$$

where, respectively, the normal stresses at different points are determined in x,y coordinates under the action of forces N, M_x, M_y, for the cross-section with area A, and, respectively, by the moments of inertia relative to the main axes of inertia I_x, I_y.

5. Results of investigating the effect of vortex shedding on structures

5. 1. Eigenfrequencies, critical speeds, and forms of vibrations of buildings

For each of the four structures, the natural oscillation frequencies and critical velocities were calculated, and the conditions for the onset of the effect of vortex shedding on the structure were established; the characteristic form of oscillations is shown in Fig. 5. The results of our calculations are given in Tables 1–4.

Table 1

Results of calculating the natural frequencies of oscillations and critical speeds of vortex shedding for structure 1 (the second and third frequencies are outside the resonant limits and are not taken into account by SCAD)

Oscillation frequency, Hz	Critical velocity, m/s	The form of natural oscillations in which vortex shedding occurs
1.2	3.54	Form 1

Table 2

Results of calculating the natural frequencies of oscillations and critical speeds of vortex shedding for structure 2

Oscillation frequency, Hz	Critical velocity, m/s	The form of natural oscillations in which vortex shedding occurs
1.13	5.44	Form 1
6.4	30.8	Doesn't occur
20.449	98.5	Doesn't occur

Table 3

Results of calculating the natural frequencies of oscillations and critical speeds of vortex shedding for structure 3

Oscillation frequency, Hz	Critical velocity, m/s	The form of natural oscillations in which vortex shedding occurs
0.9751	5.82	Form 1
5.39	32	Doesn't occur
16.61	99.2	Doesn't occur

Table 4

Results of calculating the natural frequencies of oscillations and critical speeds of vortex shedding for structure 4

Oscillation frequency, Hz	Critical velocity, m/s	The form of natural oscillations in which vortex shedding occurs
0.679	5.54	Form 1
2.09	17.1	Form 2*
3.71	30.5	Doesn't occur

*Note: * – vortex shedding may occur in rare cases since the recurrence of the wind of 17 m/s is once every few years; the force effect from it can exceed the effect from the frontal win, but this aspect was not considered in the current study*

For all structures, the manifestation of vortex shedding at the first natural frequency is the most likely and is manifested already in weak and moderate wind.

5. 2. Calculation of structures for frontal wind and vortex shedding

The results of our calculation of moments of resistance from the frontal wind and vortex shedding according to EN 1991-1-4:2005 are given in Table 5.

Table 5

Results of calculating the structures

Parameter	Structure under consideration			
	Structure 1	Structure 2	Structure 3	Structure 4
Moment in resistance from frontal wind M, kNm	47.4	323.9	483.0	857.7
Moment in resistance from vortex shedding, M_v, kNm	1.404	43.6	75.4	373.25
$M_v/M{\cdot}100$ %	2.9	13.4	15.6	43.5

As the height of the structure increases, the wind load, force, and rigidity of the structure increases. As a result, the calculated forces from the frontal wind also increase. As you can see, with the increase in the height of the building, the influence of the vortex shedding also increases non-linearly.

5. 3. Analysis of meteorological data and determination of the number of oscillating cycles of buildings per year

Analysis of wind speeds and time of action according to the weather archive for a randomly selected year of 2011 from [18] is illustrated in Tables 6, 7.

According to the results of our analysis of the action of winds according to formula (4), the approximate number of oscillation cycles per year of the structure due to the action of the vortex shedding according to the first natural frequency was determined, which is:

– $14.4{\cdot}10^6$ cycles for structure 1;
– $4.3{\cdot}10^6$ cycles for structure 2;
– $3.4{\cdot}10^6$ cycles for structure 3;
– $2.{\cdot}10^6$ cycles for structure 4.

Table 6

Duration of action of winds with supercritical speed in 2011

Month	Duration of winds with a speed higher than 4 m/s, s	Duration of winds with a speed higher than 6 m/s, s
January	802,800	304,200
February	1,643,600	556,200
March	1,072,680	304,800
April	1,065,600	450,000
May	906,300	307,800
June	1,089,000	286,200
July	581,400	91,800
August	751,200	178,200
September	745,200	300,600
October	824,400	217,800
November	1,063,800	379,800
December	1,863,000	415,800
Total:	12,408,980	3,793,200

Table 7

Duration and time distribution of winds in 2011 with a speed of more than 4 m/s

Wind speed, m/s	Duration of action per year, s	Percentage of total time per year	Proportion of maximum load, converted to maximum average velocity 25 m/s, $(V_i/V_{max})^2$
4, 5	8,615,780	27.32	0.033
6	1,802,400	5.72	0.058
7	871,200	2.76	0.078
8	469,800	1.49	0.1
9	286,200	0.91	0.13
10	154,800	0.49	0.16
11	59,400	0.19	0.19
12	30,600	0.10	0.23
13	16,200	0.05	0.27
14	5,400	0.02	0.31
15	3,600	0.01	0.36

With such a number of cycles per year, it no longer makes sense to determine the number of cycles during the entire service life. Under such conditions, it is necessary to set stress limits in calculations to the level of endurance stress according to national or international standards. When calculating according to EN 1993-1-9:2005, it is necessary to take into account the endurance curves in Fig. 7.1 EN 1993-1-9:2005 taking into account the planned service life of the structure.

5. 4. Criteria for the rational shaping of cross-sections of tower structures with a continuous section

The calculation of normal stresses in the main cross-section of the structures was carried out and the effect of vortex shedding was estimated according to formula (5). For structure 1, the vortex shedding has almost no effect as it is 2.9 % of the frontal wind forces. For structures 2, 3, an approximately identical pattern appears, therefore, for clarity, the calculations for structure 3 are displayed. Fig. 7 shows a typical diagram of normal stresses taking into account the influence of vortex shedding for structure 3 with the following calculated characteristics of the support cross-section: $A=253.59$ cm^2, $I_x=I_y=108141.79$ cm^4.

Due to the fact that the forces act in mutually perpendicular directions and there are no points where the peak stress values coincide with the circular and close to it cross-sections, the influence of the vortex shedding is rather insignificant. For structure 3, the stress increase is 6 %.

Fig. 8 shows a typical diagram of normal stresses taking into account the influence of vortex shedding for structure 4 with the following calculated characteristics of the support cross-section: $A=438.9$ cm^2, $I_x=I_y=778834.5$ cm^4. As a result of the specificity of the cross-section, in certain zones, taking into account the stresses from vortex shedding, the stresses increase by 60 %, while in the beam that enters the neutral zone, the stresses change by 6 %. But at the same time, with different combinations of stresses during oscillations and the action of the wind from different sides, the redistribution of stresses in the beams of the cross-section occurs within 6 %.

Thus, for all structures considered in this study, the influence of vortex shedding due to the specificity of cross sections is not significant, despite even a relatively high level of forces for structure 4. This is explained by the fact that the peak stresses from forces in one direction fall on the neutral zone for stresses from forces in the perpendicular direction. In this regard, rectangular cross-sections, where the peak stress values in two planes simultaneously fall on the corner points, will be disadvantageous from the point of view of the effect of vortex shedding.

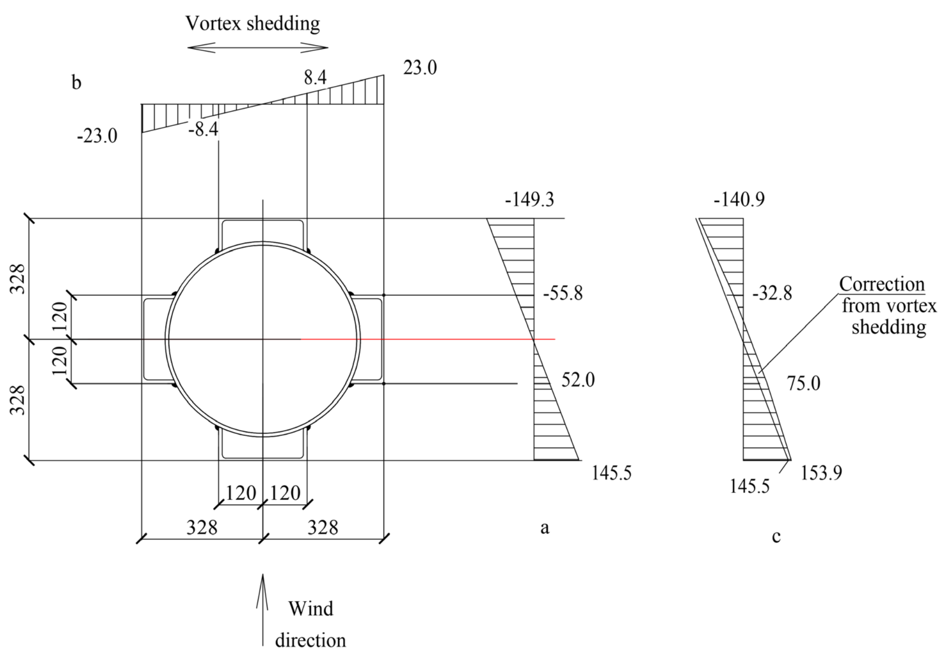

Fig. 7. Diagrams of normal stresses in the support cross-section for structure 3: *a* – normal stresses from the frontal wind, MPa; *b* – normal stresses from vortex shedding for one of the amplitude deviations, MPa; *c* – summary diagram, MPa

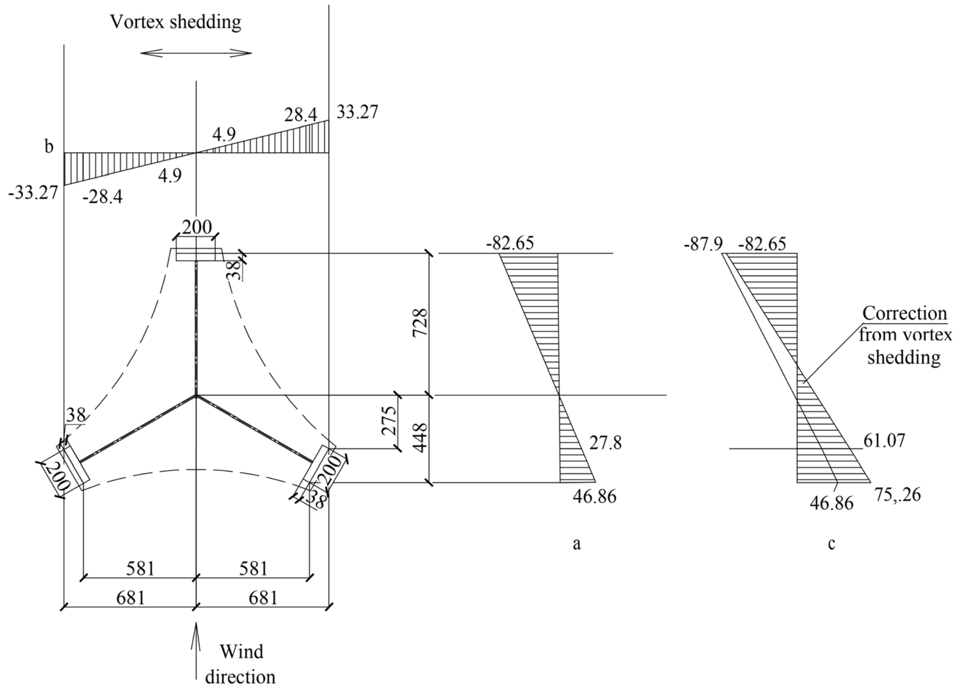

Fig. 8. Diagrams of normal stresses in the support cross-section for structure 4: *a* – normal stresses from the frontal wind, MPa; *b* – normal stresses from vortex shedding for one of the amplitude deviations, MPa; *c* – summary diagram for the combination of amplitudes that gives the maximum stress values, MPa

6. Discussion of results of investigating the effect of vortex shedding on the stressed-strained state of tower structures

After calculating critical velocities according to formula (1), the main hypothesis was confirmed, according to which, under natural and climatic conditions, in which the maximum average wind speed does not exceed 25 m/s, oscillations of structures occur according to the first natural form and frequency of oscillations. Such a trend may persist in other climatic zones, provided that the average wind speed does not exceed 30 m/s. In the case of an excess for structures 2 and 3, vortex shedding should be considered according to the second form of self-oscillations in accordance with the detected critical velocities. The second form may appear for structure 4 at an average wind speed of 17.1 m/s, which may occur once every few years. Unlike the first-form oscillations, the second form can cause forces greater than the forces from the frontal wind and requires separate consideration. Similarly, in work [15], a similar analysis of the construction of an electric lighting pole with a height of 37.9 m is given, in which the second form of oscillations can be manifested at a wind speed of 11.47 m/s, which, as also shown, gives significant forces in the system. Moreover, the probability of its occurrence and repeatability can be significantly higher than for structure 4, due to the lower critical speed. The question of the manifestation of the second form of self-oscillations largely depends on the height, geometric, stiffness, and frequency parameters, architectural form of a specific building and cannot be predicted in advance when choosing system parameters at the design stage. Oscillations from vortex shedding at the first natural frequency for the structures under study occur already under the influence of weak and moderate winds from 3.54 m/s for structure 1 to 5.82 m/s for structure 4.

An important factor for the critical speed is the width along the front of the wind action of the structure. So, hypothetically, while maintaining the frequency and stiffness parameters of the building, the critical wind speed can be changed by arranging around the building, for example, a decorative shell of a larger diameter. The oscillations themselves according to the first form of self-oscillations do not give forces exceeding the dynamic response under the action of the frontal wind, but they have a very high number of cycles and affect the durability of the structure.

The calculation of the structures for the maximum frontal wind was performed in order to assess the simultaneous effect of the frontal wind and vortex shedding on the structures. In addition, as already mentioned, the method of comparing forces from vortex shedding to forces from the action of the maximum frontal wind is indicative (Table 5). The forces from the frontal wind increase non-linearly with the increase in the height of the structure due to the increase in the wind pressure according to the logarithmic function and the increase in the support moment in a quadratic dependence on the height of the structure. At the same time, the calculation of vortex shedding based on the first form of self-oscillations showed that the bending moments in the foundations of structures from vortex shedding make up from 2.9 to 43.5 % of the moments from the maximum frontal wind with an increase in the percentage along the height.

According to the results of our studies, it can be concluded that the influence of vortex shedding on structures up to 12...15 m high is minimal. The majority of structures used in modern infrastructure have these geometric parameters – advertising ceilings, small flagpoles, street lighting poles, contact power grids of electric transport, etc. are precisely within these limits in terms of geometry and corresponding rigidity. Therefore, the effect of vortex shedding on them is very insignificant, and even this factor can be neglected. At higher altitudes, the influence of vortex shedding increases and requires careful analysis during design.

In order to determine the potential number of oscillating cycles of buildings, an analysis of a sample of winds for the city of Kyiv from the weather transcript for the arbitrarily selected year 2011 was carried out (Tables 6, 7). The total duration of the action of winds with supercritical wind speed showed that for all structures the number of oscillation cycles is from 2.6 to $14.4 \cdot 10^6$ per year. The most intense fluctuations in the number of cycles occur for structure 1, for which the critical speed of vortex shedding is close to the average wind speed in the given area. At first glance, the study of a sample of winds for one random year is not indicative, it requires further research on other years and statistical processing. However, the approximate number of cycles over 1 million per year indicates that it is necessary to take into account stress limitations in structural parts from the conditions of endurance calculations. This confirmed the hypothesis of a very large number of oscillation cycles during vortex shedding at the first natural oscillation frequency.

For the smallest building among the investigated with a height of about 12 m (structure 1), the forces from the vortex shedding make up 2.9 % of the forces of the frontal wind and do not affect the endurance in any way. Buildings with a height of more than 15 m require a serious analysis and limitation of stresses to the value of the endurance limit according to national or international standards. Thus, provided that the entire possible range of stresses at different wind speeds does not exceed the endurance limit, the phenomena associated with mechanical fatigue do not occur with an unlimited number of cycles. In the national norms of Ukraine, this limit is set at more than 10^5 dynamic cycles during the service life of the structure, in Eurocode EN 1993-1-9 it is $2 \cdot 10^6$ cycles. For these structures for the main cross-section according to the national standards of Ukraine, when using S235 steel, the endurance limit for sign-changing cyclic oscillations is 64.95 MPa (27 % of the strength limit), and for high-strength S590 steel, the endurance limit is 122.95 MPa (20 % of the strength limit). When calculating according to EN 1993-1-9, it is necessary to use the endurance curves in Fig. 7.1. EN 1993-1-9, taking into account the service life of the structure in the range of several decades and accepting the value of the endurance limit for the range from 10^7 to 10^8 cycles or even more. Observance of this factor requires close attention, it also applies to individual nodes and parts – welds, anchor bolts, etc.

When analyzing oscillations by the second eigenform, a separate serious question arises that needs to be resolved from the point of view of repeatability of cycles. The forces from vortex shedding by the second form of self-oscillations can cause mechanical resonance and exceed the forces from the frontal wind. Since they occur at higher wind speeds, it is necessary to know their repeatability. An analysis of the winds operating in Kyiv in 2011 (Table 7) showed that wind speeds above 15 m/s did not occur that year. Winds over 15 m/s with the maximum set indicator for the area of 25 m/s appear several times every 10 years, therefore, establishing the time and duration of the manifestation of wind speed over 17.1 m/s for structure 4 is possible only with careful and long-term instrumental observations in the to the construction site. The maximum calculated winds occur on average no less than once every 50 years. Here, it is also possible to limit the stresses in the system to the limit of endurance, but this can lead to significant overspending of material and an increase in the cost of the structure, especially when it fulfills an exclusively functional value without the requirements of aesthetics. Therefore, for buildings with a height of more than 20...30 m, in which the manifestation of oscillations according to the second and third forms is possible, it may be relevant to install technical means for damping vortex shedding according to [16] – pendulum dampers, spiral blades, spikes, etc.

Analysis of the influence of the simultaneous action of the wind on the stress-deformed state of the cross-section of the base and parts of the structure revealed that everything depends on the shape of the cross-section. In round and close sections, where bending moments act in mutually perpendicular directions, the peak values of stresses along one axis fall on neutral values from forces in the other direction, the influence of vortex shedding is not significant. In Fig. 7, it was shown that for structure 3, the increase in boundary stresses when taking into account the vortex shedding increases by only 6 %, while the share of forces from vortex shedding is 15.6 % of the forces from the frontal wind for this structure. For structure 4, which has a cross-section in the form of three beams, there is a redistribution of forces between the beams, as a result of which the peak stress values, taking into account the vortex shedding, also increase within 6 %. In particular, also for structures 3 and 4, it turned out that the stresses in the systems are within the limits of endurance since the cross-sections of the structures were taken under the conditions of compliance with normative deflections and movements and have reserves, including due to the discreteness of the assortment.

At the same time, for conventional rectangular cross-sections, peak stresses arise from mutually perpendicular forces that are applied at the edge points. Therefore, the forces from the vortex shedding have a greater effect on structures that are rectangular in plan, which can also be latticed in the form of spatial trusses, but on the condition that they have a continuous enclosing structure (similar to structure 4). It is also necessary to take into account vortex shedding when designing foundations that are square in plan or make them close to a round shape. Vortex shedding, unlike work [15], must be considered only simultaneously with the action of the frontal wind, the forces from which depend on its speed. The main condition for their appearance is the action of the wind with a speed higher than the critical one for this form of self-oscillations.

Our studies were performed as exclusively theoretical with the application of the analytical methods introduced in EN 1991-1-4:2005 for determining forces from wind loads both from frontal wind and from vortex shedding with its reliability assurance system. This imposes certain limitations due to the difficulties of verifying the results in practice since it is necessary to arrange constant long-term instrumental monitoring of the vibrations of buildings and the action of winds. It may turn out that the proposed provisions for limiting stresses by the endurance limit for the simultaneous action of a frontal wind with vortex shedding may provide excessive safety margins. As the analysis of the transcript of winds for one random year revealed (Table 7), the wind pressure acting on the structures for one year did not exceed 36 % of the maximum calculated one. Higher winds appear much less often. In addition, the conditions of a specific construction site can have a significant impact – the presence of neighboring facilities, the openness of the area, local elevation. Therefore, detailed research makes sense when monitoring unique structures.

Further research should focus on studying the conditions of manifestation and the frequency of repetition of oscillations according to the second natural frequency, which can give forces higher than the action of the frontal wind.

7. Conclusions

1. When studying structures, the natural frequencies and critical speeds, as well as the forms of natural oscillations under the action of vortex shedding on the structures, were determined. In structures with vortex shedding, oscillations occur at the first natural frequency of oscillations, which occur already in weak and moderate winds with a large number of oscillation cycles. As the structure heights increase, the vibration frequencies decrease for all natural modes of vibration.

2. The calculation according to the EN 1991-1-4:2005 procedure of all structures for vortex shedding with frontal wind was carried out. The magnitude of forces in the supports of structures from wind excitation is from 2.9 to 43.5 % of the forces under the action of frontal wind, depending on the height of the structure, even taking into account the nonlinear increase in forces from the frontal wind when the height of the structure increases. The effect of vortex shedding is not significant for structures up to 12–15 m high and increases above 20 m. In structures higher than 20–30 m, the manifestation of vortex shedding is also possible in the second form of self-oscillations with significantly greater internal forces, which may exceed the influence of the frontal wind.

3. An analysis of the transcript of winds for a randomly selected year for the conditions of the city of Kyiv was performed, which showed that the number of oscillation cycles per year for the studied structures is from 2.6 to 14.4 million for the most widespread manifestation of the first form of self-oscillations. This indicates that for the calculation of structures it is necessary to limit the stresses in the parts and structures to the limit of endurance. At the same time, it is possible to calculate structures for the conditions of any terrain without the need for additional assessment of the spectrum and characteristics of winds for a specific construction site. When analyzing the vortex shedding by the second form, which causes significant forces in the systems, there are difficulties with identifying the duration and number of cycles, if the critical wind speed is high and rarely repeats. Therefore, the application of structural means for damping vortex shedding is relevant.

4. The most effective are cross-sections and structural shapes of support details, for which the peak values of stresses from the force factor in one plane fall on neutral zones for stresses from the force factor in another plane. Therefore, circular cross-sections and close to them are effective, while square cross-sections are less effective. It is also necessary to take into account the structural form of the support bases by avoiding square schemes for the location of foundation bolts, etc.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

The manuscript contains references to calculations in the SCAD software package, license #19782, transferred to the Kyiv National University of Civil Engineering and Architecture on May 13, 2024.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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