On the need to take into account the effect of wind on the frame of thin-walled steel structures during installation

A V Soloviev and O N Solovieva
Department of metal and wooden structures Samara State Technical University.
Samara State Technical University, Molodogvardeyskaya 244, 443001 Samara, Russia
E-mail address: savsmr@rambler.ru

Abstract. Recently, the construction of buildings and structures using elements of light steel thin-walled structures has been increasing in Russia. The use of lightweight galvanized profiles provides a number of advantages in the manufacture, transportation and installation of frames. In the practice of designing structures of this type, the calculation of frames, as a rule, is carried out for the loads acting on the structure during its operation. In many cases, analysis of possible wind effects on frames during installation is not performed. This article examines the effect of wind on the frame of a 120-meter-long single-span building made of light steel thin-walled structures. Such structures, having a low mass, under certain parameters, can experience dynamic vibrations caused by the effect of wind. Most of the aeroelastic processes are self-oscillating in nature, occurring during energy exchange between the flow and the streamlined body. The main phenomena of aeroelasticity are flutter (stall flutter) buffeting. If we consider the issues of aeroelasticity from the point of view of the effect on the structure, then such concepts as vortex excitation, galloping across the air flow, divergence and parametric resonance should be considered. If, during the design process, the analysis of possible wind effects on the frame is not carried out and measures are not taken to reduce the negative effect of wind, this can lead to deformation of the frame elements or their destruction.

1. Introduction
Calculation of building structures for the effects of wind is a very urgent problem at the present time [1-4]. This becomes especially important when designing frames made of light steel profiles of rather long buildings. As a rule, projects provide for the erection of a supporting frame, and then the installation of a light wall and roof fence. It should be noted that the erected frames are exposed to wind influences before the installation of the wall and roof fencing. Depending on the type of terrain and wind speed, impacts can significantly contribute to the performance of the framing elements. Both the entire frame and its individual elements can fall into the zone of resonant aerodynamic vibrations. This is especially dangerous for elements of square or rectangular cross-section. When the wind stream flows around the elements of the building frame, the so-called aerodynamic instability of the aerodynamic parameters of the environment occurs. There is a sharp change in pressure associated with the separation of the air flow from the structure. Vortex formation processes appear. The emerging aerodynamic forces lead to additional loading of the frame elements. The resulting forces must be taken into account in strength calculations. The main part of aeroelastic processes is self-oscillating in nature, occurring during energy exchange between the flow and the streamlined body. The main phenomena of aeroelasticity are flutter, buffeting. If we consider the issues of aeroelasticity from the point of view of the effect on the structure, then one should analyze such phenomena as
vortex excitation, galloping across the air flow, divergence and parametric resonance. Flutter - non-damping elastic vibrations of a structure (parts of a structure) when an air flow is running at a certain (critical) speed. Flutter is a type of self-oscillation, where the source of vibration energy is the wind flow, and the feedback is realized due to the elasticity of the building structure (or building element). At certain angles of attack, a flow stall can occur. It should be noted that stall flutter is usually realized at low flow rates. Buffeting - forced vibrations of the entire structure or its parts under the action of non-stationary aerodynamic forces when the flow is disrupted from the surface of an elastic object at high angles of attack (as a rule, from poorly streamlined surfaces). When buffering, the stall flow from one part of the structure acts on another part of the structure. If the phenomenon of flutter can be studied by highlighting a certain “significantly elastic” part of the structure “locally”, then during buffeting it is necessary to consider the entire building, even its “relatively inelastic” (“rigid”) elements. The vortex excitation mechanism is similar to the flutter mechanism (stall flutter) and is associated with the fact that when the flow is running, the bluff body drops vortices alternating in a checkerboard pattern with a frequency depending on the flow velocity, size and shape of the streamlined body. Galloping across the air flow typically occurs in flexible structures and features with special cross-sectional shapes, such as power lines, cable-stayed or suspended structures. This phenomenon is a self-oscillation of the body, occurring almost perpendicular to the direction of the incident flow. Divergence is primarily associated with the twisting of a body of small transverse thickness in an air flow directed along the longitudinal axis of the structure's cross section. The phenomenon is characterized by torsional self-oscillations of the structure increasing in time (causing an increase in the drag of the structure profile) and leading to the destruction of the structure. It is also a problem of air resistance. Divergence usually occurs in bridge spans and structures with flat cross sections. Parametric resonance is characterized by a complex nature of the interaction between the structure and the incident flow and, in the general case, is associated with a change in the parameters of the dynamic system over time, leading to an increase in the amplitude of oscillations. As a rule, the natural vibration of the structure or the damping coefficient undergo a change. As an example, we can cite changes in the tension force of the cables of a suspension bridge or the tension force of the link elements and, as a consequence, the excitation of vibrations of structures.

This paper deals with the issues of aerodynamic wind effects on building frames during installation. An analysis of the causes of deformation of the frame of a single-span building and the destruction of its elements at the stage of installation due to the effect of wind is also presented.

2. Materials and methods
In accordance with the design standards for buildings and structures, as well as their elements, it is necessary to take into account the main type of wind load, resonant vortex excitation and aerodynamically unstable oscillations such as galloping, divergence and flutter.

The main type of wind load and peak wind loads are associated with the direct effect on buildings and structures of hurricane winds, maximum for the construction site, and must be taken into account when designing all structures. Resonant vortex excitation and aerodynamic unstable vibrations must be taken into account for buildings, solid-wall structures or their individual sections that have a rectilinear central axis, as well as unchanging or smoothly changing shapes and sizes of the cross-section, for which the condition \( \lambda_c > 20 \) is met, where \( \lambda_c \) is determined depending on geometric parameters of a structure or its element. Criteria for the excitation of aerodynamically unstable vibrations are established in the design standards.

So the critical wind speeds \( V [m/s] \), at which resonant vortex excitation occurs according to the \( i \)-th natural mode of vibration, are determined by the formula:

\[
V_{cr,i} = \frac{k_i \cdot f_i \cdot d}{St}
\]  

(1)

here:

- \( f_i \) (Hz) - is the natural frequency of vibrations in the \( i \)-th flexural natural form;
$d$, (m) - is the transverse dimension of the structure or element;  
$St$ - is the Strouhal number of the cross section, determined experimentally or by reference data (for rectangular sections $St = 0.11$, for square sections $St = 0.12$).  
$k_v$ - is the coefficient that takes into account the effect of trapping the natural frequency of oscillations, from the range $0.9 < k_v < 1.1$ from the condition for the implementation of the worst case loading.  
Resonant vortex excitation does not occur if:

$$V_{cr,i} > V_{\text{max}}(z_h)$$

where

$$V_{\text{max}}(z_h) - \text{maximum wind speed at } z_h \text{ level, (m/s)}$$

$$V_{\text{max}}(z_h) = 1.5\sqrt{w_0 k(z_h)}$$

here:

$w_0, \text{(Pa)}$ - the standard value of the wind pressure taken in accordance with the wind area;  
$k(z_h)$ - coefficient taking into account the change in wind pressure for the height $z_h$.  

When the wind speed reaches a critical value, there is a likelihood that the frame elements, during installation, into the resonant vortex excitation. This can lead to the accumulation of fatigue damage and in some cases to failure.

2.1. **Destruction of building frame elements from wind loads at the installation stage**

Let's consider the case of destruction of elements of a light steel frame at the stage of installation. As an example, a single-span building with a length of 120 meters is considered. The building frame diagram and the structural design of the main elements are shown in figures 1, 2.

![Figure 1. Scheme of the building frame.](image-url)
Figure 2. Transverse frame of the frame along the axis 7.

K1 - frame column (□ 200×120×4); P1 - beam (□ 350×150×5);
CB1 - vertical connection (○ 16); □1 - spacer (□ 100×100×3);
CT1 - horizontal connection (○ 12); ПП1, ПП2 - cover runs (□ 160×120×4);
C1 - tightening (□ 80×80×3); T1 - suspension (○ 12).

The project for the production of work envisaged first the installation of the frame elements, and then the installation of the elements of the wall and roof fencing. In total, 18 building frames were installed. For technical and economic reasons, the installation of wall and roof panels was postponed for 3 months. When the installation work was resumed, damage to the frame was found in the form of: destruction of the nodal elements of fastening the guy wires C1 to the column; the occurrence of cracks in the nodal element of fastening the tightening C1 to the column K1; breakage of suspensions T1 at the points of adjoining to the tightening of C1; sagging of stiffening elements and suspensions. The nature of the damage is shown in figure 3.

Figure 3. Destruction of frame elements
a) destruction of the nodal elements of fastening the guy wires C1 to the column;
b) the appearance of cracks in the nodal element of fastening the guy wires C1 to the column K1;
c) breakage of the tightening hangers;
d) sagging of tie and suspension elements.
2.2. Analysis of the causes of destruction from wind load at the stage of installation of the frame

Analysis of the causes of the destruction of the frame elements at the installation stage shows that the destruction occurred due to the effect of wind. Obviously, the wind was blowing longitudinally along the building. At the same time, the wind speed reached such a value at which the building frames fell into parametric resonance, and the puff was galloped across the air flow.

Let's analyze the parameters of the structure and the wind impact. The estimated area of the wind impact on the end of the building, in the presence of wall and roof fencing, is 115 m$^2$. In the absence of wall and roof fencing, the wind load is transferred to the building frames. The total area of the frame elements on the windward side is 230 m$^2$. It is obvious that doubling the impact area leads to overstressing of vertical and horizontal structures of connections. In addition, prestressed bond elements accompany the transition of the entire frame to parametric resonance when the wind speed reaches critical values. Residual deformations (sagging) of the bonds show that the elements have undergone such a load, which led to the formation of irreversible plastic deformations. Tightening of the building frames when the wind reaches critical speeds turned into galloping (figure 4).

![Figure 4. Schema of galloping of the frame tightening element.](image)

Since the tightening in the middle is fixed by the suspension, the galloping occurs along the second form of the natural frequency. All mounted frames are located in an open area. The maximum wind speed at a height of 3 meters (3) will be

$$V_{\text{max}}(z_p) = 1.5 \cdot 380 \cdot 0.75 = 25.3 \text{ m/s}$$

(4)

The frequency of natural vibrations of the tightening according to the $i = 2$ form will be:

$$f_i = \left(\frac{\pi \cdot i}{l}\right)^2 \sqrt{\frac{EI}{m}} = \left(\frac{3.14 \cdot 2}{21}\right)^2 \sqrt{\frac{210 \cdot 10^8 \cdot 91.4 \cdot 10^{-8}}{0.74}} = 14.4 \text{ Hz}$$

(5)

here:

- $l$ - puff length in meters;
- $E$ – the modulus of elasticity of the material;
- $I$ - the moment of inertia of the section;
- $m$ - the mass of a running meter of the tightening element.

The critical wind speed at which the resonant vortex excitation of the puff occurs along $i = 2$ of the natural vibration mode in accordance with (1) will be:

$$V_{cr,i} = \frac{k_i \cdot f_i \cdot d}{S_t} = \frac{1 \cdot 14.4 \cdot 0.08}{0.12} = 9.6 \text{ m/s}$$

(6)

here:
$d$ - the height of the tightening section in the plane perpendicular to the wind flow.

Condition (2) is not met. This means that at a wind speed of about 10 m/s, vortex excitation can occur and puff oscillations can begin (figure 4). In this case, alternating loads will arise on the nodal elements of fastening the puffs. These alternating loads led to fatigue fractures of some elements of the nodal gussets (figure 3, a, b) and breakage of suspensions (figure 3, c).

3. Conclusions
The work done on the analysis of wind effects on structures under construction showed that at certain wind speeds and angle of attack, aerodynamic vibrations of the frame and its individual elements can appear. These vibrations can lead to deformation of structures and their destruction. When designing structures, such architectural and structural solutions should be used that exclude the excitation of aerodynamically unstable vibrations.

References
[1] Barshtein M F 1978 Manual for the calculation of buildings and structures on the action of the wind (M.F. Barshtein.-M.: Stroyizdat) p 216
[2] Birbraer A N 2009 Extreme impacts on structures (SPb. Publishing house of Polytechnic University) p 594
[3] Mendis P, Ngo T, Haritos N and Hira A 2007 Wind loading on Tall Buildings EJSE (Special Issue: Loading on Structures) pp 41-54
[4] Simiu E and Scanlan R 1984 Impact of wind on buildings and structures (Moscow: Stroyizdat) p 360