3rd International Conference
„CONFERENCE ON ADVANCES IN SCIENCE AND TECHNOLOGY“ COAST 2024
29 May - 01 June 2024 HERCEG NOVI, MONTENEGRO

NUMERICAL ANALYSIS OF THE PIPE HEIGHT IMPACT ON STRUCTURAL LOADING CAUSED BY WIND PRESSURE

Snežana Vulović[1], Miloš Pešić[1], Aleksandar Bodić[2], Živana Jovanović Pešić[2], Miroslav Živković[2]
[1]Institute for Information Technologies, University of Kragujevac, Jovana Cvijića bb, 34000 Kragujevac, Serbia
[2]Faculty of Engineering, University of Kragujevac, Sestre Janjić 6, 34000 Kragujevac, Serbia

The corresponding author's e-mail address: milospesic@uni.kg.ac.rs (M. Pešić)

ABSTRACT: *Wind load calculations are crucial in structural engineering, particularly in scenarios such as steel pipe installations where exposure to external forces is significant. To investigate the wind's effect on structures, data is collected on wind impacts at specific locations, and mathematical models describing wind effects are developed and enhanced. This study focuses on wind load determination for a steel pipe using local wind speed data following Eurocode 1: Actions on structures – Part 1-4: General actions – Wind actions. Through rigorous calculations based on equations provided by the standard, the peak wind velocity, turbulence intensity, and resulting wind pressure distribution on the pipe surface are determined. Additionally, a detailed analysis is conducted on the application of wind pressure via developed FEMAP API script, facilitating precise load definition on FEM shell elements, application of calculated force which represents wind pressure on FEM shell elements on half of the model, and application of FEMAP API script calculated force which represents wind pressure on FEM shell elements on half of the model. The results highlight the importance of accurate wind load assessment in ensuring structural integrity and safety.*

Keywords: *Wind Effects, FEM Analysis, FEMAP Application Programming Interface*

---

1. INTRODUCTION

Steel pipes play a crucial role in various industrial applications, including steel manufacturing plants. Understanding the effects of wind loads on structures is essential for ensuring their stability and resilience. The paper [1] introduces a comprehensive numerical model to predict the structural behavior of transmission towers which are part of the transmission line under high-intensity wind loads, such as downburst events, which are less understood despite extensive research on normal wind loads. Wind load is the predominant force acting on greenhouses. Customized greenhouse designs tailored to localized wind loads are essential, as demonstrated in [2] estimating wind loads for a double arch-type naturally ventilated greenhouse in India. Finite Element Method simulation in ANSYS 15.0 revealed potential failure zones, emphasizing the need for precise structural design considerations in greenhouse construction to enhance structural stability. He et al. [3] proposed a computational modeling approach to assess the structural behavior of low-rise wood frame buildings under wind loads. The methodology utilizes a three-dimensional finite-element model validated through testing at the Wall of Wind Experimental Facility, providing insights into load paths and load-sharing mechanisms crucial for understanding the performance of vulnerable building components during windstorms.

The challenges posed by wind-induced motion in modern tall buildings, focusing on the complex coupled lateral and torsional effects arising from their irregular geometric shapes were investigated. By analyzing equivalent static wind loads and developing an optimal stiffness design technique, the aim of the study in paper [4] is to optimize the structural response of tall asymmetric buildings, ultimately reducing wind-induced loads and enhancing cost efficiency.

For numerical analysis in this study, FEMAP with NX Nastran solver [5] was used. This software is based on the Finite Element Method [6]. The numerical method performed in this paper is used to determine the stress state in the pipe [7]. In the next chapters the calculation of wind loads according to Eurocode 1: Actions on structures – Part 1-4: General actions – Wind actions [8] will be discussed. The developed Visual Basic script [9] which is used for the application of pressure on FEM shell elements will be explained. The FEM shell elements were used to model the pipe.

In this study, the process of wind load determination for a steel pipe by Eurocode 1: Actions on structures – Part 1-4: General actions – Wind actions were investigated. By analyzing local wind speed data and applying relevant equations from the standard, the impact of wind pressure on the pipe surface was assessed. Furthermore, this paper represents a comparative study of FEMAP API scripting, a calculated force that represents wind pressure and is applied on half of the model, and FEMAP API script calculated force that represents wind pressure and is applied on the half of the model utilization for the precise load definition, enhancing the accuracy of structural analysis.

2. CALCULATION OF WIND PRESSURE ACCORDING TO EUROCODE

Wind load is calculated based on local data on actual measured wind speed according to Eurocode 1: Actions on structures – Part 1-4: General actions – Wind actions [8]. For wind load determination, a fundamental value of basic wind velocity $v_{b,0}$ is used, which is given in the National Annex, and for the region near where the pipe will be placed. The value of $v_{b,0} = 25\ m/s$. The pipe will be placed on flat ground with regular vegetation classified as terrain category III according to Table 4.1 in standard [8]. The same table gives us the values of the roughness length $z_0 = 0.3\ m$ and the minimum height $z_{min} = 5\ m$ and $z_{max} = 200\ m$. Terrain factor k_r is calculated based on roughness length z_0 and reference roughness length $z_{0,II} = 0.05\ m$ for terrain category II:

$$k_r = 0.19 \cdot \left(\frac{z_0}{z_{0,II}}\right)^{0.07} = 0.215. \quad (1)$$

The terrain roughness factor c_r for $z_{min} \leq z \leq z_{max}$ is calculated using:

$$c_r(\mathrm{z}) = k_r \cdot \ln\left(\frac{z}{z_0}\right) \quad (2)$$

and $c_r(\mathrm{z}) = c_r(z_{min})$ for $z \le z_{min}$.
The value of the topography coefficient $c_o(z)$ is obtained from the National Annex. The value of the topography coefficient $c_o(z) = 1$ for flat terrain.
According to [8] the turbulence intensity for $z_{min} \ \le \ z \le z_{max}$ is:

$$I_v(\mathrm{z}) = \frac{k_I}{c_o(z)\cdot \ln(z/z_0)}, \tag{3}$$

and $I_v(z) = I_v(z_{min})$ for $z \le z_{min}$. Recommended value for turbulence factor k_I is 1.0, other values may be specified by the National Annex.
The mean wind velocity at height is given as:

$$v_m(\mathrm{z}) = c_r(z) \cdot c_o(z) \cdot v_{b,0} \tag{4}$$

The peak velocity pressure $q_p(z)$ accounts for turbulence intensity $I_v(z)$ and the mean wind velocity $v_m(z)$ is:

$$q_p\,(\mathrm{z}) = (1 + 7 \cdot I_v(z)) \cdot 0.5 \cdot \rho \cdot v_m(z)^2. \tag{5}$$

The recommended value of the air density according to the National Annex is $\rho = 1.25\ kg/m^3$.
Per [8] expression (4.1) basic velocity pressure is

$$q_b\ = 0.5 \cdot \rho \cdot {v_{b,0}}^2 = 390.63\ N/m^2. \tag{6}$$

According to expressions (5) and (6) the peak velocity pressure is

$$q_p\,(\mathrm{z}) = (1 + 7 \cdot I_v(z)) \cdot c_r(z)^2 \cdot c_0(z)^2 \cdot q_b\,. \tag{7}$$

The peak velosity pressure value dependence on structure height according to equation (7) is shown in Fig. 1.

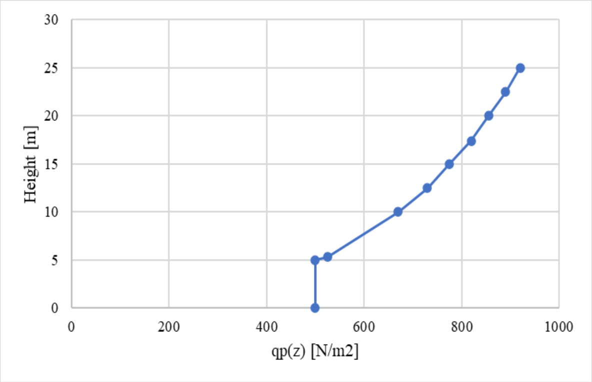


Fig. 1. Peak velocity pressure value dependence on structure height

For the reference height, the maximum height of the observed section $z_e = 25\ m$, [8] and it is used for the calculation of the peak wind velocity:

$$v(z_e) = \sqrt{\frac{2\cdot q_p\,(z_e)}{\rho}} = 38.274\ m/s. \tag{8}$$

The peak wind velocity $v(z_e)$, kinematic viscosity of the air $\nu = 15 \cdot 10^{-6} m^2/s$ and pipe diameter $b = 0.8\ m$ is used to calculate the Reynolds number:

$$R_e = \frac{b\cdot v(z_e)}{\nu} = 2.04 \cdot 10^7. \tag{9}$$

Reynolds number characterizes wind load distribution over a cylinder surface. The positions of the minimum pressure $\alpha_{min} = 75°$ and the flow separation $\alpha_A = 105°$ are obtained from Table 7.12 according to standard [8] for $R_e = 2.04 \cdot 10^7$. The distribution of load changes with the angle in regard to wind direction according to the end-effect factor $\psi_{\lambda\alpha}$ which is given by expression (7.18) in standard [8]. The indicative value of the end-effect factor (ψ_λ) in expression (7.18) [8] is determined from the diagram (7.36) in the standard [8] using the solidity ratio φ (which is for a cylinder equal to 1) and slenderness λ which can be found in the table (7.16) in [8]. Linear interpolation was used to calculate slenderness for $l = 25\ m$:

$$\lambda = 28.57. \tag{10}$$

From the diagram (7.36) in standard [8] $\psi_{\lambda\alpha}$ is 0.81.

Wind pressure on external surfaces $w_e(z)$ is calculated as:

$$w_e(z) = q_p\,(z) \cdot c_{p,0} \cdot \psi_{\lambda\alpha}, \tag{11}$$

where $c_{p,0}$ is the external pressure coefficient without free-end flow, which is given in figure (7.27) [8] for various Reynolds numbers as a function of angle α .

$$\begin{aligned} w_e(z) &= q_p\,(z) \cdot c_{p,0} && \text{for } 0° \le \alpha \le 75° \\ w_e(z) &= q_p\,(z) \cdot c_{p,0} \cdot 0.154 \cdot \cos\left(\frac{\pi}{2} \cdot \left(\frac{\alpha - 75°}{105° - 75°}\right)\right) && \text{for } 75° \le \alpha \le 105° \\ w_e(z) &= q_p\,(z) \cdot c_{p,0} \cdot 0.81, && \text{for } 105° \le \alpha \le 180°, \end{aligned} \tag{12}$$

The pressure distribution on the pipe according to equation (12) is shown in Fig. 2.

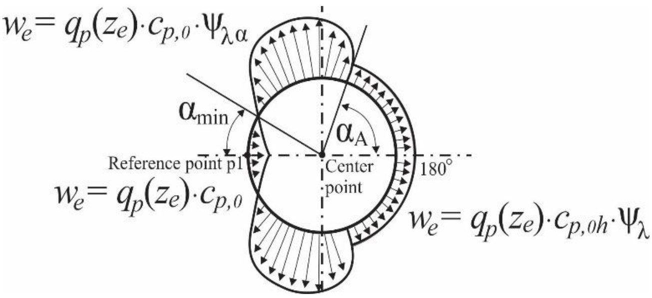


Fig. 2. Pressure distribution illustration

The reference area for the cylindrical structures is

$$\mathrm{A} = l \cdot \mathrm{b} = 25 \cdot 0.8 = 20\ m^2 \tag{13}$$

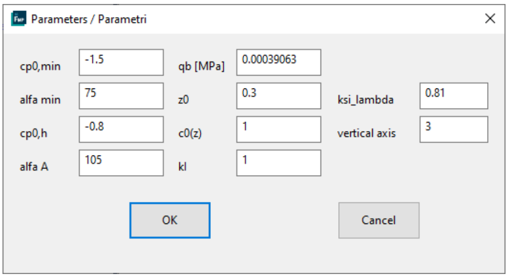
Then the resulting characteristic value of the wind-induced force on the foundation of the pipe is:

$$F_w = q_p\,(z_e) \cdot \psi_{\lambda\alpha} \cdot \mathrm{A} = 915.56 \cdot 0.81 \cdot 20 = 14832\ \mathrm{N}. \tag{14}$$

3. FEMAP API FOR LOAD DEFINITION

FEMAP is the most versatile software for pre-processing [5] i.e. FEM model preparation, which includes generation of finite element mesh and prescription of loads and boundary conditions. To apply wind pressure on the pipe wall modeled with FEM shell elements and according to equation (12), and Fig. 2, the FEMAP API script is developed in Visual Basic (API stands for Application Programming Interface). More details on the FEMAP API script application are given in the paper [9].

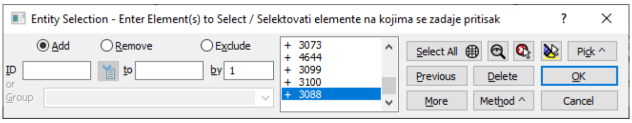
All coefficients obtained from the Eurocode 1: Actions on structures – Part 1-4: General actions – Wind actions and previously given equation are declared. These coefficients are entered into an API-generated dialog box (Fig. 3.)



cp0,min -1.5
qb [MPa] 0.00039063
alfa min 75
z0 0.3
ksi_lambda 0.81
cp0,h -0.8
c0(z) 1
vertical axis 3
alfa A 105
kl 1

Fig. 3. FEMAP API dialog box for pressure coefficients

To select finite elements for wind load prescription a selection dialog box from the FEMAP API was created as shown in Fig. 4.



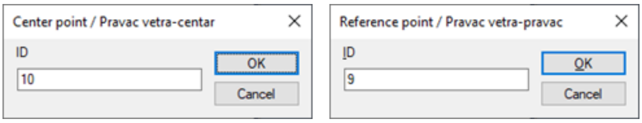
● Add ○ Remove ○ Exclude

by 1

+ 3073
+ 4644
+ 3099
+ 3100
+ 3088

Fig. 4. FEMAP API dialog box for finite element selection

After the finite elements for pressure load are selected, API generates dialog boxes for the selection of the center and the reference point.



ID 10

ID 9

Fig. 5. FEMAP API dialog boxes for point selection

Initially, it is assumed that for every finite element on which pressure is applied, the external face is face number 2 and that the wind blows in the -x direction. The vertical axis (z, i.e. 3) is selected in the first dialog box (Fig. 3.) and stored as the vertical axis.

4. RESULTS AND DISCUSSION

The wind pressure distribution on the pipe is shown in Fig. 6. This distribution is obtained from previously shown equations and applied via the FEMAP API script. It can be seen the resemblance between Fig. 2 which is an illustration of different pressure zones and Fig. 6 which gives the real results. Fig. 6 shows the values of pressure on the lowest and highest rows of finite elements on the pipe.

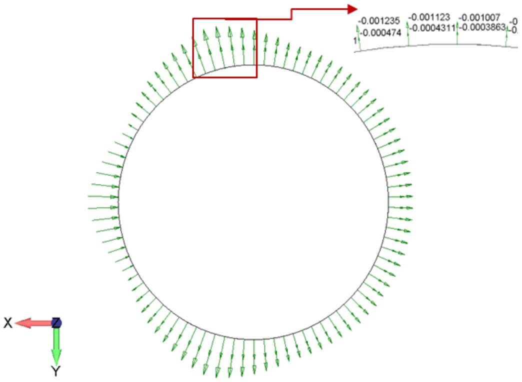


Fig. 6. Wind pressure distribution on pipe surface via API

The applying of wind pressure on cylindrical surfaces according to Eurocode 1: Actions on structures – Part 1-4: General actions – Wind actions are complicated in software where it is not possible to apply pressure via macros or code (API). An approximate method for applying wind impact on the structure involves applying pressure on half of the cylinder in the direction and orientation of the wind action (Fig. 7). In this approach, the area subjected to wind is equal to the product of the height and diameter of the pipe (dimensions of the cylindrical object under consideration). The total wind force applied in this case is equal to the force calculated by equation (14). The specified pressure is constant, i.e., it does not depend on the height of the object.

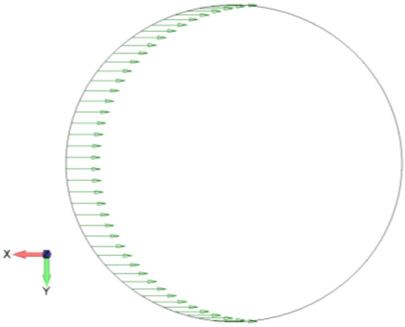


Fig. 7. Wind pressure distribution on pipe surface via analytical calculation

An examination has been conducted regarding the impact of wind load on the stresses on the pipe. The total wind force in the x-direction, specified according to Eurocode 1: Actions on structures – Part 1-4: General actions – Wind actions is 8230 N. The force obtained from equation (14) is calculated for the pressure at the top of the structure (pipe). Force (14) is relevant for the calculation of the structure's foundation. From the diagram, in Fig. 1, it can be observed that the pressure at the top of the structure is twice as high as the pressure at a height of 5 m. The ratio of the force obtained by API and the force in equation (14) is 0.554. In reality, the wind force is less than the force obtained from equation (14), so an analysis of the pipe was performed where the wind load is specified as a constant pressure on half of the model, resulting in a total force in the x-direction equal to 8899 N ($14832\ \mathrm{N} * 0.6 = 8899\ \mathrm{N}$).

In Fig. 8, the stress field on the pipe is shown for the load case where the wind is specified via the API by Eurocode 1: Actions on structures – Part 1-4: General actions – Wind actions. The maximal value of von Misses stress for this load case is 279.15 MPa.

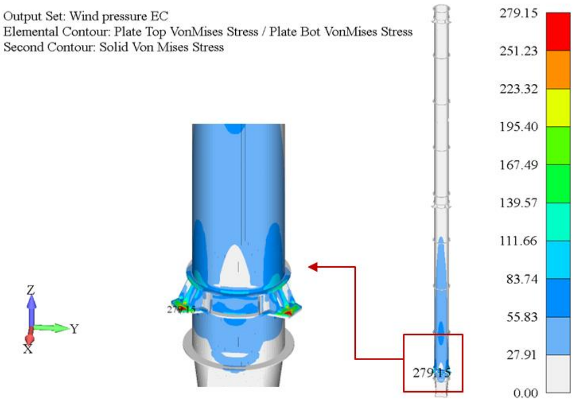


Fig. 8. Von Misses stress in the pipe: wind pressure according to Eurocode

In Fig. 9, the stress field on the pipe is shown for the load case where the wind load is applied as a constant pressure on half of the model, resulting in a total force equal to the force given by equation (14). The maximal value of von Misses stress for this load case is 438.37 MPa.

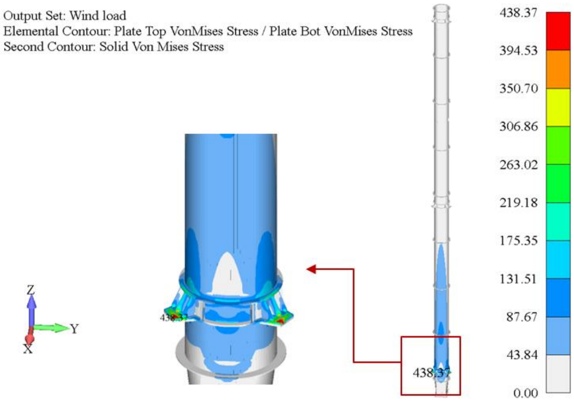


Fig. 9. Von Misses stress in the pipe: constant wind pressure

In Fig. 10, the stress field on the pipe is shown for the load case where the wind load is applied as a constant pressure on half of the model, resulting in a total force in the x-direction equal to 8899 N. The maximal value of von Misses stress for this load case is 261.64 MPa.

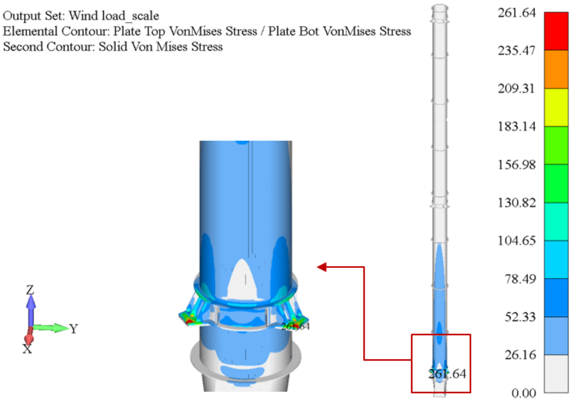


Fig. 10. Von Misses stress in the pipe: constant wind pressure (scale)

From Figures 8-10, it can be seen that the von Misses stress value is highest when the wind load is specified as a constant pressure, with the total force equal to 14832 N.

5. CONCLUSION

The analysis of wind load distribution on a steel pipe surface provides valuable insights into the structural behavior under external forces. By adhering to Eurocode 1: Actions on structures – Part 1-4: General actions – Wind actions, and employing advanced computational tools such as FEMAP API scripting, we ensure robust load definition and accurate assessment of structural response. The results indicate significant stress concentrations at specific locations on the pipe surface, emphasizing the importance of detailed wind load analysis in engineering design.

The maximal von Misses stress for the load case where wind load is applied via FEMAP API is 279.15 MPa. The maximal von Misses stress for the load case where wind load is applied with calculated force through equation (14) is 438.37 MPa. The maximal von Misses stress for the load case with the calculated force of 8899 N is 264.64 MPa. For the last two load cases, wind load was applied as a force on half of the model. As can be seen from the results in this paper, the last methodology can be used in finite element software where it is not possible to apply pressure via macros or code (API), and these efforts are warranted to enhance the reliability of numerical calculation results obtained by wind load in steel pipe installations.

ACKNOWLEDGEMENTS

This research is partly supported by the Ministry of Science, Technological Development and Innovation, Republic of Serbia, Agreement No. 451-03-66/2024-03/200378, and by the Science Fund of the Republic of Serbia, #GRANT No 7475, Prediction of damage evolution in engineering structures - PROMINENT.

6. LITERATURE

[1] Shehata, A.Y., El Damatty, A.A., Savory, E. (2005), “Finite element modeling of transmission line under downburst wind loading”, *Finite Elements in Analysis and Design*, No. 42, 71–89.

[2] Nayak, A., Ramana Rao, K.V. (2014), “Estimation of wind load on a greenhouse and evaluation of its structural stability”, *IJAE*, No. 7, 461–466.

[3] He, J., Pan, F., Cai, C.S., Habte, F., Chowdhury, A. (2018), “Finite-element modeling framework for predicting realistic responses of light-frame low-rise buildings under wind loads”, *Engineering Structures*, No. 164, 53–69.

[4] Chan, C.M., Huang, M.F., Kwok, K.C.S. (2010), “Integrated wind load analysis and stiffness optimization of tall buildings with 3D modes”, *Engineering Structures*, No. 32, 1252–1261.

[5] Femap with NX Nastran user manual.

[6] Kojić, M., Slavković, R., Živković M., Grujović, N. (1998), Metod konačnih elemenata I, Linearna analiza, (in Serbian), Kragujevac: Mašinski fakultet, Univerzitet u Kragujevcu.

[7] Kojic M. (2012), “An extension of 3-D procedure to large strain analysis of shells”, *Computer methods in applied mechanics and engineering*, Vol.191, 2247-2462.

[8] EN 1991-1-4:2003 Part 1-4: General actions – Wind actions.

[9] Vulović, S., Bojović, M., Topalović, M. (2020), “Automation of FEM Analysis Report Generation using Visual Basic FEMAP API”, *ICIST 2020 Proceedings*, Vol.1, 10-15.