EXPERIMENTAL INVESTIGATION OF WIND LOAD ON LOW-RISE INDUSTRIAL BUILDING

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UDK: 624.042.41:725.4
DOI: 10.14415/konferencijaGFS2019.030
Summary: *Aim of this paper is to investigate wind pressure distribution on low-rise industrial building based on the results from atmospheric boundary layer wind tunnel experiments. Building model is a hanger with a tilted roof with an inclination of 5°. Values of mean and fluctuating pressure coefficients measured on the surface of the roof and side walls of the model are discussed in the paper. Five wind approaching angles are considered: 0°, 15°, 30°, 45° and 90°. The investigation can offer some basic understanding of wind behaviour and effects on low-rise industrial buildings regarding different wind angles.*

Keywords: *Wind Tunnel, Low-rise Building, Wind Angle, Pressure Coefficient*

1. INTRODUCTION

Most of the structures in civil engineering are located in the lower part of the atmospheric boundary layer where wind turbulence and gradient of wind speed dominate. Wind load is one of the basic load cases for the design of structures. The loading effects of the natural wind on buildings are the complex problem which includes interaction between the wind flow and the various components of the building. One of the most affected structure parts are roofs and facades.
To provide a good wind load prediction, understanding of wind flow characteristics around the building is necessary. Many researchers addressed this problem in their papers. In [1] experimental investigation of wind pressure fields on buildings with gabled roofs with different pitch angles was conducted. Results show that the highest peak suction is experienced with 15° pitched roof at the windward roof corner for the wind angle of 15°. A numerical study of above roof wind flow characteristics in three suburban landscapes characterized by houses with different roof profiles, namely: pitched roofs, pyramidal roofs and flat roofs are presented in [2]. The obtained results

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were interpreted in the light of wind harvesting potential above the roof. Structural response due to wind load of a low-rise building was analysed in [3] using both simulated and experimental pressure fields. Dynamic structural analyses were performed and results were directly compared in terms of design forces in the structural elements. Different standards and manuals used in engineering practice give design recommendations for wind load on structures. The one that is commonly used in Europe is EN 1991-1-4 [4]. The external pressure coefficients in [4] are mainly derived from extreme value analysis of integrated multiple instantaneous pressure measurement in a wind tunnel.

The purpose of this study is to investigate the distributions of wind pressure coefficients on the roof of the low-rise industrial building model, to reveal the changes in pressure distributions for understanding the changing mechanism of pressure fields due to different approaching wind angles. Paper is organized into four sections. Section 2 refers to the experimental setup. The main flow features above the roof of the building are described in section 3. The paper ends with conclusions in Section 4.

2. EXPERIMENTAL SETUP

Experiments were conducted in the atmospheric boundary layer wind tunnel of the Ruhr-University Bochum, Germany, within a Short Term Scientific Mission of the COST Action TU1304. Tests were carried out on a 1:100th scale model of the low-rise industrial building. The approaching flow represents an urban wind exposure using the spire-roughness technique.

The characteristics of the incoming wind profile have been measured at the distance of 1m in front of the principal building. The wind field profile reproduced in the wind tunnel matches the one of the power low with the exponent 0.15.

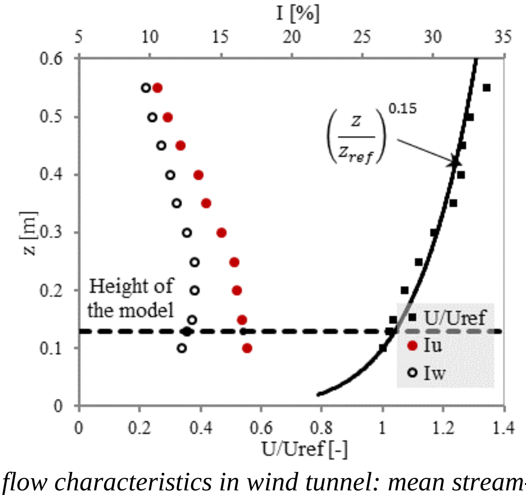


Figure 6. Wind flow characteristics in wind tunnel: mean stream-wise wind speed (U/U_{ref}) and turbulence intensities in stream-wise (I_U) and vertical (I_W) direction (coordinate z=0 is related to the floor of the wind tunnel)

In the presented wind tunnel tests for reference velocity (U_{ref}) has been adopted a value equal to 12.9m/s, measured at the height of z_{ref}=0.1m from the wind tunnel floor. Measurements of mean stream-wise wind velocity (U) and turbulence intensities in stream-wise (I_U) and vertical (I_W) directions are presented in *Figure 1*. Mean stream-wise wind speed (U_{ref}) at the referent height (z_{ref}) has been used to normalize the velocity profile for all measurements. Turbulence intensities in stream-wise and vertical directions are 17% and 12%, respectively at z_{ref}.
Building model is a low-rise tilted hanger with roof inclination of 5°. The model dimensions, length (L), width (B) and height (H) are shown in Figure 2b.

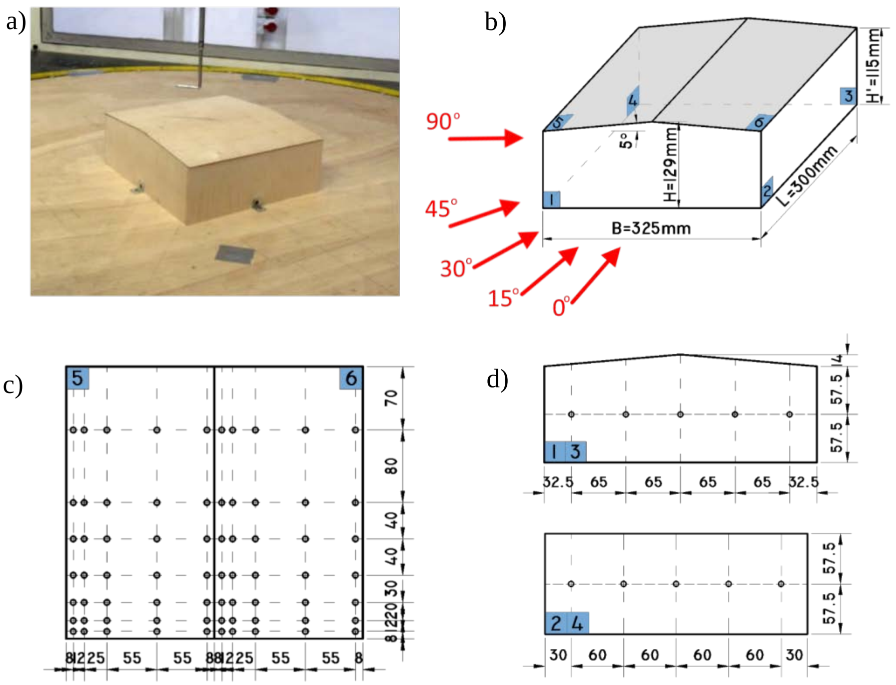


Figure 7. (a) Hanger model mounted on the rotating table in the wind tunnel, (b) dimensions of the hanger model, (c) positions of the pressure measurement points on the developed roof area of the model and (d) side walls.

Experiments were conducted for five approaching wind angles, 0°, 15°, 30°, 45° and 90°, defined in relation to the roof ridge, as reported in Figure 2b. Experiments were performed with a Reynolds number of $8.5*10^4$, which is defined based on the referent height (z_{ref}=0.1m) and referent velocity (U_{ref}=12.9m/s).
The model was equipped with 70 pressure taps on the roof of the hanger, and 20 pressure taps on the ring on its sides, whose scheme is given in Figure 2c,d. Measurements were conducted simultaneously in all points, using a multi-channel simultaneous scanning measurement system with the sampling frequency of 1000Hz.

3. EXPERIMENTAL RESULTS

Results of the experimental measurements of surface pressure over the roof of the hanger are given in the following section.

The mean surface pressure coefficients for different wind angles

Flow pattern around the hanger is analysed in the light of the pressure field. Contours of the mean surface pressure coefficients ($C_{p,mean}$) for different wind angles are presented in *Figure 8*. The pressure coefficient, C_p is calculated using the following expression:

$$C_p = (p - p_0) / (0.5 \rho U_{ref}^{\ 2}) \qquad (3)$$

Where with p_0, ρ and U_{ref} are denoted unobstructed stream pressure, air density and the reference velocity, respectively.

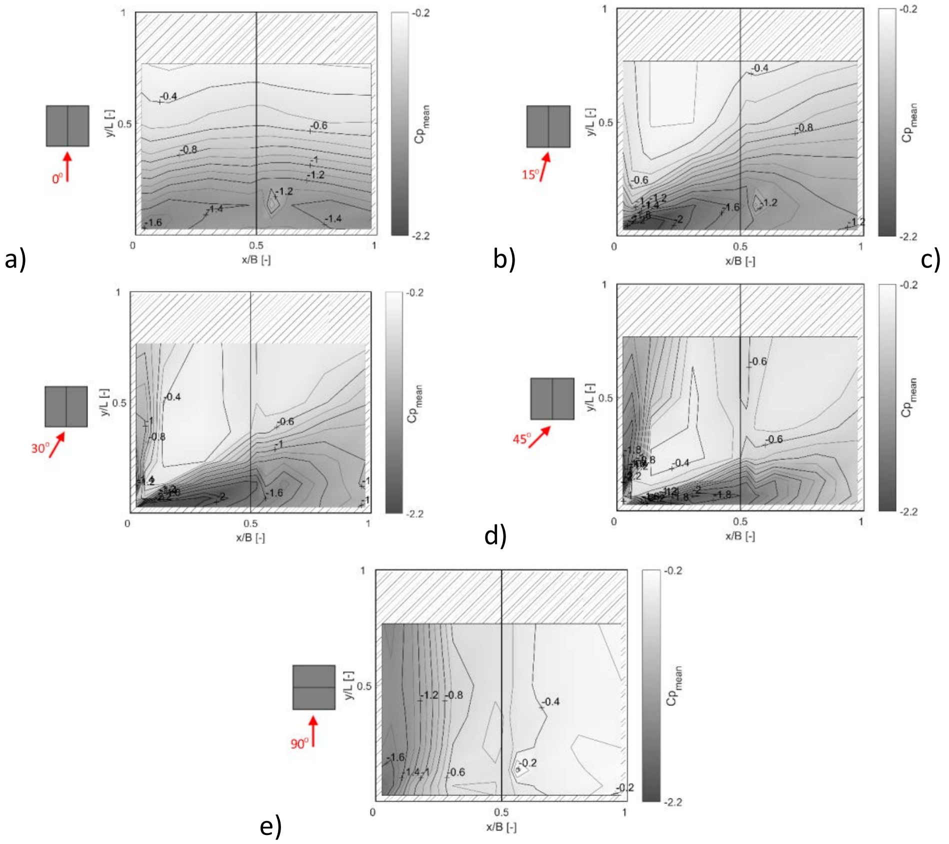


Figure 8. Contours of $C_{p,mean}$ on the roof of hanger for different approaching flow angles a) 0°, b) 15°, c) 30°, d) 45°, e) 90°

At *Figure 8*a, for 0° wind angle, the reduction of the surface pressure is noticeable close to the upstream edge, which is followed by a growth of the pressure downstream. It suggests a large separation bubble close to the windward edge. Values of $C_{p,mean}$ coefficients close to the windward side are up to -1.5 and reduce to -0.4 downstream.
Similar reduction close to the upstream edge is obtained for 15° wind angle. The other upstream edge is also showing similar behaviour only on the more enclosed area. This confirms the existence of small side-cone. In this case, $C_{p,mean}$ in the zone close to the upstream corner reaches up to the value of -2.2.
In case of 30° and 45° wind angle reduction close to both upstream edges are strongly pronounced. Namely, the pattern of pressure distribution suggests that the flow separates at the upstream edges forming two intense conical structures. Deeper insight in zone where cone separation occurs is given at *Figure 9* where the distribution of pressure coefficients is presented over the line x/B=0.33 in the light of different approaching angles. The characteristic upstream hump shape is observed for all presented wind angles, typical for the separation region followed by reattachment [5]. This shape is related to the high negative pressure values in the separation region. The largest suction was found directly below the average moving vortex core [6]. Length of the mean recirculation region is related to the peak location of the standard deviation value considering that the peak occurs just upstream of the mean reattachment position [5]. The strongest separation occurs for 30° wind angle where the highest suction can be noticed.

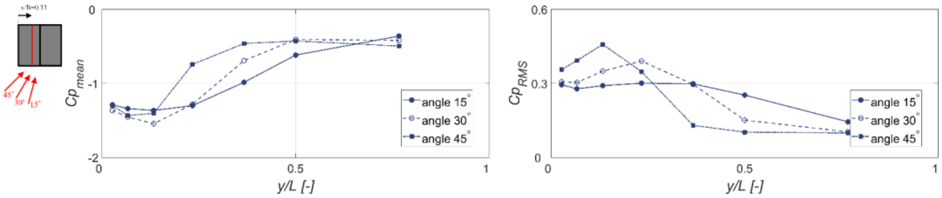


Figure 9. Mean and standard deviation distribution of pressure coefficient along roof's line x/B=0.33 for 15°, 30° and 45° wind angles

The plot in *Figure 10* shows the distribution of C_p coefficients ($C_{p,mean}$ and $C_{p,RMS}$) for 30° wind angle along lines x/B of 0.2, 0.33 and 0.4 parallel to the ridge. In this figure, spreading of the cone vortex in the direction from the upstream corner to the ridge is visible.

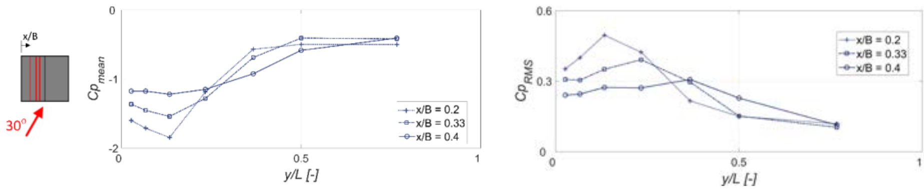


Figure 10. Mean and standard deviation distribution of pressure coefficient along the roof lines x/B of 0.2, 0.33 and 0.4 for 30° wind angle

Values of $C_{p,mean}$ in the zone close to the upstream edges are high for both 30° and 45° wind angle, reaching up to the value of -2.2. In the case of 45° wind angle distribution of $C_{p,mean}$ in *Figure 8*d shows symmetry.

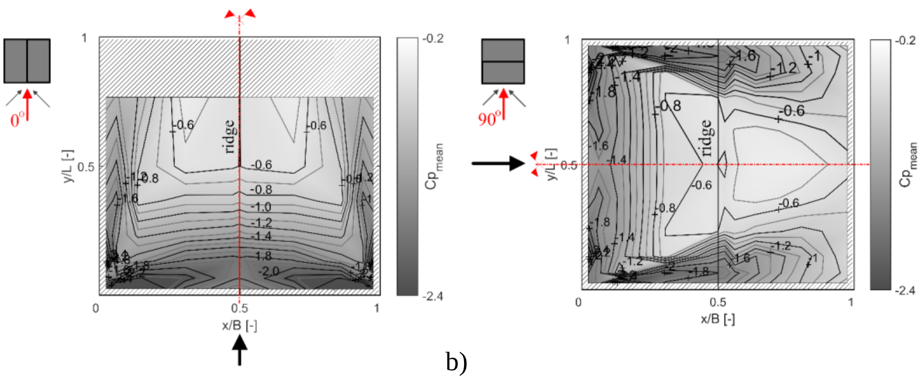
The case of 90° approaching wind angle, presented in *Figure 8*e, shows similarity with the case of 0° wind angle. The reduction of the surface pressure close to the upstream edge resulting in $C_{p,mean}$ =-1.5 is followed by a growth of the pressure downstream where $C_{p,mean}$ =-0.2.

In all analysed wind angles the whole roof area was in suction. Similar results of pressure distribution over the roof regarding different wind angles were found in the literature [7] for the flat roof of the high rise building and in [1] for low-rise building with gabled roof.

An envelope of the mean surface pressure coefficients

An envelope of experimentally obtained values of $C_{p,mean}$ over the roof of the hanger is presented in *Figure 11*. Results for wind angles of 0°, 15°, 30° and 45° are combined to create the envelope for the case in *Figure 11*a. Also, the symmetry property is utilized for the right-hand side of the roof. For the case in *Figure 11*b, results for 45° and 90° wind angles have been used for the envelope. The symmetry property is utilized for the upper half of the roof.

Looking at the distribution of the $C_{p,mean}$ pressure coefficient at the envelope in *Figure 11* for both approaching angles certain zones with extreme values of pressure coefficients are noticeable. First one is a zone around the corners on the windward side of the roof where the highest values of $C_{p,mean}$ occurs. The second one is close to the windward edge with a bit smaller $C_{p,mean}$ values but still high compared to the leeward side of the roof. One more, third zone is distinguished close to the side edges in the longitudinal direction. This zone of high suction is a consequence of cone vortex which appears when wind angle deviates from 0° or 90°.



a) b)

Figure 11. Envelope of experimentaly obtained $C_{p,mean}$ coefficients for the approaching wind angle of a) 0° and b) 90°

4. CONCLUSION

Based on the results of the experimental analysis presented in this paper, the following conclusions can be drawn:

- Surface pressure distribution is highly affected by approaching wind angle;
- Cone vortex appears close to the windward edge for wind angles of 15°, 30° and 45°, where the strongest separation occurs for 30° wind angle;
- Certain zones of extreme values of $C_{p,mean}$ pressure coefficient can be allocated at the envelopes presented in section 3, one, around the corners on the windward side of the roof, another, close to the windward edge and one close to the side edges in the longitudinal direction.

For the design of structures where wind load has a strong impact, sometimes tracking recommendations in the design codes is not enough for a deeper understanding of the issues. For such problems, depending on available resources, one should consider further experimental tests or numerical investigation (CFD), which is also left as an option in the design codes.

ACKNOWLEDGEMENT

The authors would like to acknowledge the support provided by the COST-Action TU1304 – to sponsor the Short Term Scientific Mission in which this work was undertaken. The time and support received at the Ruhr-University Bochum by the Dr.-Ing. Christian Neuhaus and Mr. Ulf Winkelmann are also acknowledged. Also author KKV would like to acknowledge the financial support by the Ministry of Education, Science and Technological development of the Republic of Serbia, in the framework of the scientific project III 42012.

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EKSPERIMENTALNO ISPITIVANJE DEJSTVA VETRA NA NISKE INDUSTRIJSKE OBJEKTE

Резиме: *Cilj ovog rada je da se istraži raspodela pritisaka na niskim industrijskim objektima usled dejstva vetra na osnovu rezultata eksperimenata iz aerotunela u atmosferskom graničnom sloju. Model objekta je hangar sa dvovodnim krovom pog uglom od 5°. Srednje vrednosti kao i fuktuacije koeficienata pritiska merene na površini krova i bočnim zidovima diskutovane su u radu. Uzeto je u obzir pet uglova dejstva vetra, 0°, 15°, 30°, 45° i 90°. Istraživanje može da pruži osnovno razumevanje ponašanja vetra, kao i uticaje različitih pravaca vetra na niske industrijske objekte sa dvovodnim krovom.*

Кључне речи: *Aerotunel, niska zgrada, pravac vetra, koeficijent pritiska*