Pressure coefficient on flat roofs of rectangular buildings

T. Lipecki

Faculty of Civil Engineering and Architecture, Lublin University of Technology, Poland.

Abstract
The paper deals with a distribution of a normalized pressure coefficient $C_p$ on the surface of flat roofs of medium-rise and high-rise buildings of rectangular cross-sections. The values of $C_p$ and $\sigma_p$ were received from boundary layer wind tunnel tests. Six different cases of the approaching flow and two groups of rectangular cross-sections of side ratios of 1:2 (2 models) and 1:4 (2 models) were applied in measurements. Varying angle of wind attack from 0° to 90°, every 15° was considered. Moreover, changes of aerodynamic pressure coefficients near the top of the models due to three dimensional characteristics of the flow around the free-end were considered.

1 Introduction
Different measurements on flat roofs both in wind tunnel tests and in full-scale as well as computer simulations with use of CFD were performed by many researches. The measurements were mainly focused on pressures and wind velocities over flat roofs of low-rise buildings of circular (Uematsu et al., 1999, Uematsu et al., 2008), square or rectangular cross-sections (Fu et al., 2005), with and without parapets (Stathopoulos et al., 1999), with different multi-level parts of the roof (Cao et al., 2012) or taking into account interference effect of neighbouring buildings (Pindado et al., 2011). Angles of wind attack perpendicular to the edges of the roof were considered (Richard & Hoxey, 2006, Hoxey, 2008), but many researches focused on oblique angles to discover conical vortices over the roof (Banks et al., 2000, Wu et al., 2001, Banks & Meroney, 2001, Kawai, 2002, Ono et al., 2008, Tryggeson & Lyberg, 2010, Li et al., 2012). In this paper the measurements of pressures on the flat roofs of vertically placed rectangular prisms are presented. Tests were conducted in the Boundary Layer Wind Tunnel in the Laboratory of Wind Engineering, Cracow, Poland. The considered ratios of roof dimensions were 1:2 (2 models) and 1:4 (2 models). Prisms of the same side ratio and different aspect ratios were examined. Dynamic surface pressures were measured with use of pressure scanners and then normalized pressure coefficients were calculated. The dependence on the wind structure and the angle of wind attack in the range of 0°-90°, every 15° was investigated.

2 Research description

2.1 Wind tunnel conditions
The rectangular prisms of the dimensions collected in Table 1 ($H$ is the height of the model, $B$ is the longer side of cross-section, $D$ is the shorter side of the cross-section, so $H/B$ is the aspect ratio, $B/D$ is the side ratio) were placed vertically in the working section of the wind tunnel.

The influence of wind structure described by the mean wind speed profile, turbulence intensity profile and PSD function was examined. Six flows with significantly different characteristics were chosen for
further measurements. Information about the wind field can be found in papers by Bęc et al. (2011), Lipecki & Jamińska (2012). Wind speed and turbulence intensity profiles are presented in Fig. 1.

Table 1: Models used in wind tunnel tests.

<table>
<thead>
<tr>
<th>Model</th>
<th>$H$</th>
<th>$B$</th>
<th>$D$</th>
<th>$H/B$</th>
<th>$B/D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>100</td>
<td>40</td>
<td>20</td>
<td>2.5</td>
<td>2</td>
</tr>
<tr>
<td>R2</td>
<td>100</td>
<td>40</td>
<td>10</td>
<td>2.5</td>
<td>4</td>
</tr>
<tr>
<td>R3</td>
<td>100</td>
<td>20</td>
<td>10</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>R4</td>
<td>100</td>
<td>20</td>
<td>5</td>
<td>5</td>
<td>4</td>
</tr>
</tbody>
</table>

Figure 1: Wind characteristics: a) mean wind speed profiles, b) turbulence intensity profiles.

2.2 Pressure measurements

Pressure taps were installed on the top cover of prisms according to the layout presented in Fig. 2.

Mean pressure coefficients were calculated according to the equation:

$$C_p = \frac{p}{p_0}$$  \hspace{1cm} (1)

where $p$ is the mean dynamic pressure measured at the point on the roof surface calculated as the mean value in time duration $t = 30$ sec., $p_0$ is the reference mean dynamic pressure (in time $t = 30$ sec.), calculated from: $p_0 = 0.5\rho v_0^2$, where: $\rho = 1.25$ kg/m$^3$ is the air density, $v_0$ is the reference wind speed measured in the right front of the model in undisturbed flow at the height $h = 70$ cm. The standard deviation of the mean wind pressure was also calculated. The exemplary time history of dynamic pressures $p_i$ in time duration $t$ is presented in Fig. 3. The sampling frequency was equal to 200 Hz, that gave 6000 probes in time $t = 30$ sec. The system accuracy was 0.1% and not less than 0.1 Pa. More information on pressure measurements on walls can be found in Lipecki et al. (2011, 2012).
3 Pressure coefficient distribution on flat roofs

Exemplary results of the pressure coefficient distribution are presented in Figs 4-5 in dependence on the wind structure (Fig. 4, at the angle of wind attack 0°), and in dependence on the angle of wind attack (Fig. 5, profile 1). Results are related to models R1 (1:2) and R2 (1:4) in Fig. 4 and to all models in Fig. 5. The dimensions of the roofs at respective horizontal and vertical axes in spatial plots are given in cm. Constant range of \( C_p \) values was applied: \( C_{p_{\text{max}}} = 0 \), \( C_{p_{\text{min}}} = -4.6 \), according to the enclosed legend. The longer side was set perpendicularly to the mean wind direction in case of the wind attack angle equal to 0°, the step of model rotation was equal to 15° according to Fig. 4a.

![Figure 4a](image)

Figure 4a: Definition of the angle of wind attack.

![Figure 4b](image)

Figure 4b: Spatial distribution of \( C_p \) on roofs, in dependence on wind structure case, for the angle of wind attack 0°, a) definition of the angle of wind attack, b) model R1, c) model R2.
Pressure coefficient $C_p$ distributions are similar in all cases of the incoming flow, as well as in all cases of considered models of side ratios of 1:2 (R1 and R3) and 1:4 (R2 and R4). Analysing spatial distributions on the roofs it can be seen that a greater suction appears at the angle of wind attack equal to 90° than 0°, in most cases of the flow, except the profile 1 which is characterized by the lowest exponent alpha in the power-law wind profile. It is related to both groups of models of side ratios of 1:2 and 1:4, and moreover, differences are greater for the smaller ones R3 and R4.

Much greater fluctuations in the pressure coefficient values $C_p$ on the roof are observed at the angle equal to 90°, so in case when wind attack the shorter wall. There is a significant reduction in suction close to the leeward edge. Changes in the maximum and minimum coefficients ($C_{p,max}$, $C_{p,min}$) of the mean pressure, in dependence on wind structure, at angles of wind attack 0° and 90° are presented in Fig. 6a, b. The greatest relative difference between the maximum $C_{p,max}$ and minimum $C_{p,min}$ suction on the roof, for particular wind structures and for the angle 0° is in case of mode R1, profile 2 and is equal to 0.603, whereas for angle 90° is in case of model R2, profile 2 and is equal to 1.796.

The highest values of suction were obtained, in majority of cases, for the profile 2, the lowest for profiles 5 and 6, for which the flow is characterized by greater exponent alpha and higher turbulence.
The differences between the highest and the lowest values of suction measured for different flows, at the angle of wind attack equal to 0° are as follows: R1: 0.473, R3: 0.534, R2: 0.506, R4: 0.472, and at the angle equal to 90°: R1: 0.373, R3: 0.353, R2: 0.726, R4: 0.420. Generally, larger differences between the profiles are for the angle 0°, so in case of wind action on longer wall.

Conical vortices which produce large increase in suction were observed on roofs of aspect ratio of 1:2 for wind angles in the range 0°-60° and on roofs of aspect ratio 1:4 for wind angles in the range 30°-60°. In general, the largest suction appears for the angle of wind attack equal to 45°. Maximum values of suction coefficients \( C_{p, \text{max}} \) in all measurements and corresponding angles are put together in Table 2. Additionally, maximum and minimum values of the \( C_p \) for angle 45° are presented in Fig. 6c. The range of wind attack angles for which the increase in suction caused by conical vortices were observed are clearly visible in Fig. 7. In this figure values of \( C_{p, \text{max}} \) in dependence on wind angles are presented. As it can be seen higher values of \( C_{p, \text{max}} \) were obtained in case of larger roofs R1 and R2.

### Table 2: Maximum suction coefficient \( C_{p, \text{max}} \) with respective angle of wind attack.

<table>
<thead>
<tr>
<th></th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
<th>P6</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
<th>P6</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha )</td>
<td>30°</td>
<td>45°</td>
<td>45°</td>
<td>45°</td>
<td>45°</td>
<td>45°</td>
<td>R4</td>
<td>-3.15</td>
<td>-3.35</td>
<td>-3.17</td>
<td>-2.93</td>
<td>-2.60</td>
</tr>
<tr>
<td>R3</td>
<td>-3.30</td>
<td>-3.46</td>
<td>-3.59</td>
<td>-3.59</td>
<td>-3.20</td>
<td>-2.87</td>
<td>R4</td>
<td>45°</td>
<td>45°</td>
<td>45°</td>
<td>45°</td>
<td>45°</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>45°</td>
<td>45°</td>
<td>45°</td>
<td>45°</td>
<td>45°</td>
<td>45°</td>
<td>R4</td>
<td>45°</td>
<td>45°</td>
<td>45°</td>
<td>45°</td>
<td>45°</td>
</tr>
</tbody>
</table>

The largest increase in suction appears at windward edge of the roof (angles 15° and 30°) and is slightly shifted to the longer edge (angles 45° and 60°), which becomes the side edge. In case of model R1 (1:2) the increase of suction at angles 15° and 30° is exactly in corner (the shift on plots is caused by location of pressure tap which were 4 cm from shorter edge), for angles 45° and 60° maximum suction appears about 12 cm from the shorter edge and it is 0.3 of the size of longer edge. Similar dependences were observed on the roof of model R3 (1:2). In case of model R2 (1:4) and angle 30° maximum suction is in windward corner, and for angle 45° it is 8 cm from shorter edge, so in 0.2 of the size of longer edge, for angle 60° it is 12 cm from the shorter edge and it is 0.3 of the dimension of...
longer edge. Similar relations were noticed on smaller roof of the model R4 (1:4), but for the angle 60° maximum suction is shifted to about 0.4 of the longer edge.

4 Reduction of pressure coefficients on walls near the roof

The decrease in values of aerodynamic pressure coefficients appears near the roof on the windward wall. This is caused by the three-dimensional character of the flow around the free-end of the prism. The vertical changes of the pressure coefficient from 72 cm, near one third of the prism height to 97 cm near the top are presented in Fig. 8.

![Figure 8: Decrease in pressure coefficients on windward wall near the flat roof](image)

- a) model R1, b) model R3, c) model R2, d) model R4,
There are values of $C_p$ measured along the centre line of the windward wall: longer one for angles of wind attack $0^\circ$-$45^\circ$ and shorter one for angles $60^\circ$-$90^\circ$. The significant decrease in values appears from 92 cm (location of pressure taps) and is similar in all cases of the wind structure. The drop in $C_p$ is more evident in positions when the longer wall is the windward one, so for angles $0^\circ$-$45^\circ$. Moreover, there is almost no decrease, for angles $60^\circ$-$90^\circ$ in case of models with side ratios of 1:4.

5 Conclusions

Pressure measurements on vertical prisms of side ratios of 1:2 and 1:4 and different aspect ratios were carried out in the wind tunnel. Coefficients of the mean wind pressure were calculated on flat roofs as well as on vertical walls in different conditions of the incoming wind and for consecutive angles of wind attack. Patterns of the spatial distribution of $C_p$ on roofs are similar between wind structure cases and between models, as well, but for different side ratios they slightly vary. The same statement is related to other angles of the wind attack. Values of $C_p$ are significantly different between profiles for the single model. Greater suction appears at the angle of wind attack equal to $90^\circ$ than to $0^\circ$, in most cases of the flow. Much greater fluctuations of $C_p$ values are observed when wind attacks the shorter wall. There is large decrease of values close to leeward edge in that case. The lowest values of $C_p$ were measured for profiles 5 and 6, for which the flow is characterized by greater exponent alpha and higher turbulence. Conical vortices were observed on roofs of aspect ratio of 1:2 for wind angles in the range $0^\circ$-$60^\circ$ and on roofs of aspect ratio 1:4 for wind angles in the range $30^\circ$-$60^\circ$. Higher values of suction coefficient related to conical vortices were obtained in case of larger roofs R1 and R2.

The significant decrease in $C_p$ values caused by 3D character of the flow around the free-end of the prism appears from 92 cm of the height of the vertical windward wall. The drop in $C_p$ is more evident in positions when the longer wall is the windward one. Moreover, there is almost no decrease, for angles $60^\circ$-$90^\circ$ in case of models with side ratios of 1:4.

6 References


