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## WIND TUNNEL TESTS OF WIND PRESSURE DISTRIBUTIONS OVER WALL AND ROOF SURFACES OF A UTILITY BUILDING WITH OPENWORK SIDE WALLS

### BADANIA MODELOWE ROZKŁADÓW CIŚNIENIA WIATRU NA POWIERZCHNIACH ŚCIAN I DACHU HALI GOSPODARCZEJ Z AŻUROWYMI ŚCIANAMI BOCZNYMI

#### Abstract

This article presents results of model tests of pressure distributions over interior and exterior surfaces of a utility building model carried out in an boundary layer wind tunnel. The tests were carried out taking into consideration different variants of solidity ratio coefficient values of the structure's side walls. The main aim of the analyses was to determine the influence of the solidity ratio coefficient values of the side walls on the wind pressure distribution over the interior and exterior surfaces of the object. Four configuration variants of the side walls were taken into account for two directions of air flow – perpendicular to the gable wall and perpendicular to the side wall. The achieved results were analysed.

*Keywords: wind tunnel tests, wind action on buildings, wind pressure distributions on wall and roof surfaces of a building*

#### Streszczenie

W artykule przedstawiono rezultaty badań modelowych w tunelu aerodynamicznym z warstwą przyścienną rozkładów ciśnienia wiatru na powierzchniach wewnętrznych i zewnętrznych modelu budynku gospodarczego. Badania przeprowadzono w różnych wariantach wartości współczynnika wypełnienia ścian bocznych konstrukcji. Celem zasadniczym przeprowadzonych analiz było wyznaczenie wpływu wartości współczynnika wypełnienia ścian bocznych na rozkład ciśnienia wiatru na powierzchniach wewnętrznych i zewnętrznych obiektu. Rozpatrzono cztery warianty konfiguracji ścian bocznych przy dwóch kierunkach napływu powietrza: prostopadłym do ściany szczytowej i prostopadłym do ściany bocznej. Przeprowadzono analizę uzyskanych wyników.

*Słowa kluczowe: badania modelowe w tunelu aerodynamicznym, działanie wiatru na budynki, rozkłady ciśnienia wiatru na powierzchniach ścian i dachu budynku*

DOI: 10.4467/2353737XCT.15.121.4158

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## 1. Introduction

In new utility buildings, it is now common to use technology in which ventilation systems are assembled in the form of permeable wind curtains on the side walls of halls and buildings mainly destined for use as storehouses, warehouses, driers, cow-houses, pigsties and horse breaking-in houses. Such a solution assures a continuous air exchange inside the object; moreover, it protects against sun exposure, insects, and limits dust getting in from the outside. The curtains are made of plastic of different parameters. An example of such a type of curtain in a utility building is shown in Fig. 1.



Fig. 1. A utility building with openwork side walls

The most commonly used solutions incorporate a two-layer system. Each layer is rolled and unrolled independently (vertically or horizontally), the outside layer always being an impenetrable fabric of permeability not exceeding 5%. The inside layer is a basic layer of determined net mesh dimensions. The state when the outside layer is fully unrolled is practically a state corresponding to a building made of solid walls. Situations with only the second layer, made of a permeable net, are realised. In the exploitation practice, situations may arise when the curtains can be wholly uplifted and then both side facades remain fully opened. The curtains can be steered manually or automatically – that is to say that the curtain draws when a given wind velocity is exceeded. Possible situations realised in practice are shown in Fig. 2.

From the design point of view, the curtain's permeability in reference to the wind pressure inside the object is of the greatest importance [1, 2]. In the designing process, additional load states occur which can change the values of wind action on particular structural elements – these are connected with various configurations of wind curtains realised on the side walls.

The aim of the tests carried out in an aerodynamic tunnel was to determine the influence of different configurations of wind curtains assembled on the side walls, on the wind pressure distribution over the surfaces of the structure. In order to carry out tests in a tunnel, a model

of utility building was built – this was based on typical solutions adopted in rural areas. Mean wind pressure was measured on external and internal surfaces of roof slopes and on the gable wall of the building model; mean wind pressure coefficients were then determined. Two wind directions were taken into account, one perpendicular to the gable wall, and one perpendicular to the side wall. Four variants of side walls which reflect actual cases realised in the exploitation practice of objects of this type were considered.

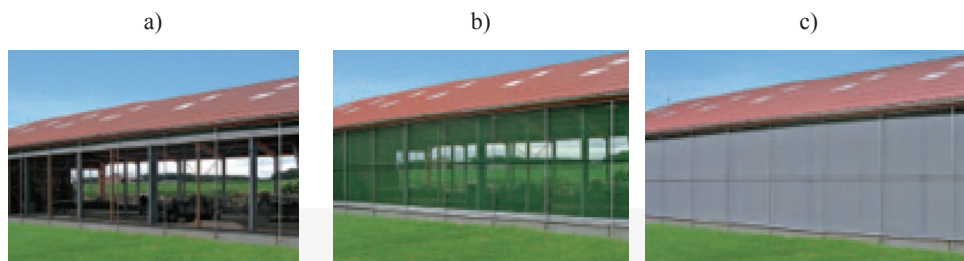


Fig. 2. A utility building with side air curtains: a) variant with uplifted curtains; b) variant with curtains permeable to wind; c) variant with curtains impermeable to wind

## 2. Description of the building model

The utility building model to be tested in an aerodynamic tunnel was made at a scale of 1:30 – this was dictated by the size of the measured space. The model consists of two longitudinal walls, two gable walls, two roof slopes and a base. The elements of the model were made of plywood. The roof is a symmetrical gable roof. Fig. 3 presents the scheme of the basic building elements.

Table 1 presents basic parameters of the building and the model

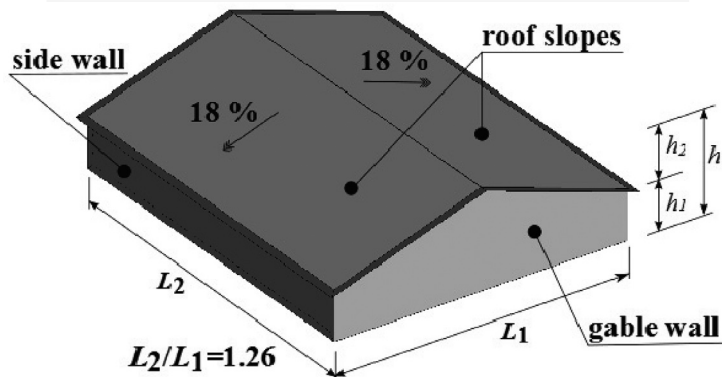


Fig. 3. Scheme of the utility building considered during wind tunnel tests

Basic parameters of the building and the model

Parameter		Actual dimension [m]	Model dimension [mm]
Width	$L_1$	37.80	1260
Length	$L_2$	30.00	1000
Height at eaves	$h_1$	5.10	170
Height at roof ridge	$h$	10.20	340
Inclination angle of roof slope	$\alpha$	18°	18°
Height of longitudinal walls plinth	-	0.50	20

The side walls of the model were built in four variants:

- variant I – the building had no side walls, the solidity ratio value  $\varphi = 0$  was realised;
- variant II – side walls were made of a net of solidity ratio  $\varphi = 0.45$ ;
- variant III – side walls were made of a net of solidity ratio  $\varphi = 0.6$ ;
- variant IV side walls were made of plywood, thus a solidity ratio  $\varphi = 1.0$  was realised.

Anti-wind curtain types applied in particular variants realised during model tests are shown in Fig. 4.

Features of nets applied during the tests on the producer's data are shown in table 2

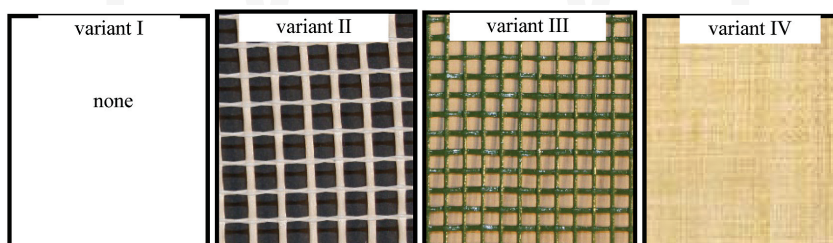


Fig. 4. Types of anti-wind curtains: a) none in variant I; b) a net with solidity ratio equal to 0.45 in variant II; c) a net with solidity ratio equal to 0.60 in variant III; d) impermeable to wind in variant IV

Parameters of the anti-wind curtains

	Variant I	Variant II	Variant III	Variant IV
Designation	Open facade	WS-N 30.30	SG-S	Closed facade
Material	-	Polyester + PVC	Polyester + PVC	plywood
Mesh	-	10 mm x 10 mm	6 mm x 6 mm	-
Filling degree	$\varphi = 0.00$	$\varphi = 0.45$	$\varphi = 0.60$	$\varphi = 1.00$
Density	-	160 g/m <sup>2</sup>	280 g/m <sup>2</sup>	-

The applied nets are made of polyester combined with elastic PVC, as a result, the material has great mechanical strength and successfully takes over wind pressure. Furthermore, what is advantageous is that the nets are resistant to weather conditions such as snow, temperature and humidity. In model tests, the equality value of the solidity ratio of the side walls was accepted as the nets' aerodynamic similarity criterion, in the actual and the model scale.

### 3. Characterization of the wind tunnel tests

The tests were carried out in an aerodynamic tunnel with a boundary layer, making use of the building model at 1:30 scale. Two wind directions were considered: perpendicular to the gable wall, marked as  $0^\circ$ , perpendicular to the side wall of the structure, marked as  $90^\circ$  (see Fig. 5).

The building model in the test section of the wind tunnel together with a model configuration at two analysed wind directions is shown in Fig. 6.

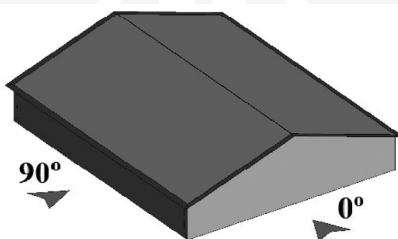


Fig. 5. The wind directions for which the wind pressure results were obtained

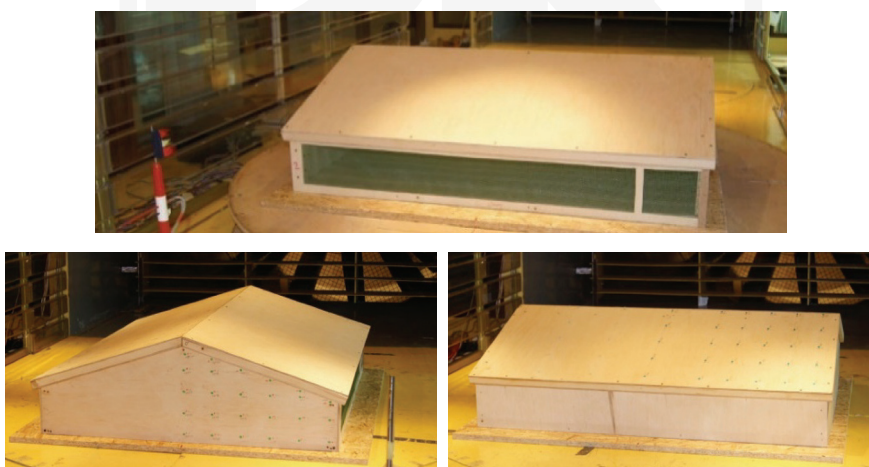


Fig. 6. The building model in the wind tunnel working section and the two analysed configurations of the wind direction during tests

The analysed model has two vertical symmetry planes; therefore, making use of this fact, detecting wind pressure taps were placed on the half of one gable wall and the half of one roof slope, as shown in Fig. 7.

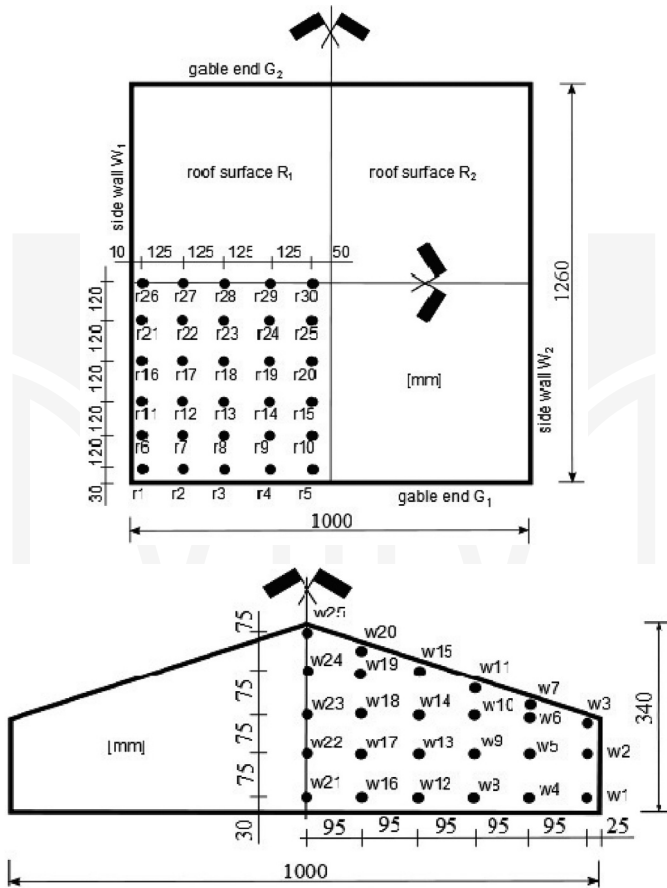


Fig. 7. Distributions of pressure taps on the gable wall and the roof slope

The distribution of pressure taps presented in Fig. 7 was the same on the internal and the external surface of the gable wall and the roof slope. On the roof slope, 30 points were assembled on the outside surface and 30 points on the internal surface in a regular manner. In the case of the gable wall, there were 25 points on each side (external and internal). Making use of the system double symmetry and carrying out the tests at four wind directions (A, B, C, D), illustrated in Fig. 8 allowed determining the wind pressure distribution coefficient over the whole area of the gable walls and over the roof slopes for two analysed wind directions  $\text{dir} = 0^\circ$  i  $\text{dir} = 90^\circ$  (see Fig. 5).

For each wind direction, the measurements were taken in four variants of side wall solidity ratio (see Fig. 9).

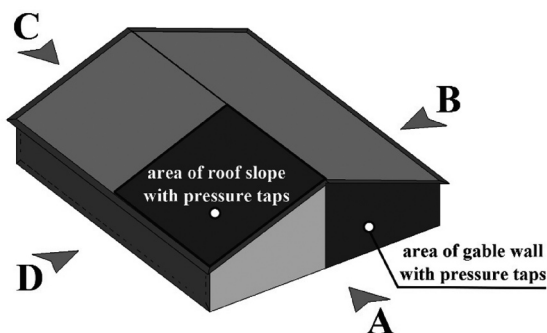


Fig. 8. The wind directions considered during wind tunnel tests

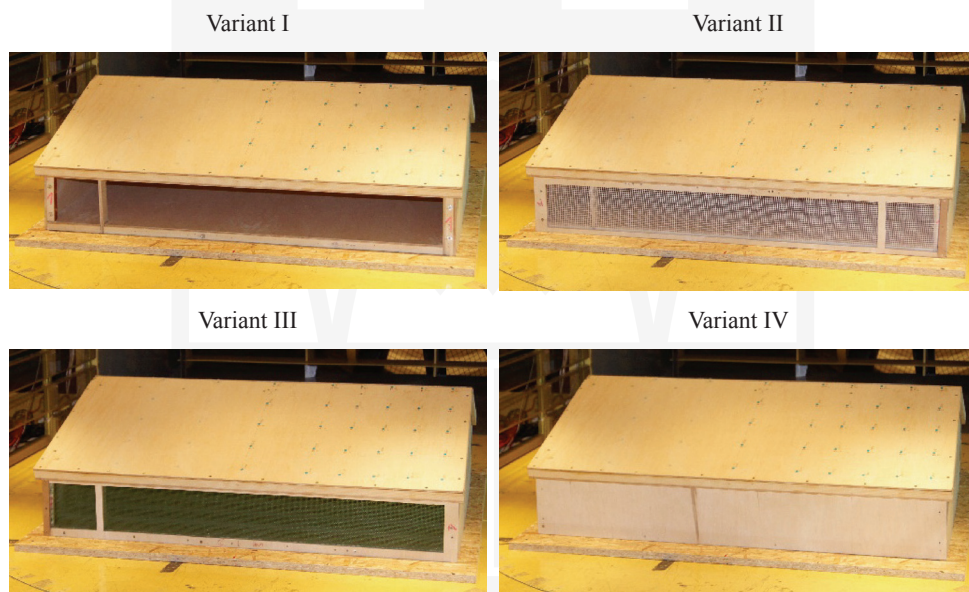


Fig. 9. Model of the utility building in the four variants of the side wall configuration in the wind tunnel working section

The experiments were performed with the following conditions: the mean wind velocity profile was constant; area-averaged turbulence intensity at the level of the building roof ridge was  $I_v = 25\%$ ; the reference velocity at the height level of the roof model was  $V_{ref} = 13.0$  m/s. The basic geometric dimensions of the working section of the tunnel were: width – 2.20 m; height – from 1.40 m at the beginning to 1.60 m at the end of the working section; length – 10 m. Formation of the mean wind velocity profile and atmospheric turbulence takes place in the first part of the working section at a length of 6 m by use of respective tubulisation networks, barriers, spires and blocks of respective geometry and a mechanically controlled height. Four characteristic segments each of 2.5 m long can be distinguished in the working

section. The side walls of the front segment are full (with windows) 2.20 m apart. The other segments have slotted side walls (with horizontal controlled slots aiming at diminution of the so called blockage effect) 2.20 m apart and full side walls with windows 3.40 m apart. In the third and fourth segment of the working section, there are two circular turntables 2 m in diameter, rotational by up to  $180^\circ$ . The first turntable is designed mainly for examination of the flow around phenomena, their visualization and for examination of wind environment climate. The other turntable is designed mainly for aerodynamic and aeroelastic investigations of buildings and structures. In the upper part of the working section, there is equipment for fixing all kinds of measurement probes and their controlled displacement for the whole working section in directions  $x$ ,  $y$ ,  $z$ . The roof of the working section may change its height; this permits control of the gradient of static pressure in the working section. Views from the side (a) and from the top (b) of the wind tunnel are presented in Fig. 10. All of the wind tunnel properties are optimized due to size of the model, its scale, external shape, roughness of the terrain – these properties are: configuration of adjustable ceiling; ejection of floor blocks; RPM of the fan; type of circulation; settings of barrier and spires. A profile pressure probe, a pressure electronic scanner – which allows measuring differential pressure in 64 taps simultaneously – and a hot-wire anemometer system were used during the experiments.

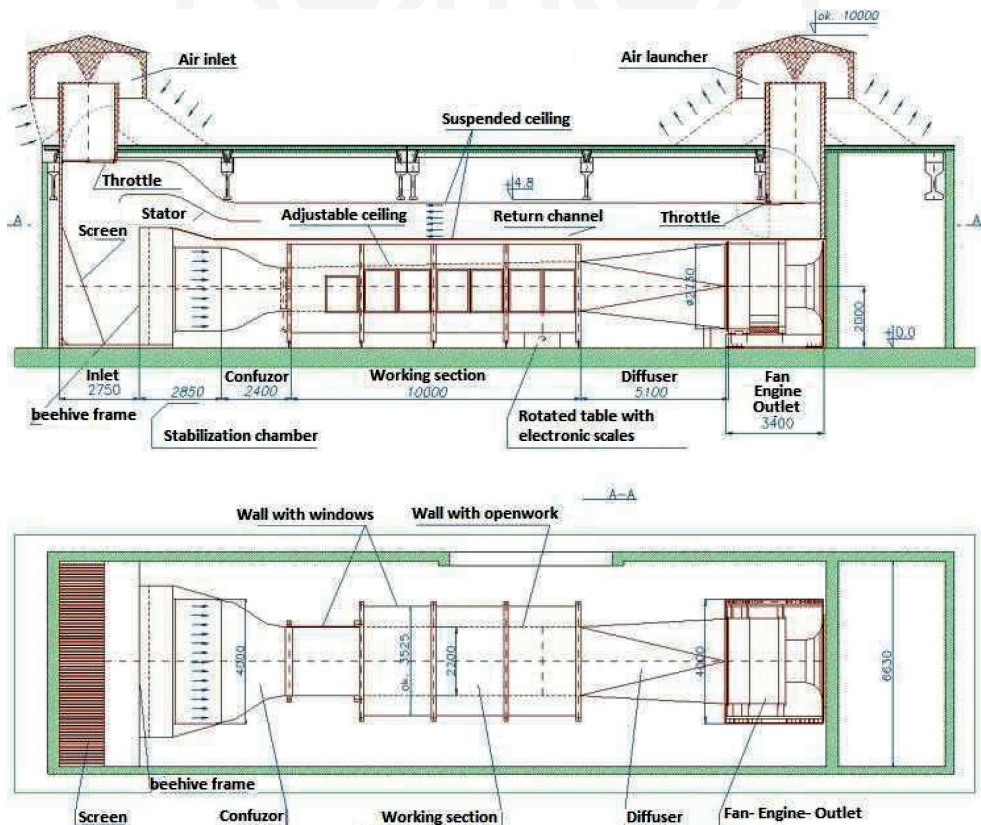


Fig. 10. Views from the side and from the top of the wind tunnel



#### 4. Results of the wind tunnel tests

Wind pressure was measured on the external and internal surfaces of the roof slopes and the gable wall of the building model. Having determined the mean wind pressure value and having measured the reference pressure at the height of the roof edge of the building model, the values of wind pressure coefficients were calculated according to formulas 1 and 2:

$$C_{pe}(x, y, z, \text{dir}) = \frac{p_e(x, y, z, \text{dir})}{q_{\text{ref}}} ; C_{pi}(x, y, z, \text{dir}) = \frac{p_i(x, y, z, \text{dir})}{q_{\text{ref}}} \quad (1)$$

$$C_{p,net}(x, y, z, \text{dir}) = C_{pe}(x, y, z, \text{dir}) - C_{pi}(x, y, z, \text{dir}) \quad (2)$$

where:  $p_e(x, y, z, \text{dir})$  – wind pressure on the external surfaces of the building model;  $p_i(x, y, z, \text{dir})$  – wind pressure on the internal surfaces of the building model;  $C_{pe}(x, y, z, \text{dir})$  – the coefficient of the external wind pressure;  $C_{pi}(x, y, z, \text{dir})$  – the coefficient of the internal wind pressure;  $C_{p,net}(x, y, z, \text{dir})$  – the coefficient of the net wind pressure; dir – the wind direction ( $0^\circ$  or  $90^\circ$ ); x, y, z – coordinates in the global system;  $q_{\text{ref}}$  – the reference pressure on the level at the height of the top level of the model roof.

The manner of marking wind pressure values on the internal and external surfaces and differential pressure was assumed according to [2] and shown in Fig.11:

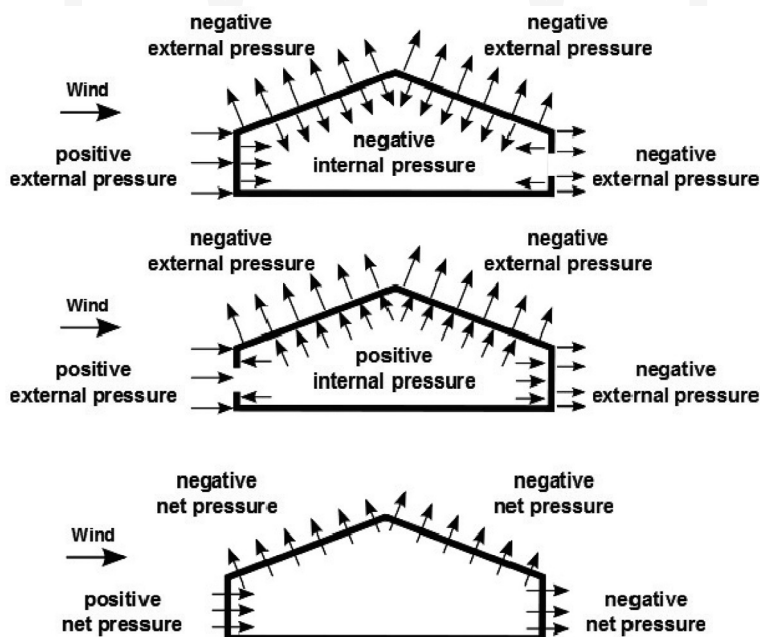


Fig. 11. Wind pressure on the building surfaces [2]

In the article, the results of measurements are presented for two wind directions in accordance with Fig. 12. In the figure, there are also names of the walls and roof slopes for which wind pressure distributions in particular cases were analysed.

Figures 13, 15 and 17 present the maps of wind pressure coefficients distributions on external  $C_{pe}$  and internal  $C_{pi}$  surfaces respectively and differential pressure  $C_{p,net}$  at wind directions  $0^\circ$  and  $90^\circ$  for four analysed variants of side wall construction (I, II, III, IV).

Tables 3, 4, 5, placed below the figures, contain minimum and maximum values of the aerodynamic coefficients of wind pressure on particular surfaces of the model in the discussed measurement situations.

Figures 14, 16 and 18 present comparison of the measured wind pressure coefficient values with the values of coefficients determined on the basis of EN 1991-1-4 Eurocode 1: Actions on structures – Part 1-4: general actions – wind actions [4]. In the figures, the maximum values of measurements are marked with square markers while the minimum values with triangle markers. For reasons of comparison, coefficients provided in the standard were made use of in the following cases:

- vertical walls of rectangular plan buildings – Figure 7.5 and Table 7.1,
- duo pitch roofs – Figure 7.8, Table 7.4a and Table 7.4b,
- canopy roofs – Table 7.7,
- free-standing walls – Table 7.9,
- chapter 7.2.9 – internal pressure.

Maximum values determined on the basis of the standard are marked with a solid line. Minimum values determined on the basis of the standard are marked with a broken line. In some measurement situations determining, on the standard basis, of the maximum or minimum values was impossible because of the lack of data. In such cases, there are no adequate extreme lines referring to standard values. It has to be stressed that the accomplished comparison is approximate because standard situations in many cases do not fully reflect the conditions in the measurement configurations realized in an aerodynamic tunnel. Comparative analyses were carried out using the standard coefficients of external pressure  $C_{pe,1}$ .

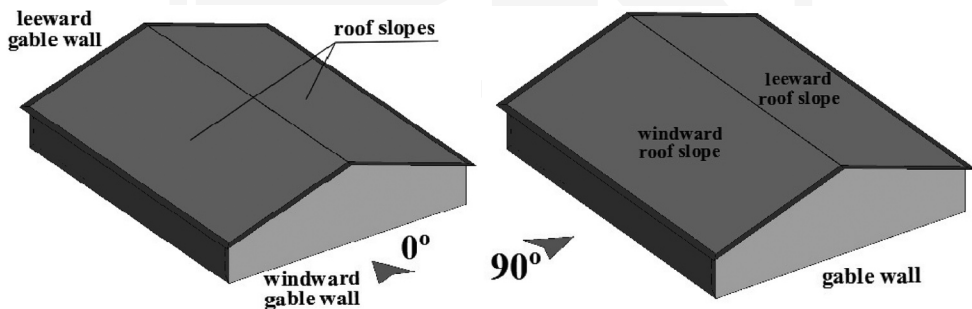


Fig. 12. The building surfaces for the analysed wind directions

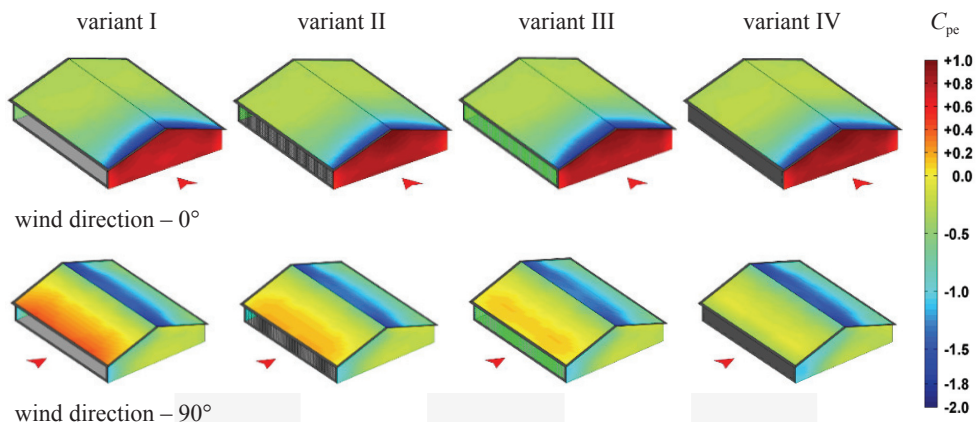


Fig. 13. Distributions of the wind pressure coefficient  $C_{pe}$  over external surfaces

Table 3

**Extreme values of the wind pressure coefficient  $C_{pe}$  over external surfaces – wind tunnel tests results**

		the wind pressure coefficient $C_{pe}$							
variant →		I		II		III		IV	
wind direction	surface ↓	max	min	max	min	max	min	max	min
0°	windward gable wall	0.9	0.4	1.0	0.4	1.0	0.4	1.0	0.4
	leeward gable wall	-0.4	-0.6	-0.4	-0.5	-0.4	-0.5	-0.4	-0.5
	roof slopes	-0.3	-1.9	-0.3	-1.7	-0.3	-1.8	-0.3	-1.8
90°	windward roof slope	0.4	-0.7	0.2	-0.7	0.1	-0.7	-0.1	-0.9
	leeward roof slope	-0.4	-1.8	-0.5	-1.7	-0.5	-1.6	-0.6	-1.8
	gable walls	0.0	-1.2	0.0	-1.1	-0.1	-1.1	-0.1	-1.1

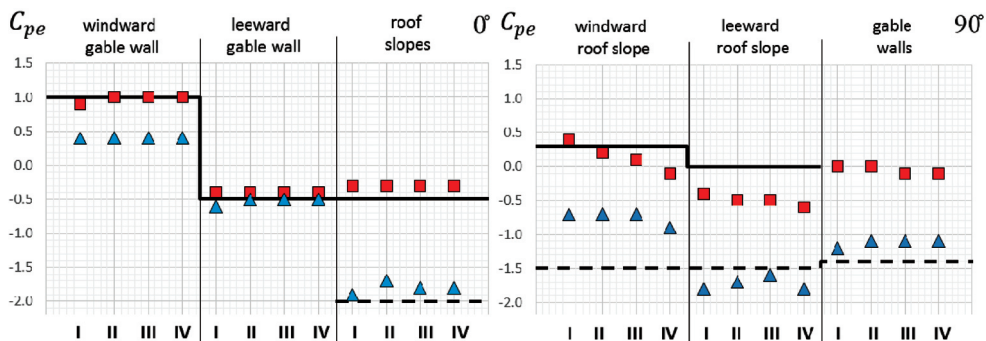


Fig. 14. Distributions of the wind pressure coefficient  $C_{pe}$  over external surfaces in comparison to the values obtained from the standard [4]

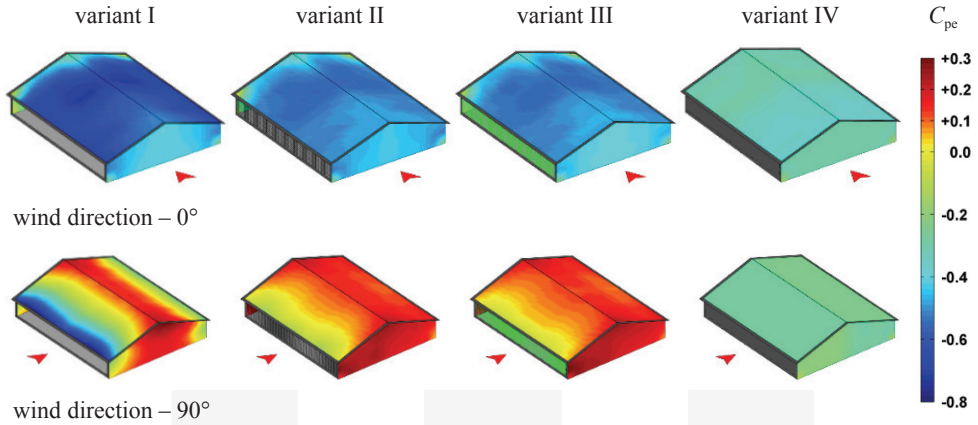


Fig. 15. Distributions of the wind pressure coefficient  $C_{pi}$  over internal surfaces

Table 4

**Extreme values of the wind pressure coefficient  $C_{pi}$  over internal surfaces – wind tunnel test results**

the wind pressure coefficient $C_{pi}$									
variant →		I		II		III		IV	
wind direction	surface ↓	max	min	max	min	max	min	max	min
0°	windward gable wall	-0.1	-0.5	-0.1	-0.5	-0.1	-0.5	-0.1	-0.3
	leeward gable wall	0.0	-0.4	0.0	-0.4	0.0	-0.4	-0.1	-0.3
	roof slopes	0.1	-0.7	0.1	-0.6	0.0	-0.6	-0.3	-0.4
90°	windward roof slope	0.2	-0.8	0.2	-0.2	0.2	-0.1	-0.3	-0.3
	leeward roof slope	0.2	-0.3	0.2	0.1	0.3	0.1	-0.2	-0.3
	gable walls	0.3	-0.3	0.3	0.0	0.3	0.0	0.0	-0.3

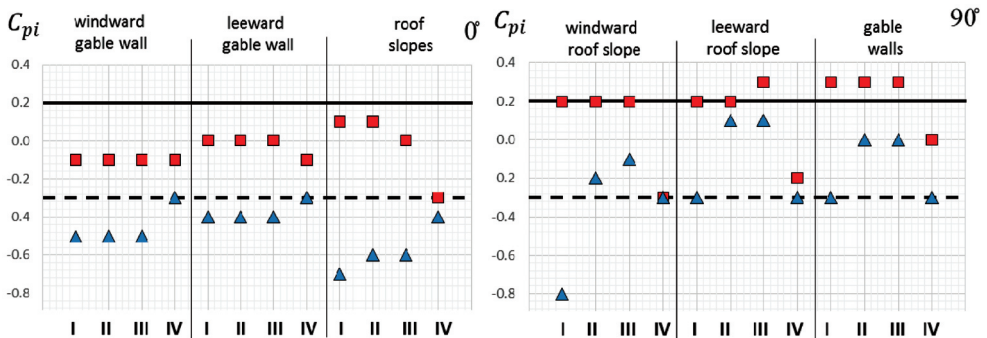


Fig. 16. Distributions of the wind pressure coefficient  $C_{pi}$  over internal surfaces in comparison to the values obtained from the standard [4]

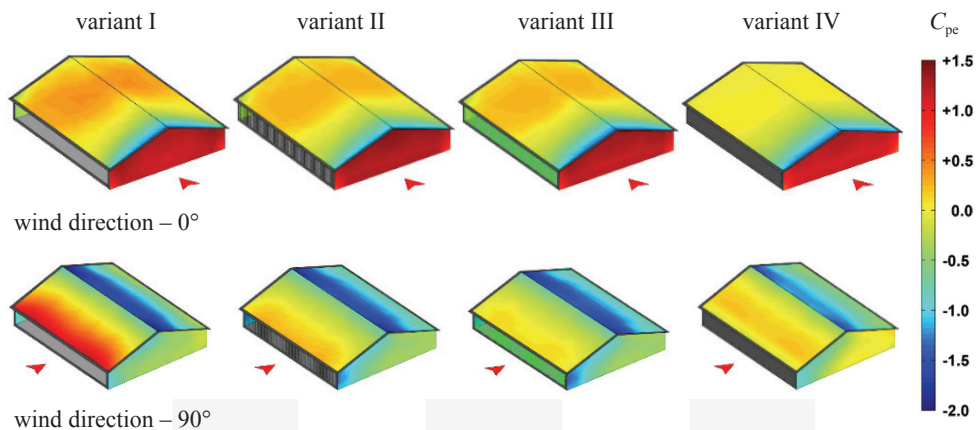


Fig. 17. Distributions of the differential wind pressure coefficient  $C_{p,net}$

Table 5

**Extreme values of the wind pressure coefficient  $C_{p,net}$  – wind tunnel tests results**

the wind pressure coefficient $C_{p,net}$									
variant →		I		II		III		IV	
wind direction	surface ↓	max	min	max	min	max	min	max	min
0°	windward gable wall	1.4	0.5	1.4	0.5	1.4	0.5	1.3	0.4
	leeward gable wall	-0.1	-0.5	-0.1	-0.4	0.0	-0.5	-0.1	-0.4
	roof slopes	0.4	-1.4	0.3	-1.2	0.3	-1.4	0.1	-1.4
90°	windward roof slope	1.1	-0.9	0.3	-0.9	0.1	-0.8	0.2	-0.6
	leeward roof slope	-0.2	-2.0	-0.7	-1.9	-0.7	-1.8	-0.4	-1.5
	gable walls	-0.1	-1.1	-0.3	-1.4	-0.3	-1.4	0.2	-1.0

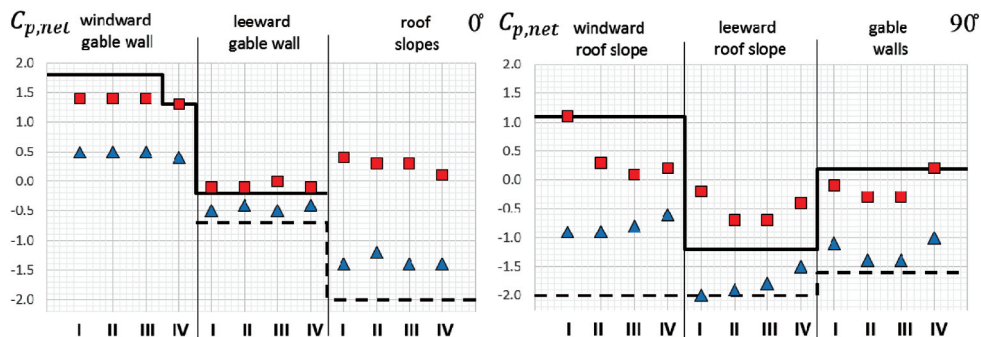


Fig. 18. Distributions of the differential wind pressure coefficient  $C_{p,net}$  in comparison to the values obtained from the standard [4]

The following regularities can be stated from the performed measurement analysis and comparison:

- with reference to wind pressure distributions over external surfaces:
  - for wind direction perpendicular to the gable wall, pressure distribution over the analysed surfaces only slightly depends on the variant of the side wall solidity ratio; distributions measured in an aerodynamic tunnel are practically identical to those obtained from the standard for a closed building;
  - for wind direction perpendicular to the side wall, variation of the wind pressure, depending on the analysed configuration variant of the side wall, can be observed mainly for the positive pressure over the windward slope; the change refers to the lower windward slope and consists of a gradual decrease of pressure together with an increase of side wall solidity ratio coefficient – the values of negative wind pressure on particular external building surfaces only slightly depend on the discussed configuration variant of the side wall.
- with reference to wind pressure distributions over internal surfaces:
  - for wind direction perpendicular to the gable wall, the pressure distribution over the analysed surfaces in variants I to III shows inconsiderable variation – in variant IV (a closed building), the distribution measured in the aerodynamic tunnel is almost a constant value of the inner pressure at a coefficient level -0.3. In variants I – III, the value of inner partial pressure was measured at a level between -0.4 to -0.6 over particular surfaces. Over the roof slopes from the leeward direction, inner pressure coefficient values may reach -0.8 – this is an unfavourable effect, causing roof slope loading;
  - for wind direction perpendicular to the side wall, the character of the inner pressure coefficient distribution in variants I – III is quite different from the variant IV when the structure is closed. In variant IV, the value of inner partial pressure is practically the same as in the case of the direction perpendicular to the gable wall – the distribution is constant and described by a pressure coefficient value of -0.3. A very large variability of the internal pressure coefficient is observed on the windward slope, where its value changes from -0.8 at the eaves area to +0.2 at the roof edge area. In the case of assembling nets on the side walls (variant II and III), the character of pressure distribution changes on the windward slope remains unchanged, while at the same time, a significant reduction of negative pressure occurs at the eaves area up to a pressure coefficient value of -0.2. A characteristic feature of internal pressure distributions over the gable walls and the leeward slope is the occurrence of uniform positive pressure described by a coefficient value of +0.2.
- with reference to differential wind pressure distributions:
  - for wind direction perpendicular to the gable wall, the character of differential pressure coefficient in variants I – IV is similar, while the biggest loading of the roof slopes occurs in the area of leeward direction in variant I;
  - for wind direction perpendicular to the side wall, the character of differential pressure coefficient is similar to the external pressure coefficient distribution. Differential pressure distributions in the case of nets applied (variant II and III) are of a transitional character between pressure distributions typical of the open and closed building.

## 5. General conclusions

The results of the measurements which were carried out in the wind tunnel allow the formulation of the following general conclusions:

- the tests showed that using permeable wind nets on the utility building side walls does not cause load states more unfavourable than those resulting from the open building configuration and the closed building configuration. Net usage causes a transitional state between one configuration and the other;
- applying the current standard [4] in the case of an open building (canopy roof) and a closed building allows the estimation of wind actions on particular roof slopes and gable wall surfaces as envelope actions for cases where nets are applied on the side walls.

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