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ESTIMATION OF CRITICAL WIND SPEED ON THE BASIS OF ROOF BLOW-OFF

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Types of wind storms in Poland and examples of economic damage, threats to human life and health caused by two extreme wind events are presented. Then, a house with the roof blown-off during the derecho wind storm in Poland on August 11-12, 2017, is considered. Based on the rafter framing of the house, i.e. wooden roof structure elements and roof covered, the weight of the roof is calculated. Two cases of the strong connection between rafter plates and knee walls are estimated. With the estimation of connection strength between rafter plates and knee walls, it was possible to calculate the total force required to blow-off the roof of the house. Next, an aerodynamic force acting on the house is calculated using pressure coefficients for a low-rise house with a gable roof. The pressure coefficients were taken from the Tokyo Polytechnic University aerodynamic database. The aerodynamic force acting on the roof blown-off was calculated for a low-rise building with a gable roof for similar ratios for length, width, and height. Three wind directions, for the unknown orientation of the building, were considered, i.e. the wind direction perpendicular, parallel, and oblique to the gable wall. By comparison, the aerodynamic force with the total force required to blow-off the roof of the house, it was possible to calculate the critical wind speed needed for the roof blown-off. This wind speed is much bigger than measured by meteorological stations on the path of the derecho.

Keywords: *derecho wind storm, damage to buildings, roof blow-off, aerodynamic coefficients, critical wind speed*

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1. INTRODUCTION

In Poland, there are threats of financial losses in the economy and to human health and safety caused by forces of nature. A report of the Government Center for Security determined that the greatest potential natural hazards, every year are floods, while wind storms with tornadoes and downbursts are ranked second [1]. This report provides a list of hazards, with the period of their occurrence, and also contains a qualitative assessment of financial losses (very large, large, medium, and small) caused by various hazards - based on historical data.

Types of wind storms in Poland and examples of economic damage, threats to human life and health caused by two extreme wind events are presented. Then, a house with the roof blown-off during the derecho wind storm in Poland on August 11-12, 2017, is considered. Based on the rafter framing of the house, i.e. wooden roof structure elements and roof covered, the weight of the roof was calculated. With the estimation of connection strength between rafter plates and knee walls, it was possible to calculate the total force required to blow-off the roof of the house. Based on the Aerodynamic Database for low-rise buildings from Tokyo Polytechnic University, it was possible to calculate the critical wind load acting on the roof blown-off [2, 3, 4]. By comparison, the critical wind load with the total force required to blow-off the roof of the house, it was possible to calculate the critical wind speed needed for the roof blown-off that is the objective of the paper. This wind speed is much bigger than measured by meteorological stations on the path of the derecho.

2. TYPES OF WIND STORMS IN POLAND

In Poland, there are three types of wind storms [5].

a) Synoptic winds generated by large and deep differences in pressure fields due to cyclical activity on the Atlantic Ocean, central and northern Europe, including Poland. These systems are large in a horizontal dimension. They may extend over a distance of 1,000 km. Several days may be taken to pass the whole distance. The western direction of the wind is constant over many hours. In Poland, it also may occur eastern terrestrial winds that in the winter bring cold air mass and in the summer heat and drought.

b) Thunderstorms are associated with advancing cold fronts. Mostly they are small disturbances in horizontal extent. They derive their energy from heat. In this process, warm moist air is convected upwards to mix the drier upper air. Then rapid cooling occurs, and the air mass loses its buoyancy and starts to rain. A strong downdraft reaches the earth and produces a moderate or strong wind - very often for several minutes. This mechanism may produce the strongest winds known as downbursts. Thunderstorms are also capable of generating severe winds for the creation of favorable meteorological conditions for small–scale air vortices – called tornadoes. In the 21st century a new type of thunderstorm with a long path, a strong storm system is reported in Poland - called "derecho". Up to now, it occurred three times, i.e. on 23 July 2009, 19 July 2015, and 11/12 August 2017. They passed from Germany or the Czech Republic through some Polish provinces with more than 500 km pass [6].

c) Formation of disturbances in the atmosphere in the sub-mountain areas duo to the mountain barrier and creating a convenient situation for the creation of so-called mountain winds (Tatra region – “halny”, Karkonosze region “fen”). These winds are warm, dry, strong, and gusty.

3. EXAMPLES OF ECONOMIC DAMAGE, THREATS TO HUMAN LIFE AND HEALTH CAUSED BY EXTREME WINDS

Due to the possibility of extreme winds which might occur in Poland in future years, it raises the following questions:

a. What order of financial losses in the economy they will cause?
b. Do these phenomena carry a risk to human health and life?

To attempt to answer these questions, let us consider the two fatal and very expensive natural phenomena that took place on August 15, 2008, and August 11-12, 2017, which present different kinds of damage caused by them.

3.1. AUGUST 15, 2008 – TORNADO INTENSITY ESTIMATED IN TORRO SCALE FROM T4 TO T5

The paper [7] documented the widespread damage and human losses after a strong tornado on August 15, 2008. The tornado struck three provinces: Opole, Katowice. and Łódź. The path had a length of 105 km, the width varied from 200 m to 400 m. The tornado 2008 damaged 1624 buildings from which 710 were qualified for repair, 779 for reconstruction and 135 to be demolished; 5 people were killed, 60 people were injured, many hectares of forests were falling, a railway line Gliwice- Strzelce Opolskie was destroyed, and several communes and district roads were impassable by fallen trees.

Table 1 presents the classification of all damaged buildings after detailed surveys and decisions taken by engineers of Polish Building Authorities dealing with what kind of work should be done to buildings, i.e. to repair, reconstruct, or demolish.

Table 1. Classification of buildings to be repaired, reconstructed or demolished [7]

Type of buildings	Number of buildings to repair	Number of buildings to reconstruct	Number of buildings to demolish	Number of buildings damaged
Houses	365	354	29	748
Farm buildings	337	414	96	847
Public buildings	8	11	10	29
Total	710	779	135	1624

In the paper [7], the wind speed of the tornado was estimated in the range of 52 to 72 m/s.

3.2. DERECHO WIND STORM IN POLAND ON AUGUST 11-12, 2017

On August 11-12, 2017, a strong wind storm occurred that resulted in substantial damage in three provinces: Wielkopolskie, Kujawsko-Pomorskie, and Pomorskie. This thunderstorm was one of the costliest wind storms in Polish history. The details about losses are given below - based on the paper [8]:

a) the death of 6 people and 62 people were injured,
b) damage to 16, 091 residential, farm, commercial, and public buildings,
c) crops were destroyed in an area covering 66, 717 hectares,
d) forests were destroyed in an area of approximately 80, 000 hectares,
e) blocked and partially damaged commune, district, and province roads over a length of about 1100 km,
f) damage to 25 high-voltage lines, 300 overhead power line poles, and over 200 cables were knocked down. Due to this damage, over 500,000 consumers were deprived of electricity at the peak of the disaster. The last recipients received electricity after 18 days (2,5 weeks),
g) the amount of losses of an invaluable natural area reached approximately 541 km^2. These include destruction affected numerous forms of the nature protection, i.e. the World Biosphere Reserve "Bory Tucholskie" inscribed on the UNESCO list, nature reserves, areas Nature 2000 (areas of special protection of birds, areas of importance for the Community), landscape parks and protected landscape areas, as well as numerous nature monuments, ecological lands, nature and landscape complexes.

In four places on the path of the derecho wind storm on August 11-12, 2017, the peak wind speeds were recorded as follows [8]: Chojnice: 31.2 m/s (112 km/h), Gniezno: 34.8 m/s (125 km/h), Chrząstowo / Noteć: 36.0 m/s (130 km/h), and Elbląg: 42.0 m/s (151 km/h).

The disaster damage estimation also quantified from an economic perspective. This was done by the Governors of three Polish provinces (Reports [9]). The amount of losses estimated using the replacement method and taking into account the methodology for calculating environmental losses is about EUR 1, 111, 790, 541. These losses include: a) EUR 855, 126, 727 loss in the natural environment, b) EUR 50, 549, 304 loss in agriculture, c) EUR 206, 114, 510 infrastructure losses, i.e. public and private property, sphere economic costs of rescue operations. Additionally, losses in forests estimated for EUR 296, 519, 427.

Based only on described two extreme wind storms and losses that they caused one may state that such extreme wind events in the future will cause significant damage to property and may cause a treat to human safety.

4. ESTIMATION OF CRITICAL EQUIVALENT WIND SPEED OF THE ONE-STORY BRICK HOUSE WITH THE ROOF BLOWN-OFF

4.1. ROOF STRUCTURE, THE WEIGHT OF THE ROOF AND CONNECTION STRENGTH BETWEEN THE ROOF AND KNEE WALLS

Fig. 1 shows the photo of the damaged house, which had a gable roof with the inclination equal 30 degrees with two eaves. This event happened during the derecho wind storm in Poland on August 11-12, 2017. The wooden roof structure presents in Fig. 2 was covered with two layers of roofing paper. During the thunderstorm, the entire roof was blown away by the wind and laid on the ground nearby the house. The knee walls, under the two rafter plates, were destroyed on both sides of the roof.

The roof area, including eaves, was (7.6 x 14.4 m) 110 m^2. The weight of the roof calculated on the base of the wooden roof structure elements and roof covered, and it is equal to $Q_R = 76$ kN.

Connection strength CS_R between rafter plates and knee walls as estimated as $CS_1 = 24$ kN for the weak connection and $CS_2 = 54$ kN for the medium connection.

Fig. 1. The house with the roof blown-off (Source: [6])

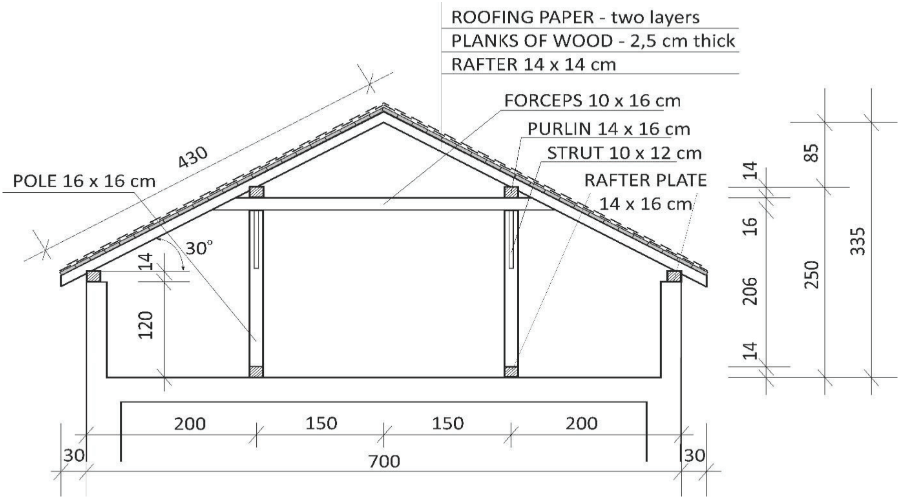

Fig. 2. Rafter framing of the house [Source: authors]

The total force required to blow off the roof of the house for two cases is as follows.

$$F_{B1} = Q_R + CS_1 = 76 + 24 = 100 \text{ kN}, \tag{1a}$$

$$F_{B2} = Q_R + CS_2 = 76 + 54 = 130 \text{ kN}. \tag{1b}$$

4.2. AERODYNAMIC COEFFICIENTS

An aerodynamic force acting on the house was calculated using pressure coefficients for a low-rise house with a gable roof. The pressure coefficients have taken from the Tokyo Polytechnic University aerodynamic database (due to courtesy of Prof. Tamura) [2,3,4]. The aerodynamic force calculated for a low-rise building with a gable roof for similar ratios for length, width, and height. To estimate the lowest critical equivalent wind speed, which at least has happened at the site, three wind directions, for the unknown orientation of the building, were considered, i.e. the wind direction perpendicular, parallel, and oblique to the gable wall, as shown in Figs. 3, 4, and 5.

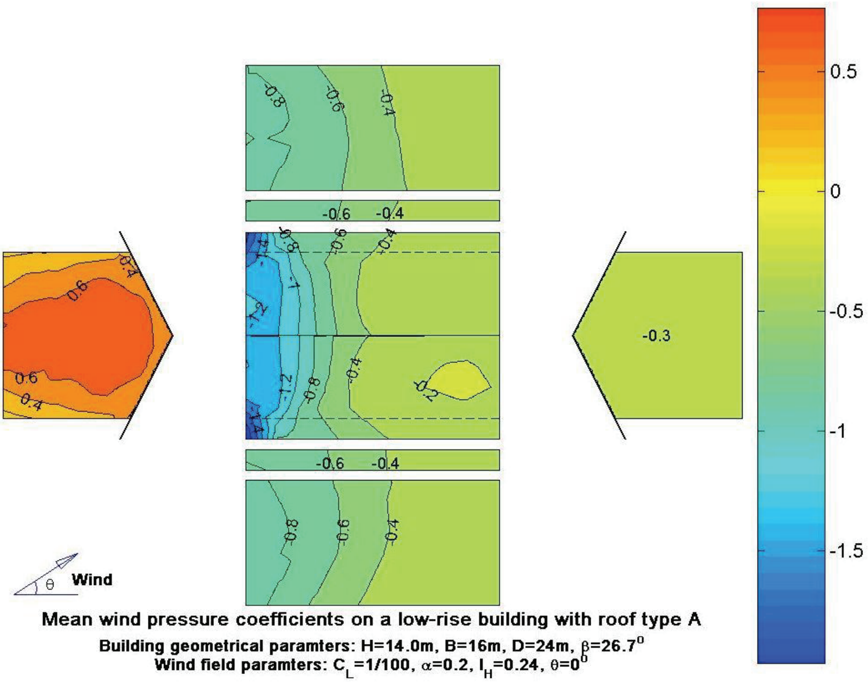

Fig. 3. Distribution of pressure coefficients of a gable roof house (roof inclination 30 degrees, the wind direction perpendicular to the gable wall), [4].

The dimensions of the house shown in Fig.1 are as follows D = 14.4 m, B = 7.0 m, H = 4.2 m. The closest model for the building with these dimensions in the Tokyo Polytechnic University aerodynamic database was the building with dimensions equal D =24 m, B = 16 m, H = 14 m with the gable roof inclination equal 26.7 degrees and also with two eaves. In this case, the pressure acting on the lower surface of the eave should be the same as the pressure acting on the adjacent wall. For example, if the wind comes from 90 degrees, the pressure acting on the lower surface of the windward eave should be the same as the windward wall, and the pressure acting on the lower surface of the leeward eave should be the same as the leeward wall.

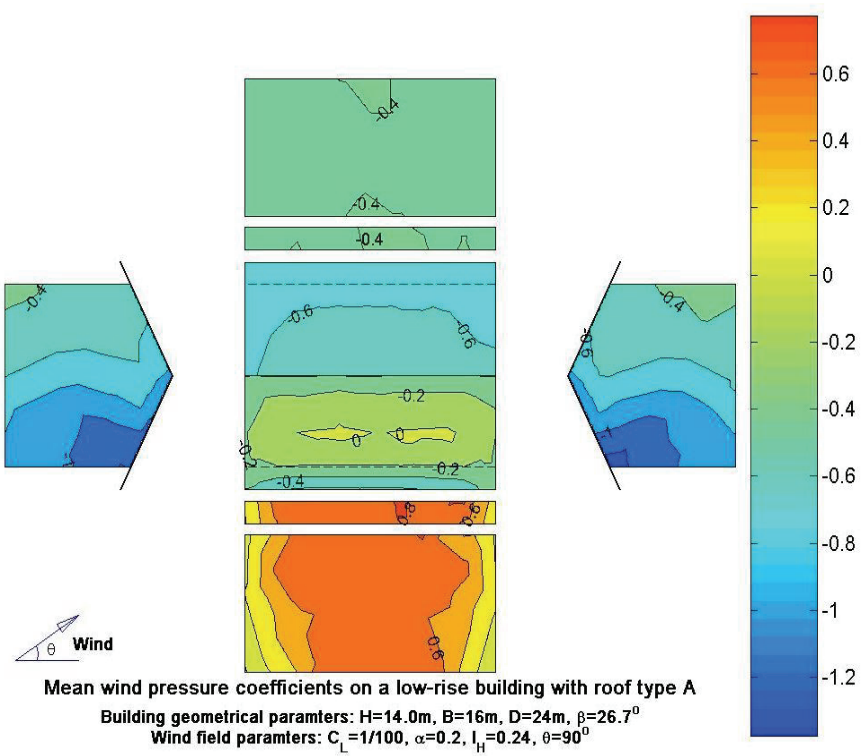

Fig. 4. Distribution of pressure coefficients of a gable roof house (roof inclination 30 degrees, the wind direction parallel to the gable wall), [4].

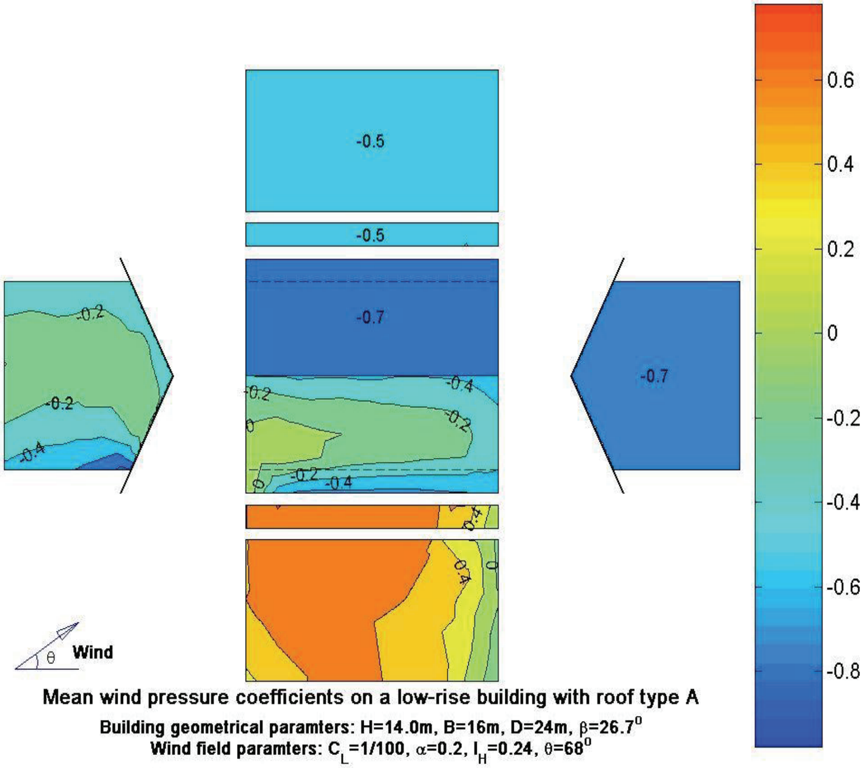

Fig. 5. Distribution of pressure coefficients of a gable roof house (roof inclination 30 degrees, the oblique wind direction), [4].

4.3. CRITICAL WIND SPEED FOR ROOF BLOWN-OFF

The authors have assumed the roof blown-off mechanisms as a simple lift-up mechanism. The evidence for this is Fig.1 on which the window glasses and external door are not broken by debris impact. Based on the Figs. 3, 4, and 5 the pressure coefficients only for windward and leeward sides of the roof, it was possible to calculate the critical wind load (W_C) acting on the roof blown-off as follows:

$$W_C = W_{L1} + W_{L2} + \ldots + W_{Li} + \ldots + W_{Ln} = \frac{1}{2}\varrho\, v^2 \left(A_1 C_{L1} + A_2 C_{L2} + \ldots + A_i C_{Li} + \ldots + A_n C_{Ln}\right) \quad (2)$$

where A_i is the part of the roof surface with C_{Li} pressure coefficient for the i (i = 1, 2, …n) part of the roof.

If the roof of the building was blown-off during a windstorm, it is obvious that the wind load had been larger than the load, which might have caused a failure; however, how much larger - we do not know. It can be written as

$$W_C \geq F_{B1} \text{ or } F_{B2}. \tag{3}$$

If we compare the critical wind load with the total force required to blow-off the roof of the house, we will be able to calculate the critical wind speed for the roof blown-off. To estimate the lowest critical wind speed, which at least happened at the site, three wind directions and two total force required to blow off the roof of the house were considered. In Table 2, the results of the calculation are given.

Table 2. Critical wind velocities for three wind directions and two total force required to blow-off the roof of the house

	V_{C1} [m/s]	V_{C2} [m/s]
Θ = 0 degree F_{B1} = 100 kN	49	………………………………..
Θ = 0 degree F_{B2} = 130 kN	………………………………..	55
Θ = 90 degree F_{B1} = 100 kN	53	………………………………..
Θ = 90 degree F_{B2} = 130 kN	………………………………..	61
Θ = 68 degree F_{B1} = 100 kN	50	………………………………..
Θ = 68 degree F_{B2} = 130 kN	………………………………..	58

5. WIND LOADING ON THE ROOF OF THE HOUSE ACCORDING TO THE POLISH STANDARD

Let us consider a rectangular detached house with the gable roof as shown in Fig. 2, for which one has to calculate a wind load (W) acting on the roof of this house, according to Polish Standard PN-77/B-02011/Az1:2009 [10].

The characteristic (p_k) and calculation load (p) caused by the wind for low-rise buildings is calculated according to PN-77 / B-02011 / Az1: 2009 from the general relationships:

$$p_k = q_k\, C_e\, C\, \beta \qquad\qquad p = p_k\, \gamma_f \tag{4}$$

where:

q_k is the characteristic dynamic pressure,

C_e is the exposure factor equal to 0.9,

C is the aerodynamic coefficient,

β is the coefficient of wind gusts equal to 1.8,

γ_f is the load factor equal to 1.5.

According to the above Standard, Poland is divided into three wind load zones, I, II, and III, for which the characteristic wind speeds and the characteristic dynamic pressures are given. The analyzed house is located in zone I. The calculations of the wind loading (W) on the roof of the house were made for two zones I, II. The results of the calculations are presented in Table 3.

Table 3. Results of calculations of the wind loading (W) on the roof of the house

	V_k [m/s]	q_k [kN/m^2]	C		p_k		p		W [kN]
			Wind-ward	Leeward	Wind-ward	Leeward	Wind-ward	Leeward	
I zone	22	0.3	-0.45	-0.40	-0.22	-0.19	-0.33	-0.29	**33.24**
II zone	26	0.42	-0.45	-0.40	-0.31	-0.27	-0.47	-0.41	**47.18**

6. CONCLUSIONS

Based on the available statistical data on the different types of wind storms which occurred in Poland in the past, estimation of critical equivalent wind speed of the one-story brick house with the roof blown-off, and comparison of wind loads based on Polish Standard the following conclusions were formulated:

1) In Poland, there are threats of financial losses in the economy and to human health and safety caused by forces of nature. The awareness of the significant wind storms like thunderstorms, tornadoes, downbursts, and derechos threat has increased in the last 5-7 years. Some years ago, the Government Center for Security started an issue of forecasting and warnings system for severe wind storms in mass media and cell phones.
2) The estimated critical equivalent wind speed on the path of the derecho wind storm in Poland on August 11-12, 2017, was in the range from 49 m/s to 61m/s, i.e. much bigger than maximum wind speed 36 m/s, measured by meteorological stations on the path of damage.
3) The calculation wind load based on the Polish Standard PN-77 / B-02011 / Az1: 2009 is equal to 33.24 kN for the first zone and 47.18 kN for the second zone. They are much smaller than the critical equivalent wind load acting on the roof was blown-off equal to 100 kN and 130 kN.

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OSZACOWANIE KRYTYCZNEJ PRĘDKOŚCI WIATRU NA PODSTAWIE ZERWANEGO DACHU

STRESZCZENIE. W dniach 11-12 sierpnia 2017 r. nad Polską przeszła rozległa burza wiatrowa. Cała burza obejmowała obszar około 540 km od Wrocławia, przez Poznań, Bydgoszcz, wzdłuż Gdyni i Gdańska oraz część Wybrzeża. Z dużą siłą wiatru przeszła przez trzy województwa: Wielkopolskie, Kujawsko-Pomorskie i Pomorskie. Pomierzone prędkości wiatru osiągnęły 130 km/h, powodując duże zniszczenia na swojej drodze, a w jednej stacji synoptycznej, tj. w Elblągu prędkość wiatru przekroczyła 150 km/h. Maksymalne prędkości wiatru zostały pomierzone

w następujących miejscowościach: Chojnice: 31.2 m/s (112 km/h), Gniezno: 34.8 m/s (125 km/h), Chrząstowo/Noteć: 36.0 m/s (130 km/h), Elbląg: 42,0 m/s (151 km/h). Ścieżka przejścia burzy była w przybliżeniu liną prostą, miała ponad 400 km długości i w trzech miejscach oddalonych około 70 km wiatr wiał z prędkością 100 km/, czyli burza spełniała kryteria burzy „derecho”. Burza wiatrowa spowodowała ofiary ludzkie i ogromne straty materialne opisane w pracy [8].

Celem artykułu jest oszacowanie krytycznej prędkości wiatru w zdarzeniu zerwania dachu jednopiętrowego ceglanego budynku podczas burzy wiatrowej w dniu 11 sierpnia 2017 r. W tym celu obliczono ciężar konstrukcji i pokrycia dachu oraz oszacowano siłę połączenia między murłatami i ściankami kolankowymi. Wzajemne porównanie obu tych sił umożliwiło obliczenie krytycznej prędkości wiatru, która okazała się znacznie większa od wartości pomierzonych na stacjach meteorologicznych.

Na Rys. 1 pokazano uszkodzony domu, który miał dwuspadowy dach o nachyleniu 30°, z dwoma okapami. To zdarzenie miało miejsce podczas burzy wiatrowej w Polsce w dniach 11–12 sierpnia 2017 r. Drewniana konstrukcja dachu (Rys. 2) była pokryta dwiema warstwami papy. Podczas burzy cały dach został zerwany przez wiatr i upadł na ziemi w pobliżu domu. Ściany kolankowe, na których były oparte murłaty, zostały zniszczone po obu stronach budynku.

Powierzchnia dachu, wraz z okapem, wynosiła 110 m^2 (7,6 × 14,4 m). Ciężar dachu (drewniane elementy konstrukcji i pokrycia) wynosiły $Q = 76$ kN.

Siłę połączenia S_P między murłatami i ściankami kolankowymi oszacowano na $S_{P1} = 24$ kN (połączenie słabe) i $S_{P2} = 54$ kN (połączenie mocniejsze).

Całkowita siła potrzebna do uniesienia dachu i jego przeniesienia w inne miejsce, przy uwzględnieniu dwóch przypadków połączenia murłat ze ściankami kolankowymi, została oszacowana na:

$$F_{Z1} = Q + S_{P1} = 76 + 24 = 100 \text{ kN}, \qquad F_{Z2} = Q + S_{P2} = 76 + 54 = 130 \text{ kN}.$$

Siłę aerodynamiczną działającą na dach domu obliczono z zastosowaniem współczynników ciśnienia dotyczących domu niskiego z dachem dwuspadowym i obustronnymi okapami. Współczynniki ciśnienia przyjęto z bazy danych Uniwersytetu w Tokio [2,3,4]. Siłę aerodynamiczną obliczono, przyjmując podobne do budynku analizowanego proporcje długości, szerokości i wysokości. Aby oszacować najniższą krytyczną równoważną prędkość wiatru, która wystąpiła w analizowanym przypadku, rozważono trzy kierunki kąta natarcia wiatru na budynek, tj. kierunek prostopadły, równoległy i skośny do ściany frontowej. Wartości współczynników aerodynamicznych w przypadku tych kierunków przedstawiono na Rys. 3, 4 i 5.

Wymiary geometryczne domu (por. Rys. 2) są następujące: $D = 14{,}4$ m, B = 7,0 m, $H = 4{,}2$ m. Najbliższym modelem budynku o tych wymiarach w bazie danych aerodynamicznych Uniwersytetu w Tokio był budynek o wymiarach: $D = 24$ m, $B = 16$ m, $H = 14$ m i o nachyleniu dachu szczytowego równym 26,7°, także z dwoma okapami. W takim przypadku parcie działające na dolną powierzchnię okapu powinno być takie samo, jak nacisk działający na ścianę sąsiadującą. Na przykład, jeśli wiatr pochodzi z kierunku 90°, ciśnienie działające na dolną powierzchnię okapu powinno być takie samo jak na ścianę nawietrzną, a ciśnienie działające na dolną powierzchnię okapu zawietrznego – takie samo, jak na ścianę zawietrzną.

Na podstawie Rys. 3, 4 i 5 i podanych tam wartości współczynników ciśnienia na nawietrznej i zawietrznej stronie dachu, możliwe było obliczenie krytycznego obciążenia wiatrem (W_C) działającego na zrzucony dach z zależności

$$W_C = W_{L1} + W_{L2} + \ldots + W_{Li} + \ldots + W_{Ln} = 0{,}5\varrho v^2 \left(A_1 C_{L1} + A_2 C_{L2} + \ldots + A_i C_{Li} + \ldots + A_n C_{Ln}\right)$$

gdzie A_i jest powierzchnią części dachu o współczynniku aerodynamicznym C_{Li} ($i = 1, 2, \ldots, n$).

Jeśli dach budynku został zerwany podczas burzy, to jest oczywiste, że obciążenie wiatrem było większe niż najmniejsze obciążenie, które mogło spowodować uniesienie w górę dachu i jego przemieszczenie na pewną odległość; jednak o ile większe – nie wiadomo. Jeśli porówna się krytyczne obciążenie wiatrem z całkowitą siłą wymaganą do uniesienia w górę dachu domu, to można obliczyć krytyczną prędkość wiatru wymaganą, aby nastąpiło podniesienie dachu i jego przeniesienie na teren otaczający budynek. Aby oszacować najniższą krytyczną prędkość wiatru, która zdarzyła się w tym miejscu, rozpatrzono trzy kierunki wiatru i dwie siły, których przekroczenie powodowało poderwanie rozważanego dachu i przemieszczenie na pewną odległość. Wyniki obliczeń krytycznych prędkości wiatru (V_{C1} i V_{C2}), dotyczące dwóch przypadków połączenia murłat ze ściankami kolankowymi i trzech kierunków wiatru, podano w Tabeli 2.

Obciążenie wiatrem (W) działające na dach analizowanego domu obliczono zgodnie z normą [10]. Obciążenie charakterystyczne (p_k) i obliczeniowe (p) wywołane wiatrem w przypadku budynków o niskiej zabudowie oblicza się na podstawie ogólnych zależności:

$$p_k = q_k\, C_e C \beta, \qquad p = p_k\, \gamma_f,$$

w których:

q_k – charakterystyczne ciśnienie prędkości wiatru, o wartości zależnej od stref obciążenia wiatrem,

Ce – współczynnik ekspozycji, który w rozpatrywanego przypadku jest równy 0,9,

C – współczynnik aerodynamiczny,

β – współczynnik działania podmuchów wiatru, który w rozpatrywanym przypadku jest równy 1,8,

γ_k – współczynnikiem obciążenia, który w rozpatrywanym przypadku jest równy 1,5.

Zgodnie z normą [10], Polska jest podzielona na trzy strefy obciążenia wiatrem, I, II i III, dla których podano charakterystyczne prędkości wiatru i charakterystyczne ciśnienia dynamicznym. Analizowany dom znajduje się w strefie I. Obciążenia wiatrem (W) na dach domu wykonano przyjmując I i II strefę obciążenia. Wyniki obliczeń podano w Tab. 3. Po porównaniu obliczonych sił W z Tab. 3 z wartościami sił $F_{Z1} = 100$ kN i $F_{Z2} = 130$ kN stwierdzamy, że siły obciążenia wiatrem W obliczone według normy PN-B-02011:P1977/Az1: 2009 są znacznie mniejsze w przypadku obu stref wiatrowych, tj strefy I i II, czyli nie mogłyby spowodować uniesienia dachu do góry i jego przemieszczenia w nowe miejsce.

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