Construction disasters caused by wind load assessment errors

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Abstract:

This article discusses the nature of wind loads on building structures and the consequences of errors in assessing these loads, which may lead to structural failures. Various methods for determining aerodynamic actions are analyzed (normative models, wind tunnel tests and CFD simulations). Examples of failures caused by wind action are presented, emphasizing the importance of dynamic analysis in the design process. Conscious consideration of the dynamic wind influence is crucial for ensuring the durability and safety of building structures. Structural catastrophes are an ever-present element accompanying facilities, during both the construction and service life phases. The possibility of such phenomena occurring in both cases is equally high and may originate from random causes associated with natural forces (floods, seismic shocks). Nevertheless, human factors and related design errors must also be acknowledged. This article presents the characteristics of wind-induced actions, with particular attention to the essence of dynamic analysis. The methods for determining aerodynamic actions and discrepancies in the obtained results are also described.

Keywords:

wind-induced loads, dynamic analysis, aerodynamic loading assessment, wind-related structural failures

1. Introduction

According to the definition contained in the Construction Law Act [1], a construction disaster is an unintentional, sudden destruction of a building structure or a part thereof, as well as of structural elements of scaffolding, elements of formwork systems, and elements intended for the use of a building structure. Depending on their nature, the causes of construction disasters can be classified into four categories: natural (random, associated with forces of nature), operational (e.g. improper maintenance of the structure), execution-related (occurring at the construction stage), and design-related. In Poland, data on construction disasters have been recorded since 1994 by the General Office of Building Control using the Register of Construction Disasters (RCD) [2]. Based on data collected in the years 2014–2024, it can be stated that the most frequent cause of disasters is the occurrence of random events, with the majority of them being disasters caused by strong winds (Fig. 1) [2,3]. Consequently, the importance of correct and aware structural design with regard to wind loading becomes even more significant. Among the remaining basic actions (including imposed and snow loads), wind action is distinguished by significant variability in time and space. Moreover, its sensitivity to environmental conditions or even to the building form itself is so significant, that each case deviating even slightly from the defined patterns should be treated in a strictly individual manner.
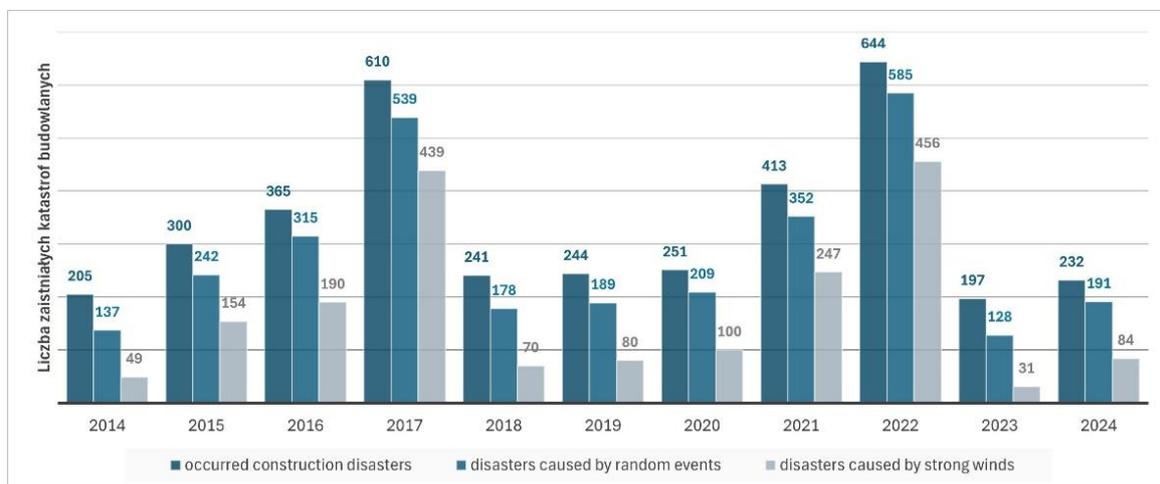

Fig. 1. Amount of construction disasters occurred in 2014-2024, with participation of disasters caused by random events and disasters caused by strong winds. Source: own study based on [2,3]

The effect of wind on structures is classified as a variable action. It has both a static character, in the form of pressure causing windward pressure or leeward suction, and a dynamic character, that is time-varying and inducing vibrations. Compared to other types of loads, it is exceptionally sensitive to environmental conditions (in particular the close vicinity of other structures), the shape and dimensions of the building and its stiffness parameters. In the case of low-rise buildings, which are characterized by high global (spatial) stiffness, wind actions play a secondary role, as imposed loads and permanent actions (including self-weight) are dominant. However, the situation changes significantly for tall and high-rise buildings (above 25 m above ground level) or structures with high slenderness (e.g. chimneys, masts). In addition to static analysis, a very important aspect is the dynamic analysis of the structure, that is the determination of the influence of vibrations on a given structure. It prevents undesirable dynamic phenomena that may lead to failure or complete destruction of the structure, such as resonance. Resonance occurs when the forcing action (in this case wind load) reaches a frequency equal to the natural frequency of the structure. The displacements of the structure then begin to increase at a very rapid rate and are not anyhow damped. After a certain time, they become so vast, that the structure undergoes almost complete destruction, thereby leading to a construction disaster. Therefore, the accurate determination of wind action is crucial to ensuring structural safety. Computational models, that enable accurate and reliable analysis of wind effects are not yet fully recognized, and their range of applications is therefore limited [4]. Three of the most common methods used for dynamic analysis are presented below.

2. Methods of determining aerodynamic actions

One of the basic approaches to determining the influence of wind actions on structures is the use of code-based models, which across European Union are described Eurocodes; in Poland it is PN-EN 1991-1-4:2008 [5]. Wind is primarily characterized by the following quantities: the 10-minute mean wind speed with a return period of 50 years (defined), the short-term gust speed with an averaging time of 1-3 s (which determines the peak value of the velocity pressure q_p), and the turbulence intensity I_v [6]. The approaches proposed by Eurocode apply to simple cases, that is structures with simple geometry, located in environmental conditions that are easy to identify. The adaptation of design standards to describe the wind loading of complex structures by combining several simple schemes does not reliably reflect the interference (i.e. overlapping) of air masses flowing around the structure [7]. This may result in the adoption of an incorrect load distribution, which constitutes a significant error already at the initial stage of analysis. The consideration of dynamic effects and structural stiffness is based on the analysis of the structural factor $c_s c_d$. It refers to flow-structure interaction mechanisms (including vortex excitation, interference galloping, and flutter) described in Annex E of the Eurocode, as well as to the dynamic characteristics of the structure (including the fundamental natural frequency and the damping decrement) described in Annex F. However, these provisions also apply only to simple cases, making it impossible to use them in more complex situations, which in practice are predominant. In such cases, the standard indicates two possible solutions: wind tunnel testing and computer simulation.

Model tests in wind tunnels constitute a different approach to investigating wind action. These methods involve analyzing the effect of wind on a scaled model of the structure. In this case, it is necessary to properly define the tunnel conditions in relation to the real conditions [8]. This method appears to closely reflect situations occurring in reality. However, such tests are relatively expensive, and research facilities are limited. Each modification of the structure (and thus of the scaled model) involves additional financial outlays. Consequently, the use of this method at the preliminary design stage is not economically reasonable.

Another approach, more commonly used by engineers and usually providing faster results, is computer simulation, also known as CFD (Computational Fluid Dynamics) analysis. The procedure includes preparing a coherent geometric model of the structure, defining the boundary conditions, and selecting the type of analysis [8]. The basis of the numerical calculations is a system of nonlinear Navier-Stokes (N-S) differential equations describing airflow, followed by the continuity equations. Their application requires the introduction of certain averaging, which may be performed either in a time- or space-related manner. Time averaging, also referred to as RANS models (Reynolds-Averaged Navier–Stokes), decomposes the instantaneous velocity and pressure components of the wind into mean and fluctuating components (i.e. instantaneous deviations from the mean value). These are the best-validated turbulence models; however, they exhibit lower accuracy in cases where vortex-dominated phenomena are prevalent. In such situations, higher accuracy can be achieved by applying spatial averaging using LES models (Large Eddy Simulation), in which vortices are simulated by spatial filtering of the airflow. Another assumption of the CFD analysis is that the fluid (in this case air) is defined as a Newtonian and incompressible medium. This results in a linear relationship between the shear stress and strain rates, as well as a constant fluid density during the flow. Additionally, the motion of air around the structure is treated as turbulent flow (i.e. causing temporal variations in velocity and pressure). The above assumptions are the closest to real conditions, as they account for the time variability of the action parameters, which is one of the main shortcomings of code-based models. Moreover, CFD analysis is relatively inexpensive – the main cost is the purchase of specialized software (for example ANSYS, RWIND), while the possibility of making modifications is virtually unlimited.

3. Examples of comparative analyses of wind action determination from the literature

The literature contains several studies comparing the methods for determining wind actions described above. One of the most widespread is the work of Japanese researchers, in which the airflow around a gable-roof building was compared for different roof slope angles [9]. A publication by a research team from the Białystok University of Technology extended these results by including code-based models according to PN-EN 1991-1-4:2008 as well as the previously applicable Polish standard PN-77/B-02011 [7]. The analysis was based on a comparison of the external wind pressure coefficient values for a wind direction of 0° (perpendicular to the ridge). The analyzed building, with dimensions of 6.6 × 6.6 × 6.0 m (height at eaves), had a gable roof considered in three slope variants: 3:10, 5:10, and 7.5:10. The coefficient values according to PN-EN 1991-1-4:2008 were determined directly as a function of the ratio h/d (where: h is the total building height, d is the building dimension parallel to the wind direction) and the roof slope angle. The calculation procedure according to PN-77/B-02011 is similar to that of the European standards. However, for walls, the coefficients are determined based on the ratios H/L and B/L, while for roof surfaces they depend on the roof slope angle and

the ratio *h/L* (where: *H* is the total height of the structure, *L* is the building dimension perpendicular to the wind direction, *B* is the building dimension parallel to the wind direction, and *h* is the building height at the eaves level) [10]. Wind tunnel tests described in [9] were conducted on a 1:30 scale model in a tunnel with dimensions of 1.8 × 1.8 × 13 m. Using various types of inlet obstacles, the roughness length was estimated, and the inlet velocity was set. The CFD computer simulation was performed using ANSYS FLUENT 14.5. RANS-type calculations (time-averaging) were applied to the four turbulence models. The remaining parameters were adjusted to match the wind tunnel test conditions as closely as possible. A summary comparison of the pressure coefficients obtained for the four models described above is presented in Fig. 2.
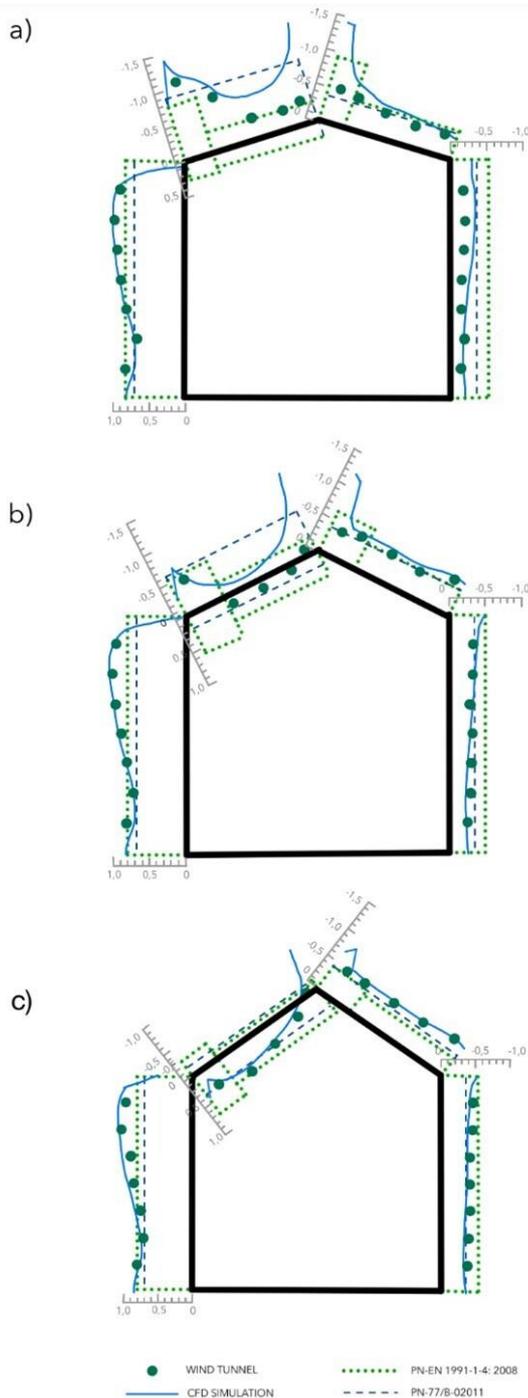
The results of the conducted analyses indicate that calculations based on code-based models in many cases provide safe values of external pressure coefficients. However, this does not mean that they accurately reflect the actual pressure distributions – particularly in the area of roof edges. In this zone, for a roof slope of 3:10, noticeable differences relative to wind tunnel tests were observed: the PN-EN 1991-1-4:2008 and PN-77/B-02011 standards may underestimate pressure coefficient values by approximately 39% and 19%, respectively. Analogous discrepancies were observed in the upper parts of the windward wall. The measured coefficient values obtained under experimental conditions are usually higher than those predicted by code-based models. The CFD analyses confirmed good agreement with the experiments. However, in the ridge region – especially for small roof slopes – a noticeable underestimation of pressure occurs, which results from differences in the distribution of turbulence energy, which is dictated by the applied numerical model [9].

4. Wind force scales

The description of wind force, its velocity, and the phenomena occurring during wind events can generally be presented using two scales: the Beaufort scale and the Fujita scale. The Beaufort scale was developed in 1805 and is used for an approximate description of wind force based on observations of the sea surface or land. It is expressed in Beaufort degrees and ranges from 0 to 12 B. Level 0 on the Beaufort scale (0 B) corresponds to zero wind speed and the absence of any noticeable phenomena on land. At level 9 B, the wind speed reaches approximately 80 km/h, at which stage light structures can be damaged. Level 12 B, which constitutes the upper limit of the scale, is associated with widespread and surface-level structural damage, and wind speed exceeds 117 km/h [11]. The second of the aforementioned scales – the Fujita scale (also known as the Fujita–Pearson scale) – was developed in 1971 and is used to describe tornado intensity based on building damage. It consists of six categories, ranging from F0 to F5. It can be interpreted as a form of continuation and extension of the Beaufort scale, since category F1 of the Fujita scale corresponds to the 12th degree of the Beaufort scale (Fig. 3). Table 1 presents the potential damage and wind speeds for all categories [12]. In 2007, the scale was updated to the Enhanced Fujita Scale (EF scale), which also compares six categories and allows a structure to be classified into an appropriate EF category based on the type of construction, the nature of the damage, and wind speed [13]. This update enables a more efficient application of the scale in the United States, where the annual frequency of tornado occurrence is the highest.
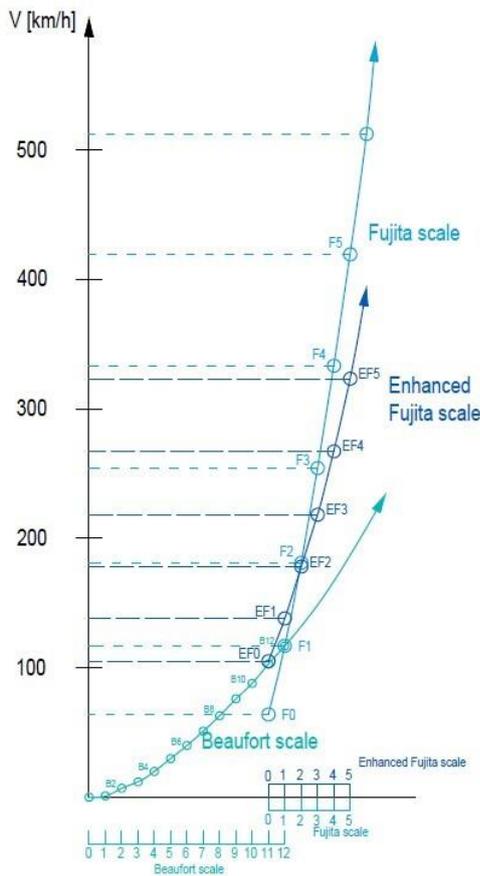

Fig. 2. Comparison of external wind pressure coefficient values for buildings with different roof slopes: a) 3:10 roof slope, b) 5:10 roof slope, c) 7.5:10 roof slope. Source: own study based on [7]

Fig. 3. Connection of the Beaufort scale, Fujita scale and Enhanced Fujita scale. Source: own study based on [12,13]

Table 1. Fujita scale description. Source: own study based on [12]

Scale	Wind speed [km/h]	Potential damage
F0	64-116	Light damage. Minor damage to roofs and chimneys; broken tree branches; uprooted shallow trees.
F1	117-180	Moderate damage. Detached roof coverings; shattered windows; camping trailers displaced or overturned; cars pushed along the ground; possible damage to buildings of temporary makeshift structure.
F2	181-253	Considerable damage. Roofs torn of residential buildings; railway cars overturned; large trees uprooted with their roots or completely broken; light objects carried at high speed; vehicles blown off highways.
F3	254-332	Severe damage. Complete destruction of buildings of traditional structure; destruction of steel structures such as warehouses; cars lifted off the ground; most trees uprooted or broken.
F4	333-418	Devastating damage. Total destruction of building regardless of their structural system; cars and trains carried through the air at high speed
F5	419-512	Incredible damage. Complete destruction of buildings with stiff and heavy structural systems; structures torn from their foundations and moved over considerable distances.

5. Construction disasters caused by aerodynamic actions

One of the most well-known disasters caused by aerodynamic effects is the collapse of the Tacoma Narrows Bridge. It occurred on November 17, 1940, in Washington, USA. At a certain point, torsional vibrations of the central span of the bridge were observed, which after some time occurred at a frequency of 0.2 Hz. The maximum vibration amplitude reached 8.5 m at a torsional angle of 45°. After approximately one hour, catastrophic failure occurred, resulting in the destruction of the central span of the bridge. This example is often mentioned as a consequence of resonance. Resonance is a phenomenon of an uncontrolled increase in vibration amplitude when a structure vibrates at a frequency equal to its natural frequency. However, it should be clarified that the direct cause of bringing the bridge into resonance was the vortex-induced vibration, which is alternating shedding of vortices from opposite sides of the structure. If vortices are shed at a frequency equal to the natural frequency of the structure, the system is put into vibrations occurring in a plane perpendicular to the wind direction [5]. It should be emphasized that high wind speed itself is not a decisive factor for this phenomenon to occur. The critical wind speed, that is the speed inducing the aforementioned vibrations, usually lies within a range of velocities that frequently occur under normal conditions. An important parameter that accounts for this speed (although not exclusively) is flow stability. The transition of laminar airflow into turbulent flow is described by the dimensionless Reynolds number, which depends on the fluid velocity, viscosity, and geometric parameters of the structure. Only their appropriate interaction contributes (or not) to the formation of vortices alternately shedding from two opposite sides of the structure, thereby inducing vibrations.

In the section of the article concerning methods for determining aerodynamic actions, reference was made to the problems encountered by models due to the inadequate representation of airflow characteristics around complex structures. The close proximity of other buildings with similar dimensions may have adverse effects if not properly defined during the design stage. A good example illustrating the influence of wind on large clustered structures is the collapse of the cooling towers in Ferrybridge, which occurred on November 1 1965 [14]. The causes of the disaster are considered to be the neglect of the dynamic action of wind during gusts, as well as the neglect of interference effects between neighboring large-scale structures. As a result of these oversights, three out of eight cooling towers collapsed [4].

Destructive wind forces, associated with tornadoes, are a phenomenon constantly affecting United Stated of America. The average number of tornadoes in the years 2010-2019 reached 1347 per year. The highest concentration is observed in the central part of the country, in the so-called Tornado Alley. This region extends from Texas to South Dakota and includes the states of Oklahoma, Kansas, Colorado and Nebraska. In May 2013, the El Reno tornado passed through the state of Oklahoma and is named as the largest tornado in the history. Its width is estimated to be over 4 km. The tornado was classified as EF3 in the Enhanced Fujita scale. As a result of this event, 8 people died, more than 200 were injured and the damage caused by wind and extensive flooding was estimated at 2,5 billion USD [15]. Another region, equally susceptible to tornado occurrence is Dixie Alley, which includes the states of Louisiana, Arkansas, Mississippi, Alabama, Tennessee and Georgia. In August 2005, Hurricane Katrina passed through this area and it is considered one of the most destructive hurricanes in the history of the USA.

It formed near the Bahamas and moved toward Dixie Alley from the Gulf of Mexico, with its overland track extending from Louisiana to Tennessee. The highest recorded wind speed reached 280 km/h. More than 1800 fatalities were reported as a result of the hurricane. Material losses were estimated at over 80 billion USD, a significant part of which was due to damages across New Orleans. Due to the failure of flood protection levees, approximately 80% of the city was flooded. Environmental losses were also extensive – it is estimated, that approximately 320 billion trees were destroyed as a result of the hurricane [16].

One of the more recent examples of disasters caused by strong winds in Poland are the damages resulting from a violent derecho-type windstorm (i.e. exceptionally extensive and long-lasting). It occurred during the night of 11-12 August 2017 and affected three voivodeships: Greater Poland, Kuyavian-Pomeranian, and Pomeranian. The average wind speed ranged from 5.4 to 66.2 km/h; according to the Beaufort scale, this corresponded to force 8 at the peak of the storm. Wind peak speed reached 151 km/h and was recorded in Elbląg. The storm caused catastrophic damage to residential and public buildings, as well as to technical infrastructure, forests, and agricultural crops. The scale of destruction included torn-off roofs, broken trees, and damaged power lines (Fig. 4.). Six people were killed, and several dozen sustained serious injuries [17]. The design approach in such situations is particularly challenging, as it is not always possible to unconditionally ensure the safety of structures under such extreme conditions. Atmospheric phenomena of this magnitude are sufficiently rare in Poland, that they are not typically considered in standard design scenarios. However, certain modifications can be introduced to reduce the likelihood of construction disasters. In the case of wind actions, low-rise buildings with compact forms, deprived of lightweight structural elements (e.g. replacing timber roof trusses with monolithic reinforced concrete slabs) and equipped with stiffening systems (e.g. masonry walls replaced by reinforced concrete walls), perform significantly better. In lightweight structures, where uplift constitutes an additional problem, an adequate level of stabilization is provided by the weight of the foundation (and thus its dimensions) and the soil resting upon it.

Examples of structures sensitive to dynamic wind actions, in addition to bridges and tall buildings, include steel chimneys. Publication [4] presents an interesting case of structural failure illustrating the level of accuracy required in dynamic calculations at the design stage. A steel chimney with a shaft diameter of 2.5 m and a height of 100 m consisted of 11 segments connected with M16 bolts. In order to improve the tightness of the flue, welds were made inside the shaft at the joints of the flanges of successive segments. However, this action reduced the damping properties of the structure, which was not taken into account at the design stage. A weld located approximately halfway up the height of the chimney cracked and the structure – previously set into vibration – returned to its equilibrium position. After repairing the defect, a series of dynamic measurements was carried out to optimize further structural modifications. In this way, steps were taken to ensure the safety of the structure and to avoid a potential construction disaster.

6. Summary

Errors in assessing the dynamic nature of wind loading, as well as limitations and inaccuracies of the applied analytical methods, undoubtedly pose a threat to the safety of building structures. Standard code-based methods, although practical and widely used, often fail to account for the complexity and variability of dynamic effects, which are particularly significant in the case of structures with complex geometry or those located in the vicinity of other buildings of similar dimensions. Historical examples of disasters, such as the collapse of the Tacoma Narrows Bridge or the cooling towers in Ferrybridge, illustrate the dramatic consequences of underestimating the influence of dynamic wind loading.

Modern analytical tools, such as CFD numerical simulations and wind tunnel model testing, offer significantly higher accuracy and reliability in reproducing real airflow conditions and structural interactions. These methods enable not only a more precise determination of pressure distributions, but also proper consideration of vibration effects induced by phenomena such as vortex shedding or resonance, which may lead to catastrophic damage.

From the perspective of design practice, an individual approach to each structure is of particular importance, with detailed consideration of its geometry and environmental conditions. Special attention should be paid to tall, slender structures and lightweight elements, which are more susceptible to dynamic wind effects. The introduction of stiffening systems can significantly reduce the risk of structural failure.

Responsible and thorough analysis of dynamic wind load effects, based on modern tools and an understanding of the underlying physical mechanisms, is essential to ensuring the safety and durability of building structures. This minimizes the risk of disasters, enhances user safety, and contributes to the protection of property.

Fig. 4. Disasters caused by derecho-type windstorm in Poland, 11-12 August 2017. Source: own study, photographed by J. Szer

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