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Research paper

Problems in designing air domes: a lesson from a construction disaster

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Abstract: Modern roofs for tennis courts, swimming pools, or playing fields can take various forms, but an increasingly popular design choice is pneumatic structures. These structures are supported by maintaining a higher internal pressure that upholds the membrane, achieved through a continuous air-blowing system. The difference between the pressure of the hall's interior and atmospheric pressure ranges from 2.5 to 3.5 hPa. In practical terms, this means that the pressure on the air-supported dome is 25–35 kg/m^2. Although these structures have been in operation in Europe for several decades, there are still reports of construction disasters of this type of facility. This article presents a case study of one such disaster, including material tests of the membrane, the analysis of technical documentation, and a discussion of recommendations and standard provisions. While determining the causes of the incident, it was shown that excessive snow load was the main cause of the disaster, and the lack of adequate legal regulations still has negative consequences affecting the safety of using air domes.

Keywords: air dome, air-supported structure, pneumatic structure, snow load, construction disaster, temporary construction

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1. Introduction

Modern roofs for tennis courts, swimming pools or sports fields can take various forms, but more and more often, the roofs are designed as pneumatic structures (Fig. 1). Halls of this type are devoid of a heavy load-bearing structure – instead, the roofing is two or three layers of material between which air is injected to separate the material and forming a so-called air cushion. The pneumatic hall is kept up due to the overpressure inside, provided by the continuous blowing of air from fans [1].

(a) (b)

Fig. 1. Pneumatic membrane structure [1]: (a) pitch roofing, (b) swimming pool roof (source: inzynierbudownictwa.pl)

The pressure difference between the interior of the structure and the atmospheric pressure is from 2.5 to 3.5 hPa, which means that the pressure on the membrane is 25–35 kg/m^2. The pressure difference at this level is not perceptible to users. There are two types of halls:

(a) pneumatic, in which the entire facility volume is pumped,
(b) with a pneumatic casing in which only the outer layer is pumped 10–40 cm thick.

In addition to the pneumatic membrane, the construction elements include aluminium profiles, keder profiles with a longitudinal slot intended for mounting the coating, and steel or glued wood elements. Two-layer or three-layer solutions are used without or with steel ropes (which stabilise the covering). Steel earth anchors or concrete ballasts can anchor the structure to the ground. The anchor must bear the load resulting from the overpressure in the hall and temporary wind gusts (tearing off the anchors). The structure of the pneumatic hall is shown in Fig. 2.

In light of the Construction Law in force in Poland [2], pneumatic structures are classified as temporary buildings (Article 3) – that is, those intended for temporary use for a period shorter than their technical durability are designed to be moved to another place or demolished and also not permanently connected to the ground. In practice, constructing an air dome for 180 days requires no building permit and only notifications (Article 29 [2]). Such a definition of a temporary facility is contrary to the provision contained in the PN-EN 1990 standard (Table 2.1) [3] that it is recommended that structures or parts of structures that are intended for repeated assembly and dismantling are not treated as temporary structures.

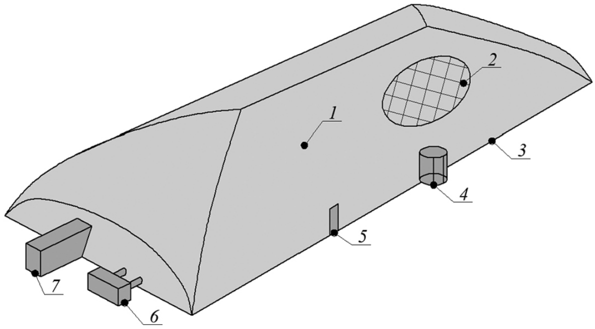


Fig. 2. Construction of an air dome; *1* – pneumatic membrane, *2* – steel ropes, *3* – anchoring system, *4* – revolving door, *5* – evacuation doors, *6* – heating and blowing system, *7* – service tunnel

A few requirements regarding air domes are included in paragraphs §288 and §289 of the technical conditions [4]. A building with a pneumatic casing may be used as a temporary PM facility (production and storage) with a fire zone fire load density of no more than 1000 MJ/m^2, provided certain requirements specified in these regulations are met. Importantly, if buildings with a pneumatic roof are intended for entertainment, exhibition, recreational or sports purposes, they should also be equipped with:

– structures placed inside or outside the building for an emergency suspension of the pneumatic shell,
– emergency shell pressure maintenance devices, which should be powered from an independent energy source,
– emergency mechanical ventilation for air exchange, which an independent energy source should also power,
– emergency exits distributed as evenly as possible around the perimeter,
– chairs permanently connected and fixed in rows of eight, arranged following the requirements of §261 [4].

Due to the lack of regulations regarding air domes, in national practice, the provisions regarding temporary facilities (tents) PN-EN 13782:2015-07 [5] and the German standard DIN 4134:1983-02 [6] are used.

2. Description of the pneumatic structure

In the area of the analysed investment, the construction of an air hall over the existing sports field was planned. The pitch's dimensions were 105 × 68 m, and the artificial grass area and the pneumatic hall in the line of anchors' dimensions were 115 × 74 m. The roof's height was 18 meters, and the maximum number of people planned to stay inside was 320. Illustrative photos of the facility are shown in Fig. 3.

The original construction design for the investment was replaced by an alternate project design that omitted the internal emergency support structure in the form of lattice columns and steel ropes connecting them, supporting the falling coating along the hall's perimeter, which is

(a) (b)

Fig. 3. The analysed pneumatic structure: (a) location view, (b) interior view (source: miastozabrze.pl)

inconsistent with the technical conditions. The purpose of this structure was to secure access to emergency exits when the envelope was falling, to increase the time needed to evacuate people and to provide a safe space in the areas leading to emergency exits. In addition, the diagonal mesh of steel ropes was abandoned in favour of a rope strapping system with eight transverse ropes and four ropes along the hall.

A three-layer coating consisting of an outer layer, an inner layer and a bubble foil between these layers was designed. It was also assumed that hot air blown from the ventilation and heating system directly between the membranes creates a thick layer of hot air over the entire surface of the hall, which increases the insulating capacity of the hall coating and stabilizes and stiffens it. Thanks to this solution, snow falling on the coating would quickly melt and slide off the smooth and slippery surface of the roof. The coating was to be attached to a steel perimeter pipe, which was to be attached to ground anchors placed approximately every 1.5 m.

3. Construction disaster

A construction disaster occurred on December 12, 2022, less than a month after the facility's opening (the hall was put into operation on November 19, 2022). Based on the available monitoring materials, the time-lapse analysis shows that the disaster occurred during snowfall that remained on the hall surface (Fig. 4a). The first stage of the disaster consisted of gradual deformation of the covering (deflection of the membrane) relative to the original shape of the structure (Fig. 4b). The deformations continued to develop for over 10 minutes. Monitoring photos at a later stage show the moment of tearing off the membrane and a sudden escape of the air inside (Fig. 4c). Approximately 33 seconds elapsed from the moment of tearing the membrane to its complete falling, with the northern emergency exits being cut off after approximately 14 seconds (Fig. 4d). Previously, the structure was characterised by a slight, uniform deflection of the membrane, which was practically impossible to observe with the unaided eye or without measuring devices. The photographs (monitoring frames) show the disaster's subsequent stages with the shell's initial outline.

(a)

(b)

(c)

(d)

Fig. 4. Subsequent phases of the construction disaster: a) initial condition of the membrane, b) gradual deformation of the membrane, c) moment of rupture of the membrane, d) cutting off the northern emergency exits

4. Inspection of the site of a construction disaster

As a result of local inspections of the disaster site, significant differences in the facility's construction were found between the construction design and the replacement design. It was found that the following deviations were introduced during construction:

- the main entrances to the facility were moved from the western side (top of the hall) to the southern side, around half the length of the hall,
- the free-standing container building for the cloakroom facilities was moved from the western side to the southern side of the hall,
- the set of fans and heaters was moved from the facility's eastern to the western side.

During the inspection eleven days after the disaster, large amounts of snow were still observed around the collapsed hall. The condition of the membrane on the pitch is shown in Fig. 5a. The structure destruction planes were located halfway along the facility's length. However, the tearing of the plating occurred outside the joint (Fig. 5b). Moreover, the presence of a layer of bubble foil, provided for in the design documentation, was not noticed. As a result of the collapse of the structure, the entrance revolving door fell over (Fig. 6a). In the southern part, after the coating fell, it was torn due to contact with the steel elements of the sports goal (Fig. 6b).

(a) (b)

Fig. 5. Condition of the membrane after the disaster – December 23, 2022: (a) coating lying on the turf, (b) tearing of the plating outside the connection

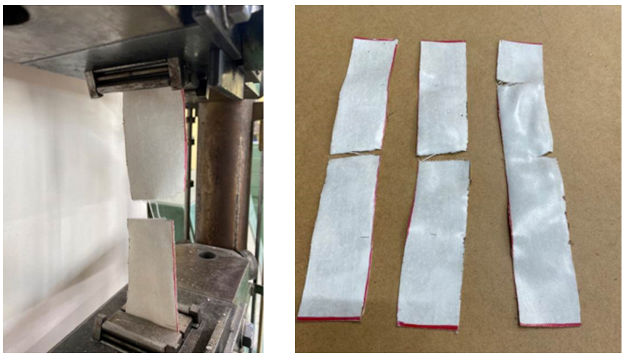
(a) (b)

Fig. 6. View of the facility after the disaster: (a) overturned entrance revolving door, (b) tearing of the covering on the edge of the sports goal

On the cladding fastening elements (peripheral pipes), there were locally visible traces of corrosion and the lack of sheets closing the pipes – in open sections – which could accumulate locally and intensify corrosion processes (Fig. 7a). Moreover, some elements of the hall's equipment were attached directly to the membrane using elements made of plastic, which locally weakened the covering material (Fig. 7b).

(a) (b)

Fig. 7. Elements of fastening and equipment of the pneumatic hall after the disaster: (a) corner connection of the peripheral steel pipe with visible traces of corrosion, (b) elements of equipment attached to the membrane with plastic clamps



(a) (b)

Fig. 8. Material tests of the plating: a) view of the selected sample in the machine strength ZD10/90, b) view of selected samples after rupture

5. Determining the causes of a construction disaster

Material tests of the membrane were performed to determine the causes of the construction disaster. For this purpose, samples of both layers of the roof membrane were taken in the area of its tear. The collected samples were weighed, and their weight was compared with the data provided in the documentation. On this basis, it was determined that the weight of the materials used was consistent with the design. Then, tensile tests of the membrane were carried out in two different testing machines, ZD10/90 (Fig. 8) and ZD100 (Fig. 9).

Samples with and without a seam were tested perpendicular and parallel to the seam, taken from the lower and upper membranes. Additionally, tests were performed on samples with an artificially made defect in the form of a cut on the edge and in the centre of the samples. In the case of the external membrane, the tensile strength along the fibres was 1.8 kN/50 mm (in the design, it was 3.2 kN/50 mm), while the tensile strength across the

(a) (b)

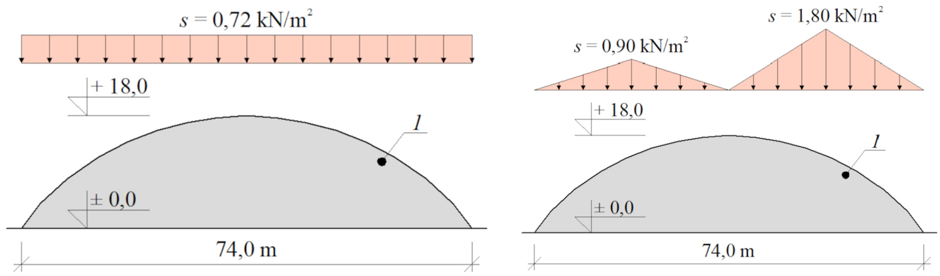
Fig. 9. Material tests of the plating: (a) testing machine ZD100,
(b) view of the selected sample after breaking

fibres was 1.83 kN/50 mm (in the project it was 3.0 kN/50 mm). The obtained strengths were, therefore, significantly lower than those assumed in the design. In tests of the internal membrane, the tensile strength along the fibres was 1.52 kN/50 mm (in the project, it was 2.4 kN/50 mm). The tensile strength across the fibres was 1.4 kN/50 mm (the design assumed 2.3 kN/50 mm). On this basis, it was found that the strength parameters of the membranes did not meet the declarations of the technical documentation.

The project also contains inconsistent information regarding the assumed height of the hall. In the drawing documentation, the facility had a height of 18.0 m – in the calculations, it was 20.0 m. The coating was designed for a maximum snow load of 0.25 kN/m^2, which corresponds to the thickness of the fresh snow cover of 25.0 cm (assuming the volume weight of snow 1.0 kN/m^3 according to Annex E to PN-EN 1991-1-3 [7]), or 12.5 cm a few hours after the snowfall (volumetric weight approx. 2.0 kN/m^3 [7]).

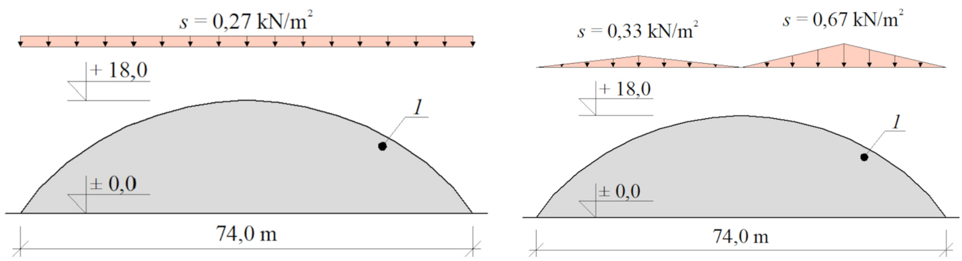
In calculations carried out according to the Eurocode, the minimum recovery period of snow loads for short-term structures is assumed to be 20 years (point 4.1(2) note 2 in PN-EN 1991-1-3 [7]). The standard for the design of temporary tent halls [5] states that if the snow does not exceed a thickness of 8.0 cm – which is to be ensured by snow removal from the roof – the snow load value may be assumed as 0.20 kN/m^2. German regulations DIN 4134:1983-02 [6] allow for a reduced snow load of 0.25 kN/m^2 for roofs with a slope of less than 70°, with mechanical snow removal from the roof.

In the case of the analysed facility, there is no provision for snow removal from the roof. From a technical point of view, the mechanical removal of snow from the roof of the air dome is unrealistic due to the geometry of the structure and the lack of access to the crown of the roof. Therefore, the postulates of both standards [5] and [6] are unmet. Recalculated snow load values according to Eurocode procedures for two cases – snow load for cylindrical roofs (variant 1 – Fig. 10) and snow load with the calculated thermal coefficient and return period for temporary structures (variant 2 – Fig. 11) indicate the load greater than assumed in the project – Table 1.



(a) (b)

Fig. 10. Snow load on the analysed air dome – variant 1: (a) evenly distributed load, (b) unevenly distributed load, 1 – the geometry of the facility



(a) (b)

Fig. 11. Snow load on the analysed air dome – variant 2: (a) evenly distributed load, (b) unevenly distributed load, 1 – the geometry of the facility

Table 1. Comparison of snow load values

Snow load	**Characteristic value [kN/m^2]**	
	load evenly distributed	**load unevenly distributed**
in the replacement project, according to DIN 4134:1983-02, with snow removal	0.25	–
PN-EN 13782:2015-07, while ensuring snow removal	0.20	–
according to Eurocode – variant 1	0.72	0.90 and 1.80
according to Eurocode – variant 2	0.27	0.33 and 0.67

Moreover, in the analysed project, safety coefficients were used, the values of which suggest that they come from the package of withdrawn Polish standards PN-B. However, the designer did not refer to any standard in this regard (he did not specify from which standard the adopted safety factors were derived). It should be added that combining standard provisions from various packages, e.g. Eurocode and withdrawn Polish Standards, is an inappropriate approach, if only due to different values of combination coefficients and partial material factors ensuring a certain level of structure reliability.

The value of the increasing factor for the internal pressure resulting from air blowing on the wrong side was adopted in the design documentation – with a value of 1.2. This approach causes a computational increase in the pressure holding the membrane – while the most unfavourable computational situations are used during design. Increasing the internal pressure in the calculations is a favourable case from the point of view of the hall's load-bearing capacity. Still, it is an entirely incorrect approach from the point of view of the Limit States method. Depending on the adopted combination of actions, the designer should have assumed a factor of less than unity or, at most, equal to 1.0 for the internal pressure.

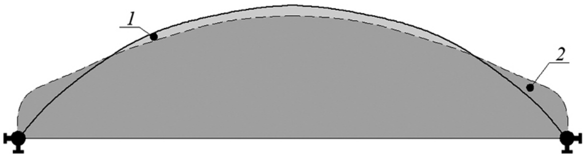
As part of the analyses, verification static calculations were also performed. It has been shown that there are three possible cases of loss of hall stability – Fig. 12. The first form is characterised by a flattening of the membrane due to the impact of snow at the top and the external walls of the coating being pushed outwards. The second and third forms are characterised by a loss of membrane stability in the support zone. The presented forms of stability loss coincide with the structure deformations visible during the analysed construction disaster.

Based on the above considerations, it can be undoubtedly stated that the direct cause of the construction disaster was snow lying on the membrane of the air dome. Although the standards [5] and [6] allow for the adoption of reduced snow load values while ensuring snow removal from the roof, such an approach is controversial in Polish conditions. Assuming a higher snow load would make it impossible to design an air hall for which the internal pressure is 0.30 kN/m^2. Even if the conditions that the investor should meet when using the tent are specified to prevent snow accumulation (e.g. the need to control the thickness of the snow cover or the temperature of the covering), in the event of heavy rainfall, clearing snow from this type of roof surface would be unrealistic. The assumptions based on the fact that hot air forced between the layers causes snow to melt are false. A sudden snowfall causes local membrane deformation. Only the tiny layer directly in contact with the coating melts. Then, water stagnation occurs, locally placing an additional load on the membrane.

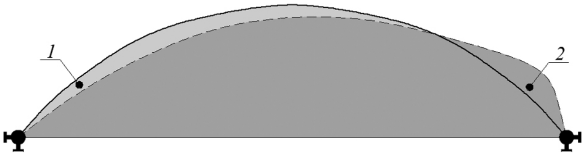
Valuable evidence confirming this mechanism of destruction are photographs taken on the day of the disaster by the construction manager (Fig. 13). The photos show not only significant amounts of snow lying on the membrane but also areas where the snow has frozen to the coating (these places are marked with red arrows). The identified errors made at the design or construction stage and using a weaker membrane material could have contributed to the disaster – but they were not its direct cause. Moreover, operational errors were also found while determining the causes of the disaster. The facility manager did not remove snow along the edges of the arena, which he should have done by the facility's instructions for use.

6. Conclusions

The construction disaster of an air dome presented in this article is not a single case of this event. In recent years, facilities of this type have been subject to failures and disasters in various parts of Poland. In February 2022, the roof of an air arena collapsed in Białystok during a football match. At some point, the balloon stretched above the pitch, began to burst



(a)



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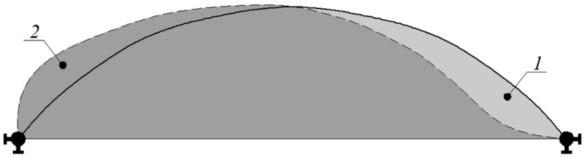


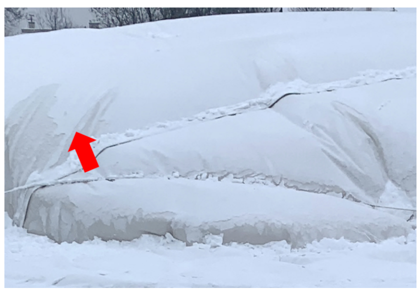
(c)

Fig. 12. Possible global forms of stability loss: 1 – the original shape of the structures, 2 – the deformed shape of the structure

(a)

(b)

(c)



(d)

Fig. 13. Photos of snow lying on the structure taken by the construction manager on the day of the disaster: (a) and (b) snow lying on the membrane, (c) and (d) snow stuck to the membrane

and fell onto the grass. In December 2022, the air dome also collapsed in Kaputy in Masovia. A year earlier, in December 2021, just a few days after installation, the sports hall in Mielec collapsed. On Sunday, January 7, 2024, the hall with the pneumatic roof of the Podkarpackie Football Center collapsed in Stalowa Wola. It is worth adding that photos from the disaster show a significant amount of snow was lying on the membrane, and the remaining cases of the mentioned disasters occurred in winter. Problems with the pneumatic structures also occurred in Minneapolis. The roof of the sports facility there was designed as a two-layer coating with dimensions of 227 × 192 m in plan and a dome height of 59 m. During operation, the coating was damaged five times due to weather conditions. After a snowstorm in December 2010, when over 40 cm of snow was on the roof, the membrane tore in several places and partially fell onto the pitch. Due to fear of an accident, the facility was finally demolished in 2014 [8].

Pneumatic structures, like tent halls, are classified in the Construction Law as temporary structures. The lack of formal provisions regarding the maximum dimensions of such facilities, which are only subject to reporting, means that large air domes are built without design documentation verified by people with construction licenses and appropriate technical knowledge [9]. This fact is surprising considering that the legislator limits the dimensions of gazebos, farm buildings and container drying rooms in qualifying facilities regarding the required building permit or notification.

Assuming that the air hall is maintained thanks to the internal overpressure of approximately 0.30 kN/m^2, premising a snow load in the design that exceeds the internal pressure value means an imbalance of forces. In practice, air domes are designed with reduced snow loads based on the expectation of snow melting. Designers, as in the case of tent halls [10], do not specify how the user is to control the thickness and weight of the snow cover on the roof. Automatic snow removal is often assumed due to heating the hall from the inside. As practice shows, in reality, during heavy snowfall, small amounts of snow melt, which causes stagnation, deformation of the coating and subsequent layers of wet snow sticking to the covering. On the other hand, mechanical snow removal is unrealistic for practical reasons – the facility's geometry, the membrane surface's slipperiness and the lack of access to the hall crown. In the case of a roof without access, except for routine maintenance and repairs, the live load in the Eurocode is 0.40 kN/m^2 [11]. This value is twice the reduced snow weight assumed in air dome designs. According to the authors, the presented issues should be legally regulated as a matter of urgency. Otherwise, there is a risk of such events occurring in the future. Wind load analysis is a separate design issue that also requires consideration. The fundamental issues requiring detailed consideration include both the appropriate assumption of the characteristic velocity of strong wind [12] and understanding the impact of wind on air domes. Such an analysis, including pressure and velocity distributions around an air dome, could be performed using Computational Fluid Dynamics (CFD) [13].

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Problemy projektowania hal pneumatycznych: wnioski z katastrofy budowlanej

Słowa kluczowe: hala pneumatyczna, powłoka pneumatyczna, konstrukcja pneumatyczna, obciążenie śniegiem, katastrofa budowlana, konstrukcja tymczasowa

Streszczenie:

Współczesne zadaszenia kortów tenisowych, basenów czy boisk mogą przybierać różne formy, coraz chętniej jednak przekrycia projektuje się jako powłoki pneumatyczne. Hale tego rodzaju pozbawione są ciężkiej konstrukcji nośnej – zamiast niej przekrycie stanowią dwie lub trzy warstwy materiału pomiędzy, które wtłaczane jest powietrze rozdzielające materiał i tworzące tzw. poduszkę powietrzną. Hala pneumatyczna utrzymywana jest w górze dzięki panującemu wewnątrz nadciśnieniu, które zapewniane jest przez ciągły nadmuch powietrza z wentylatorów. Różnica ciśnienia pomiędzy wnętrzem obiektu a ciśnieniem atmosferycznym wynosi od 2,5 do 3,5 hPa, co w praktyce oznacza, że wartość parcia ciśnienia na membranę poszycia wynosi 25–35 kg/m^2. Samo nadciśnienie tej wielkości nie jest jednak odczuwalne przez człowieka. Artykuł stanowi studium przypadku katastrofy budowlanej hali pneumatycznej nad istniejącym boiskiem sportowym o wymiarach 105 $\times$ 68 m. W ramach ustalenia przyczyn zdarzenia wykonano oględziny obiektu, analizę dostępnej dokumentacji technicznej, badania materiałowe poszycia oraz analizy obliczeniowe. Przedstawiona w niniejszym artykule katastrofa budowlana hali pneumatycznej nie jest pojedynczym przypadkiem tego rodzaju zdarzenia. W ostatnich latach obiekty tego typu ulegały awariom i katastrofom w różnych częściach Polski. W lutym 2022 roku w Białymstoku doszło do zawalenia się zadaszenia hali pneumatycznej w czasie odbywającego się wewnątrz meczu piłkarskiego. W pewnym momencie balon rozpięty nad boiskiem zaczął się rozrywać i runął na murawę. W grudniu

2022 roku zawaliła się również hala pneumatyczna w miejscowości Kaputy na Mazowszu. Rok wcześniej w grudniu 2021 roku, zaledwie kilka dni po ustawieniu, zapadła się hala sportowa w Mielcu. W niedzielę 7 stycznia 2024 roku zawaliła się hala z zadaszeniem pneumatycznym Podkarpackiego Centrum Piłki Nożnej w Stalowej Woli. Warto dodać, że zdjęcia z katastrofy pokazują znaczną ilość śniegu zalegającego na powłoce hali, a pozostałe przypadki wspomnianych katastrof miały miejsce w miesiącach zimowych. Problemy z powłoką pneumatyczną występowały również w Minneapolis. W czasie eksploatacji tamtejszy dach byłpięciokrotnie uszkadzany z powodu warunków atmosferycznych, a po burzy śnieżnej w grudniu 2010 roku, gdy na poszyciu był o ponad 40 cm śniegu, membrana rozerwała się w kilku miejscach i częściowo opadła na boisko. W obawie przed wypadkiem obiekt ostatecznie rozebrano w 2014 roku. Hale pneumatyczne podobnie jak namiotowe zakwalifikowane są w Prawie Budowlanym do obiektów tymczasowych. Brak formalnych zapisów dotyczących maksymalnych wymiarów takich obiektów, ponadto podlegających wyłącznie zgłoszeniu powoduje, że budowane są hale pneumatyczne o dużych rozmiarach bez dokumentacji projektowej zweryfikowanej przez osoby posiadające uprawnienia budowlane i odpowiednią wiedzę techniczną. Ten fakt jest zaskakujący biorąc pod uwagę, że ustawodawca w procesie kwalifikacji obiektów pod względem wymaganego pozwolenia na budowę lub zgłoszenia ogranicza wymiary altanek, budynków gospodarczych czy suszarni kontenerowych. Przy założeniach, że hala pneumatyczna utrzymuje się dzięki panującemu wewnątrz nadciśnieniu na poziomie ok. 0,30 kN/m^2, założenie w projekcie obciążenia śniegiem przewyższającego wartość ciśnienia wewnętrznego oznacza brak równowagi sił. W praktyce hale pneumatyczne są projektowanie ze zredukowanym obciążeniem śniegiem, bazując na założeniu jego topnienia. Projektanci, podobnie jak w przypadku hal namiotowych, nie precyzują w jaki sposób użytkownik ma kontrolować grubość i ciężar pokrywy śnieżnej na dachu. Najczęściej zakłada się odśnieżanie samoczynne wskutek ogrzewania hali od wewnątrz. Jak pokazuje praktyka, w rzeczywistości przy nawalnym opadzie śniegu dochodzi do topnienia jego niewielkich ilości, które powodują powstawanie zastoin, deformacje powłoki i przyklejanie się kolejnych warstw mokrego śniegu do poszycia. Odśnieżanie mechaniczne jest z kolei nierealne ze względów praktycznych – geometrię obiektu, śliskość powierzchni membrany oraz brak dostępu do korony hali. W przypadku dachu bez dostępu, z wyjątkiem zwykłego utrzymania i napraw, obciążenie użytkowe w Eurokodzie wynosi 0,40 kN/m^2. Taka wartość dwukrotnie przekracza zmniejszony ciężar śniegu przyjmowany w projektach hal pneumatycznych. Zdaniem autorów przedstawiona problematyka powinna zostać w trybie pilnym uregulowania prawnie. W przeciwnym razie istnieje ryzyko występowania tego rodzaju zdarzeń w przyszłości.

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