Technical report – September 2023

Safety analysis of large-area hall roofs in the event of unintentional loading due to heavy rainfall.

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R&D Initiatives / Research and Development Works

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There are approximately 500 construction disasters in Poland every year.

Executive summary

According to the data of the Chief Inspector of Construction Supervision, the main causes of disasters in 2014-2021 were fortuitous events including: strong winds, intense precipitation, fires. In 2021, the building structures that suffered disasters by type were: 4.9% warehouse buildings, 1.5% industrial facilities.

The collapse of the roof of a hall in Szczecin on 18 August 2023 stirred public opinion and the media. The roof collapsed over part of the hall, which is over 10,000 square metres, and there were 144 people inside at the time. All were evacuated.

The information available in the media shows that a storm front passed over the city at that time. The probable direct causes of the disaster were heavy rainfall and strong wind, as well as obstruction of the drainage system, possibly due to various reasons, including poor servicing or inadequate cross-sectional design. The collapsing roof came to rest on warehouse racks, which helped avoid tragic consequences.

Assuming a completely clogged drainage system, after 15 minutes of heavy rainfall, a 15.3 mm of water column will accumulate on one square metre of roof, which corresponds to a weight of 15.3 kg/m^2.

- **The additional load bearing reserve for a steel roof designed in accordance with applicable standards is 3.7 kg/m^2. Heavy, 15-minute rain causes the additional load bearing reserve of the steel girder to be exceeded by more than four times.**
- **For a reinforced concrete roof, this reserve is 24.3 kg/m^2. For a reinforced concrete girder, a similar heavy rain will result in only 60% of the reserve being used.**
- **Using the PANDa model to determine the duration of intense rainfall, the full load bearing reserve for a steel truss (3.7 kg/m^2) is exhausted in less than 5 minutes.**
- **Similarly, for a prestressed concrete girder, the full load bearing reserve (24.3 kg/m^2) is exhausted after more than 60 minutes.**

Given the existing risks, the current design guidelines need to be reformulated for safety reasons.

Base of the study

The basis for this technical report is a number of media reports on the collapse of part of the roof of a large-area hall, which occurred on 18 August 2023 in Szczecin at Kablowa Street (Photo 1).

The incident occurred as a strong storm front [S1] passed over the city. In the West Pomeranian Voivodeship (11 counties), IMGW-PIB issued a second-level warning for thunderstorms around 18:00. Thunderstorms were forecast, in some places with heavy rainfall of 25 mm to 40 mm, locally up to 50 mm, as a result of accumulation of rainfall from successive storm cells passing over the area, and wind gusts of up to 90 km/h [1].

Given the dynamics and increasing frequency of violent atmospheric phenomena in our area (Central Europe), it is reasonable to pay due attention to them. As the authors of paper [2] note, atmospheric and environmental influences are among the causes of construction disasters. In the world, earthquakes, floods and hurricane winds [3] are among the most frequent destructive atmospheric and environmental factors, while in Poland [2] they include: floods, hurricane winds and rainfall. The conscious perception of external factors resulting from climate change, forces one to analyse design situations, the unintended load resulting from heavy rainfall.

Photo 2. Debris accumulation on the roof edge affecting the effectiveness of the roof surface drainage system [16-S2].

Photo 1. Szczecin. Collapsed roof of the hall at Kablowa Street [S1].

The motivation for the analysis is a sense of responsibility for the construction of large-scale facilities in Poland.

In the structural design guidelines, in the standard guidelines, the action of heavy rain does not appear as individually specified (compared to e.g. snow, wind, imposed loads). The result is that it is generally overlooked, both because of the lack of standard guidance and the a priori assumption that this load will always have a lower value than the snow load. This appears to hold true for a properly designed and efficient roof drainage system. However, even if the conditions above are met, during the operation of the building, debris may accumulate on the roof slope, at accumulation points, affecting the flow capacity of the drainage system (Photo 2). The situation presented illustrates that the analysis carried out later in the report is not only theoretical, but above all practical.

The motivation for the analysis is a sense of responsibility for the construction of large-scale facilities in Poland.

Causes of building disasters

Every construction disaster poses a threat to the safety of life, health and property. According to the analyses carried out by GUND, the causes of disasters can have various origins.

Analyses carried out between 2014 and 2021 clearly show that fortuitous events are the main cause of building disasters. Figure 1(a) shows the percentage of building disasters resulting from fortuitous events against all disasters recorded in a given year. In this report, the following are considered to be fortuitous events: high winds, intense precipitation, fires, but also those related to human actions, e.g. gas explosion or traffic accidents.

Between 1995 and 2022, 9,573 construction disasters were recorded in Poland. In the last reporting year – 2022 – there were 663. The number of disasters over the years is shown in the graph in Figure 1(b). Analysing the data collected by GUND [S3] on the percentage of fortuitous events in all construction disasters and the number of disasters itself, it is clear that the number of fortuitous events is quite significant. In spite of the due diligence of the work at the stage of structural design and erection of the building, the number of disasters caused by fortuitous influences can be a cause for concern. In addition, there has been an upward trend in the number of disasters occurring in Poland in recent years. With the constantly high percentage of fortuitous events causing catastrophes, it is clear that changing climatic conditions [4] have a strong impact on erected structures.

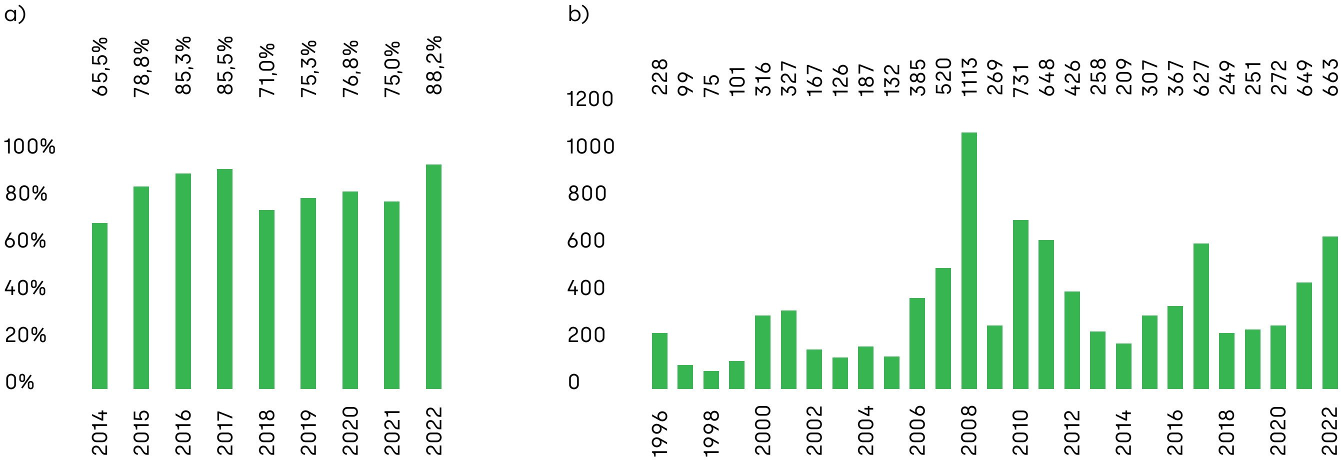

Fig. 1. Construction disasters in the years: (a) 2014-2022, percentage of catastrophic events, (b) 1996-2022, number of disasters reported [5, 6].

Roof girder loads – self-weight design coefficient

The subject of this report is a comparative analysis of prestressed concrete girders in relation to steel lattice girders, together with an attempt to identify safety provisions in optimally designed structures. Roof girders with an axial span of 24.0 m and a transverse system spacing of 6.25 m were analysed.

A steel truss with a height of 1.46 m and a gabled prestressed concrete girder with a ridge height of 1.10 m, both with a +/- 90% load capacity, were designed for the loads listed in Table 1. Finishing layer loads and variable live loads were assumed as for standard large-area halls. The environmental variable loads were collected for Szczecin, according to EN 1991-1-3 [N1] and EN 1991-1-4 [N2].

The steel truss was designed in accordance with EN 1993-1-1 [N3], with the assumption of full cooperation of the compression chord of the truss with the roofing made of trapezoidal sheet metal (protection of the compression chord against buckling). The prestressed concrete girder was designed in accordance with EN 1992-1-1 [N4].

Table 1 – Warehouse hall roof loads (surface)						
No.	Type of load	Characteristic load		Design coefficient	Design load	
		q_k [kN/m^2]		γ_f [-]	q_d [kN/m^2]	
Permanent load						
1.1	Finishing layers: PVC roofing membrane Mineral wool (0.13m) PE film Trapezoidal sheet T130 (0.80mm)	 0,01 0,15 0,01 0,10		1,35	 0,01 0,20 0,01 0,13	
	TOTAL	**0,27**			**0,36**	
Variable (live) load						
2.1	Internal installations – suspended	0,15		1,50	0,23	
2.2	Photovoltaic installation with substructure	0,25			0,38	
	TOTAL	**0,40**			**0,60**	
Variable (environmental) load						
3.1	Snow (Zone 2) (Flat roof: 2% slope)	Ridge: Valley:	0,72 0,77	1,50	Ridge: Valley:	1,08 1,16
3.2	Wind* (Boundary zones 1 and 2) Roof area "+I" (push) internal vacuum (suction)	0,18 0,27			0,27 0,41	
	TOTAL	**0,45**			**0,68**	
* The wind load is indicated only for the '+I' area due to the fact that this is the only area that consistently reacts to gravity loads. For design purposes, other areas for the flat roof should also be analysed.						

This section focuses only on the design reserve generated by the design coefficient for the self-weight of the roof girders. EN 1990 [N5] imposes a design coefficient of 1.35 on the permanent loads of the structure. Such loads include the self-weight of the structure – the self-weight of the roof girders. The steel truss selected in accordance with the above description has a mass of approx. 1,580 kg.

A prestressed concrete girder, meeting the assumptions used in the analysis, has a mass of approximately 10,600 kg. When making prefabricated elements (both steel trusses and prestressed concrete girders) under controlled production conditions, the quoted masses are approximately accurate (without significant deviations). At this point, it can be assumed that the 35% additional load assumed in the design combination for the self-weight of the structure represents a kind of hidden design reserve. If this reserve is calculated per square metre of roof area, in the case of a steel truss it is 3.7 kg/m², while in the case of prestressed concrete girders it is 24.3 kg/m². When pre-stressed concrete girders are used as a structural element of the roof, the additional load bearing reserve is therefore 20.6 kg/m².

Table 2 – Roof girder loads (surface load as per Tab. 1)				
No.	Type of load	Characteristic load	Design coefficient	Design load
		q_k [kN/m²]	Y_f [-]	q_d [kN/m²]
Permanent load				
1.1	Finishing layers (1.1)	1,69	1,35	2,28
1.2a	Variant 1: Weight of steel truss(approx. 1,580 kg)	0,66	1,35	0,89
1.2b	Variant 2: Prestressed girder weight (approx. 10,600 kg)	4,35	1,35	5,87
Steel girder load bearing reserve: 0,89 - 0,66= 0,23 kN/m || 3,7 kg/m² Concrete girder load bearing reserve: 5,87 - 4,35=1,52 kN/m || 24,3 kg/m² **Additional load-bearing reserve for the concrete girder compared to the steel girder for 1 m length:** **1,52 - 0,23 1,29 kN/m (1,29 kg/m)= || 20.6 kg/m²**				

Totalling the load on the area resulting from the span of the girders and their lateral spacing (area per roof element), the load reserve equals respectively:

- **for a steel truss: 552 kg,**
- **for a prestressed concrete girder: 3,648 kg.**

The additional load bearing reserve for the prestressed concrete girder relative to the steel girder is therefore 3,096 kg/element.

When considering the safety of large hall structures under unintended loads of climatic origin, due attention must be paid to rainfall. In comparison with climatic loads (snow, wind) and the possibility of their real quantitative deviation from the norm, the case of loading the structure with rainfall is not considered by the standards describing actions on structures. It can therefore be assumed that any occurrence of rain load on a structure is an unintended load. The omission of this load in the common approach is a result of both the lack of design guidance, standard guidance and the assumption that this load will be of lesser value than snow load. This appears to hold true for a properly designed and efficient roof drainage system. However, even if the conditions above are met, during the operation of the building, debris may accumulate on the roof slope, at accumulation points, affecting the flow capacity of the drainage system, or, as noted in [N1], in some cases the drainage may become blocked during melting and freezing of snow. This leads to the accumulation of water on the roofs of large-area halls [4].

The changes in the frequency and intensity of precipitation observed at present and forecast for the coming decades force serious reflections and consequently translate into specific challenges. Both short-term heavy rainfall, which is most often of small territorial extent, and long-lasting rainfalls of lesser intensity but large extent can cause significant damage to urban and industrial infrastructures [4].

This report also focuses on determining the amount of water that is able to accumulate on the roof of a large-area hall during heavy rainfall. The methodology for calculating the intensity of the rainfall is adopted by the system designer in consultation with the developer or the operator of the rainwater drainage network. Most system designers use the Blaszczyk method [S4] for this purpose. The standard procedure is to take the rain intensity, calculated according to Blaszczyk's equation [7], for a 15-minute design rainfall with a recurrence frequency of once every five years of $c = 5$, i.e. for a probability of $p = 20\%$ as the value of $q = 131.4$ dm^3/s·ha (reliable rain intensity). Assuming a completely unobstructed drainage system, after 15 minutes of rainfall of this intensity, a water column of 11.8 mm will collect on one square metre of roof, corresponding to a weight of 11.8 kg/m^2.

When considering the safety of large hall structures under unintended loads of climatic origin, due attention must be paid to rainfall.

The continued use of the Blaszczyk model, as a standard, reduces the safety of designed and modernised drainage systems in Poland [8], which also translates into the safety of the use of large-area halls. The obsolescence of the Blaszczyk model is mainly due to changes in the distribution of rainfall amounts in time and space, the main factor of which is strong climatic changes [9]. In Germany, the importance of this issue was recognised thirty years ago, and its solution is the systematically updated nationwide precipitation atlas KOSTRA (German: KOordinierte STarkniederschlags-Regionalisierungs-Auswertungen). In Poland, this standard was achieved through the development of the Polish Atlas of Rainfall Intensities (PANDa). It provides a digital platform containing information on the intensity of reliable rainfall for all cities in Poland. Assuming as before a 15-minute rainfall with a probability of occurrence of p = 20% (c = 5 years) as a reference point, the reliable rain intensity q will be equal to 169.89 dm3/s·ha (Fig. 2). Assuming a completely unobstructed drainage system, after 15 minutes of rainfall of this intensity, 15.3 mm of water column will collect on one square metre of roof, corresponding to a weight of 15.3 kg/m².

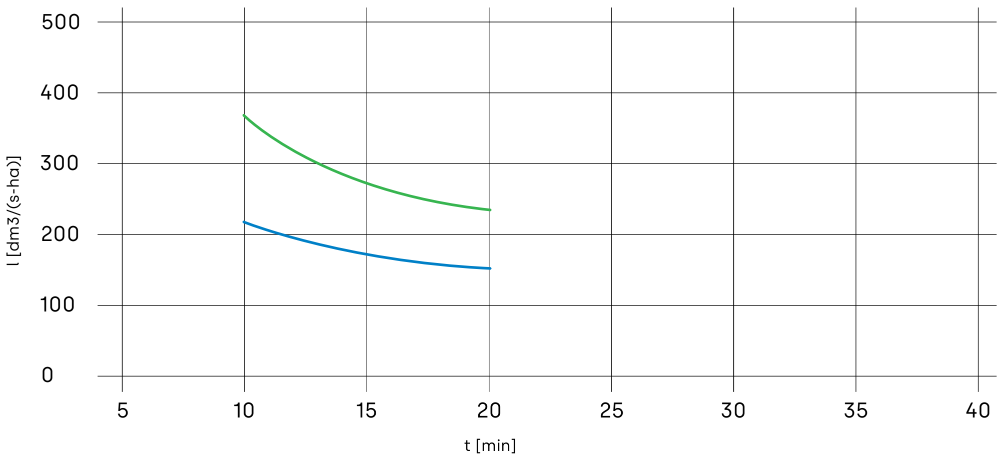

Fig. 2. Measured rain intensity as a function of rainfall duration
(blue line – probability p = 20%, green line – probability p = 2%) [PANDa].

The figures presented above clearly indicate that such an additional load would be more than 4 times the calculation reserve discussed in this section of the report for a steel truss, and about 60% exhaustion of the reserve for a prestressed concrete girder.

Using the PANDa model to determine the duration of heavy rainfall which, with a completely unobstructed drainage system, would result in the full reserve exhaustion of the steel girder in question (3.7 kg/m²), a value of less than 5 minutes was obtained. Following the same procedure for a prestressed concrete girder, the full reserve exhaustion in question (24.3 kg/m²) would take place after more than 60 minutes.

Inertia of the roof girders

The next step of the analysis carried out is to demonstrate the ‚inertia' of the roof girders analysed. To this end, the elements were analysed and selected for the same set of external loads so that their effort due to bending at the Ultimate Limit State (ULS) was equal and amounted to approximately 88%. Then, the loads were increased in increments of 25 kg/m of girder length. The results are shown in the diagram below (Fig. 3).

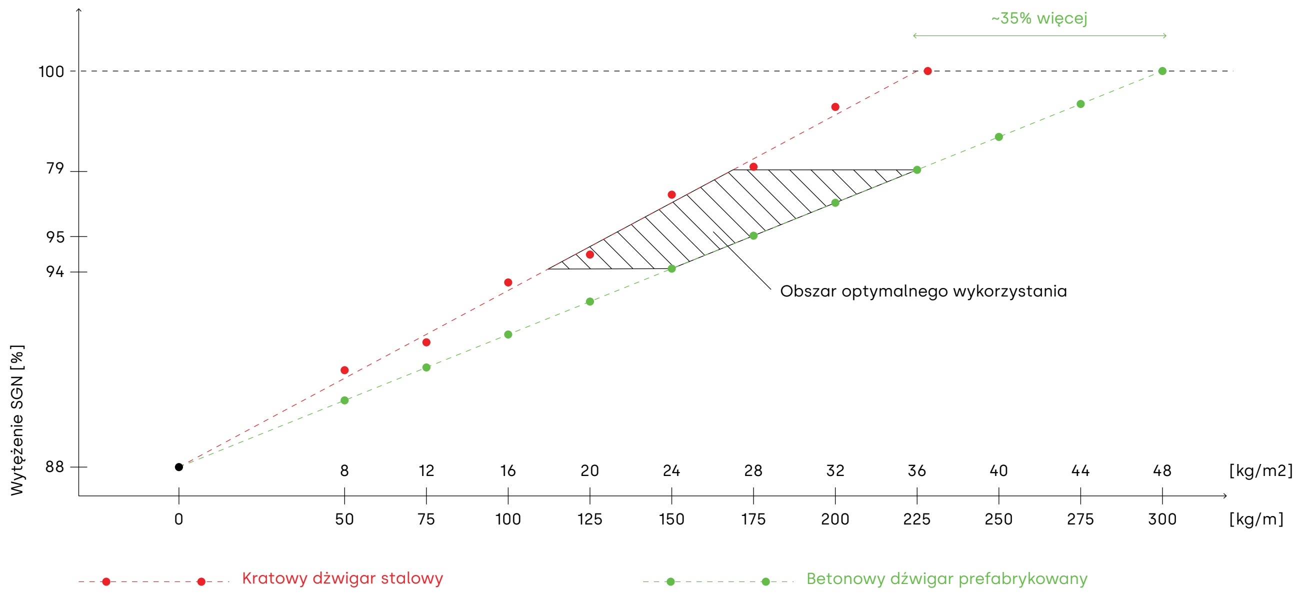

Fig. 3. Utilisation of the roof girder load capacity as the additional external load increases
(additional kilograms per metre of girder length [kg/m], additional kilograms per m² of roof [kg/m²].

The data shown in the diagram above illustrates the clearly greater inertia of a roof made using prestressed concrete girders as structural elements. With an increase by the same value of the effort in the SGN, about 35% more load can be added to a prestressed concrete girder than is the case with a steel truss. An increase in the external load by the same value causes a significantly faster increase in the effort of the steel truss than that of the pre-stressed concrete girder.

Characteristics of steel and prestressed concrete girders

A characteristic feature of large-area steel roofs made using steel trusses is the lightweight construction of the roof. In the example cited in the report, the weight of the steel truss is more than 6 times that of a prestressed concrete girder. This disproportion of weight translates into a slender structure. Optimally, due to the criterion of the mass of the structural element, the designed steel roofs take into account (which was also assumed in this report) the interaction of the truss girder with the roofing (trapezoidal sheet metal). Steel trusses show considerably lower stability (greater sensitivity to loss of stability) compared to prestressed concrete girders.

A view of the construction of a large-area hall using steel trusses is shown in Photo 3, while a hall using pre-stressed concrete girders is shown in Photo 4. The subjective perception of roof stability in the case of the two types of girders used is quite different.

Photo 3. Roof of the hall made using steel prefabrication technology [S5].

Photo 4. Roof of the hall made in prefabricated prestressed concrete technology [PEKABEX].

In addition, steel lattice girders are transported from the prefabrication plant in shorter sections, which are connected on site to form one full-span girder (e.g. 24 m). These connections are usually designed as bolted and located near the centre of the span, i.e. where the highest internal forces occur. Bolted connections, even if correctly and safely designed, but located at such a sensitive point and intended to be made on site, introduce potential additional points for error (e.g. use of bolts of the wrong strength class). This location is all the more sensitive in an emergency situation, such as a short period of heavy rainfall. In contrast to steel girders, prefabricated prestressed concrete girders are made entirely under the controlled conditions of the prefabrication plant and transported to the site for erection as a single component.

Indirectly related to the previous feature is the nature of the failure of the girders in question when the structure is overloaded. When the design internal forces are exceeded, numerous structural scratches appear in prestressed concrete girders. They indicate unintended operation of the element and suggest the necessity of safe evacuation, as well as performing a detailed visual inspection by specialists in prestressed concrete structures. The user of a prestressed concrete hall is therefore given the opportunity to react before damage to the member occurs. In the case of steel trusses, although steel itself as a material shows the possibility of significant plasticisation and safe response to structural overloading, the overloading of structural nodes at the element connection points is a dynamic phenomenon. The rupture of one connector in the joint can lead to a rapid increase in the strain on the remaining connectors and an avalanche effect of node failure.

Summary

The expected assumption is that a properly designed structure, like any component, should work reliably for many years. In reality, this is not always the case, as evidenced by the statistics quoted in chapter 2 of the study. Lack of proper maintenance and upkeep, incorrect assumptions, changing climatic conditions and human error often lead to failures or even disasters. In the context of the factors described above, the additional safety reserves „inherent" in the structure and its readiness to absorb unintended actions becomes even more important and desirable.

The analyses shown in this technical report allow prestressed concrete girders to be considered clearly more resistant to uncontrolled overloads than steel trusses. Large-area roofs made with prestressed concrete technology are characterised by high inertia and stability, which translates into an increase in the safety margin of such structures.

However, changing weather conditions force reflection and the need for changes to applicable standards. Situations where intensive rainfall may adversely affect the safe use of large-area buildings are a clear reason for such changes. Large-area roofs, where the rainfall collection area is significant, are most affected by this effect.

The above conclusions about changing climatic conditions and the reality of uncontrolled additional load from intense rainfall are also supported by a report by the Polish Economic Institute (PIE), indicating that extreme weather events have led to significant economic losses in EU member states. Floods are responsible for the largest share of losses (more than 45%), followed by storms and hail (around 33%), while heat, drought, forest fires and severe frost accounted for 20% of total losses over the period 1980-2021 [S6].

Conclusions

The analysis carried out in this report clearly shows that a large-surface roof made using prestressed concrete technology has more than 6 times the latent safety margin resulting from the design coefficients used for the self-weight of the roof girders. The additional load reserve for a prestressed concrete girder in relation to a steel girder is 3,096 kg/element (20.6 kg/m^2 roof) in the case under consideration.

In addition, it was shown that the inertia of a roof made of prestressed concrete girders as structural elements was significantly higher in relation to steel girders. An increase in the external load by the same value results in a clearly faster increase in the effort in the steel truss than in the prestressed concrete girder. With an increase of effort in the ULS by the same value, about 35% more load can be added to the prestressed concrete girder than is the case for the steel truss analysed.

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STANDARDS

[N1] EN 1991-1-3:2005 Eurocode 1 – Actions on structures – Part 1-3: General actions – Snow loads

[N2] EN 1991-1-4:2008 Eurocode 1 – Actions on structures – Part 1-4: General actions – Wind actions

[N3] EN 1993-1-1:2006 Eurocode 3 – Design of steel structures – Part 1-1: General rules and rules for buildings

[N4] EN 1992-1-1:2008 Eurocode 2 – Design of concrete structures – Part 1-1: General rules and rules for buildings

[N5] EN 1990:2004 Eurocode – Basic of structural design

WEBSITES

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[S2] https://westernspecialtycontractors.com/roof-housekeeping/ (09.2023)

[S3] https://www.gunb.gov.pl/strona/katastrofy-budowlane (12.2023)

[S4] https://poradnikprojektanta.pl/jak-wyznaczyc-miarodajne-natezenie-deszczu-dane-opadowe-w-polsce/ (09.2023)

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Poznan, 2 February 2024

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