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Operational Safety of Skeleton Frame Built Structures with a Low-Rigidity Covering

Operational Safety of Skeleton Frame Built Structures with a Low-Rigidity Covering

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Abstract. The paper discusses issues related to the safety of light skeleton frame structures with a low-rigidity covering. Non-building structures of this kind have been broadly used as large-scale greenhouses. The most commonly used layout for these structures is the multi-span layout. The paper presents legal preconditions related to construction and operation of these structures; it particularly focuses on external climatic loads, i.e. snow and wind, affecting reliability of these structures due to their uneven distribution on multi-slope roofs. One of the problems associated with the use of plastic covering is the accumulation of snow in multi-slope roof valleys. Designers sometimes happen to transfer this problem to the user of the structure by allowing obligatory snow removal in their calculations and thereby leading to situations where the snow load of the main structural frame is underestimated. The paper presents examples of structures in case of which, as a consequence of underestimating the snow load, failures can occur. In addition, a method of determining wind loads for roof shapes not provided for in standards was noted. The summary contains final conclusions regarding construction and operation of foil tunnels in Polish conditions of operation.

1. Introduction

Steel is one of the best recyclable materials in the world because the process of large-scale steel production involves added scrap metal. The light steel skeleton frame technology for structures intended e.g. for construction of foil tunnels and tent halls is very effective, and therefore commonly used. It is thus advantageous to investigate the manner in which structural solutions used in civil engineering exert an effect on subsequent stages of construction work and operations. Steel is characterised by the most advantageous ratio of weight and strength among building materials. Spatially rigid steel structure of a building is several dozen times lighter than a brick or reinforced concrete structure of a building of the same size, with both of them being capable of transferring comparable external loads. Lower weight and sizes of such structures are clearly related to lower costs of shipping from the place of manufacture to their place of installation. In spite of numerous advantages, steel structures are not sufficient at all times, which shall we demonstrated in an example of one of the built structures referred to in this paper. Nowadays, the construction market is offering a variety of foil tunnel solutions to be used in agriculture [1]. Offers include solutions where the main supporting structure is a light steel frame. The frame is comprised of repeating frame units made of square, rectangular, and round hollow structural sections (figure 1a). In case of larger spans up to 20.0 m, the problem of the supporting frame is solved by using a lattice frame, often reinforced with a tie-rod (figure 1b). Longitudinal rigidity is ensured by using slope and wall bracings as well as longitudinal rods connecting individual frames. The effect of using this method is a light structure having the correct transverse and longitudinal rigidity. The available solutions include single- (figure 1a, 1b, 1d) and multi-span tunnels (figure 1c)

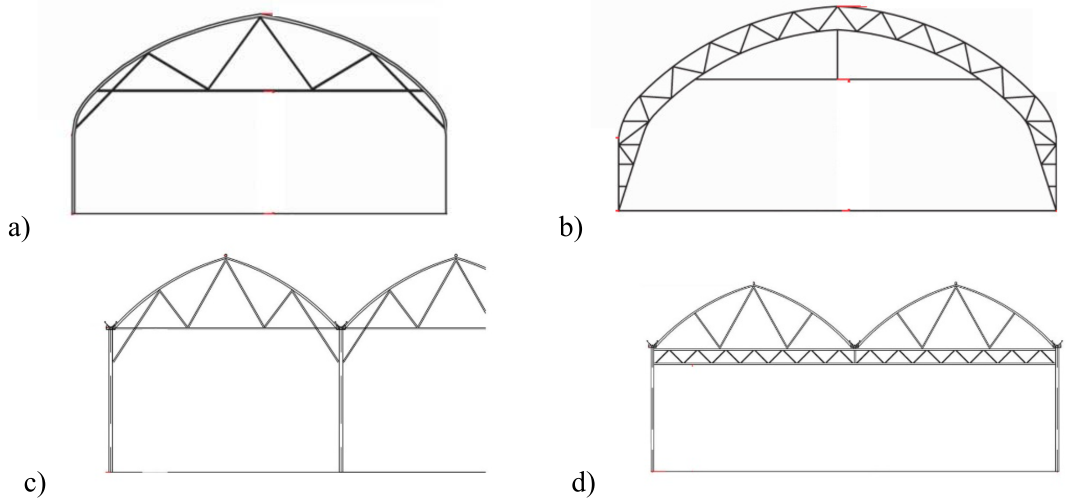

Figure 1. Cross section of the foil tunnels a) small single span tunnel – up to 9,6 m, b) large single span tunnel – up to 20,0 m, c) multi span tunnel, d) single span tunnel – span of 12,8 m

The idea of our static analysis of the construction of the foil tunnel appeared after recognition of the construction project of the object presented in section 2. It turned out that the object loads were accepted in a too simplified way. Therefore, we decided to make a precise determination of the loads and static calculations. We compiled loads of object for a large number of cases snow and wind loads. Due to the unusual shape of the roof, we have simulated wind loads in a virtual wind tunnel. Obtained results on a flat and spatial model allowed the conclusion that the roof loads should be set as for a multispan roof.

2. Case study of a light steel structure as illustrated by a foil tunnel

The main supporting structure of the foil tunnel consists of steel lattice girders with a span of 12.8 m, 0.7 m in height, spaced by 2.5 m and based on closed-section posts restrained in concrete footings. Two ‘Gothic’ arched vaults partially supported by posts on girders were rested on the trusses. The structures were designed and made of grade S235 steel. Connections between steel components were designed in category A – standard, using 8.8 (8) and 10.9 (10) bolts. Truss and column components were cross-reinforced with tube bracings in order to protect them against out-of-plane buckling.

This structure was designed to withstand snow loads applicable to the 2nd climate zone and wind loads applicable to the 1st zone. A significant element of any design is the presumed satisfaction of proper conditions of use that apply to load-bearing structures and the entire built structure. The structure should be used as required by Act [2] (Chapter 6. Maintenance of built structures) – Article 61 and 62. The user of the structure should not let snow linger on the structure, especially in gutters, so as to prevent the structure from overloads and permanent damage. The assumption (precondition) stated above is hard to adhere to because separate user manuals are not issued for such built structures and even if such a manual was available, it would be forgotten by everyone during the period of using the tunnel. Moreover, during periodic inspections of structures (Chapter 6 [2]), persons conducting such inspections assess the actual condition of the structure and skip analyses of possible load and overload conditions of the structure. Such provisions in the design are very risky as, in general, it is only the designer who can remember them and in fact this is usually the case. View of the structure under construction was shown in figure 2.

Figure 2. View of the structure under construction

3. Static strength analysis
In reference to the solution presented in Section 2, a static strength analysis was conducted on a selected fragment of the structure of the foil tunnel complex for the purposes of the paper. The enquiry covered a fragment of the built structure, plan dimensions: 12.8 x 30.0m. A cross section of the analysed built structure was shown in figure 3.

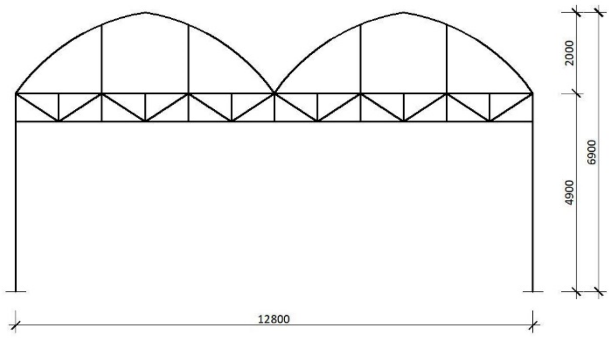

Figure 3. Cross section of the foil tunnel [3]

Calculations allowed for a permanent load of a foil roof covering with a characteristic value of 0.03 kN/m2 and self-weight load of structural components that was automatically taken into account by the program used for calculations. The snow load was determined based on standard [4]. In view of shape of the roof on the analysed structure, three load cases were allowed for in the calculations. The first case represents undrifted load arrangement of snow, the second case represents drifted load arrangement of snow on a cylindrical roof (figure 4). The third load case was determined as though it covered a multi-span roof and allowed for the possibility of snow accumulating in the roof valley (figure 5). The most serious doubts were raised as far as wind load distribution on the roof of the structure is concerned. Standard [5] provides a method of determining wind action for specific roof types. In case of simple situations, such as mono- or duo-pitched roofs or regular cylindrical roofs, the regulations clearly determine the method of load description. Unfortunately, in case of complex shapes, accurate guidelines are lacking. In the analysed case, the employed roof shape is the 'Gothic' vault shape. The shape of the roof, shown in figure 6, is structured using two curved surfaces, each having a radius r=4869 mm.

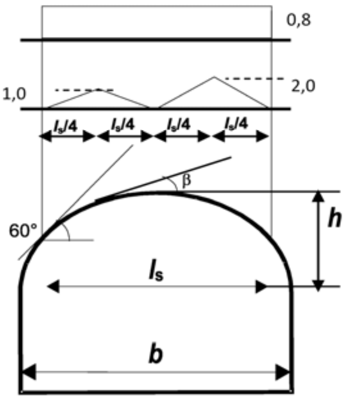

Figure 4. Cylindrical roof shape coefficients [4]

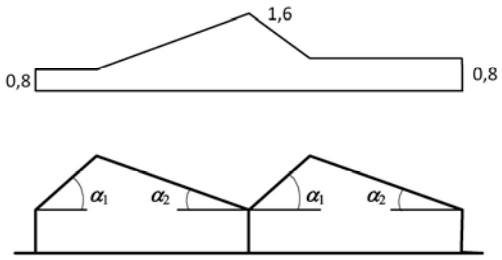

Figure 5. Multi-span roof shape coefficients [4]

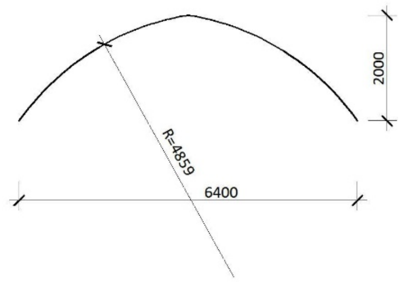

Figure 6. Shape of the 'Gothic' roof of the plastic tunnel, adapted from [3]

The description of wind loads presented in standard [5] pertains to roofs with one curved surface that is a sector of a regular cylinder. Due to much greater angles at which wind is approaching the analysed roof, load distribution appears to be closer to the duopitched roof case, therefore the calculation compares wind loads on the roof of the foil tunnel determined for the cylindrical roof shape and the duopitched roof shape. Another doubt related to wind loads pertained to the shape of the roof. In formal terms, the roof is multispan. This case has been described in detail in Article 7.2.7, standard [5], but only for roofs with constant slope; clear guidelines for a similar roof configuration with variable slope have been lacking in that standard.

Finally, three wind load cases were taken into account for the roof. Case 1 describes wind action on the surface of a cylindrical roof. The assumed values of external pressure coefficients and values of external pressure were provided in figure 8 and table 1. Wind load Case 2 was determined in accordance with principles provided in Article 7.2.7 of standard [5] for multispan roofs. Values of

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pressure coefficients for the windward slope were assumed to be the same as those for a monopitched roof, and for the other surfaces – the same as in a duopitched roof in the valley (figure 9). Due to varied pitch of the slopes, two averaged values of pitch were taken into account and shown in figure 10. The assumed values were shown in figure 11 and table 2.

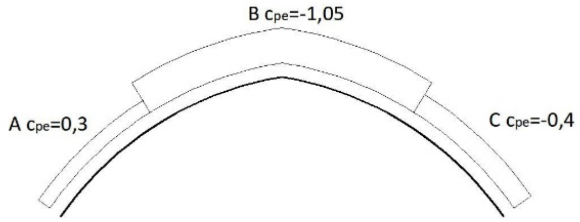


Figure 7. Distribution of external pressure coefficients on the cylindrical roof [source: authors' archive]

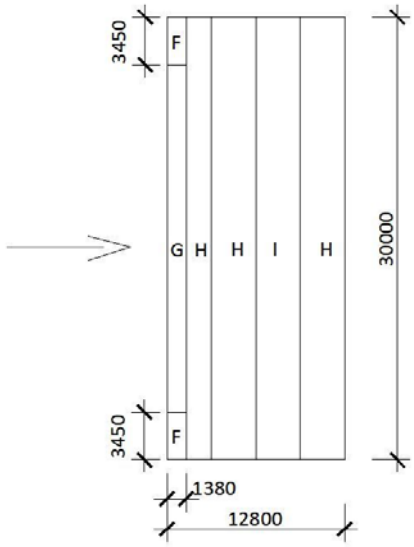


Figure 8. Wind load fields in multispan roofs [source: authors' archive]

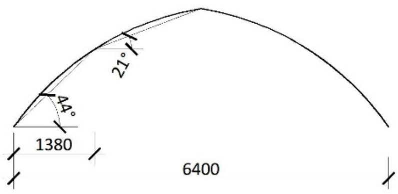


Figure 9. Pitch of the roof slopes used to describe wind loads [source: authors' archive]

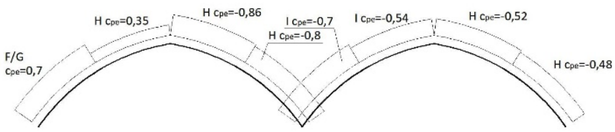


Figure 10. External pressure coefficients for the multispan roof case [source: authors' archive]

Table 1. Values of external pressure coefficients and external pressure [source: authors' archive]

Load field (markings for arched roofs)	A	B	C
External pressure coefficient c_{pe}	0,3	-1,05	-0,4
External pressure [kN/m^2]	0,19	-0,68	-0,26

Table 2. Values of external pressure coefficients and external pressure [source: authors' archive]

Load field	Windward slope			Other slopes			
	F	G	H	H_{44}	H_{21}	I_{44}	I_{21}
External pressure coefficient c_{pe}	0,7	0,7	0,35	-0,8	-0,86	-0,7	-0,54
External pressure [kN/m^2]	0,45	0,45	0,23	-0,52	-0,55	-0,45	-0,35

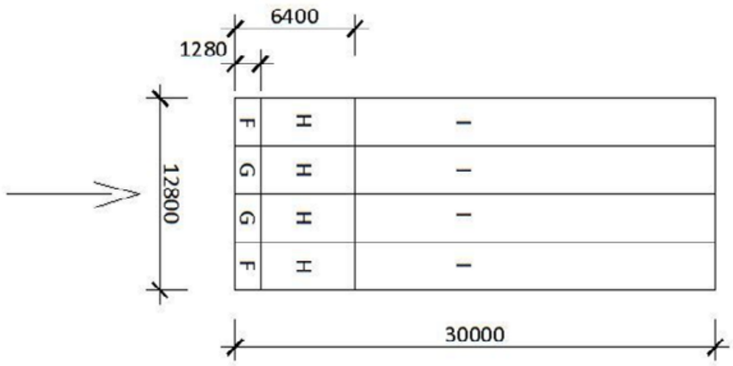


Figure 11. Roof wind load fields – case 3 [source: authors' archive]

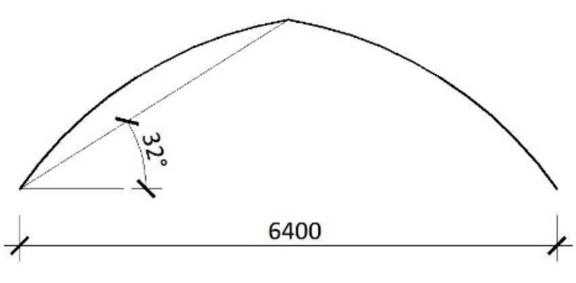


Figure 12. Roof slope pitch used to describe wind load, with wind acting in parallel to the longitudinal axis of the structure [source: authors' archive]

Values of external pressure coefficients and external pressures were shown in table 3.

Table 3. Values of external pressure coefficients and external pressure for wind acting along the longitudinal axis of the structure [source: authors' archive]

Load field	F	G	H	I
External pressure coefficient c_{pe}	-1,1	-1,4	-0,8	-0,5
External pressure [kN/m^2]	-0,71	-0,90	-0,52	-0,32

The structural system shown in figure 3 was modelled in Autodesk Robot 2018 (figure 14) and included permanent and climatic loads as well the required load combinations described above. The obtained results of static calculations in the form of envelope of cross-sectional forces were provided in figures 15÷17.

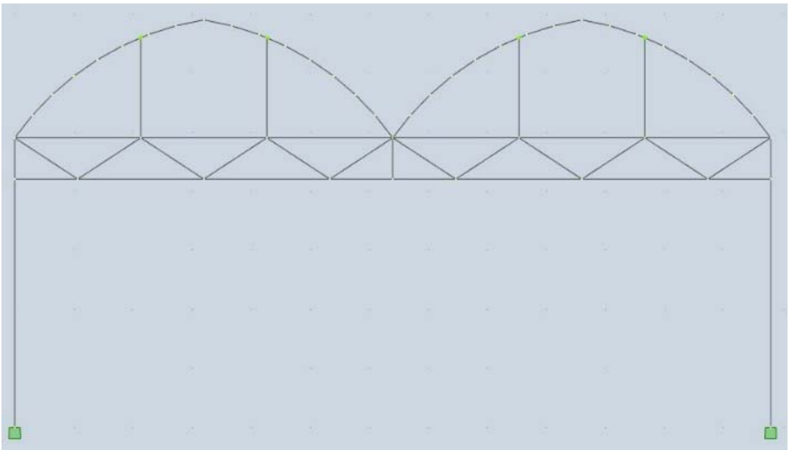


Figure 13. Strut and tie model of the analysed foil tunnel frame [source: authors' archive]

Figure 14. Envelope of bending moments [source: authors' archive]

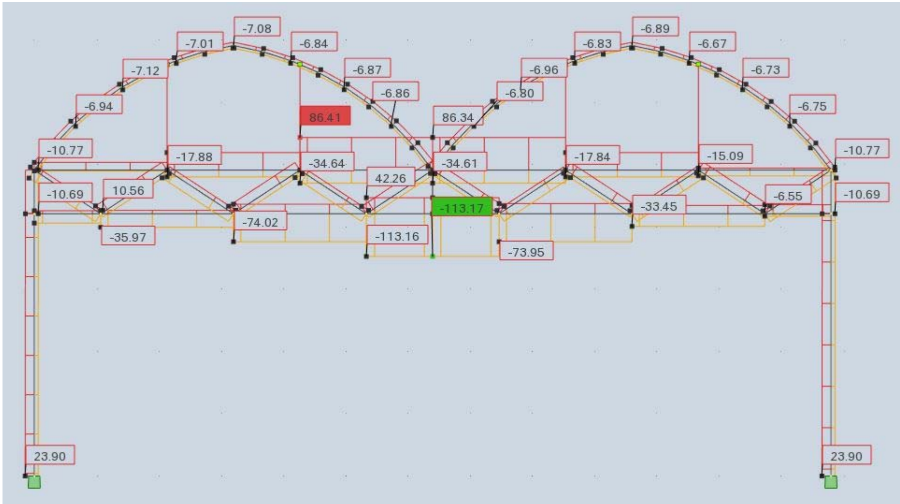


Figure 15. Envelope of axial forces [source: authors' archive]

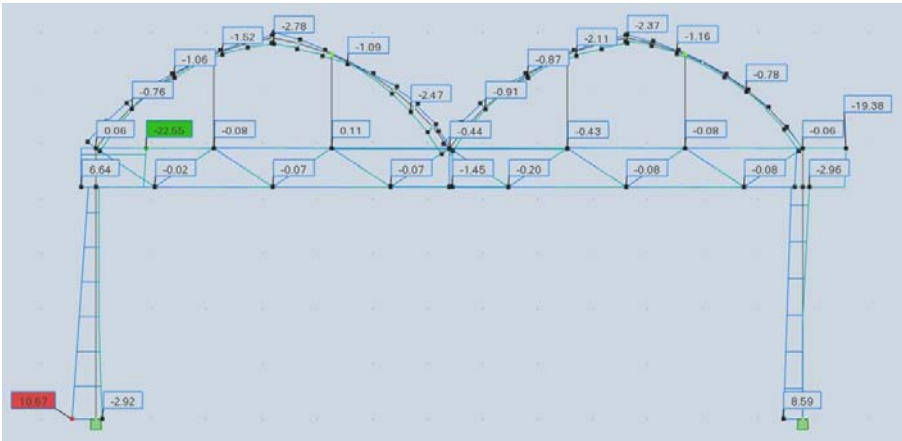


Figure 16. Envelope of shear forces [source: authors' archive]

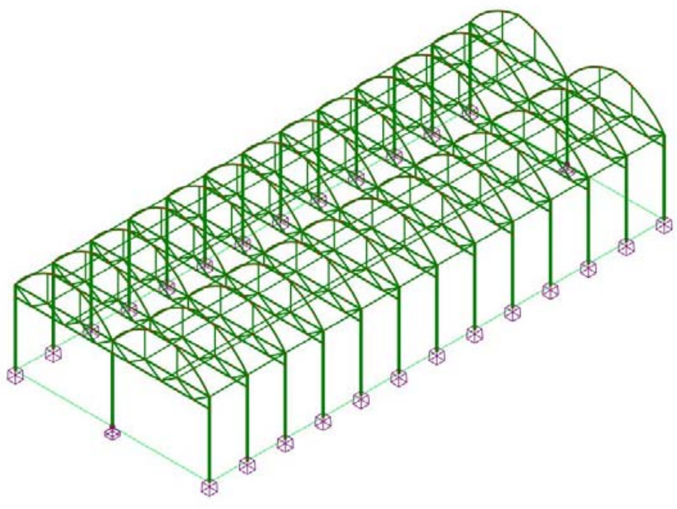


Figure. 17. Spatial FEM lattice model of the structure [source: authors' archive]

The doubts that had been aroused during wind load determination necessitated an additional wind load analysis. To this end, a spatial model of the discussed structure was created. Spatial lattice structure was generated (figure 17), permanent and snow loads were described as surface loads automatically distributed by the program among the bars using the so-called cladding function.

The main aim of this analysis was to provide a comparison with the previously obtained flat frame solution. Wind load of the model was attained based on an analysis in the virtual aerodynamic tunnel implemented in Autodesk Robot. In order to reflect standard conditions [5], wind loads were determined for wind acting perpendicularly and in parallel to the longitudinal axis of the structure, with possible deviations in wind direction of ±45°. Selected solutions achieved in the virtual tunnel analysis were shown in figures 18÷20.

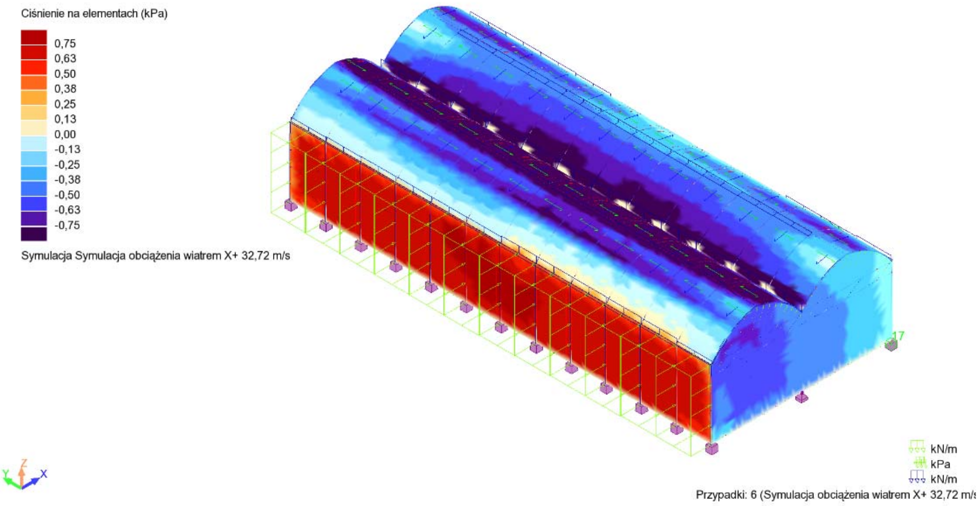


Figure 18. Wind pressure – perpendicular to the longitudinal axis [source: authors' archive]

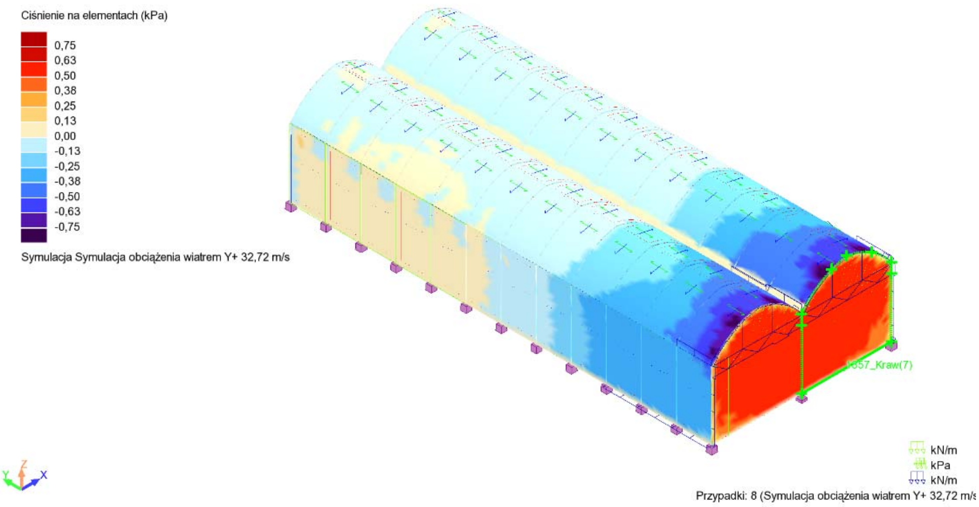


Figure 19. Wind pressure – parallel to the longitudinal axis [source: authors' archive]

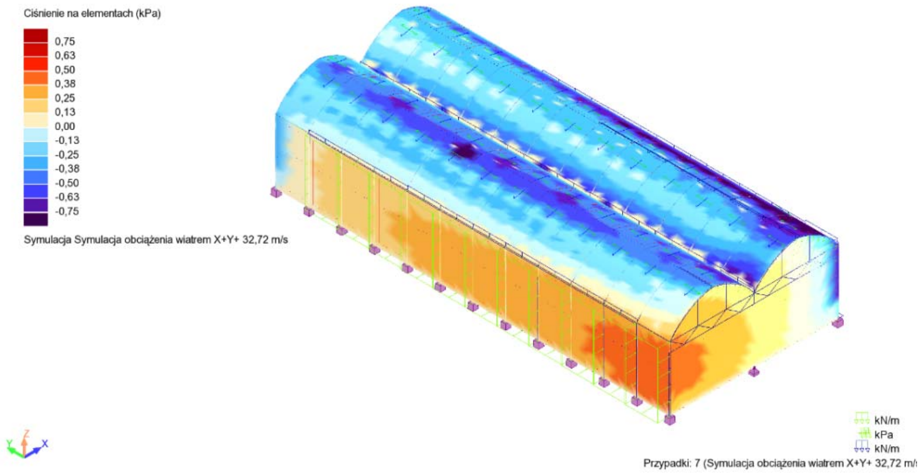


Figure 20. Wind pressure – deviating from perpendicular to the longitudinal axis by 45° [source: authors' archive]

By performing calculations on the flat model, frame loads were determined for the last-to-terminal model. The obtained graphs of internal forces for the last-to-terminal model obtained in the 3D FEM model are shown below (figures 21÷23).

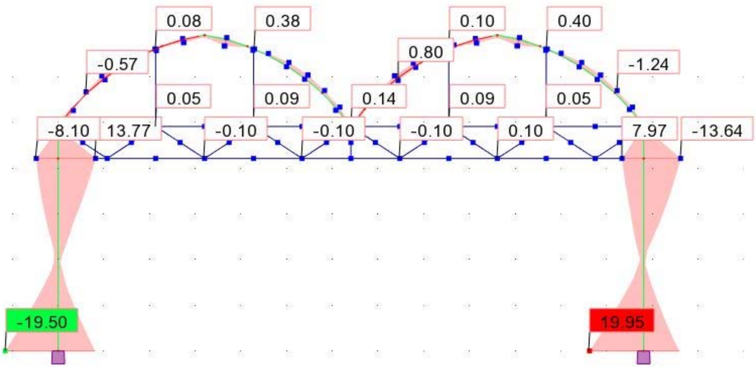


Figure 21. Envelope of bending moments My [source: authors' archive]

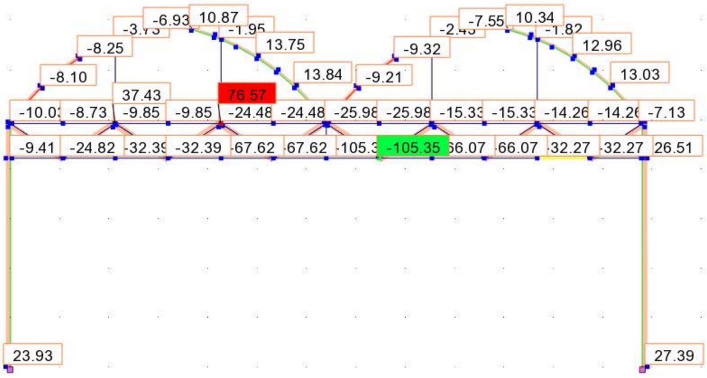


Figure 22. Envelope of axial forces Nx [source: authors' archive]

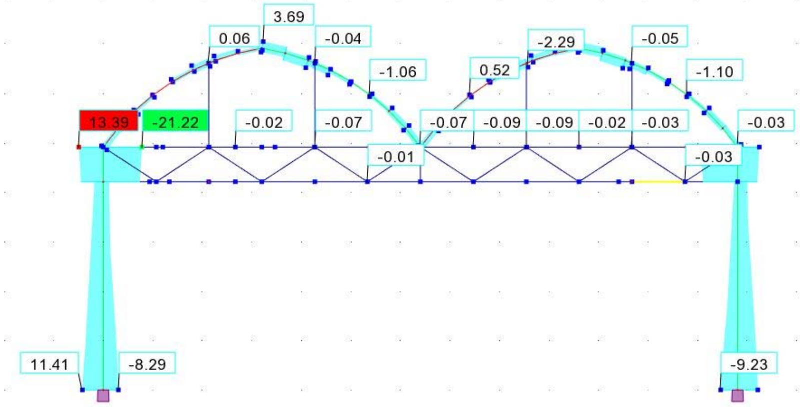


Figure 23. Envelope of shear forces [source: authors' archive]

After comparing solutions obtained for particular approaches, it can be concluded that they show great similarities. Values of internal forces for both models (flat and spatial model) are close. It can be thus concluded that the assumed method used to describe wind loads is correct.

4. Light frame structure requiring reinforcement

The verification calculations presented in Section 3 showed that assumptions for calculations made by the tunnel designer do not allow for a possible, real distribution of snow on the slopes, which can lead to a 2 ÷ 88 % value increase in internal forces in structural components and that can pose danger to the structure or safe use. Therefore, it has to be concluded that steel structures made using a low-rigidity covering are a problematic issue and factors having a substantial impact on the load-bearing capacity can easily be forgotten (in particular, loads can be underestimated). One example of this is a single-span tent hall built using the light frame technology, with an aluminium skeleton structure (span – 15.0 m) and a roof covering made of a tarpaulin material.

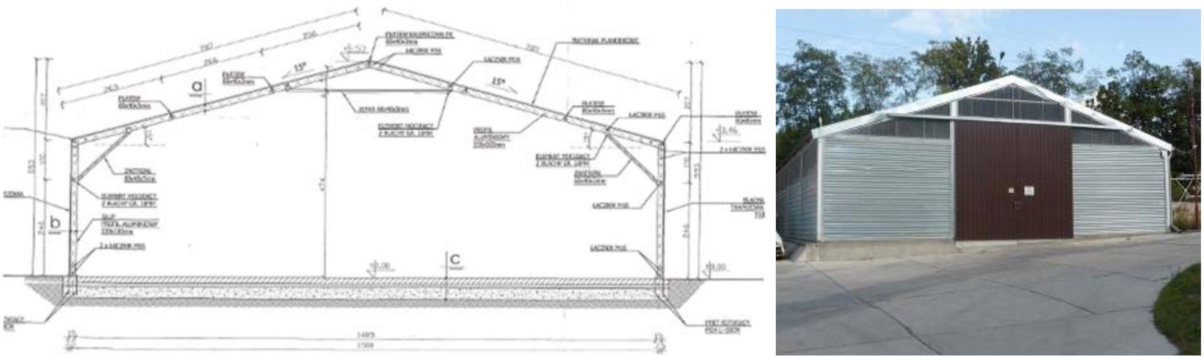
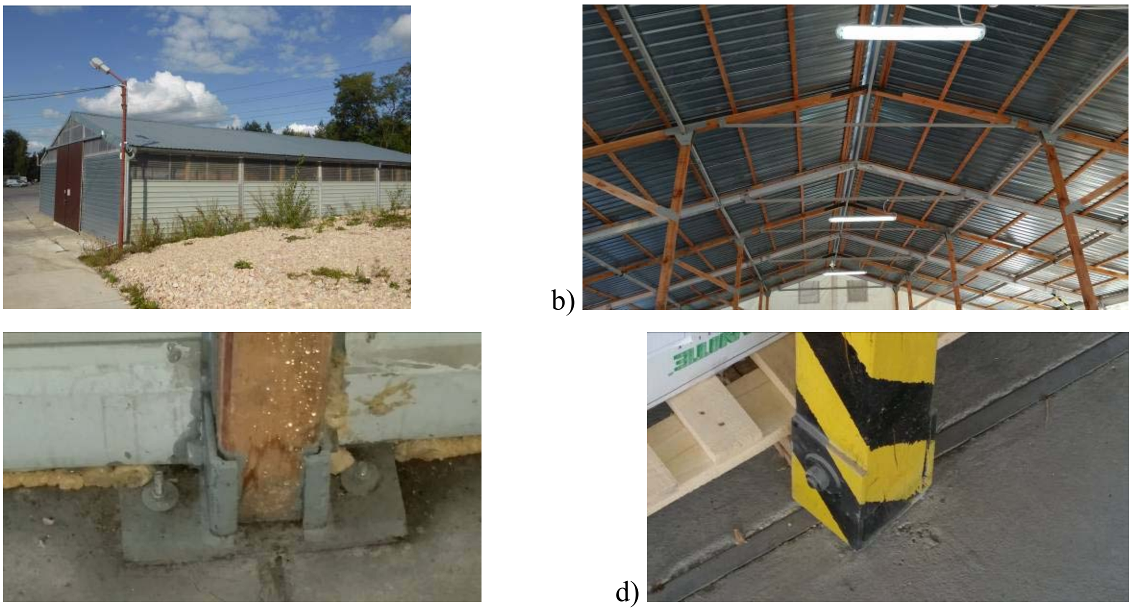


Figure 24. Considered tent hall: cross section and view

As a result of the failure conditions, it was necessary to reinforce the light skeleton frame structure and expand with a wooden post and rafter structure. The additional load-bearing structure was supported on the floor (figure 25a) and b)) in the form of a foundation plate mounted directly on the subsoil with a crushed aggregate base. Currently, the hall roof is provided by a folded sheet with polycarbonate skylights and a gable fragment covered by tarpaulin.



a) b) c) d)

Figure 25. Presented tent hall a) general view, b) inside of the hall with additional wooden structure, c) post fixed to the floor, d) post fixture

5. Summary

The main conclusions of the study may be presented in a short Conclusions section, which may stand alone or form a subsection of a Discussion or Results and Discussion section. Each built structure requires a separate approach, both at the design and fabrication stage and then during its use. Introducing less or more complex assumptions in the design content does not guarantee its maintenance in the structure use phase. The practice shows that it is quite the opposite. The performed calculation analysis of the tunnel described above demonstrated that it is extremely important for a construction design to make static and strength calculations with loads for which a properly selected combination may indicate a load distribution which is unlikely yet possible to occur. Plastic tunnels have no rigid external partition walls. Due to local deformations, film or tarpaulin providing protection of the roof from external factors may lead to an uncontrolled movement of snow and its formation not only in roof valleys of a cross section but also along the tunnel length. This is a case of local snow covering concentrations not taken into account in the calculations, which may cause film deformation, etc. This phenomenon cannot be completely eliminated, i.e. accumulation of snow on film slopes as this may occur in downtime or heating system failure periods.

The performed verification calculations demonstrated that calculation assumptions taken by the tunnel designer do not consider a possible, actual distribution of snow on slopes, which may result in an increase of inner forces in the tunnel structural members by approx. 2÷88%, posing a potential threat to the structure or use safety. Efforts are shown in table 4:

Table 4. Comparison of structural member efforts [source: authors' archive]

Structural member	Maximum design effort	Maximum effort obtained during the analysis
Roof arch CHS 60,3x2,5	0,81	1,88
Top flange RHS 60x40x3	0,98	1,77
Bottom flange RHS 60x40x3	0,65	1,02
Column RHS 120x60x4	0,99	1,50
Bracing diagonals SHS 40x3	0,34	0,34

Under the Polish climatic conditions, construction and use of such structures will be certainly effective provided that they will be treated as full-value structures or buildings. Then, the calculation procedure should consider actual conditions of their location, further structural shapes (which – in such cases – should be as simple as possible) and load arrangements and combinations. Furthermore, a possible increase of the weight of old snow covering should be included in load statements and technical descriptions, depending on the time of its accumulation.

Regarding the concerned case, it should be emphasised that it refers to a roof in the shape of a 'gothic' vault. As shown in section 3 hereof, when formulating cases of climatic loads, it is reasonable to apply a standard description for a multispan roof.

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