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ANALYSIS OF THE POSSIBILITY OF CHANGING THE SHAPE OF TENSILE MEMBRANE IN EXISTING STRUCTURE

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ABSTRACT: The article presents issues related to the design of membrane canopy. The problem is how to change the shape of the existing roofing in order to reduce problems with its snow removal. Because the durability of the membrane made from polyester fibre coated PVC is lower than a steel roof support structure, the membrane material will have to be replaced. By changing some points of the membrane there is a possibility to modify the shape of the surface from which water flows and the snow slides. The main limitation of the concept is to maximise the use of the existing structure. The analysis of options allows for choosing a more optimal shape.

Keywords: membrane structure, tensile roof, tensioned fabric structure, fabric canopy

1. INTRODUCTION

Tensile membrane structures made from polyester fibre coated PVC have certain durability and after a few decades will cause the need to replace the covering material. The supporting structure made from steel has far greater durability and the appropriate maintenance can be further used for many years.

The problem is whether it is better to replace only membrane material and retain the remaining components, or replace the whole roof with another one? There is a possibility to redesign the whole architectural layout, to introduce a new, more modern roofing, fashionable, in line with the latest trends in design and made of a different material.

The author proposes to try to use the existing structural system and to make its little correction. This allows for replacing the coating, and by the way to change the shape for a better one that fulfils its tasks, does not create additional problems, e.g. in the winter with clearing the snow.

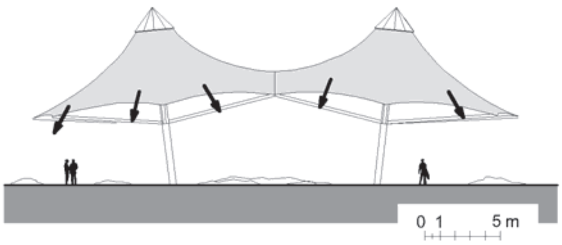


Fig. 1. Risks resulting from snow self slide

2. DESCRIPTION OF THE ANALYSED ROOF

The analysed example is the roof located in Silesia City Center – a shopping centre in Katowice. The canopy stands in front of the entrance, in the open space, where customers come in and spend time. It has a very simple and pretty form. It consists of two linked conical surfaces resembling parasols. The rain water flows down almost evenly in all directions. The roofing does not have any of limiting run-off or collecting water into the system. The result is that the rain water pours and snow falls along the ridges. Streams of water can be avoided. Unfortunately, unexpected heavy snow falls may cause concerns about the safety of customers.

The tensile roof was designed, together with the entire mall by BOSE International Planning & Architecture Studio. The roofing dimensions are 32×17,5 m which makes an area of 430 m^2. This is the area of the roofing plan, or the roofed area. The total area of tensile membrane is 508 m^2.

The lowest roofing elements are on the height of 4,5 m, and the roof top has the height 11,8 m. The tensile roof is made from technical fabric with polyester fibers coated by PVC. It is a membrane type 3 with a final coating of acrylic. Blue pyramid-shaped covers are on the top. The roofing was built in 2005.

Today, you can not see the effects of aging material through right maintenance. Despite this, there is need to think about and prepare for what to do in the future?

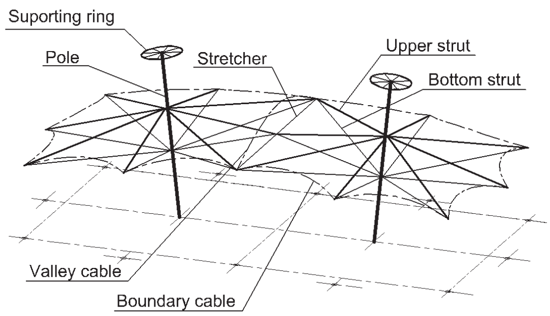


Fig. 2. Main structure elements

3. DESCRIPTION OF THE STRUCTURE

The structure consists of two symmetrical parts. Two poles leaning from each other support eight cantilevers, to which the membrane is attached at the endings. Every cantilever consists of two struts: upper and lower one. At the top every pole is supported by a ring, to which the central part of the membrane is fastened. Both parts of the structure are connected in three hubs. There is an additional stretcher between them.

Fig. 3. The top of the pole with supporting ring

The poles consist of two parts: the lower and the upper one. The upper part has a smaller diameter and it is inserted to the main part with a larger diameter. Thanks to such a solution, a long changing of every pole is possible.

The movable part of the pole is connected with a supporting ring to which is fastened to the central part of the membrane. Thanks to that, it is possible to control of the ring position and the membrane tension at the same time.

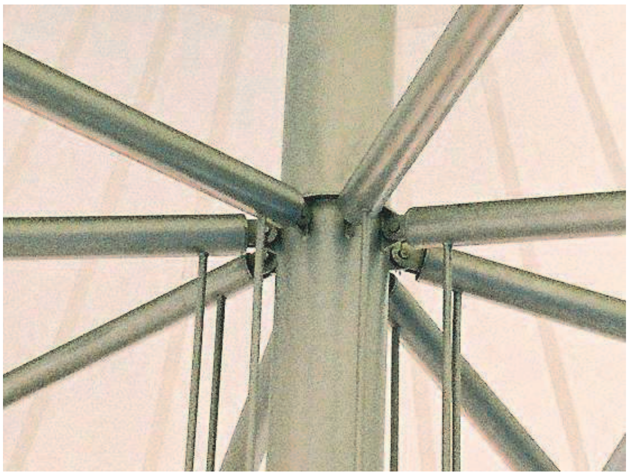


Fig. 4. Fastening of the upper struts

An additional vertical bar is put between the main struts of every cantilever. The struts and the bar create a closed triangle, thus assuring appropriate geometry during transportation and installation. The cantilevers are fastened to the poles by bolts. These connections are hinges, but the arrangement of two connected struts to the pole doesn't allow for vertical movement of the membrane fastening points. However, the lateral movement is eliminated with membrane tension and boundary cables.

The upper and the lower struts are fixed on the ends of every cantilever. A metal sheet is attached to the endings with cables and the corner of the membrane attached to the metal sheet. The fastenings are shown in photos No. 6 and 7.

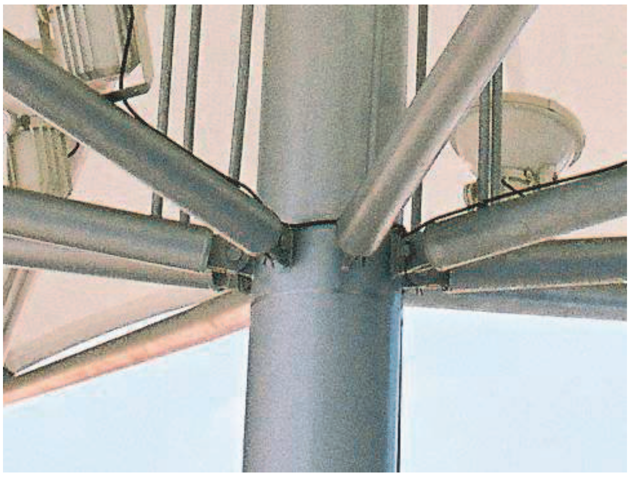


Fig. 5. Fastening of the lower struts

As it is necessary to obtain even tension, the membrane fastening should be precisely adjustable. Another reason for the adjustment necessity is the fact that the membrane material is subject to relaxation under long-term loads. Therefore, checking whether preliminary tension needs to be increased is necessary from time to time.

Fig. 6. Fastening the membrane to the corner metal sheet

Fig. 7. Adjustable fastening edge struts

In case of the roofing discussed the adjustability of the preliminary tension is provided in several points:

1. the supporting ring may be moved upwards by means of sliding part of the pole up,
2. the corner metal sheets may be moved in relation to the cantilevers,
3. the edge struts may be ended with threaded rods, which enables change of their length, which in turn adjusts the tension of the whole membrane,
4. the basket strut is also ended with a threaded rod, which enables pulling the membrane downwards.

In the centre where both parts are connected, there is a basket strut. It is placed over the membrane. It protects the membrane canopy against being snatched by the wind and at the same time assures appropriate tension for the membrane.

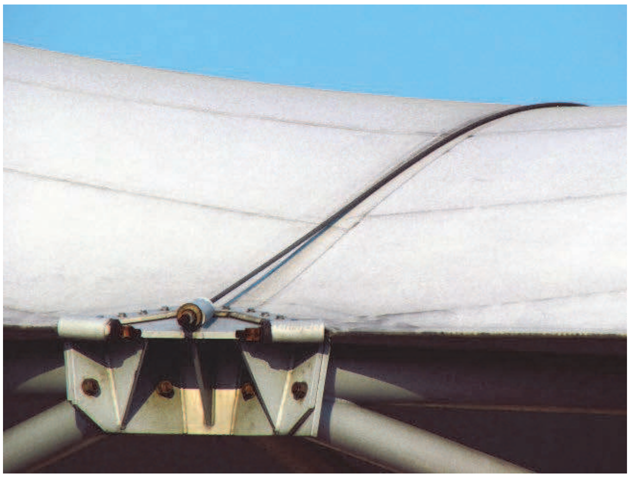


Fig. 8. Fastening the basket strut

The structure designed and made in this way allows for replacement of any structural element, if necessary. Upon removal of the tensioned membrane, the individual parts of the membrane may be disassembled. This is possible thanks to the application of bolt or screw joints.

4. EXISTING ROOFING SHAPE ANALYSIS

The shape of the tensioned membrane is not a typical geometric form, unlike the canopies of traditional roofs. Therefore, contour lines were determine in order to define the surface properties. This enables the determination of the surface inclination in a specific point and the determination of the water flow direction.

The distances between the contour lines depend on the inclination, the shorter the distance the larger is the surface inclination in this point. Thanks to determination of the contour lines and slope direction, it is possible to make an impartial comparison of the surfaces in the further analysis.

The contour lines have been determined in virtue of a computer model. Such model has been created basing on the project documentation made available by the facility owner.

Fig. 9. Height scale

The heights of the lines determined on the membrane surface differ by 1m. The colour scale was used, in order to increase the legibility. The same scale was used herein further.

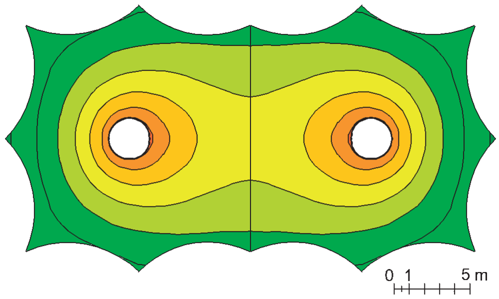


Fig. 10. Contour line of the present membrane shape

The above picture shows that the lateral fragments of the surface are of larger inclination than the central ones. It makes no significant difference in case of rainfalls. However, in case of snowfalls, the small inclination causes snow accumulation. Larger inclination, however, causes that the snow slides down, which is visible in the next photograph. .

Snow accumulation on the roofing itself is not dangerous for the roofing itself, if the loads do not exceed the figures anticipated in the strength calculations. However, in this case it raises fear. because the mall clients may stay directly under it, particularly because the snow is difficult to be removed from this height.

Fig. 11. The small inclination causes snow accumulation

The drawing presented further shows the slope lines marked. It is significant in this picture that the areas marked A and B have a similar length of the eaves line, while their surfaces differ. As a result, by far more water flows down from area B during rainfalls than from area A. Such shape of the roofing causes that water and snow fall along all the edge line and some more near the centre.

The fact that the smaller inclination gathers much more snow is a more serious issue here. The result may be that the falling snow layer will be thicker or more compact there.

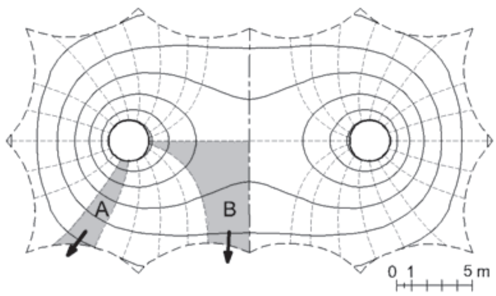


Fig. 12. Analysis of the shape

Based on the distance between the contour lines, we may determine the inclination of the fabric canopy in a given point. The areas marked in the drawing below have inclination below 25° i.e. 46,6%. This is a conventional value of inclination provided by manufacturers of tent halls. Some people say that in our climate the snow automatically slides down from the membrane already with inclination above 22°.

When the inclination is lower, the snow slides down with temperatures above zero Celsius only or if the membrane is subjected to vibrations. Apparently, large part of the roofing is exposed to snow build-up, especially the central belt. In addition, the outer corners have lower inclination. This is confirmed by numerous photos taken by the author with various weather conditions. These are the areas the snow builds up for the longest time.

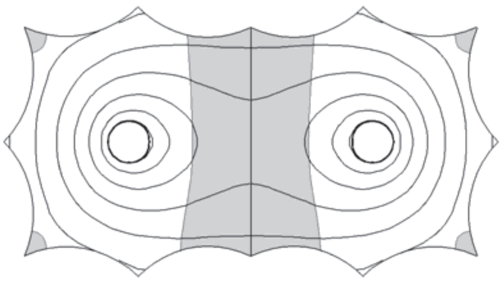


Fig. 12. Membrane inclination below 25°

5. SUGGESTED CHANGES

The essence of the analysis suggested by the author is an attempt to change the shape. Using some of the structure elements and changing some of them only, we may try to change the shape of the membrane. Moving the membrane fastening points may cause that the tensioned canopy fabric will be of a different shape.

Certainly, tensioning the existing membrane to the extent that its shape significantly changes is impossible. The membrane is not flexible enough. However, an attempt to do it could be possible if the membrane fabric is replaced. Perhaps, this will have to be done within a few years, due to the material aging or accidental damage. The replacement of a few steel cantilevers with others, of a different shape, however, shall enable the modification of the membrane fastening points.

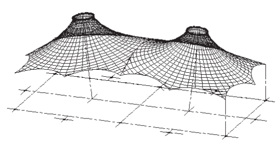
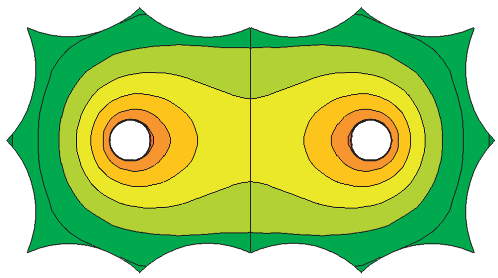
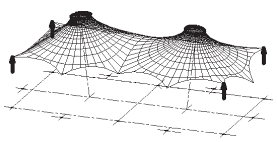
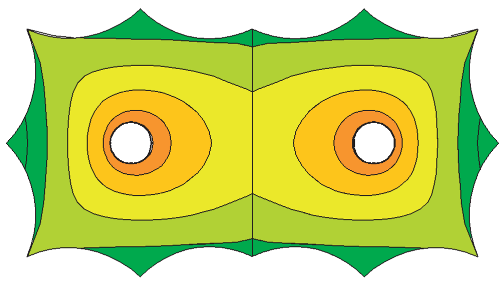
An analysis consisting in moving selected points was taken up to check if the change of shape can improve the roofing properties. To make the difference distinct, the moving distance was 2,0 m. The moving direction of specific knots in relation to the present position has been marked in the schemes. The points were moved symmetrically in all the cases, thus maintaining the nature of the roofing.

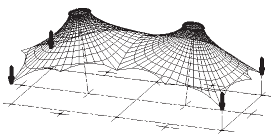
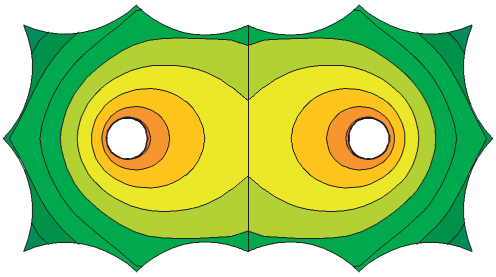
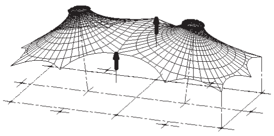
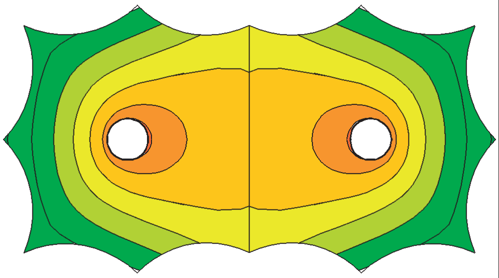
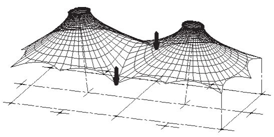
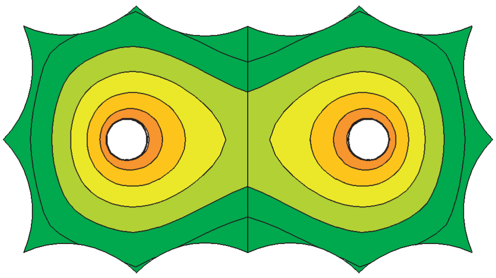
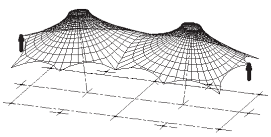
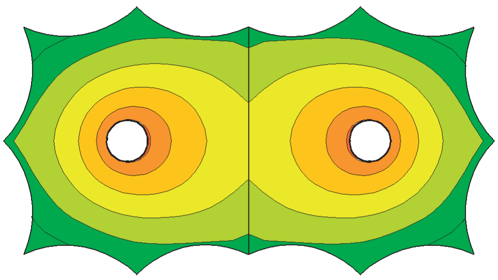
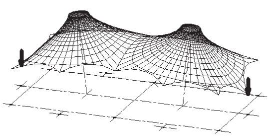
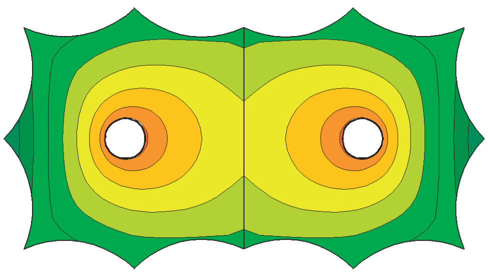
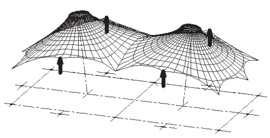
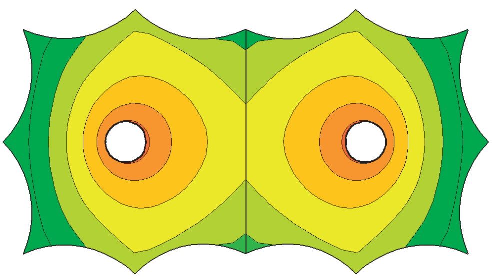
The maintenance of the existing roofing layout was the assumption of the tests. Only the heights of some elements were changed. Maintaining the layout should not significantly increase the loads, the snow loads in particular. Such loads constitute the highest figure with calculation for permanent membrane roofs.

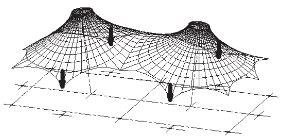
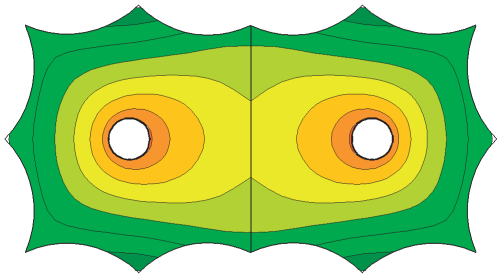
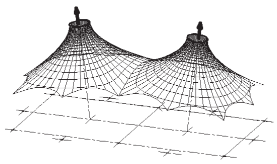
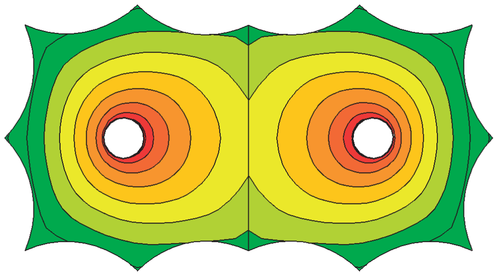
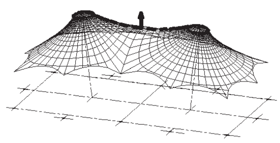
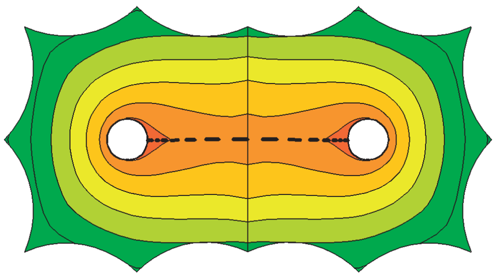
The location change of the membrane fastening points brings about the necessity for determining a new shape of the tensioned membrane. This may be done with the use of physical models, like Frei Otto initially used to do, or by means of computer models. The models used in this paper were generated be means of the easiest procedures based on the force density method.

Similar models can be obtained using e.g. SketchUp plugin for form finding by Ferrari. As the analysis comprises the stage of conceptual discussion on selection of the best roofing form and concerns no strength calculations, it was not necessary to use any professional program to generate membranes. With the use of easiest tools, the architect chooses the shape that is afterwards agreed upon in detail with the structural engineer and membrane manufacturer .

Table 1.

Item	Scheme	Contour line layout	Remarks
Status quo			The contour lines' shape is approximately oval, in the upper part concentrically located around the supporting rings. The inclination on the sides is higher than in the central part.
1.	 Outer corners elevated		The contour lines in the upper part have not been changes, while straightening or even bending in the opposite direction is clearly visible in the lower part.

2.	 Outer corners lowered		The contour lines' shape is closer to concentric circles around the supporting rings. Even the lower fragments of the surface have large inclination.
3.	 Inner knots elevated including the basket line		The contour lines form a shape close to a large oval covering the whole roofing. The roofing part (in the centre) has been increased as well, now in an almost flat position.
4.	 Inner knots lowered including the basket line		The contour lines' shape is close to that of the existing roofing, but the part in a flat position in the centre has been reduced.
5.	 Lateral knots elevated		The contour lines' shape is of more elongated ovals. The inclination on the sides only has been reduced.
6.	 Lateral knots lowered		The contour lines in the upper part are of a similar shape to the existing one, while in the lower part the clearly straighten or even bend in the opposite direction. The inclination in the lateral parts has been more increased.
7.	 Knots elevated		The contour lines in the upper part are of more circular shape and in the lower part – that of transversely set ovals. The central part has almost remained unchanges.

8.	 Knots lowered		The contour lines have been more straightened and in the lower part their shape is almost rectangular.
9.	 Supporting rings elevated		The contour lines' shape is more circular. The area with very low inclination has been reduced, inclination in all directions has been increased.
10.	 Strut between the rings has been introduced		The contour lines' shape resembles strongly elongated ovals, the area with low inclination is small and the contour lines in the central part have been significantly straightened.

Variant 9 provides the elevation of the upper rings supporting the membrane. This is due to the fact that the upper part of the pole is replaceable and thus its height can be increased. Like in the other variants, the anticipated change of position was by 2,0 m.

In variant 10 the introduction of a so-called anti-snow rope was provided. Such solutions are applied to other membrane roofs, as protection against overloads in case of very intense snowfalls. It is most frequently a type of strut connecting the elevated points of the surface and it runs along the watershed line so as not to be an obstacle to the snow sliding down.

Thanks to such rope, the elevation of the central part of the roofing is possible. The analysis provides elevation by 2,0 m, without changing the position of the other points.

6. CONCLUSIONS

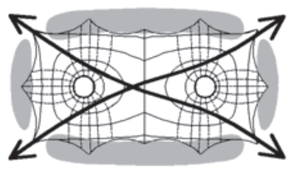
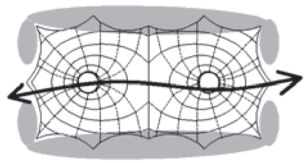
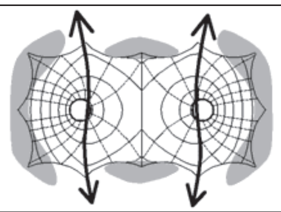
The analysis carried out as above suggests that in come cases the membrane's inclination has been increased and in some other cases it has been reduced.

Variant 3 indicates that an attempt to elevate the central knots along with the basket line is a wrong solution. In drawing 13 we can see that there is a belt of low inclination in the centre. If the basket strut is elevated, the area distinctly increases. A very large area is positions on almost identical height. To reduce the area of snow build-up, we should try to lower the central knots (variant 4).

In another case, e.g. variant 2, the lowering of the outer corners has been provided. It increases the membrane's inclination in this place, which is a good solution, because the snow would not build up there. While selecting appropriate variants, we may find a solution with the smallest snow build-up area.

Another solution may be an opposite action. By elevating the corners, we may cause more water and snow flowing/sliding down in selected points only, instead falling along the entire roof ridges. Appropriate elements of landscape architecture to protect the area the snow would fall onto. The protective fences are not necessary, but e.g. some kinds of plant pots, low walls, decorative elements, strong enough to withstand the snow falling on them.
Below there are variant s with the area the snow will fall on marked grey. The direction of people walking omitting dangerous places is also presented therein.

Table 2.

Item	Scheme
1.	
5.	
7.	

As the restriction of people passing under the roof cannot be exercises to such an extent, the introduction of the anti-snow rope seems to be the best solution. The only thing to be done is to check whether any additional load, the lateral load of the ring is possible in terms of strength. The introduction of the anti-snow rope may reduce the snow build-up area most and the membrane shall be automatically cleaned of snow thanks to it.

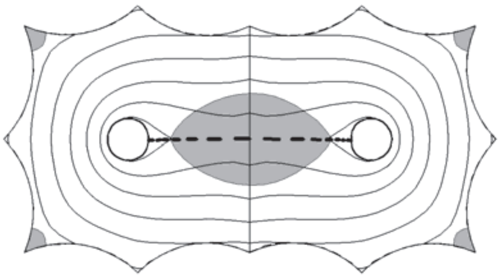


Fig. 10. Membrane inclination below 25°

7. SUMMARY

All the changes of the structural layout require the strength analysis. The introduction of any additional elements of change of their position causes the change of load configuration of some parts. In some cases it may appear that, in spite of the correct inclination, there may be places with the surface being too straight. Under the wind pressure, the membrane may flutter dangerously.

It may further appear that since the existing project was completed the snow build-up standards have changed (2006).

A more precise determination of the shape is possible with the use of programs taking the loads and material properties into the consideration. The most important effect of the analysis carried out is the possibility to compare the results of selecting a specific type of shape. Thanks to such analysis we may foresee the direction of modifying the roof shape in order to restrict the issues while using such roofing.

The analysis also included a comparative method constituting in search for the surface shape differences basing on the contour line layouts. The method may be used for the design process at the preliminary stage of preparing the architectural concept, when the material parameters, extent of loads and initial tension are not yet determined and only the shape of the tensioned membrane. The article first of all presents the shape analysis potentials, which is necessary at the architectural concept stage. when the preliminary analysis of the roof.

8. REFERENCES

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3. K. Gerlic, *Design Elements for Snow-Load Resistant Membrane Roofs*. Beyond the limits of man. Proceedings of the IASS 2013 Symposium, Wroclaw, Poland, 23-27 September 2013. Eds: J. B. Obrębski, R. Tarczewski. International Association for Shell and Spatial Structures. Oficyna Wydaw. Politechniki Wrocławskiej, Wrocław 2013.

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