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Design Elements for Snow-Load Resistant Membrane Roofs

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Summary: The paper presents discussion on the issues related to design and use of tensioned fabric roofing and occurring in the winter. In case such structures are used as permanent, all-season ones, the issues of snow load and the methods of snow removal arise. The importance of the issue is emphasized by the fact that errors were not avoided even in major projects, such as the modernization of Dresden Central Railway Station or the Gelsenkirchen stadium.

Keywords: *membrane structure, tensile roof, tensioned fabric structure, snow load.*

1. INTRODUCTION

The attractive form and diffused light transmission through the fabric encourage the designers to use membrane structures. Sunlight deflection improves the microclimate of the roofed space, while its light weight makes it convenient for covering really large spans. Unfortunately, the application of such roofs as permanent, all-weather structures causes additional issues. The periodic snow loads significantly exceed the roof's dead load and the snow sliding down is dangerous to the people below. Moreover, the roofing formed improperly causes the roof snow overloads upon heavy snowfalls. The significant height of the roof, in turn, makes it difficult or even impossible to remove the snow. The low tear strength of the fabric impedes the mechanical snow removal. Furthermore, the massive area of the roof gathers so much snow that the manual removal is labor-consuming and costly, and, in some cases – impossible. Therefore, the proper selection of the spatial form for membrane roofing is so important.

The properties of the soft membrane fabric cause that double curvature and appropriate initial tension is required. It can be obtained thanks to appropriately selected support structure. In such case the membrane is not deformed under dead load and external loads, such as wind and snow. Providing appropriate curvature is not enough, the membrane surface should also be appropriately inclined to avoid water and snow bags. A momentary standstill causes local increase of the membrane load and this in turn lowering and even greater, faster accumulation of the snowfalls increasing the load. The analysis of examples of two damages caused by snow shall serve to confirm the essence of membrane roofing formation issue.

2. ANALYSIS OF DAMAGES

The wide experience of German companies initiated by Frei Otto activity has resulted in a large number of interesting membrane structure buildings erected in Germany. In addition, their geographic location in the central part of Europe is associated with really intensive snowfalls occurring there regularly. Therefore, this is the best location for analysis of this kind of structures.

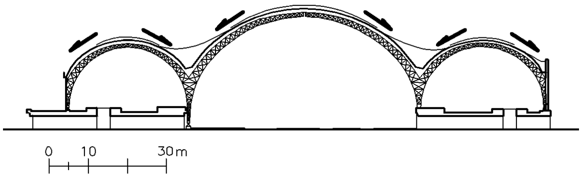

Fig. 1. Cross-sectional view of the platform hall of Dresden main railway station (based on [2])

The roofing of the platform hall of Dresden main railway station is supported by the historical structure of riveted truss arches. Sir Norman Foster, world famous architect, anticipated replacement of the dark, non-transparent roofing with bright modern membrane in his modernization design of the station. Daylight penetrating through the translucent membrane totally changed the hall decoration. It is evenly lit, while the steel elements contrasting with the roofing represent a valuable enhancement of the historical structure authenticity. In addition, the white fabric reflects thermal radiation and it is nice and cool in the hall on hot days. In order to obtain appropriate strength, the roofing was made from PTFE coated fiberglass. Even the resistance to the exhaust gases of the locomotives stopping at the station was checked.

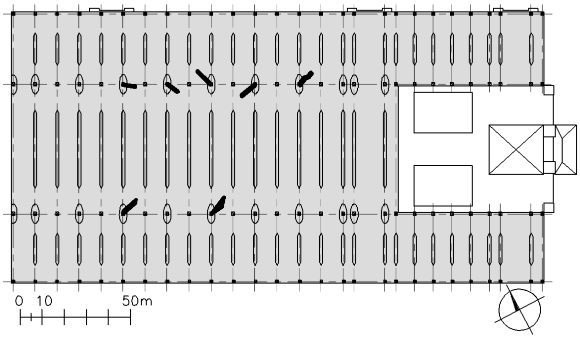

Fig. 2. The roofing damage points (worked on materials from [3])

Unfortunately, the use of the three-aisle hall supported on arches results in several pockets in the roofing with rainwater and snow accumulating therein. The water runs down the designed drain pipes. It is much worse in case of snow. It accumulates in the pockets where neither mechanical nor manual removal is possible. The reinforcement of the points has been foreseen through design of large steel bell footings and additional reinforcement of the membrane in the form of anti-snow ropes to support the accumulated snow. Nevertheless, after very intense snowfalls the roofing was damaged in late December, 2010. The loosely installed anti-snow ropes underwent tension due to snow load and membrane deflection. It caused a take-over of part of the load in the upper part of the covering pockets, while the lower part of the membrane is attached to the steel funnel serving to collect the rainwater to the drain pipes. Filling the pockets caused the membrane break and the snow load falling directly on the platforms.

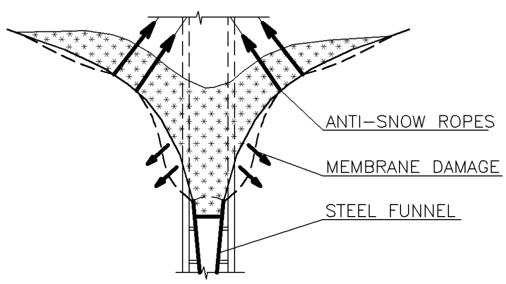

Fig. 3. Diagram of the damage occurrence in the membrane pockets (author)

Fig. 4. One of the damages in the Dresden railway station roofing (author)

The holes made in this way relieved the membrane, which stopped any further damages. Each of over eight pockets has one fissure. To protect the people staying on the platforms, it was necessary to make an instant protection of the roofing. Protective mesh supporting the membrane from the bottom was introduced. This was applied in the points of damage and wherever some distinct deflections appeared caused by the snow lying on top. Most of the holes were covered by another layer of membrane, which clearly reduces the material's translucence and visually underlines the damages. The facility owner, i.e. German Rail demands post-warranty repair of the damages, due to failure to provide appropriate durability of the structure. Unfortunately, the replacement of the entire roofing covering the area of 30 000 m^2 is necessary. Panels cut with utmost precision cross the entire width of the station. This was done in order to minimize the number of seams. The serious issue at present is how to replace part of the damaged roof without dismantling the whole, particularly with the membrane being permanently stressed. The railway company does not permit to apply any further layers. Moreover, the contractor cannot do it, due to financial difficulties. The case has not been settled by date.

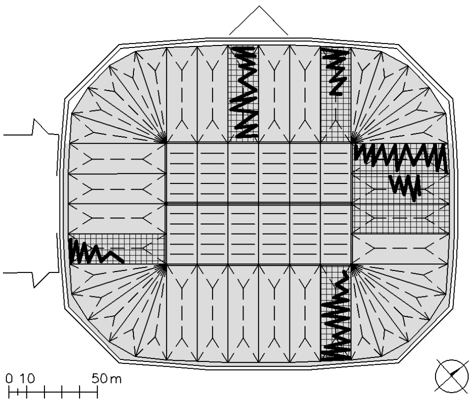

Fig. 5. Damage of the stadium roof in Gelsenkirchen (worked on [4])

Another example of issues caused by snow is the roof damage of Schalke 04 team stadium in Gelsenkirchen. The modern structure was built in 2001. Its present name is Veltins Arena. The stadium roof consists of two parts: fixed over the seats and retractable over the pitch. The roof structure is a 3D steel truss terminated with a cylindrical cradle. Arch rails enable to move the two rigid panels of the retractable roof. On the outer edge, there is a kind of broken ring along the stadium's perimeter. All the roof truss rods are circular pipes the roofing is attached to. To provide the appropriate amount of light, the whole is covered by a double PTFE coated fiberglass membranes. The contractor was Birdair.

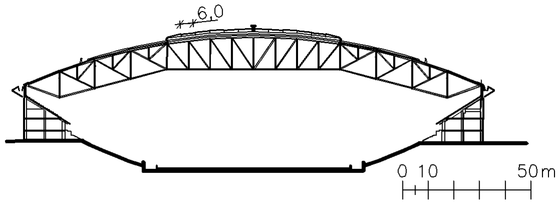

Fig. 6. Cross-section of the stadium in Gelsenkirchen (based on [4]

In the same winter of 2010/2011, after very intense snowfalls, immense damages occurred, some of the fissures reached several dozen meters even. Ultimately, 7 roof panels had to be replaced.

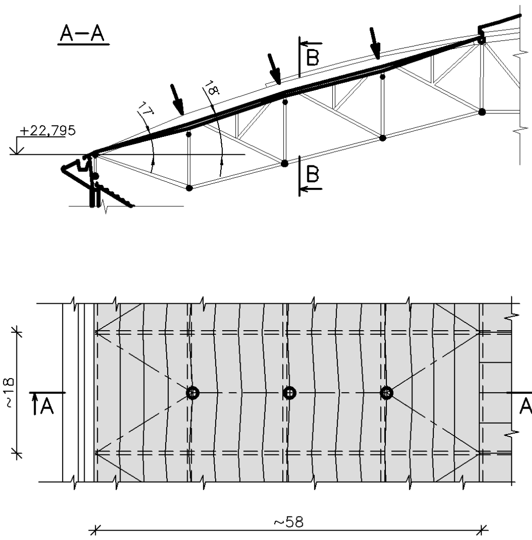

Fig. 7. Mounting roof panels of the stadium (worked on [4])

The roof designer, in spite of substantial height, has a slight slope. The central part of the roof is situated almost horizontally. The membrane in these points is supported by arch ribs spaced every 6 m. In spite of the slight slope, the densely spacer supports provide sufficient stability for the membrane. The situation is worse for the fixed part of the roof. Although the roof truss knots are similarly spaced, the membrane is attached to the outer edges of the specific panels only. For the rectangular panels this is ca. 18 x 58 m. To provide the appropriate curvature, the specific panels are stressed from the bottom in three points. This protects them against being lifted by the wind.

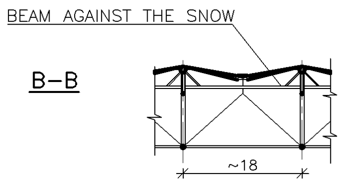

Fig. 8. Cross-section of the roof panel mounting (worked by author)

Unfortunately, in case of snow load, it causes a significant reduction of the slope. The lower part of the truss at the outer edge is inclined at 22° angle only. In addition, the snow load causes the membrane's lowering. Unfortunately, the lack of loose outer edge does not enable even relocation of the entire roofing. The edge ring the membrane is attached to causes further reduction of inclination or even produces a kind of a threshold stopping the snow slide. Under the membrane there are steel pipes functioning as an additional support in case of heave snow loads. The distance between them is ca. 15 m. Unfortunately, the accumulated snow, not removed on time, caused the roofing damage.

In both cases the main causes of the damages were the excessive snowfalls. However, were the types of roofing better matched or additional solutions anticipated, no unnecessary costs would have had to be borne.

3. EXAMPLES OF SOLUTIONS

Based on Polish examples, we can say that most facilities with membrane structures have no devices for snow load evaluation. During intense snowfalls, the persons guarding the facilities should take all the efforts to prevent any danger to people or property caused by snow accumulated on the roof. It means observation whether the snow cover thickness is not excessive and whether is does not cause any distinct deflection that could start the process of damage of part or the whole structure. As the evaluation is made visually, without any measurements, it is not too precise. With the appropriate inclination of the roof slopes, the snow begins to slide. For the facility owner, it is necessary to assure such possibility and to secure the places the snow slides onto. This is most often performed through fencing or warning against danger. In case of some facilities, the area surrounding it is locked or restricted, for example in case of some open-air theaters or stadiums. The situation is worse when such facility is used in the winter.

Roofing over the open-air theatre audience was built in Ustroń in 2003 and in 2010 it was extended over the stage. Its shape resembles a saddle resting on two steel arches. The roofing was designed by Marcin Gałkowski, while the covering was made by HP Gasser, Switzerland [1]. The fabric used is spread all year round, therefore it was necessary to adapt it to low temperature and rain/snowfalls. The open air theater area is fenced and access there to is allowed for events only. In spite of large area, ca. 1800 m^2 there are no issues related to snow removal. The covering formed properly causes spontaneous snow slide. Sometimes very high heaps of snow accumulate in these points. In such cases the facility administrator removes the heaps by means o fan excavator so that the rest of the snow may further spontaneously slide down from the covering.

Fig. 9. Summer Open-Air Theater in Szczecin (author)

A newer example of roofing is the open-air theater in Wisła. It is located ca. 430 m above the sea level, which results in the highest snow load. The characteristic load of the soil is Q_K = 1,98 kN/m^2. The theater was commissioned in 2010. The roofing consists of two coverings made from fabric and connected by a roof-light composed of green and blue glass. The inclined steel arches articulately connected with the floor form the support structure, simultaneously stressing the fabric spread between them, producing distinct saddle-like surfaces.

Fig. 10. Metal rainwater drainpipe in Wisła (author)

The roofing correctly designer with well matched slopes of the roof pitches, effectively drains the rainwater and accumulated snow. The open-air theater is located near the town center and has no fencing, which enabled direct access thereto at any time of day or year. The neighboring pedestrian passage and the bars or restaurants located nearby additionally encourage people to pass by and stay under the roofing. The open-air theater is a real attraction of the place and its large area provides protection to large number of people.

In spite of the free access to the area offered by the open-air theater roofing, its maintenance causes no issues. The high inclination of the pitches enables proper drainage of the water to special drainpipes, mounted in the bottom part of the roofing. The spacing of the supports and entrances produces such a configuration that there is no snow slide hazard. The open-air theater in Wisła is perhaps the only to hold events in spite of winter weather. During the Winter Olympic Games in Vancouver, the theater presented live transmissions of ski dumping by the famous inhabitant of Wisła – Adam Małysz. With the temperature below zero Celsius, snow and torches – a sample of the Olympics was created.

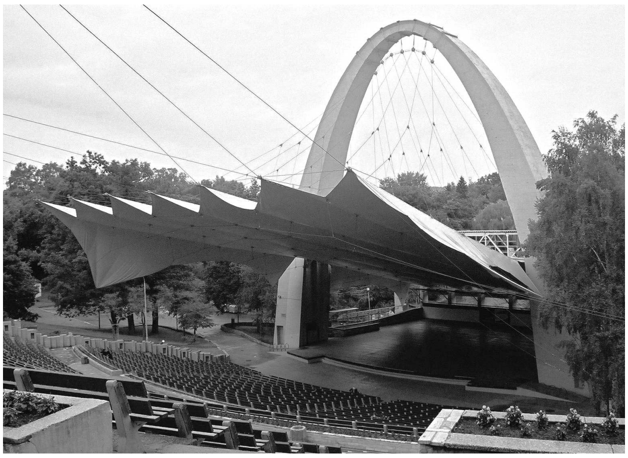

Fig. 11. Summer open-air theater in Szczecin (author)

Very interesting solution is the method of fixing the membrane in the Summer Open-Air Theater in Szczecin. The roofing with dimensions 47×45 m is suspended under a historical concrete arch by means of a set of ropes. The designer Marcin Fiuk foresaw the possible exceeding of the permitted load. To minimize the effects of excessive snowfalls, specially designed mountings for the load-bearing ropes were used.

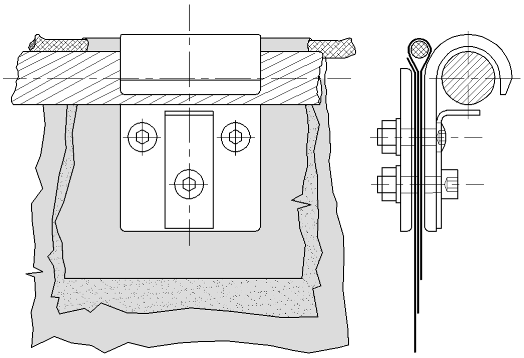

Fig. 12. Hook protecting against overload (based on sketch M. Fiuk)

Appropriately matched hooks were used, ones that will straighten under excessive load, which in turn will cause the membrane's deflection. Otherwise the whole structure might have been destroyed. Unhooking one or several hooks will be distinctly visible as it will cause the membrane's hang down. In such case the intervention of relevant services will be necessary. They will have to remove the snow and replace the worn mounting. Although the roofing was made in 2000, none of the hooks has broken by date.

Another, a little earlier solution is the roofing in front of the entrance to Silesia Shopping Centre in Katowice. The architectural design was prepared by Bose, while the construction design was made by Stabil. The structure was commissioned in 2005. The roofing is in the form of two joined conical parasols, covered with white fabric. The covering is near the historic shaft of the former coal-mine. Due to the big pedestrian traffic, the roofing is to protect against rain and sunlight near the entrance providing an opportunity to create various events or simply being a meeting point. The large size of the roofing and the light color of the fabric protect the space against overheating not only on a hot summer day. The concrete floor is not heated hanks to being in the shade all day and later maintains the heat, unlike other open spaces. An interesting structure with slightly inclined posts represents an attractive architectural touch. At nighttime it is additionally illuminated, which still improves the visual values of the entire structure.

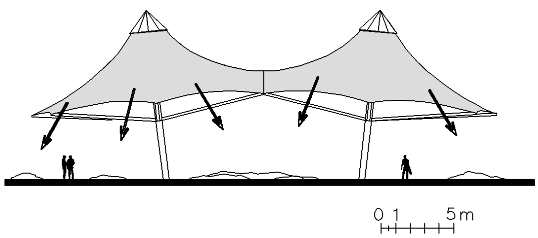

Fig. 13. Fear of the snow sliding down. (author)

As it appears, the untypical structure causes problems to the center administrators. The parasols rest on central steel posts. The conical shape is achieved through fixing the covering to the central rings supported by the posts and to the external tie bars on the edge spread on steel outriggers. The water flows down the coverings, like in case of traditional umbrellas, outside without any drain or standpipes. Such solution causes that the center's customers must watch their ways to avoid getting wet. The issue is even more serious with snowfalls. The central rings situated on a large height cause that most of the roof is steep. The snow does not accumulate during the snowfalls but slides down to the edges. The snow accumulation areas appear along the lower, gently sloping fragments only and they slide down under the weight of the upper snow loads. Therefore, the snow loads slide down during snowfalls or directly afterwards. Luckily, the snow is neither compacted nor frozen.

Trying to prevent the snow fragments sliding down, the facility administrators ensure to remove all the snow from the roof on rime. It appears that removing the snow from this type of roof is not easy. It is impossible to climb and walk on the roof so steep. Any attempt to remove the snow with the use of external jacks is expensive and difficult. The roofing itself is situated on a few meter height, so any attempt to remove the snow standing on the ground is difficult. The only solution is to watch the roofing and manual pushing of fragments of overhanging snow beyond the roof edges. It seems that such procedures are unnecessary, as the snow sliding down does not accumulate into large lumps, moreover, it slides down directly after the snowfalls, so its consistency is fluffy. Removing the snow from the roofing is rather an action preventing the potential concerns of the shopping center customers, out of care about the company good image.

It should be mentioned in this point that on 28th January, 2006 an exhibition hall collapsed under snow load. It caused death of 65 people and injuries of 170. The main reason was the excessive accumulation of snow on a flat roof with a light, steel structure. The snow load is critical for the durability of a light structure and it is even more crucial for membrane structures where the covering's dead weight is even lighter. The changed way of thinking on the safety of structures in Poland under snow loads, contributed to the amendment of the building law and issuance of relevant directives. The following provision has been enforced among others: „Public utility buildings with premises designed for significant number of people to stay therein, such as: auditoriums, sports, exhibition, fair, shopping, railway station halls should be furnished, depending on demands, with devices for permanent inspection of the parameters significant for the structure's safety, such as: relocations, deformations and stresses in the structure." [8]

4. MONITORING

The monitoring system is a new solution increasing the structure's safety. The first example of using monitoring in a facility with membrane structure is the open-air theatre in Płock. More precisely, it is a tie-bar structure covered with a PVC membrane. Due to the problems occurring during the erection and concerns for the roofing structure's safety, it was furnished with the structure monitoring system. Its purpose is most of all the inspection of the structure's condition and increasing the safety of the facility use. The monitoring design was developed by Krzysztof Żółtowski in 2008. Based on the static-strength analysis of the structure, the type of devices were indicated as well as the location of the measuring point for the monitoring purposes. This was the foundation for determining that the most representative index of the roofing structure changes are vertical relocations. In the central part of the roofing, 5 relocation sensors were anticipated, mounted in the tie-bar knot points. In addition temperature sensors were installed over and under the covering, wind velocity measurement devices and cameras enabling observation of the roofing and its nearest surroundings. Thus, the assessment of the reasons for the occurring relocations is possible. The entire system is connected with the Central Processing Unit that records the results on an ongoing basis. The permanent access to the results is provided through the Internet.

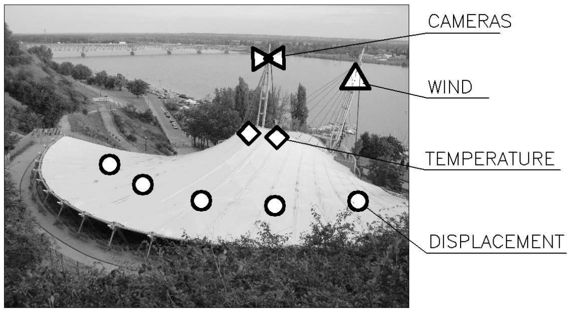

Fig. 14. Layout scheme of the load monitoring elements in the Płock open-air theatre (based on [6], photo author)

The threshold deformations were determined based on the static-strength analysis. In this way the facility services know that if the level of 150 mm is exceeded on any sensor, they will have to start to remove the snow from the roof. When the level of 200 mm is exceeded, the people from the facility will have to be evacuated and the access from outside restricted. After the load has been relieved, the structure demands detailed inspection. The threshold wind velocities have been determined in a similar way. If the average wind velocity measured for 10 minutes is above 15 m/s, no events should be organized in the facility, while with wind velocity above 20 m/s, staying of any people in direct vicinity of the structure will be strictly prohibited. .

Fig. 15. The roofing of the Forest Opera in Sopot (author)

The interviews with designers and facility owners suggest that the newest example of roofing with monitoring erected in Poland is the Forest Opera in Sopot. The open-air theatre is the largest and the most famous structure in Poland, due to its history. The open-air theatre used to have roofing as early as in the 1960's. It used to be temporary roofing, dismantled every year before the winter. After the modernization in 2010-2012 the facility has permanent roofing. The structure is supported by two arches inclining towards each other, their span is 102 and 93 m. Two symmetrical patches of membrane, 1800 m^2 each, reinforced with anti-snow ropes, are tied to the main support structure. According to the design inspiration, the form of roofing was to suggest the form of a leaf laid among the trees.

Fig. 16. Measuring points – prism reflectors mounted directly on the membrane (author)

The facility has a top class structure monitoring system. Such system monitors 28 measuring points simultaneously. Some of the points observed are situated on the support structure (resting points of the main steel arches), which represent the points of reference for the measurements. What's even more interesting for this facility is the fact that some of the measuring points are directly on the membrane. The major element of the measuring module is the automatic tachymeter measuring the prism reflector's locations. The measurement of the relocations enables the evaluation of the technical condition of the facility and the creep processes resulting from long-term loads, snow-loads, for example. The system also measures vibrations and temperature of the structure in four points and measures the basic weather data, such as air temperature, humidity, wind velocity and direction.

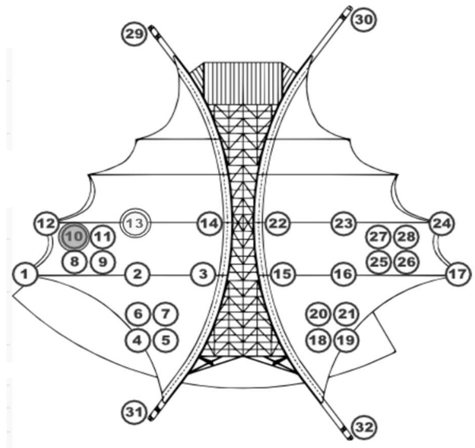

Fig. 17. Outlay scheme of the measuring points [5]

Below a sample diagram of a measuring point's relocations is presented. This is point No 10, located on the lowest level, along the longest panel. It is situated on the west patch, from the direction of the adjacent tall forest The diagram presents the results of measurements held throughout 150 days (from December, 2012 to May, 2013). The following is presented in the diagram:
- periods when the roofing was loaded with snow,
- the way the load changed due to subsequent snowfalls (the growth of loads without dramatic leaps),
- rapid changes of snow load caused by the snow sliding off the top parts of the roofing and loading the lower parts,
- reduction of snow load caused by spontaneous sliding of the snow from the roof or as a result of snow removal carried out by teams of specialists.
The extreme deflection of the roofing for measuring point No 10 was 120 cm. The measuring results inform on the roof loads, which results in the necessity for the snow removal.

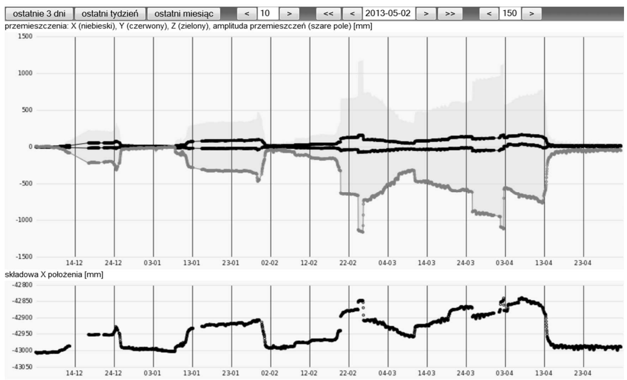

Fig. 18. Diagram of measuring point No 10 relocations throughout 150 days [5]

The largest facility in Poland with membrane roofing is Stadion Narodowy [The National Stadium]. The roof span with projection approximate to ellipse is ca. 280×250 m. The prestigious structure commissioned for Euro Football Cup 2012 has a permanent roof covering the area of 54 000 m^2 and retractable roof with the area of 10 500 m^2. The permanent roof is made from a fiberglass PTFE coated fabric. It consists of 72 panels mounted to the external, compressed ring, internal (double) stretched ring and to radial tie-bars. The varying dimensions of the particular roof panels are ca. 75 x 10 m. In addition to mounting along the edges, the membrane is also supported by handing arches spaced ca. 8 m, which provides them with appropriate curvature and causes that even with heavy snow loads, no large snow sack are accumulated. The internal roof is retracted from a garage located in the central spire. In the central part of the stadium roofing four bundles each consisting of three ropes was used to connect the internal (lower) ring with the lower part of the spire. The upper part of the spire is connected by a system of 60 radial spaced ropes connected with the internal (upper) rope ring. Along the radial ropes the mountings of the retractable roof made with the PVC coated polyester fabric. The upper internal rope ring is maintained at a constant distance from the lower internal rope ring by means of 60 tubular struts.

The roof has a monitoring system for the steel-rope structure. The system consists of the following elements:
- deformation sensors mounted on the load-carrying roped and the steel structure,
- temperature sensors,
- weather station measuring the air temperature and humidity and wind velocity,
- accelerometers to measure vibrations,
- cameras for visual evaluation,
- recorders,
- server with equipment and power supply.

Most of the measuring devices are placed in cabinets providing appropriate temperature in the winter. They are often situated in hard to reach places on very large heights. The system analyzes the locations of the characteristic points, including without limitation the stretched internal ring and the spire. In addition, the devices to measure vibrations, temperature, wind velocity and cameras enabling the roof observation are installed. The system proved itself to be appropriate in the winter 2012/2013, when the large number of snowfalls forced the necessity to remove the snow from the roofing. It was made manually by specialized teams of alpinists. The structure monitoring system in the National Stadium is further expanded and improved on an ongoing basis.

5. SNOW REMOVAL

Disregarding the fact whether the facility has a monitoring system or not, or the facility administrator inspects the roofing visually, it is a human responsibility to decide what to do in case of emergency. If the amount of snow significantly exceeds the permitted figures, its removal is indispensable. It is possible, provided the roofing is shaped appropriately. The membrane strength enables individual people to walk on it. They are able to remove the snow, using appropriate protections. In such case they must not use any sharp tools so as not to damage the membrane. Snow accumulation into heaps is not permitted either, as it may lead to local excess of the membrane's strength. The designer, while planning the possibility of snow removal, should provide appropriate solutions, enabling climbing the roof, protection of people and tools against falling and the possibility to throw the snow down. Solutions of this kind are costly. More frequently such system of supports is designed that will transport the loads, even with excessive snowfalls.

6. SUMMARY

The case studies carried out suggest that the monitoring of the structure snow loads is very important. The basic issue is the appropriate shape of the roofing. The proper inclination of the membrane should be provided and any closed hollows or bell-footings, where the snow accumulates, should be avoided. In such case an appropriate support structure should be designed, e.g. the number of anti-snow ropes should be anticipated in Dresden. Moreover, as system of heating cables, applied in drainpipes, may be introduced to facilitate the snow melting and water flow. The heating cables could be even placed along the membrane seams, which would not deteriorate the architectural solution's attractiveness.

A similar situation is in Gelsenkirchen. As the roofing has a low inclination and curvature, there should be more supporting elements implemented. The curvature of each particular panel could have been increased through higher diversification of the (upper and lower) edge points' heights. Moreover the polyester fibers are subject to much higher elongations before tearing than fiberglass. Such change of shape under the load changes the internal forces and often protects against tearing.

To increase the structures' safety the monitoring and notification systems can be used, however the question what to do in such cases remains open. Although walking on the membrane and snow removal is possible, the amount of snow accumulating on the roofing exceeds the manual removal potentials. The use of spontaneous snow sliding off the roof is a much better solution.

The last question is the adaptation of the space development under the roofing to avoid collision with the snow sliding down. It seems obvious, but in numerous cases it is conspicuous to have been neglected by the designer.

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