Ponding Effect: Nonlinear Loading on Tensile Surface Structures

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Abstract. *This paper deals with a potentially dangerous phenomenon known as the ponding effect that may occur on tensile surface structures. This phenomenon may cause a local disorder that might lead to a fatal damage and collapse of the structure. The aim is to create and verify a searching algorithm in order to localise a possible ponding effect occurrence. Its main purpose is to scan the membrane surface deformed under snow load and locate areas prone to accumulation of melted snow. Thereafter the area of water pond is calculated and the area is loaded with an additional weight. A verification is made on the conical structure considering a variety of height to length ratios.*

Keywords

Algorithm, ponding effect, snow load, tensile surface structure.

1. Introduction

Contemporary structures require proper modern solutions. It is inevitable that structure design requirements are on the rise in order to ensure proper utilisation of building materials. This effort leads to the construction of much lighter structures. An optimization process of a structure design is relevant, but a proper original design is crucial. The best way to lighten the structure is to select a proper roof design in the first place, because the roof of a large span structure makes a significant contribution to the total weight of the structure.

The weight itself is not the only reason why the popularity of tensile surface structures is on the rise. The material of a tensile surface may resist an incredible amount of load without suffering permanent damage. On the other hand, there are limitations such as deformability, low resistance to damage by sharp objects or the risk of major damage in case of failure of certain parts of the structure.

Especially the deformability of a membrane material is the most limiting factor. In case of an inappropriate design the structure may deform in an unfavorable way. Hence, the risk of ponding effect is increased in certain areas. The ponding effect means accumulation of water or melted snow on a deformed surface. This additional load may cause larger local deformations and the volume of accumulated water may increase. This phenomena appears in the areas on a membrane surface with lower inclination such as in Figure 1.

It may occur that those disadvantages may lead to distrust of this particular type of structures. Fortunately, modern day technology allows us to analyze and calculate complex structures with very high precision. The popularity growth of membrane structures facilitated the development in the industry. Stronger materials have been developed, more accurate equations formed and software tools for the professionals have been developed. Hence, tensile surface structures have become more common regardless of the location.

2. Tensile surface structures

Double curved tensile surfaces are divided into two groups according to their Gaussian curvature. Surfaces with positive Gaussian curvature are called synclastic. These structures must be air inflated to ensure proper functionality. On the other hand, there are anticlastic surfaces with negative Gaussian curvature such as saddle shaped surfaces which are mechanically tensioned. Commonly used shapes are hyperbolic paraboloid, cone or ridge and valley [1], [2] and [3].

2.1. Anticlastic surfaces

The shape of a structure is important not only because of the aesthetic aspect, but also due to different ways of transferring an external load applied on the surface. Double curvature allows carrying the weight of snow in the hanging direction and the dynamic forces from wind load in the arching direction. Also the arrangement of yarns in the surface regarding the structure shape is important due to different tensile strength in two main directions. Stiffness in the warp direction is higher so it is aligned with the hanging direction. On the contrary, weft direction is aligned with the arching direction of the membrane [1] and [4].

2.2. Ponding effect

The vital requirement for proper design of a membrane structure is the evaluation of water the accumulation resistance of a surface deformed by heavy snow load. Deflection limits of a membrane material cannot be simply determined as in the case of conventional buildings [5]. Hence, especially surfaces with low inclination are prone to ponding of ice, snow or water. Melted snow from higher positions may overload certain endangered areas and cause a volume increase of accumulated water [6], [7]. It may end up overcoming the tensile strength of the membrane material which usually leads to the rupture of the membrane surface. However, even if an extreme tension does not overcome the tensile strength of the membrane surface, a deformed surface may collide with the supporting structure underneath.

Sometimes it is not possible to repair a damaged membrane surface due to the irreversible deformations. Subsequent scope of replacement depends on the structure itself. Unfortunately it is inevitable to replace an entire roof covering such as in the case of the platform hall of the Dresden main railway station which is a costly and onerous operation [8].

The most common way to remove snow from a membrane roof with insufficient inclination is by hand. A worker standing on the roof removing snow is in itself an additional concentrated load on the membrane surface. This type of loading on tensile surface structures and its consequences are not covered by any standard nor recommendation. The comparison of uniform snow load and concentrated load on a membrane surface is published in [9]. It has been proven that there are areas on certain types of membrane surface structures where a concentrated load causes larger deformations than uniform snow load. Those areas are located near the lower supports which is usually an area endangered by ponding effect. Hence, closer examination of the phenomenon is necessary.

2.3. Algorithm

In order to verify the occurrence of areas with a tendency to water accumulation on deformed membrane surfaces, a searching algorithm has been developed. The aim is not only to detect areas, but also to calculate the appropriate loading and apply it to the area.

The algorithm scans through the points of the deformed mesh and evaluates risky locations with a certain concentric inclination. Subsequently, those areas are examined in more detail and their boundaries defined. In order to apply proper loading, the level of pond surface is obtained and the adequate surface load added.

In order to ensure accuracy, the algorithm runs in each iteration of the nonlinear analysis. An enlargement of the water pond is checked and an appropriate increment of the loading calculated. In this manner, the resistance to accumulated water of the structure is evaluated.

3. Analysis of ponding effect

The algorithm has been developed and implemented in FEM solver by FEM Consulting which is used in RFEM software.

3.1. Computational model

The aim of the study is to analyze cone shaped structures and draw attention to the necessary design principles regarding resistance to water ponding.

1) Geometry

Figure 1 shows the analyzed cone shaped structure and its dimensions. The rigid base is square shaped with length L = 10 m. The highest point of the structure is a rigid circle with diameter d = 2 m. It is supported by a line hinged support. For the purpose of the study the height H of the structure is variable from 1.00 m to 3.50 m with a step size equal to 0.25 m. Local axis x and y of the surfaces are identical to the tangential and radial directions respectively.

2) Woven fabric

In order to thoroughly verify the given structure, each type of fabric material in the software database has been used. The thickness t of the surface is 1.00 mm Material properties are shown in table 1.

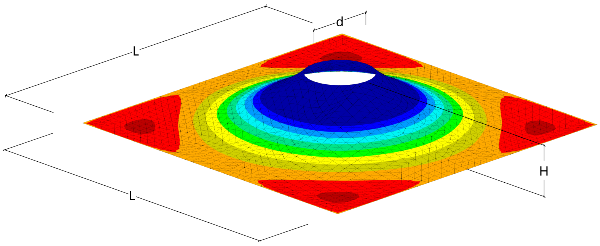

Fig. 1: Contour lines and dimensions of computational model with ponding water in highlighted corner areas.

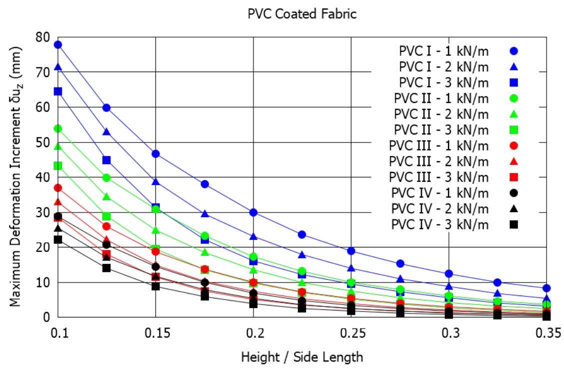

Fig. 2: Max δu_z (mm) from accumulated water on PVC.

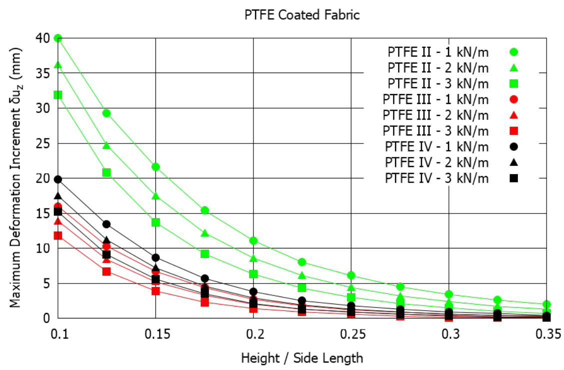

Fig. 3: Max δu_z (mm) from accumulated water on PTFE.

Firstly, a polyester textile coated with PVC (Poly Vinyl Chloride) is analyzed. There are four types of textiles with different properties such as Young modulus E_x, E_y and tensile strength f_x, f_y. Warp and weft of the material correspond to the local axes. The minimum prestress level for PVC type I is 0.70 kN·m^{-1} and for type IV is 2.00 kN·m^{-1} [1].

Secondly, there is a glass textile coated with PTFE (Poly Tetra Fluoro Ethylene) with a higher recommended prestress level. The bare minimum value of the prestress is 2.00 kN·m^{-1}, but this type of material is often prestress to 5.00 kN·m^{-1} [1].

Those recommendations are violated in the study for the educational purposes.

Tab. 1: Material properties.

Type		E_x (kN/m)	E_y (kN/m)	f_x (kN/m)	f_y (kN/m)
PVC	I	720	590	60	60
	II	990	810	88	79
	III	1220	810	115	102
	IV	1570	1160	149	128
PTFE	II	1220	1000	100	84
	III	2130	1310	138	118
	IV	2000	1520	146	130

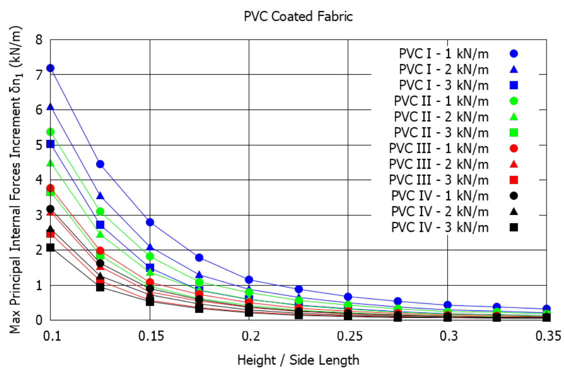

Fig. 4: Max δn_1 $(\mathrm{kN \cdot m^{-1}})$ from accumulated water on PVC.

3) Prestress level

Stress along axis is given as the input parameter of form-finding method. As mentioned above, there are some minimum level recommendations for specific types of material, but it is an engineer's task to find the correct input stress to obtain the required shape. For that reason, there are three prestress levels for each structure and material.

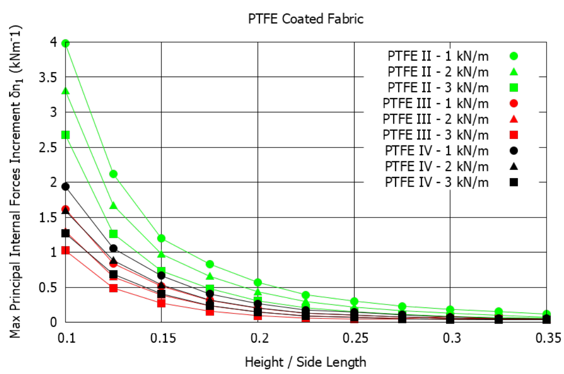

Fig. 5: Max δn_1 $(\mathrm{kN \cdot m^{-1}})$ from accumulated water on PTFE.

4) Snow load

The model was loaded with 1.00 kN·m^{-2} in global Z direction on the projected area in order to initialise water ponding in the areas near the lower corner supports. The four risky areas are highlighted in Figure 1.

3.2. Results and discussion

Firstly, maximum deformation increments in z direction $\delta \mathbf{u}_z$ in the corner areas were recorded on various configurations. There are graphs showing the development of maximum deformation increments depending on the height to side length ratio on PVC coated fabric in Figure 2 and PTFE coated fabric in Figure 3.

It is apparent that even for a larger height to length ratio there is a risk of water ponding in case of insufficient prestress level. Also, the results prove that for stronger materials such as PVC type III and IV it is possible to use less durable and cheaper options with higher prestress levels due to its overlapping curves. Similarly, materials PTFE III and IV are interchangeable.

It has been proven that the risk of ponding is strongly dependent on the initial design. If a smaller height to side length ratio is necessary, it is recommended to use a stronger material which is more expensive and requires a higher minimal level of prestress.

Concurrently, the maximum increments of principal internal forces $\delta \mathbf{n}_1$ were recorded. It has been proven that the highest increments of principal internal forces are not in the area of the accumulated water, but in the highest points of the conical membrane structure. This threatens particularly the peripheral fibers of the membrane surface which are usually reinforced with a steel element.

In conclusion, the most important result was the behavior of stronger types of PTFE coated materials. Due to their specific material properties, the weaker type PTFE type III achieved better results for smaller height to side length ratios. This is due to their distribution of modulus of elasticity in the warp and weft directions. This outcome is applicable only to the conical membrane structures with the same orientation of local coordinate systems.

4. Conclusion

This paper focuses on the evaluation of the water ponding resistance of a deformed surface. Hence, the searching algorithm for the localization of a possible ponding effect occurrence was developed and its results analyzed.

Tensile surface structures may provide an excellent service only in case of a proper and thorough design. Hence, different combinations of geometry, prestress and material of conical membrane structures have been calculated and compared.

The possibilities of shape choice are limitless, but as it has been proved, it is necessary to take into an account every unfavorable phenomena in order to provide a proper solution. However, the choice of covering material is equally important as are other aspects of the structure. This ascertainment confirms the complexity of membrane structures.

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