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EXPLORATION OF THE SUITABLE TENSIONED MEMBRANE PROPERTIES FOR THE PHOTOVOLTAICS INTEGRATION

Vuk Milošević[1]
Janusz Marchwiński[2]
Elena Lucchi[3]

Abstract

The possibilities for the integration of tensioned membrane structures and photovoltaics have been researched intensively in the past decade. This integration has huge potential and is intended to bring benefits to both of these individual systems. This paper presents a preliminary communication of the research that is intended to facilitate the PV/membrane integration. Upon reviewing the current body of knowledge in the field, it is concluded that the mechanical properties of PV are known, some integration already occurred, both of the systems are still being perfected, however, it is not clear what properties a membrane structure needs to have in order to be suitable for the PV integration. Therefore, the goal of this research is to find out the relation between some of the structural parameters and the strains of the membrane, which are already determined as critical for the photovoltaics efficiency. The methodology of the research is laid out in this paper. A numerical simulation will be conducted in order to achieve membrane strains lower than the critical. For this, a set of variable parameters are selected and altered. The results should help the designers in choosing the values of the structural parameters, with the goal of designing tensioned membrane structures suitable for the integrations with photovoltaics.

Key words: *Tensioned Membrane, Membrane Structure, Photovoltaics, Numerical Simulation, Membrane Strain, PV/Membrane Integration*

[1] Dr., Associate Professor, Faculty of Civil Engineering and Architecture, University of Niš, vukamer@yahoo.com; ORCID 0000-0003-1211-215X
[2] Dr., Associate Professor, Faculty of Architecture, University of Ecology and Management in Warsaw, Poland, j.marchwinski@wseiz.pl; ORCID 0000-0003-3897-3580
[3] Dr., Assistant Professor, Faculty of Architecture, Politecnico di Milano, Italy, elena.lucchi@polimi.it ORCID 0000-0002-3671-6460

1. INTRODUCTION

Both tensioned membrane structures and photovoltaics are highly advanced systems and both are still being perfected. Tensile membranes are extremely efficient when it comes to the amount of self-weight compared to the area being covered. This is a result of their thinness and the optimal shape they take for each of the given boundaries. In addition, they are esthetically very pleasing, which is a great benefit, as this attracts much attention and visits (Figure 1). On the other hand, photovoltaics are seen as a way to solving the energy crisis. Transforming the solar energy into electrical energy is expected to provide enough power supplies so that most of the buildings become independent from the external network. For this to be achieved, two strategies are currently deployed – reducing the energy consumption in buildings, and increasing the efficiency of photovoltaics. Once the efficiency of the PV achieves high levels, there will be less need to continue working on the reduction of energy consumption. Until then, the amount of area covered by the PV will still be of high importance. Therefore, the idea of integrating photovoltaics into tensile membranes arose. Membranes provide large areas for possible PV integration and are often used to cover open spaces. However, due to their lightweight nature, their coupling with heavy panels is not optimal, which is why organic PV cells (OPV) technology is currently the best option for membrane integration. This integration calls for additional research and this paper is dedicated to the exploration of suitable membrane properties for the PV integration.

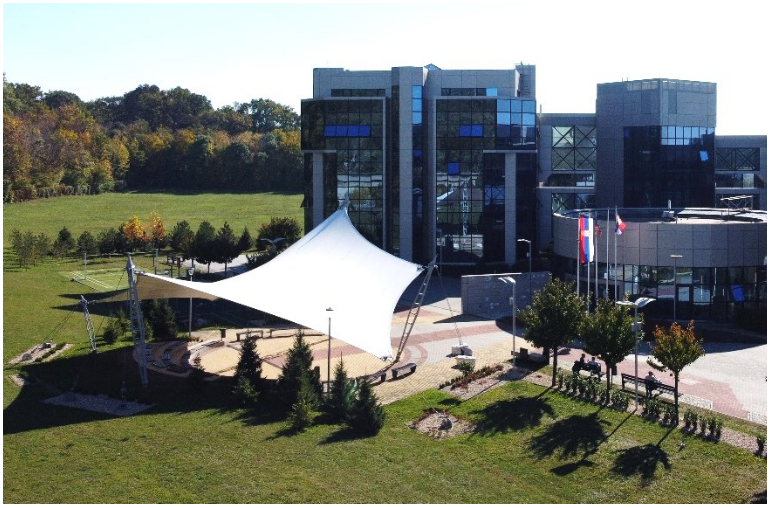

Figure 1. Tensioned membrane at the Science and Technology Park Belgrade, by Artech (courtesy of www.artech.rs)

Fan et al. provided a major contribution to this field of research [1]. They conducted experimental investigation of the mechanical robustness of the OPV module and membrane-printed functional layers for flexible solar cells. Review of the membrane integrated PV has already been presented [2,3]. Irradiation analysis of membrane structures for the purpose of covering with photovoltaics has also been presented [4]. Membrane stresses and deflections under external loads have been analyzed on hypar [5] and barrel-vault shaped membranes [6,7]. Different aspects of integration of PV onto ETFE cushions have been explored [8], including structural [9] and electrical, thermal and mechanical properties [10]. Mechanical properties of membranes have also been experimentally tested [11]. One study has been done on the life cycle assessment and life cycle cost analysis of a pneumatic ETFE membrane incorporating PV cells [12]. Another article has analyzed a case study to assess the feasibility of textile envelope in different parts of Europe [13].

The goal of this research is to investigate what properties a tensile membrane would need to have to be suitable for the integration with the photovoltaics. This paper does not present the results of the research, but rather provides a discussion and explanation of the methodology used for the research. Once the research is complete, the results will be published, and it is expected that they will give clear guidance for the designers of tensile membranes on how to design or modify their designs in order to incorporate the PV on architectural membranes. This should help in wider application of the PV-integrated membrane structures, which will as a result lead to a greener and more sustainable future.

2. RESEARCH BASIS AND MOTIVATION

Currently, three different membrane materials are most frequently used. These are two fabric coated materials and one foil material. Polyvinylchloride (PVC) coated polyester fabric and polytetrafluoroethylene (PTFE) coated glass fabrics are woven materials, while ethylene-tetrafluoroethylene copolymer (ETFE) is a foil. There are some important differences between them. Foil is much thinner and can be transparent, while woven membrane materials are translucent and can cover larger spans. Due to the latter difference, ETFE is most commonly used for pneumatic structures. Therefore, this research will focus more on the fabric membranes as it is interested in covering larger areas. Even among the fabric-based membranes there are some significant differences. PTFE materials in general have better mechanical properties and a longer life span, while PVC membranes are cheaper. Both of these material types are further classified according to their properties. The appropriate material for each designed tensioned membrane structure is selected according to the mechanical and other important properties of the material.

Mechanical properties of the membrane material can be regarded as a link between the photovoltaics and the membrane, while, at the same time, mechanical properties of the PV are the limiting factor for their integration. The main problem is that PV cells still cannot withstand large strains which are specific for tensioned membranes and do not occur in structures made from traditional building materials. This became one of the major obstacles in incorporating PV onto membranes. Research about the strains of OPV was conducted by Fan et al. [1] and it became the base point for the research presented in this paper. Starting from the results obtained by Fan et al. this research aims to find out what properties a tensioned membrane structure needs to have, in order to allow for the integration with the OPV, regarding the strain limitation of photovoltaic cells.

Three existing strategies are explained in the paper [1] for PV/membrane integration. These are the mechanical integration, lamination, and direct printing of OPV modules on the substrate. The research goes on to experimentally investigate the commercial OPV module and the new, membrane printed OPV modules. For the latter type, several different options were examined in order to compare them. Stability, mechanical and electrical characterization tests were conducted on the commercial OPV module. A nominal stress-strain curve is shown and a failure mechanism of different layers is described. However, this information does not give data about the actual efficiency of the module under strain. Therefore, strain is given in relation to the normalized efficiency and the electrode 1 conductance. Based on previous research, a 20% drop compared to the initial efficiency is used as a limit. According to the experiment, it correlates to the strain of 1.8%, which is then considered as the critical strain. For the printed OPV the results show the relation between the strain and the normalized conductance. A critical strain level has not been defined, but the results show that these printed modules show much larger strains compared to the commercial ones, tested in the first part of the experiment. Scotta et al. did a research [14] on membranes with embedded flexible photovoltaic cells. They reported that after the stress of 22 N/mm the power production decreases significantly for the tested samples.

The mentioned results motivated research to find out what the properties of a tensioned membrane structure would be, that can respond to the limitations set by the photovoltaic cells, or more specifically, have strains lower than the set critical strains for the OPV. Therefore, a research methodology has been set and presented in this paper. The research deals with the properties of the membranes and does not further explore the photovoltaic part of the integrated system.

3. METHODOLOGY

There were several important aspects to be consider while setting up this research. Once the topic and the scope were defined, it was necessary to plan the methodology of the simulation. For this, parameters to be analyzed had to be selected. Since the strains under load are examined, the appropriate loads were defined. Finally, the result analysis methodology needed to be adopted. To all of the mentioned topics, a separate subchapter is devoted.

3.1. Simulation

The strain analysis of the tensioned membrane structures will be conducted as a simulation. In the first phase of the research, the simulation will be done as a numerical simulation. Due to the complex behavior of membranes, some simplifications need to be made in this case. There are now many different methodologies on how to numerically test tensioned membranes. Commonly used software apply different methods for this. Finite element analysis software Sofistik was already used for many numerical simulations of membranes [15]. It does not account for the nonlinear material behavior of membranes. Therefore, the results will not be the same as in physical testing, but behavior and trends can be observed and general conclusions will be obtained. This will allow for more precise setting of the physical experiment which will happen in the second phase of the research. Further details about this phase will be given once phase one is completed.

3.2. Parameters

The selection of parameters to be analyzed is the essential for this research. Having in mind the goal of the research, the search for the properties of membrane structures that can facilitate the integration with the photovoltaic cells, it is important to define structural parameters that need to be fixed during testing, and the ones that will be varied. In this way, the research will produce conclusions in the form of recommendations on how to select the values of the variable parameters in order to be able to incorporate photovoltaics onto membrane structures.

The first constant parameter of the membrane structure is the membrane form. For this research a hypar shaped membrane is selected. The membrane will have four edges and four corners. Corners will alternately be positioned as low and high, in order to get the hypar shape of the membrane. Other usual forms of membranes are cone and barrel-vault, however, hypar is selected for the testing as the most frequently used one. The base of the structure will be square-shaped. Variations to the shape of the base are possible, but in order to limit the number of variables, only square is considered.

The thickness of the membrane is fixed at 1 mm during the entire testing. Despite slightly different thicknesses of different analyzed materials, the change of this parameter will not have an important impact on the results, due to the low weight of the membrane with regards to the covered area. The properties of the steel cables used as edge cables will also remain the same throughout the study. The cables will have a diameter of 12 mm and the elastic modulus of 205 kN/mm^2. The size of the finite element of the membrane will be approximately 0.1x0.1 m. This size was selected in accordance with the applied loads.

As for the variable parameters, a list of six parameters is defined. These are the membrane material, the size of the base, the height of the model, the patterning direction, the type of edge supports, and the intensity of the prestress. A similar list of variable parameters was used in a different study that dealt with the deflections of membranes [16]. Here, not only the research topic is different, but also the testing process is different, as now a limit value for the strains is defined, and the appropriate parameter values have to be found. Therefore, it would not make sense to try to define the analyzed values in advance. Instead, the initial testing will start with the parameters that are expected to have a larger influence, based on the previous experience with testing membrane structures. These are the size and the height of the model and the membrane material properties. Afterwards, other parameters will be analyzed. The results will confirm whether the assumption about the significance of influence of these parameters was correct.

Six parameters selected for analysis essentially define the tensioned membrane structure. The size of the base is directed by the span, and is usually given as a requirement to the designer, although sometimes there is a possibility to divide the structure into several smaller ones [17]. The height of the structure, in relation to the size of the base, defines the curvature of the membrane, which is known to have a large impact on the behavior of the membrane under load. The type of membrane edges has a subtle effect on the form of the membrane, but straight membrane edges usually mean more massive and heavy supports. The patterning direction of the membrane impacts the visual appearance of the structure, but it also has structural implications. Intensity of the prestress and membrane material are closely related. They are usually the last parameters to be defined, and are used for structural adjustments to the structure, when the designer is already satisfied with the appearance of the design.

3.3. Loads

Three types of loads have been selected for simulation. These are the loads that are known to have large impact on the strain of the membrane. The first one is snow load. Although snowfalls do not occur at all locations, it is a very common load for most of the structures. The second applied load is the wind load that is often the dominant load in the structural calculation of membranes. The third load is the concentrated load that occurs mostly from the weight of people on the membrane. This load is specific, because in case that it produces unfavorable results, the recommendation to forbid access to the membrane can be given, which is not the case with the two other analyzed loads. In this case, all maintenance, inspection and repair have to be done using cranes or other devices to allow workers to approach the upper side of the membrane without standing on it.

Loads acting on the structure, as well as some of the structural properties, have to be simplified in the testing. For snow load this is of lesser importance, since its action is not very complex. Most importantly it will be assumed that the load acts with the same intensity across the entire membrane, which is not the case in reality. For wind load simplifications are much more significant, as wind is a dynamic action that will be applied as a static load in this testing. Load from humans walking on the membrane also has a dynamic component that will be ignored during the analysis. The exact load values and parameters will be selected with regard to the previous studies done on membrane stresses and deflections.

3.4. Results analysis

The testing will start by applying each of the loads individually to the initial model of the tensile membrane structure. The maximal strain results will be monitored. Based on the obtained results, the parameters will be varied in order to find the sets of parameters that define different membrane structures that are suitable for the application of PV cells on them. One variable parameter will be varied at a time. For each new set of parameters, a new numerical model will be built. Once the dependency of the strain on the parameter value is established and the strains are lower than the defined critical strains, the variation of the next parameter starts. The procedure will be continued until all parameters are analyzed.

There is a risk that strains lower than the critical cannot be achieved. In this case, a change in the results analysis should be made. Instead of monitoring maximal strains, all strains of the membrane will be analyzed. The goal of this is to find parts of the membrane suitable for PV integration, since the most strained parts are unsuitable for this. In this case, conclusions will have to include this aspect of the analysis, so that recommendations will be given to designers even for the membranes that are not entirely suitable for integration.

4. CONCLUDING REMARKS

This paper presents the methodological set up for a research dealing with finding the appropriate parameters of tensioned membrane structures to make them suitable for integration with photovoltaic cells. It is intended as an introduction to the research, whose results will be presented in the articles to follow. In the paper, a brief overview of the existing literature in the field is given. Based on the state-of-theart, the research question is formed and the motivation for the research is elaborated. Then, the methodology of the research is discussed and presented. The significance of analyzed variables and their role in defining a tensioned membrane structure is given. The testing process is presented, as well as the results analysis, that will have an impact on the testing methodology.

It is expected that the results of this study will provide an understanding of the relation between the six analyzed parameters and the membrane strains under load. This knowledge will be useful even when the photovoltaic cells advance and no longer have the same critical strains as defined in this study. Therefore, the results will be of help to designers of membrane structures when the integration of PV cells is intended. The novelty of this research is in providing values for structural parameters, compared to existing research where individual cells or parts of the membranes are tested. Once the production of transparent flexible photovoltaic cells begins, they may become an integral part of every membrane, as soon as cost effectiveness is achieved. It can be concluded that we are still at the beginning of the road towards membrane integrated photovoltaics, and that this research is a small step towards future developments that are likely to make humanity more energy independent.

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