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Design Optimization of Tensile Structures Integrating Thin-Film Photovoltaic Panels

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Abstract: The potential of incorporating thin-film photovoltaic (PV) technology into buildings makes it an ideal renewable energy solution not only for traditional structures but also for innovative designs featuring free-form envelopes, such as membrane structures. Integrating PV technology into these structures represents a significant advancement in the market. However, challenges and uncertainties have emerged regarding the feasibility of such systems, as they depend on a variety of complex factors that must be considered during the design phase. These factors include the diverse three- dimensional geometries of membrane structures, which influence the distribution, orientation, and shading of PV modules, as well as the stresses and deflections experienced by both the structure and the modules. Due to the complexity of these interactions, they are difficult to analyze without using parametric tools capable of assessing multiple parameters simultaneously. In response, a parametric PV model using Grasshopper was developed to examine the factors affecting the payback time of the PV system, such as layout orientation, shadowing effects, and the maximum deflection allowed for the membrane surface under different loading conditions. The model ultimately calculates the available clear surface area for placing PV modules. This paper demonstrates the efficiency of Grasshopper as a parametric tool for evaluating the viability of flexible PV systems on tensile structures.

Keywords: *MIPV Membrane Integrated Photovoltaics; Parametric Design; Grasshopper; Membrane Structures.*

1. Introduction

PV solar technology is highly regarded as one of the best renewable energy sources for buildings. Flexible thin-film technology is particularly promising, not only for conventional architecture but also for cutting-edge designs that utilize free-form membrane structures. The integration of flexible solar modules into pre-tensioned membrane structures allows for diverse design possibilities. However, many questions remain about the practicality of these systems for various membrane structures, and how both the structure and the PV modules behave under different environmental and mechanical conditions. A thorough understanding of these elements is essential to maximize the potential of integrated systems.

2. Tensile Structures Integrating Photovoltaics

2.1. State of the Art

The first attempts to integrate flexible PV modules into membrane fabrics occurred in 1998, when FTL Studio introduced the first tensile fabric pavilion at the National Design Museum in New York, featuring transparent PVC fabric with embedded flexible PV technology. However, due to the instability of the fabric material over time, more durable materials were sought for accommodating solar technology. Further experiments included embedding modules into PVC- coated polyester fabrics and PTFE-coated glass fibers, using techniques developed specifically to match the properties of the materials. One of the early attempts involved Hightex, which welded an amorphous silicon module onto a four-point sail structure made of PTFE/glass. Although this system was further developed, issues such as vapor condensation emerged a year after installation.

A multi-layer attachment system was later developed by Saint Gobain Performance Plastics in the USA, enabling the mounting of flexible solar modules onto PTFE/glass fabrics. This system included a layer of single-coated PTFE/glass laminated with FEP, which allows for heat sealing without damaging the single-coated PTFE/glass laminated with FEP, which allows for heat sealing without damaging the materials. The Velcro hook strip was key to providing a temporary solution for module attachment, see fig.1

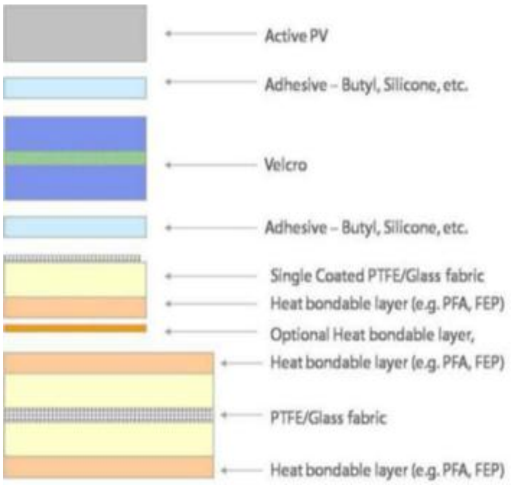

Fig.1: Layers structuring of the the System attaching Flexible PV to PTFE/Glass (Cremers, Hightex)

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2.2. Challenges Facing Photovoltaic Integration into Membrane Structures

Despite these advancements, challenges remain regarding the application of these systems to various membrane structures and their performance under diverse environmental conditions. Successful integration of flexible PV into membrane structures requires careful consideration of multiple complex factors, such as the PV later's longevity, Membrane geometries, module orientation, shadowing effects, and stress distribution within each project. As stated by Cremers [1] that While integrating flexible PV technology into membrane structures has the potential to unlock new market opportunities, several challenges remain. These include understanding the impact of PV system yield based on membrane geometries with single or double curvature, the distribution of stresses and deflections across the membrane, and the effects of shadowing on PV module placement. Additionally, the longevity and stability of the PV layer within the tensile membrane must be considered. Previous research has explored technical and manufacturing aspects related to integrating organic photovoltaics into membrane ETFE foils for use in pneumatic roofs and facades, highlighting issues like stress levels and curvature. Mechanical tests have shown that highly extensible encapsulants used in lamination can accommodate significant elongation differences, reducing loads on the solar cells [5].

3. Design Consideration of Integrating Flexible PV into Membranes

To optimize the performance of PV modules on membrane structures, the model developed in this research considers factors such as orientation, tilt angle, shading, and deflection, with the aim of maximizing energy yield. Tests suggest that PV modules should be installed flat with a 30° tilt facing south, with a maximum slope of 60° for optimal performance. When dealing with large PV surfaces that may be shaded, parallel connection between modules is recommended to ensure consistent voltage and current. Variations in curvature and orientation of membrane surfaces can also impact energy yield by as much as 5%.

For higher PV output, membrane forms with less curvature and clearer orientations are preferred. Due to varying forces on the membrane surface and the relaxation of the material over time, the tilt angle of the solar modules may shift from its optimized position. As a result, adjusting the tilt angle in mechanically pre-stressed PTFE/Glass membrane roofs is possible, but it would require additional investment. From an architectural perspective, architects often use PV as a surface that provides a clear visual effect. The rhythm created by the grid of solar modules significantly influences the visual perception of the membrane, especially when used effectively. Linear arrangements of modules in parallel patterns are more desirable than radial ones.

3.1. Parametric Design Optimization Model

The Grasshopper plugin for Rhino serves as a parametric modeling tool with a graphical node-based interface that includes a wide range of components, parameters, and constraints to create and manage any 3D parametric model [6]. These features make Grasshopper particularly effective for exploration, especially during the early stages of design [7]. Various parametric workflows have successfully optimized environmental factors such as daylighting and energy performance using methods like genetic optimization and exhaustive search [11,9]. These applications extend beyond static design optimization to include dynamic and responsive systems.

The parametric model for evaluating PV system performance uses Grasshopper and incorporates various parameters such as deflection, orientation, and shading. The process involves filtering the membrane surfaces based on these factors to determine the available area for PV integration. The model also incorporates environmental factors like solar radiation and deflection under wind and snow loading, ensuring that only the most suitable areas for PV installation are selected. Through this process, the final result provides the total clear surface area available for PV integration, expressed as a percentage of the total membrane area.

The parametric photovoltaic (PV) model is designed to assess environmental factors that influence the payback time of PV systems, including solar access, shading, and the site's latitude, which affects the optimal orientation and tilt of the MIPV system. In addition to analyzing daylighting patterns on the geometry, the model incorporates membrane deflection into the process, using a definition to evaluate the maximum allowable fabric deflection under various loading conditions, such as wind and snow, in areas suitable for PV module installation. It also determines the feasibility of PV integration by calculating the total clear surface area available on the chosen geometry, developed in Grasshopper by parametric design specialist Ayman Wagdy, who introduced advanced techniques for parametric workflows in daylighting analysis (Wagdy, 2012), the model operates in three stages. These stages function as a sequential filtering process based on defined parameters: deflection, orientation, and shadowing.

This review shows that while research on optimizing thin- film photovoltaics for membrane structures is still limited, parametric design workflows have proven valuable in identifying the best locations for PV installation, improving energy efficiency and overall performance. The parametric model developed in this research is an essential tool for evaluating the feasibility of integrating PV modules into membrane geometries and optimizing their performance.

3.2. Allowable Deflection Test

The numerical design and analysis of membrane geometries are initially carried out using specialized form- finding and structural analysis software developed by Form_TL Ingenieure für Tragwerk und Leichtbau. The first geometry analyzed is a 5x5m hyperbolic paraboloid (hypar) structure with a height-to-length ratio of 1:5, as shown in Fig. 2. The analysis generates three deflected geometries corresponding to the loading conditions of pre-stress, wind, and snow. These deflected forms are subsequently evaluated using a deflection definition that ensures the maximum allowable deflection within the same module surface is maintained. A screenshot of the deflection definition is provided in Fig. 3.

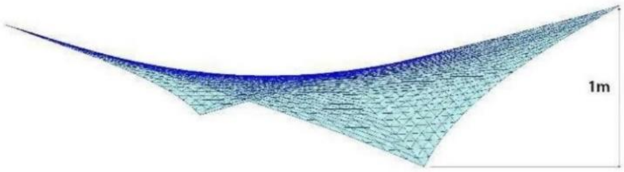

Fig.2: 5x5 m hypar structure with a 1:5 m height to length, form-ratio of 0.2

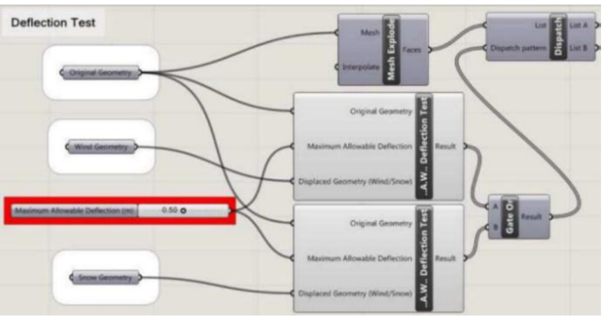

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Fig.3: Screenshot of the deflection test definition (Ayman Wagdy©)

All surfaces with deflection values exceeding the allowable limits are excluded from the total area available for PV module installation. As illustrated in Fig. 4 and Fig. 5 for a hypar structure, the model evaluates membrane surfaces by adjusting the maximum allowable deflection distances between the deformed geometries under pre-stress and snow loading, reducing the range from 0.95 m to 0.84 m. Only surfaces with deflection values within this specified range are considered for PV integration. It is important to note that the allowable deflection value should be determined based on the mechanical testing of the PV modules. The output of this process identifies only the meshes that fall within the specified deflection range.

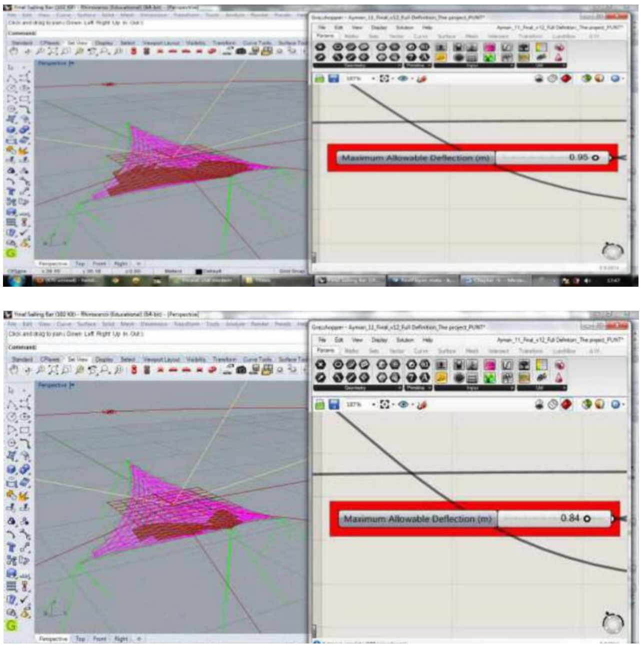

Fig.4 & Fig.5: Filtering membrane surfaces by different values of allowable deflection.

3.3. Orientation Test

Following the deflection test, a second filtering process focuses on the orientation of the structure. To account for the daily and annual movement of the sun, a specific definition is developed to analyze the surfaces exposed to solar radiation. This is achieved by defining the north direction and specifying the horizontal and vertical angles within which the PV modules must be constrained, as shown in Fig. 6. A maximum zenith angle of 60 degrees is set, aligning with the recommended inclination for surfaces accommodating PV modules.

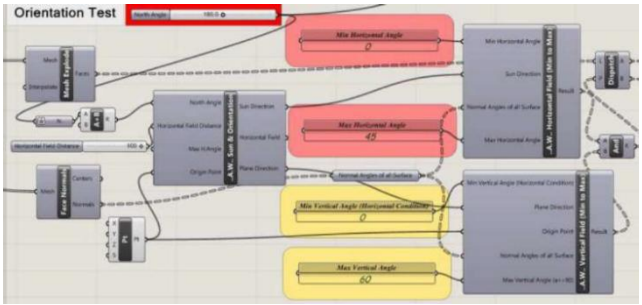

Fig.6: Screenshot for the Definition of Orientation test (Ayman Wagdy©)

The Grasshopper model is connected to a solar database of global solar radiance, developed by the Oregon Laboratory, to enhance accuracy. Figs. 7 and 8 illustrate how the model identifies different surface areas that fall within the specified solar radiation angles for an arch structure on September 21 and November 21 at 12 p.m. The angles used in the analysis are based on the sun path for Milan, Italy. The last process is concerned with excluding all membrane surfaces subjected to shading under the specified date and times. The input geometry in this process is the membrane surfaces that fulfilled the previous conditions of deflection and orientation. The results are expressed by the final clear surface area available for PV integration giving a percentage to the total membrane area.

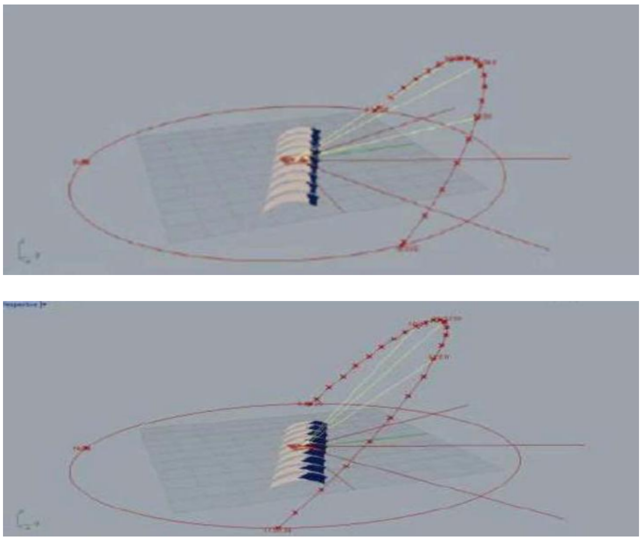

Fig.7 & Fig.8: Sun path for Milano City in 21 September and 21 November, respectively.

4. Conclusion

Integrating flexible solar modules in pre-tensioned membrane structures allows for a wide design varieties of shapes and geometries. This study is dedicated to a parametric environmental model which is developed to analyse the applicability of PV modules to the selected geometry through calculating the membrane surface area free of shading, well oriented to solar radiation and within the allowable range of deflection. The Diverse range of membrane forms and the intricate factors influencing the integration process are highlighting a set of complicated factors, including the PV panels orientation, the curvature of tensile fabric surface and the effect of shadowing have to be all taken on board during the design process for an optimized performance of flexible photovoltaics modules.

When the membrane geometry is to be decided by the architect, the following aspects should be considered. Based on the parametric evaluation model performed on different membrane forms, clear orientation to south and avoid shade will result in higher PV performance. Less panels curvature and clear orientation, percentage of clear membrane areas for allocating repetitive grid of PV modules. The geometry of arch forms provide an appropriate surface for accommodating PV modules. Less curved arch forms exhibit low structural performance in terms of generated stresses when compared to high curved arches nevertheless, PV system yield would perform better on flatter geometries. The parametric PV analysis performed on arch forms proved that about 40% of the arch surface can accommodate PV modules if well oriented.

Conflicts of interest

The authors declare no conflicts of interest.

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