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The Structural Behaviour of PTFE/Glass Fabric Structures Integrating Flexible Photovoltaic Modules

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1. INTRODUCTION

Although the potentials of integrating thin-film Photovoltaic into buildings make it the recommended technology not only for traditional architecture but also for applications where envelopes are characterized by free morphologies such as membrane structures, integrating flexible Photovoltaic technology into architectural fabrics are still facing critical research questions related to the structural behavior of the integrated system under different loading conditions, the feasibility of their application for the wide varieties of membrane forms, the impact of environmental aspects on integrated elements and the know-how of incorporating PV system into the design and engineering phases of membrane projects. The paper investigates the impact of integrating flexible PV modules into PTFE/Glass hypar structures through a multi-layer attachment system developed by an US company. The system is incorporated in the form finding process of four different hypar form-ratios exploring all problematic aspects and then numerically analyzed for determination of structural behaviour under different loading conditions.

2. ATTACHING FLEXIBLE PV TO PTFE/GLASS FABRICS

Developing techniques for integrating flexible Photovoltaic modules into PTFE/Glass fabrics have special requirements related to material and mechanical issues for system flexibility. PTFE, as the basic material for PTFE/glass fabrics, has one of the lowest coefficients of friction against any solid. Whereas PTFE is preferably used where non-stick surfaces against dirt are targeted, it's also where the challenge exists to attach other materials to PTFE by means of adhesion or welding. The attachment system should also accommodate special techniques for the flexibility to install and de-install modules for maintenance issues when needed without destroying the supporting PTFE/glass fabric. A multi-layer attachment system has been developed by Saint Gobain Performance Plastics that can mount flexible solar modules to PTFE/Glass fabrics. The system composes of a first layer of single coated PTFE/glass which is laminated to a thin layer FEP on the side of PTFE coating which cannot be hot welded. Therefore, the FEP layer with melting point of 280°C is used for the heat sealing with temperatures over 280°C. This temperature would destroy both the butyl adhesive and the polyester of the Velcro hook. For this reason, the single-side coated PTFE/glass strips are welded before a special type of Velcro hook strip is glued onto it. The velcro layer is the key solution to the targeted replaceable use of modules and is finally adhered to the thin-film solar module. Fig.1. indicates the structure of the attachment system.

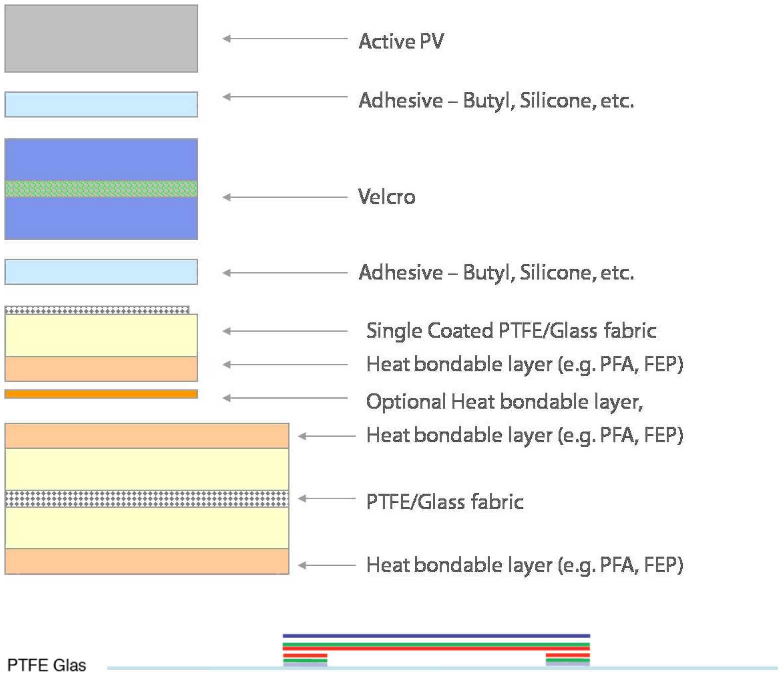

Fig.1: Layers structuring of the System attaching flexible PV to PTFE/Glass (Cremers, Hightex GmbH/ SolarLoc System by Saint-Gobain PP)

The installation steps are as follow: In the first step, two one-sided laminated PTFE/glass membrane strips are welded to the supporting PTFE/glass with a distance of the module width with the coated side on the membrane surface. In the second step, the Velcro hook strip of the same dimensions as the previously single side coated PTFE/Glass membrane strips are glued onto it with a hotmelt. It should be noted that preheating the raw glass fabric improves the adhesion of the glue. In the third step, the flexible PV module with Velcro loop is unrolled and attached to the structural membrane Velcro hook strips, See Fig. 2,3,4&5. Cables should be put in membrane pockets for protection. The system is developed but further studies on the structural behavior of the membrane surface and the know-how of integrating these systems into the engineering phase are still lacking. And these are the targeted questions for the following part.



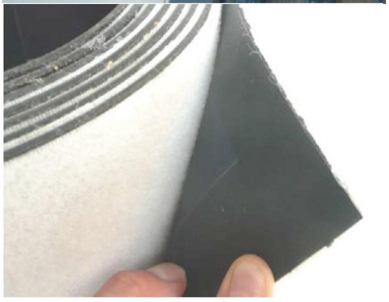


Fig.2: Upper left: Welding the PTFE / glass membrane strip to the membrane structure using "iron".
Fig.3: Upper right: Stick the Velcro hook strip with butyl
Fig.4: Lower left: Velcro layer
Fig.5: Lower right: Application of flexible PV module to the membrane
(Fig. 2-5: Cremers, Hightex GmbH)

3. MECHANICAL PROPERTIES OF THE ATTACHING SYSTEM

As indicated in the Fig.1, the designed system for fixing the solar modules on PTFE/Glass fabrics composes of layer of single coated PTFE/Glass welded to the membrane on the coated side and adhered to Velcro on the other side. The solar module is then glued to the Velcro using adhesives. Understanding the mechanical behaviour of the fixing system is essentially required to analyze the structural performance of the membrane when modules are integrated. As the true behaviour of coated woven fabrics is highly nonlinear and can only be determined by extensive biaxial testing, assuming equivalent linear elastic material properties are generally adopted for analysis and design when obtaining the accurate values from bi-axial testing is not provided. The required mechanical values such as the elastic modulus and shear stiffness represent the input data for form-finding and structural analysis phases of the designed prototype in the next research step. For determining the actual mechanical properties for these layers, some bi-axial tests are commonly required. These tests are recommended as a step in the future research. In the case of unavailability of the fabrics mechanical values, these values are commonly assumed in relation to other fabrics values. The materials integrated were selected and fixed in a way that insures the flexibility of layers to absorb forces generated by the membrane. The only stiff layer is the single coated PTFE/Glass which is welded directly to the main membrane surface made of PTFE/Glass. From the mechanical behaviour perspective, the whole fixing system layers can be then considered as one layer of single coated PTFE/Glass, taking into account the self-weight of the layers that's usually provided in further design steps. Therefore, an assumption is made to consider additional values of a typical PTFE/Glass elastic modulus and shear stiffness for the fixing system. Therefore, where the whole PTFE/Glass membrane surface has the values of eax=2.0 MN/m, eay=1.8 MN/m, eap=1.0 MN/m and G=0.1 MN/m, the surface of welded fixing system has double the previous values leading to elastic modulus of eax =4.0 MN/m, eay=3.6 MN/m, eap=2.0 MN/m and shear stiffness of G=0.2 MN/m. A constant value of 1 KN/m was used for the whole load cases.

4. NUMERICAL DESIGN AND STRUCTURAL ANALYSIS OF A FOUR-POINTS HYPAR PROTOTYPE INTEGRATING FLEXIBLE SOLAR MODULE

4.1. DESCRIPTION OF STUDY

In order to investigate the structural behaviour of PTFE/Glass fabric structure integrating flexible solar module, a 5x5 m 4-points hypar structure is numerically designed and analyzed under different loading conditions. As the study considers the importance of the form-ratio on the structural behaviour of the integrated elements, the analysis considers four different forms of 1:5m, 2:5m, 3:5m & 4:5m height to side length which corresponds to ratios of 0.2, 0.4, 0.6 & 0.8 respectively. The higher the form ratio is the more curved the structure. Based on the fact that the behaviour of membrane structures depends on curvature and geometric aspects rather than span, the analysis can be applicable on the wide range of membrane scales. In order to reduce the number of parameters, a constant value of 1:1 prestress in warp and weft directions has been used for all forms under all load conditions. Generally, an increase in prestress will reduce deflections while increasing stresses and vice-versa. Uniform wind uplift and uniform snow loads are assumed to be (1KN/m²). The Analysis Targets:

1- Investigating the impact of adding flexible solar modules on the form-finding process in relation to different form-ratios.
2- Studying the relation between different form-ratios and their impact on integrating PV modules and the generated stresses and deflection values.
3- Investigating the behavior of the structure under live loads, wind and snow.

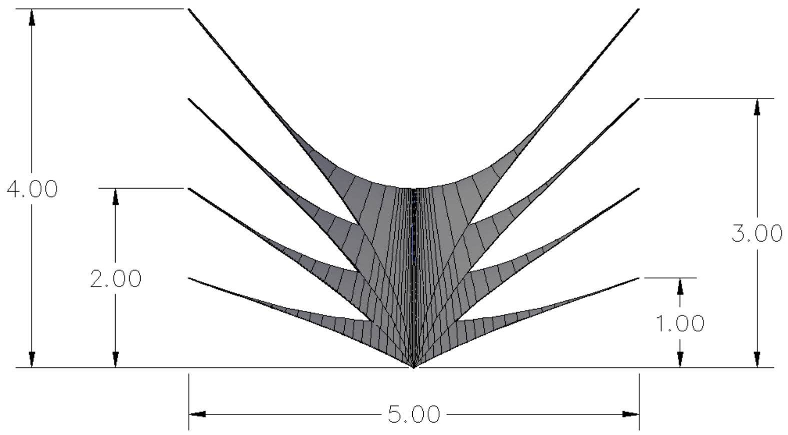

Fig.6: Four form ratios investigated of 5x5m Hypar structures (M. Ibrahim H.)

The numerical design and analysis is performed using form-finding and structural analysis software programs. The analysis is performed on two stages: the form-finding phase using TLform program, load analysis phase using TLload and WinNetz programs.

4.2. FORM-FINDING PROCESS OF A HYPAR STRUCTURE INTEGRATING FLEXIBLE PV MODULE

The form-finding process starts by defining numerically the geometry system points, lines and regions. The hypar geometry is firstly generated and the flexible solar module fixing system geometry is defined. According to the inhomogeneity of triangulation grid between the defined regions of the membrane and PV surface, the resulted form-finding process showed an instability condition. This has led to redefining the membrane geometry in a grid ratio close to the fixing system dimensions. This problem represents the first consideration that should be taken into account during the form-finding phase which has more significant impact proportionally with the increase of project scale. The form-finding process is then performed for the hypar with the four aforementioned form ratios of 0.2, 0.4, 0.6 and 0.8. The second problem during the form-finding is explored when the form was generated. Because the system lines during the form-finding are generally free positioned in x,y,z coordinates following the geodesic form, this resulted in changing the geometry and dimensions of the pre-defined PV regions which turned from straight rectangular to curved and smaller geometry. A final solution is investigated by approximately defining wider dimensions than the real ones for the PV fixing system, depending on the curvature of structure, that nearly changes to the real dimensions after the form is generated. The impact of the structure curvature on the modified definition of PV region is investigated and described in the following part. Fig.6 is indicating the primary (marked in red) and modified (marked in blue) modules defined regions resulting in nearly the actual dimensions after generating the form. It’s concluded that the more curved the structure is the more significant the geometry change.

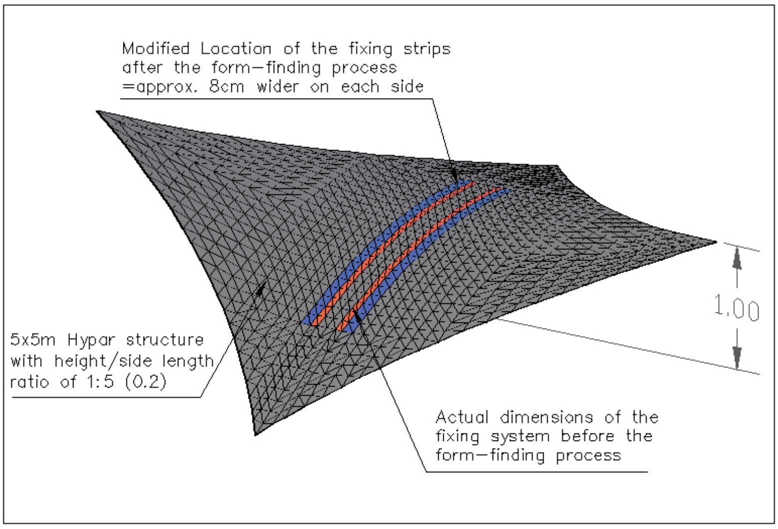

Fig.7: 5x5 m hypar form with 1m high points and form ratio of 0.2 (M. Ibrahim H.)

4.3. STRUCTURAL ANALYSIS OF A HYPAR STRUCTURE INTEGRATING FLEXIBLE PV

The structural performance of membranes can be evaluated by the two main factors of stresses and deflection. In this analysis, the stresses on warp and weft directions are tested for the four different hypar form-ratios under wind and snow loading. For comparable results, the analysis is performed for both conditions when PV is integrated or not. The results are analyzed and evaluated trying to understand the relation between the aforementioned parameters and the boundary conditions for PV integration regarding the proposed geometries. Fig.9 indicates the stresses analysis of the less curved form ratios (0.2) which showed an increase level of stresses on warp direction of 27% at the edges of fixing system decreasing gradually till reaching 17% increase from 6 to 7KN/M at the center of strips. Regarding the stresses on weft direction under snowload, as indicated in Fig.10, the results showed slight increase of stresses at the strips edges that could be ignored.

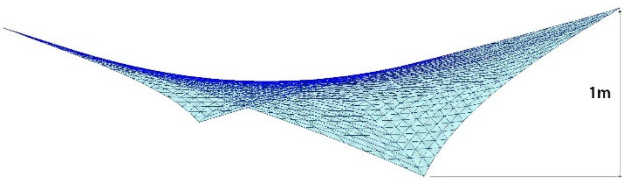

Fig.8: 5x5 m hypar structure with a 1:5 m height to length, form-ratio of 0.2 (M. Ibrahim H.)

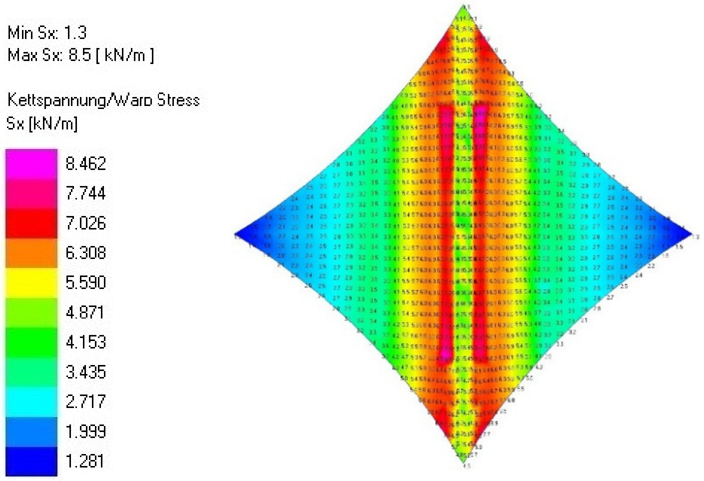

Fig.9: Warp stresses under wind load with PV integration (M. Ibrahim H.)

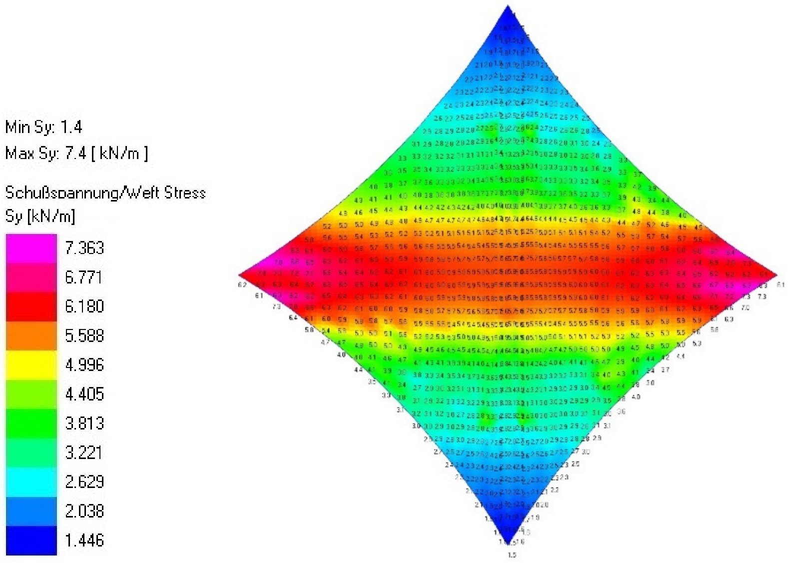

Fig.10: Weft stresses under snow load with PV integration (M. Ibrahim H.)

4.4. IMPACT OF PV INTEGRATION ON MEMBRANE STRESSES

The performed analysis on the four hypar forms showed that the generated tensile stresses are relatively higher for less curved forms than those generated in more curved ones, ranging from 5.8, 3.9, 3.7 then 2.3 for 1m, 2m, 3m and 4m high hypar respectively, as indicated in Fig.11. Adding a flexible PV module resulted in an increase of stresses that is proportional to the level of curvature. The more curved the structure is the more sensitivity and higher percentage of stresses increase at the surface of membrane where the module will be installed.

The results showed an increase of stresses ranging between 20% and 35% of the original generated stresses before integrating modules. These values should be taken into account during the structural analysis when the integration of flexible PV modules is targeted. All investigated forms exhibited higher stresses levels at the edges of strips which will be analyzed separately in the next parts. The following chart indicates the impact of adding the module on the tensile stresses on warp direction generated for each form under windload. It should be noted that the first three forms are generated from the same geometry definition for the form finding process. Whereas because of geometrical and form instability problems with the fourth form using the same definition, the fourth form with the highest curvature is separately redefined. This is the reason why the analysis showed a significant increase of stresses of about 62% at the form-ratio of (0.6) which could be attributed to some form-finding issues that resulted in higher generated stresses. Therefore, the results of this form have to be excluded from the analysis.

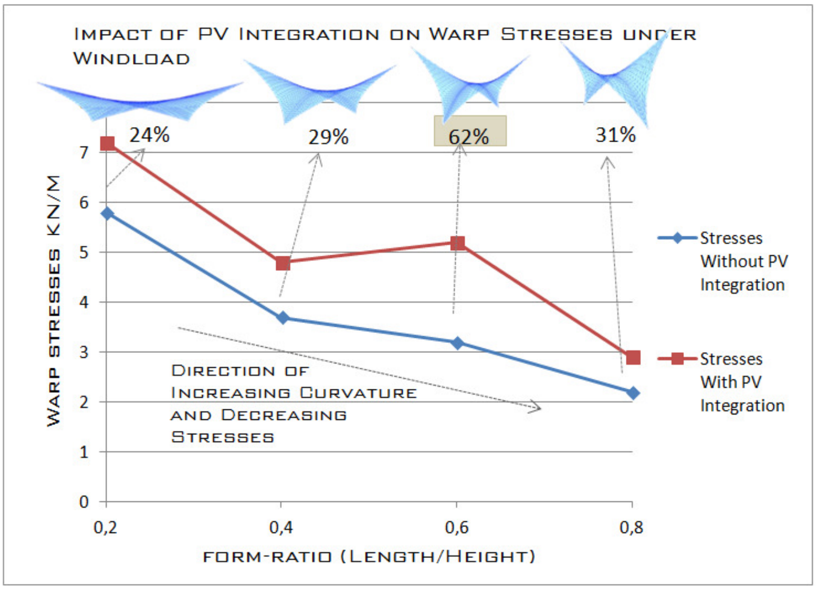

Fig.11: Impact of PV integration on warp stresses (M. Ibrahim H.)

A common observation between all results was analysed regarding the relative increase of warp and weft stresses at the edges of the fixing system strips under different load cases. This can be attributable to the used geometry of the added layer where the forces are moving from single to double layers of PTFE/Glass through sharp and short edge line. Two recommendations are proposed trying to decrease generated stresses at that part. The first solution could be by changing the form of strips ends in a way that allows the distribution of forces along wider edge line more smoothly. Fig.12 indicates the actual and proposed design for the edges. This solution is not numerically investigated in the current research and should be a part of required research in the future.

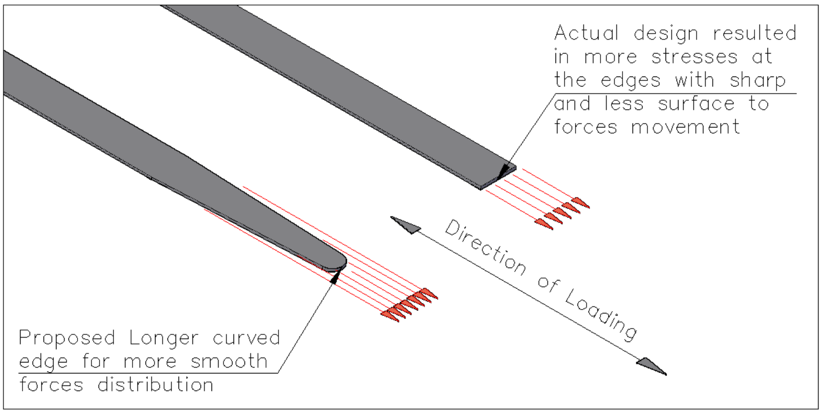

Fig.12: Impact of edges geometry on forces distribution (M. Ibrahim H.)

The second solution for decreasing the stresses generated at the strips edges is reducing the stiffness of the PTFE/Glass layer of the fixing system. The stiffness is reduced 200% to 125% and the same package of structural analysis is performed in order to compare the behavior of the structure using both stiffness values. The results, as indicated in Fig.13, showed that by decreasing the stiffness of the PTFE/Glass, the stresses applied on warp direction under windload dropped from 4.8 to 3.8 KN/M when the module is added. While the stresses decreased from 1 to 0.9 KN/M by welding the layer before adding the PV module under prestress load condition. The results are promising for future research by testing the impact of material mechanical properties on the structural behavior concluding with the optimum material characteristics for PV integration on PTFE/Glass membranes.

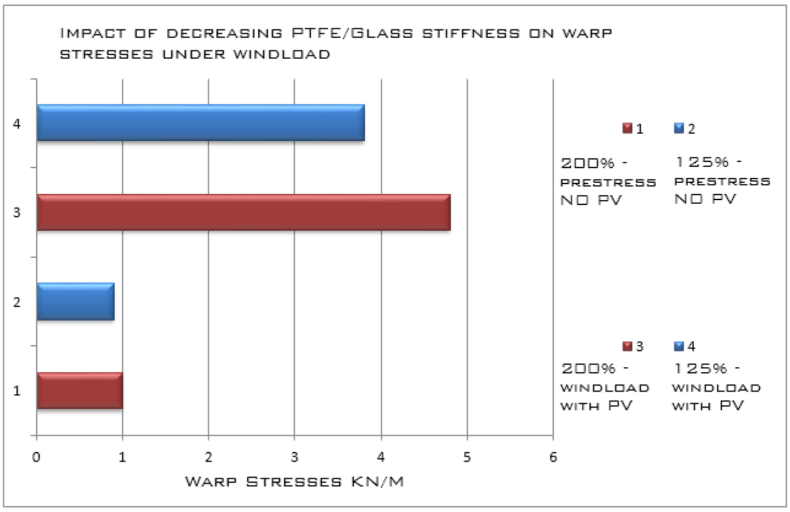

Fig.13: Impact of decreased PTFE/Glass stiffness on stresses (M. Ibrahim H.)

5. CONCLUSION

Realizing flexible photovoltaic technology into membrane projects is an integrative process that has to be involved already in the early design stages of form finding and structural analysis. The performed analysis of attaching flexible PV modules to coated fabrics for architectural applications showed promising results in terms of the modules impact on the structural behaviour and the level of generated stresses that has to be calculated for each single project. However, further research is required to investigate the impact of such integration on the module's performance.

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