ISSN (ONLINE): 2454-9762
ISSN (PRINT): 2454-9762
Available online at www.ijarmate.com

International Journal of Advanced Research in Management, Architecture, Technology and Engineering (IJARMATE)
Vol. 2, Issue 9, September 2016

An innovative proposal for a saddle-shaped movable membrane structure

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***Abstract*— This paper presents a novel retractable roof designed to cover a courtyard in Islamic Art University of Tabriz in Iran. This courtyard is a place of gathering and also is being used for temporary exhibitions. While the buildings around the courtyard were built recently, other buildings placed in the campus are almost 100 years old, so it was important to take account the architectural features of the neighboring architecture. This roof was expected to attract visitors and become an attractive feature of the university while protecting occupants from the strong sun and winter snows. The aim of this paper is to propose to a retractable roof structure that covers the 8*14 meters space below the courtyard in its deployed configuration and also being capable of bearing heavy snow loads and withstands gusty winds especially in winter season. This retractable roof can also provide ventilation when it's required. In this paper, a lightweight modular retractable roof is proposed which in its deployed configuration fully covers the whole courtyard. By the use of saddle-shaped membrane modules, both aesthetic and functional aspects were executed. The anticlastic form of the membrane skin gives enough strength to bear heavy loads and also facilitate the collection of the rainwater and the maintenance of the structure. Each unit is composed of four sub-modules of saddle-formed membranes attached together in a rectangular plan configuration, which is capable of rotating around a horizontal axis. By rotation of each unit it be-comes possible to slide all beams in one direction and transform the whole roof on the basis of environmental changes and user's ambitions. The roof in its fully open configuration changes to a compact bundle of saddle-formed membrane structures placed on one side of the roof. In this paper the main design criteria and the de-tailed design materials and different configurations of the roof along with its functional and aesthetic features are presented.**

***Keywords*— membrane, deployable, saddle shaped, textile, structure, movable.**

I. Introduction

Architectural structures that integrate motion have been eye-catching for architects and engineers. Nowadays, most constructions are static and are designed to fulfill a unique and predestined purpose during their lifetime. But in an era where nearly every-thing proceeds dynamically, it is interesting to explore non-static structures. A large group of

structures have the ability to transform themselves from a small, closed or stowed configuration to a much larger, open or deployed

configuration. The obtained structures are generally referred to as deployable structures [1]. As deployable structures have strong vitalities, they can respond to the changes of the ambient conditions like intensity of solar radiation, wind, rain and snow. The deployable are characterized by their dual functionality as load-bearing structures or mechanisms. As load-bearing structures they transfer live and dead loads and as mechanisms they provide for the reversible alteration of their form [2]. This paper presents a novel retractable roof structure composed of kinked glass-fiber reinforced polymer frame and membrane skin designed for a courtyard in the campus of Tabriz Islamic Art University (TIAU). This courtyard is being used for many special occasions like religious ceremonies, galleries, and it is also a place of gathering for students. However, being open-air, performances are depended on the changeable weather of Tabriz and therefore, most of the time in a year this place is only being used as a passing route. It was important to design a retractable roof structure for this courtyard that can easily adapt to climate changes and makes it possible to extend its use during all seasons. This roof was expected to attract visitors and become an attractive feature of the university while protecting occupants from the strong sun and winter snows. The aim of this paper is to propose a retractable roof structure that covers the 8*14 meters space below the courtyard in its fully deployed configuration and also is capable of bearing heavy snow loads and withstands gusty winds especially in winter seasons. This retractable roof can also provide ventilation when it's required.

II. ARCHITECTURAL DESIGN CONCEPT AND DESIGN EXPECTATION AND LIMITATIONS

It was aimed to design a retractable roof structure that could be opened and closed frequently in a short period of time. It was important not to impose any new structural elements that interfere with the function and appearance of the existing building. The proposed retractable roof structure should be able to open partially and fully as required and also be movable in vertical direction in order to change the height of the space as needed. It should allow controlling the light and energy penetration into the building. At the same time it has to be executable, simple and, affordable and be an asset to the TIAU. It should also have the advantage of speed and ease of erection and dismantling. Though this building has been built recently, the main buildings of this university are almost 100 years old and are historically and nationally valuable (Fig.1). In the design process, architectural features and the values of these buildings was taken into account while at the same time the proposed roof was aimed to become an asset to the university and attract visitors. The campus that incorporates this retractable roof cannot only benefit from the advantages gained by deplorability but also from the unique quality and flexibility of the space created.

This retractable roof is supposed to cover the 8*14 square meters space underneath. Since it was asked not to add any additional structural elements that interfere with the appearance of the building, it was important to use light-weight structures. Despite the traditional structures and materials used in the campus, it was decided to design the roof by modern materials and structures as well as use of the form that can not only respond properly to the architectural requirements but also resembles the architectural patterns of Iranian historic architecture. It was necessary to use lightweight structures that are capable of carrying loads and at the same time being used as cover. Due to the performance of the structure, ease of erection and the ability to accommodate with different climatic and formal conditions, the design process, from the very beginning was paralleled with material properties and their functionality. The GFRP membrane fabric was chosen as the main material of the design due to the characteristic explained later in this paper.

Figure 1. Tabriz Islamic Art University. [2].

A. Proposed Structure

Since membrane structures require minimal supporting elements of hard structures and due to its light weight and capability of providing very good level of daylight, it was decided to use it as the main structure of the deployable roof. The proposed retractable roof structure meets the main design requirements as explained earlier including adaptability to various climate conditions associated with the weather of Tabriz and the required functions of the building

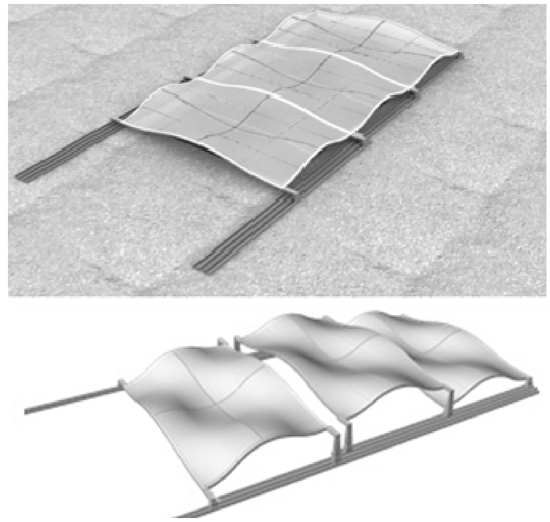
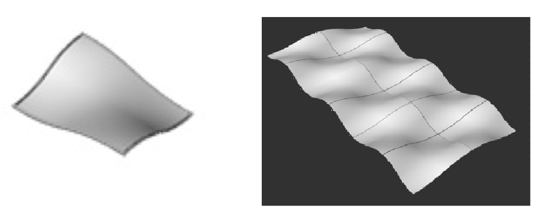


Figure 2. Perspective view of the retractable roof

. This retractable roof structure is realized from saddle-formed membrane structures supported by kinked glass reinforced polymer frame structures. This doubly curved form provides structural stability and stiffness for tensioned membrane due to the effectiveness of its structural behavior. It also can be erected again and again at different places as a result of its lightweight. Figure 2 shows a perspective view of the proposed roof. As shown in figure 3, the roof consists of three main modules while each module itself is achieved from 4 anticlastic sub-sections The saddle shape is used in order to give the membrane the strength to bear both downward and upward loads [4] and increase the stability of the whole system in the harsh climate of Tabriz especially in the winter period. The saddle-shaped membrane also resembles the Iranian ancient patterns and at the same time responds properly to the design requirements and aesthetic considerations. The anticlastic form of the membrane skin gives enough strength to bear heavy loads and also facilitate the collection of the rainwater and the maintenance of the structure. The ponding of rainwater and accumulation of snow on the roof had to be avoided.



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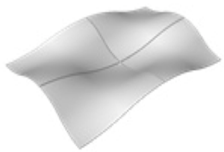

Figure 3. Sub module and main module of the retractable roof

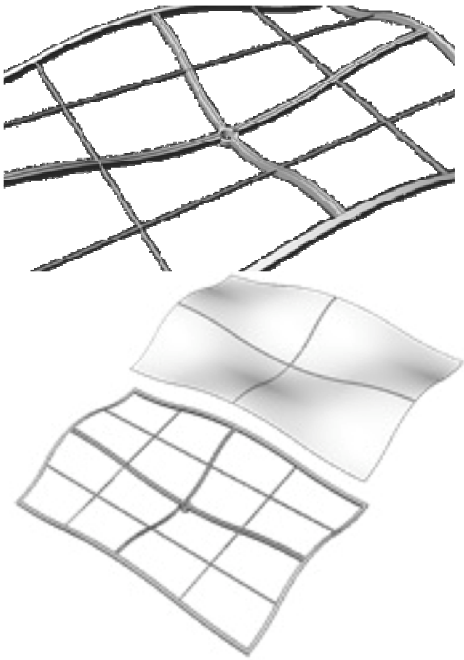

Figure 4. Rainwater collection

The roof form allows fast and easy drainage of water and snow. The doubly curved membrane surface determines the flow of water. Collection and drainage of this water to-ward low point is part of the design scope. The rainwater are collected on the center of each module and transferred to the gutter placed at the center of each module to deliver the water to the gutters placed on the roof (Fig.4).

Each four sub-sections are arranged in a rectangular plan configuration, forming a main module, therefore it's easier to control the movement of the structure. These three main modules are capable of rotation around a horizontal axis in order to provide ventilation as required (fig.5).

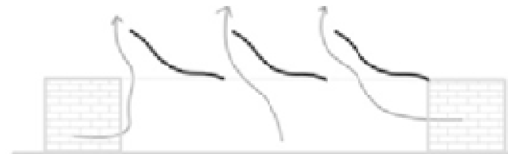

Figure 5. Ventilation provided by module rotation

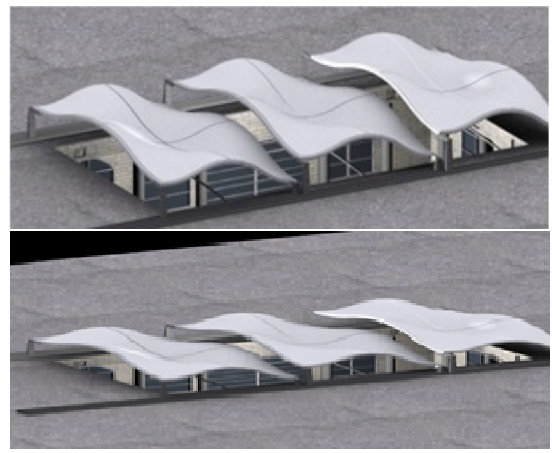

Figure 6. Deployment based on user's ambitions

In order to achieve the fully retracted configuration all three modules should slides over each other on their associated two tracks placed on both longitudinal ends of the courtyard either separately or simultaneously. Twelve hydraulic-operated pistons placed under the main frame of each module provide the upward and downward movement of the modules. In order retract and operate the roof, at first all three modules rotate around a horizontal axis. By doing this, it becomes possible to slide all beams in one direction and prevent interaction. Each module can also operate individually in order to meet environmental changes and user's ambitions (Fig.6).

The modules slide on rail all together toward one side of the roof. When the second module approaches the first one, it moves downward. The same goes with the third module in order to provide a compact bundled configuration. The result would be a retracted configuration. The roof in its fully open configuration transforms to a compact bundle of saddled-form membrane structures attack on top of each other and is stored on one side of the structure as shown in the picture 7. In order to achieve the deployed configuration the same process would be reversed. To increase the height of the roof when it is needed, the three modules move upward by means of pistons placed underneath of each module.

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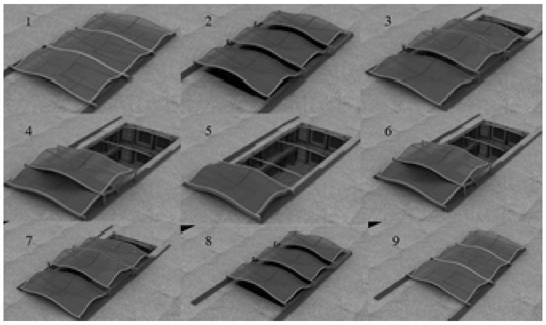

Figure 7. Deployment mechanism

A. Possibilities of changing the scale and further uses

Due to its modularity, it is possible to use the same proposal for smaller or larger retractable roof systems by in-creasing and decreasing the number of segments employed based on the design constrains and requirements. Since fabric structures could be used in most of the world's cli-mate zones and also a large number of different functions due to the capability of copping with a wide range of spans as well as the ability to choose different levels of translucency and in some instances transparent ones, allowing as much or as little natural daylight as required into the place therefore it provides the possibility to use this proposal worldwide [6]. However, it should be considered that any changes in the scale of the modules require recalculation of structural elements and redesign of the operating system. There are three main factors in the design of fabric structures: the choice of surface, level of prestress and sur-face deformability 4[6]. By knowing the applied pressure and the membrane tension, the radius of the curvature could be easily calculated. In the design process by the use of this module, if there are geometric constraints and specific curvature is required, by changes in prestress values, the membrane deflections could be easily controlled in or-der to achieve the desired module. Design values for wind and snow, depending on the site of the project should be taken into account. Choosing the right size of the module as an architectural solution needs to be in scale with the building task in relations to formal, structural aspects as well as economic. It should be noticed that the membrane material should be chosen based on the climate zone of the projects the required level of transparency as well as other functional aspects like Membrane Stress Factor. Figure 8 shows an example of saddle-shaped modules with 8 and 32 sub-modules.

B. Covering material

The form finding and configuration of a fabric membrane employed, as a structural element is different from that of many types of building materials. Their lightweight and versatility in shape and structure provides a great range of dynamic and three-dimensional options and makes their form-finding process more complex. In this research we used fabric as main covering material. The lightness and flexibility of fiber material allows the structure to be carried and deployed. These characteristics are beneficial in the design of retractable roof as it eases the deployment. The fabric used in this project is a woven fiberglass coated with polytetra fluoroethylene (PTFE) due to its structural features and its durability and low maintenance since it is heat resistant and waterproof therefore it diminishes the need for services. PTFE Coated Glass Cloth, which has more than 30 years design life, is the most durable architectural membrane [5]. Light-transition ability, lightness and its life cycle for around 30 years are other criteria that were taken into consideration for selecting this material in this proposal.

C. GFRP (glass-fiber reinforced polymer) as main structural material

In order to counter balance the membrane tension it was important to use a strong enough supporting system to avoid deformed membrane. Conventionally steel or alu-minum are being used as the main structural frame for membrane structures, but due to flexibility, lightness and strength required for retractable panels, GFRP is used as the main structural material. It can be stronger than steel and sheet metals while it is lighter. GFRP was suitable to be used as frame structures and also as beams to support sub modules. By use of this material, the safety of the structure is guaranteed during the heavy snow loads of Tabriz in winter times and it ensure the smooth deployment of the structure due to its lightness in comparison to many con-ventional materials. It is also environmentally tough and doesn't need maintenance afterward.

Figure 8. Possibility to change the number of the modules

III. DETAILING AND CONNECTIONS

It was decided to use rigid edges to achieve the desired

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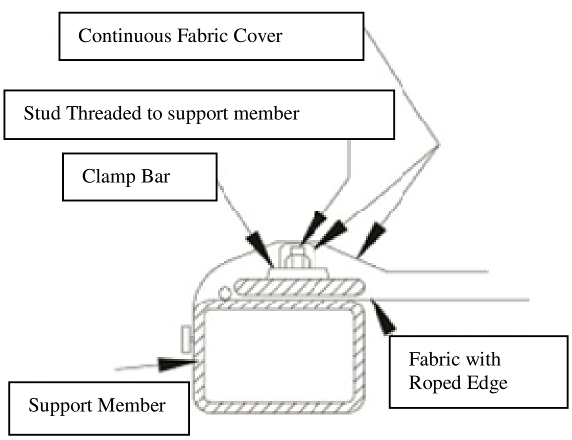
form since it can be rounded and forms continuous warped frame along the perimeter of the membrane. Boundaries in a membrane structure have to be arranged in three dimensions to create double curvature [6].

The rigid structure of the continuous boundary is arranged from curved stiff GFRP and it makes it possible to adjust the form and dimension to provide sufficient strength and stiffness. Termination of a fabric membrane at a rigid edge condition is accomplished by fabric roped edge and clamping hardware. Figures 9 and 10 show the Connection of the membrane to the rigid frame.

By clamping membrane skin in the middle of two kinked GFRP frames, the required saddle-formed roof would be approached and it could be assured that the roof would maintain its shape during the time and the wind load would not affect it easily since the membrane structures are not susceptible to vibration, fatigue, excessive deflection or instability. GRP frame gives the membrane skin the strength to bear heavy loads (Fig.11).

To achieve the retracted configuration, the pistons move on the rails forward while they provide upward movement as well as rotational movement around horizontal axis. It was provided by connecting GFRP beam to the pistons by means of a hinge on each piston (Fig.12, 13). Just the upward and downward movement of the piston could easily control the hinge movements.



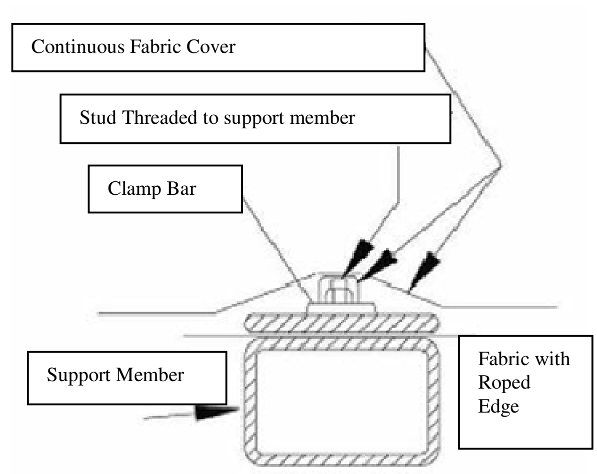


Figure 10.Middle clamping of membrane skin

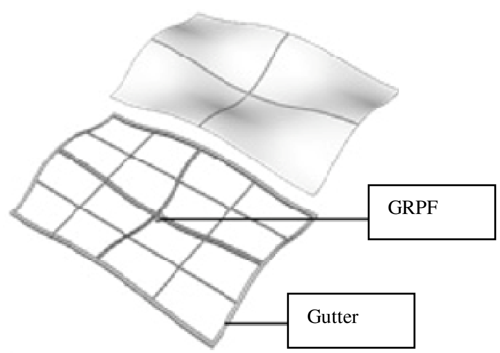


Figure 11. GRP frame structure

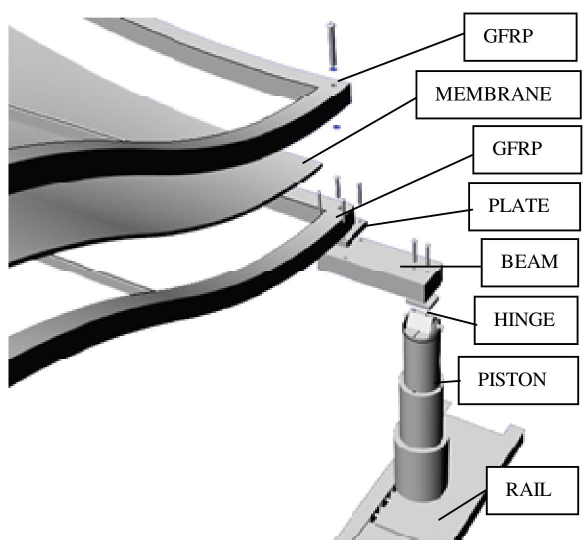


Figure 12. Piston detail

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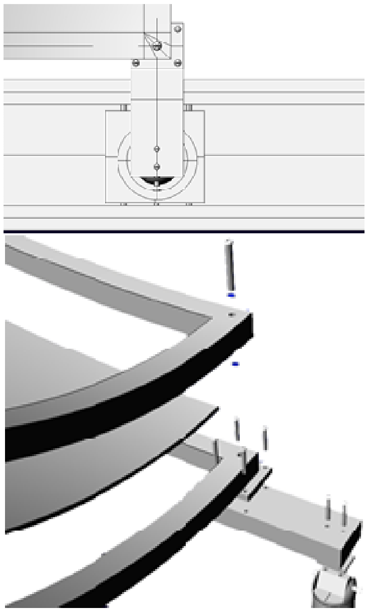

Figure 12. Piston detail

IV. Conclusion

This paper discussed a retractable roof designed to cover a courtyard in TIAU. This retractable roof can be opened and closed frequently in short period of time. It was aimed to design a roof that could be opened and closed partially to provide ventilation when it is needed. Since it was asked not to add any additional elements to the existing building it was decided to use lightweight structure. The saddle-shaped membrane structure was chosen as the module to start the design with since its lightweight and versatility in shape and structure provides a great range of three-dimensional options. This three-dimensional saddle form of the membrane gives it the strength to bear heavy snow loads. It also responds to aesthetical requirements of the project. The GRP frame was chosen as frame structure to increase the load bearing capacity of the retractable roof. The roof reaches its retracted configuration by means of pistons placed underneath each module. Each module can rotate around a horizontal axis by hinge connections that attach each module to the pistons. The roof in its deployed configuration fully covers the roof while in its retracted configuration; it is placed in one side of the roof. It is possible to use the main module of this roof in further designs since it could be easily adapted to different sizes, scales and geometric constraints in order to be used in a wild range of spans and different functions, though changes in details and connections might be needed due to the design requirements.

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(Periodical style)

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