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Innovative Cable Net Curved-Glass Photovoltaic Façade

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Abstract

Building Integrated PhotoVoltaic (BIPV) facades have been present for decades in various forms and building application types. However, they have not yet reached their potential due to the strict technical PhotoVoltaic (PV) requirements, the design and simulation complexity, as well as their limited aesthetics, demonstrated by a lack of visual innovation and customization in comparison with other building elements.

The main objective of this paper is to improve both overall visual effect and building performance through an integrated solar design approach. In order to address these requirements, this paper presents an innovative performance-based design methodology for a BIPV façade. The approach uses parametric design framework to define a typological set of BIPV modules, each with its particular performances, allowing module and performance variation across a façade surface. Therefore, each module can take a specific position in respect to the urban settings and indoor requirements, in order to optimize and improve the overall performance. Moreover, design criteria are not compromised, as this innovative methodology takes into account variable requirements with unique design system that lead to the consistent appearance, and embrace a paneling customization with just a small set of BIPV modules.

This design concept has been demonstrated on a curved-glass BIPV façade that is mounted on a cable-net structure. The result is a high-performance optically dynamic façade, with a smooth and curvy appearance.

Keywords: BIPV, Performance-based design, Solar design, Parametric design framework, Curved glass, Cable-net structure

1. Introduction

The cable net structures found their application firstly in materializing free-form shapes in order to decrease material weight and significantly reduce custom-cut elements and therefore the price. As long as tension principles are respected, the cable nets can be applied to any surface no matter of complexity, whether being single or double curved [1]. This application feature allows a great amount of design freedom on one side and certainty and feasibility on another. Their first application dates back to 1950s while first worldwide known project had appeared in 1972 when Frei Otto and Günther Behnisch finished Munich Olympic Stadium [2] - Figure 1.

Figure 1: Frei Otto and Günther Behnisch - Munich Olympic Stadium 1972

This project presented a cornerstone for the emergence of a very efficient new type of lightweight construction, suitable for small and long spans. Since then, a proven track record has been established thanks to many significant projects, among others Maritime Museum by Gerkan Marg & Partner and Werner Sobek, and Rhön Clinic by Lamm, Weber & Donath and Werner Sobek - Figure 2. They all followed to great extent the idea of combining the two extremely efficient methods of glazing and the steel cable net construction, where uniformly sized “shingled” glass panels are supported by galvanized high-tensile steel cable net of diverse mesh geometry, using standardized stainless steel fittings. Interestingly though, those early applications of cable nets were double-curved surfaces that use the pre-tension to stabilize the structure, against large in-service deflections caused by the complex dynamic behavior under lateral wind loads [3]. In this setting, deflections due to the wind and seismic loads are smaller than those of a comparable planar cable net, because it has been designed as a partially deflected form. Kempinski Hotel in Munich in 1993 represents the first built planar cable-net curtain wall and it was soon followed by other projects, such as Time Warner Center in New York and the Poly Corporation Headquarters in Beijing - Figure 2. Since then, many curtain walls have been built representing the ideal solution for both visual and structural lightness and cost optimal constructions. This paper presents one such case, where an innovative contribution is presented in all part of the curtain wall: grid layout, custom designed cable to glass fasteners and curved glass tiles incorporating Photovoltaic cells.

Figure 2: Poly Corporation Headquarters (left), Rhön Clinic (middle), Maritime Museum (right)

2. Objectives

As buildings consume almost half of the world energy, EU government made initiatives to decrease the energy consumption and the carbon footprint in old as well as new buildings. One such initiative is Energy Performance of Buildings Directive that requires all new buildings to be "nearly Zero Energy Buildings - nZEB" starting from 2020. In order to respond to these high-performance standards, this paper presents an innovative cable net application as the first Building-Integrated PhotoVoltaic (BIPV) curtain wall made of cable net and curved glass tiles. This kind of hybrid façade has both active and passive properties, which are necessary for reaching both the high-energy efficiency and the user comfort. The energy efficiency is achieved through the ability to control the solar heat gains, thus reducing energy consumption as well as producing electricity from PV. Reaching goal of both a high overall building efficiency and the user comfort means finding an optimal balance of these multiple criteria, rather than considering them separately or maximizing a single performance. This approach requires a specific design methodology to overcome incoherent issues. During a recently concluded BIPV project called TIFAIN [4], we analyzed the current market offer that does not well reflect the architects' needs and visions, especially in the terms of PV integration, aesthetics and customization. We have seen here a great opportunity to propose a radically new design concept, able to respond to the increasingly demanding current and future sustainable trends and, consequently, redefine the existing market. Therefore, this paper proposes the most advanced integrative performance-based design methodology, which takes into account multiple criteria such as the high building energy efficiency, the energy generation by PV and the user comfort, to achieve a symbiosis of both outstanding design and high performance in a unique design solution.

The cable net curtain wall is imagined as a façade layer able to address multiple performances at various scales, from local to global. Instead of using standard, float glass shingles that perform the same properties all over the façade, this concept offers a variety of curved glass tiles that enable the mass customization as well as a greater control of different performances. Therefore, the main idea of this façade concept is to merge high-performance with bespoke design and aesthetics in a systemic process of performance-based design, where the performance requirements and the physical properties of light directly influence the geometry and shape of each single tile or façade element. This innovative procedure materializes a design feature that improves performance, rather than decreasing it like in most of the cases. This one of a kind concept makes it very versatile, practical and useful for the range of applications and project requirements. It can be used as the first layer of a ventilated or non-ventilated double skin façades, suitable for new buildings or for adding a new layer in the case of refurbishing. The glass tiles can be also combined to form an Insulated Glazing Unit (IGU), thus making it suitable for a single layer curtain wall.

3. Design innovation

The design methodology starts from designing a typology of façade modules and particularly defining common features and diversification parameters. The façade is designed as a series of a curved, transparent, and medium to large sized complex shape modules that can be made of a transparent glass or plastic with a planar central area, able to be transparent or opaque, depending on the integration of different PV cell technologies and colors - Figure 3. Specifically, the façade modules have a rhomboid-shaped glass with an inner core, where a PV cell is placed. The design feature of the PV rotation creates a curved glass surface that emphasizes smooth reflections and creates façade identity. This property also increases the PV energy generation, owing to the solar concentration on PV and better PV angle setting, as well as controlling the light deflection for improved daylighting and glare. In the case of a transparent central area, module functions as a daylight redirecting device only, while with the PV it also becomes an active façade module that produces energy. This central area can be rotated at several predefined angles that characterize specific properties of each module, manifested in variable sun control in terms of reflection, transmission and absorption of the PV cells. This design feature also allows the variation of aesthetic effects such as colors, transparency, surface curvature and caustics. The standard size makes typology modules able for substitution and customization of layouts that can be defined later in the end-user design process. By combining only several modules with different PV technologies and rotation angles, it would be possible to create various layouts, as so providing custom solutions for a specific urban context and climate, building owner requirements, as well as responding to particular end-user demands.

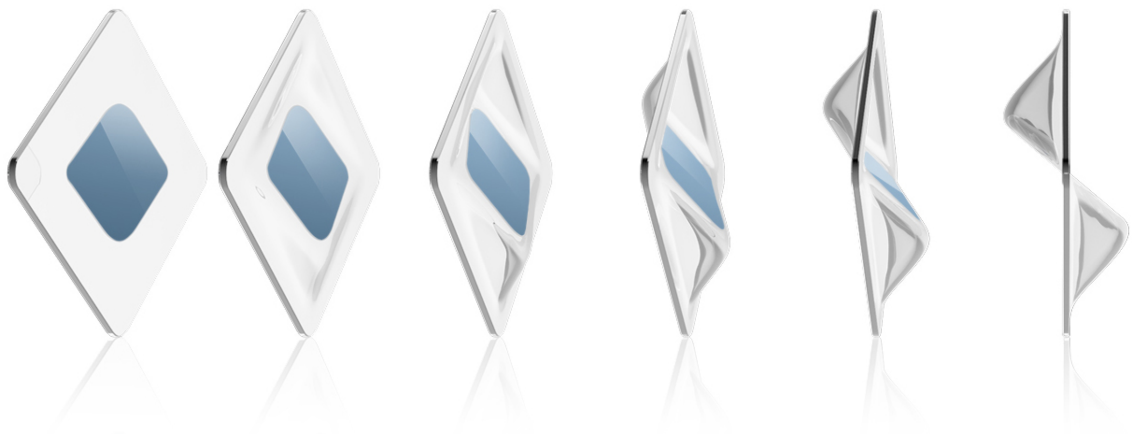

Figure 3: Typology of façade modules

4. Structural innovation

This concept uses a standard two-way cable system with crossing angles of 60 and 30 degrees. This supporting system defines a "diamond" tessellation pattern that matches with the rhomboid shape of glass tiles. The cables are meant to be pre-tensioned to withstand tensile forces greater than 1MPa in both ways. Gravitational loads from the glass tiles are carried through the fittings in the nodes. Due to the custom crossing angle, fittings are custom-made as 4-part stainless steel casting to fix the intersecting cables of the net and support glass tiles in two opposite corners while other two are just held on for disabling rotation but allow in-service deflection - Figure 4. The cable net structure takes an advantage of cable net minimal volume avoiding dense grid aesthetic, typically caused by a glass-supporting aluminum or steel frame structure. Particularly, cable net minimizes the visible structure from the inside and outside and allows more light to enter the interior. Each cable is composed of cold-drawn wires twisted together in a wire strand. The strand consists of individual wires twisted about a central core wire. The wire rope is made by twisting the strand cables about a central core strand. The glass tiles are fastened to fittings through the patch plates and the silicon adhesive bonding and, additionally, they are supported from all four lateral sides - Figure 5. This way of support creates smooth and seamless looking façade from the exterior side, to emphasize the curvature and the reflections and make the transparency of glass the standout feature.

Figure 4: Cable net façade cut-out detail

Figure 5: Structural fitting node detail

5. Glass innovation

One of the most distinct features of this concept is the curved glass. Contrary to the common float glass process that produces flat glass panels, the glass tiles here used are designed for the pressed glass production process (also called hollow glass process). In this process, melted glass is injected into rotational moulds and pressed to form a curved shape. Due to the imperfections caused by heat shock, the glass surface is always slightly wavy. This is used as a design feature as whole glass geometry is composed of curves so imperfections work together with the shape, to express fluidity and distorted reflections. Moreover, a curved glass profile increases the strength, so the glass thickness can be minimized. The glass is additionally strengthened by the heat shock that causes pre-tension inside the glass. Two glass processes could be comparable considering the price, meaning that curve glass aesthetics comes at no price. This is particularly attractive, knowing that bending and shaping flat glass drastically increases the price due to the excessive energy needed for heating the glass, even by a number of times. Therefore, the pressed glass process allows significant energy savings for having curved glass, without re-heating leads to a much more environment-friendly solution. This innovative BIPV curved glass façade concept was specifically designed for LUXION® glass that is completely colorless and has the highest transparency on the market that exceeds 96%. This enables perfect reflections and transparency to maximize sun concentration on PV cells and deflection of the light for daylighting - Figure 6.

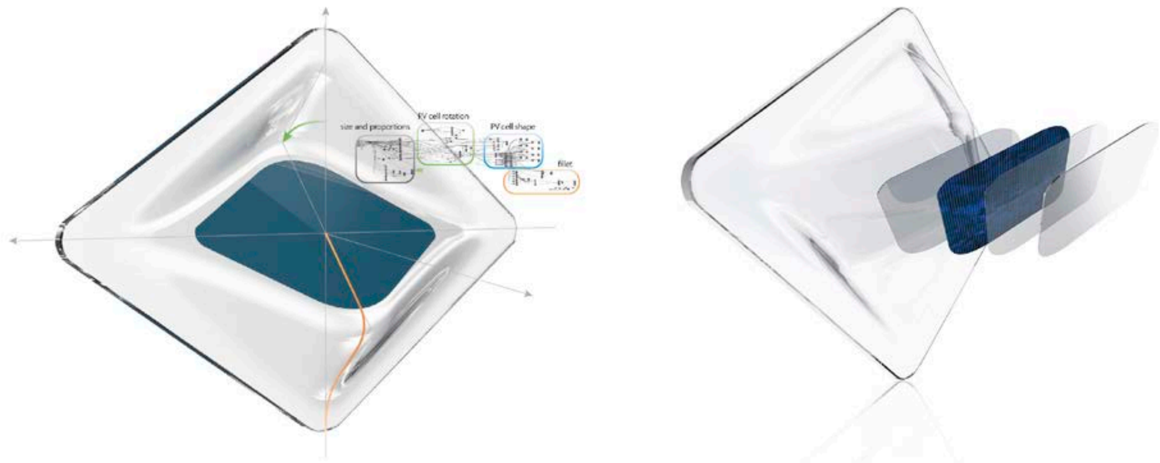

Figure 6: Curved glass tiles

6. Photovoltaics innovation

The rotational feature that creates the glass curvature was specifically designed to produce a semi-concentration effect and increase the amount of solar irradiation on the PV cell surface. As mostly used PV cell type c-Si is very sensitive to the angle setting, the rotation angle should generally correspond to the latitude of the project location and orientation of the façade. Due to the Lambert's cosine law and Fresnel effect [5], rotation of PV cell to optimize sun incident angle can lead to the increase in PV energy potential and generation of up to 45% [6]. Consequently, this solution can produce the same energy as the standard flat glass BIPV vertical façade with less PV surface and significant cost savings. Moreover, as ratio of opaque vs. transparent parts is much higher in favor of transparency, this concept directly improves daylighting and clear views.

The central core of the glass tile is designed as a flat element, as the standard c-Si cells are rigid and do not support bending. However, the flat core also perfectly allows the placing of other types of cells, per example the second and third generation ones, such as thin film and Dye-sensitized solar cells. The uniform size of PV area also enables the mass production and customization, as one tile can be substituted with another. A variety of choices enables the versatility of this design concept to adjust the PV types according to the specific project and the budget requirements, while keeping the design consistency. In other words, the PV integration is here imagined as a benefit for the concept and choice of the cells and the amount of power that could be produced can greatly vary. Even if decided not to include PV, the curved glass still works for the design and daylighting requirements.

7. Conclusion and future work

The concept aims to innovate within interdisciplinary context and propose a unique hybrid type of BIPV and cable nets. It demonstrates a method of transferring multi-criteria requirements from design and performance realms into digital working data that could be handled with parametric and computational approach. This type of data-driven methodology is proved very effective in managing various criteria thus reaching the main objective – high performing and high aesthetic façade solution that actively contributes to the Building Energy Balance.

Despite significant improvements in design and performance, in comparison with standard curtain wall systems, this concept is still in prototype phase and requires prototyping and testing in order to improve operational and maintenance performance. Furthermore, it requires innovative solutions particularly in the field of electrical wiring, nano-inverters and batteries to be able to improve energy conversion, transfer and storage or grid connection. On the other hand, prototyping and testing would uncover possible installing and operational issues, specifically placing new and replacing individual malfunctioning modules, cleaning and maintenance, air tightness as well as wind resistance and dynamical behavior under wind loads.

Due to the specific requirements from the project partners concerning production, this concept explores only pressed glass modules with limit in dimension of around 50cm. Overcoming this limitation in either blending modules in post-production, increasing mold size or considering custom molding during float glass process would additionally improve aesthetic and performance. It will also allow creating many different single or multi-layer solutions for cavity closed, air ventilated and insulating glazing facades. Authors believe that only such a hybrid concept together with numerous design customization options for a relatively small price tag that matches one of common cable nets can really boost the application of BIPV, addressing the high-energy demands.

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