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GEOMETRIC PATTERNS AND DYNAMICS OF FOLDABLE MODULI FOR ADAPTIVE FAÇADES

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Abstract. *The design of buildings with a limited environmental impact and improved energy efficiency is nowadays of fundamental importance to face the challenge of reducing pollution and saving natural resources, without giving up comfort, indoor air quality and well-being. In fact, it is well known that the building industry is one of the largest consumers of material and energy resources and, among the many parts that make up a building, façades are responsible for a huge energy exchange with the surrounding environment. Therefore, both the research world and industry are very interested in effective solutions for smart and climate adaptable façades. A variety of concepts and solutions, which are competing with each other, have indeed already been developed. However, the field is not yet mature and an increase in emerging and innovative solutions is expected and requires future research and further challenges to be addressed. Recent studies have paid attention to the mechanics of folding sunscreens made with origami panels activated by stretching or releasing strings, following the tensegrity design philosophy. The present contribution is aimed at promoting innovative technological solutions based on the study of new models for foldable façade modules, paying attention to geometric patterns, deployability and mechanical properties.*

Keywords: Tensegrity, Solar Façades, Mashrabiya, Deployability, Dynamic Response.

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1 INTRODUCTION

One of the main challenges that contemporary architecture and civil engineering have to face is the construction of sustainable buildings with high energy efficiency, capable of limiting their environmental impact by minimizing the pollution they produce and the consumption of natural resources. It is well known, in fact, that the building industry is among the largest consumers of material resources and energy, accounting for about 40% of final energy consumption in the European Union (EU) [1]. Sustainability is thus among the main objectives of Horizon 2020 [2], the EU program for research and innovation. The challenge of the EU is maintaining the current standards of living while decreasing the energy dependence on fossil fuels and reducing CO_2 emissions by between 80% and 85% compared to 1990 [3].

Since the energy consumption of buildings is mostly related to air conditioning and domestic hot water, electricity and gas [4], increasing importance has been given to the concept of energy efficient buildings (EEBs), able to guarantee a condition of well-being inside, minimizing the use of non-renewable energy sources, through the integration of "active" and "passive" typological solutions. Among the many parts that make up a building, façades are responsible for a huge energy exchange with the surrounding environment. Hence, to save energy, the building envelope must perform more than the simple function of separating the external space from the inside, with insulation. The envelope is thus assigned the task of regulating the energy flow related to the passage of heat, the transmission of light and solar radiation and minimizing energy consumption due to air conditioning. Therefore, both the research world and industry are very interested in effective solutions for smart and climate adaptable facades. A variety of concepts and solutions, as for instance double envelope systems, which are considered with increasing interest in the EEB design [5, 6], have indeed already been developed. However, the field is not yet mature and an increase in emerging and innovative solutions is expected and requires future research and further challenges to be addressed [7]. Recent studies have paid attention to the mechanics of folding sunscreens made with origami panels activated by stretching or releasing strings, following the tensegrity design philosophy [8]. Glazing systems with morphing capabilities controlled by pairs of superelastic cables reversibly actuated against each other have also been considered, where superelasticity is also exploited to improve the structural behavior of the façade system subjected to wind loads [9]. The possibility of harvesting energy under the action of wind loads or partially recovering energy from the folding/unfolding mechanism has also been considered in the literature [10].

The present paper, which is focused on dynamic solar screens and shading systems for façades improving energy performance of buildings, is organized as follows. In Sect. 2, we briefly report about two of the existing state-of-the-art dynamic solar shading systems. Then, Sect. 3 is devoted to the operating principles of tensegrity structures and the possible advantages in using them as building envelopes. Basics on dynamics and foldability of tensegrity are reported in Sect. 4. Finally, some remarks given in Sect. 5 conclude the paper.

2 STATE OF THE ART OF DYNAMIC SOLAR FAÇADES

The present section is devoted to a brief description of two significant examples of adaptive dynamic façades, that indeed constitute the state of the art of contemporary architectural research about the building envelope, that, over time, has been transformed from a static and energetically passive element into a dynamic, permeable, and selective interface, designed to adapt to changes in external environmental conditions and positively affect the thermo-hygrometric and environmental parameters that guarantee comfort of users. Both examples are interesting, modern reinterpretations of the traditional, wooden shading façades, the so-called "mashrabiyas" [11], common in Arab culture. Mashrabiyas are able to filter the light and control the air flow to reduce the temperature and increase the humidity of the internal environments of a building.

The first example we consider is the building of the Institut du Monde Arabe (IMA). Located in Paris, France, the building of the IMA, designed by Jean Nouvel, Pierre Soria, Gilbert Lezénés and Architecture Studio, has become a fundamental reference for dynamic façades. In particular, the rectangular, south-west façade of IMA is a lattice made up of square modules equipped with motorized steel diaphragms, connected to photosensitive sensors. The diaphragms open and close every hour to regulate the amount of natural light that enters the building, resulting in a dynamic shading system. It is emphasized in [12], to which we refer for further details, that the adaptive façade of the IMA exemplifies the strengths and limitations of mechanically operated designs.

The second example is the adaptive dynamic façade of the Al Bahar Towers, located in Abu Dhabi, where the climate is very hot and humid, especially in the summer, with up to 100% humidity and temperatures that reach 50°C, thus making a cooling system an equipment of paramount importance for buildings. The cooling of the glass façades of the buildings is guaranteed by a system of panels activated by low consumption electric linear actuators and which dynamically responds to the position of the sun during the day. The result is a scalable hexagonal shading device that acts as a solar barrier. This shading system allows the building to reach and maintain optimal thermo-hygrometric well-being, protecting the inhabitants from the glare of the sun rays and, at the same time, guaranteeing the right privacy. The shading system is based on modules made of six panels, coated in polytetrafluoroethylene (PTFE), mounted on a supporting structure made up of duplex stainless-steel frames [13, 14].

3 TENSEGRITY SOLAR FAÇADES

The design of active solar façades may exploit the advantages of tensegrity paradigm, that leads to light, deployable and foldable structures. If well designed, the core module quickly becomes scalable and is capable of being replicated to generate large-scale patterns.

Among the many different possible definition of "tensegrity", the most widely accepted [15] is that can be given by quoting words by Motro [16], i.e. "tensegrity system is a system in a stable self-equilibrated state comprising a discontinuous set of compressed components inside a continuum of tensioned components."

Theoretical and experimental studies [17] have highlighted that lightness, modularity, synergy, self-stability, fractal properties, enantimorphism, distributability and foldability are typical characteristics of tensegrity structures.

In particular, foldability makes tensegrity structures useful in many applications in which transport and storage must be considered. For instance, in the field of extra-terrestrial applications, transport costs, lightness of materials and optimization of the available space are of paramount importance [16].

The tensegrity structural paradigm can be exploited at different levels in the design of EEBs, since tensegrity assemblies are minimum mass structures able to carry many different load conditions, including compressive, tensile (under given stiffness constraints) and torsional loads without yielding and instability phenomena [18–20].

Thanks to their special ability to act as extremely light systems with "morphing" abilities [8, 21–24], tensegrity structures allow designing dynamic solar screens leading to a limited use of materials accompanied by a low level of energy consumption. A tensegrity reinterpretation of the system adopted in Al Bahar Towers is considered in [8, 25].

Furthermore, tensegrity-based dynamic faądes can also be exploited to harvest energy from the environment, by converting mechanical energy stored in strings into electrical energy [10, 21, 26] or from solar panels, that can be endowed in the structure and modeled as special rigid members [21, 27].

Finally, tensegrity lattices may be designed to operate as multi-scale actuators, capable of transferring energy through compact solitary waves thanks to their highly non-linear dynamic behavior [28–31].

4 DYNAMICS AND DEPLOYABILITY

This section illustrates a model for the numerical simulation of the dynamics of tensegrity systems. The procedure, already applied to solar façades in [32], with appropriate changes generalizes that presented in [33, 34] to account for the presence of wind forces [10, 35, 36].

Let us assume that the tensegrity structure is composed of n_n frictionless nodes, n_b straight, uniform, rigid bars, and n_s elastic strings, which carry only tensile forces.

The positions of nodes $\mathbf{n}_i \in \mathbb{R}^3$, $i \in [1, \ldots, n_n]$, and external forces acting on them are respectively stored in node an load matrices

$$\mathbf{N} = \begin{bmatrix} \mathbf{n}_1 & \mathbf{n}_2 & \cdots & \mathbf{n}_i & \cdots & \mathbf{n}_{n_n} \end{bmatrix} \in \mathbb{R}^{3\times n_n}\,, \tag{1}$$

$$\mathbf{W} = \begin{bmatrix} \mathbf{w}_1 & \mathbf{w}_2 & \cdots & \mathbf{w}_i & \cdots & \mathbf{w}_{n_n} \end{bmatrix} \in \mathbb{R}^{3\times n_n}\,. \tag{2}$$

By calling $\mathbf{b}_i$ and $\mathbf{s}_i$ the vectors connecting the end nodes of the i^{th} bar and i^{th} string, respectively, and $\mathbf{r}_i$ the position vector of the center of mass of the i^{th} bar, all of them are grouped in matrices

$$\mathbf{B} = \begin{bmatrix} \mathbf{b}_1 & \mathbf{b}_2 & \cdots & \mathbf{b}_i & \cdots & \mathbf{b}_{n_b} \end{bmatrix} \in \mathbb{R}^{3\times n_b}\,, \tag{3}$$

$$\mathbf{S} = \begin{bmatrix} \mathbf{s}_1 & \mathbf{s}_2 & \cdots & \mathbf{s}_i & \cdots & \mathbf{s}_{n_s} \end{bmatrix} \in \mathbb{R}^{3\times n_s}\,, \tag{4}$$

$$\mathbf{R} = \begin{bmatrix} \mathbf{r}_1 & \mathbf{r}_2 & \cdots & \mathbf{r}_i & \cdots & \mathbf{r}_{n_b} \end{bmatrix} \in \mathbb{R}^{3\times n_b}\,. \tag{5}$$

Let us introduce the connectivity matrices of bars $\mathbf{C_B} \in \mathbb{R}^{n_b\times n_n}$, cables $\mathbf{C_S} \in \mathbb{R}^{n_s\times n_n}$, and centers of mass $\mathbf{C_R} \in \mathbb{R}^{n_b\times n_n}$. The generic $(i,j)^{\text{th}}$ entry of $\mathbf{C_B}$ (or of $\mathbf{C_S}$) takes values -1 or 1, if $\mathbf{b}_i$ (or $\mathbf{s}_i$) is directed away from, or toward node j^{th}, respectively, or 0 if $\mathbf{b}_i$ (or $\mathbf{s}_i$) does not touch node j. Similarly to $\mathbf{C_B}$ and $\mathbf{C_S}$, matrix $\mathbf{C_R} \in \mathbb{R}^{n_b\times n_n}$ is a connectivity matrix. Its i^{th} row stores the bar $\mathbf{b}_i$ and its $(i,j)^{\text{th}}$ entry takes values 1/2, if $\mathbf{b}_i$ touches node j, or 0, otherwise [37]. The connectivity matrices allows rewriting Eqns. (3)–(5) as

$$\mathbf{B} = \mathbf{N}\mathbf{C}_\mathbf{B}^\mathbf{T}\,, \tag{6}$$

$$\mathbf{S} = \mathbf{N}\mathbf{C}_\mathbf{S}^\mathbf{T}\,, \tag{7}$$

$$\mathbf{R} = \mathbf{N}\mathbf{C}_\mathbf{R}^\mathbf{T}\,. \tag{8}$$

The matrix equation of motion of a tensegrity system is written as [38]

$$\ddot{\mathbf{N}}\mathbf{M} + \mathbf{N}\mathbf{K} = \mathbf{W}\,, \tag{9}$$

where $\mathbf{N}$ and $\mathbf{W}$ have been already defined by Eqn. (1) and Eqn. (2), respectively, $\ddot{\mathbf{N}}$ stands for the second derivative of $\mathbf{N}$ with respect to time, $\mathbf{M}$ is the mass matrix and $\mathbf{K}$ is the stiffness matrix. The last two are computed as

$$\mathbf{M} = \frac{1}{12}\mathbf{C_B}^T\hat{\boldsymbol{m}}\mathbf{C_B} + \mathbf{C_R}^T\hat{\boldsymbol{m}}\mathbf{C_R} \in \mathbb{R}^{n_n \times n_n}\,, \tag{10}$$

$$\mathbf{K} = \mathbf{C_S}^T\hat{\boldsymbol{\gamma}}\mathbf{C_S} - \mathbf{C_B}^T\hat{\boldsymbol{\lambda}}\mathbf{C_B} \in \mathbb{R}^{n_n \times n_n}\,, \tag{11}$$

where $\hat{\boldsymbol{m}} \in \mathbb{R}^{n_b \times n_b}$ and $\hat{\boldsymbol{\gamma}} \in \mathbb{R}^{n_s \times n_s}$ are diagonal matrices. The generic entry $(i,i)^{\text{th}}$ of $\hat{\boldsymbol{m}}$ is the mass m_i, $i \in [1,\ldots,n_b]$ of the i^{th} bar, while entry $(i,i)^{\text{th}}$ of $\hat{\boldsymbol{\gamma}}$ stands for the force density γ_i, $i \in [1,\ldots,n_s]$ along the i^{th} string, given by

$$\gamma_i = \max\left[0, K_i\left(1 - \frac{L_i}{s_i}\right)\right] + \gamma_{ci}\,, \tag{12}$$

where K_i, L_i, and $s_i = \|\mathbf{s}_i\|$ are the axial stiffness, the rest length, and the current length of the string, respectively, and γ_{ci} is the damping force density, computed as

$$\gamma_{ci} = \begin{cases} c_i\dfrac{\dot{s}_i}{s_i}\,, & \text{if } s_i \geq L_i\,, \\ 0\,, & \text{otherwise.} \end{cases} \tag{13}$$

The diagonal matrix $\hat{\boldsymbol{\lambda}} \in \mathbb{R}^{n_b \times n_b}$ in Eqn. (11) collects force densities in bars and is given by

$$\hat{\boldsymbol{\lambda}} = -\frac{1}{12}\left\lfloor \dot{\mathbf{B}}^{\mathbf{T}}\dot{\mathbf{B}} \right\rfloor \hat{\boldsymbol{m}}\hat{\boldsymbol{\ell}}^{-2} - \frac{1}{2}\left\lfloor \mathbf{B}^T\left(\mathbf{W} - \mathbf{S}\hat{\boldsymbol{\gamma}}\mathbf{C_S}\right)\mathbf{C_B^T} \right\rfloor \hat{\boldsymbol{\ell}}^{-2}\,, \tag{14}$$

where $\hat{\boldsymbol{\ell}}^{-2} \in \mathbb{R}^{n_b \times n_b}$ is a diagonal matrix, whose entries are $\ell_k^{-2} = \|\mathbf{b}_k\|^{-2}$, and $\lfloor \mathbf{A} \rfloor$ is a matrix keeping the diagonal terms of the generic square matrix $\mathbf{A}$, while all the off-diagonal entries are set to zero.

The stiffness matrix $\mathbf{K}$ is not constant, being a function of time and the mechanical variables $\mathbf{N}$, $\dot{\mathbf{N}}$, and $\hat{\gamma}$, i.e. $\mathbf{K} = \mathbf{K}(t, \mathbf{N}\dot{\mathbf{N}}, \hat{\gamma})$.

The numerical integration of Eqn. (9) is made by employing the algorithm described in [33, 34], which is based on fourth-order Runge-Kutta schemes.

As a basic module of a façade one can consider the deployable structure reported in Fig.1, which is a tensegrity system of class 6, meaning that the maximum number of bars concurring in each node is at most 6 (see the classification introduced in [18]).

5 CONCLUDING REMARKS

The present contribution aims to promote innovative technological solutions to design shading façades of energy efficient buildings through tensegrity systems, which can also be exploited as actuators to orient solar panels and as devices to harvest the wind-generated energy.

Recent studies have paid attention to the mechanics of tensegrity sunscreens activated by stretching or releasing strings, also exploring the possibility of wind energy harvesting. Glazing systems, with morphing capabilities, actuated with superelastic strings have also been considered in literature.

Future research in the field of tensegrity structures will focus on the possibility of using composite materials to design of dynamic shading façades, also using rapid prototyping of different architectural shapes through 3D and 4D printing technologies, at laboratory and full scales.

In conclusion, lightness, controllability and even the high artistic value of tensegrity structure are distinguished characteristics that can be exploited in the near future applications to building faądes. Research in the field of tensegrity applied to buildings must necessarily take into account functionality and eco-sustainability.

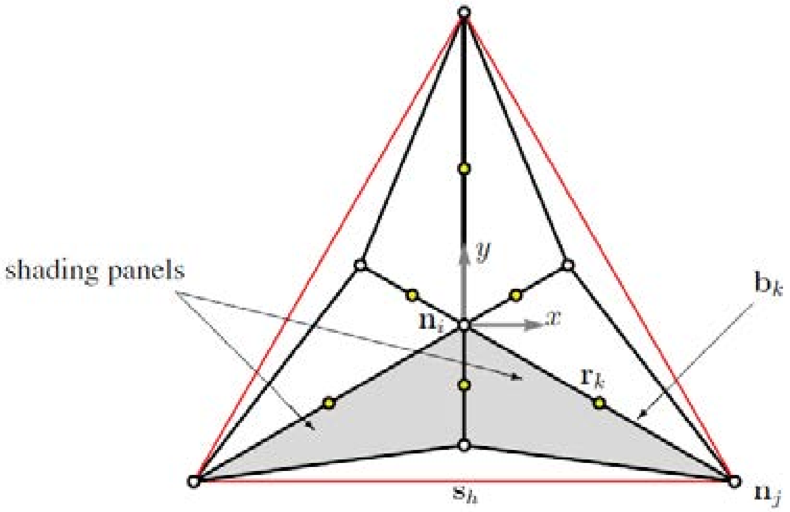

Figure 1: Schematic view of a foldable class 6 sunscreen tensegrity system: nodes are depicted as white disks (as $\mathbf{n}_i$ and $\mathbf{n}_j$); red colored members are strings (as the generic $\mathbf{s}_h$); black colored members are bars (as $\mathbf{b}_k$); yellow disks (as $\mathbf{r}_k$) stand for centers of mass of bars.

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