Composite solar façades and wind generators with tensegrity architecture

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Abstract

The urgent need for sustainable buildings calls for the adoption of active building façades that harvest wind and solar energy through on-site wind power generators and solar panels. Particularly interesting is the use of tensegrity structures for the construction of renewable energy supplies, due to their easy integration with solar and acoustical panels, which can form special rigid members of the structure. The present study deals with the design of active façades based on tensegrity units, which supports shading devices and/or solar panels. The tensegrity units are foldable and deployable and are controlled by stretching or relaxing selected cables. Wind generators to convert the strain energy stored in the cables of wind-excited units into electrical power are also designed. The proposed structures offer portable applications for small spans and are easy to assemble using prefabricated component parts in the case of large spans.

1. Introduction

Sustainable building is one area where innovation is constantly being challenged. At present the hardest goal is transforming the current situation where the construction sector has high fossil fuel consumption, is one of the largest producers of non-reusable waste and one of the biggest polluters. In fact, the environmental impact of building design and construction is enormous: in Europe buildings are responsible, directly or indirectly, for approximately 40% of total primary energy consumption and for around 36% of CO2 total emissions [1,2]. The European Union is imposing increasingly stringent obligations on member countries in terms of energy efficiency and reduction of climate-altering emissions [3].

Sustainability criteria can minimize or eliminate negative environmental impacts through a conscious choice of design and constructive practices better than those commonly in use. This design approach allows a reduction in operating costs, an increase in market value and users' productivity [4]. Therefore, sustainable design means taking into account (in addition to traditional requirements of security, usability, comfort and management) a number of new requirements related to general building design (shape, floor plan, equipment and distribution), to systems, to building a life cycle (flexibility and reversibility of technological conception) and to indoor comfort [5].

A recent study has investigated the use of tensegrity structures for the construction of active solar façades of Energy Efficient Buildings (EEB) [6]. A tensegrity structure (or system) consists of a rigid body system (tensegrity configuration), usually loaded in compression, which is stabilized through the insertion of prestressed tensile cables (or strings) between its elements [7]. Some of the main advantages deriving from the use of tensegrity architectures in EEBs are the following:

- it has been shown that the tensegrity architecture provides minimal mass structures for a variety of loading conditions, including structures subject to cantilevered bending load; compressive load; tensile load (under given stiffness constraints); torsion load; and simply supported boundary conditions (e.g. a bridge), without yielding and buckling [7–9];
- the special ability of the tensegrity architecture in integrating control functions within the design of the structure: in controlled tensegrity systems the mechanics of the controller...
and the structure can naturally cooperate, through the change of the configurational equilibrium of the structure, as opposed to traditional control systems, where often the control pushes against the equilibrium of the structure [11];

- the possibility to look at a tensegrity building as a multiscale sensor/actuator, which in particular features highly nonlinear dynamical behavior [12–15];
- the possibility to harvest energy from the environment (such as, e.g., wind and seismic energy), through the conversion of the mechanical energy stored in the structure into electric energy [16,17];
- the possibility to construct controllable tensegrity façades, wings, and ventilated walls around the building [6];
- the easy integration of tensegrity structures with solar and acoustical panels, which can be identified with special rigid or deformable composite members of the structure [6,7,18–22].

The present work continues the study initiated in Ref. [6], by proposing a methodology that supports the development of the design and construction process of new façade components with tensegrity architecture (see the discussion in Sect. 2). The concept of the examined tensegrity façade system, whose activation motion mimics the dynamics a blinking sail, is presented in Section 3. In Sect. 4 the activation mechanisms of an elementary module of such a structure is presented. The uses of the proposed façade system as a dynamic sun-screen or a wind-energy harvesting device are respectively illustrated in Sects. 5 and 6. The main conclusions of the present study and directions of future work oriented to the application of tensegrity architectures to design of next-generation façades of EEBS are given in Section 7.

2. From structure to envelope

In order to create artificial places in which to conduct the primary activities of living, human beings have developed increasingly complex envelope systems and components capable of ensuring living conditions fitting each room. Over time architecture has therefore evolved from a simple shelter from the elements (rain, wind, sun, intrusion of people or animals, cold, hot, etc.) to an element representative of society (thanks to formal and material solutions), to an indoor comfort control system (through quantity and quality of light, ventilation, heating and cooling).

The envelope has moved from being an energetically passive to a dynamic and interactive element of the complex energy system that regulates building operation. The gradual freeing of the outer skin from a structural function has had the inevitable consequence of a split between envelope and structure. The envelope is released from the load-bearing structure and becomes a closure element used mainly to adjust energy flows linked to the passage of heat, light transmission for adequate illumination of the interior and the protection of the solar radiation in the months with higher temperatures.

An overview of the constructive scene shows that new types of double skin smart envelope must be able to form any kind of shape, even the most complex, as well as protecting the external surfaces of the building from sunshine.

The demand for energy efficient buildings calls for the adoption of active façades that are able to mitigate air conditioning consumption resulting from direct exposure to solar rays, as well as harvest wind and solar energy through on-site wind power generators, integrated photovoltaic systems, and/or solar hot water panels. The dynamic façade system is an innovative solution that meets the current market needs in the building envelope sector. In the last few years, this market sector has been rapidly developing owing to the possibility to harvest energy from the environment (such as, e.g., wind and seismic energy), through the conversion of the mechanical energy stored in the structure into electric energy [6,7,18–22].

4. Activation mechanism

Let us examine the motion of the blinking sail elementary module described in the previous section, which is produced by applying suitable elongations to the cables 1–3 and 3–5. At the current time $t$, the elongation rate of the $m$-th element connecting nodes $i$ and $j$ is given by the compatibility equation.

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\[ \dot{u}_m = (\vec{u}_j - \vec{u}_i) \cdot \vec{a}_m \]  

(1)

where \( \vec{u}_i \) and \( \vec{u}_j \) denote the velocity vectors of the nodes \( i \) and \( j \), respectively; \( \vec{a}_m \) is the unit vector parallel to segment connecting such nodes (pointing towards node \( j \)); and \( \ell_m \) is the current length of the element.

Upon assembling the free (i.e., unconstrained) Cartesian components of the velocities of all the nodes into a global velocity vector \( \vec{q} \), and the elongation rates in all the bars and cables into a vector of control variables \( \vec{e} \), we can rewrite the compatibility equations of the overall structure into the following matrix form

\[ B \vec{q} = \vec{e} \]  

(2)

where \( B \) denotes the instantaneous kinematic (or compatibility) matrix [6].

Let us now consider a prescribed time history \( \vec{e} = \vec{e}(t) \) of the control variables. The motion generated by such an actuation strategy of the structure is computed from the integral equation

\[ \vec{q} = \int_{0}^{t} \vec{q}(t) \, dt = \int_{0}^{t} B^{-1} \vec{e} \, dt \]  

(3)

where \( B^{-1} \) is the inverse of the kinematic matrix \( B \) in correspondence with the current configuration of the structure, which it is assumed exist.

The examined actuation mechanism of the blinking sail module is illustrated in Fig. 3. It is generated by actuating the cables 1–3 and 3–5, through the application of the elongation histories indicated in correspondence with the different panels of Fig. 3. The remaining members of the module remain unstretched during the motion of the structure illustrated in Fig. 3. By suitably changing the tension in the cables 1–3 and 3–5, it is seen from such a Figure that the nodes 3 and 5 moves outward along the z-axis (with respect to the building surface), while nodes 2 and 4 move in the x-y plane by producing the folding of the module, whose deformation resembles that of a sail inflated by the wind. The aspect angles of the module initially assume the values \( \alpha = 0 \) and \( \beta = 45^\circ \) (top-left configuration in Fig. 3), as we already noticed, and assume the values \( \alpha = 45^\circ \) and \( \beta = 38^\circ \) in the fully folded configuration.

5. Blinking sail solar façade

The activation mechanism illustrated in Fig. 3 is at the basis of the solar façade system illustrated in Figs. 4 and 5. Such a smart skin of an EEB consists of several rhombus-shaped elementary modules assembled together. The modules are dynamic and can change configuration according to the actuation mechanism in Fig. 3, by
modifying the shading properties of the envelope. Fig. 4 shows the fully-closed configuration of the blinking sail solar façade, while Figs. 5 and 6 shows partially- and fully-open configurations.

The blinking sail screens are composed of by a collection of foldable (“origami”) eyes (rhomboidal modules) equipped with bendable, composite photovoltaic modules in correspondence with the perimeter bar elements [18–21], and/or fiber-membrane sails [22]. Such modules are opened (i.e., folded out) at night, and are progressively closed during daylight hours, through the actuation strategy illustrated in Sect. 4. The screens are designed to reduce the solar irradiation of the served building, and to produce marked decreases in air conditioning consumption. The implementations show in Figs. 4 and 5 refer to a potential application of the blinking sail solar façade in the campus of the University of Salerno (Fisciano, Salerno).

6. Blinking sail wind energy harvester

The blinking sail wind energy harvester consists of a system of foldable modules similar to that of the façade illustrated in the
previous section, which is now designed to convert wind-induced motion of a membrane attached to the generic module into electrical energy. The blinking sail module is formed in this case by all stretchable elements (strings) attached to a rigid truss protruding from the served building (cf. Figs. 7 and 8). Such cables are connected to a fiber-reinforced membrane sail [22] that is inflated by the wind. Additional cables attached to the module wrap around a generator rotor (Fig. 7). The wind-flow induced elongations of such cables rotate the generator, creating power for immediate use of the served building, to operate solar façades, etc. In addition, the aeroelastic flutter of the wind-excited membrane, eventually equipped piezoelectric or electromagnetic actuators, can be employed to harvest supplementary energy from wind [16,17].

Fig. 7 shows the functional diagram of the elementary module of the wind-energy harvesting façade, which is inspired by the wave-powered station-keeping illustrated in Chapter 1 of reference [7]. Fig. 8 instead illustrates potential applications of the blinking sail wind energy harvester in correspondence with blind façades of residential buildings serving the campus of the University of Salerno (Fisciano, Salerno).

7. Concluding remarks and future work

We have formulated tensegrity solutions for the design of active façades that are able to harvest wind and solar energy through on-site wind power generator, and offer portable applications for small...
spans and in the case of large spans can be easily assembled using prefabricated components.

The adoption of active shading façades allows the reduction of energy consumption and significantly reduce carbon dioxide emissions of buildings. The proposed tensegrity sun screens are opened and closed by controlling the elongation in a limited number of cables (cf. Sect. 5). Such screens are controlled by stretching or relaxing selected cables, and are used to orient the solar panels towards the sun, and/or to build innovative wind generators, which convert the strain energy stored in the cables of wind-excited units into electrical power. The elongations of the cables rotate an external generator, creating power for the operation of the building (Sect. 6).

A new tensegrity façade system that we address to future work will be designed like a fish scale envelope (Fan-Fish System, cf. Fig. 9). In most biological nomenclature, a scale is a small rigid plate that grows out of an animal’s skin to provide protection. The skin of most fishes is covered with scales that are partially superimposed. We aim at the design of an active shading system structured like fish skin. Such a skin like structure would be extremely suitable to form a curtain wall of a few metres that can be placed over the building façade. Each scale would be shaped like a fan in order to allow the opening and the closing of the system, which would make...
the solar screens adaptive (Fig. 10). Furthermore it would be possible to place solar panels on the fan slats. Some initial prototypes of elementary modules of a fan-fish solar facade are illustrated in Fig. 10.

Additional future research lines include the design of different deployment schemes and the optimal design of polyhedral envelopes of energy efficient buildings, to be carried out by combining parametric design approaches [8–10] with energy optimization techniques [6]. The use of additive manufacturing techniques and recycled materials for the design and fabrication of next generation of solar facade also awaits attention [33–41], with the aim of developing sustainable kinetic membranes and panels with high thermal insulation properties.

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References