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# INNOVATIVE STRUCTURES FOR DYNAMIC SOLAR FAÇADES

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**Abstract.**

*Recent studies have investigated the use of tensegrity structures for the construction of active solar façades of Energy Efficient Buildings (EEBs). The present work moves along such lines by proposing a methodology that supports the development of the design and construction process of new façade components with tensegrity architecture. The activation motion of the examined tensegrity façade system mimics the dynamics a blinking sail. The use of the proposed façade system as a dynamic sun-screen or a wind-energy harvesting device is presented, with the aim of illustrating the application of tensegrity architectures to the design of next-generation dynamic solar façades of EEBs.*


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## 1. INTRODUCTION

A civil structural system is composed of the design of: structures; HVAC (heating, ventilating and air conditioning) system; electrical system; sighting design; etc. Such systems have traditionally been designed in the order listed, in sequence. Modern building technology must be more efficient and sustainable, both in construction and in operation [1]-[5].

Recent studies have investigated the use of tensegrity structures for the construction of active solar façades of Energy Efficient Buildings (EEB), by profiting of the special ability of tensegrity structures in serving as controllable, deployable, and smart systems [6]-[12].

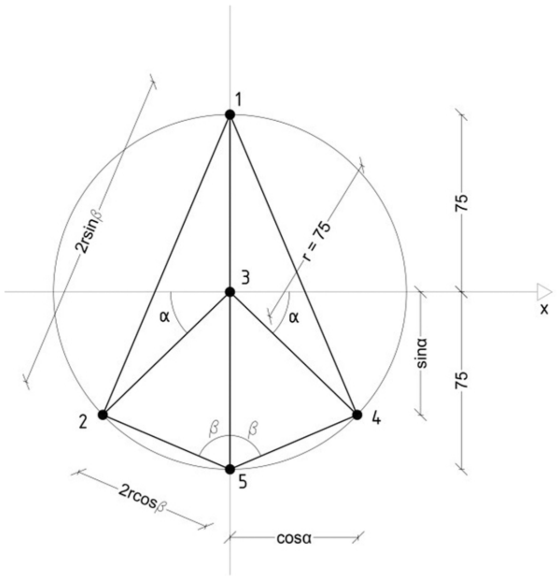
The present work moves along the lines of the research presented in Refs. [6]-[7], by proposing a methodology that supports the development of the design and construction process of new façade components with tensegrity architecture. The uses of the proposed tensegrity façade system as a dynamic sun-screen or a wind-energy harvesting device are discussed through mechanical and technological arguments. We close by outlining directions of future research devoted to exploit the use of tensegrity concepts within innovative façades of energy efficient buildings.

## 2. DESIGN AND OPERATION OF A DYNAMIC SOLAR FAÇADE WITH TENSEGRITY ARCHITECTURE

Adaptive architecture must be considered the future of contemporary architectural research because it can decrease the energy balance of buildings by controlling thermal energy, light energy and sound waves [13]. This research aimed to identify design principles and operative tools for the design and production of innovative building envelopes that could integrate renewable energy, in form of photovoltaic and solar thermal panels.

Sunscreens absorb and reflect incident solar radiation but cannot transfer solar heat gain directly into the building. When sun screens transform incident sunlight into electricity for immediate use or transmit thermal energy into the building by use of electrical or mechanical equipment, they are called opaque sunscreens and form part of an active solar façade. In this research, we designed two innovative prototypes according to the fundamentals of the tensegrity structural system [8].

The façade system that we study in this work is designed like a set of *blinking sails*, which is inspired by the wave-powered station-keeping buoy with tensegrity architecture illustrated in Chapter 1 of reference [8], and a recent US patent on a blinking sail windmill [14]. The module of this structure is composed of six bars (compressive members), two cables (tensile members) and five nodes. Node 1 is fixed on the sub-structure, nodes 2 and 4 are constrained to move in the x-y plane (parallel to the building façade), node 5 is constrained to move along the z-axis (perpendicular to the building façade) and node 3 is free to move within the space. The design of the elementary module depends on two angular aspect variables $\alpha$ and $\beta$, which define the node coordinates as shown in Fig. 1. Our next developments assume $\alpha = 0$ and $\beta = 45°$ in the undeformed (planar) configuration of the blinking sail module.




| | | | |
|---|---|---|---|
| node 1 | 0 | r | 0 |
| node 2 | -rcosα | -rsinα | 0 |
| node 3 | 0 | 0 | 0 |
| node 4 | rcosα | -rsinα | 0 |
| node 5 | 0 | -r | 0 |

$0<\alpha<|\pi|$

Figure 1. Blinking sail façade system – Geometry of the elementary module

We will see later on that the blinking sail structure illustrated in Figs. 1-2 can operate as an adaptive solar screen or a wind harvester device. In both cases, such a structure is equipped with bendable, composite photovoltaic modules and/or fiber-membrane sails. Each elementary module of such a façade system is shaped like a rhombus (Fig. 2) and is actuated by controlling the elongations of selected cables, in such a way that the motion of the structure mimics a blinking sail.

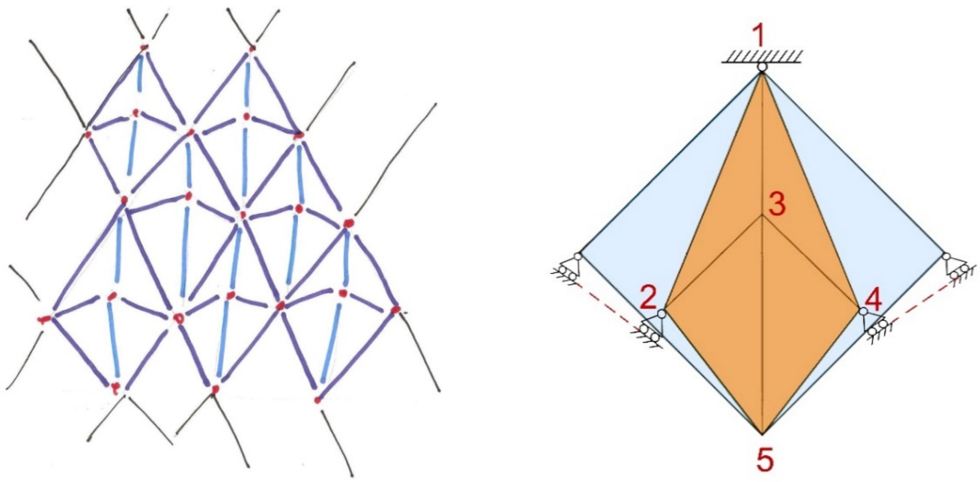



Figure 2. Conceptual (left) and mechanical (right) models of the blinking sail façade system.

Let us examine the motion of the blinking sail elementary module described in Fig. 2, 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*

$$\dot{e}_m = (\dot{\boldsymbol{u}}_j - \dot{\boldsymbol{u}}_i) \cdot \boldsymbol{a}_m \tag{1}$$

where $\dot{\boldsymbol{u}}_i$ and $\dot{\boldsymbol{u}}_j$ denote the velocity vectors of the nodes *i* and *j*, respectively; $\boldsymbol{a}_m$ 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 $\dot{\boldsymbol{q}}$, and the elongation rates in all the bars and cables into a vector of control variables $\dot{\boldsymbol{e}}$, we can rewrite the compatibility equations of the overall structure into the following matrix form

$$\mathbf{B}\,\dot{\boldsymbol{q}} = \dot{\boldsymbol{e}} \tag{2}$$

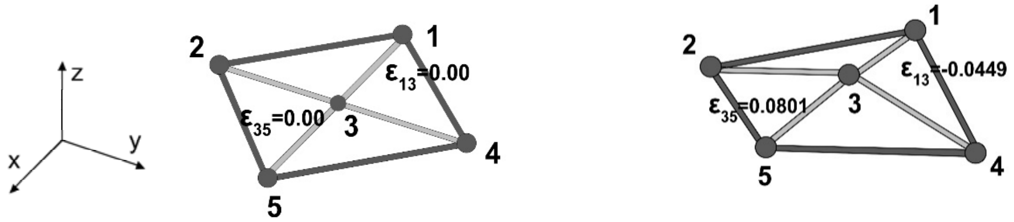
where $\mathbf{B}$ denotes the instantaneous *kinematic* (or *compatibility*) *matrix* [6].

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

$$\boldsymbol{q} = \int_0^t \dot{\boldsymbol{q}}\, dt = \int_0^t \mathbf{B}^{-1}\, \dot{\bar{\boldsymbol{e}}}\, dt \tag{3}$$

where $\mathbf{B}^{-1}$ is the inverse of the kinematic matrix $\mathbf{B}$ 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 Figure 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 Figure 3. The remaining members of the module remain unstretched during the motion of the structure illustrated in Figure 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 $\beta = 45°$ (top-left configuration in Fig. 3), as we already noticed, and assume the values $\alpha = 45°$ and $\beta = 38°$ in the fully folded configuration.



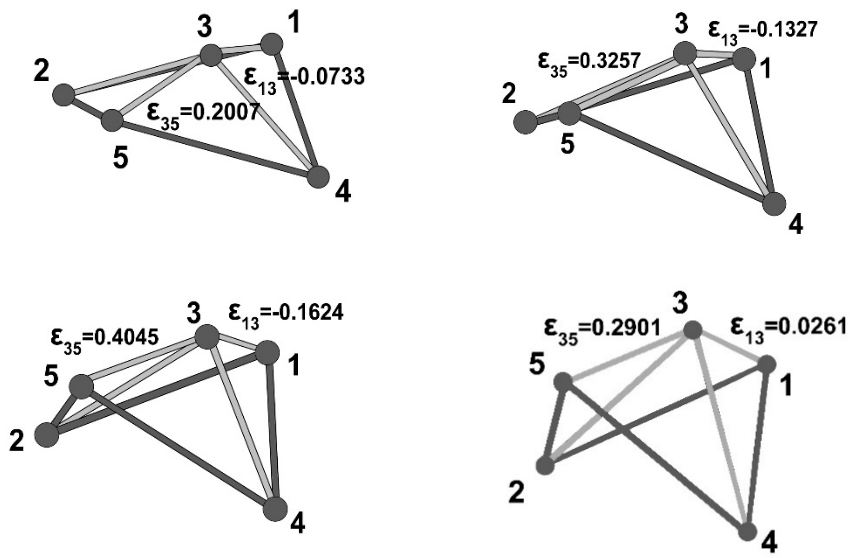



Figure 3. Activation mechanism of the Blinking sail module.

## 3. ENGINEERING APPLICATIONS

The activation mechanism illustrated in Figure 3 is at the basis of the solar façade system illustrated in Fig. 4. 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.


Figure 4. Blinking sail solar façade

A blinking sail wind energy harvester can also be designed in order 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. Fig. 5). Such cables are connected to a fiber-reinforced membrane sail that is inflated by the wind. Additional cables attached to the module wrap around a generator rotor (Fig. 5). The wind-flow induced elongations of such cables rotate the generator, creating power for immediate use of the served building, 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. Fig. 5 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 [8].

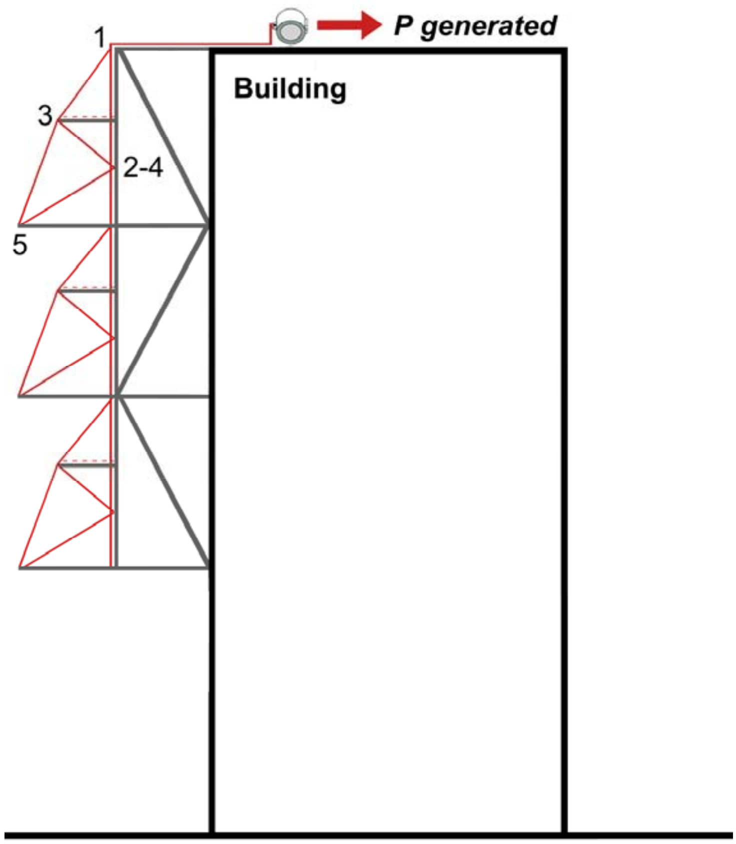



Figure 5. Functional diagram of the wind-energy harvester module

## 4. CONCLUDING REMARKS

We have formulates 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.

Future research lines include the design of different deployment schemes and the optimal design of sustainable kinetic membranes and panels for energy efficient buildings, to be carried out by combining parametric design approaches, energy optimization techniques, sustainable materials and additive manufacturing techniques [48]-[53].

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