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RENEWABLE ENERGY TENSEGRITY STRUCTURES

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Abstract. *We design novel sun barriers of energy efficient buildings. Making use of morphing lattices, we design sun screens that can be opened and closed during different hours of the day and periods of the year, by controlling the stretching of a limited number of cables. The struts of the screens remain undeformed during the opening and closure operations and can therefore support rigid plates, such as, e.g., solar panels and/or shading panels. Such morphing abilities lead us to the design of lightweight sun screens whose actuation requires reduced low energy consumption and minimal friction effects. We end with a review of novel "responsive architectures" for energy efficient buildings, which make use of tensegrity structures at different levels (primary and secondary structures) in order to respond to the natural environment by changing their mechanical and heating, ventilating and air-conditioning properties.*

1. INTRODUCTION

It is known that the construction industry significantly contributes to overall energy consumption (up to 40% in the European Union, cf. [1], and directive 31/2010/UE) and there is an urgent need for sustainable buildings that are able to reduce CO2 emissions by 90% and energy consumption by as much as 50% [2]. Renewable energy technologies have significant deployment potential as resources are spread globally, in contrast to the conventional sources such as gas, coal and oil, which are more geographically concentrated. Globally, renewable generation is estimated to rise to 25% of gross power generation in 2018, up from 20% in 2011 as deployment spreads out globally [1] (Figure 1).

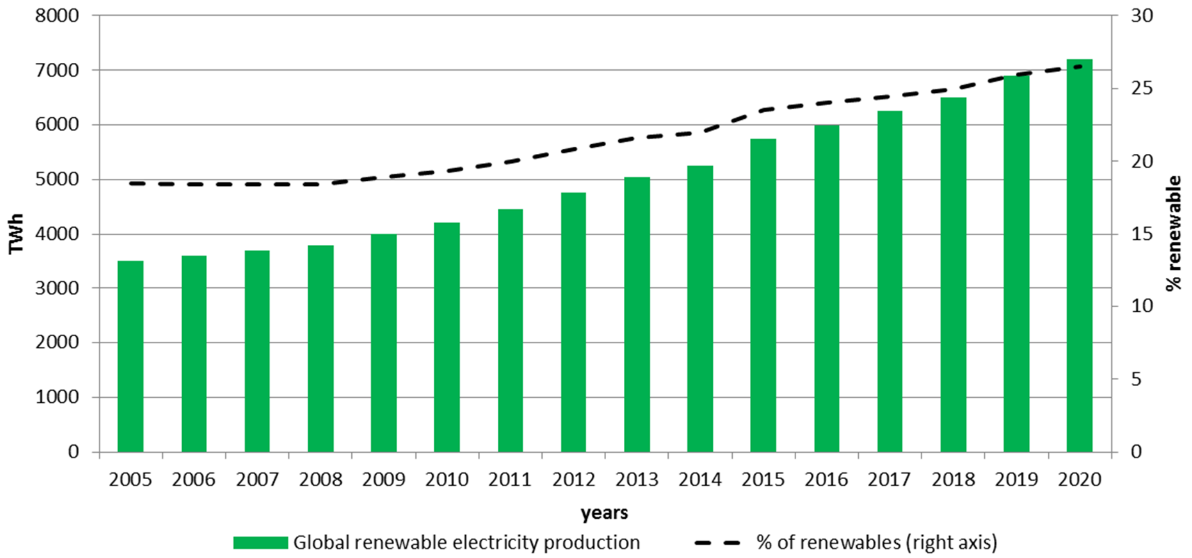

Figure 1: Global renewable electricity production by region, historical and projected (source: ref. [1]).

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, and to harvest wind and solar energy through on-site wind power generators [3], building integrated photovoltaic (BIPV) systems, and/or solar hot water panels [4]. The building of the future also needs to be safer with respect to natural hazards, such as earthquakes and high winds, and more energy efficient in terms of making components and subsystems multidisciplinary (e.g., combining structural design with heating, ventilation and air conditioning design) [5].

Tensegrity structures are prestressable truss structures, which are obtained by connecting compressive members (bars or struts) through the use of pre-stretched tensile elements (cables or strings) [6]. Motivated by nature, where tensegrity concepts appear in every cell, in the microstructure of the spider silk, and in the arrangement of bones and tendons for control of locomotion in animals and humans [7], engineers have only recently developed efficient analytical methods for exploiting tensegrity concepts in engineering design [8-10]. Form-finding of truss-like structures continues to be an active research area, due to both their easy control (geometry, size, topology and prestress control), and the fact that tensegrity structures provide minimum mass systems under different loading conditions [6,7,11]. The use of tensegrity structures for the construction of renewable energy supplies requires further attention, due to the special ability of tensegrity systems to convert the strain energy stored in cables into electrical energy [7]. There is also the question of their easy integration into solar and acoustical panels, which can be physically identified with special rigid members of the structure.

The present work deals with the design of novel lattices with morphing abilities, to be used as cost-effective shading screens for energy efficient buildings. A tensegrity solution for the actuated façade panels of the well-known Al Bahar Towers in Abu Dhabi is presented. Designed recently by Aedas Architects, using a different technology [12], this façade mimics the shading lattice-work "mashrabiya". The "origami" tensegrity panels designed in the present work are opened (i.e., folded out) at night, and are progressively closed during daylight hours by controlling the tension in selected cables. Such lightweight morphing lattices require minimal storage of internal energy, and lighter friction between parts, as compared, for instance, to the piston-actuated technology adopted by Aedas Architects [12].

2. ON THE ACTUATION OF MORPHING LATTICES

Let us examine the motion of the elementary truss lattice shown in Figure 2. The axial strain rate of the *k*-th element connecting nodes *i* and *j* is given by:

$$\dot{\varepsilon}_k = \frac{1}{\ell_k}\left(\dot{\boldsymbol{u}}_j - \dot{\boldsymbol{u}}_i\right) \cdot \boldsymbol{k} \tag{1}$$

where $\boldsymbol{k}$ is the unit vector parallel to the element at the current time t (pointing towards node *j*); $\dot{\boldsymbol{u}}_i$ and $\dot{\boldsymbol{u}}_j$ are the velocity vectors of the nodes *i* and *j*, respectively; and ℓ_k is the length of the element at time t.

On introducing a Cartesian frame $\{0, x_1, x_2, x_3\}$, and letting *N* denote the total number of nodes of the lattice, it is convenient to collect the Cartesian components of the velocity vectors of the different nodes into the following array with *3N* entries:

$$\dot{\boldsymbol{u}} = [\dot{u}_{1,1}\ \dot{u}_{1,2}\ \dot{u}_{1,3} \ldots\ \dot{u}_{N,1}\dot{u}_{N,2}\dot{u}_{N,3}]^{\boldsymbol{T}} \tag{2}$$

$\dot{u}_{i,n}$ being the component of $\dot{\boldsymbol{u}}_i$ with respect to the x_n-axis (n = 1,2,3), and *T* denoting the transposition symbol. Similarly, said *M* the total number of truss elements composing the lattice, it is useful to collect the axial strain rates of all lattice elements into the following array with *M* entries:

$$\dot{\boldsymbol{\epsilon}} = [\dot{\varepsilon}_1 \ldots\ \dot{\varepsilon}_M]^{\boldsymbol{T}} \tag{3}$$

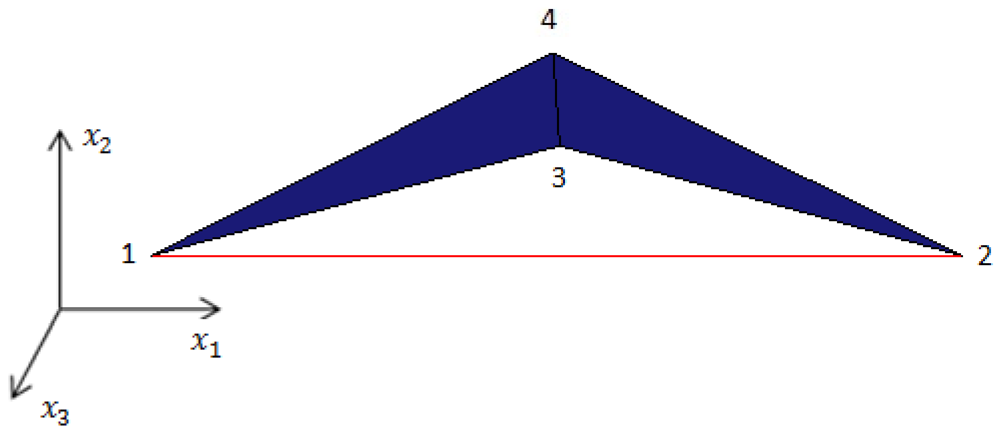

Figure 2: Elementary truss lattice.

It is an easy task to cast the compatibility equations (1) pertaining to all the lattice elements into the following matrix form

$$\boldsymbol{C}\,\dot{\boldsymbol{u}} = \dot{\boldsymbol{\varepsilon}} \tag{4}$$

$\boldsymbol{C}$ denoting the M × N compatibility matrix such that its k-th row has entry $-k_{\mathrm{n}}/\ell_{\mathrm{k}}$ in correspondence with $\dot{u}_{\mathrm{i,n}}$; entry $k_{\mathrm{n}}/\ell_{\mathrm{k}}$ in correspondence with $\dot{u}_{\mathrm{j,n}}$ (n = 1,2,3), and all the remaining entries equal to zero.

We now assume that a given number P of velocity components are forced to be zero, due to the presence of externals constrains that limit the possibilities of motion of the lattice. By suitably sorting the velocity vector $\dot{\boldsymbol{u}}$, we can rewrite the matrix equation (4) as follows

$$[\boldsymbol{C_1} \quad \vdots \quad \boldsymbol{C_2}] \begin{bmatrix} \dot{\boldsymbol{u}}_1 \\ \cdots \\ \dot{\boldsymbol{u}}_2 \end{bmatrix} = \dot{\boldsymbol{\varepsilon}} \tag{5}$$

where $\dot{\boldsymbol{u}}_1$ is the array with $Q=(3N\text{-}P)$ entries that collects the unconstrained velocity components of the nodes; $\dot{\boldsymbol{u}}_2$ is the P-dimensional array collecting the nodal velocity components constrained to zero; $\boldsymbol{C_1}$ is a M × Q submatrix of $\boldsymbol{C}$; and $\boldsymbol{C_2}$ is the complementary M × P submatrix of $\boldsymbol{C}$. In minimal coordinates, the compatibility equations of the constrained lattice are written as follows

$$\mathbf{B}\,\dot{\boldsymbol{q}} = \dot{\boldsymbol{\varepsilon}} \tag{6}$$

with $\mathbf{B} = \boldsymbol{C_1}$ (*kinematic matrix*) [13], and $\dot{\boldsymbol{q}} = \dot{\boldsymbol{u}}_1$.

We say that the lattice is *morphing* [14], if it results:

$$r = M = Q \tag{7}$$

r denoting the rank of the kinematic matrix **B**. The assumption (7) implies that the system of compatibility equations (6) has a unique solution $\dot{\boldsymbol{q}} \in \mathbb{R}^{\boldsymbol{Q}}$ for any given $\dot{\boldsymbol{\varepsilon}} \in \mathbb{R}^{\boldsymbol{M}}$, $\mathbb{R}$ denoting the set of real numbers. It is worth noting that, in a morphing lattice, one can produce the motion of the structure by actuating a single element, i.e., by prescribing that a single entry of $\dot{\boldsymbol{\varepsilon}}$ is nonzero. As a consequence, the actuation of morphing lattices requires minimal storage of internal energy [14]. Given an "actuation" history $\dot{\boldsymbol{\varepsilon}} = \dot{\bar{\boldsymbol{\varepsilon}}}$, the positons of the vertices of a morphing lattice at the current time t are computed from the integral equation

$$\boldsymbol{q} = \int_0^t \dot{\boldsymbol{q}}\,dt = = \int_0^t \mathbf{B}^{-1}\,\dot{\bar{\boldsymbol{\varepsilon}}}\,dt \tag{8}$$

$\mathbf{B}^{-1}$ denoting the inverse of the kinematic matrix **B**, which there exists and is unique under the assumption (7).

Assuming the action of quasi-stating loading and making use of the principle of virtual work, it is an easy task to obtain the following expression of the equilibrium problem of the lattice [7,13]

$$\mathbf{A}\,\boldsymbol{t} = \boldsymbol{f} \tag{9}$$

where $\boldsymbol{A} = \mathbf{B}^{\boldsymbol{T}}$ is the *static* (or *equilibrium*) *matrix*; $\boldsymbol{t} \in \mathbb{R}^{\boldsymbol{M}}$ is the array collecting the axial forces carried the lattice elements (or *bar tensions* [13]), and $\boldsymbol{f} \in \mathbb{R}^{\boldsymbol{Q}}$ is the array of the active nodal forces. It follows from (7) that a morphing lattice is statically and kinematically determinate (or *isostatic*) [13].

We now get back to the lattice structure in Figure 2, assuming that nodes 1 and 2 are constrained to move along the lines 1-4 and 2-4, respectively, and that node 4 is constrained to move along the x_3-axis. Under such assumptions, it is not difficult to show that the structure in Figure 2 is morphing and can be controlled by actuating only the string 1-2, that is, prescribing nonzero axial strain in such an element, and zero axial strains in all the remaining elements. This actuation mechanism leaves unchanged the lengths of the edges of the triangles 1-3-4 and 2-3-4, which therefore move rigidly over time (Figure 3).

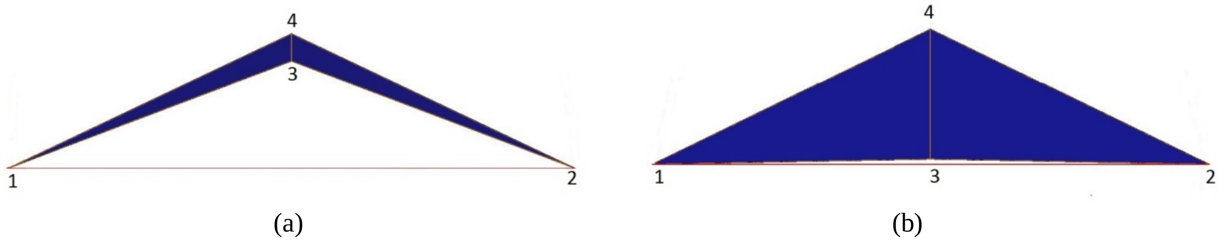

Figure 3: Motion produced by the actuation of the string 1-2: (a) string 1-2 unstretched; (b) string 1-2 stretched to 6.25%.

3. "MASHRABIYA" SHADING SCREENS

The morphing abilities of the elementary lattice structure illustrated in Figure 3 can be exploited to design a tensegrity solution for the actuated façade panels of the well-known Al Bahar Towers in Abu Dhabi. Designed recently by Aedas Architects, using a different technology, such panels are intended to mimic the shading lattice-work "mashrabiya" [12].

Let us assume that the x_3-axis of the elementary lattice in Figure 2 is perpendicular to the building façade to be shaded, and that such a façade is placed at the quote $x_3 = -2.00$ m. Let us also suppose that the nodes of such a structure have the following position vectors $\boldsymbol{n}_i$ ($i = 1,..,4$) in correspondence with the open configuration of the lattice (Figure 3a)

$$\boldsymbol{n}_1 = \begin{bmatrix} 0.125 \\ 0.057 \\ 0.045 \end{bmatrix} \text{m}, \quad \boldsymbol{n}_2 = \begin{bmatrix} 3.875 \\ 0.057 \\ 0.045 \end{bmatrix} \text{m}, \quad \boldsymbol{n}_3 = \begin{bmatrix} 2.000 \\ 0.738 \\ -0.262 \end{bmatrix} \text{m}, \quad \boldsymbol{n}_4 = \begin{bmatrix} 2.000 \\ 1.000 \\ 0.968 \end{bmatrix} \text{m} \tag{10}$$

By inserting shading panels in correspondence with the triangular facets 1-4-3 and 2-4-3 of the elementary lattice, and replicating such a structure over space as shown in Figure 4, we can form mashrabiya-like shading screens that can be opened and closed by actuating a single string for each elementary module.

The shading mechanism played by such screens, which is graphically illustrated in Figure 4, assumes that the actuated strings are unstretched in correspondence with the open configuration of the screens, and subject to a 6.25% axial strain in correspondence with the fully-closed configuration. Such a mechanism has been numerically studied by integrating Eqn. (8) through an explicit 4th order Runge-Kutta scheme with step size $\Delta\boldsymbol{\varepsilon} = 0.01\%$. An animation of the mechanism in Figure 4 is given in [15]. The force vectors depicted in Figure 4 are proportional to the amplitude of the elongations of the perimeter strings. The elongations of the actuated strings placed in the interior of the screens are not shown for visual clarity.

4. CONCLUDING REMARKS

We have presented an application of morphing lattices with tensegrity architecture to design adaptable envelopes for energy efficient buildings. We have designed "origami" panels of shading screens that can be opened (i.e., folded out) at night (configuration on top-left of Figure 4), and can be progressively closed during daylight hours (cf., e.g., the fully closed configuration on bottom-right of Figure 4), by controlling the elongation in selected strings.

The operation mechanisms of such screens can be powered by the renewable energy derived from photovoltaic panels and/or microeolic power generators. Their aim is to markedly mitigate air conditioning consumption resulting from direct exposure to solar rays, reducing carbon dioxide emissions. Common issues discussed by architects and engineers are the relative importance of a façade's U-value (the insulation characteristics) versus its G-value (the shading coefficient). The cable-actuated shading screens illustrated in Figure 4 require minimal storage of internal energy [14], and reduced operation costs (due to lighter friction between parts and reduced mass), as compared, for instance, to the piston-actuated technology adopted by Aedas Architects [12]. They offer portable applications for small spans, and can be easily assembled for prefabricated component parts in the case of large spans.

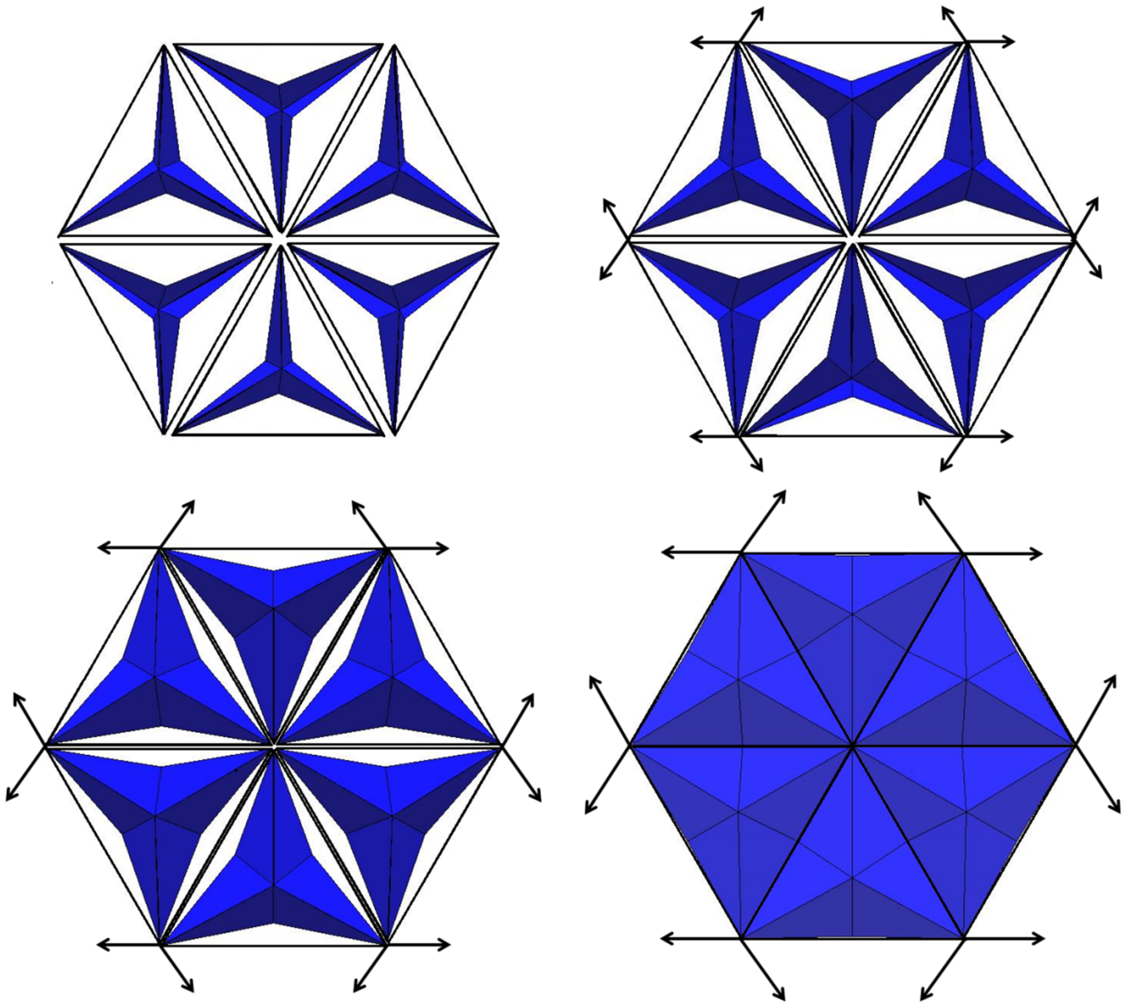

Figure 4: Actuation mechanism of mashrabiya shading screens with tensegrity architecture (an animation of such mechanisms is given in [15]).

Extensions of the present study dealing with bioinspired membranes [16-19], which are able to orient solar panels towards the sun, to adjust the thickness of ventilated walls, and to form innovative microeolic power generators will be addressed in future work. Such structures will assemble tensegrity units, whose rigid parts will consist either of 1D struts, or 2D/3D solid elements of various shape and material (floor slabs, airfoil ribs, solar panels, acoustical panels, etc.). The tensile elements of the tensegrity units will instead consist of cables of various dimensions. Each unit will be equipped with sensors and actuators in correspondence with selected elements, which will be connected by wires or wireless devices to a data transfer system. Its operation will be controlled by external motors and generators, or by a single apparatus that alternatively works as generator or motor (Figure 5). Some preliminary results and animations related to this ongoing research project are given in [15].

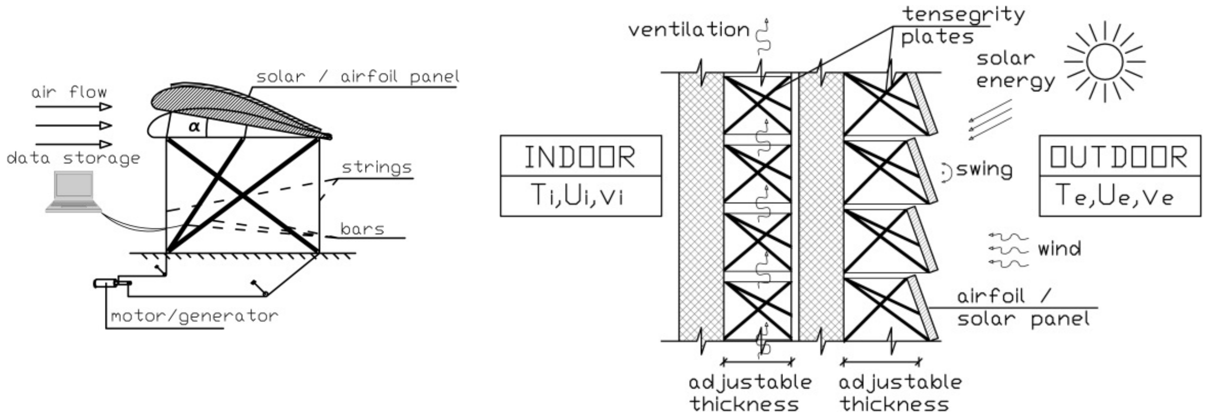

Figure 5: Morphing skins of energy efficient buildings based on tensegrity structures: (a) tensegrity unit; (b) responsive solar façade and ventilated wall [15].

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REFERENCES

[1] L.P. Lombard, J. Ortiz , C. Pout, A review on buildings energy consumption information. Energy and Buildings, **40**,394-398, 2010.

[2] European Commission, HORIZON 2020 Work Programme 2014-2015, PART 5.ii, Page 98, 2014.

[3] F. Balduzzi, A. Bianchini, L. Ferrari, Microeolic turbines in the built environment: Influence of the installation site on the potential energy yield. *Renewable Energy*, **45**, 163-174, 2012.

[4] T.E. Kuhn, S. Herkel, H-M. Henning, Active solar facades (PV and solar thermal). In: PALENC 2010, http://publica.fraunhofer.de/documentsN-161087.html , 2010

[5] R.E. Skelton, Structural systems: a marriage of structural engineering and system science. *Journal of Structural Control*, **9**,113-133, 2002.

[6] R.E Skelton, F. Fraternali, G. Carpentieri, A. Micheletti, Minimum mass design of tensegrity bridges with parametric architecture and multiscale complexity. *Mechanics Research Communications*, **58**, 124-132, 2014.

[7] R.E. Skelton, M.C. de Oliveira, *Tensegrity Systems.* Springer,2010

[8] F. Fraternali, G. Carpentieri, A. Amendola, On the mechanical modeling of the extreme softening/stiffening response of axially loaded tensegrity prisms. *Journal of the Mechanics and Physics of Solids*, **74**, 136-157, 2014.

[9] F. Fraternali, L. Senatore, C. Daraio, Solitary waves on tensegrity lattices. *Journal of the Mechanics and Physics of Solids*, **60**, 1137-1144, 2012.

[10] F. Fraternali, G. Carpentieri, A. Amendola, R.E. Skelton, V.F. Nesterenko, Multiscale tunability of solitary wave dynamics in tensegrity metamaterials. *Applied Physics Letters*, **105**, 201903, 2014.

[11] A.G. Tilbert, S. Pellegrino, Review of form-finding methods for tensegrity structures. *International Journal of Space Structures* ,**18**, 209–223, 2011.

[12] Aedas Architects website, http://www.aedas.com/

[13] Hutchinson, R.G., Fleck, N.A., The structural performance of the periodic truss. *Journal of the Mechanics and Physics of Solids*, **54**, 756-782, 2012.

[14] N.A. Fleck ,V.S Deshpande, M.F. Ashby, Micro-architectured materials: past, present and future. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **466**, 2495–2516, 2010.

[15] Project webpage: http://www.fernandofraternaliresearch.com/MAE_project.asp?pg=7

[16] F. Fraternali, C.D Lorenz, G. Marcelli, On the estimation of the curvatures and bending rigidity of membrane networks via a local maximum-entropy approach. *Journal of Computational Physics*, **231**, 528-540, 2012.

[17] F. Fraternali, G.Marcelli, A multiscale approach to the elastic moduli of biomembrane networks. *Biomechanics and Modeling in Mechanobiology*, **11 (7)**, 1097-1108,2012

[18] B. Schmidt, F. Fraternali, Universal formulae for the limiting elastic energy of membrane networks. *Journal of the Mechanics and Physics of Solids*, **60**, 172-180, 2012.

[19] F. Fraternali, I. Farina, G. Carpentieri. A discrete-to-continuum approach to the curvatures of membrane networks and parametric surfaces. *Mechanics Research Communications*, **56**, 18-15, 2014.