SOFT "TENSEGRITY LIKE" PANEL: CONCEPTUAL DESIGN AND FORM - FINDING

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ABSTRACT

A new type of "tensegrity like" panel is presented, using a conceptual design based on a structural composition comprising two parallel layers of tensile membrane with, in between, a woven structure of bent strips. A prototype has been made to demonstrate its feasibility and a mechanical study is performed to investigate the relationship between the shape of the panel and its internal initial forces. The objective is to write the structure governing equations and, then, to propose different form-finding approaches. The form control method therefore allows determining the tension in the membranes according to specified panel geometry. The force control strategy provides the form of the undulating strip in accordance to a required tension in the membranes. Several numerical calculations, based on the prototype characteristics, are presented. Potential applications are then discussed, mainly for façade cladding as well as a possible adaptation of the panel to curved surfaces.

Keywords: *Tensegrity panel, tensile membrane, form-finding*

1. BACKGROUND

Originally investigated by engineers or artists like R. B. Fuller [1] and K. Snelson [6], tensegrity systems were subsequently studied for modules with varying structural complexity, for instance the triplex (figure 1, left) or the expanded octahedron (figure 1, right).

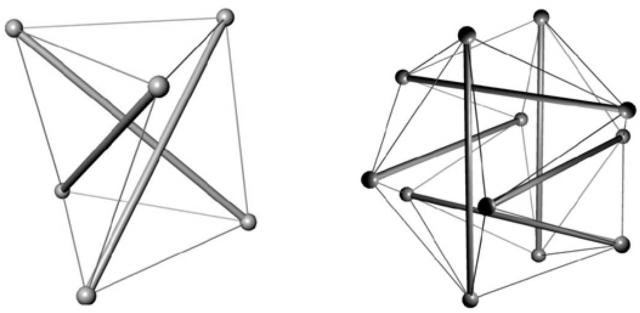


Figure 1. *Basic tensegrity modules*

Since these systems are selfstressed spatial structures in equilibrium composed of compressed struts connected to tensioned cables, the purpose was to determine the relationship between their geometry and the distribution of internal forces in the elements. Such study is called form-finding and is a necessary stage in tensegrity system design. Two groups of methods may be employed [3]: the form controlled ones, where possible forces are determined from a given shape, and the force controlled ones, which consist in calculating the shapes associated with specified forces. A load analysis can obviously be performed only after the form-finding stage which determines the initial form and forces.

The studies on tensegrity modules have led to the development of grids based on the assembly of modules [2]. One example is presented in figure 2 consisting of horizontal upper and lower layers of cables with internal tilted components in between (struts and cables).

The next step has entailed with the design of woven tensegrity grids [4, 5]. This is based on a bidirectional weave of tilted struts; it is then impossible to isolate a module is this grid.

Tensioned cables create two horizontal upper and lower layers; internal elements (cables and struts) are located in between (figure 3, left).

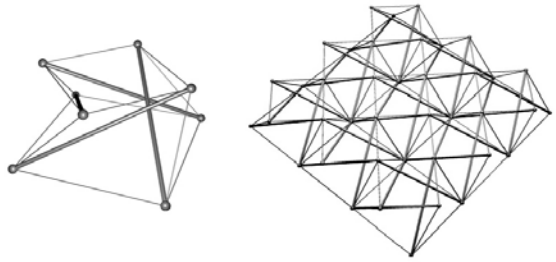


Figure 2. *Tensegrity grid composed of identical modules*

A 10m by 10m grid was built at Montpellier University to test the scale one feasibility (Tensarch project, 2000; figure 3, right).

2. CONCEPTUAL DESIGN OF THE SOFT "TENSEGRITY LIKE" PANEL

The soft "tensegrity like" panel results from numerous experimental treatments based on physical models. It is composed of two flat layers of tensile membrane with undulating strips in between. The inner strips are compressed and equilibrate the tension in the membranes. Since they are not straight, they are also bent and define waves. Additional peripheral cables connect the membranes to the extremities of the strips to ensure the membrane tensions.

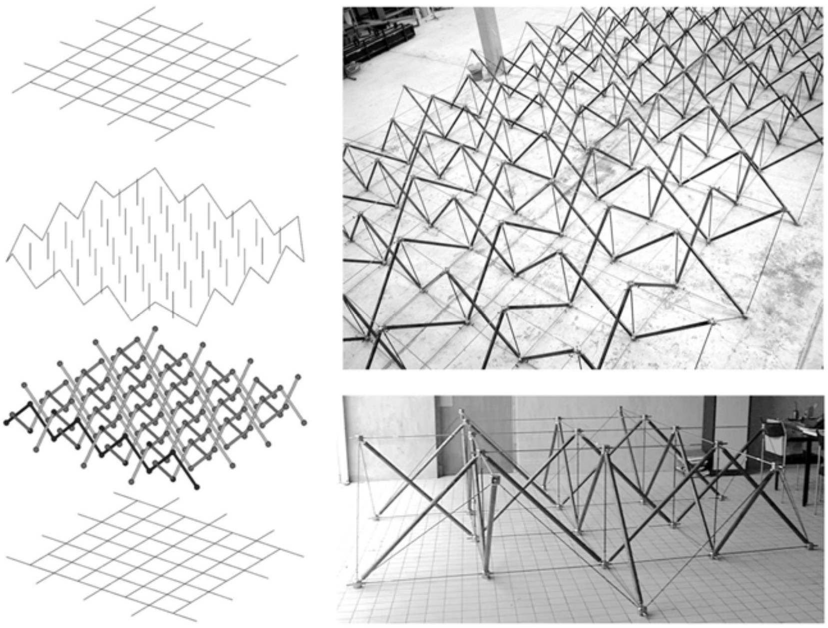


Figure 3. *Woven tensegrity grid (Tensarch project)*

A prototype (figure 4) has been made in collaboration with the company Ferrari, one of the leaders in the manufacture of composite textiles and membranes. The size of this squared panel is roughly 2.2 m by 2.2 m for 0.22 m width. We emphasize on these small dimensions and consequently choose to call this system a "panel" preferably to a "grid" or a "structure". The membrane is a fabric developed by Ferrari and called Defender 7761 composed of PVC coated steel threads.

Each of the 14 undulating strips (7 parallels in two orthogonal directions) has 3 repetitive identical interior wave segments (same amplitude and wavelength) and 2 identical boundary segments.

They are constructed from a fiber glass composite material manufactured by pultrusion with a 35 mm by 3 mm cross sectional area. In this prototype, the strips are connected to the membrane with rivets (figure 5).

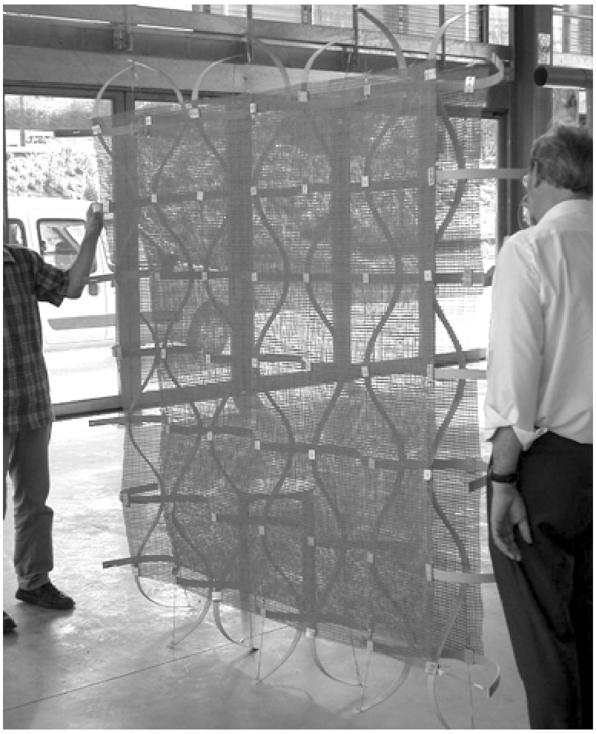


Figure 4. *Soft "tensegrity like" panel (external view)*

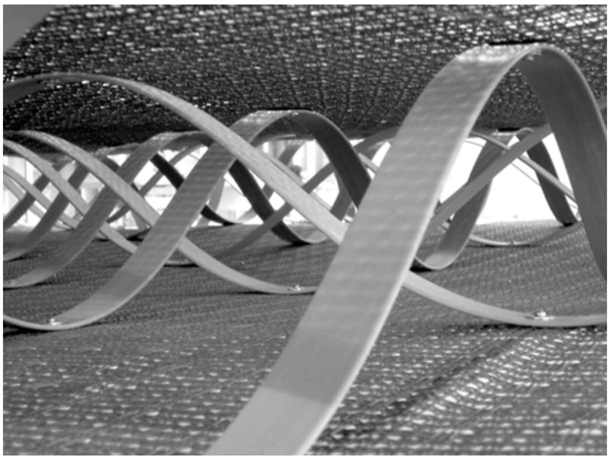


Figure 5. *Panel internal view*

3. FORM-FINDING OF THE SOFT "TENSEGRITY LIKE" PANEL

3.1. Objective of the study

The purpose is to determine the relationships between the geometrical characteristics of the panel (dimensions, shape of an inner strip) and the internal forces in the elements (tension in the membranes, bending moment and compression in the strips).

Such a study corresponds to a form-finding analysis and could be envisaged according to a form control or a force control strategy. In the form control method, the designer specifies the dimensions of the panel (side length and height) and will determine the corresponding tension in the membrane. In the force control method, the membrane tension is imposed and the panel dimensions resulting from an appropriate strip shape are determined. The presented study is based on seven steps:

- The geometrical parameters are first presented as well as the chosen mechanical hypothesis.

- After that, an analysis of one half strip allows writing its static equilibrium and to calculate its internal forces (compression and bending moment at characteristic points).

- Then, one half-wave segment of an undulating strip is isolated to determine the precise relationships between its actions (internal forces and external forces exerted by the membranes) and its geometry.

- The obtained results allow proposing a solving method devoted to the form control strategy and to the force control strategy.

- The approach is after that completed by analyzing the boundary segment of a strip.

- Finally, the calculation of the strip geometry is presented.

3.2. Panel description and hypothesis

The panel dimensions are given in figure 6. They are dependant on the shape of the undulating strips. Hence, the panel height corresponds to the strip wave amplitude *a* and the side length is a multiple of the strip wavelength ℓ (added to the distances ℓ' of the boundary segments). For instance, the side length of the prototype panel is $3\,\ell + 2\,\ell' \approx 2.20\,\mathrm{m}$ with $a \approx 0.22\,\mathrm{m}$. The length of the strip over one wavelength is L.

The upper points of the panel are labeled A to G and the lower H to K.

If we consider one strip from a mechanical point of view, the actions may be divided into two categories:

- the internal forces: the compression axial force *N* and the bending moment *M*.

- the "external" forces due to the two membranes and to the two peripheral cables.

The tension in the upper membrane generates external forces between the points BC (i.e. the force T_{BC}), CD (T_{CD}), DE (T_{DE}) and EF (T_{EF}). The lower membrane creates tension forces between HI (T_{HI}), IJ (T_{IJ}) and JK (T_{JK}). Since the interior wave segments have the same shape (amplitude and wavelength), these forces are identical. The tensions in the two membranes are hence constant and equal. As a result, the membrane external forces are $T_{BC} = T_{CD} = T_{DE} = T_{EF} = T_{HI} = T_{IJ} = T_{JK} = T$. This property will be used in the next step of the study to solve the equilibrium equations of a strip (3.3).

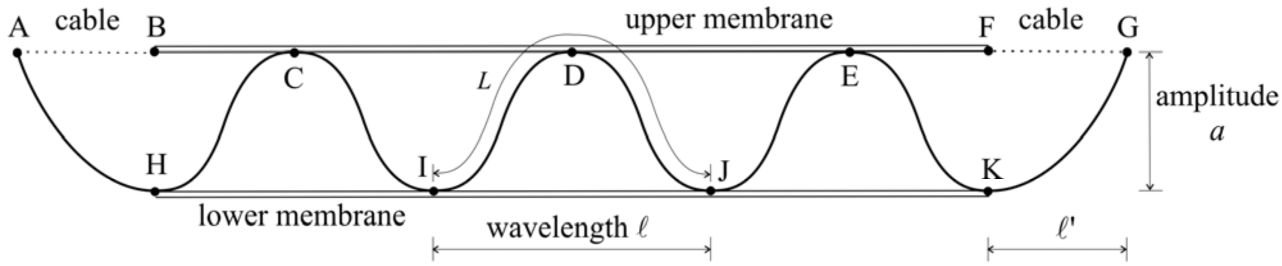


Figure 6. *Panel dimensions*

In this case of an uniform membrane tension and since the distance between two parallel strips is equal to the wavelength ℓ, the relationship between the membrane tension T_m and the external membrane force T acting on the points C, D, E and H, I, J, K is $T = \ell\, T_m$.

The peripheral cables are parallel to the membranes and connect them to the extremities of the boundary strips. The tensions in these cables create pulling external forces T_{AB} and T_{FG} on the boundary segments. The panel symmetry leads to $T_{AB} = T_{FG}$.

The last point deals with the material behavior of the composite strip. We will henceforth assume that this behavior is elastic linear.

3.3. Analysis of one half strip

This part aims to write the static equilibrium of a half strip divided in segments and to determine the resulting internal forces at the cutting sections.

Because of the symmetry, a strip is divided in four segments (AH, HC, CI and ID, see figure 6). The actions (internal forces *N* and *M*, external tensions due to the membranes and to the cables) acting on the extremities of every part are represented in figure 7.

The equilibrium of the different parts leads to

$$\begin{cases} \text{Part AH}: T_{AB} + T_{HI} = N_H \text{ and } M_H = a\, T_{AB} \\ \text{Part HC}: N_H + T_{CD} = N_C + T_{BC} \text{ and } M_H + M_C = a\, N_H \\ \text{Part CI}: N_C + T_{IJ} = N_I + T_{HI} \text{ and } M_C + M_I = a\, N_C \\ \text{Part ID}: N_I + T_{DE} = N_D + T_{CD} \text{ and } M_I + M_D = a\, N_I \end{cases} \tag{1}$$

Since 8 equations are written for 14 unknowns, 5 conditions must be at least specified. They are fixed by the geometrical repetitiveness of the interior strip segments, leading to a uniform membrane tension and identical external forces:

$$T_{BC} = T_{CD} = T_{DE} = T_{HI} = T_{IJ} = T \tag{2}$$

Moreover, the horizontal equilibrium of nodes B and F gives $T_{AB} = T_{BC} = T$.

Hence, the resulting internal forces at the ends of the different segments are

$$N_H = N_C = N_I = N_D = 2T \quad \text{and} \quad M_H = M_C = M_I = M_D = a\, T \tag{3}$$

The bending moment in the strip is thus the same at the upper and lower points. The resulting actions at the segment extremities (the sum of the internal and external forces) are represented in figure 8.

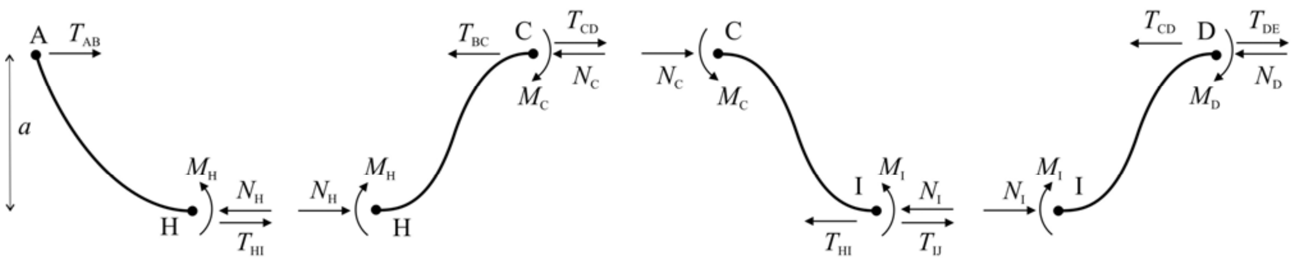


Figure 7. *Actions on the different segments of one half strip*

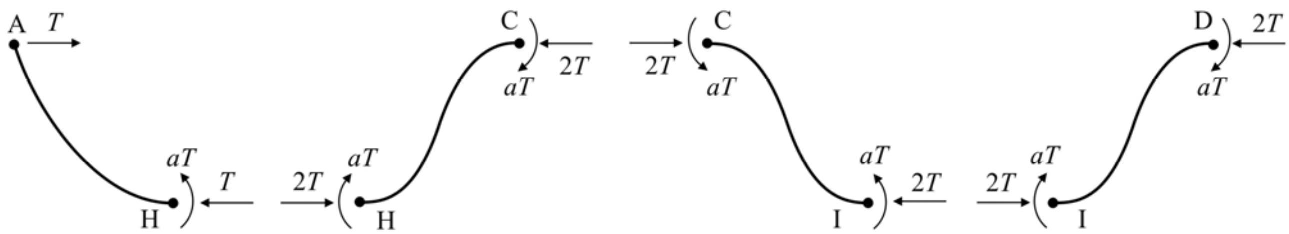


Figure 8. *Actions for a uniform membrane tension*

3.4. Analysis of one half-wave segment

One half of a strip segment wave is isolated, for instance the part ID (figure 9). Its amplitude is equal to a and the half wavelength is $\ell/2$. The length of this half-wave segment is equal to $L/2$.

The objective of this analysis is to obtain a relationship between the strip geometry (amplitude a and segment length L) and the compression force $N_{\mathrm{I}} = N_{\mathrm{D}} = 2T$.

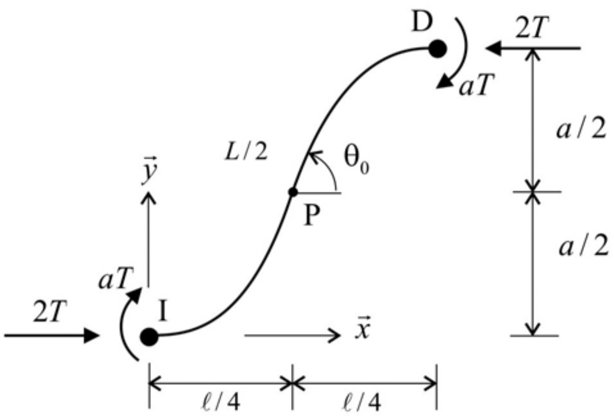


Figure 9. *Half-wave segment of the strip*

The bending moment *M*, written in a global coordinate system $(\vec{x}, \vec{y})$, is [7]

$$M = (a - 2y)T \tag{4}$$

Two close plane cross-sections S_1 and S_2 of the strip, initially parallel before bending, have a relative angle equal to $d\theta$ and are distant from ds (length of the strip neutral axis between S_1 and S_2, verifying $ds^2 \approx dx^2 + dy^2$, see figure 10).The behavior of the composite material is elastic linear with a Young's modulus equal to *E*.

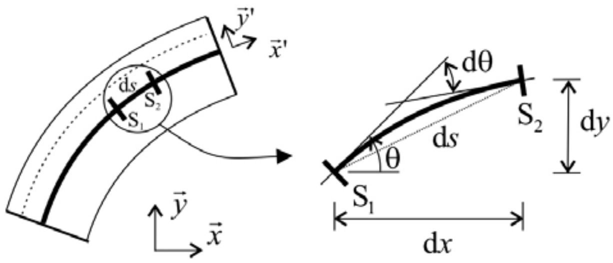


Figure 10. *Relative rotation of two sections*

The normal relative strain ε of a strip fiber bearing a normal stress σ and located at the distance y' of the neutral axis is

$$\varepsilon = \frac{d\theta}{ds} y' \text{ which also verifies } \varepsilon = \frac{\sigma}{E} = \frac{1}{EI} M\, y' \tag{5}$$

(where I is the strip cross-section second moment of inertia). Therefore

$$\frac{d\theta}{ds} = \alpha^2 (a - 2y) \text{ with } \alpha^2 = \frac{T}{EI} \quad (6)$$

Since $dy \approx ds \sin\theta$, it comes

$$\frac{d^2\theta}{ds^2} = -2\alpha^2 \frac{dy}{ds} = -2\alpha^2 \sin\theta \quad \text{and so}$$

$$2\frac{d\theta}{ds}\frac{d^2\theta}{ds^2} = -4\alpha^2 \sin\theta \frac{d\theta}{ds} \quad (7)$$

By integrating

$$\left(\frac{d\theta}{ds}\right)^2 = 4\alpha^2 \cos\theta + C_1 \quad (8)$$

The constant C_1 may be determined by considering that for the point I ($x = 0$ and $y = 0$) the angle θ is equal to zero

$$\frac{d\theta}{ds} = a\alpha^2 \text{ and thus } C_1 = \alpha^2 (a^2\alpha^2 - 4) \quad (9)$$

The governing relationship is then

$$\frac{d\theta}{ds} = 2\alpha\left(\cos\theta + \frac{1}{4}a^2\alpha^2 - 1\right)^{1/2} \quad \text{or}$$

$$\frac{d\theta}{ds} = a\alpha^2 \left(1 - \left(\frac{2\sqrt{2}}{a\alpha}\right)^2 \sin^2\left(\frac{\theta}{2}\right)\right)^{1/2} \quad (10)$$

It can be rewritten as

$$a\alpha^2\, ds = \frac{2\, d\varphi}{(1 - k^2 \sin^2\varphi)^{1/2}} \quad \text{with the parameters}$$

$$k = \frac{2\sqrt{2}}{a\alpha} \text{ and } \varphi = \frac{\theta}{2} \quad (11)$$

If we consider that at middle height (point P with $x = \ell/4$ and $y = a/2$) the angle is $\theta = \theta_0$ and $\frac{d\theta}{ds} = 0$, then

$$4\alpha^2 \cos\theta_0 + C_1 = 0 \text{ and } \theta_0 = \arccos\left(1 - \frac{2}{k^2}\right) \quad (12)$$

The length of the half-wave segment $L/2$ may be calculated by integration and considering that for $s = 0$ (point I) then $\theta = 0$ ($\varphi = 0$) and for $s = \frac{L}{4}$ (point P) then $\theta = \theta_0$ (i.e. $\varphi = \frac{\theta_0}{2}$)

$$a\alpha^2 \int_0^{L/4} ds = \frac{1}{4} a\alpha^2 L = \int_0^{\theta_0/2} \frac{2\, d\varphi}{(1 - k^2 \sin^2\varphi)^{1/2}} \quad (13)$$

Since k and θ_0 depend on T, it is rewritten as

$$\frac{aLT}{4EI} = \int_0^{\theta_0/2} \frac{2\, d\varphi}{(1 - k^2 \sin^2\varphi)^{1/2}} \text{ or } \frac{aLT}{4EI} = \Pi(T) \quad (14)$$

This equation is highly useful because it provides a relationship between the external force T due to the uniform membrane tension and the shape of the strip (amplitude a, segment length L). It will be used during the form-finding procedures.

3.5. Form control strategy

This aims to give to the designer the possibility of determining the uniform membrane tension T_m from a specified geometry (strip amplitude a and wavelength ℓ). By considering that the amplitude and the strip rigidity EI are imposed, the approach is as follows:

A. From a given value for the strip segment length L, the corresponding external force T is calculated by using (14)

$$T = \frac{4EI}{aL}\Pi(T) \quad (15)$$

This equation is however non linear and in the form of $T = f(T)$.

We solve it by using the fixed point method: from an initial estimated value T^0, the iterative sequence $T^{i+1} = f(T^i)$ is performed until it converges to the sought value of T.

B. The associated wavelength ℓ is subsequently determined. Since $dx \approx ds\cos\theta = ds\cos(2\varphi)$ and $\ell/4 = \int_0^{\ell/4} dx = \int_0^{\theta_0/2} \cos(2\varphi)\, ds$, we have

$$\ell = \frac{4}{a\alpha^2}\int_0^{\theta_0/2} \frac{2\cos(2\varphi)\,d\varphi}{(1-k^2\sin^2\varphi)^{1/2}} \qquad (16)$$

Then, the membrane tension is calculated with $T_m = T/\ell$.

C. By repeating this approach for different values of the length *L*, the curves $T(L)$, $\ell(L)$ and $T_m(L)$ are obtained. By writing differently the data, it gives the curve $T_m(\ell)$ and thus the search relationship between the membrane tension T_m and the strip wavelength ℓ (that defines the panel dimensions).

D. The last step consists in evaluating the maximum normal stress in the strip to check if it remains admissible by the material. For a rectangular *b* by *t* sectional area, we have

$$\sigma_{\max} = \frac{6M_{\max}}{bt^2} + \frac{N_{\max}}{bt} = \frac{\ell T_m}{bt}\left(\frac{6a}{t}+2\right) \qquad (17)$$

A numerical application is presented relative to the prototype panel ($a = 22$ cm, strip cross-section moment of inertia $I = 78.75\ \text{mm}^4$, composite $E = 36000$ MPa and ultimate bending strength $f_u = 1000$ MPa). The graphs in figure 11 show the variation of the wavelength and of the membrane tension according to the length *L*.

More exploitable curves $T_m(\ell)$ and $\sigma_{\max}(\ell)$, used in the form control strategy, are also presented in figure 12.

For the prototype panel, the wavelength is roughly $\ell \approx 60$ cm. The membrane tension is therefore $T_m \approx 17$ daN/m with $\sigma_{\max} \approx 75$ MPa. This membrane tension is very low, mainly because of practical reasons. The experimental panel was assembled "by hand" and the technological choices (rivets…) posed difficulties for having higher forces.

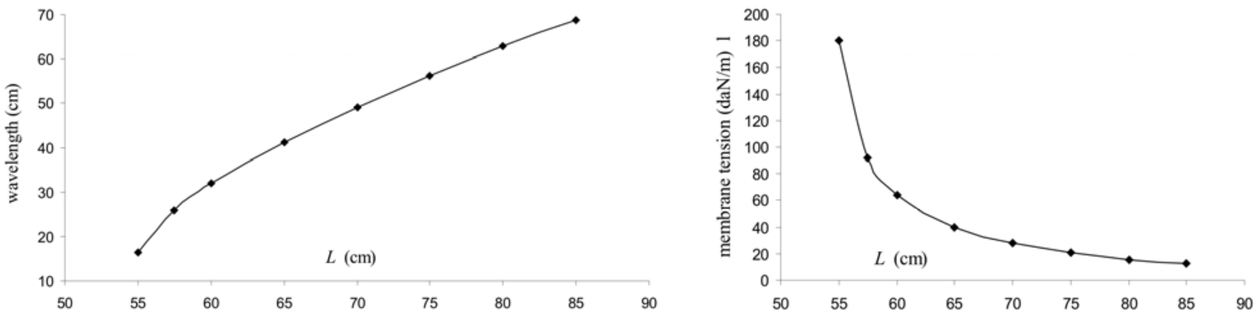


***Figure 11**. Curves $\ell(L)$ and $T_m(L)$*

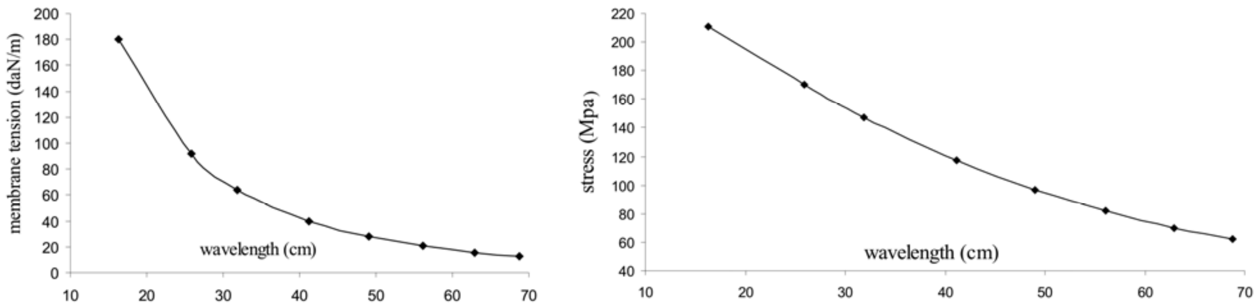


***Figure 12.** Form control strategy: curves $T_m(\ell)$ and $\sigma_{\max}(\ell)$*

3.6. Force control strategy

This approach aims to give the possibility of determining the panel dimensions, depending on an appropriate strip shape (wavelength ℓ), from a specified uniform membrane tension T_m.

The approach is as follows (we consider that the strip rigidity *EI* is imposed):

A. From a given value for the force *T*, the corresponding wavelength ℓ is calculated according to (16). The associate membrane tension is then $T_m = T / \ell$.

B. The length L can then be obtained with (15)

$$L = \frac{4EI}{a} \frac{\prod(T)}{T} \qquad (18)$$

C. By repeating this procedure for different values of the tension T, the curves $\ell(T)$, $T_m(T)$ and $L(T)$ are obtained. Differently written, it gives the relationship $\ell(T_m)$ between the panel dimension and the membrane tension.

D. Then, the length $L(T_m)$, necessary to build the panel, and the maximum normal stress $\sigma_{\max}(T_m)$, coming from (17), are given.

An application is presented for the prototype panel ($a = 22$ cm, 35 mm by 3 mm composite strip with $E = 36000$ MPa). The graphs in figure 13 illustrate the variation of the wavelength ℓ and of the membrane tension T_m with the force T.

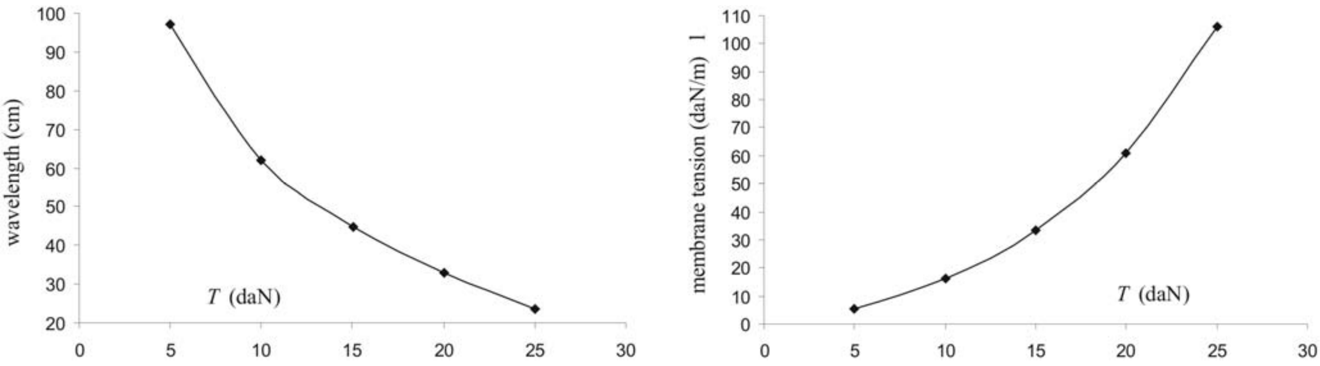


Figure 13. *Curves* $\ell(T)$ *and* $T_m(T)$

The curve presented in figure 14 shows the relationship between the strip wavelength ℓ and the membrane tension T_m. This means that, from a required tension, the designer can determine the appropriate value of the wavelength and, thus, can extrapolate the size of the panel.

The corresponding values for the length L and for the maximum normal stress $\sigma_{\max}$ can then be determined according to the membrane tension. These curves are presented in figure 15.

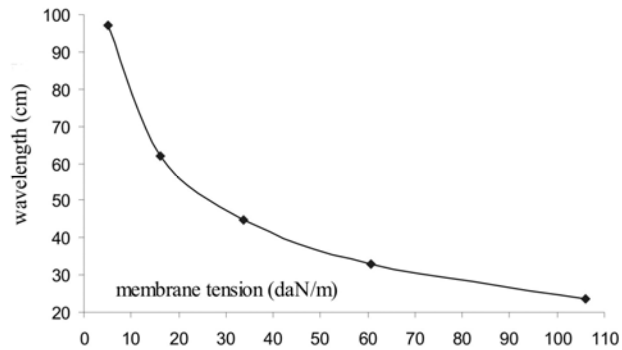


Figure 14*. Force control strategy: curve* $\ell(T_m)$

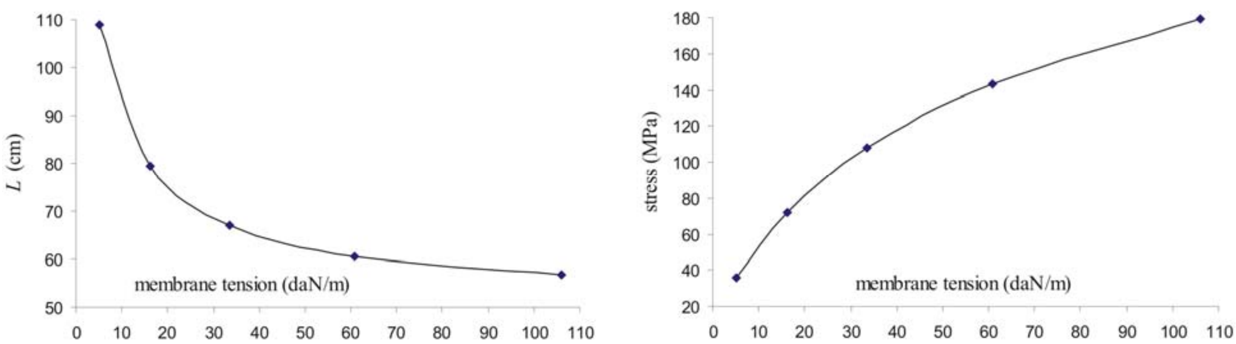


Figure 15: *Force control strategy: curves* $L(T_m)$ *and* $\sigma_{\max}(T_m)$

3.7. Form-finding for a strip boundary wave

Once the membrane tension and the strip wavelength have been calculated, the shape of the strip boundary segments must be determined.

The objective is to calculate, from the given uniform membrane tension T_m, the length L' of a strip boundary segment and its associate horizontal distance ℓ'.

We isolate for that purpose the segment KG (figure 16). The tension in the peripheral cable is determined according to the uniform membrane tension $T_{FG} = T = \ell\, T_m$.

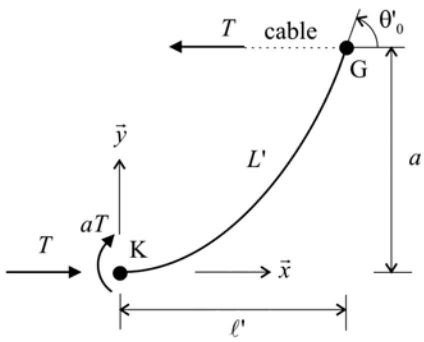


Figure 16. *Strip boundary wave*

Then, the equilibrium of the segment KG leads to the same equations as previously written (section 3.4), excepted different values for the coefficients C_1 and k : $C'_1 = \alpha^2(\alpha^2 a^2 - 2)$ and $k' = 2/(a\alpha)$.

The following governing relationship is obtained

$$a\alpha^2 \int_0^{L'} \mathrm{d}s = a\alpha^2 L' = \int_0^{\theta'_0/2} \frac{2\,\mathrm{d}\varphi}{(1-k'^2\sin^2\varphi)^{1/2}} = \Pi'(T)$$

$$\text{with } \theta'_0 = \arccos\left(1-\frac{2}{k'^2}\right) \qquad (19)$$

Hence, the length of the strip boundary wave L' and its corresponding horizontal distance ℓ' are

$$L' = \frac{EI}{a}\frac{\Pi'(T)}{T} \quad \text{and}$$

$$\ell' = \frac{1}{a\alpha^2}\int_0^{\theta'_0/2} \frac{2\cos(2\varphi)\,\mathrm{d}\varphi}{(1-k'^2\sin^2\varphi)^{1/2}} \qquad (20)$$

Moreover, the maximum normal stress is

$$\sigma'_{\max} = \frac{6M_{\max}}{bt^2} + \frac{N_{\max}}{bt} = \frac{\ell T_m}{bt}\left(\frac{6a}{t}+1\right) \qquad (21)$$

An application is performed considering the experimental panel ($a = 22$ cm, 35 mm by 3 mm composite strip with $E = 36000$ MPa) and, as measured on the prototype, $\ell \approx 60$ cm. The graphs presented in figure 17 show the variation of the length L', the distance ℓ' and of the maximum stress $\sigma'_{\max}$ according to the membrane tension.

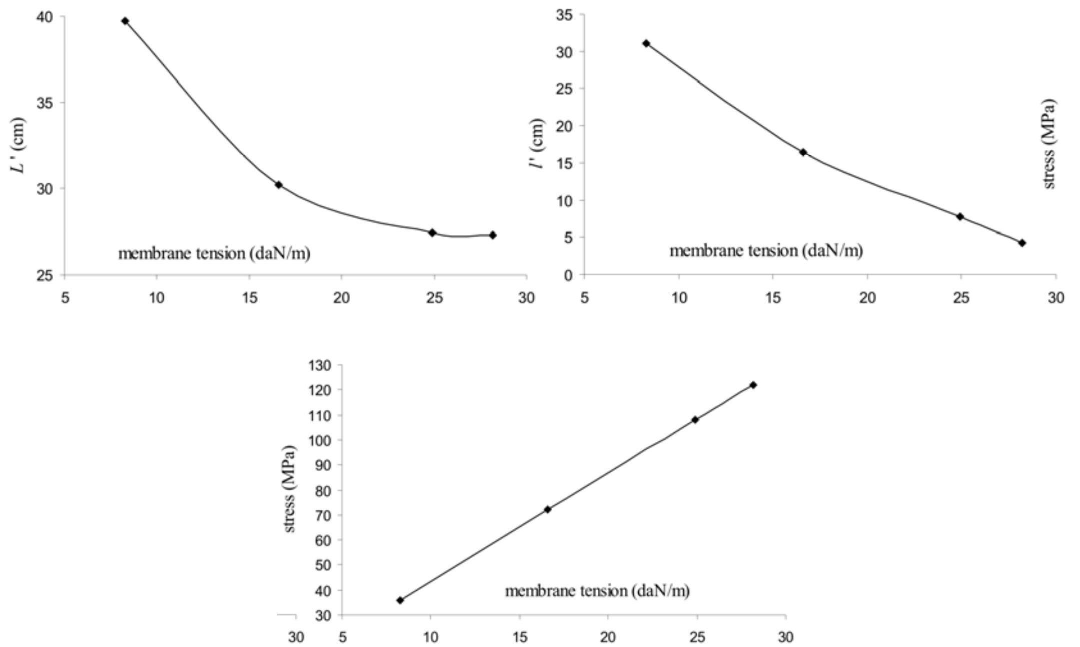


Figure 17. *Curves* $L'(T_m)$, $\ell'(T_m)$ *and* $\sigma'_{\max}(T_m)$ *for a strip boundary wave*

In the prototype panel, the distance $\ell' \approx 20\,\text{cm}$ was measured. It confirms that the membrane tension T_m is close to $16\,\text{daN/m}$.

The first and second curves are important because they clearly show that, from a given strip cross-section, there is a limit value to the membrane tension. For $T_m \approx 30\,\text{daN/m}$ it comes $\ell' \approx 5\,\text{cm}$, and this horizontal distance appears to be close to a practical limit for the construction of a panel. If the required membrane tension is higher, the cross sectional area of the strip have to be increased.

Hence, this study at the boundary defines the strip dimensioning according to the membrane tension. We note that, since it depends on the strip rigidity EI, this parameter can be changed either by modifying the strip cross sectional area (value of I) or choosing an other material (value of E).

3.8. Shape of a strip wave segment

When all the dimensions and forces have been determined, the geometry of the undulating strips must be accurately defined. The objective of this section is to calculate the shape of one wave segment of the strip (for instance the part IP, see figure 9). The whole strip geometry can then be easily obtained by symmetry and replication.

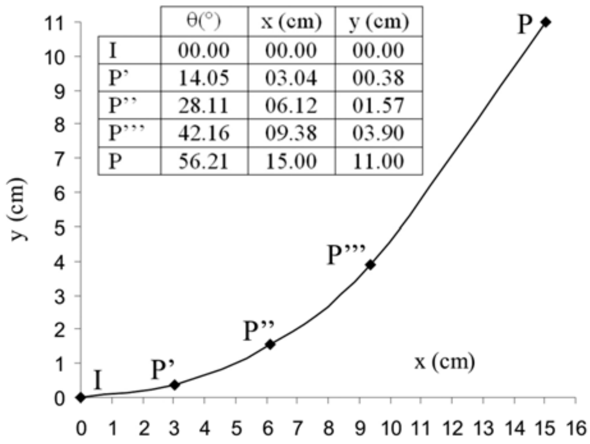
The x and y coordinates of one point located on a wave strip segment can be calculated by considering the angle θ as the shape parameter (figures 9 and 10). We have therefore

$$x(\theta) = \frac{1}{a\alpha^2}\int_0^{\theta/2} \frac{2\cos(2\varphi)\,d\varphi}{(1-k^2\sin^2\varphi)^{1/2}} \quad \text{and}$$

$$y(\theta) = \frac{1}{a\alpha^2}\int_0^{\theta/2} \frac{2\sin(2\varphi)\,d\varphi}{(1-k^2\sin^2\varphi)^{1/2}} \qquad (22)$$

An application is performed for the prototype panel with a membrane tension equal to $17\,\text{daN/m}$ (hence angle $\theta_0 = 56.21°$ for the point P at mid-height). A discrete geometry is obtained by calculating the position of several points. The shape computed for five points I, P’, P’’, P’’’ and P (four portions) is represented in figure 18.

The length of the portions varies and decreases close to the point I. Since this also corresponds to the zone where the normal stress in the strip is maximal, this discretization is appropriate for a FEM analysis.



	θ(°)	x (cm)	y (cm)
I	00.00	00.00	00.00
P’	14.05	03.04	00.38
P’’	28.11	06.12	01.57
P’’’	42.16	09.38	03.90
P	56.21	15.00	11.00

Figure 18. *Shape of the strip wave segment (part IP)*

4. DISCUSSION

The objective of this paper is to present the conceptual design and form-finding of a “tensegrity like” soft panel. Developments are currently pursued in three main directions.

A. Mechanical behavior analysis: The knowledge of the panel dimensions and initial forces provides the necessary data for a FEM analysis with various loading cases. This aims to study the system strength and stiffness, including a possible slackening of the membranes and cables leading to instability phenomena. Experimental testing using tachometry measurements are currently performed to be compared with the numerical results (figure 19, left and middle).

B. Curved panel generation: When the panel is not fixed, mechanisms occur perpendicularly to the flat membranes and the strips can rotate relatively. The panel may therefore be deformed by flexing to generate an anticlastic shape. Numerical studies, using imposed displacements on the edges, are pursued (figure 19, right) in association with experimental testing.

C. Applications: This panel may be characterized by its light weight and flexibility when it is not fixed on the edges. In contrast, when boundary conditions are imposed, the first behavior analysis results show a good rigidity compared to its own weight. Some applications may be therefore anticipated, mainly for surface cladding (roofing or wall) made of flat or curved precast panels fixed onto a rigid structure. Moreover, the two layers of membranes can be of various types (waterproofed, solar filtration effects…) and offer the possibility of inserting in between air, or material for thermal, or acoustic insulation.

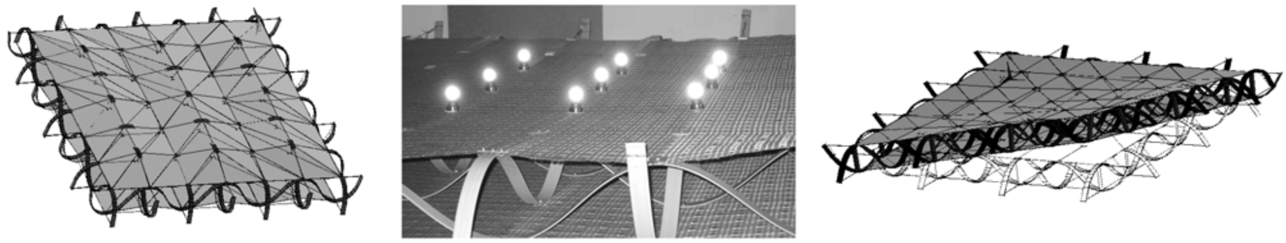


Figure 19. *FEM analysis, experimental testing and anticlastic panel generation*

5. CONCLUSION

Following the construction of a flat soft "tensegrity like" panel prototype, a mechanical analysis is presented to determine the governing relationships between the system geometry and its initial forces. A first form-finding approach is thus proposed to provide a form control method. It allows determination of the tension in the membrane layers from a given strip geometry (amplitude and length of a wave segment). A force control strategy allows then calculating the characteristics of the strip (amplitude and wavelength) according to a required membrane tension. The boundary segment of a strip is also analyzed to give information for its cross-section dimensions. Finally, the geometry of the undulating strip is calculated. Several results are presented, dealing with the prototype panel, and by considering different levels of membrane tension or strip wavelength.

The results obtained are exploitable for a load analysis under external actions. Perspectives deal with the study of the panel mechanical behavior, the possibility to flex it to generate curved shapes and structural cladding applications.

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