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REVIEW

Tensioned Auxetic Structures Manual Calculus

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ABSTRACT

Auxetic materials have several properties very useful to be applied to architecture structures. This paper is aimed to test structurally a specific auxetic structure model. This hypothesis will be checked: if auxetic materials have innovative properties in nanoscale then they will also have these properties in macro-scale. But there are some differences between these dissimilar scales. In the nanoscale auxetic structures have rigid knots with flexible bars, but in the macroscale they will have articulated knots and a cable that stabilizes the set.

A unity of the hexagonal reentrant structure will be tested in order to obtain its structural characteristics. The application of this structure and its behavior in architecture are not yet known, that's why this auxetic model will become an experimental model to establish a structural evaluation of one of the most innovative auxetic geometries, to apply to the construction of new architectures. The results of this research will be clarified by their structural evaluation, by means of the utilization of manual calculus. The reentrant hexagonal geometry provides a strong foundation for research of application of new structural systems on the production of architecture, while identifying transformations that new geometries and their application techniques, will contribute to the development and divulgation of new spatial and typological solutions. That is the reason to claim a detailed analysis to advance on the design and construction of new architectures.

1. Introduction

Auxetic materials are a special type of materials that have a negative Poisson's ratio: they get fat when they are stretched and they get slim when they are compressed. Auxetic behavior is a scale-independent property: this auxetic behavior can be achieved at different structural levels, from molecular to macroscopic level. The internal structure of the material (geometry) is very important to obtain the auxetic effect. The negative Poisson's ratio is the reason why auxetic materials show some particular features when they are compared to conventional materials [1].

In recent years, auxetic material research have been carried out by authors such as R. Lakes, Prall y Gaoyuan, Smith, Alderson, Master-Evans, Grima and others[2], studying their geometry, properties and applications of these auxetic materials, in theoretical and experimental basis since the last third of the 20th century. The applications that have emerged up to the present, include sectors such as textile, industry, aerospace, protection, biomedical, sensors and actuators[3]. In all these cases patterns are defined like continuous structures. The application of these geometries and their behavior in the scalar level of

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architecture like bars and knots structures with tendons, are not yet known, that's why the behavior of these articulated auxetic structures will become experimental models to establish a structural and constructive evaluation of the most innovative variable geometries, to apply to the construction of new transformable architectures.

On this way, the structural behavior of similar structures to the rigid auxetic geometries known in the nanoscale will be studied. But the patterns will be defined like articulated structures with bars and knots which are self-stabilized by tensors. These tensors could be materialized by a new type of buckling-restrained braces (BRB), namely a pre-tensioned cable stayed buckling-restrained brace (PCS-BRB) design by Yan-Lin Guo, Peng-Peng Fu, Peng Zhou and Jing-Zhong Tong, which is formed through introducing an additional structural system of pre-tensioned cables and a number of cross-arms to the outside of a common BRB [4].

The final purpose is seeing if the characteristics of the reentrant hexagonal structure have an adequate behavior that can be useful in order to provide a future constructive definition of developments with this type of geometries in the transformable architecture scale.

2. Material and Methods

A single unit of hexagonal re-entrant auxetic structure exposed in "Transformables 2013 International Congress" [5] will be calculated. The analysis will be realized using bar structures with articulated joints and external pre-forces (tendons) that keep the structure balanced, this mean using auxetic structures as a structure that works due a forces balance. The idea is obtaining the equilibrated positions (aperture angles depending on the force that the tendon supports) defining equilibrium of forces equations.

So, the first item will be calculating a simple auxetic hexagonal structure with balance forces of tendons in order to test if it is auto stabilized and if it improves its structural behavior. All this will be done by hand.

3. Theory

It is expected that the auxetic structures exhibit many attractive properties, such as the high shear modulus [6-8], high indentation resistivity [9-10], high fracture toughness [11] and high energy absorption [12-15].

Many authors have designed and controlled molecular auxetic structures to develop these structures [16]. Textile fibers have been engineered from molecular auxetic polymers with a rigid rod re-orientation approach to the design of auxetic polymers. Auxetic geometric patterns are increasingly used in the generation of novel products, especially in the fields of intelligent expandable actuators, morphological structures of forms and minimally invasive implantable devices. As for smart actuators based on auxetic structures, some investigations were mentioned about the behavior of the shape memory polyurethane foams with auxetic properties, initiated with several stages of post-processing [17]. This behavior is a one-way effect, and it is an embedded property of the polyurethane (PU) constituent of the foam. In the field of medical devices, recent research has evaluated the properties of some auxetic geometries to implement expandable stents [18]. In this paper, a systematic study on the influence of the continuous cell geometry of a cardiovascular stent on its radial compliance and longitudinal strain was presented. Some recent studies regarding shape memory auxetics alloys (SMA) were used for the development of drop-down satellite antennas [19]. The antenna is made using a hybrid truss/honeycomb concept, where the ligaments provide axial deformation (they are flexible), and bending is transmitted through rotating cylinders.

The research of materials for tensile effort has been crucial due to the fact that continuous tension is the main support of structures under investigation.

Before the 18th Century, efficient "push-and-pull" structures would have been inconceivable, because of the inability to get effective behavior of material under tension. Edmonson [20] establishes that, until that moment, only the tensile strength of wood had been wronged (mainly in construction of the ships), but its tensile had not comparison with the stone masonry compression.

However this situation changed greatly in 1851 with the first mass production of steel. That steel was able to attain similar to stone masonry, in both compression and tensile, resulted in a lot of new possibilities and, according to Edmonson [20], a new era of tensional design was opened with the building of the Brooklyn Bridge. Fuller [20] said: "Tension is a very new thing".

The development of steels and other alloys of them led to unexpected results in terms of resistance, weight and performances of materials, which permitted architects and engineers to create new structural concepts and designs. These novel materials not only allowed to get better the resistance of the elements, but also to decrease their cross-section and, consequently, their weight.

However, the type of load modifies the behavior of elements under this load. The tendency of a lineal element is to augment its cross-section when it is compressed along its main axis, (because of the Poisson's ratio effect) and to bulge, which means that it loses its straight form. Conversely, the same element tends to become thinner when it

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is tensioned in the same direction, and more importantly, it "reaffirms" its straight axis. That is why the innovation in materials is vital for the pre-stressed structures future. Compressed elements will be more resistant to buckling, and tensioned members will have better resistance to the tensile forces.

The most recent resources were adopted by some works. These works benefit of their most privileged properties, especially their tensile strength.

The first cable roofs were designed by V. G. Shookhov in 1896 according to Tibert [21]. This Russian engineer developed four pavilions with pending roofs at an exhibition in Nizjny-Novgorod (Russia). Some other structures were proposed during the 1930s after this first attempt, but they were not very important examples.

Apart from the suspension bridges, the importance of tension was elevated to the same level that compression had had during the preceding centuries by other types of bridges. An example is the cable-stayed bridges, which support the deck and also put it under compression by use of the stressed cables. Thus, the cover is prestressed and balanced. Barrios de Luna Bridge in Asturias (Spain), by Javier Manterola, is a very good example, what demonstrates this principle perfectly in its two towers and its main span of 440 m[22].

The Festival of Britain's South Bank Exhibition took place in London in 1951, just three years after the official discovery of tensegrity. In occasion of this, a competition was organized to build a "Vertical Feature", a basic element of international exhibitions. The Skylon was designed by Philip Powell and Hidalgo Moya (inspired and helped by their former Felix Samuely), and it is selected as the best proposal and built near the Dome of Discovery.

Some authors [23-24] establish that this needle-shaped structure was a monument with no functional purpose. However, it became a symbol for the festival, a beacon of technological and social potentialities and, finally, a reference for future architects and engineers. The 300-foot-high needle was a cigar-shaped aluminum-clad body, suspended almost invisibly by only three wires, and seemed to float 40 feet above the ground.

The structure was made-up of a cradle of prestressed steel wires and three splayed pylons. According to Moya: "By an amazing stroke of genius (Felix Samuely) arranged a system of hydraulic jacks underneath the three smaller pylons. Once the whole structure was assembled, he pumped up these jacks and raised the pylons. This put tension or stresses into all the cables and by doing that the whole thing became a stressed structure. This reduced the number of wires needed to anchor the Skylon and halved the amount of oscillation in the structure. This lack of support made the structure look tremendously hazardous. You felt there weren't enough wires to hold it up, which made it tremendously exciting [24].

The stable equilibrium due to its particular configuration provides the feeling of not having enough cables to hold the zeppelin-like shape element up. A diagram displayed by Francis [25] explains the condition for stability of a post supported by stressed wires. If one cable is attached to the soil, the equilibrium of the stanchion will depend on the position where the other chain is held: it collapses if it is fixed in a point down the level of the post. Exist an unstable equilibrium (it fall down with any movement) if the post is at the same level. However, the set is in a stable equilibrium if it is held in a point on the ground; in other words, it tends to return to the erect position when there is any alteration of this situation. Skylon has a similar diagram.

Consequently, the point of application of the ends of the cables that fix a strut conditions the equilibrium of it in a three-dimensional space.

The exploitation of tensile cables was not only improved during the 1950s, but also appear other elements such as membranes, materials and tissues.

In 1950, Matthew Nowicki designed the State Fair Arena, at Raleigh (North Carolina), following his intuitive concepts of suspended roofs.

A German architecture student called Frei Otto had a brief look at the plans and drawings during an USA exchange trip that same year, and he was completely fascinated by the novel idea. In fact, he carried out a doctoral thesis presented in 1952 in which he developed a systematic investigation about this. It was the first comprehensive documentation on suspended roofs [22, 26].

Frei Otto founded the Development Centre for Lightweight Construction five years later in Berlin, and it was included in 1964 in The Institute of Light Surface Structures at the Stuttgart University, to encourage the increase of the tensile architecture research. Therefore, the tensile properties of materials were exploited in order to develop some important works. These materials were especially steel, but also polyurethane, glass fibre, PVC, cotton-polyester mix, acrylic panels, polyester... Between these projects, there was an early four-point tent as a Music Pavilion of the Bundesgartenschau, Kassel (Germany) in 1955, the first large wire-frame network structure with cloth lining, the German pavilion at the World's fair in Montreal 1967 and the famous Olympic Stadium in Munich in 1972, whose structure was calculated by Jörg Schlaich.

A dome made out of plastic skin and wooden struts was built by Pugh [27]. The plastic skin was the component in tension that was supported by the compression members of the structure.

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The name of "tensegrity" has been extended to include any type of pin-connected structure in which some of the frame members are bars only in compression or cables only in tension as W. O. Williams [28] points out. This is the case of the "Wire Wheel Domes" or "Cable-Domes", designed by David Geiger [29]. Since then, many domes have been built with this technique, in which a set of radial tensegrity bundles are connected to an external ring in compression, and converges to an internal ring to join all of them.

Even though some engineers and architects consider these roof structures as tensegrities, Motro [30] identify them as false tensegrities quickly since they have a compressed member in the borderline. It should be recalled that Fuller [31] patented a similar kind of structure, which he later called "Aspension". Geiger designed the first cable-domes for the Olympics in Seoul (1986), followed by the first oval cable-dome, the Redbird Arena in Illinois (1988), the Florida Suncoast Dome in St. Petersburg (1988), and the Tayouan Arena in Taiwan (1993). In fact, the biggest dome built in the world to date was the Georgia Dome in Atlanta (1992) by Levy and Weidlinger Associates, which was demolished in 2017.

By the shortage of the cable-dome network it might be interesting to note that these structures are not very determinate in classical linear terms and have several independent mechanisms, or in other words, inextensional modes of deformation [32].

4. Calculation

A six articulated bars structure in which the bars are called a, b, c, d, e and f, and the knots are called 1, 2, 3, 4, 5 and 6 will be studied. The structure have two tendons in order to stabilize the structure (one of these going to knot 1 to knot 3, and the other going to knot 4 to knot 6) as the figure 1 shows. The rotations are only permitted around the y axis because it is the axis in which the structure is opened and closed. The structure has 6 restrictions. It has 3 restrictions to the displacements + 1 restriction to the rotation respecting to the x axis in the left support. And it has 2 restrictions to the displacements in the y and z axis in the right support.

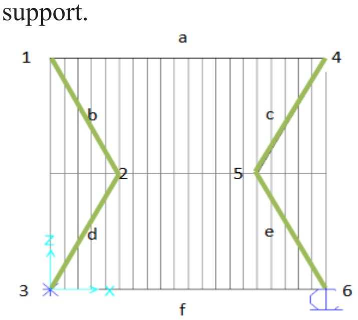

Figure 1. Six articulated bars with tendons structure

The structure will be calculated by manual methods in this manner: if the figure 1 is supposed to appear only with bars and articulated, (without external forces), the system is folded only by the own height action. That is why the own height depends on the gravity acceleration. If we insert a cable or tendon in the interior of the bars, the structure will remain open in a certain position depending on the tensile force applied. This force depends on the longitude of the cable: if the cable is shorter more tension will be obtained and therefore, more opening.

Through this way, the first thing that we need to know is the mass and the length of the bars: we will consider bb = bc = bd = be = 1m and ba = bf = 2m, where "b" is the bar. To graphical effects of calculation we consider despicable the dimensions of the bars (like thickness and density of the knots) to be able to fold totally the structure. A standardized 100.6 round hollow profile is considered to effects of calculus. This profile has a maximum tensile resistance of Nt,u = A · fy = 1770mm2 · 215N/mm2 = 380550N = 380,55KN

In where

A, area of the transversal section

fy, calculus resistance of steel

fy = 215N/mm2 is chosen because it is the fy more unfavorable for the different types of designations and nominal thicknesses in steels. fy = 215N/mm2 corresponds to a steel S235.

As buckling capability by bending, in centered compression, of a constant section bar, it can be taken

Nb,Rd = χ · A · fyd

In where

A, area of the transversal section in classes 1, 2 y 3, or effective area Aeff in sections of class 4,

fyd, calculus resistance of steel, when it is chosen fyd = fy / γM1 with γM1 = 1,05 according to 2.3.3 section of the CTE's DBSE-A [33], where γM1 is the partial safety factor for instability phenomena.

χ, reduction coefficient by buckling, the value of which can be obtained in the 6.3.2.1 section of the CTE's DBSE-A [33] on the basis of the reduced slenderness and the appropriate buckling curve.

The square root of the ratio between the plastic resistance of the calculation section and the critical compression by buckling is called reduced slenderness (λ). Its value is

$$\bar{\lambda} = \sqrt{\frac{Af_y}{N_{cr}}}$$

$$N_{crit} = N_{Eul} := \frac{\pi^2 EI_f}{L^2}$$

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where

E, modulus of elasticity (Esteel = 210000MPa = 210000·106 Pa =);

I, moment of inertia of the area of the section for flexion in the considered plane;

L, buckling length of the piece. It is equivalent to the distance between points of inflection of the buckling deformation that is greater. For canonical cases it is defined in the table 6.1 of the CTE's DBSE-A [33] depending on the length of the piece. For different conditions for axial load or section it is defined in later sections.

$$I_x = I_y = \frac{1}{4}\pi R^4$$

The Area Moment of Inertia for a hollow cylindrical section is as follows:

To the proposed case,

I = 490,87cm4 – 294,37cm4 = 196,5 cm4 = 1,965·10-6m4 (it is the same that the number given in the table)

And the Area of a hollow cylindrical section is:

A = p R2

Where

R, radius of the hollow cylindrical section

To the proposed case,

A = 502 mm2- 442 mm2 = 1771,86 mm2 = 17,7 cm2 (it is the same that the number given in the table)

In this way,

$$N_{crit} = 2 \times \frac{210000 \cdot 10^6 \frac{kg}{m \cdot s^2} \cdot (1/4 \cdot \pi \cdot \quad R^4 - 1/4 \cdot \pi \cdot \quad r^4)}{(2m)^2} = 2 \times \frac{210000 \cdot 10^6 \frac{kg}{m \cdot s^2} \cdot (1/4 \cdot \pi \cdot \quad (0{,}05m)^4 - 1/4 \cdot \pi \cdot \quad (0{,}044m)^4)}{(2m)^2}$$

$$N_{crit} = 2 \times \frac{210000 \cdot 10^6 \frac{kg}{m \cdot s^2} \cdot (4{,}9087385212 \cdot 10^{-6} m^4 - 2{,}9437477146 \cdot 10^{-6} m^4)}{(2m)^2}$$

$$N_{crit} = 2 \times \frac{210000 \cdot 10^6 \frac{kg}{m \cdot s^2} \cdot 1{,}9649908066 \cdot 10^{-6} m^4}{(2m)^2} = 1018173{,}06\ kg \cdot m/s^2\ (N)$$

Then,

$$\lambda = \sqrt{\frac{(\quad 50^2 mm^2 - \quad 44^2 mm^2) \quad 215\ N/mm^2}{1018173{,}06\ N}} = \sqrt{0{,}37415} = 0{,}611678$$

is determined from the reduced slenderness and according to the figure 6.3 of the CTE's DBSE-A [33] exposed in continuation like figure 2. It is supposed a cold formed profile because it is the most unfavorable case of round hollow profiles exposed in the Figure 2. Buckling curve depending on the cross section of the CTE's DBSE-A [33].

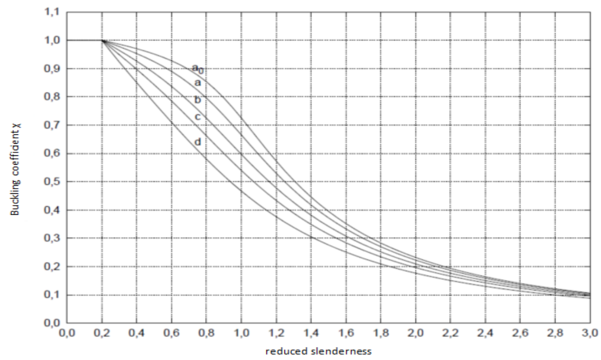

Figure 2. Buckling curves, CTE's DBSE-A

A buckling coefficient χ of 0,775 is obtained according to the figure 3 and the provided dates. So, for these bars the buckling capacity by flexion in centered compression can be taken like:

$$N_{b,Rd} = x \cdot A \cdot f_{yd} = 0{,}775 \cdot 1771{,}86\ mm^2 \cdot \frac{215 N/mm^2}{1{,}05}$$

$$= 281177{,}03\ N = 281{,}177\ KN$$

A maximum compression effort of 280 KN will be considered. So, a cable that supports 280 KN of tensile will have to be calculated in order to compensate the compression effort and to balance the structure:

$$= \frac{F}{A} \Rightarrow b = \frac{F_b}{A_b} = \frac{280KN}{17{,}70cm^2} = 15{,}82\ KN/cm^2$$

The tension which supports the cable will have to be much greater than the one that supports the bar, because its section is much smaller. So, a cable 19×GALVA 8 will be chosen, because it owns a very high tensile strength and a very big section. The properties of this cable appear on figure 3.

19x7 Galva	1960 N/mm2	EN 12 385-4
Nominal diameter (mm)	**approximate weight (kg/m)**	**breaking load (kg)**
8	0.257	4200

Figure 3. Table of steel cables

The maximum tensile strength that the cable is capable of support is *1960 · 50,24 = 98470,4 N = 98,47 KN*

With all these data different positions of the structure will be calculated in order to verify the structural behavior of these balanced forces structures. In no case the maximum tension admissible of compression for the bar will can be exceeded. In the same way, in no case the maximum tension admissible of tensile for the cable will can be exceeded.

5. Results

The 100.6 considered standard hollow round profile has a bar “d” mass of m_{bd} = 13,90kp/m = 13,90 kg

The cable has a mass of m_c = 0,257kg/m => $m_{c\ 1m}$ = 0,257kg

So, the total mass to the bar + the cable is $m_{Td} = m_{bd} + m_{c1m}$ = 13,89kg + 0,257kg = 14,147kg

The own weight for a total mass of m_{Td} is $P_{pd} = m_{Td} \cdot g$ = 14,147kg · 9,81 m/s^2 = 138,78 N, where “g” is the gravitational acceleration.

The vertical component of the force that the cable supports is the equivalent to the reaction that would have the structure in the basis. The results of the all cases of calculus are exposed in continuation.

5.1 Results for Own Weight of the Vertical Bar and Cabled

In this calculus case the masses of the weight force of the vertical bar and the proportional cable are the only ones considered.

For a totally deployed structure (a=90°), the base reaction in the knot 3 is

$R_3 = P_{bd+cd} + P_{bb+cb}$ = 138,78 N + 138,78 N = 277,56 N = 0,27756 KN

Where

P_{bd+cd}, own weight of “d” bar and the “d” cable

P_{bb+cb}, own weight of “b” bar and the “b” cable

The bar and the cable support perfectly this force.

Calculus with this weight will be done in order to find the aperture of the structure depending on the components of the force on bar “d” in the axis represents in the figure 4. The obtained results are in the figure 4 too.

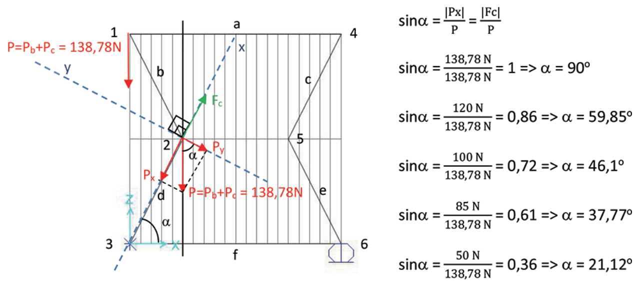

Figure 4. Considered loads and structure apertures for these loads

The result is totally coherent because when tension and force (these two properties are directly proportional) decreases the structure is more closed.

5.2 Own Weight of the Vertical and Horizontal Bars and Cable

The weight of the vertical and horizontal elements that fall over to the considered bar “d” is added to the own weight of the bar “d” and the cable. So:

m_{bd} = 13,90kp/m = 13,90 kg

m_{cd} = 0,257kg/m => $m_{c\ 1m}$ = 0,257kg

$m_{Td} = m_{bd} + m_{cd}$ = 13,89kg + 0,257kg = 14,147kg

$P_{pd} = m_{Td} \cdot g$ = 14,147kg · 9,81 m/s^2 = 138,78 N

$m_{over\ d} = m_{bb} + m_{cb} + m_{ba}$ = 13,89kg + 0,257kg + 13,89kg = 28,037kg

where

$m_{over\ d}$, mass over “d” bar

m_{bb}, “b” bar mass

m_{cb}, “b” cable mass

m_{ba}, “a” bar mass

$P_{over\ d} = m_{over\ d} \cdot g$ = 28,037kg · 9,81 m/s^2 = 275,04 N

$F_{T2d} = P_{pd} + P_{over\ d}$ = 138,78 N + 275,04 N = 413,82N

Where

F_{T2d}, total force on “d” to the case 2

Calculus with this weight will be done in order to find the aperture of the structure depending on the components of the force on bar “d” in the axis represents in the figure 5. The obtained results are in the figure 5 too.

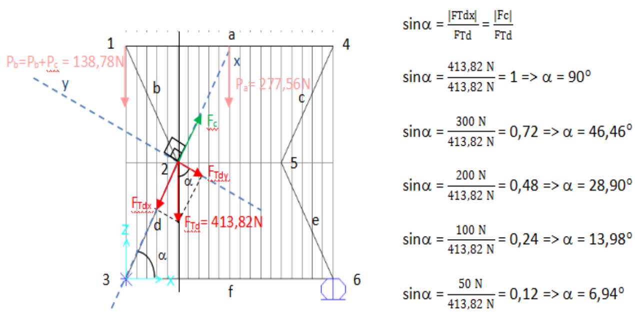

Figure 5. Considered loads and structure apertures for these loads

The result is totally coherent because when tension and force (these two properties are directly proportional) decreases the structure is more closed.

5.3 Own Weight of the Vertical and Horizontal Bars and Cable and Vertical Exterior Forces

The vertical exterior forces than can affect are:

- Ported constructional elements, 1,2 KN/m
- Use overload, 5KN/m
- Snow, 5KN/m

These loads have been defined with a basis of the CTE DB-SE-AE [34]. The forces considered are:

$F_{T2d} = P_{pd} + P_{over\ d}$ = 138,78 N + 275,04 N = 413,82N

$F_{ve\ d}$ = 11,2KN = 11200N

Where

$F_{ve\ d}$, vertical exterior force on “d”

$F_{T3d} = F_{T2d} + F_{ve\ d}$ = 413,82N + 11200N = 11613,82N

Where

F_{T3d}, total force on “d” to the case 3

Calculus with this weight will be done in order to find the aperture of the structure depending on the components

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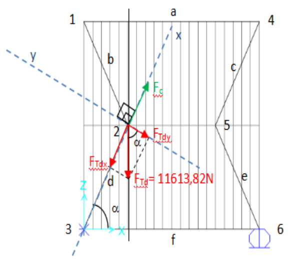
of the force on bar "d" in the axis represents in the figure 6. The obtained results are in the figure 6 too.



$$\sin\alpha = \frac{|FTdx|}{FTd} = \frac{|Fc|}{FTd}$$

$$\sin\alpha = \frac{11613{,}82\ N}{11613{,}82\ N} = 1 \Rightarrow \alpha = 90°$$

$$\sin\alpha = \frac{7000\ N}{11613{,}82\ N} = 0{,}60 \Rightarrow \alpha = 37{,}07°$$

$$\sin\alpha = \frac{2000\ N}{11613{,}82\ N} = 0{,}17 \Rightarrow \alpha = 9{,}92°$$

$$\sin\alpha = \frac{500\ N}{11613{,}82\ N} = 0{,}04 \Rightarrow \alpha = 2{,}47°$$

$$\sin\alpha = \frac{50\ N}{11613{,}82\ N} = 0{,}004 \Rightarrow \alpha = 0{,}25°$$

Figure 6. Considered loads and structure apertures for these loads

The result is totally coherent because when tension and force (these two properties are directly proportional) decreases the structure is more closed.

5.4 Own Weight of the Vertical and Horizontal Bars and Cable, Vertical Exterior Forces and Horizontal Exterior Forces

The horizontal exterior force which can affect is 1,6 KN like horizontal load of wind. This load has been defined with a basis of the CTE DB-SE-AE [34]. The forces considered are:

$F_{T3d} = F_{T2d} + F_{ve\ d} = 413{,}82N + 11200N = 11613{,}82N$

$F_{Tdh} = 1600N$

Where

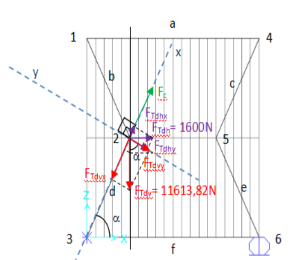
FTdh, total applied horizontal force on "d" to the case 4

FT4d = FT3d + FTdh = 11613,82N + 1600N = 13213,82N

Where

FT4d, total force on "d" to the case 4

Calculus with this weight will be done in order to find the aperture of the structure depending on the components of the force on bar "d" in the axis represents in the figure 7. The obtained results are in the figure 7 too.



$$F_c = F_{Tdvx} + F_{Tdhx}$$

$$\sin\alpha = \frac{|FTdvx|}{FTdv} = \frac{|Fc|}{FTd}$$

$$\sin\alpha = \frac{13213{,}82\ N}{13213{,}82\ N} = 1 \Rightarrow \alpha = 90°$$

$$\sin\alpha = \frac{10000\ N}{13213{,}82\ N} = 0{,}76 \Rightarrow \alpha = 49{,}18°$$

$$\sin\alpha = \frac{7000\ N}{13213{,}82\ N} = 0{,}53 \Rightarrow \alpha = 31{,}99°$$

$$\sin\alpha = \frac{2000\ N}{13213{,}82\ N} = 0{,}15 \Rightarrow \alpha = 8{,}71°$$

$$\sin\alpha = \frac{1000\ N}{13213{,}82\ N} = 0{,}08 \Rightarrow \alpha = 4{,}34°$$

Figure 7. Considered loads and structure apertures for these loads

The result is totally coherent because when tension and force (these two properties are directly proportional) decreases the structure is more closed.

6. Discussion

In this paper an analysis of forces and positions in structures with articulated joints with external pre-forces that keep the structure balanced has been made. This mean using auxetic structures as a structure that works due a forces balance.

As a result we have obtained very elastic structures that receive only small forces on their bars when a load is applied. These structures could work fine if we piled them and apply loads caused by wind, quakes...

The maximum force that is supported by the cable in the proposed conditions is 13213,82 N or 13,21 KN. This force satisfies the characteristics of the cables that exist in the market.

The opening and closing positions according to the applied stresses are totally coherent. All these positions support the external forces typical in architecture.

7. Conclusion

It is concluded that auxetic structures, used in other disciplines, could be very useful in architecture, creating a new structural conception for architecture and resolving current problems. It's very useful the negative Poisson´s ratio applied in the change of scale according to the use of auxetic geometries.

Concretely, it is concluded that this structure work correctly to the tensions and loads proposed. So, it is a new possibility to explorer in the discipline of architecture.

As a future line could be studied the auxetic structures for architecture made with Self-compacting Concrete containing Silica Quicksand[35], whose high quality has been achieved for SCC mixture contains the quicksand and silica fume contents with low lubricant admixture dosage.

Appendices

A. Pressure exerted by the wind

The wind action q_e can be expressed like $q_e = q_b \cdot c_e \cdot c_p$, where:

q_b, dynamic pressure of the wind. In simplified form can be adopted 0,5 KN/m^2 in all points of Spain. More accurate values can be obtained by the annexed D of the CTE DB-SE-AE [34]. These more accurate values evaluate the geographical location of the work.

c_e, exposition coefficient, variable with the height of the point considered. This coefficient evaluates the roughness of the environment where the construction is located.

To urban buildings until 8 floors can be taken a constant height independent value of 2,0.

c_p, wind coefficient or pressure coefficient. It depends on the shape and orientation of the surface respect to the wind. It also depends on the situation of the point respect to the surface edges. A negative value indicates suction. For this structure a value of 0,8 is taken.

So:

$q_e = q_b \cdot c_e \cdot c_p = 0{,}5\ KN/m^2 \cdot 2 \cdot 0{,}8 = 0{,}8\ KN/m^2 = 800\ N/m^2$

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