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Article

A comparative study of the pliability of 2D auxetic architectonic structures by means of CAD

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Abstract: Auxetic materials are a special type of materials that have a negative Poisson's ratio (NPR): they get wider when they are stretched and they get narrower when they are compressed. In this paper a comparative study of 2D patterns of auxetic geometries, carried out by means of computer-aided design, is presented. The study consists of the development of a CAD library of auxetic geometries to apply them to architecture. The geometric behavior of the eighteen auxetic 2D patterns is tested from the developed library in order to develop a systematic comparison, analyzing relevant properties of these geometries, such as maximum achievable area reductions in relation with the total length of the bars of the structure, in order to obtain a growth factor.

Keywords: auxetic; architecture; geometries; patterns; growth

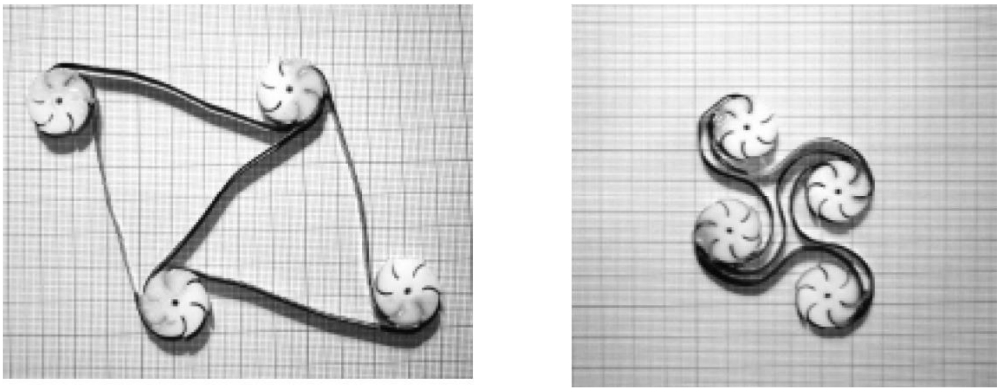
1. Introduction

If a material is stretched, it usually thins. The Poisson's ratio, $v = -d\varepsilon_{trans} / \varepsilon_{axial}$, ε_{trans} and ε_{axial}, can define numerically this change of dimensions, which are the transverse and axial deformations when the material expands or contracts in the axial direction. Generally speaking, v_{ij} is the Poisson's ratio, that provides a measure of the section narrowing of a prism of linear and isotropic elastic material that indicates a compression in the 'j' direction when a stretching is applied in the 'i' direction. Most materials have Poisson's ratio values ranging between 0.0 and 0.5. A perfectly incompressible isotropic material elastically deformed at small strains would have a Poisson's ratio of exactly 0.5.

Auxetic materials are a special type of materials that have a negative Poisson's ratio (NPR): they get wider when they stretch and thinner when compressed [1–4]. The auxetic properties of natural materials (skins, some minerals ...) and artificial materials (Gore-Tex®, foams, polymeric foams) have been described.

Some auxetic and potentially auxetic geometries, usually classified as "reentrant", "chiral" and "rotating" because of the characteristics that generate the auxetic behavior, have been explained in previous reviews and investigations [5]. The models that are in nature or have been designed by other authors in scales different to architecture have rigid nodes and flexible bars, but the present paper studies the behavior of articulated nodes and rigid bars.

Many authors have designed and controlled molecular auxetic structures to develop these structures [6]. 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 [7]. This behavior is a one-way effect, and it is an embedded property of the polyurethane (PU) constituent of the foam [8]. In the field of medical devices, recent research has evaluated the properties of some auxetic geometries to implement expandable stents [9]. 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 [10]. As shown in **Figure 1**, 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. In **Figure 1a** can be seen an extended hexagonal chiral unit cell and in **Figure 1b** can be seen a compressed hexagonal chiral unit cell.



(a) **(b)**

Figure 1. (a) extended; **(b)** compressed hexagonal chiral unit cell [10].

Zhong et al. [11] analyzed the existing structure shapes, material types, manufacturing processes and mechanical behaviors, that were reported and discussed. Liu et al. [12,13] examined the current applications and characteristics of these structures, development directions for auxetic meta-materials were highlighted to meet future engineering demands for multi-functionality.

Articulated nodes and rigid bars information in the scale of the architecture has not been provided. The application of these materials and their behavior in architecture, and at the scalar level of it, is not yet known. That is why the auxetic materials will become experimental models that will establish the most relevant properties for the design of the most innovative variable geometries, which will be applied to the construction of new transformable architectures.

The first deployable structure patent is found in 1944 [14], with the “Improvements in supports for tents, marquees, temporary bridges and other portable structure” patent. As shown in **Figure 2**, this patent was for a structure that consisted in a long cannon vault composed by a succession of lowered and folding bows. So, deployable structures are a relatively recent discipline.

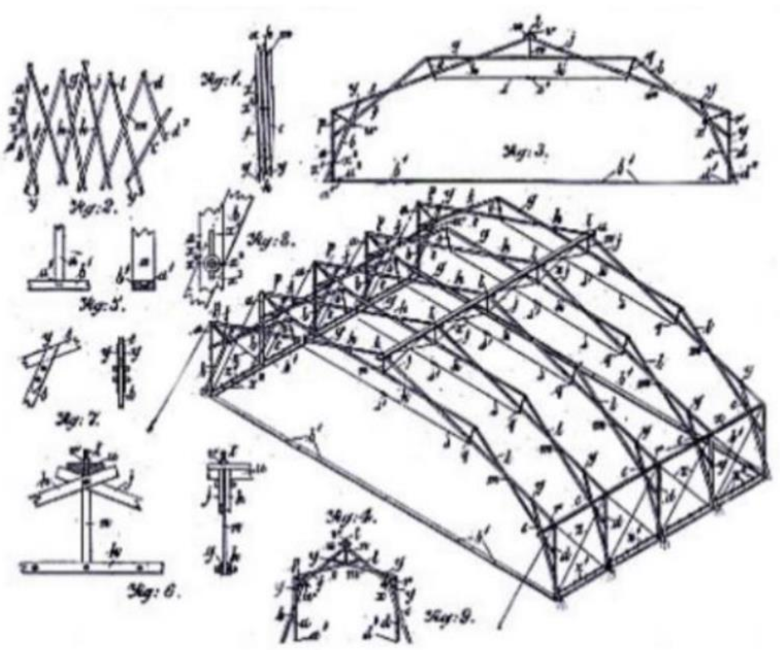


Figure 2. Improvements in supports for tents, marquees, temporary bridges and other portable structure, patented by Barde Salden Watkins in 1944 [14].

R. Buckminster Fuller was a great exponent of this discipline of structures in the 50s. Fuller developed his first geodesic dome patent in 1951 [13] and he kept studying this type of structure throughout his professional career. In **Figure 3** can be seen his geodesic system, developed in 1954.

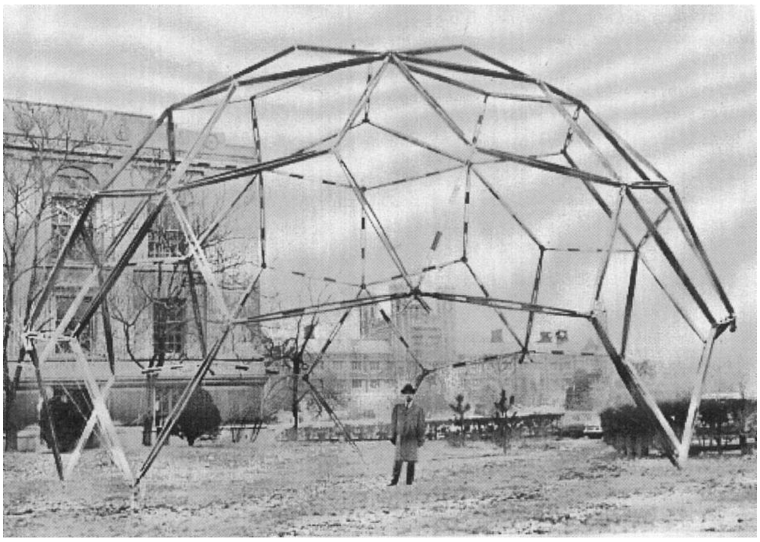


Figure 3. Geodesic system of Buckminster Füller, 1954 [14].

Emilio Pérez Piñero was the inventor of deployability [15], based on modularity, light weight and transformability concepts. His main innovation is a spatial deployable structure of bars, as shown in **Figure 4**, achieved thanks to articulated nodes using scissor mechanisms and formed of three or four bars linked in one interior point. This system had not been documented before and he protected it by patents between 1961 and 1972. Nowadays, there are solutions of this not understood or exceeded by subsequent investigators.

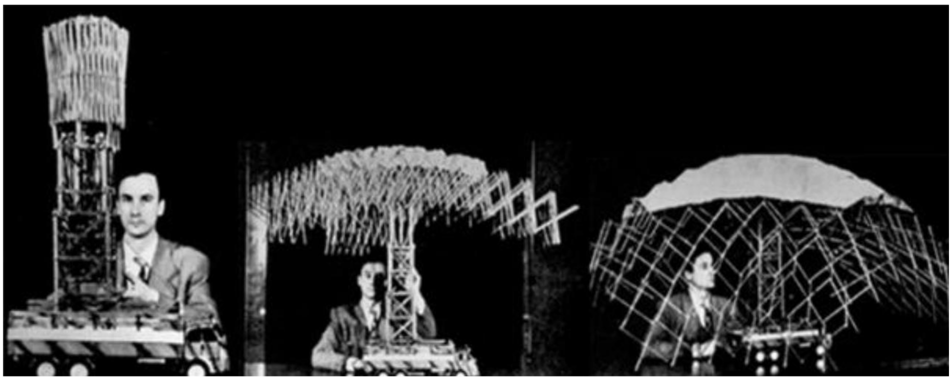


Figure 4. Piñero's transformable shell of Piñero, 1962 [14].

Recently, in the 80s, Calatrava [16] preferred the use of articulated arms instead of scissors in proposals that made him famous, like the foldable entrance for the Ernsting store, in 1983, and many others. In 1988 he presented his thesis "The pliability of three-dimensional structures" [16], in which he carried out a geometric study of the deployable structures from rhomboidal, polyhedral, cubic and spherical modules, as shown in **Figure 5**. Later on, he designed movable roofs and cantilevers based on articulated single arms.

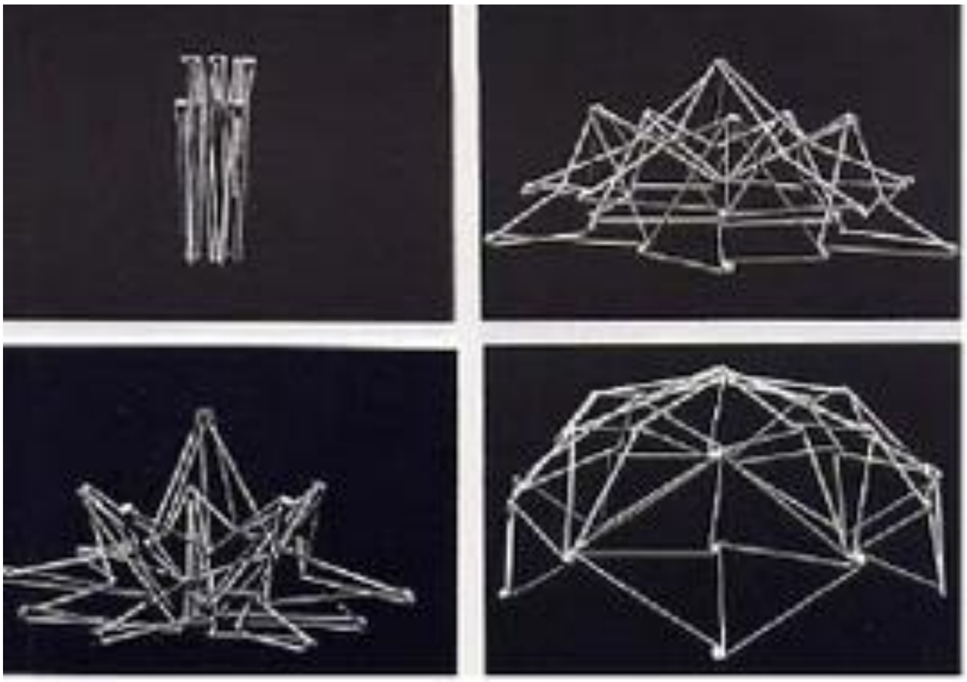


Figure 5. Images of Santiago Calatrava thesis [14].

The additional information of the relevant properties of different auxetic geometries with articulated nodes and rigid bars, systematic and comparative, would be beneficial for the development of novel foldable structures for architecture.

In this study, a comparative study of 2D patterns of auxetic geometries carried out by means of computer-aided design is presented. The beginning of the presented research focuses on the generation of a CAD library of auxetic and potentially auxetic geometries for 18 2D models of architecture, adapted or based on the information of previous papers, patents and conference, and others have been developed by us. So, results are totally independent of materials. It is a theoretical study useful to know the capacity of folding in structures usable in architecture.

When the CAD library is developed, the properties of some auxetic geometries were checked and a systematic comparison was developed, studying the special properties of those geometries for the creation of deployable structures for architecture, such as maximum area reductions (in relation with the total length of the bars of the structure), in order to obtain a growth factor.

The relationship between the CAD analysis and physical models is presented at the end of the paper; in order to understand how a structure actually works. 2D CAD auxetic models are mechanisms that need to be fixed in a determinate position to become structures.

According to state of the art, the present study constitutes the only comprehensive comparative study of auxetic geometries in architecture, done so far. The geometric variations on these models could be infinite, since we could verify multitude behaviors varying the size of each 2D structure bar. However, this study of geometric variations for the same pattern will not be developed. A comparison between regular 2D patterns will be carried out.

2. Computer-aided designs

2.1. Design method and configuration

Some geometric patterns are developed using AutoCAD, by obtaining different cells of units and combining them into 2D patterns. The structures were generated in the models by drawing lines of one meter. These lines correspond to the bars. First of all, an individual cell is generated and, later, by combining these cells a 2D pattern is generated. Possible positions of different auxetic typologies have been modeled in the space since they are completely folded until they reach their maximum opening, in order to analyze the relationship between the amount of used mass and the surface achieved. For this, the total length of bars used in the construction of each structure will be counted, as an analogy to the quantity of mass.

The goal is to obtain the lightness of auxetic structures and their capacity of pliability in order to make drop-down structures. The most important thing is the relation between full spaces and empty spaces. Full spaces are the bars, this is, everything that has some mass. Empty space is the volume of the structure, all that doesn't have mass. This is a theoretical study, because bars in reality have material, but this will be considered for future investigations. In the present study the focus will only be on the relation between quantity of bars and volume when the nodes are totally articulated.

In this study we will look for a general behavior, so the length perfectly identifies those linear elements used. The relationship between area (A) and length (L) will give us a relation (K) between said units, helping us to understand the growth values of these very particular structures.

The area of each figure will correspond to the square, circumference or polygon (as appropriate), where the figure is inscribed. From the division and the subtraction of Kmáx and Kmín, FC (:) and FC (-) growth factors of each structure will be obtained. The applicable patterns are studied individually in order to establish structural developments according to the size, as well as transforming architectures that follow novel geometric developments in deployable auxetic architectures. We have tried to obtain structures with similar overall dimensions, although some differences appear due to the use of cell units with different degrees of complexity (see **Table 1**).

Auxetic structures are classified in some groups depending on their geometric configurations [4]: re-entrant structures, chiral structures, rotating units, angle-ply laminates, hard molecules, microporous polymers model and liquid crystalline polymer model. Actually, the auxetic materials need not have internal inhomogeneity with structures, as shown in **Table 1**. There is a large number of auxetic homogeneous materials, especially anisotropic crystals, having negative Poisson's ratio in one or more directions. Moreover, some aerogels, which are considered, as homogeneous and isotropic, may exhibit auxetic behavior [17]. To use geometries like structural elements for deployable structures we are going to select re-entrant structures, chiral structures, rotating units and microporous polymers model, because they have the possibility of folding like mechanisms.

These structures are: hexagonal re-entrant structure [18–22], star re-entrant structure [21], triangular re-entrant structure [23], square re-entrant structure, hexagonal honeycomb re-entrant structure [4], square grid re-entrant structure [4], lozenge grid re-entrant structure [24], triangular, square, rectangular, hexagonal and circular chiral structures [25], triangular, square, rectangular and different rectangles rotating units [26], square and rectangular microporous polymers [4].

Such limit cases help us also to obtain the maximum area reduction attainable by each of the structures considered here, which is indeed useful for design tasks linked to deployable architectures. **Table 1** includes some images of 2D potentially auxetic individual structures for providing the deployable development applied in assessing the behavior of the different geometries–structures under study.

Table 1. Deployable development of auxetic 2D patterns, own elaboration.

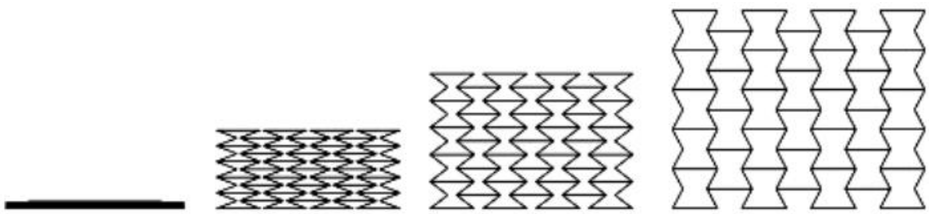
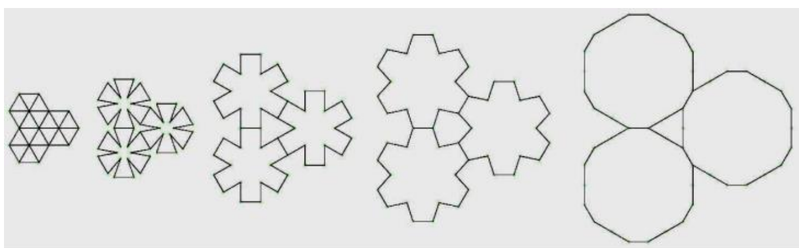
Name		**Deployable 2D development**
Re-entrant structures	Hexagonal	
	Star	
	Deployable development of auxetic 2D patterns, own elaboration	

Table 1. (*Continued*).

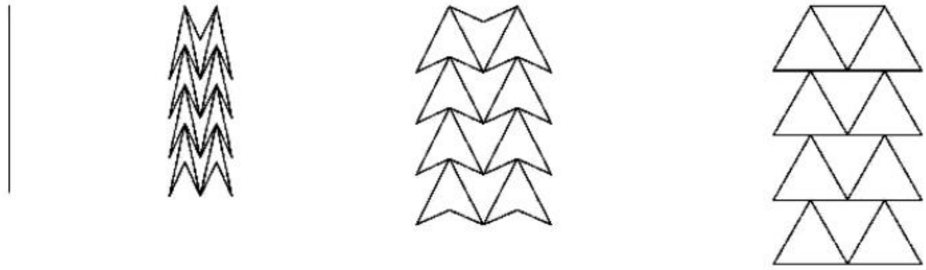
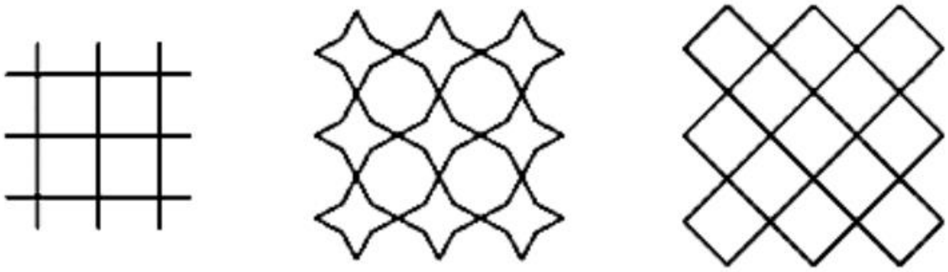
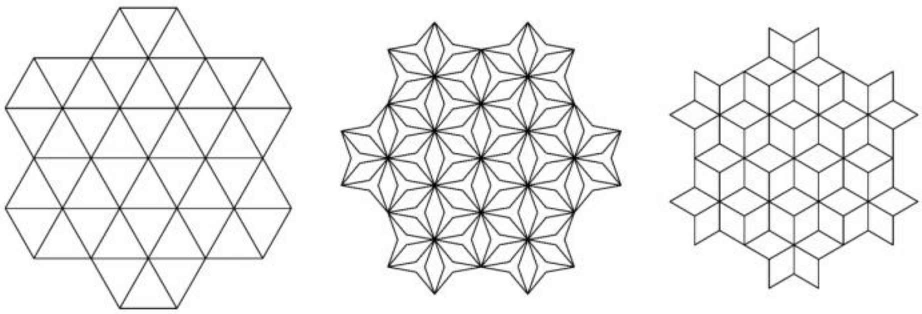
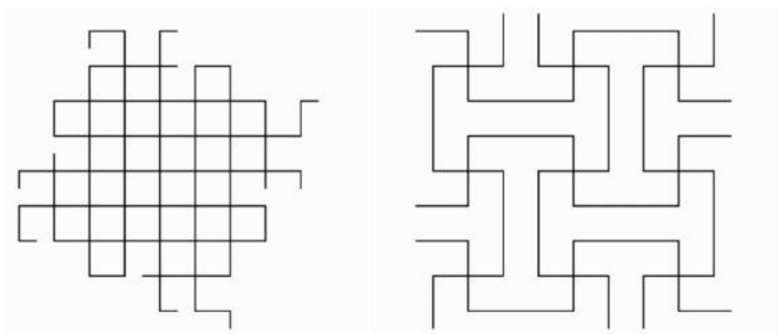
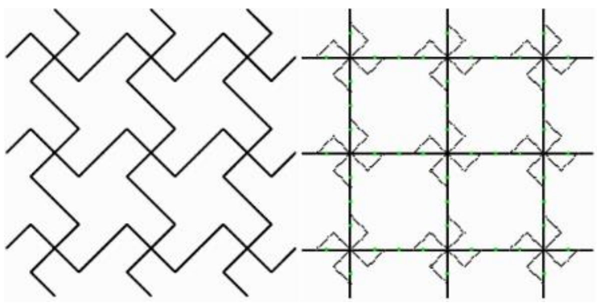
Name	**Deployable 2D development**
Triangular	
Square	
Hexagonal honeycomb	
Square grid	
Lozenge grid	
Deployable development of auxetic 2D patterns, own elaboration	

Table 1. (*Continued*).

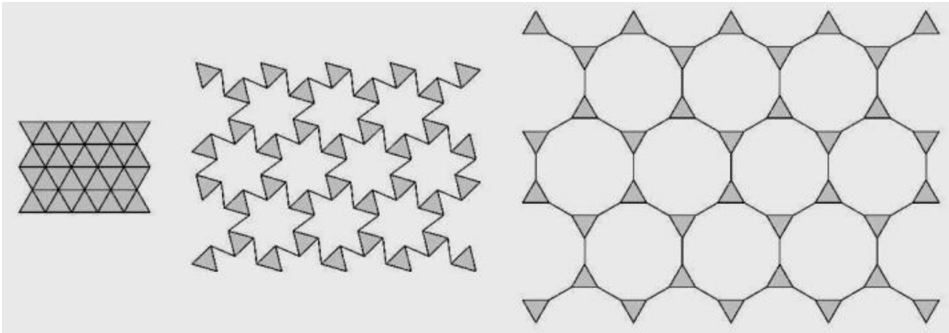
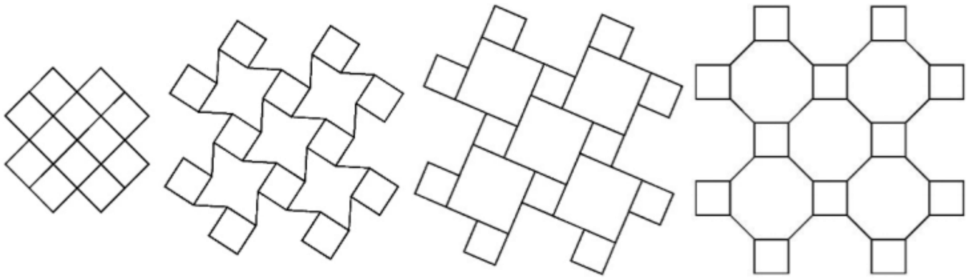
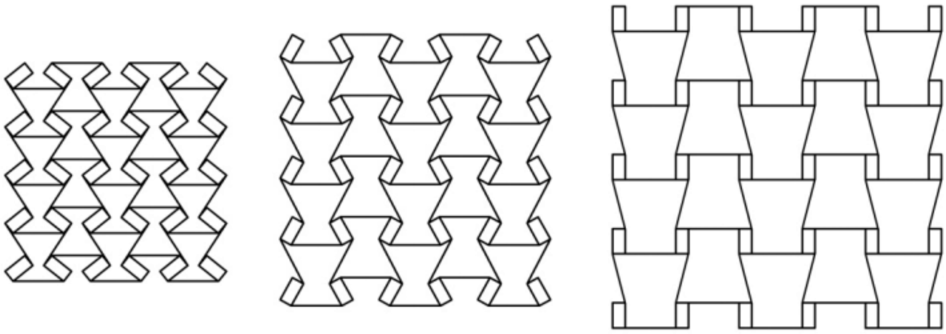
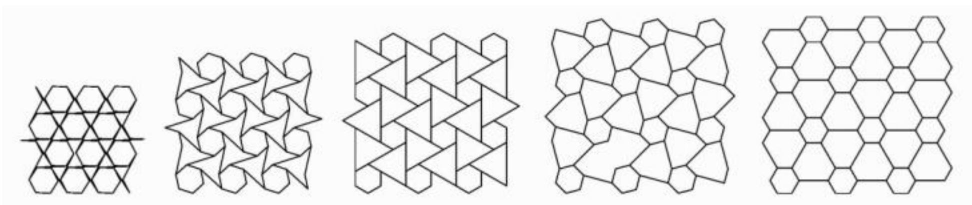
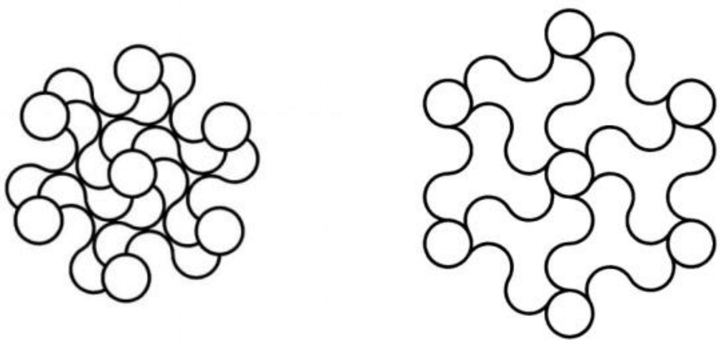
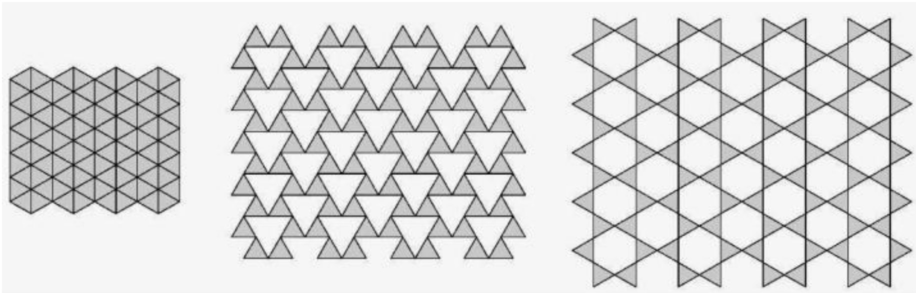
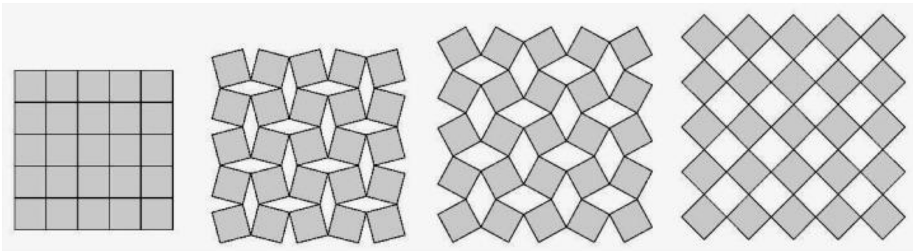
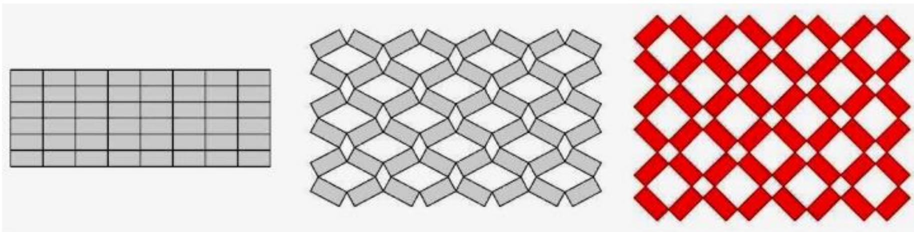
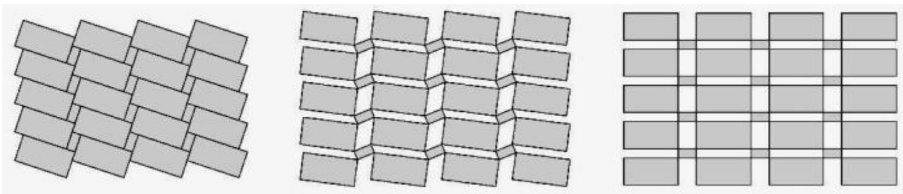
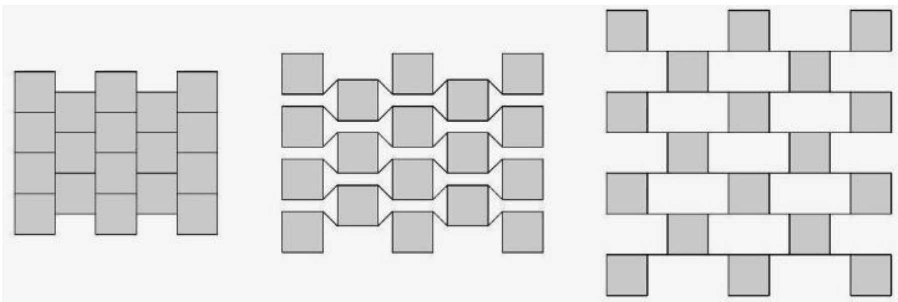
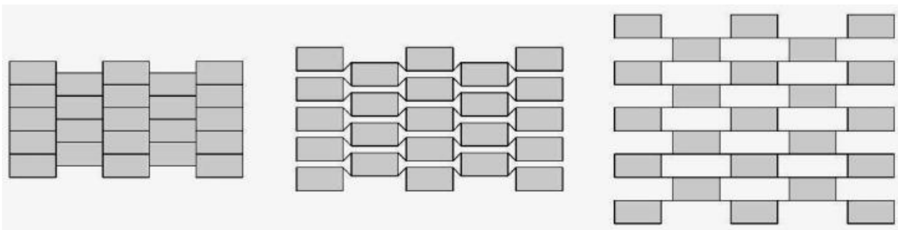
Name		Deployable 2D development
	Triangular	
	Square	
Chiral structures	Rectangular	
	Hexagonal	
	Circular	
	Deployable development of auxetic 2D patterns, own elaboration	

Table 1. (*Continued*).

Name		**Deployable 2D development**
Rotating units	Triangular	
	Square	
	Rectangular	
	Different rectangles	
Microporous polymers	Square	
	Rectangular	

Deployable development of auxetic 2D patterns, own elaboration

Note: Rigid cell of the chiral structures, rotating units and microporous polymers can be full of or without any mass.

2.2. CAD library of auxetic geometries

CAD development of auxetic and potentially auxetic patterns in order to study them is summarized in **Table 1**, which shows respectively the different CAD patterns of 2D auxetic structures designed. Most of these names and geometries are picked from previous publications, research, patents and websites, and some of them present significant adaptations or even our own new designs.

2.3. Comparative study of the individual 2D structures

A total of 18 2D auxetic structures have been modeled in order to obtain detailed information such as maximum area reductions attainable in relation to the total length of the bars of the structure, in order to obtain a growth factor.

Table 1 provides an additional performance map, relevant for using these kinds of geometries as structural elements. The values of growth factor (FC (:) and FC (-)) of the 2D auxetic structures have been normalized, by dividing area (A) and length (L).

2.4. Final summary and discussion

A summary of results, with the significant design awarded properties for the planar 2D auxetic structures under study, is included in **Table 1**. From these results (see **Table 1**) it is important to establish general trends and connections between the different properties of 2D auxetic geometries. It is important to comment on some highly interesting details.

The table that contains the values to study the geometric behavior of the 2D auxetic structures is presented below (**Table 2**), in which:

L—Total length of bars in the considered structure;

V_{min}—Minimum volume in the considered structure;

V_{max}—Maximum volume in the considered structure;

K_{min}—Vmin/L minimum ratio;

K_{max}—Vmax/L maximum ratio;

FC (:)—Kmax/Kmin growth factor;

FC (-)—Kmax-Kmin growth factor;

M.P.—Microporous polymers.

If the result is #¡DIV/0!, it significance is that is a division by 0.

Table 2. Geometric behavior of auxetic 2D patterns (own elaboration).

Name		***L***	A_{min}	A_{max}	K_{min}	K_{max}	**FC (:)**	**FC (-)**
Re-entrant structures	Hexagonal	79.00	0.00	35.00	0.00	0.44	#¡DIV/0!	0.44
	Star	114.00	21.99	233.03	0.19	2.04	10.60	1.85
	Triangular	73.00	0.00	13.86	0.00	0.19	#¡DIV/0!	0.19
	Square	72.00	36.00	72.00	0.50	1.00	2.00	0.50
	Hexagonal honeycomb	126.00	16.49	21.99	0.13	0.17	1.33	0.04
	Square grid	152.00	88.20	121.00	0.58	0.80	1.37	0.22
	Lozenge grid	72.00	72.00	144.00	1.00	2.00	2.00	1.00

Table 2. (*Continued*).

Name		*L*	A_{min}	A_{max}	K_{min}	K_{max}	FC (:)	FC (-)
Chiral structures	Triangular	216.00	17.32	189.99	0.08	0.88	10.97	0.80
	Square	64.00	14.00	55.46	0.22	0.87	3.96	0.65
	Rectangular	376.00	302.44	662.79	0.80	1.76	2.19	0.96
	Hexagonal	141.96	45.74	157.62	0.32	1.11	3.45	0.79
	Circular	119.32	94.07	153.94	0.79	1.29	1.64	0.50
Rotating units	Triangular	84.00	13.86	48.50	0.17	0.58	3.50	0.41
	Square	100.00	25.00	50.00	0.25	0.50	2.00	0.25
	Rectangular	288.00	96.00	195.96	0.33	0.68	2.04	0.35
	Different rectangles	432.00	445.50	570.00	1.03	1.32	1.28	0.29
M.P.	Square	84.00	20.00	49.00	0.24	0.58	2.45	0.35
	Rectangular	154.00	50.00	108.00	0.32	0.70	2.16	0.38

From **Table 2**, we can create **Figure 6**, in which we can see, in a more visual way, the behavior of the 2D auxetic structures, by FC (:) and FC (-). **Figure 6** shows a series of bars in red that indicates the division growth factor FC (:) and, in blue, a series of bars that indicates the subtraction growth factor FC (-). Near to each bar appears the geometry of the corresponding pattern, in order to understand quickly the values of each 2D pattern.

It can be seen that the star-shaped reentrant structure has a growth factor that is far above the average, so it would be very interesting to apply it as a deployable auxetic structure. However, it has the limitation that it is one of the structures that folds less in the auxetic form (**Table 2** and **Figure 1**), so that their joints would have to be designed in a way that allows turns which generate non-auxetic folding. Like most 2D reentrant structures, they consist of joints in a single plane of several rods.

The turns that allow these joints go from 0° to 150°. At first the apparent solution would be to give the articulation more breadth of rotation. However, if we study the geometry, the only form of non-auxetic folding for total packing of the structure is to develop an intermediate joint in the bars remaining on the outside after obtaining maximum auxetic folding. In addition, it would be necessary to introduce an opening system that allows opening this auxetic geometry to obtain its folding and packaging suitable for transport.

On the other hand, overall growth factors for 2D chiral structures are observed, highlighting the triangular chiral structure by FC (:). The maximum folding of this type of structures is the polygon around which the bars rotate. If we wanted larger compacting, as in the previous structure, we would have to resort to non-auxetic final folds (and this always counts on the fact that the base polygon has no mass inside). For chiral structures, non-auxetic folding is easier to achieve, since it only consists of opening one of the vertices of the polygon and giving more rotation to the joints so that some bars can be folded over others.

It should also be noted that the 2D hexagonal reentrant, triangular reentrant and tetrahedral reentrant structures are fully folded auxetically. It is an exceptional property when working with these geometries for deployable structures.

CAD development for some types of auxetic geometries is provided (re-entrant, chiral, rotating…, all of which are 2D planar structures) and establishes the structures typical values such as maximum area reductions attainable in relation with the total length of the bars of the structure. These values allow us to obtain a growth factor. We have also tried to find some typically described 'auxetic' geometries, whose response is actually not auxetic in their maximum aperture when they are 2D patterns, like the rectangular rotating unit (in red).

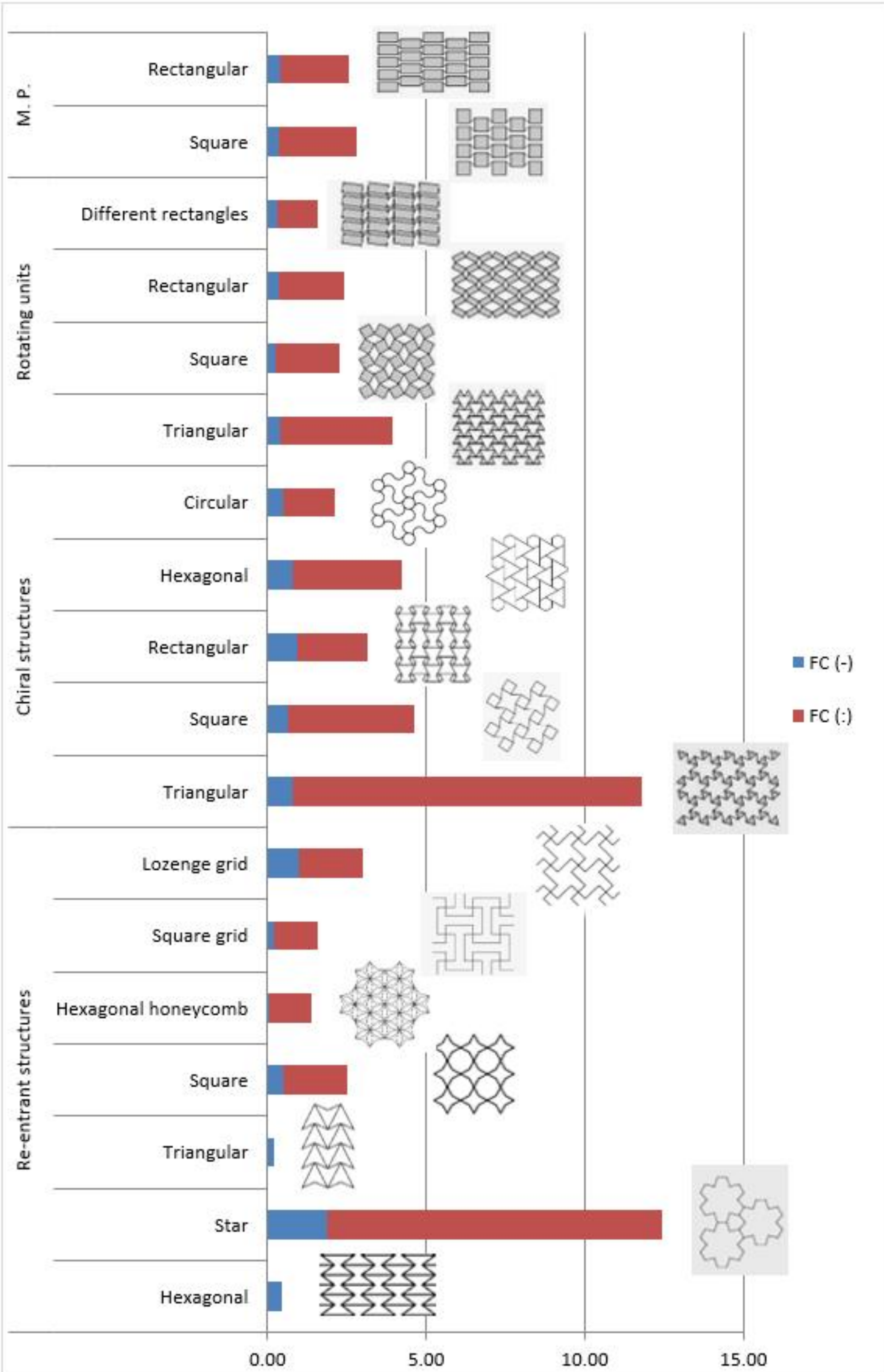


Figure 6. Comparison between growth factors of auxetic 2D reentrant structures. They have been generated by division FC (:) and by subtraction FC (-) (Own elaboration).

The provided values for the diverse properties of the auxetic structures can be interpreted as an initial objective for each of the reviewed designs, to assist in the tasks of metamaterial selection for architecture. Once a design is selected for its growth factor, the specific effects of the geometric changes must be addressed, in case the adaptation of the final property is necessary for a specific application.

Interesting new designs, generated by modifications of some auxetic revisions here, take advantage of self-contact during compression as a way to promote stress relief and greater reductions in area or volume [18,19]. It would be possible to obtain modifications of the designs included in this library to promote such a possibility. The adaptation of the 2D auxetic structures can be a source of inspiration in order to make similar design changes in other three-dimensional auxetic structures. In respect to future directions, it would also be interesting in providing an additional review centered on auxetics with a combination of a set of 2D auxetic patterns, which gradually helps to improve the present CAD development of auxetic geometries.

3. Physic models

3.1. Materials and methods

Triangular quiral structures have the best properties in terms of architectural applications, considering the lightness and pliability results, so a physic model of this kind of structure is presented.

First of all, 24 triangles and 30 bars of paperboard are built. Second, these triangles and bars are joined by nails as articulations. The distance between nails is 6 cm. At this stage, a mechanism is obtained. But in architecture we can't work with mechanisms, so we must convert them to structures.

In order to stabilize the whole, some nails are fixed to the base wood as boundary conditions and some elastic bands join the nails in the appropriate position to produce the right behavior.

3.2. Discussion

When creating a physical prototype, it is a mechanism, so it can be observed at **Figure 7**. It must be stabilized at the desired position.

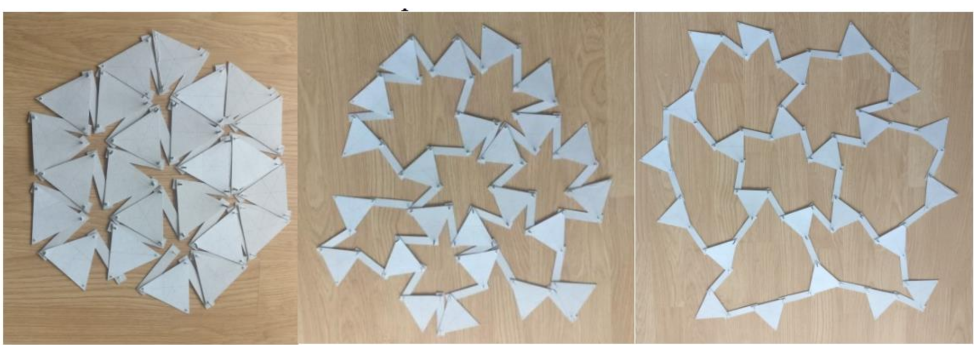


Figure 7. Physical prototype of 2D triangular quiral auxetic structure (Own elaboration).

As we are working on 2D structures, we must first define the boundary conditions, which obtain by fixing some end nodes. As per **Figure 8**, the central part of the prototype continues acting as a mechanism, so that it can be stabilized by a tension system.

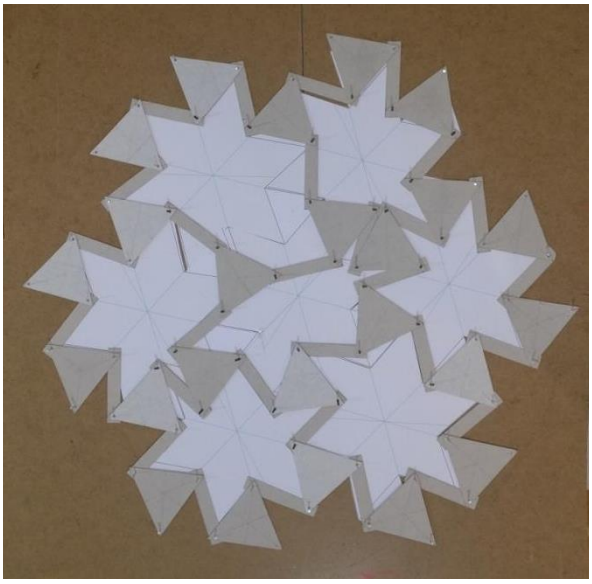


Figure 8. Physical prototype of 2D triangular quiral auxetic structure with some end nodes fixed (Own elaboration).

In **Figure 9** we can observe that, when tension is neutralized and the structure is triangulated, a regular and nondeformable whole is obtained.

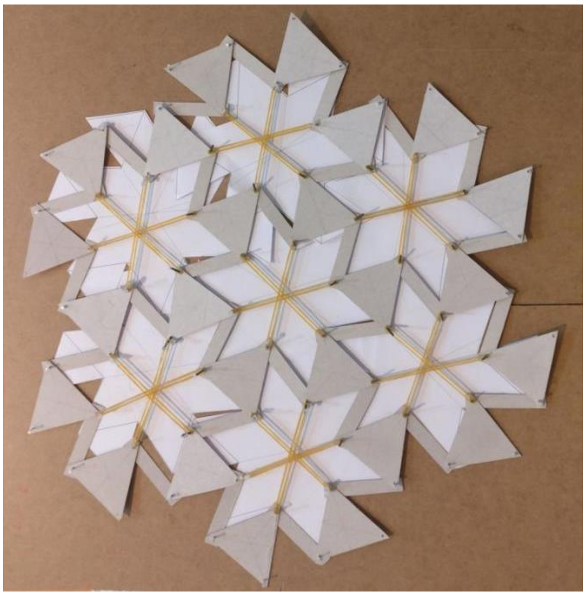


Figure 9. Physical prototype of 2D triangular quiral auxetic structure with some end nodes fixed and some elastic bands join the nails (Own elaboration).

4. Conclusions

A total of 18 potentially 2D auxetic geometries have been designed for obtaining relevant design properties, such as maximum area reductions attainable in relation with the total length of the bars of the structure, in order to procure a growth factor. Hourglass voids, treated as hexagonal reentrant structure, which, as is known, produce auxetic behavior has a medium growth factor in relation to the other auxetic studied patterns.

The results from the simulations helped to validate the auxetic behavior of these 18 geometries. It could be considered more models to cover more potential cases for 2D auxetic materials. The models of 2D auxetic geometries and the information inferred from them may be useful for developing of novel architectures based on these interesting properties. Rectangular rotating unit can generate non-auxetic behavior in its 2D combination. The individual non-auxetic geometries could be auxetic through combination. That is how they might be useful for developing foldable structures, even though such folding cannot be obtained by the individual structure.

Consequently, a physical prototype is developed in order to see the real possibilities of auxetic 2D structures. From these prototypes we obtain the same results that CAD models are obtained, referred to as lightness and pliability. But the main problem is stabilization, because in architecture mechanisms can not be used. The solution is fixing boundary conditions and some tensions to stabilize the structure in the desired position.

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