Development of reentrant hexatruss structures to apply to architecture

Desarrollo de estructuras reentrantes hexatruss para aplicar a la arquitectura

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Abstract
Architecture is totally linked to the knowledge and study of geometry. The re-entrant hexatruss structure is part of the auxetic structures. These structures, characterized by its negative Poisson's ratio, change their geometric configuration from a line to a surface and from a surface to a volume or spatial framework. This project is based on establishing those re-entrant hexatruss geometries to be able to build new spaces in architecture, studying analytically geometric and structural properties of auxetic materials and structures that can be a part of the architecture construction.

Key words: re-entrant hexatruss structure, geometry, structural behavior, scalar transformations, Negative Poisson's Ratio.

Resumen
La arquitectura está profundamente ligada al conocimiento y estudio de la geometría. La estructura reentrante hexatruss se encuadra dentro de las estructuras auxéticas. Estas estructuras, caracterizadas por su coeficiente de Poisson negativo, pueden transformar su configuración geométrica desde una línea a una superficie, y desde una superficie a un volumen o entramado espacial. Esta publicación se fundamenta en establecer una combinación de geometrías reentrantes hexatruss que sean capaces de construir nuevos espacios en arquitectura, estudiando analíticamente las caracterizaciones geométricas y estructurales de dicha estructura que puedan formar parte de la construcción de la arquitectura.

Palabras clave: estructura reentrante hexatruss, geometría, comportamiento estructural, transformaciones escalares, coeficiente de Poisson negativo.

Introduction

Auxetic materials have several very useful properties to be applied to architecture structures (Álvarez & Anaya, 2013). They are a special type of materials that have a negative Poisson's ratio: they get wider when they are stretched and they get narrower 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 (Alderson, 1999). If auxetic materials show some particular features by their special internal geometries, it is considered that in architecture something similar can happen. That is why we are going to study the auxetic geometries: to apply a change in their scale, to incorporate these geometries to the architecture like other authors have done previously.

We can often find some scientific developments based on nature, like the relations that Robert le Ricolais (Mimram, 1983) investigates: this supports that the change of scale hypothesis is feasible. Biological form can reflect the physical and mathematical principles (Thompson, 1980), like D'Arcy Thompson said. However, we can't have an arbitrary form in all spatial scales, because there are some restrictions imposed by physical laws. For example, it is feasible to imagine an ant with the elephant size, but physical laws don't make possible its real existence, because the enormous ant would collapse under its own weight. Therefore, the interaction between geometry and physics restricts the variety of organism forms: this is one of the principal topics we are going to work with, we want to test structurally in the macroscale the geometries that are already controlled in the nanoscale, studying if their conversion to the big scale is feasible. That is, our goal is to find if the structural behavior remains uniform while the scale is changing, whose geometry, structure and form are the same.

In addition to a variety of possible sizes we have to add the multiplicity of morphologies, which give us a lot of possibilities to work and apply on architecture, generating dynamic architectures with a variable form and a lot of news possibilities. The formation of ordered structures which we are going to work with is the result of collective processes of repetition of the unity. In these systems we have scales from the size of a single unit to the scale that characterizes the entire group; in these cases the individual behavior indicates nothing (Álvarez & Anaya, 2014) - or very little - of what happens to the collectivity. These ordered structures, generically, are called patterns.

This way, we are going to study the behavior of one of these patterns when we change their scale to a bigger one to take part in architecture. The study of this exceptional behavior in a very big scale like architecture, implies a revolution in a construction world, because the structural concept and its behavior changes roundly (very new forms that also improve with the loads are going to be produced). This opens some new research, experimentation and innovation paths, with which we can solve current problems.

The research is based on mathematical and geometric basic rules, in which the problems of form are in first instance mathematic and geometric problems, and the problems of growth are, in fact, physic problems, because the matter reflects physic laws. Therefore, the emergence of ordered structures is a result of physicochemical processes, and since some of the laws that govern these processes are expressed in mathematical terms, then, in the final analysis, the underlying mechanisms which explain the appearance of structures are grounded in maths.

This paper is aimed at testing structurally a specific auxetic structure model to know the performance of the auxetic hexatruss structure like architectonic structure. We want to check this hypothesis: if auxetic materials have innovative properties in nanoscale, then they will also have these properties in macroscale.

The hexatruss lattice is an extension of auxetic lattices to 3D (Dirrenberger, Forest & Jeulin, 2013). This structure can make a symmetrical collapse of a 24-sided polyhedron with cubic symmetry if it is triangulated. It is very comparable to the unit-cell used in Doyoyo and Hu (2006) for modelling auxetic foams. The application of this structure and their behavior in architecture are not yet known, that is why this auxetic model will become an experimental model to establish a structural and constructive evaluation of one of the most innovative auxetic geometries, to apply to the construction of new architectures. The results of research and investigation will become apparent by their structural evaluation, with the utilization of calculation programs, by comparison with traditional structures.

The re-entrant hexatruss geometry provides a strong foundation on the research of the application of new structural and constructive 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.

Methodology

According to the effect that negative Poisson´s ratio has in the auxetic structures, these develop new structural properties that make them unique and extremely versatile (Liu & Hu, 2010):

1. Porosity: These structures have a lot of porosity. We must have in mind that a better porosity less structural rigidity. This property is very good to absorb movements.

2. Shear properties: According the elasticity equations, if we have constant the elasticity modulus and we obtain a negative Poisson’s ratio, we can change the properties of structure. For example, with a Poisson’s ratio of -1, we obtain that it is very difficult to deform by shear structure, but very easy to deform in volume.

3. Resistance: Resistance can be increased in auxetic structures due to negative Poisson’s ratio. When we press these structures, they obtain compress. This creates a denser and hard structure.

4. Fracture toughness: Compared to non-auxetic structures, auxetic structures have increased fracture toughness. Auxetic structures also have high crack resistance.

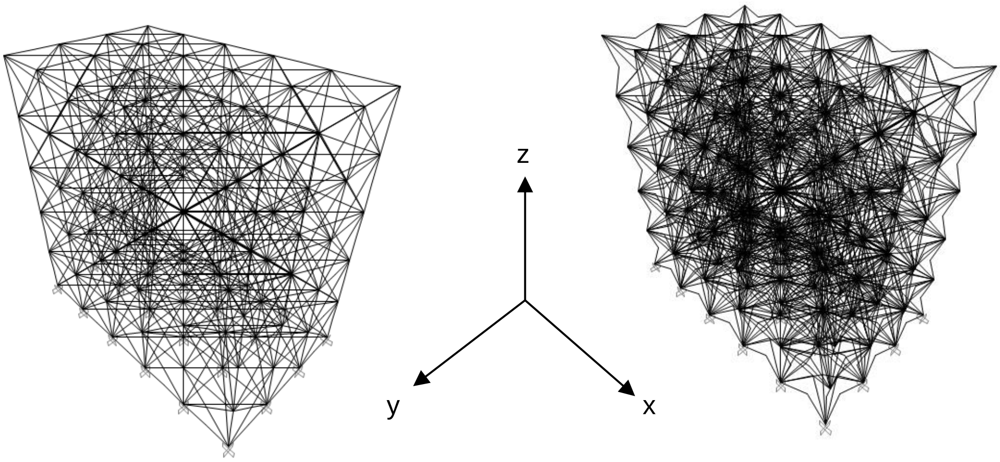
5. Energy absorption: Auxetic structures show overall superiority energy absorption, such as ultrasonic, acoustic and damping, compared to the conventional structures. They have very good functionality with loads: these forms are better with loads.

6. Variable permeability: Auxetic materials are able to open pores by stretching and close these pores by compression.

These properties will be tested in architecture in order to prove if the auxetic effect is useful in this field.

The used methodology consists of studying auxetic hextatruss structure using SAP2000 software. A building design by repetition of this kind of auxetic structural pattern will be tested and compared with itself in its open position that structurally has a traditional behavior. We will consider a reinforced concrete (defined as HA-25 in SAP2000) structure with rigid knots in order to simulate the auxetic effect as it appears in the nature at nanoscale. As for the calculus purpose, we consider a residential building with a facade of 3 (Y direction) x 5 (X direction) x 5 (Z direction) auxetic cells. We consider for each cell 2.5 m external bars. Sections are 30x30cm (supports of the 3 highest floors and bracing of the 2 lower floors), 35x35cm (supports of the 2 lower floors), 25x25cm (vertical tie together elements of the 3 highest floors), 70x30cm (interior beams), 60x30cm (facade beams) and 50x30cm (horizontal tie together elements), according to the Figure 1.

Figure 1. Left: Traditional structure. Right: Auxetic structure. Source: own elaboration.



Loads appear on Table 1. These loads are distributed according to a static lineal analysis associated to gravitational actions and wind; and a modal analysis to obtain structure vibration modes for quake spectral modal analysis. Different EHE-08 calculus combinations will be made for Last Limit States (LLS) and Service Limit States (SLS), as well as surrounding combination in LLS aimed at finding out the worst forces.

As for the results that we will analyze will be vibration modes, displacements and rotations, worst forces in the structure, reactions in foundations and Poisson's Ratio, in order to test the properties that have been presented.

Table 1. Loads considered table. Source: own elaboration.

	Permanent loads	Use loads	Snow loads	Wind X (direction +/-)	Wind Y (direction +/-)
$V_{\text{interior housing}}$	33 KN/m	11 KN/m	-	-	-
$V_{\text{perimeter housing}}$	22 KN/m	5 KN/m	-	-	-
$V_{\text{interior roof}}$	30.25 KN/m	5.5 KN/m	2.75 KN/m	-	-
$V_{\text{perimeter roof}}$	16.25 KN/m	2.5 KN/m	1.25 KN/m	-	-
$P_{1\ \text{pressure}}$	-	-	-	1.875 KN/m	2.2 KN/m
$P_{1\ \text{suction}}$	-	-	-	1 KN/m	1.375 KN/m
$P_{2\ \text{pressure}}$	-	-	-	4.125 KN/m	4.4 KN/m
$P_{2\ \text{suction}}$	-	-	-	2.2 KN/m	2.75 KN/m
$P_{3\ \text{pressure}}$	-	-	-	-	3.8 KN/m
$P_{3\ \text{suction}}$	-	-	-	-	2.375 KN/m

Note: Structure own weight is automatically considered by SAP2000 depending on the sections defined. Masses used to calculate quake effects are defined in NCSE-02 section 3.2, including own structure masses, permanent masses and a percentage of 50% of use overload. Snow overload and ceiling use overload are not considered for quake effects.

Results

After the completion of structural analysis we have obtained the results shown below:

Vibration modes

The vibration modes have been obtained for a linear response spectrum, to the traditional structure (Table 2) and to the auxetic structure (Table 3).

Table 2. Traditional structure base reactions. Source: own elaboration.

OutputCase Text	StepType Text	GlobalFX KN	GlobalFY KN	GlobalFZ KN	GlobalMX KN-m	GlobalMY KN-m	GlobalMZ KN-m
MOD-ESP-X	Max	3372.148	0.001627	0.00111	0.018	64603.0939	42136.4422
MOD-ESP-Y	Max	0.0002906	3484.668	0.0003548	68539.3527	0.0055	26135.6291

Table 3. Auxetic structure base reactions. Source: own elaboration.

OutputCase Text	StepType Text	GlobalFX KN	GlobalFY KN	GlobalFZ KN	GlobalMX KN-m	GlobalMY KN-m	GlobalMZ KN-m
MOD-ESP-X	Max	7386.85	0.00005496	0.034	0.4021	126195.9057	87719.3536
MOD-ESP-Y	Max	0.0000347	7830.036	0.03	135188.5066	0.2156	55792.9251

Joint displacements and rotations

The Table 4 shows the most unfavorable joint displacements and rotations for the traditional pattern and for the auxetic pattern:

Table 4. The most unfavorable displacements and rotations to the traditional and auxetic pattern. Source: own elaboration.

		Displacements (m)			Rotations (rad)		
		x	y	z	x	y	z
Traditional	Max	0.005426	0.003601	6.87E-09	0.000823	0.000914	2.38E-11
pattern	Min	-0.005426	-0.003601	-0.006204	-0.000823	-0.000914	-2.38E-11
Auxetic	Max	0.008032	0.005309	0	0.030294	0.03046	0.000001024
pattern	Min	-0.008033	-0.005306	-0.59533	-0.03036	-0.030508	-1.246E-08

Structure forces

The Table 5 shows the most unfavorable forces for the traditional structure and for the auxetic structure for different combinations: axial, moment, shear and torsion.

Table 5. The most unfavorable forces for the traditional structure and for the auxetic structure. Source: own elaboration.

		Shear V2 (KN)	Axial P (KN)	Torsion T (KN/m)	Moment M3 (KN/m)
Traditional	Max	159.783	48.957	7.7422	72.4205
pattern	Min	-159.783	-1182.27	-7.7422	-136.5229
Auxetic	Max	6135.487	24644.078	421.7042	2419.5087
pattern	Min	-6135.481	-118220.952	-416.7547	-3494.4493

Foundation reactions

The Table 6 shows the most unfavorable foundation reactions.

Table 6. The most unfavorable foundation reactions to the traditional and auxetic structure. Source: own elaboration.

		Forces (KN)			Moments (KN/m)		
		x	y	z	x	y	z
Traditional	Max	325.939	318.259	3009.912	139.1585	139.9978	0.7564
pattern	Min	-325.939	-318.259	239.631	-139.1585	-139.9978	-0.7564
Auxetic	Max	169887.91	170235.57	716568.755	11982.264	11976.583	22.1062
pattern	Min	-169759.85	-170329.53	421.403	-11985.920	-11973.608	-22.1188

Poisson's Ratio

The formula of Poisson´s Ratio is $\nu = -\frac{\varepsilon_y}{\varepsilon_x} = -\frac{\varepsilon_z}{\varepsilon_x}$
Being:
ε_x, relative elongation in the x direction
ε_y, relative elongation in the y direction
ε_z, relative elongation in the z direction

For all combinations of the hexatruss structure the relative elongation in all directions is 15%, that is why the Poisson´s Ratio is -1. The variations in relation with the traditional structure are the porosity and the permeability.

Discussion

There are more reactions in foundations in the auxetic structure than in the traditional one. These results are worse than the obtained in the individual pattern (Álvarez & Anaya, 2014), in which the worst base reactions and the biggest displacements were balanced out with much lesser rotations in the joints and moments in structure horizontal axis of approximately half of the value than in the traditional structure (on the vertical axis these moments are greater than on the auxetic one).

By observing forces that were produced in the individual pattern of auxetic structure, we could see that shear and torsion forces that appeared in auxetic structure were much smaller than the ones in the traditional structure, and moments were more or less equal, maybe a bit bigger.

So, if we considered the properties that have studied other authors (Liu & Hu, 2010) we can see that with the negative Poisson´s ratio the porosity and the permeability have some variations respect to the traditional structure. The forces that appeared in auxetic structure are much bigger than the ones in the traditional structure, so the shear and resistance properties have not good for auxetic structures in architecture. Fracture toughness and energy absorption could be useful for the complete structure if the forces in bars were good, but for the actual behavior the bars could be broken with big external forces.

This is not the same that in other applications occur (Yang, Vora & Chang, 2018), in which the auxetic materials could be effective in reducing the shock forces. Each structure and material combination demonstrated unique structural properties such as stiffness, Poisson's ratio, and efficiency in shock absorption. Auxetic structures showed better shock absorption performance than non-auxetic ones.

It is considered that the unfavourable results in the whole pattern of auxetic structure have been obtained by the increase of its own weight due to the greater number of bars according to the way of combining the structure. They are also considered to be unfavourable for having made such a structure as a linear structural form constructed from bars. If we continue this analysis using structures with articulated joints with external pre-forces that keep the structure balanced, this means that using auxetic structures as a structure that works due a forces balance, we change the obtained behaviour in another one in which the structures are self-balanced.

Architectured materials with rationally designed geometries could be used to create mechanical metamaterials with unprecedented or rare properties and functionalities (Mirzaali, Janbaz, Strano, Vergani & Zadpoor, 2018).

Conclusions

The computations show that the gain in using auxetic structures may no be very large at least for the considered structure. This fact has been observed in other fields like mechanical engineering. The benefit of auxetic microstructures can be observed only in some precise situations.

The contribution is useful in showing the limitations of auxetic structures. In this paper an analysis of forces in a bars type structure with rigid knots has been made. As a result we have obtained very elastic structures that receive big forces on their bars when a load is applied. These structures could work fine by wind, quakes..., but we need controlling the forces that act in the bars. This analysis could be continued using structures with articulated joints with external pre-forces that keep the structure balanced, this mean using auxetic structures as a structure that works due a forces balance.

For this reason, we conclude that we have to underpin an exhaustive analysis in order to advance in the design and construction of auxetic architectures.

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