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Deployable Structures System, Hexagonal X-frame. Three Case Studies

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Abstract

This article is part of a research that seeks methods to control movement of the deployable structures with textile membranes. The maximum strength of the textile will be used to stabilize and control the movement of the deployable structures. This research proposes 3 cases of study, starting with its geometric design and finishing with the end result of a low cost prototype to scale. The idea is to analyze and study the morphology of the hexagonal module with straight bars. With support of algorithmic design and physical models, make the verifications of movement and geometry. It aims to design 3 different geometric configurations, starting from the hexagonal module. It also seeks to analyze the mechanical behavior of its joints and check their deformation with the construction of intermediate-scale prototypes. Finally, it is expected that tools of support will be used for the design of x-frame deployable structures with hexagonal modules. The construction of the prototypes was done with the help of the students of the Valles School of architecture. ETSAV.

Keywords

Deployable, X-Frame, *prototypes, structure, pavilion,*

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Vol. 4 (2) / February 2017

Introduction

Nowadays deployable and transforming structures are more common in architecture. The quick assembly, flexibility, the lightweight materials, and the easy transportability are the most important features of these systems. The deployable structures with straight bars enhance these features, occupying little space when the structure is closed.
This research seeks different morphological possibilities of deployable structures with straight bars, with approximations of habitability, either as an independent module that allows repetition to form a habitable whole, or as independent elements, which will help to build systems of habitability, whether being with roof elements, facade or walls of the interior of habitable systems.
The morphology of deployable structures is related to the concepts of solid geometry, and this is the starting point of this research. Other essential points are the examination of the transformation and the search for appropriate geometries for a system of habitability. The exploration of form is also very important in this research since it seeks to surfaces of double curvature, synclastic surfaces or anticlastic surfaces with systems of straight bars as a solution of a container element. As shown in figure 1.

Deployable structures systems articulated with straight bars have two possibilities grouping surfaces, square and triangular module or hexagonal module in their transformation. The groupings in both cases make it possible to solve double curvature surfaces; therefore the examinations made in this research blend both groups and explore new possibilities of more complex geometric configurations, not only at surface but also with spatial configurations of the object to make a self-supporting structure, which is habitable.
The recommended solutions for the joints of the deployable structures are designed according to the number of bars that reach each node and the structure of the proposed material. The idea is that they are easily manufactured and support the process of folding and unfolding required for the proper functioning of the system. Additionally they should serve as anchor points or support of the membrane or fabric.
The methodology is experimental, with the development of physical and digital models, and it supports parametric design tools. In the first phase it is the search form and the digital checking of the geometry and movement of the structure in its fold and unfold. Secondly, developing the scale prototypes, and exploring the construction details, fabric membrane pattern and the tension movement of the structure. Figure 2.

The starting point is the theoretical basis of the deployable structures. This has been submitted since the 60's Buckminster Fuller is a source of extensive information of geometric studies. He designed innovative structural systems such as tensegrity and geodesic. Therefore this background information is part of this research study. Similarly, another important character was Emilio Perez Piñero, a pioneer in designing deployable structures. His designs have all been recommended and investigated in the transformable architecture.
Nowadays, there are research groups, developing new proposals of deployable structures with straight bars, to such an extent that there are specific conferences for this type of architecture. In September 2013 the first International Congress of transformable architecture was celebrated in Seville, Spain. Figure 3. This was in order to connect the sources of research in these structures and to share information. In general there are two very clear lines of research. The first is focused on parametric design and theoretical analysis of deployable structures. The second is the problem of the joins in the development of full-scale prototypes.

ISSN 2309-0103
www.enhsa.net/archidoct
Vol. 4 (2) / February 2017

Deployable Structures System, Hexagonal X-frame - Three Case Studies

Figure 1.
Deployable Structures System, Hexagonal X-frame - typologies.

Figure 2.
Proposal microarchitecture with Hexagonal X-frame

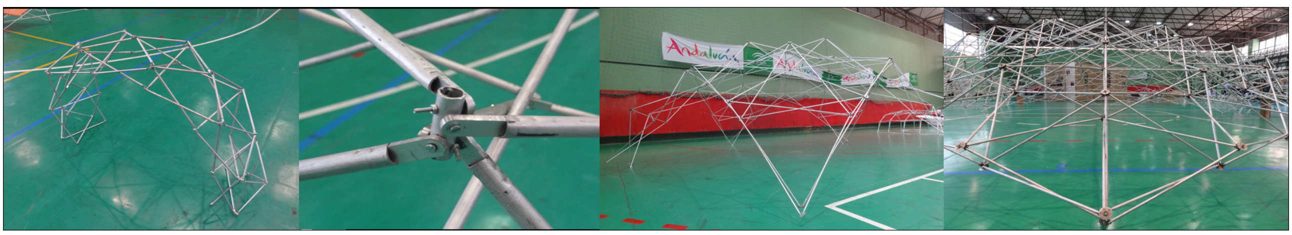

Figure 3.
Prototypes, Felix Escrig. Conference Transformables 2013. Sevilla, Spain.

ISSN 2309-0103
www.enhsa.net/archidoct
Vol. 4 (2) / February 2017

This research aims to approach these two problems and suggest a methodology using 3 case studies. The final phase, is the selection of a prototype. Its construction on real scale will lead us to solve in an integral way the entire system, and will enable us to check each one of the solutions through software and digital design which are seen to be an approximation of reality.

Geometry and parametric design

The design process and geometric exploration of the hexagonal X-frame, begins with the analysis and study of the theory of solids. Understanding the concepts of transformation, duality, tessellations, non-continuous groupings and more games solid geometric, is the basis of this initial study. The theory of solids, is directly related to the final configuration of the Hexagonal X-frame module, as well as the possibilities of groupings, checking of movement and control, the final stability and its relationship with the textile membrane or skin. Therefore the beginning of this research consists of the geometric understanding of the Platonic solids and archimedean. Regular and non-regular. As shown in Figure 4. The deployable system structures of straight bars have two possibilities of grouping in surfaces: square and triangular modules or hexagonal modules in the transformation. The groupings in both cases can be solved through double-curved surfaces. The investigations made for this research, mix both groups and explore new possibilities of more complex geometric configurations, not only superficially but also with spatial configurations that make the object a self-supporting structure and also a habitable one. Finally for the case studies, the hexagonal X-frame model was selected.

Geometrical exploration has two phases. The first one is a practical, which consists of tests using small models. These are made with sticks and flexible plastic pipes. The joints are made with elastic bands as in Figure 5. This first approach serves to check the movement and aids understanding of space. Deployable solids, flat mesh, and sinclásticas were designed, as well as modular configurations and spatial groupings.
The second phase is aimed at the parametric design. At this point the objective was to design basic modules. Several alternatives were designed in order to obtain a variety of modules, which eventually led to groupings. The geometry for the design of the modules consists of circles. X-frame bars and their movement are always registered in a circle. The parametric design was made with Grasshopper, under the platform of rhinoceros. Figure 6.
The units of hex module X-frame proved to be the most stable showing motion and tension. They also proved to be the best option of horizontal, vertical and spatial groupings. In the process of design and exploration of the hexagonal module, two groups were found: the first being the continuous spatial groupings (that is, filling the space completely) and the second one being non-continuous spatial groupings (allowing empty spaces in space or on the surface).

This part of the research allowed further exploration of the X-frame deployable structures and also provided alternative morphologies without a specific use (important in detecting potential groups in the hexagonal modules X-frame).

Physical Models and Digital Models

Following on from the geometry exploration process, the hexagonal module was chosen for prototype designing. The hexagonal module can be of three types.

ISSN 2309-0103
www.enhsa.net/archidoct
Vol. 4 (2) / February 2017

Figure 4.
Deployable Structures System, Hexagonal X-frame - Exploration.

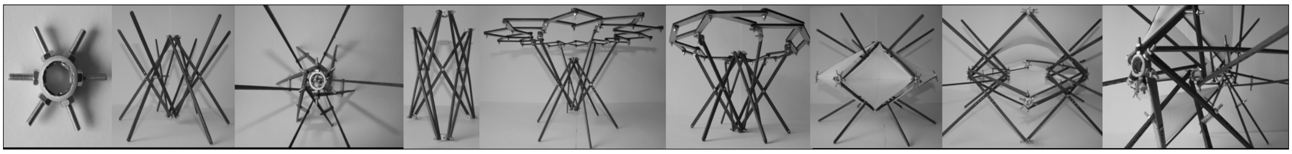

Figure 5.
Development of scale models - Hexagonal X-frame.

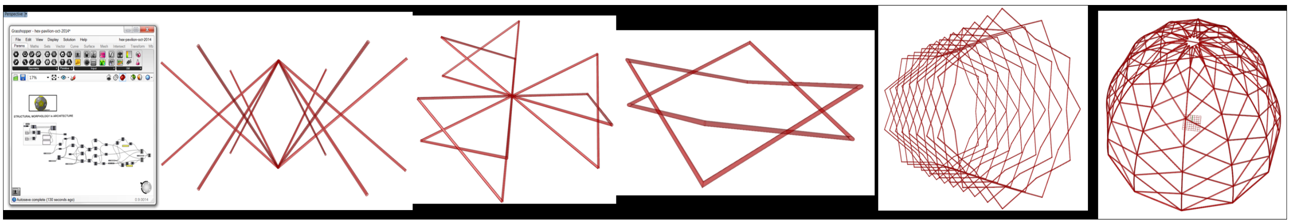

Figure 6.
Parametric Definitions whit Grasshopper software. Exploration.

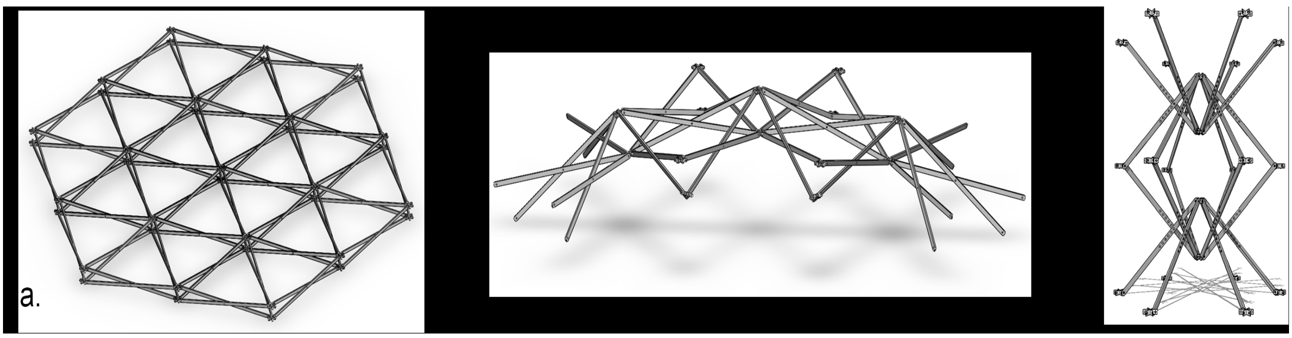

Figure 7.
a. Symmetrical hexagonal module. b. External eccentric hexagonal module. c. Internal eccentric hexagonal module

Deployable Structures System, Hexagonal X-frame - Three Case Studies

ISSN 2309-0103
www.enhsa.net/archidoct
Vol. 4 (2) / February 2017

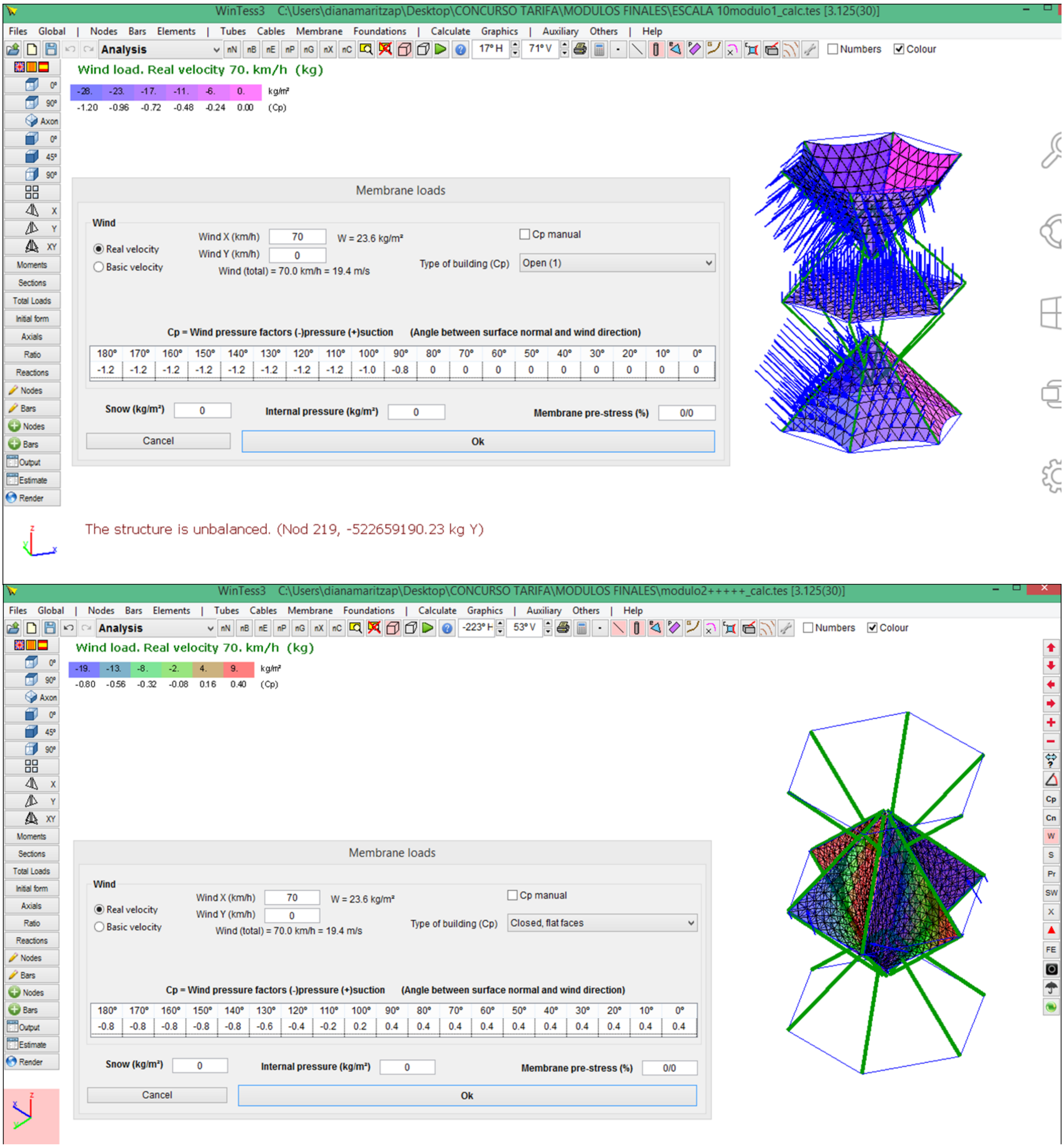

Figure 8.
Theoretical analysis of the hexagonal module x-frame in Wintess, software by Ramon Sastre Sastre.

ISSN 2309-0103
www.enhsa.net/archidoct
Vol. 4 (2) / February 2017

a. Symmetrical hexagonal module. This is formed by six pairs of straight bars jointed at the center of the distance of each bar. This configuration allows for flat meshes, linear and spatial groupings with orthogonal displacement.
b. External eccentric hexagonal module. This is formed by six pairs of straight bars jointed and oriented toward the lower or upper face of the module. This is to say short bars are opening or closing, up or down the module. This configuration allows for groupings according to curving eccentricity. Therefore, the greater the eccentricity, the bigger is the curvature. It also allows for sinclásticas and anticlastic surfaces to be made.
c. Internal eccentric hexagonal module. This is formed by six pairs of straight bars jointed with eccentricity at the center module. That is to say that the central diamond is smaller. This configuration allows flat mesh, linear and spatial groupings to be made with orthogonal displacement. The difference between the first options and this one is that "c" allows you to adjust the diamond to a smaller or larger size, as required by the diamond inside the hexagonal module. This type of module is useful for non-continuous spatial groupings.

The development of physical models, helps to understand the path of a module when it is grouped. It also allowed for a low-cost design of a piece of hexagonal union, for the production of the models. The joint is made of pcv cut rings with 3/4 inch diameter, with manual drilling with angles of 60 °. This piece allowed models to be further developed and made with more rigid materials, and also enabled us to see the deformations of the bars according to their groupings.
Digital models were also created to support the theoretical analysis module. Stresses, displacements and deformations of the module. This stage follows on as a development of this investigation, providing us with information of how the module would behave in reality. On the one hand, we have the mechanical behavior of the bars, made in SolidWorks Simulations. Finite Element Analysis (FEA). As shown in Fig. 8. On the other hand, a study of wind loads and a proposal covering the membrane module. This analysis is made with the WINTESS3 software designed by professor Ramon Sastre Sastre.
This item is part of future research, which is expected to have a theoretical analysis of the x-frame hexagonal module and also of its mechanical behavior in continuous and non-continuous groupings. For the current stage of the study, these results served as reference for the development of scale prototypes.
In the FEA of the x-frame hexagonal module, as can be seen in Fig.ure 9, the lateral displacement and torsion bars are subjected to a point load in the center of the joint. The maximum stresses at the ends of the bars can also be seen. With this analysis, it can be concluded that the design of a connecting piece to prevent displacement of the bars and to prevent it from collapsing is subjected to the twisting of each mule.

Case study 1 - Domo Erizo

Sinclástic design surfaces from a system formed of straight jointed bars. It is formed by external eccentric hexagonal modules. The work was completed in collaboration with students from PEI Javeriana University of Colombia in the summer of 2015, Barcelona.
The definition of the geometry of the Pavilion Erizo is given by a hexagonal base module. The module consists of six eccentric scissors node attached to circulate tangentially as shown in Fig.ure 10. This basic unit is repeated six times to form first a first hexagon, which is repeated ten times forming a triangle in plan and at the end of this geometry, to each of its ends, two more units are added. As can be seen in the diagram, it generates a

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Vol. 4 (2) / February 2017

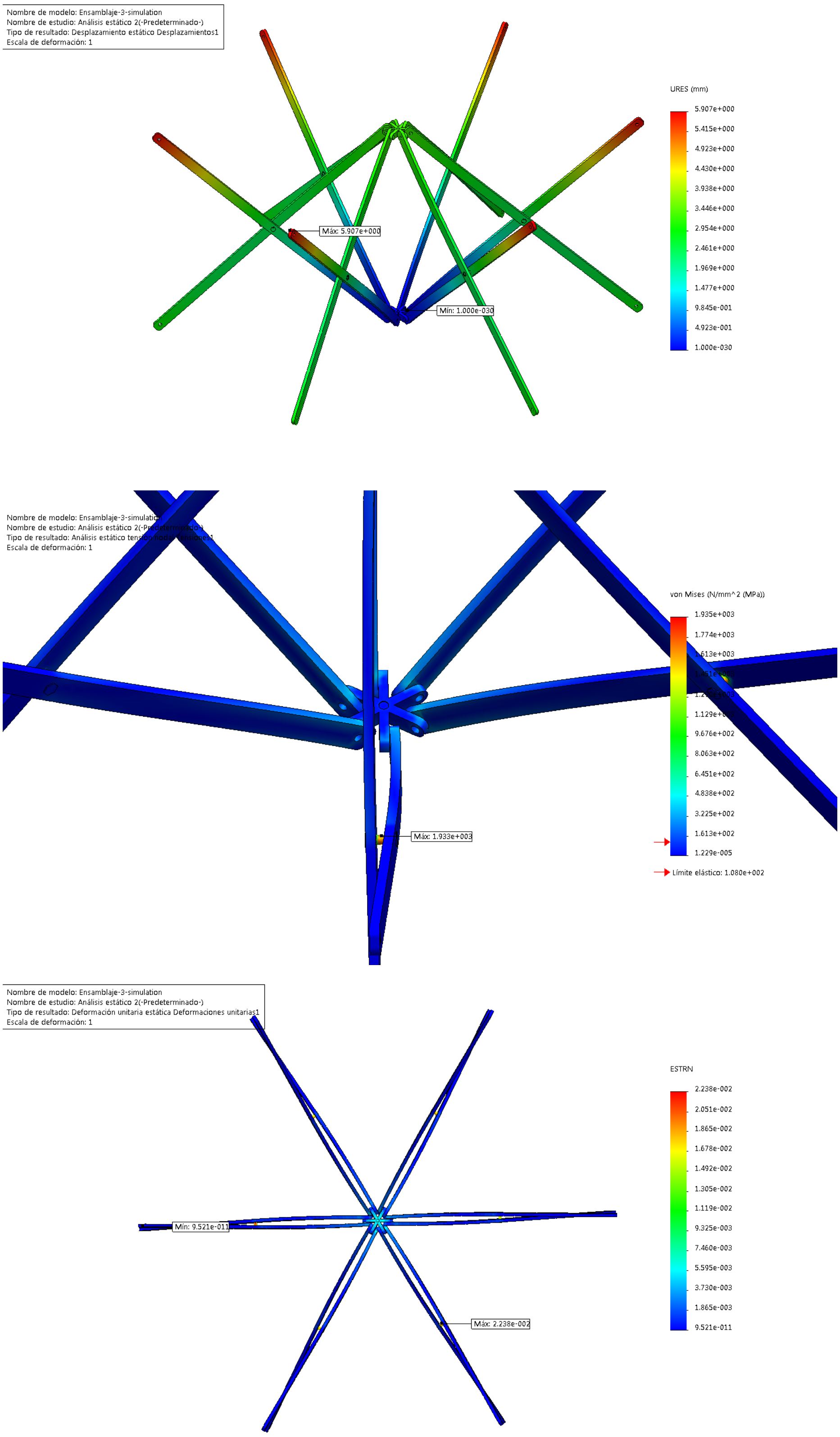

Figure 9.
Finite Element Analysis (FEA). a. Tensions. b. Deformations. c. Displacements

ISSN 2309-0103
www.enhsa.net/archidoct
Vol. 4 (2) / February 2017

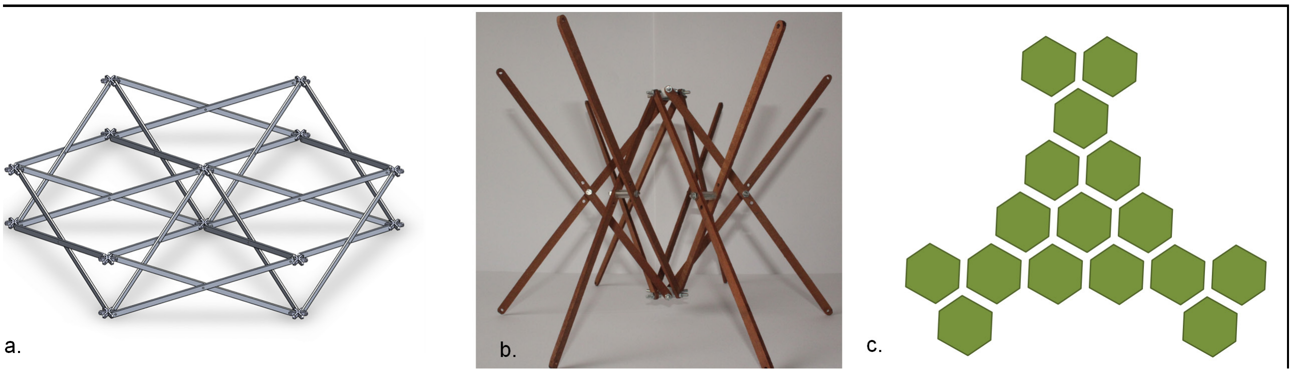

Figure 10.
Geometry Dome Erizo.

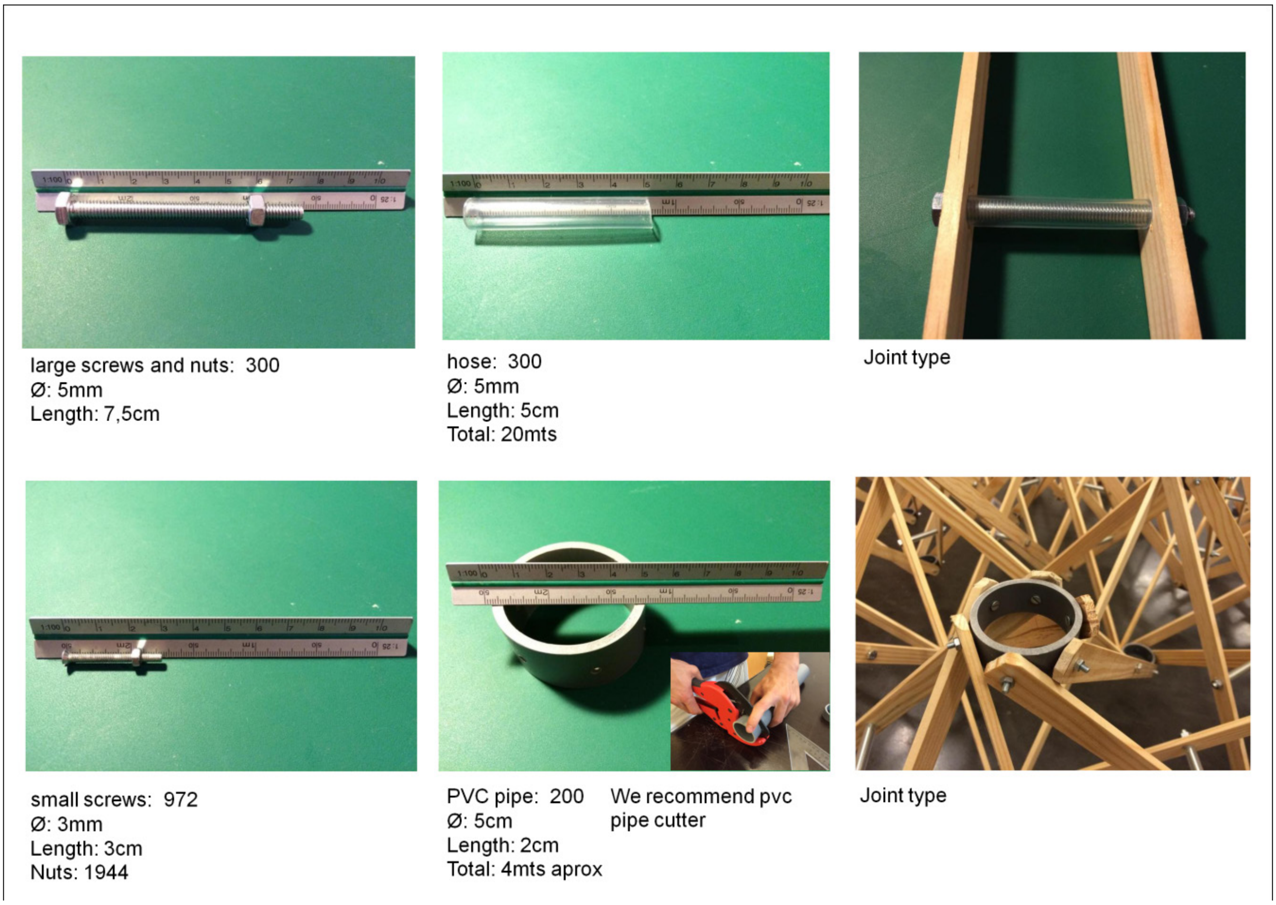

Figure 11.
Materials

ISSN 2309-0103
www.enhsa.net/archidoct
Vol. 4 (2) / February 2017

final structure consisting of sixteen basic modules.
The Erizo Pavilion develops through all joints and bars of the same characteristic, whereby the assembly and disassembly is fast and versatile. The specific characteristics of the system used in this structure corresponds to straight eccentric hinged together scissors system generates such curves depending on the eccentricity of the articulation between each bar composing the scissors. El module is formed by six pairs of scissors in wood that are joined at their ends to the knot of PVC plastic tangentially, as we can see in the scheme.
The materials used to build the scissors were: pine wood, nuts, bolts, plastic hoses, PVC pipes, plastic caps and angels. As for the tools, they were sent to cut the wood for better timing. Then the students were ordered to cut PVC pipe to generate knots. As shown in Figure. 11. Also with the defined measures they cut the plastic hose, which along with long screws serves as a separator between the wood elements of the scissors. For the preparation of the material, it had to be measured and sent to cut the wood, then labeled and made the holes of the scissors.
Pieces of wood were joined by long screws which were separated by the plastic hose. Short screws were used to attach the timber to the knot of PVC. The module was formed by six pairs of straight scissors, which were joined together tangentially to a circular PVC knot. After having the six basic modules forming the first hexagonal unit, this process is repeated until the final sixteen modules, which will join concentrically, as shown in the photos. To assemble the deployable structure, plastic angel caps were used to fix end result of sinclásticas geometry. Figure 12.
For the manufacture and assembly of equipment Erizo Pavilion, the team was divided into six groups, each of them responsible for the first six modules, which would later on unite to form a common ground of sinclásticas and eccentric straight scissors. The preparation of the material took two days and the assembly was done in one day. All work was conducted by a team of nearly 60 students. Figure 13.
The structure had several problems. The most obvious was his geometry. The geometry did not complete a circuit or circle. Therefore it was unstable due to its weight. This was solved by using a lock on certain benchmarks of geometry. It was clear that the pop-dome system needed an additional structure to control for when the structure element closes or expands. A system of motion control is needed. The proposal of mechanical locking is able to stabilize the geometry and the natural shape of the dome.

Case study 2 - Tower Hive

Tower Hive, is a proposal that was presented to the IFAC (International Art Festival and construction). www.ifac.me - The tower project was to design a visual point of reference for an ecological village in Bergen, Netherlands. The proposal is designed using internal eccentric hexagonal modules. That is to say that it allows for orthogonal configurations with eccentric bars. This module was ideal for making a vertical linear configuration and for giving the impression of floating modules, as shown in Figure 14.
The Hive Tower can be used for public lighting, a garden element, or a city landmark (outdoor public space). In all the cases will be a "hito" or reference or meeting point in the city.
The landmarks within the urban space are pieces of unique architecture designed so that their height stands out from the other buildings around. The function of these benchmarks is to serve as guideposts in the urban space. The ordinary citizen may be found within the city oriented through urban elements.

ISSN 2309-0103
www.enhsa.net/archidoct
Vol. 4 (2) / February 2017

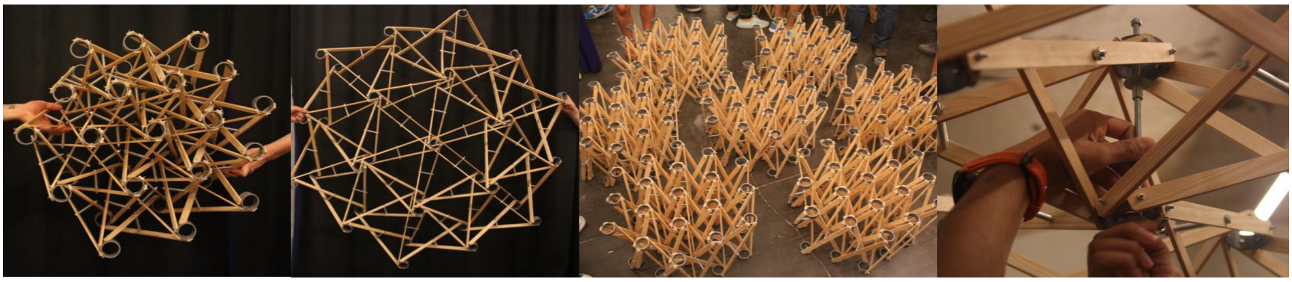

Figure 12.
Dome Erizo. Construction process.

Figure 13.
Dome Erizo. Views.

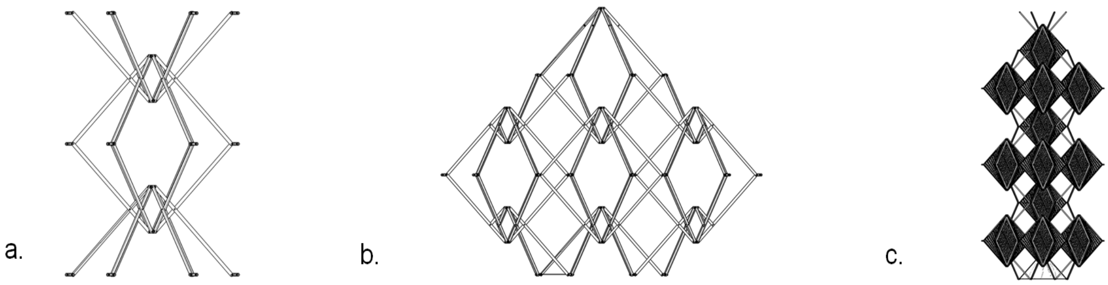

Figure 14.
Fig. 14- Geometry whit Internal eccentric hexagonal module.

ISSN 2309-0103
www.enhsa.net/archidoct
Vol. 4 (2) / February 2017

Figure 15.
Tower Hive - Construction process.

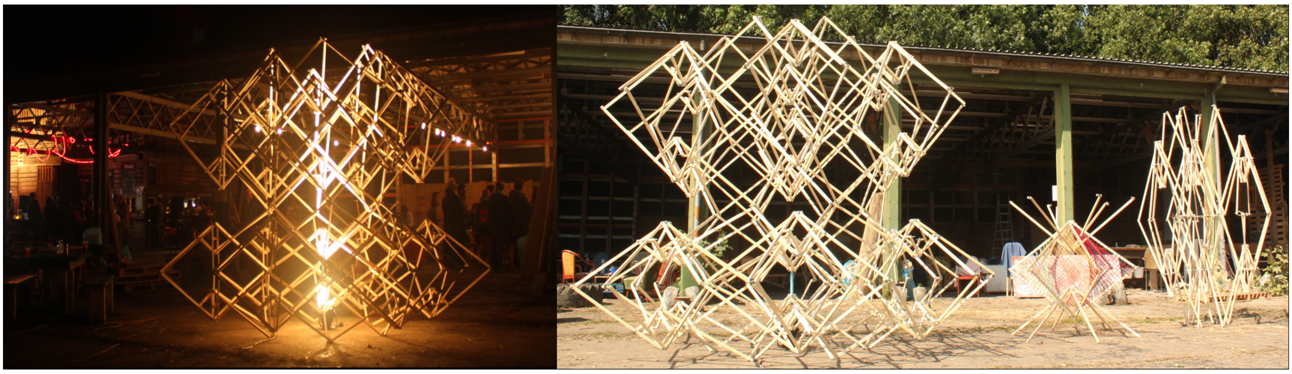

Figure 16.
Tower Hive - Viewe.

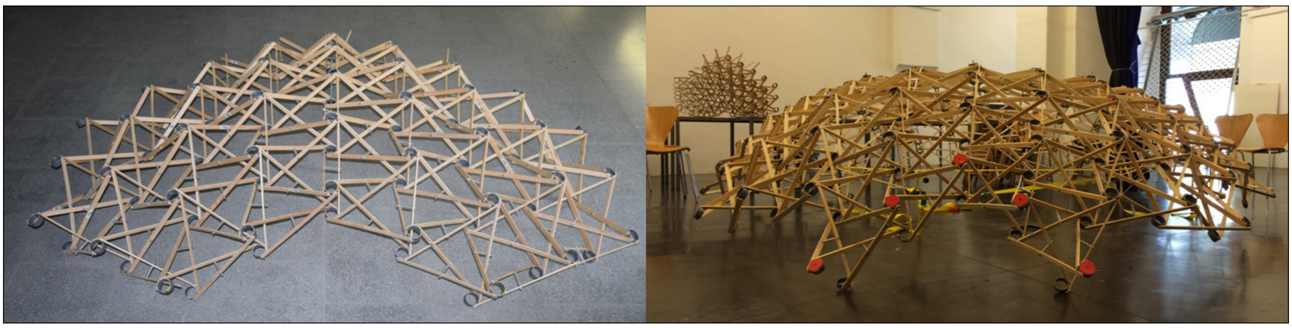

Figure 17.
Shells triangular base and a hexagonal base.

ISSN 2309-0103
www.enhsa.net/archidoct
Vol. 4 (2) / February 2017

The Hive Tower could be a good example of a landmark or public lighting as it has two very important characteristics: height and light. Both characteristics help to guide people through the city.

The main idea is to build a tower with deployable system scissors, understanding the concepts of the practical part: the fold-ability and retention, the morphology of the deployable structures and the geometry. All done with the help of the software used for parametric design and physical scale models.

Hive Tower is an rising deployable structure, consisting of a system of articulated symmetric bars grouped in a hexagonal base. The bars are 1 meter long and a 40mm x 15mm section. The articulated rod system allows the structure to fold and unfold quickly with the use of human force. Accessories for bars joints are designed in aluminum or recycled materials such as pvc. Hexagonal unions, receive 6 pairs of jointed rods to setup the whole system. The same connections are used as joints at the ends of each bar system. The bars joined at the center of the tower, form a structure, which serves reciprocal movement limit of the system.

The construction of the tower was made with the participation of fifteen students from different countries who participated in the festival. The proposed methodology was to make a production line for enlistment of material. The wood used was plywood. Pvc rings. And the union fittings in galvanized steel. Figure 15

The assembly of the structure is made by composite modules. The tower is divided into three parts for better handling. Each compound module was made up of 16 x-frame hexagonal modules. Each module individually could be folded and unfolded easily. When modules were fixed on top of each other, problems presented themselves. The pin structure was affecting the bearing capacity of the bars. Buckling was seen at the bottom, in the lower load bar because of overload, and there was also torsion in the bars in the nearest parts PVC rings.

The problem of overload on the structure was solved with a locking system, since the weight of the structure was forcing the folding system. This prototype was the need for a motion control system. With an additional element to the frame the loading of the structure is stopped by its own weight. The experiment was done with a small module using a mesh as a future cover for the community of the town. This exercise was surprising since it managed to achieve the load control of the of the module by its own weight (as shown in Figure16).

At this point of exploration with real prototypes, we considered the need for a motion control system for deployable structures. At the moment they are focused in situ, temporary mechanical solutions. The tower mount was put together using only two out of the three modules. The third module was used to show the movement of the structure. A height of approximately seven meters was achieved when it was unfolded, and about 4 meters when folded. As an exercise of morphology and constructive solutions this step was very gratifying and very helpful to learn the real physical behavior of a deployable structure to intermediate scale.

Case Study 3 - Mobile Hanging SMiA

Mobile hanging was an exercise in recycling and reuse of the dome. Normally the construction of these pavilions or approximation exercises, have a short life cycle. The Erizo dome was an example of this reality. This research and the research group SMiA (Structural Morphology in Architecture) wanted to give a new use to the structure and turn it into a temporary exhibition in the main hall of the ETSAV. The idea was to cover double

ISSN 2309-0103
www.enhsa.net/archidoct
Vol. 4 (2) / February 2017

broker height ETSAV. For this, four sinclásticas shells were designed: three shells of a triangular base and one of a hexagonal base. The idea was to form an undulating anticlastic surface using the four shells. Figure 17.
In this prototype we were looking to check the behavior of the structure and the wall units from a single point. The assembly process was relatively quick as in three hours it was finalized. Each of the shells, began to shape in their own particular way due to gravity. The shells achieved their maximum opening point, making it easy to deploy. The structure showed no major deformations due to own weight as seen in the previous two proposals. Similarly, locking elements were considered to prevent movement. This ensured greater stability of the mobile. Currently the structure is exposed for a period of 5-6 months. As shown in Figure18.
The proposition serves as an exercise to explore the possibility of making and designing a system of deployable hexagonal modules structured with x-frame, which can be assembled and disassembled quickly with the same elements but different configurations. The idea is to use equal linear elements (bars) and one standard binding system, different types of habitats or constructed spaces in order to give the structure durability and reusing of this.

Conclusions and future research

The experience of building prototypes to a medium scale of deployable structures is very positive. Scaling, the design of the joints, the mechanical behavior of the prototype, its weight, the transition from the digital to the prototype, and deformations, are some of the things, which can be seen in this practical. While the propositions were raised as inexpensive prototypes, they were considered the best materials and therefore its investment was something to consider. This processing was possible, thanks to collective resources.
The change of scale. This is one of the most valuable conclusions. Physically verifying the results of the theoretical analysis FEA (Finite Element Analysis) which with the development of a small-scale model, are imperceptible deformations or displacements. Also, having control of the actual or approximate weight of the structure, the joints, and accessories. However, when changing the scale it is more difficult to control the movement of the structure, so it is necessary to consider motion control systems.
Motion control systems. The hexagonal system x-frame deployable structures, require additional elements to the structure to control its maximum open point or minimum point of closure. The hypothesis is to integrate the mechanical characteristics of the membranes and resistance to the maximum stresses, so that these serve as a maximum aperture control system. The three case studies presented stability and movement control problems. In all three cases the use of additional elements was necessary to block the movement and stabilize its shape.
Deformation and torsion bars. The changing step from working with models to working with a prototype of intermediate scale, requires checking the dimensions of the elements, materials and designs of joints. The drop-down structure system requires designing of its unions. With designs made to prevent displacement of the bars and reduce deformations.
Finally, as further research, we want to complete the theoretical analysis of the hexagonal module, and if possible physical analysis of a laboratory scale module. The aim is to include in these analyzes the behavior of the module integrated in the membrane textil as a proposition of a roof.
The idea to design a deployable structures system hexagonal x-frame like a construction system and propose mechanisms for motion control, integrated membrane systems and developing clusters as approximations of habitability are the future of this research. This is the idea of a modular, compact and lightweight construction system. Fig.ure 19.

ISSN 2309-0103
www.enhsa.net/archidoct
Vol. 4 (2) / February 2017

Figure 18.
Mobile Hanging SMiA. Views.

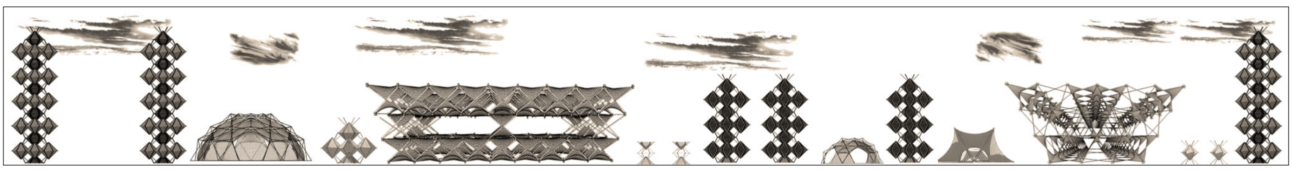

Figure 19.
Future hits - Portable and deployable cities - Microarchitecture.

ISSN 2309-0103
www.enhsa.net/archidoct
Vol. 4 (2) / February 2017

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