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Expandable covers of skew modules for emergency buildings

J. Pérez-Valcárcel, M. Muñoz-Vidal, M. J. Freire-Tellado, Isaac R. López-César, F. Suárez-Riestra
Group of Architectural Structures (GEA). Singular structures (GES)
Universidade da Coruña, Corunna. Spain

ABSTRACT

Deployable structures can be a good response to disaster situations, where it is necessary to provide services to a displaced population. They can be compacted into a lightweight and easily transportable package and deployed where needed providing an enclosure for use, quickly and efficiently. In this article, the possibilities of deployable structures of oblique modules are investigated, a subject little studied, but of great interest due to its many possibilities. The geometric conditions of the different modules and the typologies that can be considered are analyzed. The possibility of using the reciprocal links system developed by the authors is also estudied in these meshes. Finally, the performance of a pyramidal dome that uses reciprocal linkages at the ends of its bar, is analyzed in an analytical and experimental way. Both the theoretical calculations and the experimental tests allow demonstrating the viability and effectiveness of this structural type.

Keywords— *Expandable structures; deployable structures; reciprocal linkages; lightweight structures; temporary buildings; emergency buildings*

I. INTRODUCTION

Emergency situations produced both by natural disasters and by human action, are an obvious social concern. A catastrophic situation can occur anywhere at any time and in any country. It is necessary to provide mechanisms that can alleviate the consequences of the disaster, among them one of the most pressing is the housing needs of affected people.

The authors are conducting research on possible solutions to these housing needs during an emergency. It is necessary to solve both the housing needs and the various services demanded after the disaster. This article proposes and analyzes solutions for common areas such as canteens, schools, nurseries, restrooms, meeting places, places of worship, etc., uses for which solutions based on deployable structures represent a quick and effective response.

Deployable structures are articulated bar structures that can radically alter their shape from a folded position in which they are collected in a compact bundle of bars to an open or unfolded position in which they cover a wide space: an umbrella is a classic example of deployable structures.

Most of the deployable structures are formed by elements composed of a pair of bars with a central through joint, similar to that of scissors, which are usually called scissor-like elements, hereinafter SLE. Joining these SLEs at the ends of the bars by means of articulated joints, triangular, squared, pentagonal, hexagonal can be formed. Combining these modules generates a deployable structure.

The structure in the closed position can be stored awaiting its use. In an emergency situation that requires it, it is loaded onto a lorry and moved to the point where it is needed. Therefore, a correct design of deployable structures must take into account that they are light, compact, easy to transport and easy to deploy with simple means. With these characteristics, the structure can be deployed in a very short time and be quickly operational.

According to their geometry, the SLEs are classified between straight, polar (curved), translational (oblique) or angulated units, which combined form straight, curved or oblique modules, according to the SLEs employed. These basic modules are shown in Figure 1.

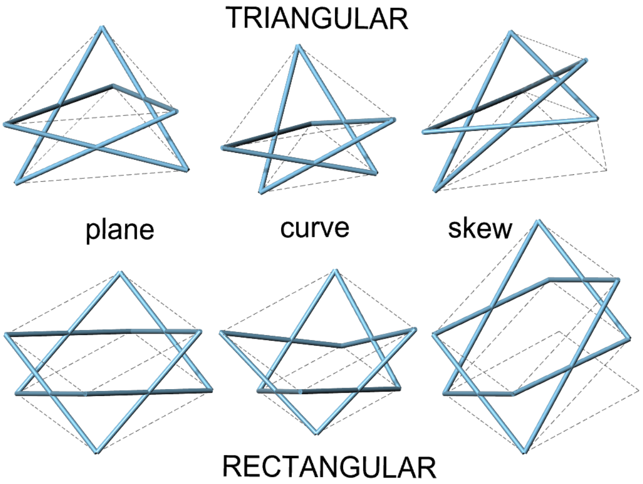

Figure 1. SLE modulus used for explandable structures.

In this article, various proposals based on the use of oblique module structures will be analyzed, but implementing a radical advance proposed by the authors: the nodes used are limkages on reciprocal supports (Perez-Valcárcel et al. 2021) that multiply the load bearing capacity and rigidity of the deployed structure under gravitational loads.

Deployable structures have a long history, despite being fairly recent. In the 1960s, the Spanish architect Emilio Pérez Piñero (1961a, 1961b, 1968) designed and built the first deployable structures of bundles of bars with a central joint.

In Spain, starting in 1984, the group formed around Escrig resumed research on deployable structures, which included Pérez-Valcárcel in 1986 and also Sánchez Sánchez since 1992 on the occasion of the construction of the San Pablo pool cover in Seville (Escrig et al. 1988, 1996, 1999) (Pérez-Valcárcel et al. 1992, 1995).

On the other side of the Atlantic, a research group was organized around Professor Zalevsky in which ideas such as bistable deployable structures were developed, with the decisive contributions of Zeigler (1976) and Krishnapillai (1985) and which would be the subject of a successful study continued by Professor Gantes since 1989. (1989, 1991, 1993, 2001). Outside the bistable sphere but also related to this group, the works of Hernández and Zalewsky (1991, 2005) should be mentioned. The contributions of Hoberman and Pellegrino are equally remarkable.

In this century the work of De Temmerman (2007) and Akgün (2011) have been decisive for the formation of research groups about the matter.

Regarding the use of translational elements,: Escrig et al (1986) proposed their use in large deployable umbrellas in the 1980s but without characterizing them; Sánchez-Cuenca (1996) identifies the type and developed a good number of geometric proposals for roofs, Raskin (1998) applies it to columns with flat and spatial blades; Lagnbecker (1999, 2001) conceived 'stress-free' fold-out covers of translational units with positive and negative curvature; Krishnapillai (1985) and then Gantes (1991) propose diagonalized translational modules to form bistable structures. In 2017 Roovers and De Temmerman carried out a complete analysis of the conditions of the type. Later, Freire et al (2020) added a new group of solutions called Bias Deployable Grids, BDG.

The contributions of this text are framed in the following four aspects.

- Study of the constructive constraints of the meshes formed by oblique modules and the conditions for their geometric and kinematic compatibility.

- Proposal of various designs with oblique modules. The different types of possible modules are analyzed. Proposals are developed for triangular and square modules and other structures that combine both types of modules. These structures apply specifically to emergency buildings.
- Development of reciprocal nodes to the specific case of these structures.
- Theoretical and experimental analysis of this type of structure.

From the initial definition, the characteristics of oblique module meshes and their construction conditions are described (Section II). Section III describes the different solutions proposed for emergency buildings. The materials and methods used in the experimental analysis are described, as well as the models tested (Section IV). The results obtained are analyzed and the results of the theoretical calculation and those obtained in the tests are compared (Section V). The conclusions and perspectives are presented in Section VI.

II. DESCRIPTION OF SKEW MODULE MESHES

The meshes to be analyzed are designed to be employed as common use enclosures in emergency situations. For this reason, it is necessary their design and, especially, their linkages -that are the most expensive elements of the set- be as simple as possible. It is also necessary that they be lightweight, both for their transport and above all to facilitate the unfolding and fixing tasks, without resorting to powerful mechanical aids. For this type of use, the most suitable are solutions with medium spans, between 8 and 12 m.

In other works of the research project that is being developed, various typologies have been studied. In this article, the structures formed by triangular or square skew (translational) modules will be analyzed. They are very regular modules that normally only need two types of bars and whose nodes can have all the same size, which allows a simple and economical manufacture and assembly. In addition, the resulting structures allow defining sloping roofs with easy water evacuation.

A. *Oblique module typologies*

In the case of triangular modulus, the oblique modulus condition is achieved by raising one of the vertices, so the affected vertex is indifferent (Figure 2a). On the other hand, in square modules, three different situations are possible:

- Displacement of two contiguous vertices in the same direction (Figure 2b). This module is generally used to generate gable roofs.
- Displacement of two opposite vertices in opposite directions (Figure 2c). This module is generally used to generate pyramidal domes.
- Displacement of two opposite vertices in the same direction (Figure 2d). This module is generally used to generate meshes whose coverage is formed by hyperbolic paraboloids.

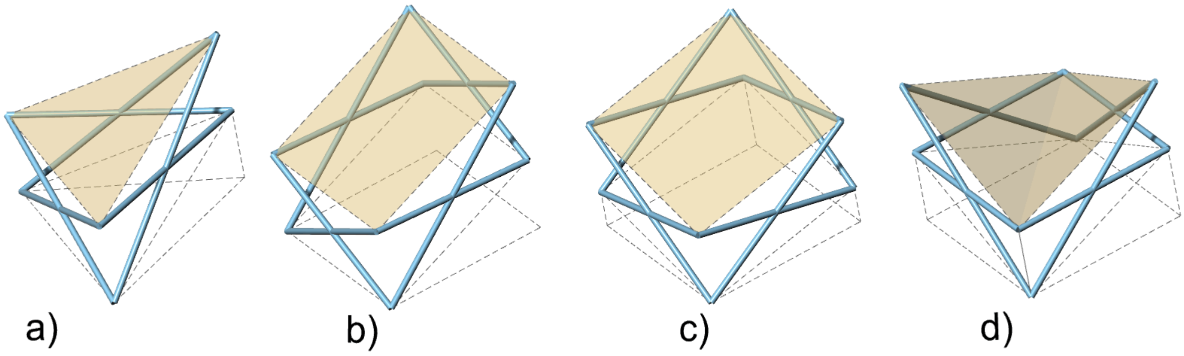

Figure 2. Oblique modulus

B. *Used linkages*

The essential element in the design of the deployable structures is a linkage that allows the necessary turns for the deployment of the structure. In most cases, the linkages at the ends of the SLEs are hinges which allow an unlimited rotation of the bars. However, reciprocal linkages that limit the rotation and also allow reducing the stresses on the bars and the deformations of the structure are also possible.

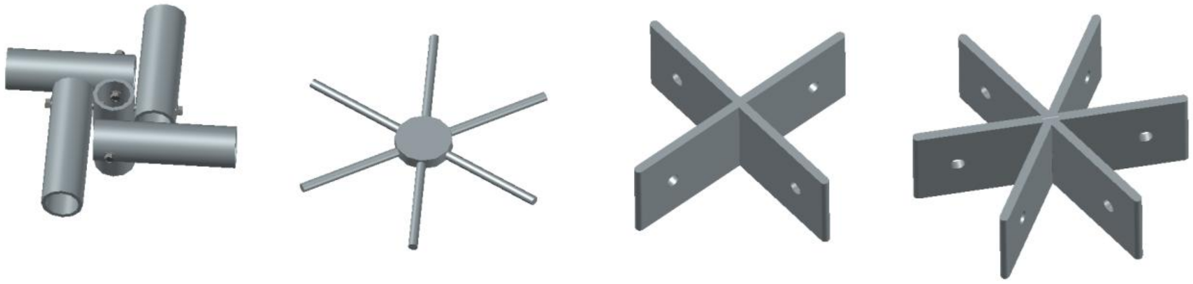

Figure 3. Articulated linkages

Articulated linkages have been widely studied since the first works (Figure 3). In general, the only condition is that they have a sufficient size to allow the packing of the bars in the folded position. The two most common types are the cylindrical and the fin linkages. They are the best solutions for meshes with triangular modules, since six bars concur in the interior nodes and a reciprocal linkage would require such a large size that it would be very ineffective.

Reciprocal linkages must have a specific width that depends on the diameter of the bars that meet in it and the angles they form. These nodes have been studied in detail in reference in a recent article (Pérez-Valcárcel et al., 2021).

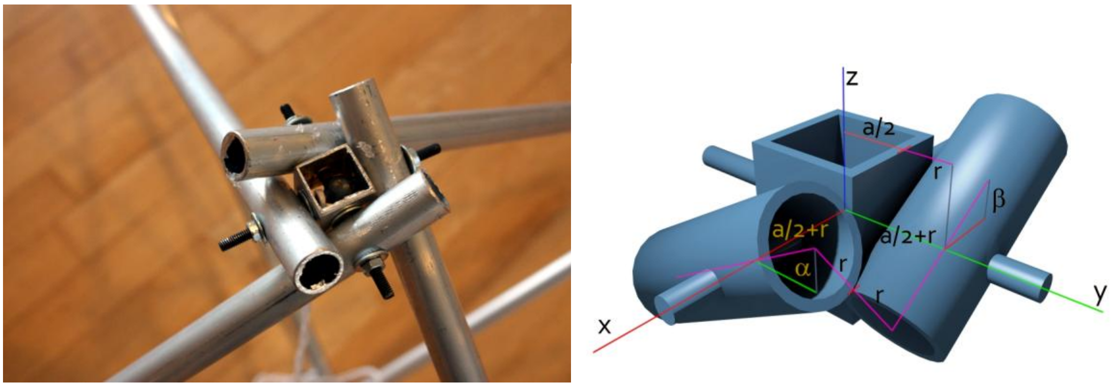

Figure 4. Reciprocal linkages

The use of the reciprocal joints means that the linkage has to be of minimum size which depends on the diameter of the bars and the desired angle of opening. To analyse the most general case, the bar opening angles are hypothesised to be different, **α, β**, where **a** is the width of the linkage and **d** is the diameter of the bars which meet it, respectively.

The separation between the axes of the bars may be determined by applying the condition that the distance between the two straight lines that cross is **d** = **2r**, considering that the bars touch at the point of contact. The relationship between the width of the linkage **a** and that of the bar **d** is

$$\frac{a}{d} = \frac{2\cdot\sqrt{\sin^2\alpha\cdot\cos^2\beta + \cos^2\alpha\cdot\sin^2\beta + \cos^2\alpha\cdot\cos^2\beta}}{\sin(\alpha+\beta)} - 1 \qquad [1]$$

This equation makes it possible to determine the diameter or width that the linkage must have so that the bars form a reciprocal joint with specific angles of opening α and β.

For this reason, in the generation of reciprocal linkages meshes, it is especially important to determine the angles formed by the bars that concur in the linkage in the deployed position to ensure that the bars rest each one on the adjacent one, making this link effective. This condition implies a certain complication in the case of oblique modules, as they have different angles. The width of the linkage would be different in both directions, but the construction of irregular linkages is complicated and expensive. The best solution is to use a link with the minimum size necessary and supplement with a nut or washer the end where it is necessary.

C. Geometrical condictions of depployement

In the case of skew modules, the way of packing the bars is somewhat different from that of other types of meshes. In flat or curved structures the height of the closed package is practically that of the length of the longest bar. On the other hand, in skew modules, each module folds somewhat lower (or above) than the previous one, so the height of the package is somewhat higher (Figure 3). It can be estimated approximately as.

$$H = 2 \cdot L_1 + 2 \cdot (n\text{-}1) \cdot (L_1 - L_2) \qquad [2]$$

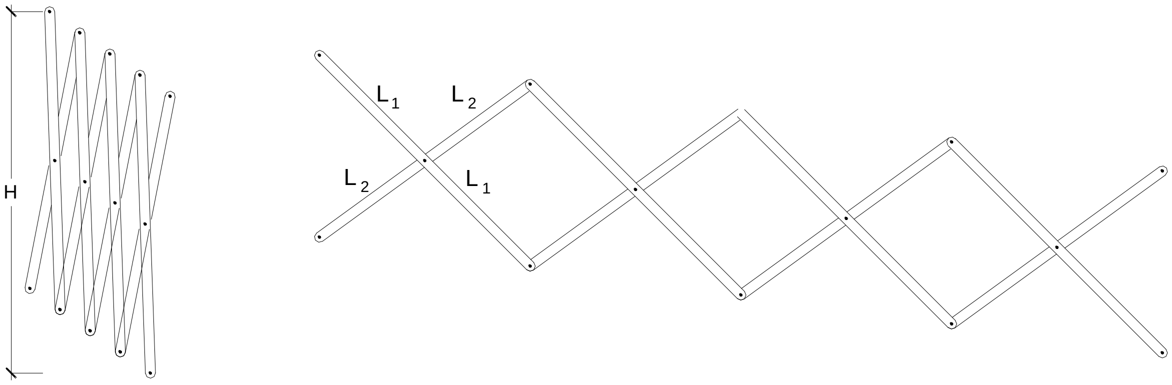

Figure 5.- Scheme of folding of an oblique module.

This means that as the number of modules and the inclination of the planes increases, the package can acquire somewhat larger dimensions, which can make it difficult to transport. With everything for, average spans like the ones that are proposed does not pose a problem.

It is interesting to define the geometric conditions to determine the lengths of the bars, as seen in figure 4.

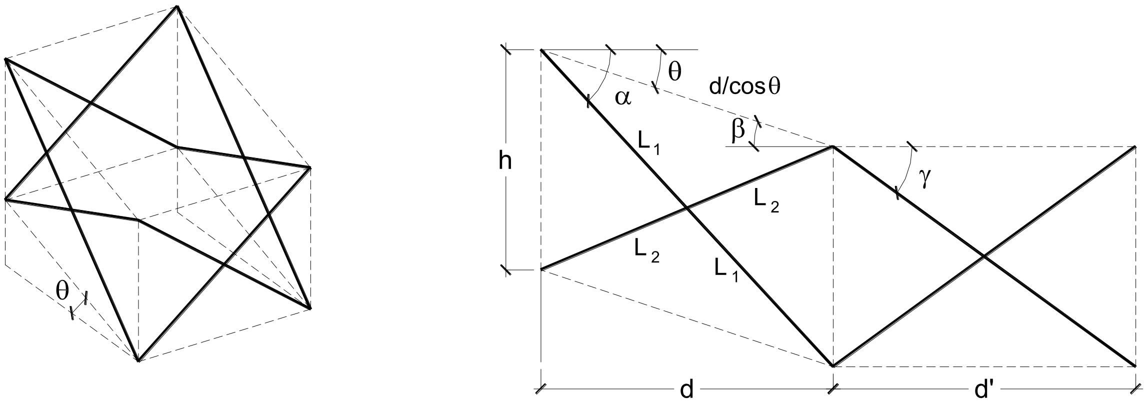

Figure 6.- Definition of the lengths of the bars and the angles with the horizontal plane.

For oblique deployment, it is important to define as parameters the height of the mesh **h** and the opening of the SLE **d**, but also the slope of the roof **θ**. Applying the cosine theorem

$$\begin{aligned} L_1 &= \frac{1}{2}\sqrt{h^2 + \frac{d^2}{\cos^2\theta} + \frac{2d\cdot h}{\cos\theta}\cdot\sin^2\theta} \\ L_2 &= \frac{1}{2}\sqrt{h^2 + \frac{d^2}{\cos^2\theta} - \frac{2d\cdot h}{\cos\theta}\cdot\sin^2\theta} \end{aligned} \qquad [3]$$

It is also important to determine the angles that the bars make with the horizontal plane, because the direction of the axis of the link is vertical.

$$\cos\alpha = \frac{d}{2L_1} \quad ; \quad \cos\beta = \frac{d}{2L_2} \quad ; \quad d' = \sqrt{(L_1+L_2)^2 - h^2} \quad ; \quad \cos\gamma = \frac{d'}{L_1+L_2} \qquad [4]$$

D. Support conditions

The skew module structures have a structural behavior similar to that of other typologies studied in previous works. In order for them to be folded and unfolded, it is necessary for them to be mechanisms, which are subsequently applied external constraints that turn them into authentic structures, that is, they are capable of resisting the external loads to which they will be subjected. Therefore, the correct definition of these constraints is essential to achieve a lightweight and efficient structure.

In some cases of structures such as vaults or curved domes, their profile may allow the roof structure to rest directly on the ground. The linkages are fixed on it providing sufficient constraint. However, skew module structures do not normally have enough inclination to allow this type of support without losing excessive interior space. The most common solution in this case is to support them on masts.

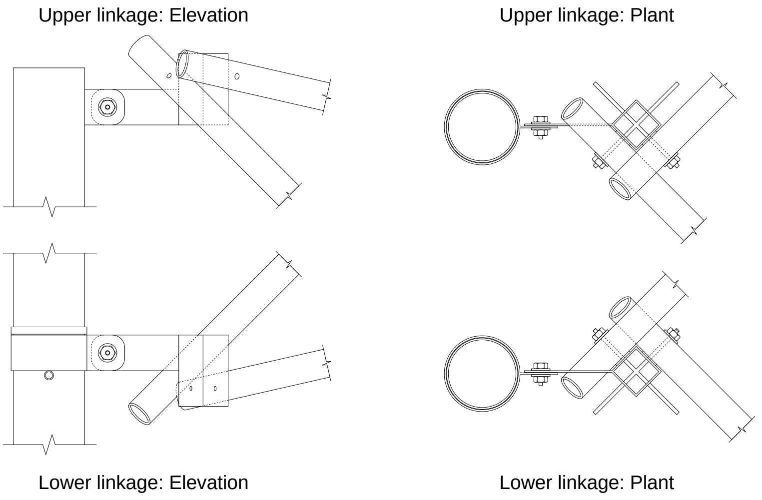

Figure 7. Support of the folding structure on the mast

The structural behavior of this type of roof improves considerably if the two nodes that concur in it are fixed to the mast. For this it is necessary to design specific elements so that the upper knot allows articulation and the lower knot slides on the mast until it is locked in its final position. Simple systems similar to the umbrella top or a simple bolt are effective enough.

E. Textile cover

In expandable structures, the definition of the roof is especially important. In most cases, textile covers have been used (Escrig et al. 1994; Pérez-Valcárcel et al. 2019). Rigid sheet metal systems that are placed on the structure after deployment have also been used Pérez Piñero 1968. Finally there are some interesting proposals with rigid sheets that are folded with the bar structure (Pérez-

Valcárcel et al. 1995). They are very attractive solutions, but they are not applicable for emergency buildings as they are excessively complicated and expensive.

For emergency buildings, the most suitable solution is a textile cover that can be folded together with the bundle of bars and that when unfolded is placed in its final position. Various systems have been proposed and it was even used on the San Pablo pool cover with success (Escrig et al. 1996).

The design of a controlled folding system of the textile is very necessary, since otherwise the SLEs when closed could work like a scissors, cutting the textile. A simple and efficient system is the one indicated in the figure. It consists of a ribbon attached at its ends to the linkages of the opposite layer. When closing the structure the opposing linkages of the scissors move away and the ribbon pulls the textile, that folds into the gap between the SLEs. When the textile is placed on the upper face, the ribbon is fixed at the linkages on the lower face and vice versa. It is advisable to leave enough slack in the ribbon and adjust it in the workshop before assembly. For this to occur, the sum of lengths between the ribbon section and the textile must be equal to that of the two sections of the SLE.

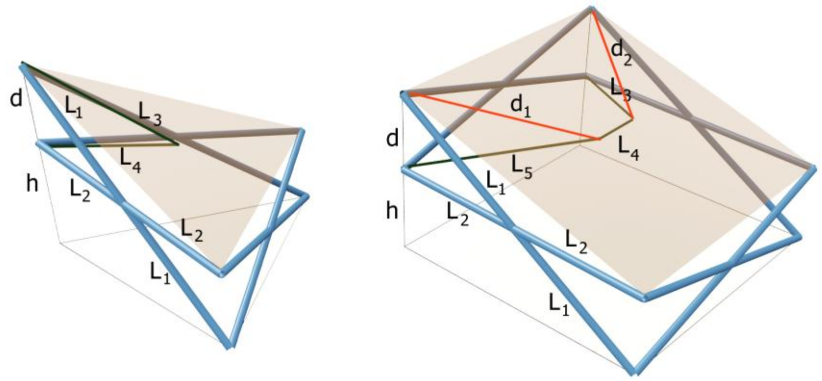

Figure 8. Geometric conditions for the self-folding of the textile cover

Triangular modules $L_1 + L_2 = L_3 + L_4$

Square modules $L_1 + L_2 = L_3 + d_1 = L_5 + d_2$ [5]

When the modules are regular, the length of the tape can be calculated immediately. With irregular modules the geometric conditions can be more complex, so it is advisable to calculate it by trial and error.

III. APPLICATION TO EMERGENCY BUILDINGS

The aforementioned modules allow you to define a large number of deployable structures, but not all of them are useful for use in emergency situations. Those of greatest interest are the umbrellas that allow the construction of stands for small businesses and the vaults and domes for community areas.

A. *Umbrelas*

Umbrellas are some of the easiest deployable structures to build. They are also especially suitable for temporary use, since they can be easily folded and unfolded depending on the weather conditions. In the case of emergency constructions, they are especially useful for markets, an essential element for exchange or small business functions. This activity is essential after a catastrophe, since it allows the resumption of part of the social uses, seriously affected after a disaster.

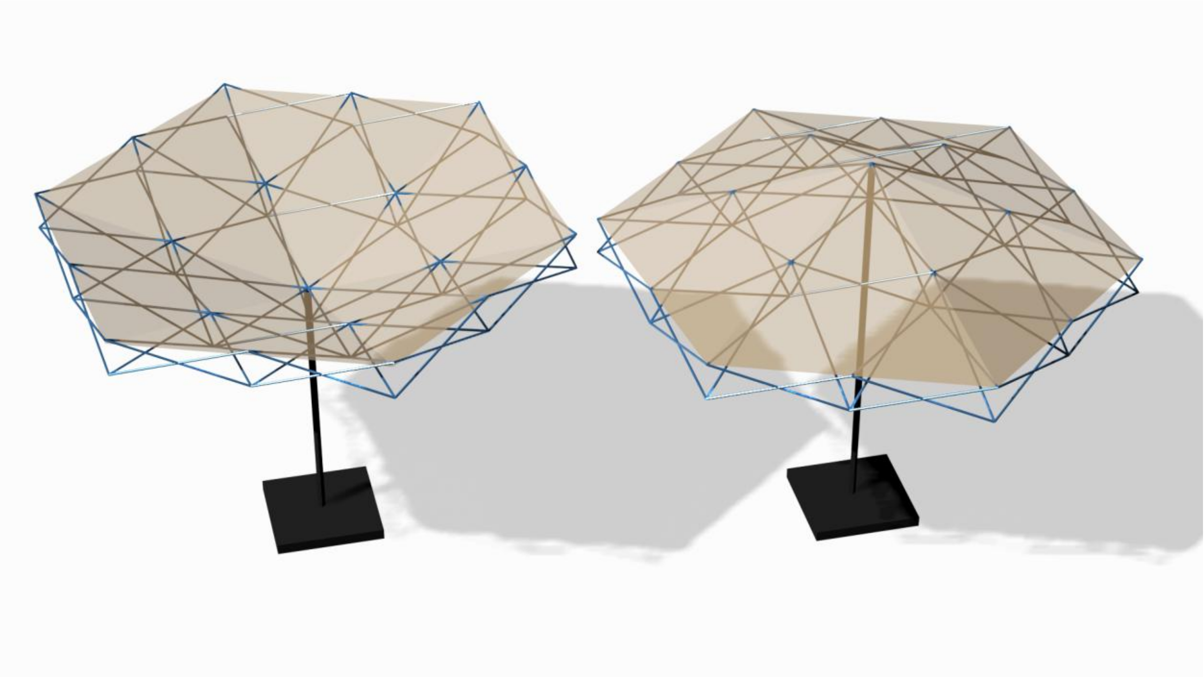

Figure 9. Expandable umbrella with triangular modulus

These structures were one of the first proposals by Escrig and Pérez-Valcárcel, as in the case of those designed to cover the Plaza de San Francisco in Seville, which was never realized (Escrig et al. 1986). Curved beam umbrellas were also proposed for the roof of the Asturias Pavilion at EXPO'92 in Seville, which was also not executed (Pérez-Valcárcel et al. 1991b).

With oblique triangular modules, triangular or hexagonal, concave or convex umbrellas can be executed. Concave roofs have better structural behavior, but convex roofs provide a better solution for the evacuation of rainwater.

The most interesting solutions for oblique square modules consist of the generation of four-sided structures, both towards the outside and inside. Even if we use modules of the hyperbolic paraboloid type, textile surfaces with continuous valleys can be generated, which allow an excellent evacuation of rainwater.

Figure 10. Expandable umbrella with square modulus

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B. Gable roofs

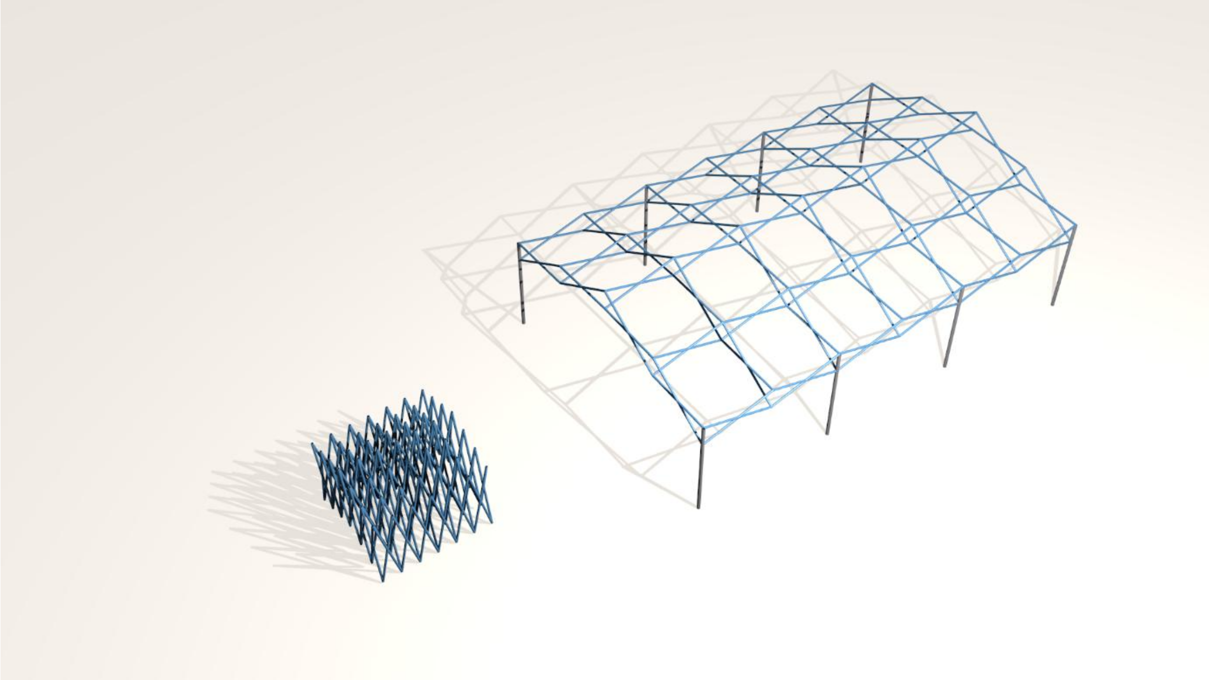

Figure 11. Gable roof folded and deployed

Gable roofs are one of the simplest and most useful structures that can be executed with oblique square modules. They have two drawbacks that need to be taken into account. On the one hand they have a low stiffness to angular distortion. On the other hand, if solid support is not sought, they have a tendency to strong horizontal movements. In emergency buildings with medium spans, effective solutions can be designed at low cost.

The problem of angular bracing is usually solved with additional bars in large structures. For small span roofs, the bracing provided by the textile roof is sufficient. Regarding horizontal displacements, the structure improves its performance when supported by properly designed masts, as indicated in II.D.

C. Pyramidal domes

Deployable domes have also been widely studied and several have even been built, using triangular or square modules. Spherical domes have generally been proposed, such as those of the Pérez Piñero Theater or the sail domes of the San Pablo roof, already mentioned. The proposal for the competition for the roof of the Bergisel Stadion in Innsbruck can also be mentioned as example of big expandable structures (Pérez-Valcárcel et al. 1992). By contrast, pyramidal domes have received little attention, despite their good performance.

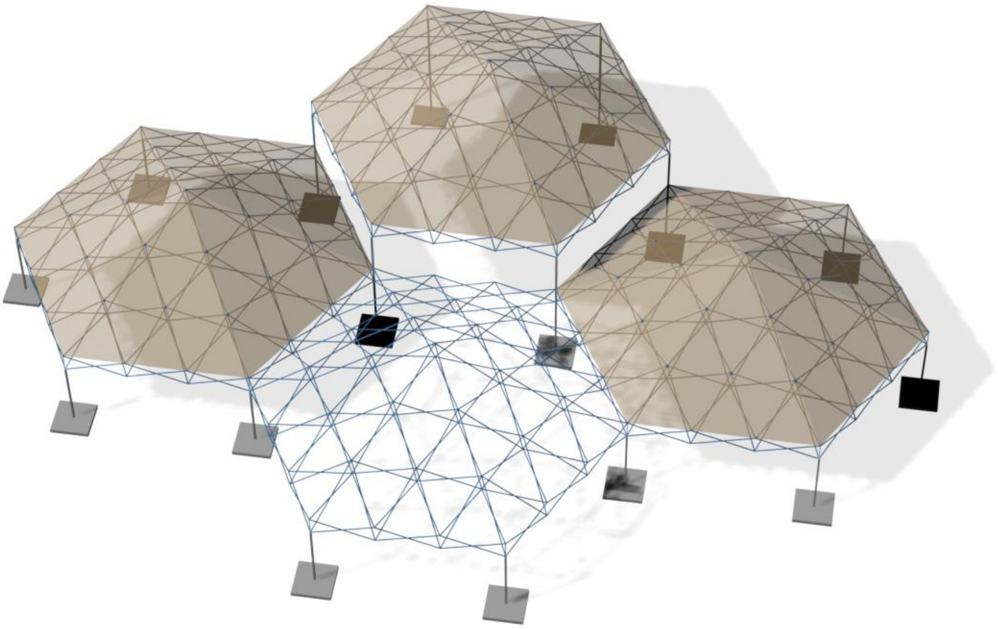

Figure 12. Pyramidal domes of triangular modules

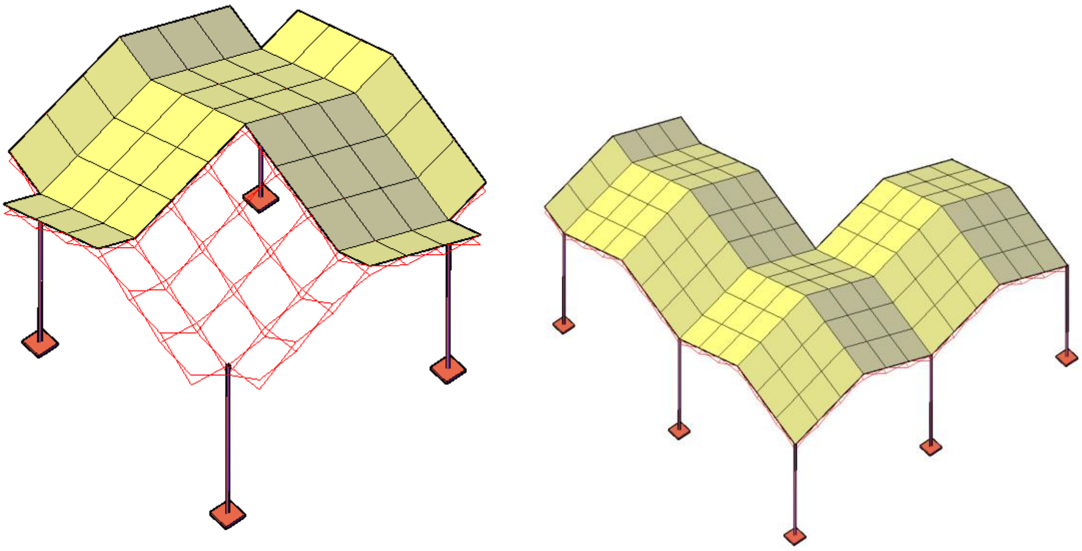

Figure 13. Pyramidal domes of square modules

These domes require a perimeter strapping with cables in case of large spans. In spans of medium or short width, as is usual in the proposed use, the supports on the masts described may be sufficient (Figures 12, 13). However, the most effective system is also the strapping with cables that can be combined with the support on masts. In the tests carried out it has been possible to verify the effectiveness of these systems.

D. Other typologies

The modules analyzed allow the execution of various typologies, even mixing modules of different types, as shown in the figure 14.

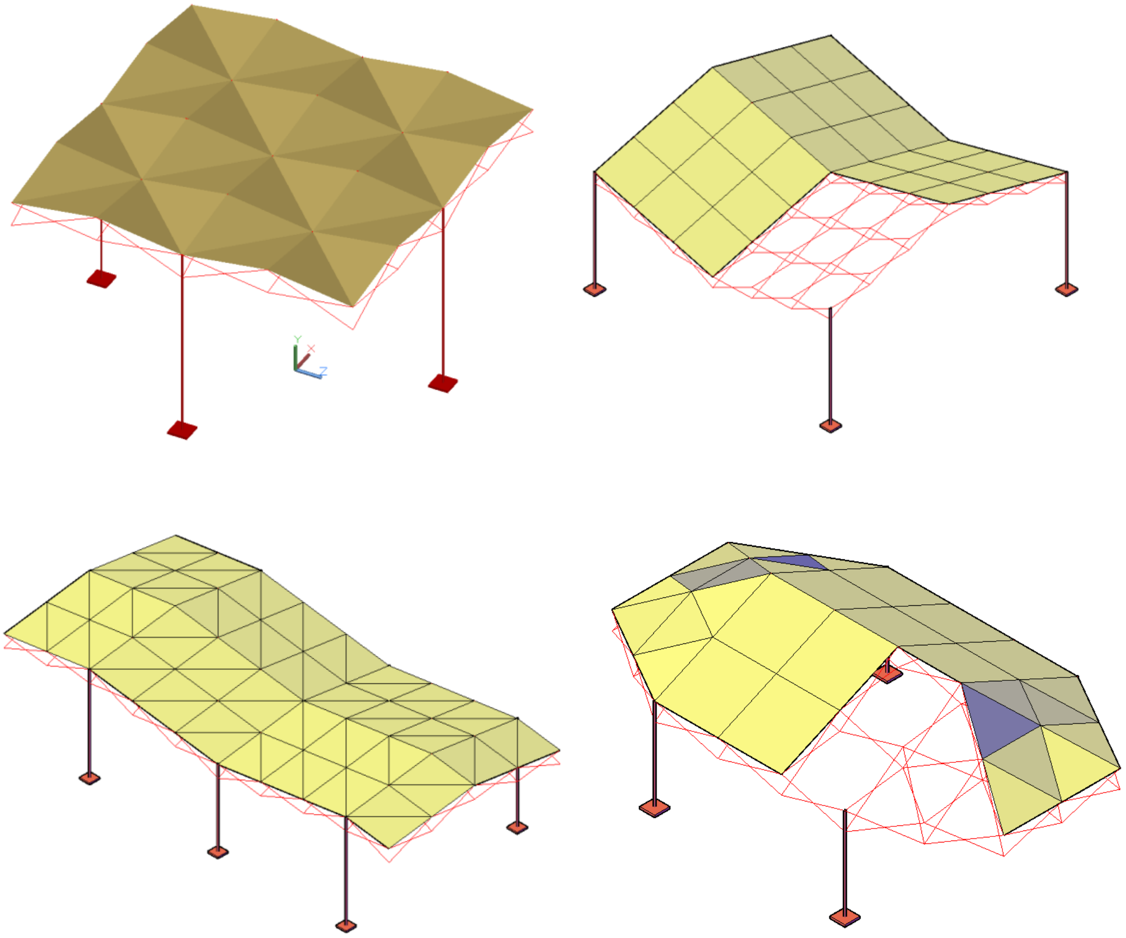

Figure 14. Other types of expandable structures with oblique modules

IV. MATERIALS AND METHODS

To verify the effectiveness of this type of mesh, a series of tests have been carried out with a pyramidal cover model. It has been built with reciprocal linkages and has been tested in four different situations, with and without cross bars in the corner, and in both cases with a perimeter tie with and without a cable. The aim is to verify the effectiveness of both systems to propose the most suitable solutions in reality.

A. Materials

The test model bars are T5 6060-type Ø16 mm and 1.9 mm thick aluminium tubes (aluminium – magnesium - silicon) (figure 20). They have a specific weight of 2700 kN/m^3, a modulus of elasticity of 69500 N/mm^2, an elastic limit of 185 N/mm^2 and a failure load of 220 N/mm^2. Ø13 mm and 1.5 mm thick aluminium tubes made of the same material were used for the bracing bars that were placed at the corners of the mesh in some tests.

The linkages are composed of sections of hollow aluminium tube (SHS) of the same quality. They are 20 mm across, 1 mm thick and 20 mm tall. The pivots are composed of 4 mm threaded steel bars that are welded to the central part. The bolts and threaded bars are in 5.6 quality steel according to ISO 898-1. They have a modulus of elasticity of 200000 N/mm^2, an elastic limit of 300 N/mm^2 and a failure load of 500 N/mm^2 with a 20% elongation.

The bracing cables are 1x19, 1.5 mm, according to the European EN 1906: 2012 standard. They have an ultimate strength of 1960 N/mm^2 and yield strength of 1570 N/mm^2.

B. *Used models*

The test model has been built at 1: 4 scale with the bars and nodes described. It is a simple structure, since they can be made with two types of bars that have the same lengths. In addition, the ratio between the diameter of the node and that of the bar D / d is always the same, so all the nodes are equal, although it is necessary to increase the distance in some of them by means of washers. For all this, its manufacture and assembly are especially simple according to the intended use.

C. *Test organization*

The mesh was tested in four different cases. First, the mesh was tested without bracing bars in the corners and without cables. The deformations were very large, in accordance with the provisions of the theoretical calculation, which is why it was found that a structure under these conditions is excessively deformable and lacks practical utility. Subsequently, three tests were carried out with different bracing systems that were effective. In the first case, bracing bars were placed in the corners, joining the upper and lower linkages. In the second, cables were placed connecting the support points of the base. Finally, the tests were carried out with the bracing bars and the tying cables. In all the tests, a previous loading step was performed first so that the linkages were adjusted. This is an aspect of the utmost importance in deployable structures. Being mobile structures, it is necessary that the joints and linkages have a certain tolerance. Upon entering into load, the structure readjusts and has a certain initial displacement. After the discharge of this previous step, the structure retains that adjustment position, although there is a slight recovery. When carrying out the next load step, the structure deforms according to the applied load. This is essential if you want to validate the calculation methods with the experimental results. Adjustment shifts would distort the measured results and prevent effective contrast.

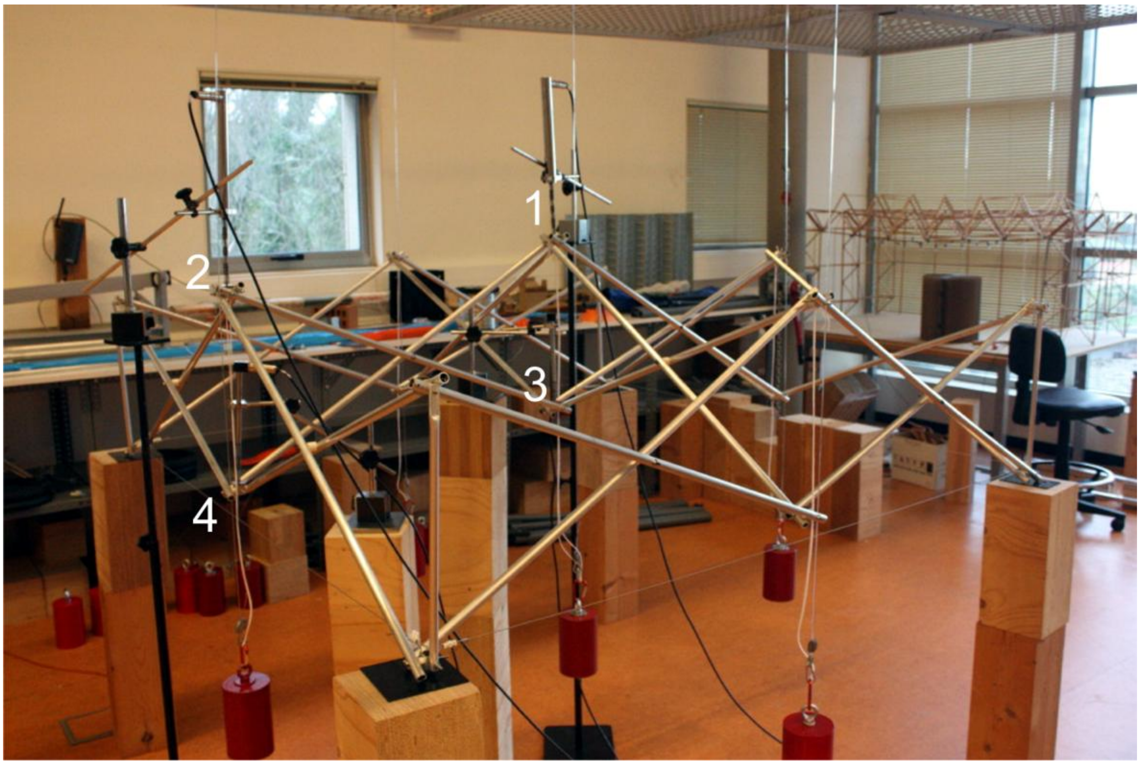

Figure 15. Model test

V. RESULTS AND DISCUSSION

A. *Theoretical model*

Verifications of the tested models have been carried out through the Despleg19.1 program that uses matrix structural analysis. In this case, the mesh uses reciprocal linkages and the program assigns to the end linkages of the bars a degree of embedment that is calculated by the program and entered as data (Pérez-Valcárcel et al., 2019). In the internal points of the bars, the program assumes a bolt connection. Consider that the displacements of both points attached to the linkage are equal, but the bars can rotate freely around the pivot.

Table 1 Displacements calculated by Deepleg

	With additional bars No cables				Without additional bars Braced cables				With additional bars Braced cables			
	Displacements mm				Displacements mm				Displacements mm			
Points	1	2	3	4	1	2	3	4	1	2	3	4
Theoretical	-27.79	-18.22	-23.18	-8.59	-14.38	-4.97	-10.59	-4.86	-9.47	-3.04	-6.89	-3.09

B. *Experimental results*

The tests were carried out with the loads placed on the nodes of the upper layer and with the displacement sensors at the points indicated in figure 14. A progressive load was entered for about 5 seconds. The charge was held for a period sufficient to fully stabilize the displacements for approximately 10 seconds and then progressively discharged for 5 seconds. For each of the cases, three tests were performed. The results are very similar, so no further tests were considered necessary. Table 2 indicates the measured results and their average value.

Table 2 Displacements measured in test

	With additional bars No cables				Without additional bars Braced cables				With additional bars Braced cables			
	Displacements mm				Displacements mm				Displacements mm			
Points	1	2	3	4	1	2	3	4	1	2	3	4
Test 1	-28.42	-18.75	-23.47	-9.67	-15.38	-6.67	-11.57	-4.76	-11.72	-3.00	-9.90	-4.85
Test 2	-28.71	-19.19	-23.70	-9.77	-15.09	-6.30	-11.37	-4.69	-11.21	-2.86	-9.23	-4.37
Test 3	-27.98	-18.75	-23.20	-9.22	-15.01	-6.37	-11.34	-4.56	-11.43	-3.00	-10.11	-4.82
Averaged	-28.37	-18.90	-23.46	-9.55	-15.16	-6.45	-11.43	-4.67	-11.45	-2.95	-9.75	-4.68

C. *Discussion*

As indicated, the first test of the mesh without additional bars and without bracing cables was unsuccessful. The only resistant mechanism that the mesh had to not be a mechanism, were reciprocal linkages. These linkages prevented the collapse of the structure, which with articulated ones would undoubtedly have occurred, but instead the displacements were so strong that their use was not suitable. Therefore, the tests focused on analyzing the effects of the different possible bracing systems.

The results obtained have been compared to test the effectiveness of these bracing systems. It is observed that in the case of meshes without tying cables, the coincidence is very high, especially in the central nodes, which are the ones with the greatest deformations. In this case, the fit of the model is very high, so the experimental results are very close to the theoretical ones, which supports the effectiveness of the calculation model. The results of the meshes with bracing cables show little differences in absolute value, but greater in relative terms. In the realization of the model there have been difficulties to tension the cable effectively, which justifies these differences.

Table 3 Displacements comparison

	With additional bars No cables				Without additional bars Braced cables				With additional bars Braced cables			
	Displacements mm				Displacements mm				Displacements mm			
Points	1	2	3	4	1	2	3	4	1	2	3	4
Theoretical	-27.79	-18.22	-23.18	-8.59	-14.38	-4.97	-10.59	-4.86	-9.47	-3.04	-6.89	-3.09
Averaged	-28.37	-18.90	-23.46	-9.55	-15.16	-6.45	-11.43	-4.67	-11.45	-2.95	-9.75	-4.68
Increase mm	-0.58	-0.68	-0.28	-0.96	-0.78	-1.48	-0.84	0.19	-1.98	0.09	-2.86	-1.59
Increase %	2.1%	3.7%	1.2%	11.2%	5.4%	29.7%	7.9%	-3.9%	20.9%	-2.8%	41.5%	51.4%

For the meshes braced by cables, the experimental results are more representative, which even with the errors in the assembly of the cables, show that the efficiency of the bracing systems is very high. The inclusion of bracing cables only causes the displacements of the central node to be 53.43% of those of the mesh with only the bracing bars. If additional bars are placed in addition to the cables, the displacement decreases to 40.36%.

VI. CONCLUSIONS

The use of oblique modules in the design of deployable structures allows a wide set of meshes of great interest and utility for emergency enclosures. These modules can incorporate the textile cover so that the deployment and putting into use is faster. They also allow the use of reciprocal links, which improves their resistance capacity and limits displacements. Likewise, the effectiveness of the proposed bracing systems has been demonstrated.

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