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A new type of Reciprocal Structures: Deployable yurts for Emergency Situations.

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Abstract

Deployable structures are a good solution for emergency buildings due to their lightweight and compact characteristics that allow them to be transported to wherever they are needed, especially in emergency situations. Generally, folding structures have been designed with modules comprised of straight bars, forming a scissor joint. They are efficient systems, although they have the disadvantage of being excessively deformable, requiring the use of large and consequently heavier sections.

Recently, interesting proposals have been made based on deployable systems with parallel arches and also with arches or frames with multiple intersections. Dome solutions have been proposed with vertical and horizontal axis joints with reciprocal support in the linkages that increase their efficiency.

In this document, a new system is proposed for deployable structures based on a similar system of multiple intersections, but composed of straight bars. This allows them to be applied to a traditional and highly effective design, the yurt. The deployable yurts developed have multiple applications for common types of structures used in emergency situations.

Keywords: deployable yurts; deployable structures; reciprocal linkages; lightweight structures; temporar buildings; emergency buildings.

1. Introduction

Recently there has been extensive development in the field of lightweight structures, which affects, among others, two very interesting typologies: deployable structures and reciprocal structures. Numerous studies are being carried out, many of them focused on self-constructing buildings or those used to tackle emergency situations, which adapt these typologies. Their main strengths are, in addition to their aesthetic qualities, their lightness, ease of construction and transportation, and their reduced cost.

Deployable structures are defined as structures that can be folded into a compact package and opened to form an architectural enclosure. They can be fixed in one place to allow successive opening and closing processes, for seasonal reasons, such as the cover of the San Pablo swimming pool [1] or depending on the needs of use as in the Jaén Auditorium [2]. However, it is often of interest that they can be transported [3, 4, 5]. They can be built in a factory, stored compactly, and transported to the locations where they are required.

For this reason they are very useful for emergency buildings. It is possible to keep a range of these items in stock, transport them to the site where an emergency has occurred and deploy them so that they can be used to meet the accommodation and service needs of the affected population.

Deployable structures have been the subject of numerous studies. The first works are those of the Spanish architect Emilio Pérez Piñero, who built the first deployable structure, which was the Portable Pavilion for the XXV Years of Peace Exhibition in 1964 [4], made up of flat deployable modules measuring 9x12 m. The system chosen was that of square-plan beam modules. Later, Escrig and Pérez-Valcárcel carried out numerous studies on both the design and calculation of folding structures with scissor modules [6, 7, 8]. These studies were carried out on the covering of the San Pablo swimming pool in Seville [1]. It consists of a mesh of two 30x30 m. dome modules with quadrangular scissor modules that are joined to form the cover of an Olympic pool, resulting in a 30x60m enclosure. To date, this building is the last large-span folding bar structure to be built.

Despite the difficulties in translating their proposals into practice, there have been numerous studies on deployable structures, such as those by

Gantes [9,10,11], Sánchez Cuenca [12,13], Hernández Merchán [14], N. de Temmerman [15,16,17], Charles Hoberman [18], Tibert [19], Pellegrino [20], José Sánchez [21], K. Kawaguchi [22] and Liew [23].

In general, deployable structures consist of a basic element that is a pair of bars that are articulated at an inner point by means of a pivot. This assembly is called an SLE (Scissor Like Element). By joining several SLE by their ends with joints, modules are formed, which in turn form the complete structure.

The SLEs are usually arranged in vertical or near vertical planes, with the axes of rotation being approximately horizontal. It is a solution that provides rigidity to structures that tend to be quite deformable. There are also some interesting proposals in which SLE are arranged in planes close to the horizontal, such as Hoberman's Iris Dome [18]. These structures are generally more deformable, so it is necessary to use larger bars, resulting in heavier structures.

Deployable structures can also be created with elements other than SLEs. The patents of F. Escrig [24] and S. Toshiaki can be cited [25], where the concept of a pair of bars forming a scissor is replaced by that of a pair of arches forming a trestle, with horizontal axis bolts. Escrig et al proposed various solutions based on arrays of arches capable of covering large enclosures. One very remarkable achievement is the roof of the Auditorium in Jaen (Spain), formed by crossed arches on horizontal axis bolts [26]. Recently, Estévez et al have patented a detachable system of arches [27] and Muñoz et al have proposed an interesting solution for domes formed by arches with multiple intersections [28]. This system combines domes with vertical axis pivots or with radial axis pivots, which form enclosures that can be transported in a very compact way.

The other line of investigation indicated refers to reciprocal structures. These are defined as structures made up of elements that support each other in such a way that an enclosure can be covered with pieces smaller than the span to be covered. There are well-known precedents for this system, such as the one described by Serlio [29] or the Ponte Arcuato in Leonardo da Vinci's Codex Atlantico [30].

Studies of their resistant behaviour have been carried out that prove their effectiveness, such as those by Sánchez el al. 30] or those of Choo et al. Their main disadvantage is that the failure of one piece can cause the structure to collapse. To avoid this, it is advisable to create redundant connections, in which a possible failure can be compensated by the adjacent parts.

Numerous studies have been carried out analysing various typologies of significant interest. Almost all of them have focused on fixed reciprocal structures such as those at Popovič [32] or those of Maziar [33]. These structures tend to offer good resistance and rigidity, but have the disadvantage of needing to be assembled on site. They are not easy to assemble and require specialised personnel, which makes them difficult to install in emergency situations. There are some proposals for shelters with reciprocal frames that allow for relatively simple and fast construction, such as the one proposed by Popovič et al. These structures are of great interest, but since they are not deployable they are unrelated to this article.

Reciprocal structures are usually more rigid and stable than deployable ones. Therefore, an interesting line of research may consist of combining the advantages of both systems. The idea is to design deployable structures in which, once open, the elements are mutually supportive. In this way, structures that can be folded, transported and deployed can be created which, at the same time, offer improved resistance, such as reciprocal structures.

Very few studies of these reciprocal deployable structures exist. We can cite the patent by Pérez-Valcárcel et al. which proposes deployable structures formed by SLE whose ends are reciprocal, which improves their resistance and rigidity conditions [35].

In general, most of the studies cited are aimed at creating relatively large structures. However, for the design of valid solutions for emergency buildings, it is more appropriate to use small or medium sized structures with simple linkages and bars that do not require additional elements. There are some recent studies that analyse this problem [36, 37]

This article proposes and analyses new structures similar to those of the multi-arch structures proposed by Muñoz et al [29], but using straight bars, which allows for designs that are easier to manufacture and therefore cheaper. A new typology is proposed based on a traditionally transportable element: the yurt. A framing system will be defined that can be folded for transportation and whose elements, when deployed, are mutually supportive. The result is a very light, easily deployable and highly resistant structure that can be used for emergency buildings, which is the main object of the research being developed.

To our best knowledge, no other architectural or civil engineering application of the concept of fully deployable yurts exists today. Until now, this structural type has been developed following traditional guidelines. Specifically, the radial unfolding of the roof is hardly unprecedented, except for the arch structures already mentioned. Regarding the folding structure of the walls, two different proposals are made, which can be used interchangeably according to the needs of use.

The objective of this contribution is to discuss the behaviour, both theoretical and experimental, of deployable yurts with reciprocal linkages, in order to obtain a deep understanding of their structural response.

The originality of this article focuses on the following three aspects:

- Investigation of the geometric and kinetic feasibility of deployable yurt structures built using reciprocal linkages.
- The study of structural efficiency of the system. It is analysed with theoretical models and the results are compared with the experimental analysis in models.
- The investigation of the application of structures of this type to emergency buildings. Both isolated buildings and possible groupings for community uses are analysed.

The objective of the work is the structural response of deployable yurts with reciprocal linkages and their practical applications. The reciprocal linkage system allows the design of folding structures that are stronger and less deformable than conventional ones, with kinematic conditions that allow compact packaging and easy transport. This implies opening a line of research relevant to future work.

From the initial definition, the traditional yurt and the advantages of the proposed system are analysed (Section 2). The possible typologies of reciprocal folding yurts, their architectural components, the deployment systems and the necessary kinematic conditions are studied (Section 3). The materials and methods used in the experimental analysis (Section 4) and the results obtained are described, including the comparison between the results of the theoretical calculation and those obtained in the tests (Section 5). Possible architectural proposals for the use of these structures in emergency situations are also analysed (Section 6). The conclusions and perspectives are presented in Section 7.

2. A proposal for a new type of reciprocal deployable structures.

The yurt is a tent that is widely used by Mongolian tribes. It can reach a considerable size, making it possible to house entire families, which in tribal settings are usually very large. The construction method of the traditional yurt consists of a half-timbered wall, which is folded into a compact package. The wall unfolds in a circular shape and is fixed on a wooden door that provides access to the interior. Wooden slats are placed on the wall grid and supported by a central post, which is usually decorated with the identifying elements of the family that occupies it. This post can be replaced by a ring in smaller or more modest yurts. Once the structure is built, the yurt is covered with skins and tied with ropes, bracing the entire assembly.

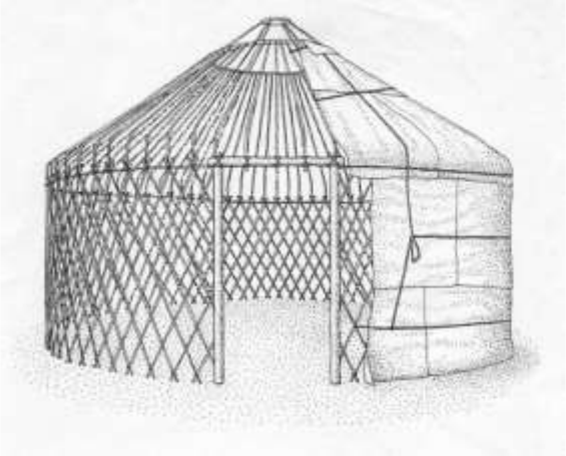

Figure 1: Diagram of a yurt (E. Martín).

The traditional yurt offers many advantages, which is why it is still used today. It is even common to see yurts built in the courtyards of modern houses in Mongolia. Different types of modern yurt variants are frequently proposed, especially for academic or self-construction purposes, but systematic studies of these are rare. We can cite Hamish Foulerton's patent "Collapsible yurt" which has the disadvantage of using a somewhat complex mechanism, which means it is of little use for emergency construction [38]. There are various examples of Chinese patents, but in some cases they are variants of the traditional yurt, and in others they involve very complex mechanisms, meaning that once again they are not suitable for emergency buildings, which is the objective sought.

The traditional yurt is not very suitable for this use, as it entails an excessive number of assembly operations on the building site itself. In the case of the Mongolian people, they have traditionally acquired skills that allow them to assemble their yurts quickly and efficiently, but it is very difficult for personnel without this knowledge. That is why a new system is proposed, which allows the structure to be completely folded and which can be operational with just a few operations on site that can be easily carried out by unskilled personnel. The idea is that those who are affected by the emergency can actively collaborate in the work on their own settlement. This is an aspect of the utmost importance that is highlighted in all manuals, such as Sphera [39] or UNDRO [40].

3. Types of deployable yurts.

The elements that define a yurt from a structural point of view are the roof and the walls. In addition to these basic elements, the yurt has other complementary elements which are also important such as the cloth cover, the skylight, and the door and window openings. These elements are fitted after deployment and should be properly designed to facilitate assembly
As we have seen, in traditional yurts the walls are foldable, while the roof is not. In order to achieve the objectives of this research, the aim is to design fully deployable yurt structures.

3.1 The roof structure.

The condition of deployability on the deck requires that the sum of the lengths of the two sides of each rhombus be equal, so that they can be attached at deployment. A structure with radial deployment, as intended, has to have central symmetry. The base must be a regular polygon which can be a square, pentagon, hexagon or octagon. Multi-sided polygons are possible, although the bars would have an excessive number of intersections, making them complicated to assemble and excessively heavy. The most suitable solutions are the hexagon and the octagon, since they provide a balance between the lack of rigidity of the solutions of squares and pentagons and the difficulty of mounting polygons with more than 8 sides. Using as bases the external polygon and an internal polygon similar to it, we can build star-shaped polygons, which fulfil the conditions of deployability and which can have reciprocal supports, making it possible to reduce the number of pivots.

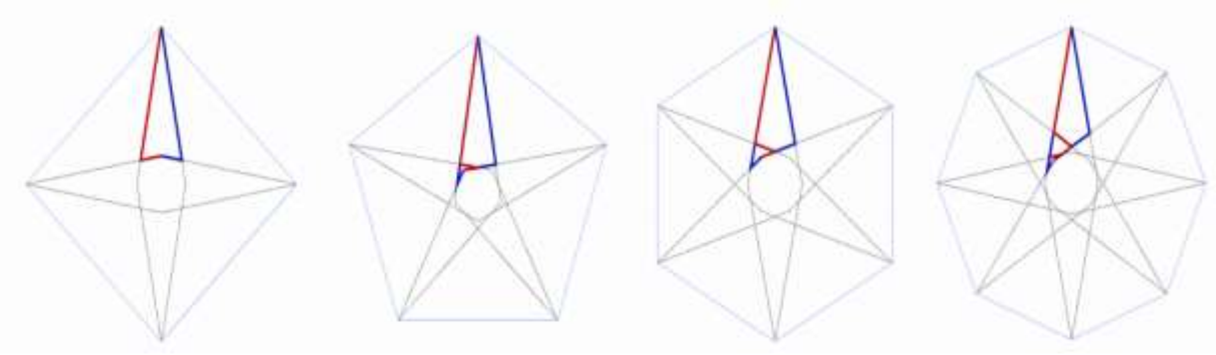

Figure 2: Diagrams of deployable yurts.

In order to make the assembly deployable, one set of bars needs to pass over the others. Figure 3 shows the bars in the upper layer in red and the bars in the lower layer in blue. With a hexagonal pattern, each bar has three joints and a reciprocal support. With an octagonal pattern, the bars have three joints, a crossing point in the non-contact space, and a reciprocal support. If the roof is flat, the two sets of bars could be in contact with each other, but if the roof is sloping, it is necessary to separate both sets so that the bars can rotate on vertical pivots. In section 4 the necessary clearances will be discussed, which are easily resolved constructively with Teflon rings.

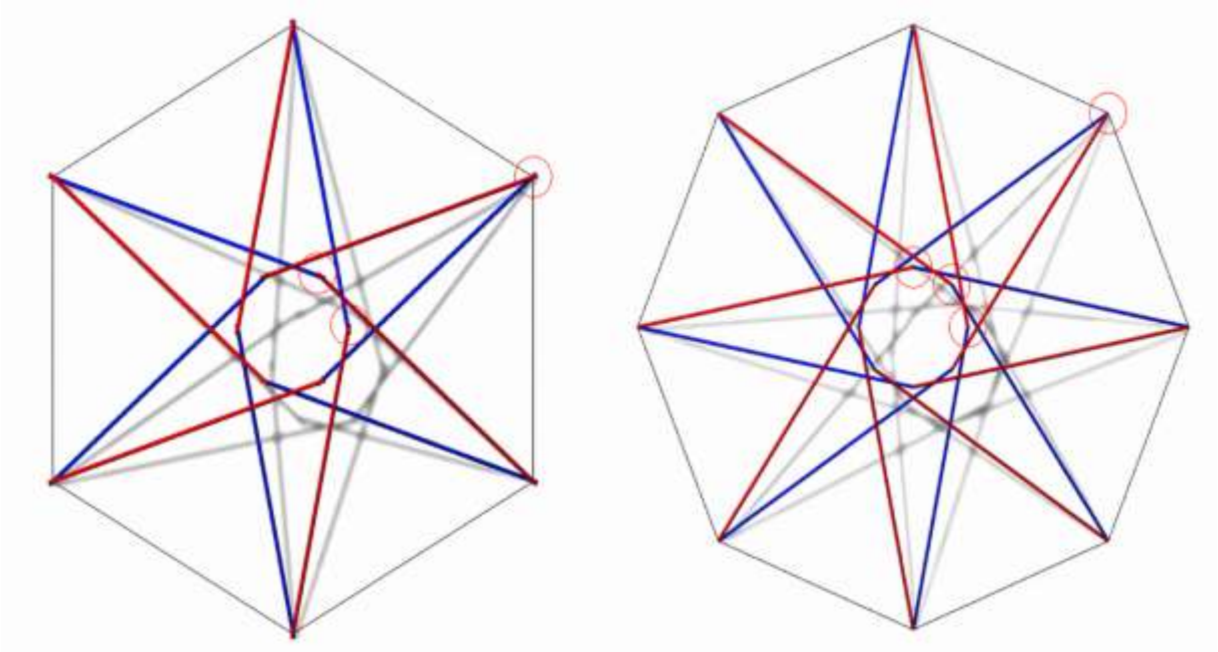

Figure 3: Position of bar assemblies in hexagonal and octagonal roof coverings.

To allow the assembly to be folded, the pins marked with circles in figure 3 must be released. This allows a compact package to be formed that can be stored and transported. Once on site, the cover is deployed and the indicated pins are fixed in place. Figure 4 shows how the yurt cover structure can be folded and deployed.

The slope of the roof should not be too steep, in order to avoid problems of kinematic incompatibility. The recommended slope is between 15º and 20º.

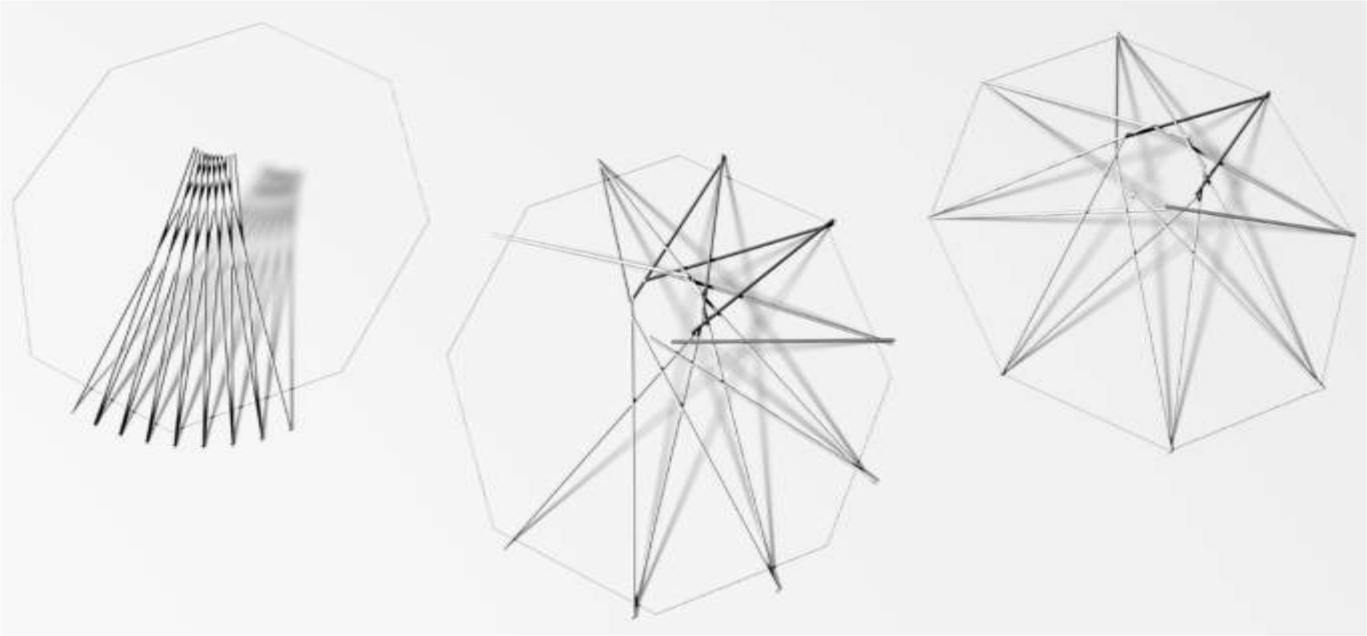

Figure 4: Diagram showing how the roof covering of the yurt is deployed.

3.2 Wall structure.

For the design of the wall structure, it is necessary to take into account that the traditional layout of the side surface of the yurt is not particularly suitable for the type of roof designed. In these yurts the wall is formed by a latticework of wooden slats with multiple intersections and which unfolds in a circular fashion. Although it is foldable, it is unsuitable for a yurt that can be deployed in conjunction with the roof. Furthermore, this framework is too bulky for temporary buildings. It would imply an excessive number of joints, a complicated assembly process, and a higher cost. Therefore, the most suitable solutions must be adapted to the pattern of the roof, have few joints and use few bars, taking advantage of the best performance characteristics of the material used, which is aluminium.

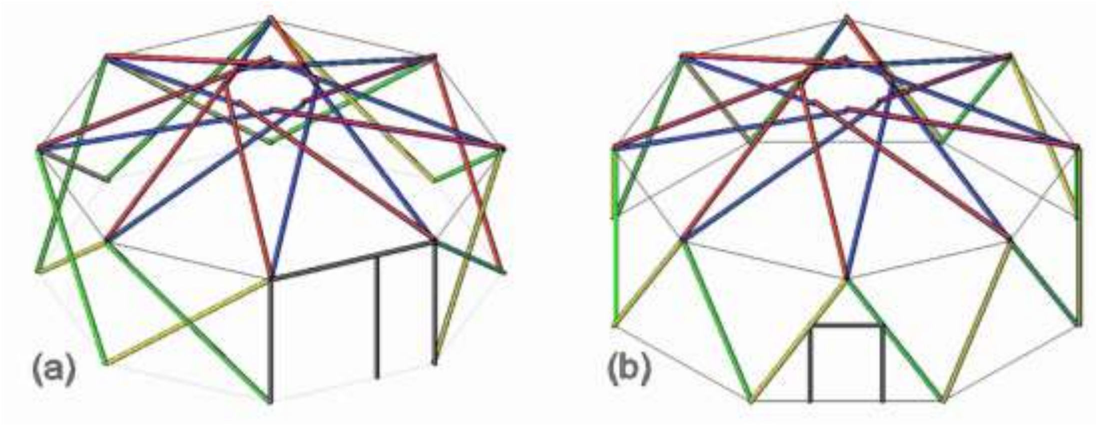

Figure 5: Diagrams of the wall structure.

Two types of solutions have been studied, the use of which depends on the type of construction that is most appropriate for each specific problem, and which are shown in figure 4. The first type (a) is based on configuring the walls with SLE that can be deployed together with the roof. The second type (b) uses sloping pillars that are hinged at the base.

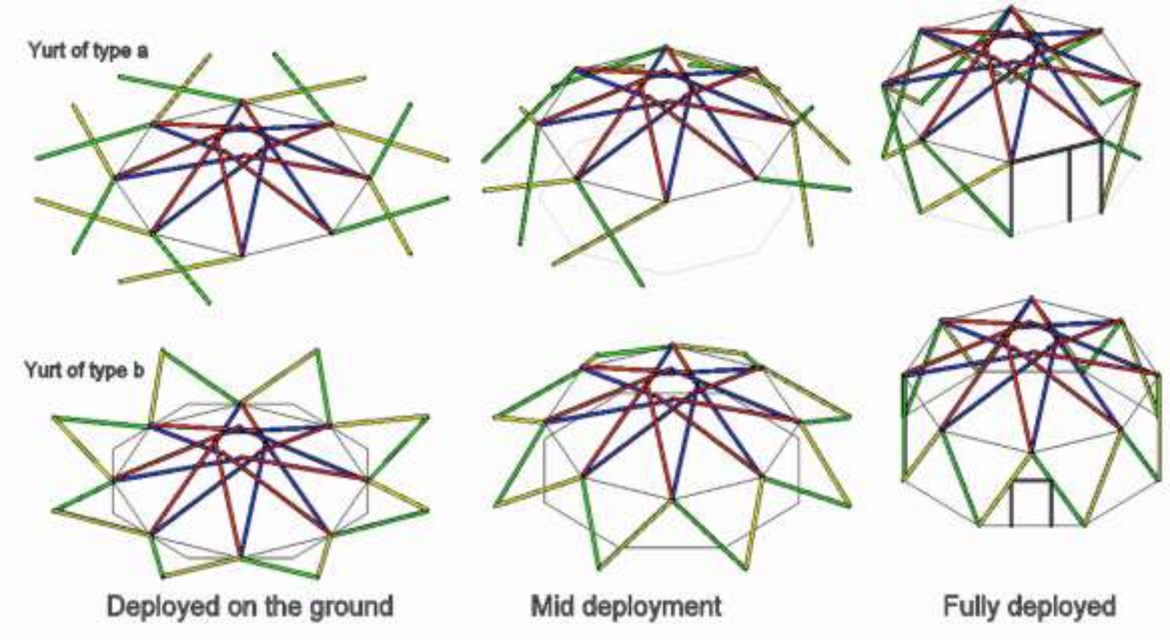

Figure 6: Diagram showing the assembly process for type (a) and (b) yurts.

In both cases, two deployment solutions are possible:

Solution 1.- By placing the bundle of bars in a vertical position and rotating the roof bars, the assembly can be unfolded radially. In the case of type a) yurts the assembly is supported in midway positions from a 120° deployment angle, while type b) yurts need to be braced throughout the entire radial deployment process. The main disadvantage of this system is that it is necessary to secure the closing linkages with the structure in its final position. This means that work must be done at height, which is always a difficulty. As for the textile cover, this can only be deployed together with the structure if it is placed underneath this structure. In addition, it is necessary to include a sealing joint for the fabric, which can always cause watertightness problems.

Solution 2.- The second type of deployment is considered the most useful. It consists of radially deploying the entire structure on the ground or on trestles at a reduced height that allows work to be carried out comfortably. In this position the closing pins are fixed in place, the textile cover and the necessary finishing elements, such as the skylight, are attached. Even the roof could be made of a non-textile material, if desired. Then the entire assembly is hoisted and the SLEs (a) or sloping posts (b) are attached to the base.

In both cases it is necessary to define a linkage that allows a rotation of the vertical axis so that the facade surfaces go from an angle of 180º when folded to 120º or 135º when deployed, and another with a horizontal axis for the roof. The latter is folded in extension with the structure of the walls and must rotate until it reaches the final pitch, which is usually about 20º, involving a rotation of approximately 70º. The piece must be carefully designed, although the problem is limited as only a few linkages are required, either 6 or 8 depending on the type of yurt. One linkage model is shown in figure 6, which has the benefit of being equally valid for models a and b. This linkage was made with a 3D printer and tested on the models for kinematic compatibility studies. These tests are described in section 4 and demonstrate the efficiency of the system.

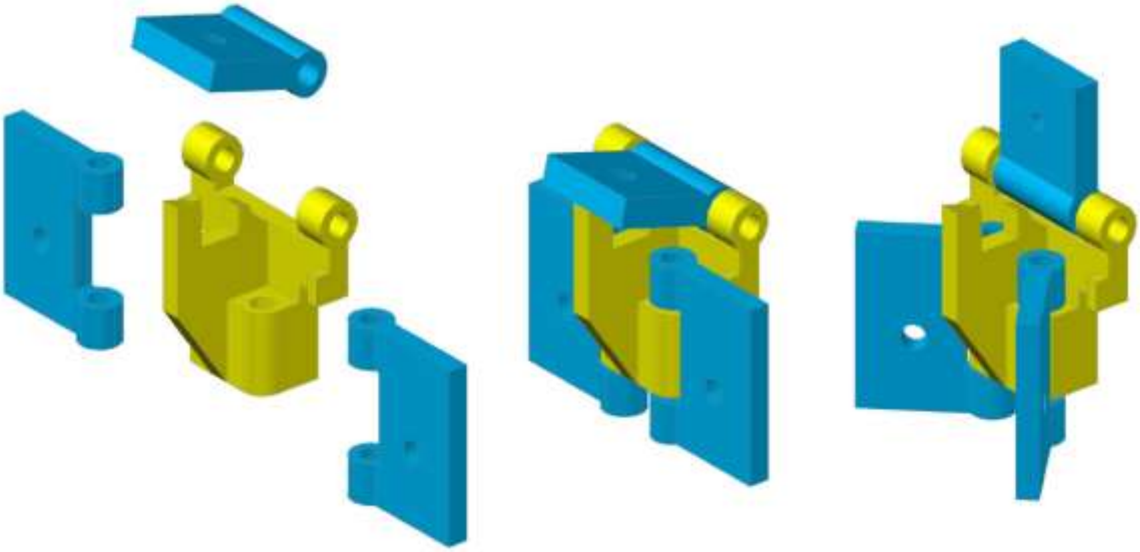

Figure 7: Model of the upper perimeter linkage

3.3 Non-structural elements.

The traditional yurt has a hide covering. It is a very effective system and offers a reasonable performance in a very hostile environment. In the proposed solution, an artificial textile covering is used with the appropriate performance in terms of insulation.

Yurts have a central ring that serves as a support for the roof battens and also serves as a smoke outlet. With the proposed folding elements a central hole remains, similar to the traditional yurt. It can be used as a smoke vent, although modern yurts are often fitted with modern air conditioning systems. Its normal use is as a skylight and this will be the proposed application.

If deployed at height, the skylight should be attached after the roof is fixed in place. However, the lifting system can be attached immediately after building the roof at ground level and then hoisted with the assembly.

The proposed systems leave ample space in which to install the doors and windows, which require auxiliary bars to form the frame. These bars can be folded with the assembly if they have a central ball-and-socket joint, but it is much simpler and more useful to fit them once the structure has been deployed. The bars of the main structure are designed with the support points where these auxiliary bars are attached.

3.4 Kinematic compatibility verifications

The first condition that a deployable structure must satisfy is kinematic compatibility throughout the entire folding and deployment process. In this case the main problem occurs because the rotation axis is vertical and the bars are inclined. Figure 8 shows the diagram of the roof and figure 9 a detail of the model tested, which is described in section 4.

At the linkage of the central ring D it is necessary to separate the axes of the bars so that the structure can rotate. If this separation is maintained along the entire length of bar 1-2, it touches bar 7-8 at linkage C, forming a reciprocal support. However, at linkage B there is no contact between bar 1-2 and 5-6. Although a pivot could be placed at this point, calculations show that it would be inefficient and would also mean that assembly will be more complex.

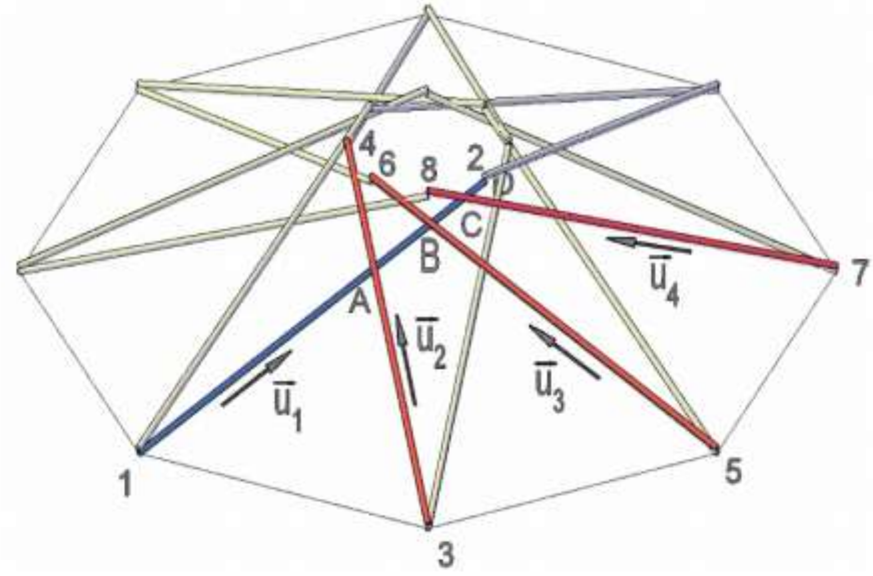

Figure 8: Diagram of intersections between bars

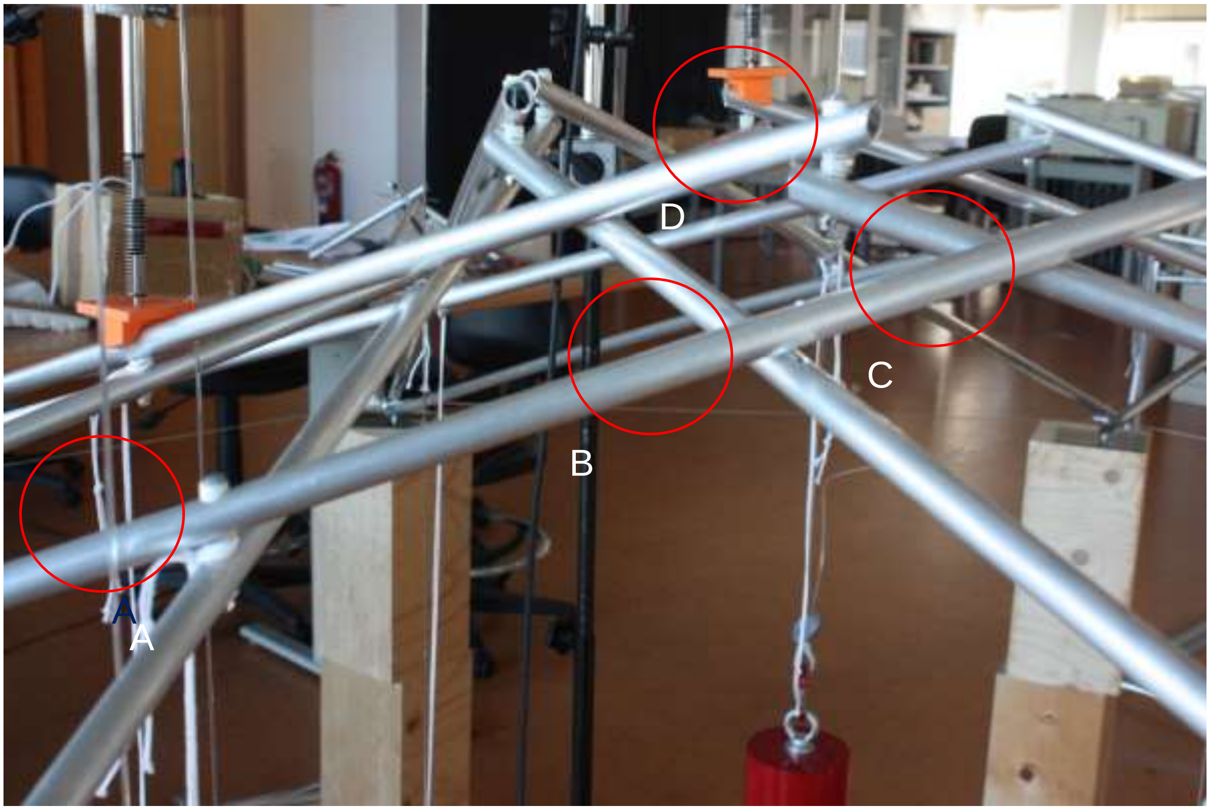

Figure 9: Close-up of linkages in the test model.

Two types of geometrical conditions must be met. The distance between the bars of the D linkage must allow for the rotation of the vertical axis. Secondly, the distance between the axes of the bars at linkage C must be equal to the diameter of the bars that cross each other. This latter condition is crucial, since if it is not met, the bars could become jammed during the opening process.

The distance between the intersecting bars depends on their pitch and the diameter of the inner ring, which determines the horizontal opening angle. The coordinates of the ends of the bars can be easily determined.

Any bar of the type marked in blue as 1-2 in figure 7 intersects with three other bars at points A, B, C and D. To calculate the distance between the intersecting lines it is necessary to define a point and the unit vector of each line. The simplest solution is to take those of the base as i-points. Bar 1-2 is located on the base plane, while the bars that cross over it, 3-4, 5-6 and 7-8 are displaced vertically by a distance d, which must be determined. The coordinates of the points on the base of the roof will be:

$$1\,(x_1, y_1, z_1) \qquad 2\,(x_2, y_2, z_2 + d) \qquad 3\,(x_3, y_3, z_3 + d) \qquad 4\,(x_4, y_4, z_4 + d)$$

The Uni

The unit vectors joining the start-end points of each bar i, j will be

$$\vec{u}_i \left(\frac{x_j - x_i}{L}, \frac{y_j - y_i}{L}, \frac{z_j - z_i}{L} \right)$$

The distance between two straight lines that cross in space is the mixed product, divided by the vector product modulus.

$$s = \frac{\left| P_1P_2 \cdot \vec{u}_1 \cdot \vec{u}_2 \right|}{\left| \vec{u}_1 \times \vec{u}_2 \right|}$$

In order to achieve kinematic compatibility, the distance between the axes of the bars at points A, B and C must be greater than the diameter D of the bars. In the proposed structures, points A and B meet this condition without any problem. However, point C is the most critical point and defines the distance d at which the bars must be separated.

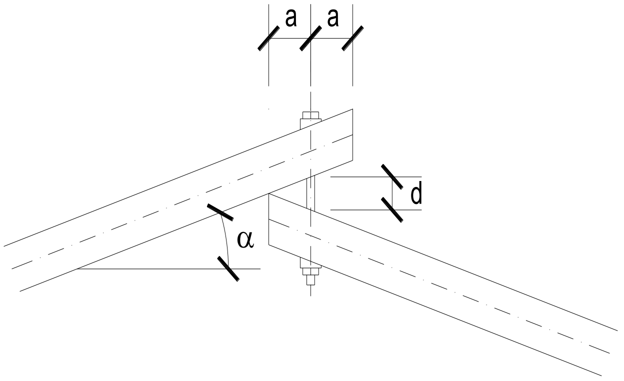

Figure 10: Intersection in upper linkages

At point D the gap d is defined by the distance from the pivot axis to the end of the bar a and by the angle □. (figure 10)

$$d = 2 \cdot a \cdot \tan \alpha$$

In the test model, a = 7.5 mm and □ = 18.79º. As a result, d = 5.10 mm.

4. Materials and methods.

Two types of models were developed to test the structural effectiveness of this proposal. Firstly, two simple models of an octagonal yurt were built with 13 mm aluminium tubes and plastic linkages made with a 3D printer, according to the designs called a and b (**figure 5**). The roof has a diameter of 1550 mm and a height of 270 mm and is built on an octagon measuring 600 mm on each side, with bars 850 mm long. These models do not have sufficient strength to be tested in the laboratory, especially because of the weakness of the linkages, but they are very useful for testing the kinematic conditions of folding and deployment, and therefore the constructive efficiency of the proposed yurts.

Figure 11: Models used to test kinematic compatibility. Type a) and b) yurts.

Secondly, a model with resistant linkages was made of the cover of an octagonal yurt. In this case it is not a question of checking the kinematic conditions for folding and deployment, but rather the strength of the structure. This model was tested in the structure laboratory of the School of Architecture of the University of A Coruña. Since the main problem to be analysed was the behaviour under load, the experiments were designed to measure the deformations. For this purpose, the model was placed on a load bench that allows for loading-unloading cycles, and the displacements were measured to compare them with the theoretical results.

4.1 Materials

The bars of the test model are t-5 state type 6060 aluminium tubes (aluminium - magnesium - silicon), according to the European EN 755-9:2016 standard. Their mechanical characteristics are:

Elastic modulus	69500 N/mm2
Breaking load	220 N/mm2
Elastic limit	185 N/mm2
Specific weight	2700 kN/m3

The linkages are made of steel plates with three holes: the central one for the articulation of the bars and the lateral ones for fixing the bracing cable. The steel is S-275 according to Eurocode 3, EN 1993-1-3:2006/AC:2009 with the following properties:

Breaking load	500 N/mm2
Elastic limit	275 N/mm2

The screws are 5.6 quality M4 steel as per ISO 898-1 with the following properties:

Breaking load	500 N/mm2
Elastic limit	300 N/mm2

The bracing cables 1x19, 1.5 mm, as per the European EN 1906: 2012 standard, with the following properties:

Breaking load	1960 N/mm2
Elastic limit	1570 N/mm2

4.2 Test Setup

A model of the octagonal base yurt was constructed to test the effectiveness of the roofing framework. It is a 1:4 scale model of the structure designed for emergency buildings. The main use for which it is intended is the construction of buildings for community use, such as schools, kindergartens, meeting places, religious premises, etc.

The model is built with aluminium tubes with joints and reciprocal supports. A steel cable is attached to the perimeter, which works as a bracing. The diameter of the roof is 2.625 m with one side of the octagon of 1.012 m. The height of the central ring is 0.458 m, resulting in a slope of 18.79º.

The actual distance between the two sets of bars is 5 mm. Although it was calculated to be 5.10 mm, the rotation is 157.72º less than 180º, so it is a sufficient gap. Moreover, this separation is necessary so that linkage C (figure 8) comes into contact and provides a reciprocal support. This separation is achieved with Teflon rings, to allow for rotation of the vertical axis. The bars extend 7.5 mm from the axis of the end pins.

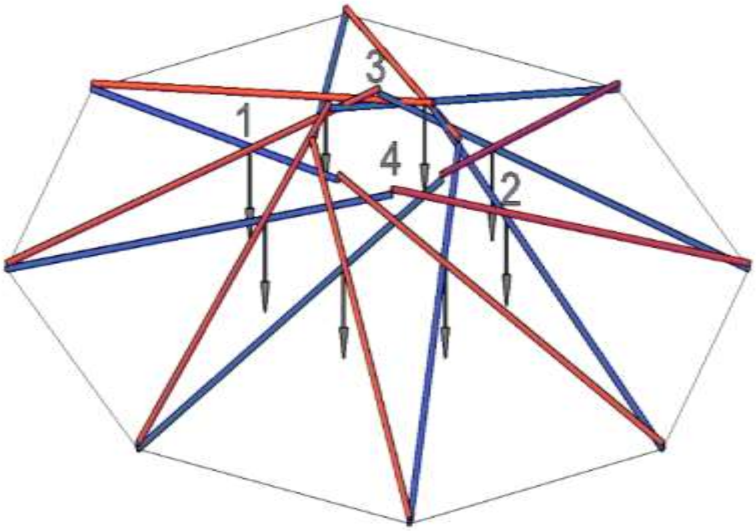

Figure 12: Model used in the tests

This module was tested on a load bench in order to measure the displacements. Loading-unloading cycles were performed and the results were compared with the theoretical ones in order to validate the calculation model.

4.3 Tests

The models were tested for loading and unloading. Eight 10 kgf (98.1 N) loads were applied to the intermediate linkages of the upper layer, and displacements were measured with extensometers in the centre of the mesh and at one of the loaded points using Schreiber Sm407.100.2.T inductive displacement sensors with linearity < 0.25% and deviation < 0.01%/ºC. Similarly, the deformations of other points were measured with digital Y103 extensometers with an accuracy of ±0.1 mm. The position of the sensors and the applied loads are shown in **figure 11.**

The models were supported directly on the eight lower linkages, on pieces of wood with polyethylene sheets interspersed to allow the supports to slide. Friction is minimal, so the only effective constraint is vertical displacement. This is a very realistic situation for the mesh, similar to the one it would have when it is supported on the framework of the walls, since the possible horizontal movement is limited by the perimeter cable. As what we are seeking is the greatest efficiency in the presence of vertical displacements, it was considered appropriate to design the model for the closest possible situation to reality.

The applied load is equivalent to an approximate load of 0.162 kN/m2. It is a load similar to that of a real structure of these characteristics, so we consider it to be a realistic test.

Test process: First of all it is necessary to apply a preload so that the linkages can adapt. In deployable structures it is especially important to carry out this preloading procedure in the tests. As they are mobile structures, the joints and linkages must have a certain tolerance, or otherwise they would prevent deployment. When entering in load the structure is readjusted and has a certain initial displacement. After the unloading of this previous step, the structure maintains this adjustment position, and when the next step is applied, it deforms according to the applied load. However, there is always a tolerance in the linkages, which in this case has been valued at 0.2 mm, taking into account the actual dimensions of the bolts and holes. It is essential to consider this effect if the aim is to validate the calculation methods with the experimental results.

5. Results and discussion.

The effectiveness of this type of structure, as in all cases of deployable structures, must be analysed from two points of view. Firstly, they must be deployable, which means that their movements must be compatible during the folding and deployment phases. This is defined as kinematic compatibility. However, it also needs to be an efficient structure and therefore capable of withstanding loads. This is particularly important, since to enable folding it must be a mechanism and after deployment it must be given the necessary constraints for its proper functioning. Therefore both aspects must be studied.

5.1 Kinematic compatibility

For the correct operation of any type of deployable structure, it is essential to guarantee strict compliance with kinematic compatibility conditions. Without this it is not possible for the structure to function correctly in the folding and deployment processes. These conditions were established in section 3, but it is necessary to check the mechanisms that guarantee them. This is one of the main uses of the models in these studies. Just as for the studies of stresses and deformations, it is necessary to apply the laws of mechanical similarity. In the case of kinematic conditions, a correctly designed model guarantees its compliance in the real prototype.

Tests were carried out with the models designed for this type of study (**Figure 11**). This model of the type a) yurt, supported on SLE, made it possible to verify that the movement of the whole structure occurred along the expected axes of rotation. At no time was there any interference in the movement of the different bars. The package in the folded position is very compact, and the deployed mesh adopts its final shape without any problems. The linkages that have been previously loosened to allow the mesh to be folded are adjusted appropriately in their final position.

Figure 13: Radial deployment of a model of a type a) yurt.

The structure is folded into two bundles of bars, for the roof and wall, joined by the perimeter linkages. When unfolded, a stable position is soon achieved, with an opening angle exceeding 120º. In the final position it works equally without closing the side wall with a SLE, although in a real model it would be convenient to fit bars in place to close the rectangle and allow a door to be fitted. Once in its final position, it is attached to the planned foundation.

Figure 14: Deployment by raising of a model of a type b) yurt

The second model is a type b) yurt, specially designed to be deployed on the ground and raised to its final position. In this case the structure is mounted completely on the floor and is lifted into its final position by a simple crane or by pulling the lower linkages with hoists. Here too, after lifting, the structure is attached to the designated foundations.

5.2 Numerical analysis

The structural analysis of the proposed structure was carried out with the application RFEM 5.20, 3D finite element analysis software from Dlubal Software GmbH, based in Tiefenbach, Germany, and licensed for educational and research use on behalf of the UDC.

The software is designed for the static and dynamic analysis of structures consisting of both bar, surface, and volumetric elements. RFEM provides deformations, internal forces, support forces as well as contact stresses. The programme allows for a linear-type analysis, but also for geometric and mechanical non-linearity.

It is considered that the bar joints on each bolt allow for vertical axis rotation and maintain the continuity of the bars. This happens in type A and D linkages (figure 8). In type B linkages there is no contact since the bars cross without touching. However, in the case of type C linkages, it must be considered that the one bar rests on the other. The software used allows for a non-linear analysis that takes into account this type of constraint.

Constraints were applied at all points of the base in order to consider that the model is simply supported and only vertical displacement is prevented at the edge linkages. The loads are those from the real model, and the results refer to the application points of the sensors.

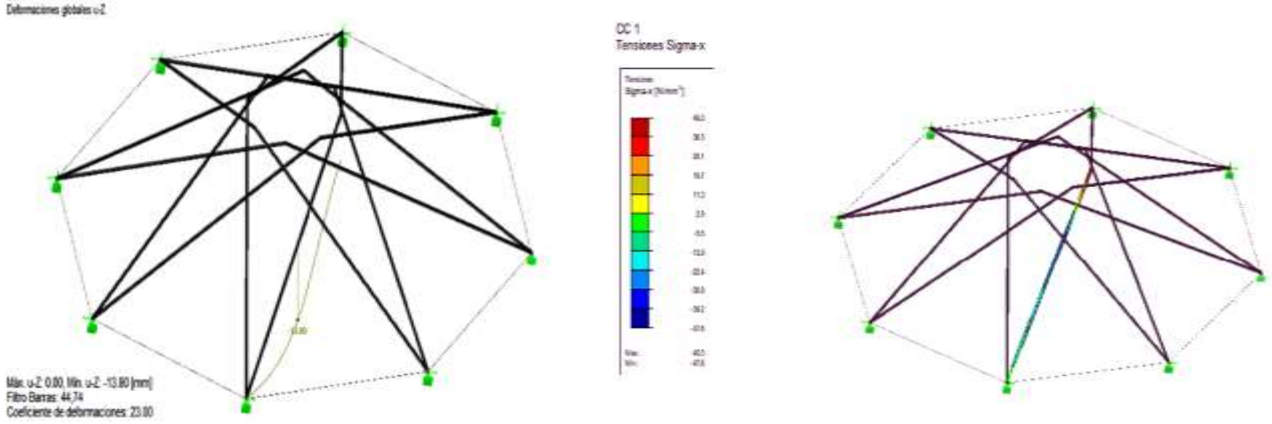

Figure 15: Results of the theoretical calculations

It should be noted that folding structures have a certain tolerance to allow for folding and unfolding movements. In the models used the diameter of the bolt is 4 mm, while the diameter of the hole in the bar is 4.2 mm. This implies a tolerance of 0.2 mm which is introduced as an initial displacement of the bars.

5.3 Experimental analysis

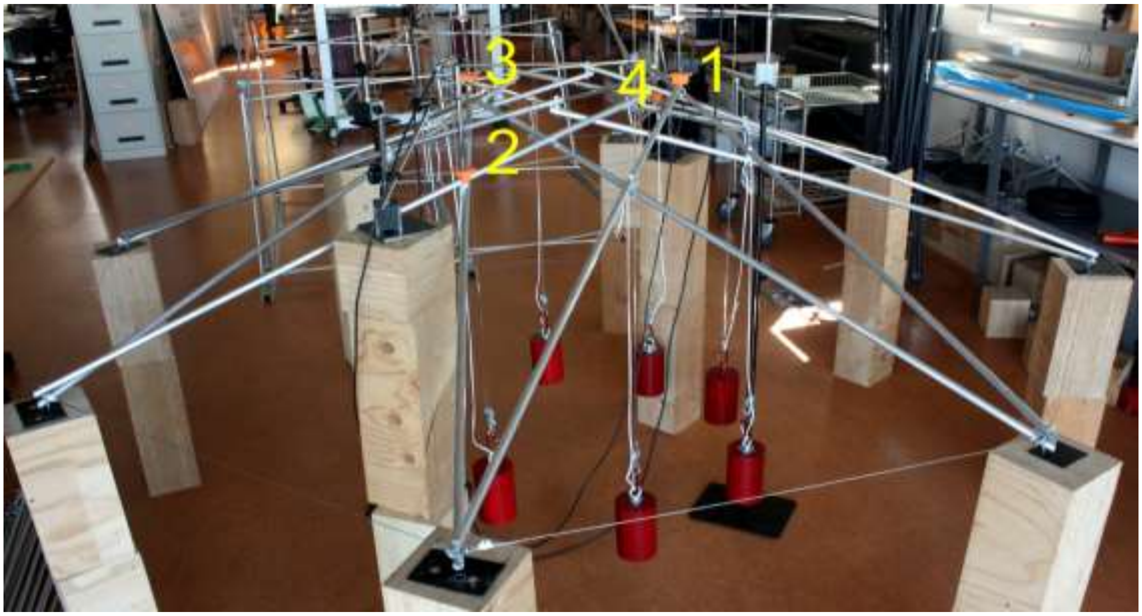

Figure 16: Test model.

The tests were carried out with the loads distributed in the linkages of the upper layer and with the displacement sensors in the points indicated in figure 16. The load was maintained for a sufficient period to stabilise the displacements between 10 and 15 seconds and then progressively discharged for 5 seconds. Four tests were carried out to check that no relaxation phenomena occurred.

In summary, the results of the tests carried out were the following:

	Displacements mm			
Points	1	2	3	4
Test 1	13.18	13.84	6.74	8.18
Test 2	13.26	13.70	6.72	8.22
Test 3	13.11	13.78	6.78	8.15
Test 4	13.18	13.77	6.71	8.15
Average value	13.18	13.77	6.74	8.18
Standard deviation	0.06	0.00	0.04	0.01

Table 1: Displacements measured in the yurt model

The experimental results show good agreement between all tests with a maximum standard deviation of 0.04 mm. This indicates that the behaviour of the structure was clearly linear, and after the initial test the linkages were adjusted to the expected tolerances.

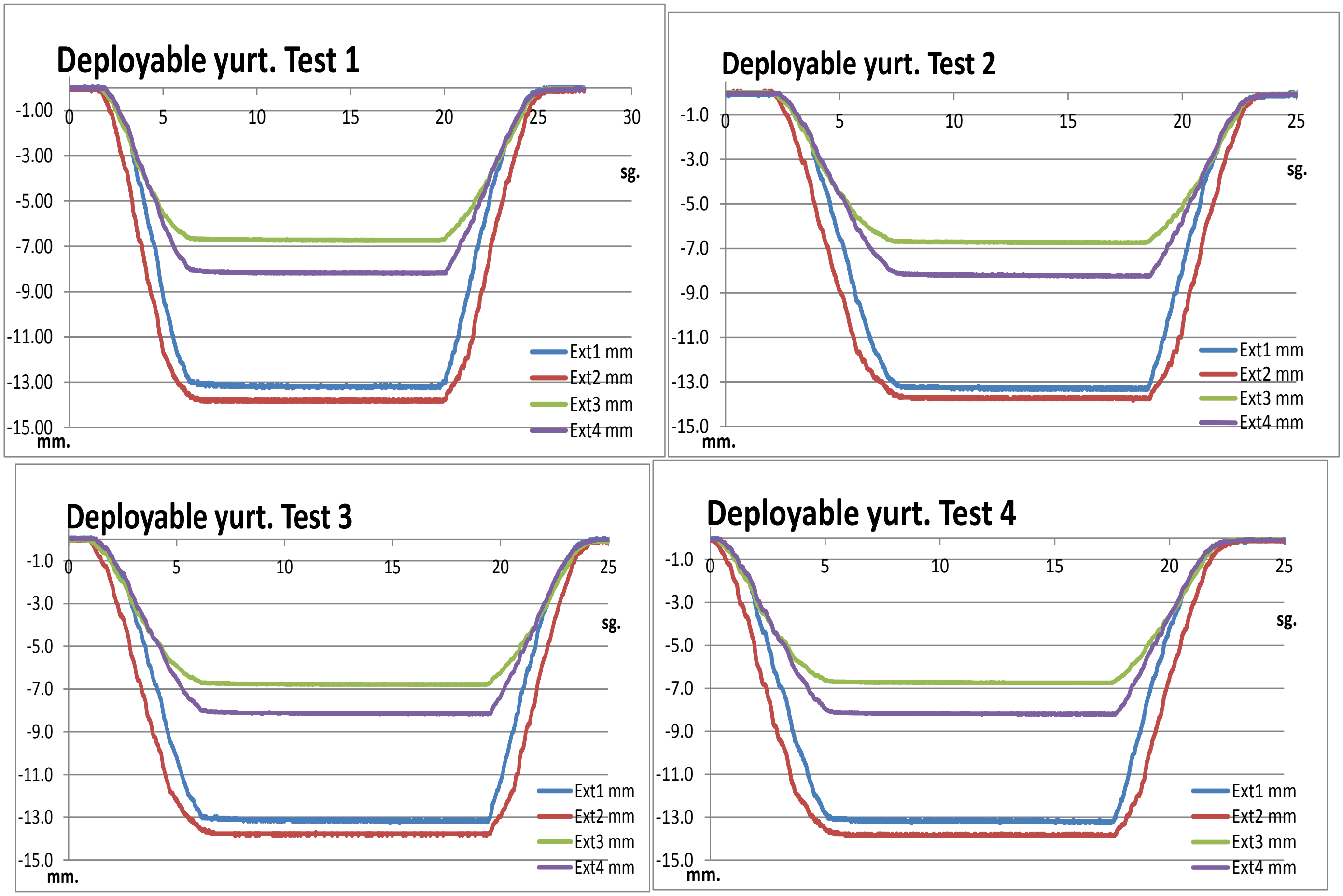

Figure 17: Experimental results.

	Displacements in points (mm)			
	1	2	3	4
Theoretical results	11.91	11.91	8.81	8.81
Average exp. value	13.18	13.77	6.74	8.18
Deviation	10.69%	15.63%	-23.53%	-7.19%

Table 2: Comparison between theoretical and experimental results

If the results of the theoretical model are compared with the experimental ones, it can be seen that the measured results present a good fit. In the case of intermediate linkages 1 and 2, which are the ones with the highest loads, the measured results are slightly higher than the theoretical ones. The most unfavourable is that of sensor 2, which is 15.63%. On the contrary, for points 3 and 4, which correspond to the upper ring, the results are lower than the theoretical ones. The highest deviation corresponds to sensor 3 with a value of -23.53%. The performance of the canopy is similar to that of a bar in which the reciprocal support is slightly more effective than that predicted by the theory, as a result of which points 1 and 2 would tend to be lower, and points 3 and 4 to be higher.

The experimental results offer reduced values. The deflection/span ratio is 1/762, which according to mechanical similarity conditions, would be the same in a real structure.

6. Architectural proposals.

The proposed structure allows for the design of different enclosures necessary for an emergency situation, such as health care centres, canteens, schools, day-care centres, or places of worship,. For this purpose, a basic element is proposed consisting of a deployable yurt with an octagonal base, 10.50 m in diameter, wall height of 3.50 m and a total height of 4.55 m. The usable floor area is 76.50 m^2, and the modules can be joined together if a larger surface is required.

The structure is made of 60.5 mm aluminium tubing. It has been designed to resist the gravity and wind loads provided for in EC-1.

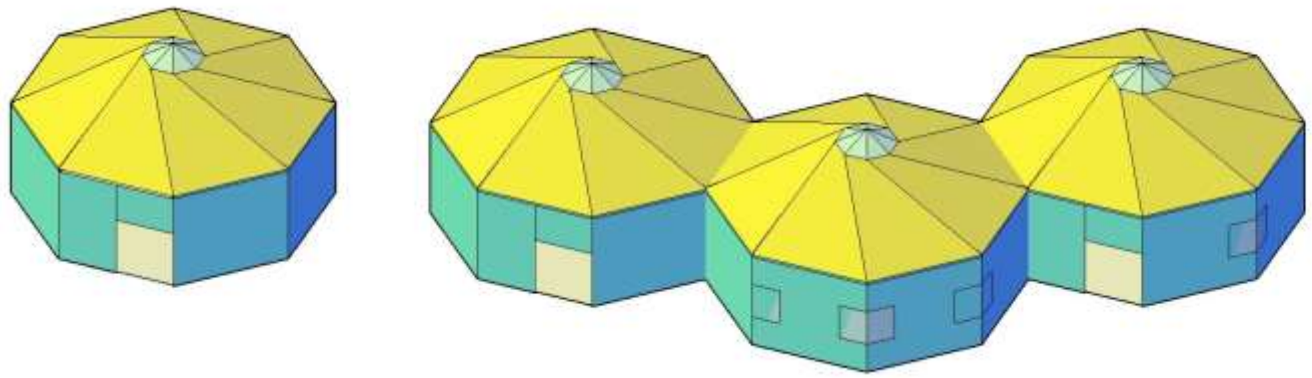

Figure 18: Type a) deployable yurt and an interconnected group of yurts.

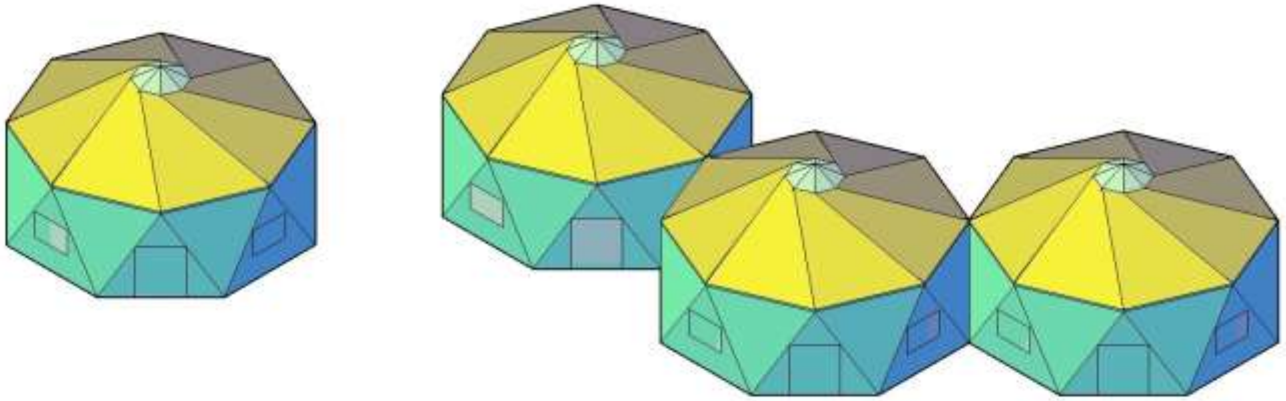

Figure 19: Type b) deployable yurt and an interconnected group of yurts.

The proposed models can be easily connected together according to the architectural requirements. To do so, they must be attached on one of their sides in what is considered to be the most appropriate manner. In the case of type a) yurts, the core of the structure is a straight octagonal cylinder. Their sides are equal vertical rectangles, meaning that grouping them together is very simple by sharing one side. This means that guttering must be installed at the point where they connect, so that rainwater can run off.

In the case of type b) yurts, the structure is comprised of triangular sections. As the floor and roof base are two octagons of equal radius rotated by 22.5º, the edge linkages of the roof structure project outside the enclosure, so if the structure is to be doubled, both yurts will only have one of the roof edge linkages in common, avoiding any interference with the water drainage from the roof. However, as the sides of the enclosures are sloping triangles with different bases, connecting the yurts leaves a space between them that needs to be closed by adding a couple of flat triangular sections (Figure 19).

Another possible solution is to extend the octagon of the base, so that it completely encloses the octagon that forms the roof, in such a way that the projection of the vertices of the latter coincides with the centres of the faces of the former. In this way, the enclosure alternates a series of vertical triangles with other sloping ones, which are connected by one of the vertical triangles that is shared by both structures (**Figure 20).**

7. Conclusions.

The proposed system combines the advantages of deployable structures in terms of compactness and ease of transport and erection with those of reciprocal systems. Its application to a traditional building such as the yurt makes it possible to considerably increase the potential of this system.

In comparison to traditional folding bar structures, they offer the advantage of greater structural stability once the folded structure has been deployed, although it is not as compact as in the bar system. On the other hand, it solves one of their main problems, which is to achieve simple and economical linkages, since they are usually the most expensive elements. In this case, all the internal joints are pinned, which is a very simple and cheap solution. Only the perimeter linkages of the canopy are slightly more complex, although they are very few in number.

When combined with a textile canopy system, they can be a solution for the need to temporarily enclose medium sized spaces, using a transportable structure that is quick and easy to deploy. Their size is generally limited by the maximum size of the package that can be accommodated in a conventional transportation vehicle, about 12 meters long by 3 meters high. This allows for domes of up to 11.50 m in diameter and 3.50 m in height within these limits. Tests have been carried out with a 1:4 scale model which show that the theoretical calculation results and the experimental results are in good agreement. There is geometric compatibility in the folding and unfolding processes with the two proposed options. The linkages that have been designed allow all of the envisaged rotations without any incompatibilities. Furthermore, the displacements are reduced, with lower span/axis ratios than those required by the regulations.

The dimensions proposed for reasons of transportability are sufficient for many uses. Specifically, in the field of research on constructions for disaster situations, these solutions can be very useful in community areas, such as canteens, schools, or religious spaces. With the dimensions obtained, a conventional truck could transport between 24 and 30 yurts of this kind.

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