TESTING PHRAGMITES AUSTRALIS FOR DOUBLE CURVATURE DEPLOYABLE STRUCTURES

CÉSAR FERRO and MARÍA-MERCEDES ANDRADE

Faculty of Architecture, Design and Arts, Pontifical Catholic University of Ecuador, Quito, Ecuador

Felix Escrig’s cover for the San Pablo Swimming Pool in Seville is one of the few examples of an actual application of a biaxial mesh of pantographs in Architecture. A structure that can contain space, easily transforming from a planar surface into a double curvature one, is rarely used as a solution to cover grand areas. In addition, most deployable structures use industrialized components with almost negligible dimensional variations. Analyzing Escrig’s structure with help from both physical and digital models, it is possible to understand its mechanical behavior and the changes in mesh morphology during the deployment process. These models showed how the biaxial mesh suffered some important angular deformations due to the rods and nodes adapting to the double-curvature shape during deployment, resulting in rod and node fatigue, which needed to be addressed before adapting the geometry to a heterogeneous material. This paper describes the geometric implications of using common reed (*Phragmites australis*) in the construction of double curvature deployable structures, examining the behavior of this heterogeneous material if employed on the manufacture of both rods and nodes. Using a scale model built from an adapted design, the geometry of the reed structure was tested. The heterogeneity of the reed required a redesign of the pivots of the blades and the nodes. This redesign showed that it is possible to use common reed for the construction of deployable double-curvature structures if certain mechanical design considerations, detailed as guidelines in this paper, are observed.

Keywords: Technology, Morphology, Pantographs, Scissor-like elements, Geometrical analysis, Light architecture, Transformable structures.

1 INTRODUCTION

In 1996, Felix Escrig designed and built a deployable structure to cover the San Pablo Olympic Pool in Seville, Spain. The main goal of this structure was to enclose the 50-by-25-meter pool during the Winter months to provide proper acclimatization, which, for Escrig, was the justification for an itinerant structure. The geometry Escrig defined for the deployable structure was based in two spherical meshes. To solve the double curvature dome, he proposed a system of scissor-like elements (SLE) consisting of straight hinged rods.

The SLE based deployable systems have a remote origin: from a huntsman’s stool (a bundle module where three or four rods concurrent at one joint) and Mongolian yurt (a system of deployable bidimensional meshes that, when folded, form a cylinder), up to the more complex structures, like those developed by Chuck Hobberman, which employ angled rods to allow a radial deploy. Among these systems, it is important to note the contribution of Emilio Pérez Piñero, who
developed a deployable mesh system based in a beam module, like that of the huntsman’s stool, to cover large surfaces.

The interest of this article on F. Escrig’s structures, especially on his deployable roof for the San Pablo Pool in Seville, is directly linked to the architectural applicability of these systems on a larger scale. Contrary to E. Pérez Piñero, F. Escrig employed a blade module (Figure 1) in which the basic component is comprised by only two rods connected at the joint, like a pair of scissors, the SLE. The advances made by F. Escrig on these systems helped him gain mechanical, geometrical, and material optimization, which makes its application in architecture more feasible.

Figure 1. Bundle module (left) and blade module (right).

F. Escrig’s design for the San Pablo Pool in Seville, the present study case, uses aluminum rods and nodes. These elements, being industrially manufactured, guarantee the precision required in this type of mechanical system. This precision allows an optimization of the assembly process, control over mechanical failures, adjustments of node sizes and, therefore, the capacity of the structure to be folded in compact packages.

Common reed (Phragmites australis), as well as guadua and bamboo, belong to the grass family known in taxonomy as Poaceae. In the last three decades, these types of grasses have gained notoriety in the construction field thanks to architectural projects such as those by Colombian architect Simón Vélez, and Mario Seixas et al. (2014), who propose the use of bamboo for the construction of deployable single-curvature bended meshes.

In Ecuador, common reed was used in buildings up until mid-twentieth century, as in other Andean countries. Its use in construction was limited to light non-structural elements, such as ceilings or space partitions, both of which received a finishing layer of sprayed earth mortar.

Nowadays, however, common reed is mostly used as a weaving material for the manufacture of daily use objects, such as baskets and floor mats, thanks to the elasticity of its fibers. To prepare the material for weaving, the reeds are cut along the direction of the fibers to obtain long strips.

Like other species of the Poaceae family, common reed has a cylindrical stem with solid nodes, from where the leaves and the branches grow, and hollow internodal sections. Reeds can grow up to four meters tall, and its stems can get as thick as two centimeters. However, the stems thickness reduces the taller the reed grows. Unlike other construction elements that come from plants, reeds’ stems can be straight enough to be used without needing a sawing process.

Considering all the advantages of common reed as a construction material, including the ones exposed above, and the relative ease to obtain the material due to its abundance and inexpensiveness, the starting point of this study was to prove its suitability as a bar component of
a double-curvature deployable structure. The starting geometry for such structure was that of the roof of the San Pablo pool in Seville by F. Escrig. Therefore, the models permitted the development of mechanical design guidelines applicable in the construction of these structures.

2 GEOMETRICAL DEFINITION

The roof of the San Pablo pool by F. Escrig is based in SLE polar units (Escrig et al. 1996, Escrig 2012, Escrig et al. 2014), as shown in Figure 2. The repetition of these SLE units creates a system where their pivots form a straight line when the structure is folded. However, the line described by the SLE pivots curves as the structure deploys. Therefore, as the structure expands, the radius of the arch decreases. In SLE polar units, the pivot axis of the scissors is placed asymmetrically so that \( l > k \) (Fig. 2).

![Figure 2. SLE polar unit deploy.](image)

This unidimensional deploying system also allows the creation of bidimensional meshes (Figure 3). These meshes are made of blade modules (as shown in Figure 1), which are polar units replicated both in the X axis and the Y axis. This type of units requires the design of a hinged node that connect the blades on both axis without interfering with the rods’ rotation. Therefore, each axis will be deployed as an arch, which allows the biaxial mesh to adopt the double curvature.

![Figure 3. Deployment process of a biaxial mesh with polar units, from left to right: folded dome, intermediated phase, fully deployed dome.](image)

F. Escrig used two 30-by-30-meter spherical meshes to cover the 50-by-25-meter pool. Each mesh was made of six-by-six-meter blade modules with a key height of eight meters. These design parameters define the spherical mesh radius and, by extension, the length of the rods. The pivot hinge of the polar units was set as \( 2\delta = \alpha \), as shown in Figure 4.
These criteria established the length of the rods in 5.38 meters, and the distances between pivots l and k in 2711 mm and 2665 mm, respectively. For this design, all the rods are of the same length and all the nodes are identical, thus optimizing the manufacturing and construction process. For the rods, Escrig used ø120 mm aluminum structural bars with a five millimeters width, at the ends of which the fixing plates were incorporated for the simplification of the node and the maximization of the system’s foldability.

In order to change the structural aluminum rods from the geometry described above into reed rods, a one-to-five model of one of the spherical caps was built. Given that the main goal of this study was to define design guidelines for this type of mechanisms, the textile cover was omitted.

3 DESIGN ADJUSTMENTS FOR MECHANICAL DEVELOPMENT

The reed structure was designed from a SLE double-curvature mesh. As in the roof of the San Pablo pool, the structure used polar units in both the X and the Y axis. Since the rods for the structure were made from the stems of common reed, the following criteria, based on the physical attributes of the material, were analyzed during the redesign of Escrig’s cover:

- Variable diameter of the stem: An error margin must be set so that most of the reed stem’s can be used, regardless of its diameter variations.
- Inaccurate straightness of the stem: Considering the material, the rod will not be completely straight; therefore, what should be considered is the alignment of the pivots. However, on a cylindrical surface, the pivots must also be aligned to the axis of the cylinder to avoid mismatches and mechanical obstructions due to its own morphology.
- Anisotropy: Common reed’s fibers tend to separate along the stem’s internodal sections. The nodes stop these fissures or cracks.
- Internodal variability: The distance between nodes (the length of the internodal sections) is highly variable. There might be coincidence between a pivot and a node.

Considering all the previous criteria, it stands to hypothesize that the error margin set in the design, for this type of material, might also help absorb the angular deformations of the mesh as it deploys and adopts its double curvature. On the other hand, it is a given that the same levels of precision and foldability of San Pablo pool’s roof structure are unobtainable for this study. However, the geometrical and material optimizations were maintained; that is, the reed structure only used two components: a standard rod and a standard hinge node.
3.1 Mesh Design Settings

After checking the reed stems, and having them measured and cut, the diameters of the reed rods vary from 15 mm up to 20 mm (Fig. 5). In this case, the larger the variation range allowed in the design as part of the error margin, the more usable the material will be. This error margin forced the redesign of the rods position in accordance with the design axis, which, in turn, forced the redesign the axis between blades, and the nodes. Figure 6 shows some possibilities for the relocation of the rods to accommodate the error margin.

![Figure 5. Definition of the rod diameter section ranges.](image)

![Figure 6. Various possibilities for the relocation of the rods in accordance with the design axis.](image)

3.2 Node Design Settings

Trying to keep maximum system foldability, maintaining the previously describes conditions, a cylindrical node which would receive four rods was proposed. In the original structure, to get the node working properly, F. Escrig used terminal plates that prevented the rods from blocking the movement of one another. This phenomenon, in which the rods block each other’s movements, corresponds to the reciprocal structures, and there could be developed a way to take advantage of it in another study. In this case, to accommodate the error margin and simplify the manufacturing of the nodes, the cylindrical node diameter was increased to 30 mm.
3.3 Rod Design Settings

The need to absorb the error margin of the rods’ section diameter variability led to a redesign of the SLE’s pivot hinge. This redesign added an adjustable separator which aligns each rod to the node. The rods are aligned by their inner face, which renders the outer face geometry negligible.

4 DESIGN GUIDELINES FOR REED DEPLOYABLE STRUCTURES

During the construction process there were some mishaps that had to be addressed on the go. Based on those, a brief design guideline was developed with some important criteria to consider:

- Material selection: Before cutting the rods, the reed stems’ straightness must be checked to discard the ones that are crooked or bent. To do this, a string can be used. In the model built for this study, the string was aligned within 90% of the stems. It is also important to discard stems that are cracked or broken.
- Rods manufacture: For the model, the reed stems where cut in segments with a length of 1200 mm for the rods. It is important to consider that the first cut must be made 30 mm after of the stem’s node to guarantee the rigidity of the space in contact with the hinges to avoid fracture. For the second cut, at the other end of the rod, it is impossible to predict how far the node will be; therefore, this end of the rod must be reinforced.
- Selection of the right working face of the rods: To avoid blocking the movement of the rods during the deploying process, the hinge nodes must be aligned with the flattest face of the rod. To detect which face of the rod is the flattest, they were rolled over a leveled table. As the rods stopped rolling on their flattest face, this was identified with a mark.
- Alignment and pivot axis drill on the rods: To show the precise points where the axis for the pivots were to be drilled, a template must be created. This template must allow the alignment of the rods and should be placed on top of the marked (flat) face of the rod.

5 CONCLUSIONS

Deployable structures are justified when there is a demand for itinerancy. Therefore, they require materials that provide both lightness and stability. Common reed is an economical material, with a significantly lower environmental impact than that of aluminum. The heterogeneous nature of the material might seem to pose a problem at first glance due to mechanical requirements of double-curved deployable structures. Material stress was detected on the rods as the system was deployed due to the deformation of the mesh as it adopted the double curvature. The stress over the rods was greater at the union with the hinge node, where the rods fractured. However, the design adaptations developed for the use of common reed for the SLE allowed the correct mechanical performance of the structure. Future research is needed to compare how rod and node stress fare on single and double curvature meshes, to propose node redesign, and to evaluate their performance in deploy easiness, and structural stability during and after the deployment process.

References