Reusable Inflatable Formwork for Complex Shape Concrete Shells

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Abstract. Construction of concrete shells is expensive and generates wastes from the fabrication of formworks. Being non-reusable, these elements have a negative impact on the life-cycle assessment of the construction. The purpose of this research is to design and build a new inexpensive formwork system made of inflatable structures for precast and thin concrete shells construction.

By sealing two membranes according to a pattern, this system allows the construction of complex inflated shapes. The sealing pattern is designed such that, once inflated, the planar metric becomes not uniform and generates a 3D surface following Gauss's Theorema Egregium, a classical result of differential geometry. This design of the seal pattern is guided by a numerical tool capable of accurately predicting the inflated shape. The simulations are compared to physical models made of fabrics, before manufacturing inflatable formwork prototypes in composite membranes from about 1 to three metres wide. Support is set up to pour concrete on the inflatable formwork without damaging it for reuse. The resulting thin concrete shell and its fabrication method are eligible for wider-scale application in the AEC industry.

Keywords: Inflatable structure · Pneumatic structure · Formwork · Concrete · Membrane

1 Interest of Creating Concrete Elements from Inflatable Structures

Custom-made concrete formworks are expensive and represent a large amount of waste in the Architecture, Engineering, and Construction (AEC) industry. Regarding standard construction with planar concrete panels, 53% (formwork materials and installation) of the concrete structure costs are spent on formworks. When complex and unique formwork must be created, they represent 88% of the total concrete construction costs (see

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Fig. 1). These formworks are themselves complex and expensive elements without being reusable: they have a negative impact on the life-cycle assessment of the construction project.

These difficulties partly explain why concrete shells disappeared at the end of the 20th century, despite the undeniable architectural quality they provided to the spaces created [1].

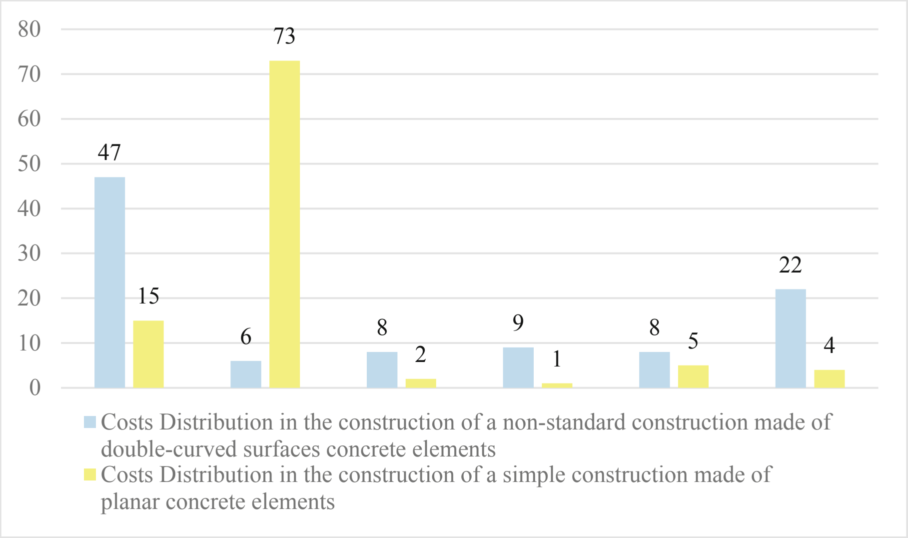


Fig. 1. Costs distribution in the construction of a simple and a complex concrete structure [2, 3].

This research aims to create a new economic formwork system for precast concrete shells. Inflatable structures are attractive for their lightweight properties and diverse realisable shapes, even complex. Moreover, they are inexpensive because they are composed of standard sheet materials and air.

Inflatable structures have already been used as formwork elements to fabricate concrete shells, for example, Domecrete by Heifetz, Bini-Shells by Dante Bini [4], the two-chamber system formwork for Bubble Housing System by Heinz Isler [5] and the Pneumatic Formwork Systems in Structural Engineering by [6]. Both these examples consist of a unique patterned membrane such that once inflated, it becomes a constant mean curvature surface (see Fig. 2 1a, 1b, 1c). This inflated volume is used to lift fresh concrete or set precast concrete elements to create domed shells.

In the present work, we propose to create an inflated surface made of two flat membranes without patterning, sealed according to a 2D pattern (see Fig. 2 2a, 2b, 2c). Once inflated, the seals become valleys delimiting mountains, inflated cavities. This technique was introduced by [7], who created models made of sealed paper that bends once inflated.

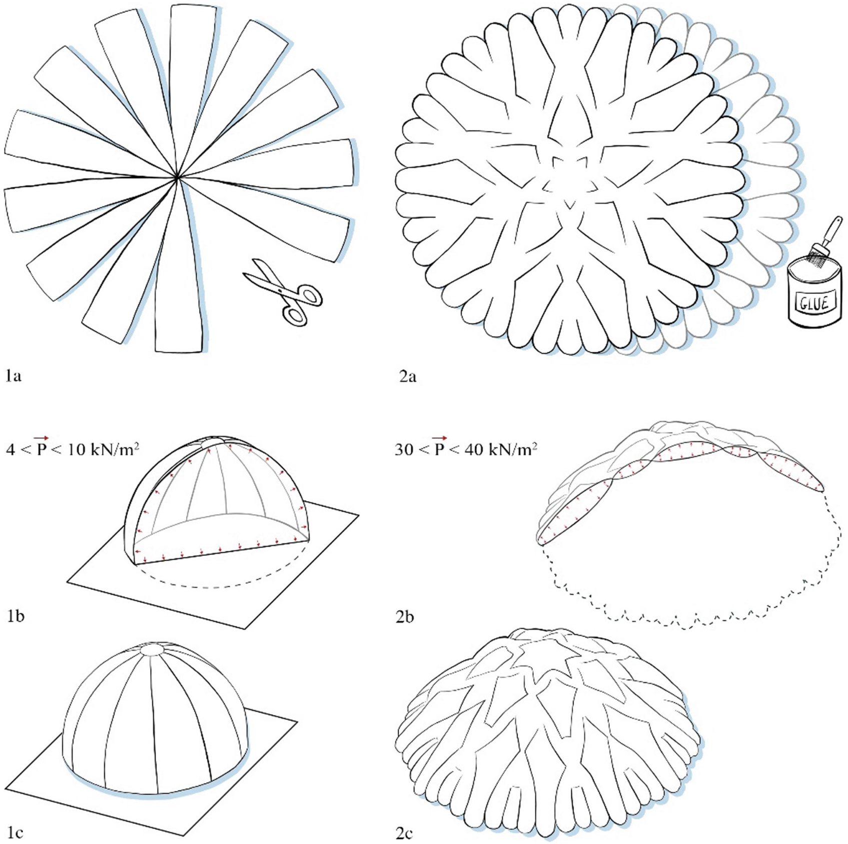


Fig. 2. Patterning (1a, 1b, 1c) and 2 layers glued (2a, 2b, 2c) technique for fabricate an inflatable structure.

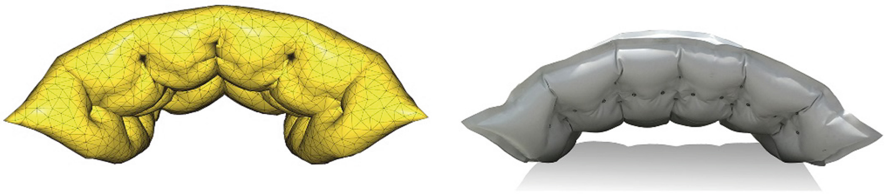
We first describe the geometry principles and simulation tools. Then, the design of the 2D pattern to reach a chosen shape is explained. Finally, we present the fabrication of the inflated formwork and the construction of the concrete shell.

2 Interest of Creating Concrete Elements from Inflatable Structures

As seen in Sect. 1, we choose to explore a method without patterning. An in-house tool, InflatableSheetSimulator [7], simulates the inflated sheets numerically using the finite element method, starting from the 2D pattern made of an external contour and internal lines. The tool generates two meshes connected by the 2D pattern. Custom parameters are the resolution of the mesh, the thickness and Young's Modulus of the fabric, and the internal pressure. The sheets are modelled with tension field theory [8], a very efficient convexified membrane model: when membrane stress is under compression, its stiffness vanishes so that wrinkling instabilities are regularised. A linear triangle interpolation is sufficient for this modelling.

Fig. 3. Manufactured models with 2 sheets of fabric sealed according a 2D pattern.

We also use physical models to observe the 3D shapes created by the sealed patterns on the two layers sheets. Two TPU coated Nylon fabric layers are sealed according to a 2D pattern with an air supply to inflate the created model (see Fig. 3).



1a 1b

Fig. 4. Simulation of inflated sheets (1a) and fabricated prototype (1b) with the same 2D pattern.

Prototypes in composite membranes, a full-scale construction material, are also manufactured and compared to the numerical simulation in which the shape is very close. (see Fig. 4). These simulations are very realistic and help the design of the sealing patterns by quickly verifying their effect on the inflated geometry.

Let us illustrate how inflation may change the metric of the surface in a simple case (see Fig. 5). We seal two sheets according to parallel lines. When inflating, tubes appear, and the metric changes only in the transverse direction. The distance between two seals d_1 tends to be a half-circle with air pressure in two dimensions. With d_2 as the orthogonal projection in the plane of the pattern between two seals, for a maximal contraction, we have $d_2 = \frac{2}{\pi} d_1$. The contraction factor λ, induced by air pressure, can vary from $\frac{2}{\pi}$ to 1. In our case, the contraction is maximal in the tubes transverse direction, $\lambda_1 = \frac{2}{\pi}$ and non-existent along with the seals, $\lambda_2 = 1$. This lack of contraction makes assembly lines behave as soft hinges. When varying the orientation of seals, the sheets take on a 3D shape.

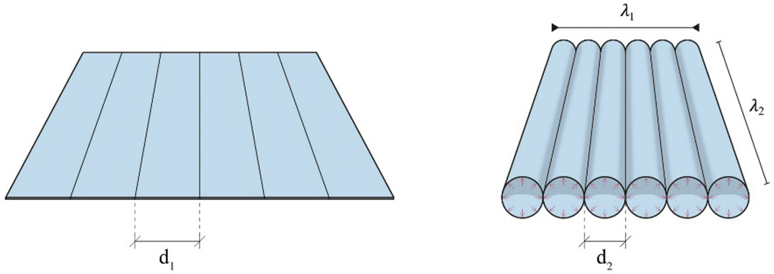


Fig. 5. Two layers sealed according to parallel lines and inflated.

3 Design of a Pattern for a Concrete Dome

For the first project of inflatable formwork conception and fabrication, the target shape is a dome. This positive double curvature form is chosen to simplify the boundary conditions.

From 2 discs of membrane, we can obtain positive or negative double curvature surfaces by changing the plane metric thanks to air pressure and non-parallel seals. The patterns are composed of long seals (curves or straight lines) and smaller ones as subdivisions (see Fig. 8 1b) to harmonise the cavity sizes and discretisation that refine the shape. With a pattern composed of radial lines (see Fig. 6 1), the conical tube retraction changes the ratio between area and perimeter. The perimeter becomes shorter, and the surface goes out of its plane to reach a double positive curvature. On the other hand, with a pattern composed of concentric lines (see Fig. 6 2), the surface area shrinks, and the perimeter stays unchanged: the surface becomes a double negative curvature.

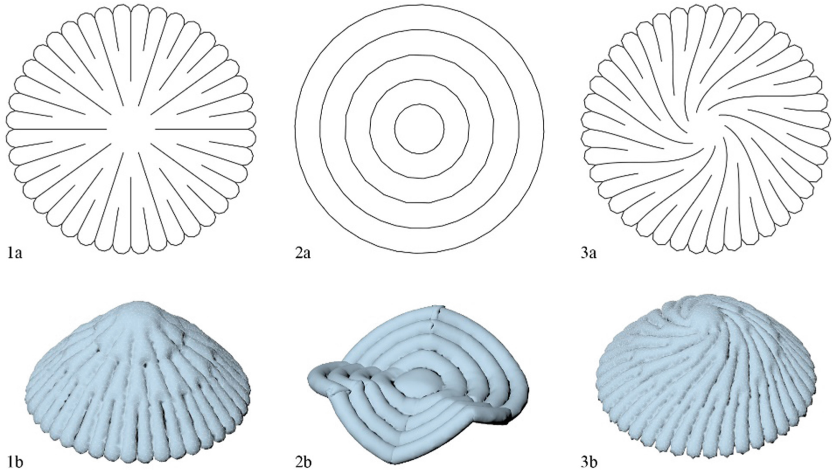


Fig. 6. 2D patterns and simulation of 2 sheets sealed according to the pattern. Radial lines 2D pattern (1a) and simulation (1b). Concentric curves 2D pattern (2a) and simulation (2b). Curves 2D pattern (3a) and simulation (3b).

When we pour concrete on the inflated structure, these curves become the ribs of the concrete element. A parallel numerical structural study has been made on concrete shell structures cast by our inflatable formwork system [9]. Two concrete shells, one smooth (Shell 1) and the other one ribbed (Shell 2) (see Fig. 7), have been structurally analyzed with a karamba solver.

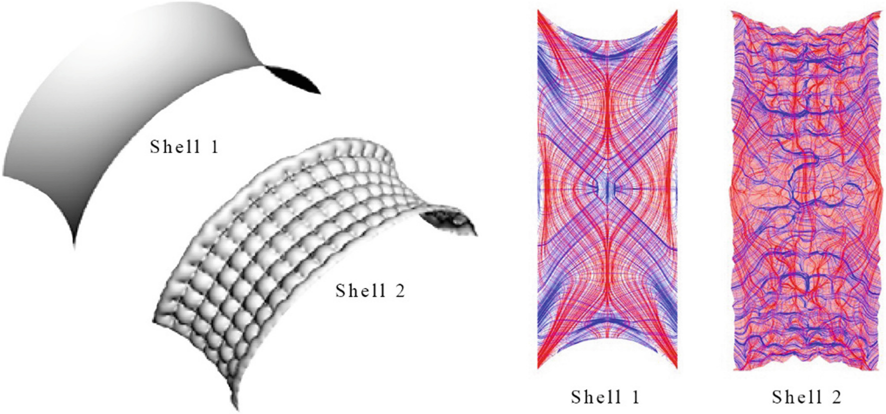


Fig. 7. Shell numerical models and principal stresses simulation (compression in red, tension in blue). [9].

The two shells are 5 m long and 2.5 m large. Shell 1 is 34 mm thick, determined by the maximal admitted compression and tension stresses under a classical load case with a bending displacement less than L/300 (With L as the length between the two supports); his weight is 1537 kg. Shell 2 has the same weight but is only 30 mm thick despite a larger surface with the ribs. The ribs allow reducing the quantity of concrete.

The structural analysis shows the principal compression and tension stresses; if we compare the two shells, the behaviour of Shell 2 is close to Shell 1. The buckling load factor appears higher on the ribbed shell (144) than on the smooth shell (57), thus the ribs make Shell 2 more resistant to buckling. To conclude, if the ribs are well placed, they benefit the shell's structural behaviour. They permit to slim down the thickness of the shell and be more resistant to buckling.

Siefert et al. [10] propose an array of curves as a sealed pattern to reach parabola shape (see Fig. 6 3), which is ideal for the compression behaviour of the concrete shell. Unfortunately, the ribs generated by this pattern are not efficient for the concrete shell stability. The inflated sheet numerical simulation form is as satisfying as the fabricated prototype but is very unstable. During inflation, a rotation appears to shape the parabola. This rotation repeats itself when we apply a load on the upper part of the inflated dome (see Fig. 8 1). In contrast, the prototype made with the conic pattern (see Fig. 8 2) shows no rotation during inflation. The radial tubes make the inflatable structure very stiff.

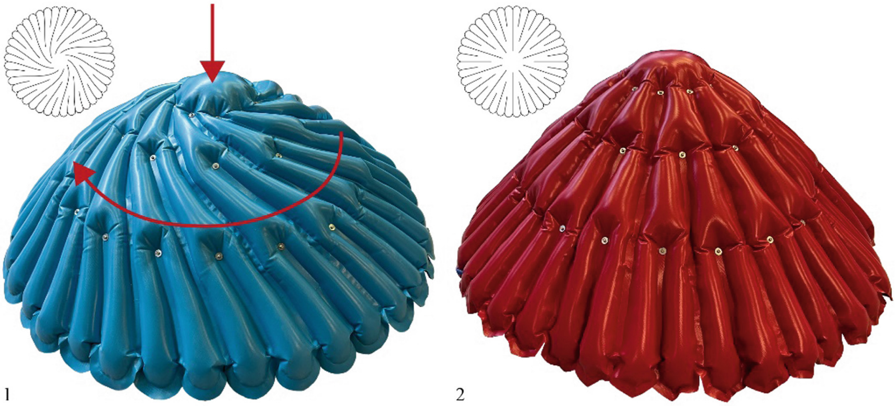


Fig. 8. Prototypes with spirals pattern (1) and cone pattern (2).

We propose to add a second mirror array of spirals to the first (see Fig. 9 1c), inspired by the ribs of the Palazzetto Dello Sport in Rome by Pier Luigi Nervi, built in 1957 [11]. From this array, we propose three ways to design the pattern (see Fig. 9 2):

2a. To keep the curves of the array to achieve effective cross-concrete ribs. In this configuration, the inflatable structure is quite flexible since there are no air continuities from one limit to another of the pattern and the seals behave like soft hinges.

2b. To draw rhombus by keeping inflated spiral tubes. The spiral tubes bring stiffness to the inflated dome and favour the inflatable deployment into parabola shape, but the discontinuous ribs are not efficient.

2c. This third model is an arrangement between air continuities ensuring the stability of the inflatable and continuous joints generating efficient ribs for the concrete shell. Radial air continuities reinforce the inflatable formwork as observed on the inflatable cone (see Fig. 8 2), which is very stiff. The peeling force at seals is higher when the cavity is more extensive, and there is stress concentration at the ends and open angles of seals. The layout of this pattern is very convenient since the opened angles turn toward the small cavities.

It is necessary to tweak these patterns through different parameters: the minimal distance between 2 seals to ensure a correct air supply, the number of units (set of repeating lines) in the polar array and the number and hierarchy of the intermediate curves to have a good definition and discretisation of the shape. These parameters settings depend on the size of the manufactured inflatable, as was done with pattern 2c (see Fig. 9). Indeed, the difference in the size of the cavities of the pattern c is reduced to uniformise the tension in the membrane and thus correctly inflate each cavity at a certain pressure, avoiding deflated cavities or seal peeling off.

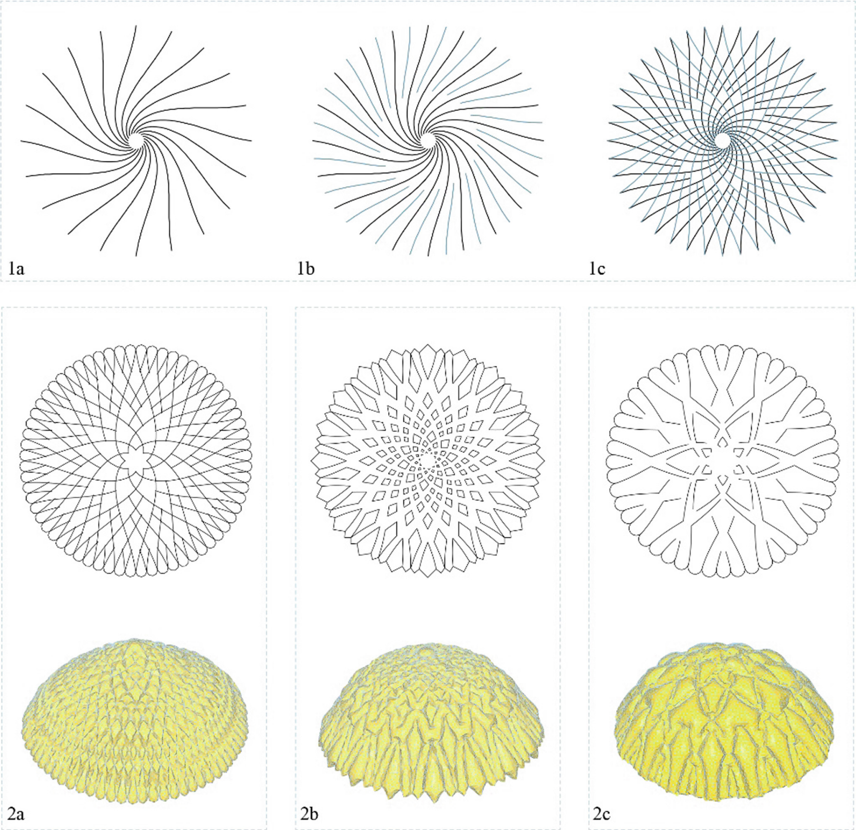


Fig. 9. From an array (1), 3 patterns are drawn (2a, 2b, 2c).

The relation between the peeling force per unit length ρ (N/m) along the seam, the pressure p (N/m^2), the area A (m^2) and the perimeter l (m) of the cavity writes as follows:

$$\rho = \frac{pA}{l} \tag{1}$$

The number of units in the polar array stays unchanged, but the unit is modified by adding a third degree of discretisation. These new curves divide the perimeter of the inflatable twice as much, from 40 parts in the first version to 80 in the second, which refines the shape.

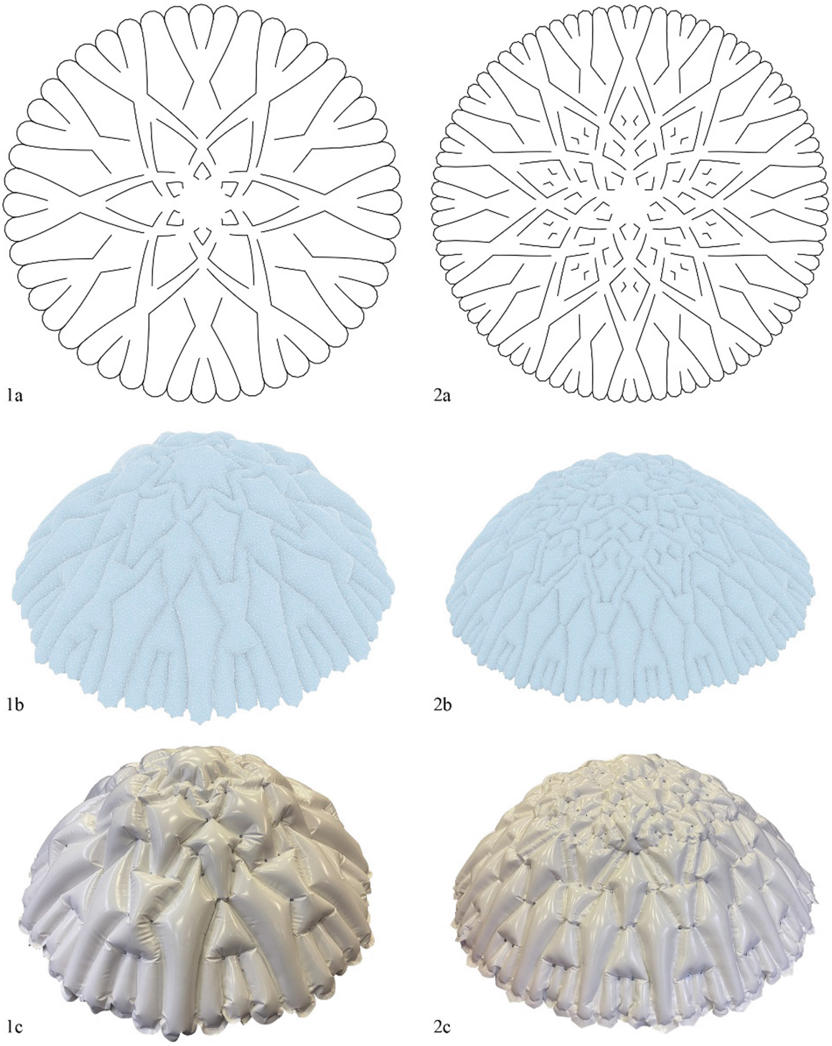


Fig. 10. Modifications of the pattern 2c (Fig. 9).

4 Fabrication of the Inflatable Formwork and Concrete Shell

The used membranes are inextensible to control the deformation and construct stiff inflatable structures in order the formwork carries the concrete. The tension in the membrane has to be sufficient to resist the applied load, thanks to the air pressure between the two membranes.

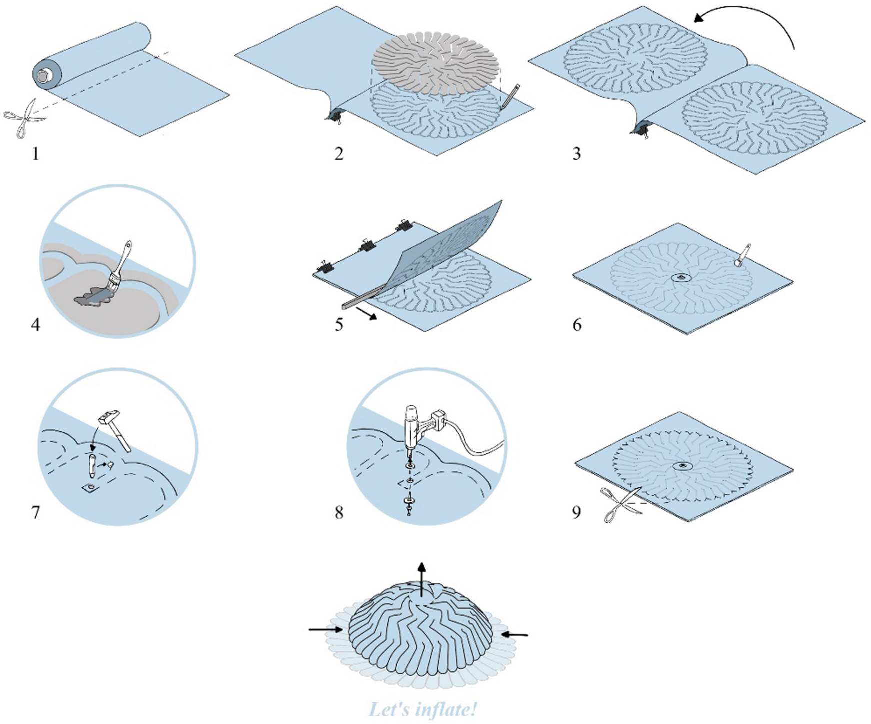


Fig. 11. Protocol of an inflatable fabrication, from step 1 to step 9.

Since the joints are subjected to peeling stresses, their strength is much lower than traditional membrane assembly exposed to shear stresses, so they must be reinforced for large scale models. We use a composite membrane composed of a prestressed polyester fibres mesh; with two sides coated with PVC. The PVC coat is thicker than the tiny model's fabric, allowing us to create more robust assemblies.

These membranes are generally assembled by high-frequency welding, seaming or gluing. The high-frequency welding works with electrodes, and the standard ones are straight with little diversity. The patterns are curved; it would be necessary to discretize the curves, as made on prototype Fig. 8.1, and in certain cases fabricate specific and expensive electrodes. Hence, we are using glue which is cheaper and allows the creation of assemblies of whatever shape. We measured the ultimate tensile strengths of these two assemblies through tensile testing with several test specimens: membrane strips assembled by high-frequency welding or gluing. For each test, the membrane failed and not the assemblies, showing that the assemblies are stronger than the membrane. The glue seems to be the best option for its ease of application and resistance capacities.

After several manufacturing trials, we established a protocol to ensure the accuracy and robustness of the creation of the inflatable and to gain in rapidity (see Fig. 11). This method has been used to produce prototypes with diameters of 1.35 m and 2.70 m (deflated).

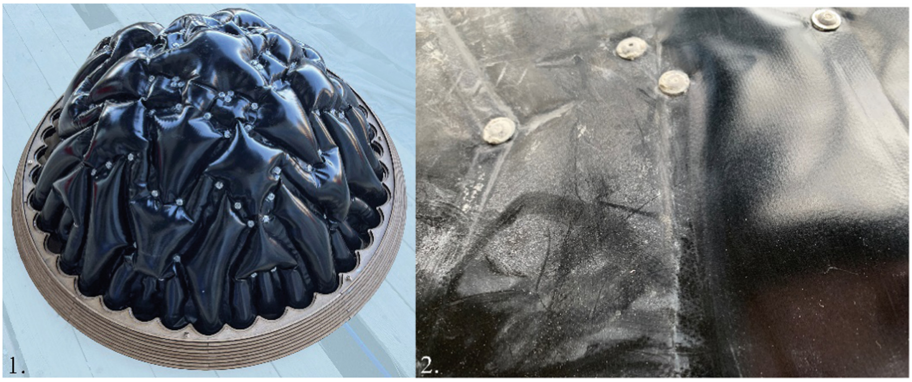


Fig. 12. Inflatable Formwork with support (1). Reusable inflatable Formwork after concrete shell fabrication (2).

The pattern is reproduced and the glue is applied using a laser-cut stencil. Once the glue has dried, the glued pattern is reinforced with rivets at the ends and corners. The rivets are positioned with washers on both sides of the membrane. They support the tensile strength locally by applying pressure. A dozen 1.35 m prototypes with different patterns have been made to observe the generated geometry using the full-scale membrane and this fabrication technique. These tests serve to determine the width of the glued seals and the minimal space between them. Also, the air distribution has been checked and adapted. Three inflatables of 2.70 m diameters (deflated) are made with this technique: one with the spiral pattern (see Fig. 6 3) and two with the pattern 2c (see Fig. 10). The last inflatable is the most accomplished, stiff and with a well-defined shape.

Some concrete shells have been made with a formwork of 1,35 m diameter deflated. Wooden support is a traction ring at the basement of the inflatable structure (see Fig. 12 1), designed from the numerical simulation to fit the edges of the inflatable. The air pressure inside the glued membranes is up to 40 kN/m^2 to construct the shell. The support is attached to the inflatable with adhesive tape, a reversible fastener to avoid damage to the membranes. A silicone seal ensures continuity between the inflatable and the support. Silicone covers the rivets to prevent them from being sealed in the concrete.

The concrete mix is composed of 45% sand, 45% cement and 10% of water. Some glass fibres (1% of the total volume) are added to prevent eventual cracking during shrinkage when the concrete hardens. First, a thin slip (a fluid mix of cement and water only) is poured on the inflatable to fill the valleys. After this first layer dries, a thicker layer of 1,5 cm of concrete mix is added. The concrete sets in about 2 h, and then the inflatable formwork is deflated to remove the membranes. The inflatable formwork is intact and perfectly reusable (see Fig. 12 2) (Fig. 13).

Fig. 13. A concrete shell made with an inflatable formwork.

5 Conclusion and Outlooks

This new concrete casting technique attempts to answer the costs and environmental problems of the formworks in the AEC industry. Pneumatic solutions exist and are used on construction sites such as Resair®, for instance, to make reservations in concrete structures using inflatable elements.

Unlike other pneumatic formwork solutions, our proposition can achieve a wider variety of shapes and can be automated. The next step of this research is to cast a wider shell with the bigger inflatable formworks (see Fig. 10) by using concrete spraying.

Other shapes, such as a double negative curvature surface, are the next goal for fabrication and casting. For the moment, the limiting size of the inflatable formwork is determined by the width of the membrane, but we can make a seal between two widths to create larger inflatables. We can use standard scaffolding elements to help the inflated skin to cross and reinforce it locally with future strategies to create an extensive inflatable formwork. It will undoubtedly be necessary to reinforce the concrete with steel for such a wide shell.

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