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Erection of post-formed gridshells by means of inflatable membrane technology

Alessandro Liuti and Alberto Pugnale
The University of Melbourne, Melbourne, Australia
alessandro.liuti@unimelb.edu.au, alberto.pugnale@unimelb.edu.au

Abstract: This paper describes a new erection technique for post-formed timber gridshells based on an inflatable membrane technology. All well-known gridshell construction techniques are either based on the pulling/pushing up a flat grid of laths, or on the easing down of a grid of quads from a certain height. These techniques already suffer from shortcomings at the small scale; when applied to the large scale, the lack of a standardised and cost-effective erection method implies that new techniques have to be thought up each time. This is one of the reasons why gridshells are have only been designed for exceptional projects, such as the Downland Museum or the Mannheim Multihalle. Gridshells are not widely applied to common projects, even though they enable large spans to be covered with the minimum amount of material, they are fast to construct and are entirely recyclable. In this work, an inflatable membrane has been designed and used to erect a gridshell prototype with a footprint of 55m^2. Inspiration comes from the work of the architect Dante Bini, who, since 1964, has been realising hundreds of inflatable concrete domes around the world.

Keywords: Gridshells; inflatable membrane technology; construction techniques; form-finding.

1. Introduction

Shell structures carry loads through membrane action, and with reduced or no bending. This behaviour allows shells to feature an optimal stress distribution over the full cross section (Sasaki, 2014). Gridshell structures discretise the features of double-curved shells into a lightweight grid (Baverel et al., 2012). This allows, on the one hand, the structural self-weight to be reduced and, on the other (hand), the loads to be transferred only through compression forces (Bulenda and Knippers, 2001).

The term “gridshell” is broadly used to describe two categories of reticulated structures: post-formed gridshells and lattice structures. These categories differ as far as the materials, nodal configurations and construction methods are concerned. Lattice structures are generally made of steel and assembled directly in their final shape by bolting or welding rigid beam elements at the nodes - such as in the case of the court roof of the British Museum. Post-formed gridshells are timber products which are assembled by loosely connecting layers of linear laths in a flat grid of quads with hinge joints; this grid is subsequently post-formed into a double-curved shape, and then stiffened by means of bracing, shear blocks and connection tightening (Knippers and Helbig, 2009). It is worth noticing that the laths run through the nodes; connections can either be made using bolts or clamps. Bolts have been used, for instance, in the Mannheim Multihalle, whereas clamps were designed for the Downland museum.

Gridshells have been widely studied in terms of form-finding and, more recently, optimisation; as the work of Frei Otto is the main reference for the design and erection of timber gridshells (Hennicke, 1974), so the work of Jörg Schlaich is for the design and construction of steel gridshells (Holgate, 1997).

Two main categories of erection techniques are explained in Quinn and Gengnagel (2014): the first one is called “pull-up”/“push-up” and the second one “ease down”; a third technique, based on an inflatable membrane technology, has recently been outlined as a promising research topic.

1.1. Current construction processes for gridshells

Post-formed gridshells generally undergo more stress during construction than during operation. Erection is thus a key phase for gridshell design, due to the high variations in bending, in the asymmetric load conditions and in the heterogeneous curvatures. The two best known techniques are illustrated briefly hereafter, and the advantages and complications of their usage are highlighted.

“Pull-up” / “push-up” construction techniques involve assembling the flat grid on the ground and then lifting it up, either by means of cables and cranes (“pull-up”), or using a static formwork and jacking towers (“push-up”) (Quinn and Gengnagel 2014). The first method draws benefits from the speed of construction. However, the nodes receive concentrated stress, and this can easily induce breaks; moreover, horizontal restraint cannot be provided and the use of cranes can be costly and require calm weather for their operation. The second method applies the same lifting principles, but by means of a low-cost technology. The Mannheim Multihalle is one of the largest and most relevant gridshells in this category (Burkhardt and Otto, 1978). The final form of the Multihalle was developed by means of scale-models; this allowed the most efficient form of pure compression to be determined for a model that was too complex and time-consuming to be calculated numerically at that time (Addis, 2013). The construction process started by laying the double-layered timber grid on the ground in a flat position. Holes and slots were carefully drilled for each one of the over 33,000 joints, thus providing them with hinge features (Harris, 2004). The initial choice was to use cranes for the erection, but eventually a system of jacking towers was used to reduce the costs (Happold and Liddell, 1975). In one year, the grid was lifted to its final position by pushing upward from below and pushing inward from the sides (see Figure 1). The construction phase ended with the joints being tightened and shear blocks and bracing cables being placed in position (Burkhardt and Otto, 1978). This erection technique, applied at a large scale, proved to be highly time-consuming and imprecise; moreover, a 1.5% lath breaking ratio was observed (Harris et al. 2003).

The “ease down” construction technique starts with a flat grid being assembled on a raised level and then its edges being bent down by means of modular scaffolds and mechanical formworks (Quinn and Gengnagel, 2014). The Downland Open Air Museum, by Buro Happold, shows how this technology offers, on the one hand, better safety for the workers and a lower breaking ratio, but, on the other hand, still involves high costs. Unlike the Multihalle, the flat lath mesh was laid on scaffolding at the shell hump top level and was post-formed to its final configuration by means of a scaffolding structure and forklift trucks (see Figure 1). After the lowering process, the gridshell was fixed at its supports and stiffened with a pre-stressed cable network (Harris et al. 2003). Adriaenssens et al (2014) have pointed out that fixing the shell both at the sides and ends provides this erection technique with more precision, and that post-forming the grid under a gravity load leads to a more homogeneous distribution of the strains.

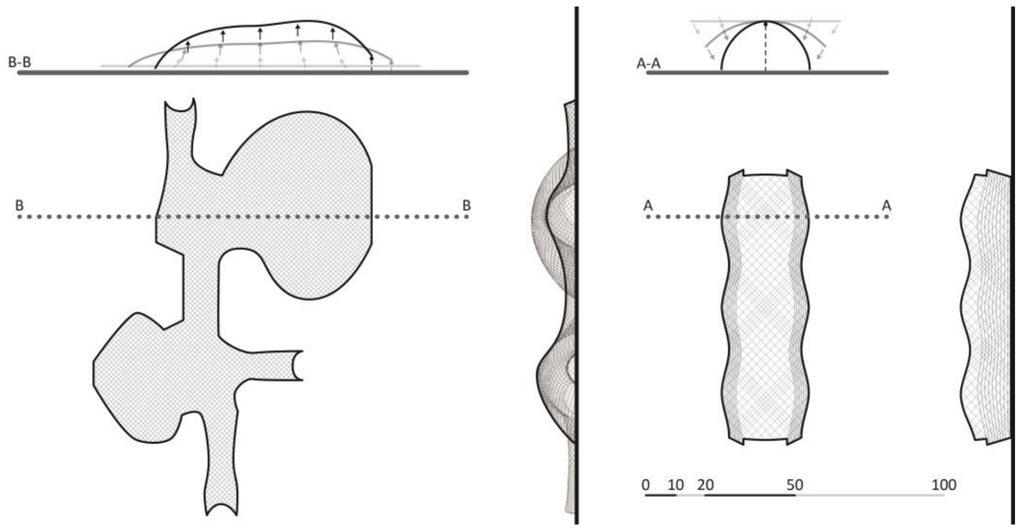

Figure 1: Left: Mannheim Multihalle by Frei Otto and the "push-up" erection process (1973-74). Right: Downland gridshell and a description of the "ease-down" lowering process (2002).

The aforementioned examples help to illustrate that, despite featuring a seamless integration between the material and form, shell structures still lack appropriate sustainable solutions for their construction and fabrication. The commonly used construction techniques for gridshells are highly demanding, in terms of resources and budget. These are among the reasons that generally discourage the use of shell structures. Moreover, the precise positioning of the joints in the correct final position still remains an open issue.

Fabrication-related shortcomings already arise at a small scale. When scaled to a larger scale, the lack of a standardised, cost-effective erection method implies that techniques have to be reinvented each and every time, and gridshells only become affordable for exceptional projects, such as the Downland Museum or the Multihalle in Mannheim.

2. Constructing with inflatable membranes

Historical examples show how membrane technology has provided an alternative means of construction through the centuries (Veenendaal et al., 2011). The potential of it is to seamlessly approximate ruled surfaces; moreover, the membrane's flexibility allows fabric formworks to deflect and adapt under the weight of wet concrete. These features benefit membrane technology with an interesting potential in easily generating shapes of pure tension (compression if inverted), especially in comparison to traditional rigid formworks.

2.1. Inflatable membranes in shells construction

Early applications of the membrane technology to shell structures can be found in the work of James Waller. His patented "Ctesiphon" system relies on a set of catenary steel frames from which a fabric formwork is stretched; having a modular compressive catenary system allowed him to simplify the construction process, while minimising the use of steel reinforcement. (Waller and Aston, 1953).

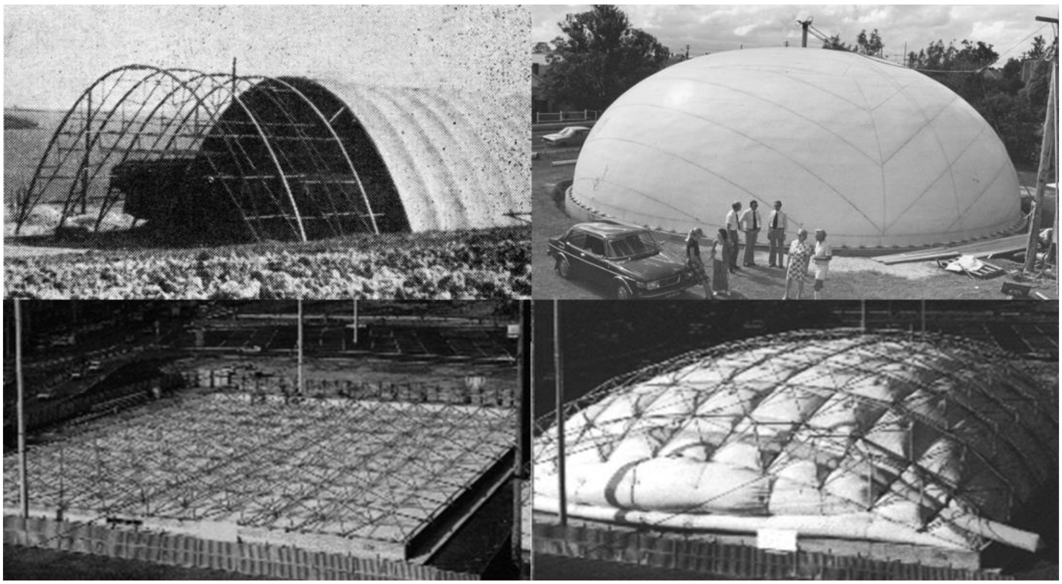

Figure 2: Top left: Ctesiphon shell catenary frames (Credits: Waller and Aston, 1953); Top right: Binishell system during RC levelling. Bottom: one-day erection of the 1990 World Cup structure in Udine; inflatable flat stage in the morning, on the left, and in the evening, on the right (Credits: Bini, 2014).

Another technology applied to RC shells was proposed by Wallace Neff when, in the 40s, he pioneered the use of inflatable domes as formworks for concrete bubble houses (Neff, 1941). This technology was further explored by Dante Bini with his patented "Binishell" system for RC shells. Such a system relies on a rather intuitive form-finding / construction procedure (Bini and Fontana, 2014):

- after laying rebar, concrete is poured over a flat pneumatic preformed formwork;
- the membrane is inflated, and the shell is raised to its final position;
- after seasoning, holes for openings are cut.

Although providing RC shells with inflatable formworks was not an entirely new technique, Bini has had the merit of integrating them with James H. Marsh's "Lift-Shape" patent to erect and bend reinforcements to the desired shapes (Marsh, 1961).

2.2. Inflatable membranes in gridshells construction

Dante Bini's "Binistar" system involves applying inflatable pneumatic membranes to steel space frame structures. This automatic construction method was developed for pneumatically-lifting telescopic steel spatial structures; an air-tight pre-shaped PVC-polyester membrane was used to lift the frame structure from the footing-level to its final position. At the end of the construction process, the membrane remained in tension, suspended from the nodal points of the structure as a leak-free final cover. The galvanised steel space frame was composed of a series of telescopic pipes which were mechanically fixed after completing the inflation (Bini, 1993). The various building projects include temporary buildings for sports, such as the 1990 World Cup Championship (see figure 2), or events, such as the 1992 Expo Pavilion in Seville.

3. Post-forming through inflatable membrane technology

The previously presented applications of inflatable membranes to shell structures showed promising potential in terms of automation, construction speed and shape control. This part of the paper describes the redevelopment of a timber gridshell by means of this technology. The case study is based on the post-formed Accoya timber gridshell built at the University of Melbourne in October 2014 (coordinators Pugnale, Colabella, Pone, www.karamba3d.com/accoya-timber-gridshell). The design of this gridshell arose as a variation of the Alida Woodome series, designed and constructed by Gridshell.it. Redeveloping a well-known structure first allows the construction technique to be focused on rather than the design; it also allows a comparison to be made of different processes that result in the same outcome.

Figure 3 shows the flat and post-formed configurations of the gridshell along with the Accoya timber properties (New Zealand grown Radiata Pine). The 11x11m^2 orthogonal grid is made of 50mm wide and 19mm thick timber laths, arranged in two layers in each direction. The lath spacing is 500mm for each layer.

Starting from the post-formed gridshell configuration, a physical model and a numerical model have been developed. Initially, the numerical model made it possible to determine the most appropriate membrane geometry to use for the post-forming of the gridshell. The physical model then made it possible, on the one hand, to understand the overall behaviour of the system and, on the other hand, to deal with technological issues related to the joints, connections and materials. Finally, a refined numerical model led to a better refining of the theoretical aspects of the problem.

3.1. Numerical model

The numerical model of the gridshell has been developed as follows. First, a flat configuration of the gridshell was drawn on the Rhinoceros CAD platform. Second, the two lath layers were parametrised by means of Grasshopper (Rhinoceros plugin). Third, the parametric model was translated into a spring system by means of Kangaroo (Grasshopper physical simulator plugin). Then, a preliminary bending process was simulated using the Accoya timber properties and the shape of the Alida Woodome by Gridshell.it (Pone et al, 2013). Finally, a more accurate bending was implemented by iteratively imposing displacement to the edge joints during the dynamic relaxation. Working with such a double-curved structure has allowed, on the one hand, to minimise the nodal vertical displacements and, on the other hand, to optimise the structural response to vertical and horizontal loads.

Once the double-curved post-formed configuration had been obtained, the inflatable cushion membrane shape and properties were determined. The cushion was made by welding two slightly convex square sheets at the edges. After running several inflation-collision simulations, the membrane that best fitted the post-formed gridshell was chosen (see Figure 3). Setting inextensible - rather than rubbery - material properties made it possible to have a better control of the final shape of the membrane. Wrinkling was considered irrelevant as far as the overall behaviour of the system was concerned. A $7.2x7.2m^2$ mesh was chosen as the most suitable solution; having a smaller cushion than the post-formed gridshell also made it possible to avoid self-intersections during the collision simulation.

Figure 3 shows how the inextensible cable and pulley system works in the initial configurations t_0, in the intermediate phase t* and in the final configuration t_1. Pulleys were positioned on the ground along the vertical projection of the cushion at t_1, in correspondence to the external and middle points of each free edge. Several assumptions were made to develop this system:

- to transform a vertical push into horizontal traction;
- to ground-restrain the free edges of the gridshell during the whole erection process;
- to allow a precise control of the final position of the joints;
- to use longer ropes than the laths to obtain an initial t_0 stress-free configuration.

Ground-stoppers were placed according to the post-formed gridshell configuration in order to control where to stop the bending process at moment t_1.

The traction and lifting forces were calculated, in Kangaroo, by approximating the cables and membrane with net force vectors. Given the final gridshell configuration, these force variables were determined by applying prescribed displacements to the flat gridshell.

The material and geometric properties were set and verified by means of both numerical and physical benchmarks.

3.2. Physical model

Figure 4 shows the 1:7 scale prototype that has been developed to simulate the system. The Accoya gridshell was modelled as a single-layer Poplar-timber gridshell. Continuous laths were connected at the joints with bolts and nuts; this allowed the 1:1 structure to be approximated with a reduced bending stiffness. An easier bending procedure was thus achieved.

The square membrane was fabricated as a PVC coated polyester strip. Vinyl Cement glue and duct tape were used to seal the strips together to prevent tangential forces from lacerating the membrane; welding two simple flat sheets together- rather than pre-curved surfaces – made it possible to facilitate the membrane fabrication process. A Halkey-Roberts valve was then placed on the PVC fabric and sealed. In order to seal the upper and lower halves together, a sewing-machine was first used and then duct tape was placed along the edges; this cautious solution has proved to be necessary to prevent tangential forces from tearing the two halves apart.

Implementing buttonhole-guides along the sealing led to a better control of the cable system. A 150g/m multifilament twisted twine was chosen for the cables. A trial-and-error iteration between the physical and numerical models made it possible to determine the geometry and properties of such a system (see Figures 3 and 4).

It has been discovered that swelling affects the membrane in two ways. During the first phase t_0-t*, the membrane rises and shrinks horizontally at the same time; the gridshell only receives an upwards push from the contact. However, once the membrane reaches moment t*, the cable system becomes tensioned; this triggers a secondary lifting effect in which centripetal edge forces induce bending and hence push the gridshell upwards. (see the bottom images in Figure 3 and the central ones in Figure 4).

The details were developed considering real-scale inflatable models (i.e. valve system, guides and d-rings, welding technology). The use of eyenuts as pulleys was crucial for several reasons:

- to transform the membrane vertical push into a horizontal traction for the gridshell, hence allowing lifting;
- to ground-restrain the gridshell edges during the lifting process, hence allowing an easy development of the ground-connections at the end of the process;
- to secure a precise final position of the free edges of the gridshell, hence making the whole process more controllable.

Gridshell - Accoya timber properties

5th percentile values	Bending strength	$f_{m,k}$	24 N/mm ^{2}
	Tensile strength	$f_{t,0,k}$	14 N/mm ^{2}
	Shear strength	$f_{v,k}$	4 N/mm ^{2}
Mean values	Young's modulus	$E_{0,k}$	7400 N/mm ^{2}
	Shear modulus	$G_{0,m}$	690 N/mm ^{2}
	Density	ρ_m	460 kg/m ^{3}

Membrane - PVC coated polyester properties

Tensile strength	Warp	2275N/50mm
Tensile strength	Weft	2420N/50mm
Elongation at break	Warp	20%
Elongation at break	Weft	27%
Density	ρm	680 g/m ^{2}

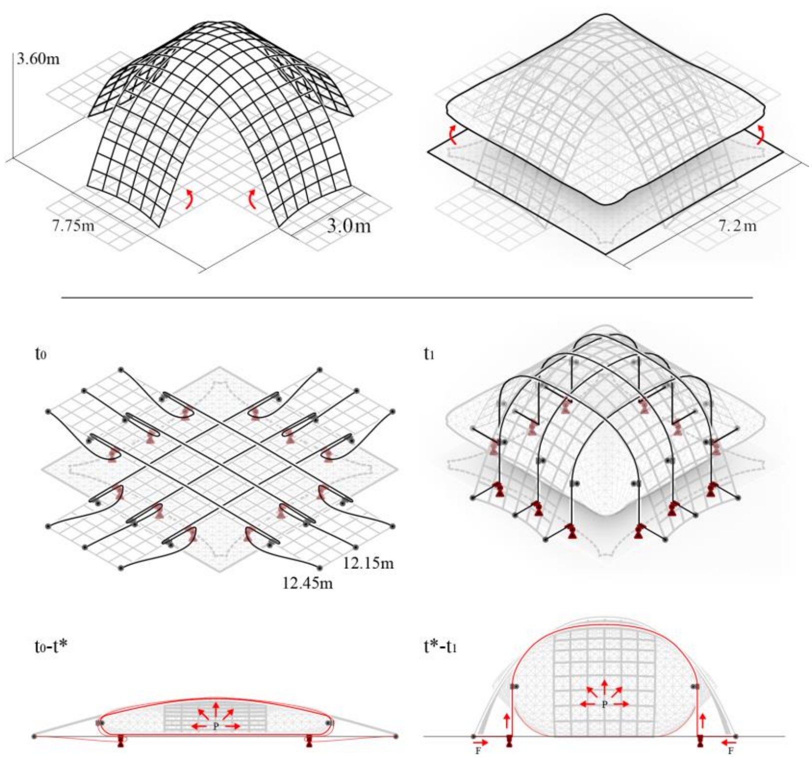

Figure 3: Top: Gridshell and membrane properties; initial flat state and post-formed states of the system. Bottom: cable system before (t_0) and after (t_1) the inflation process. Cables tensioning occurs at moment t*. The illustrated process is concluded before the bracing and shear blocks are installed.

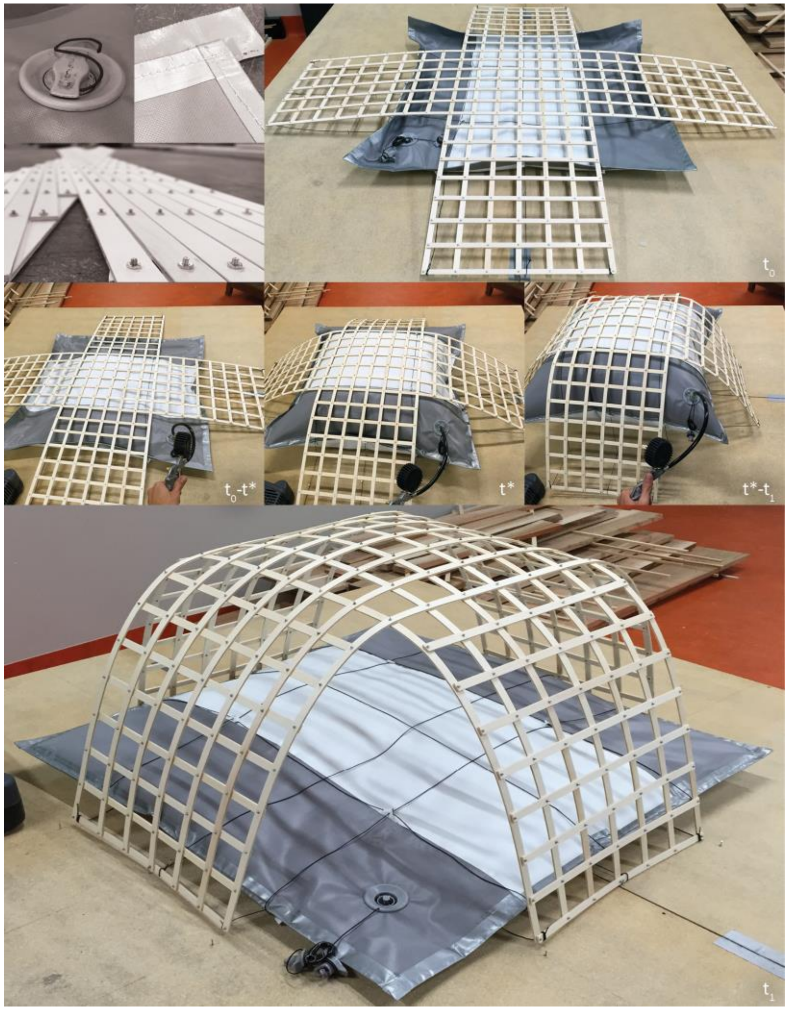

Figure 4: Top left: valve, stitching and joint details. Main: gridshell erection phases from t_0 to t_1.

4. Conclusions

The idea of using an inflatable membrane technology for the erection of post-formed timber gridshells arose from a review of the issues of the existing construction methods, but also looking back at Dante Bini's air structures. An inflatable membrane has therefore been designed to erect a 55m^2 timber gridshell, with the aim of increasing construction speed, safety and form control. An already existing gridshell was chosen as a case study to compare this alternative technique with a more conventional one: the Accoya timber gridshell, developed at the University of Melbourne in October 2014.

A numerical model and a physical model have been developed to simulate the erection process. The numerical model has been used to determine the geometric and structural properties of the timber, membrane and cables. The 1:7 scale model has instead been helpful to design the membrane/rope system and verify the results of the numerical simulation. The details of the physical model have been prototyped in order to be easily replicable at a full scale. It is worth noting that this technology focuses only on the erection phase; in order to provide the gridshell with structural stability, the installation of bracing and shear blocks on the final structure would also be required.

This new erection technique still requires further developments and tests on a few aspects:

- the numerical model needs to be refined in a higher-level FEM solver to extrapolate both lath nodal stress and membrane tension during the erection process. This step would be necessary to simulate the erection of a 1:1 scale model. A higher-end FEM software would allow the performance of different shapes and types of membranes to be compared. For instance, planar membranes can be cheaper and easier to fabricate, but double-curved membranes can stick better to the gridshell and hence reduce the lath breaking ratio while increasing the precision necessary to reach the final form;
- an internal cable system should be implemented and tested to link specific key-points between the upper half and the lower half of the membrane. This system would allow better control to be obtained of the membrane geometry and hence of the final gridshell configuration;
- this technique should be tested for the construction of different gridshell geometries, in order to verify its potential for standardisation;
- a more flexible system of modular membrane cushions should be developed, in order to allow application to multiple and different gridshell geometries, dimensions and configurations. As Dante Bini has pointed out (Bini et al. 2014), providing an erection system with a reusable technology is relevant to reduce construction costs;
- this technique should be tested on a full-scale prototype in order to obtain reliable data on its speed, safety and form-control. This would allow a comparison to be made between this technique and the current construction methods.

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