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The Airshell prototype: a timber gridshell erected through a pneumatic formwork

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Abstract

This paper presents the construction of *Airshell*, a small timber gridshell prototype erected by employing a pneumatic formwork. Inspired by the work of Frei Otto and Dante Bini, the technique is based on a pneumatic membrane and an *Arduino*® board – the former used as dynamic formwork and the latter to monitor both the structure height and the membrane pressure throughout the process.

The prototype was erected in Pesaro, Italy, in December 2016; the design replicates a gridshell built in Lecce in 2009 by the Italian company *Gridshell.it*, which was built through a more conventional push-up technique. A comparison between the two erection methods is therefore proposed in terms of construction speed and accuracy/precision of the built form.

Design and technological aspects, as well as time frame and budget of the proposed construction technique are detailed within the text. The paper also discusses the relationship between the digital simulation of the erection process, which was already formulated by Liuti et al. in 2015, and the actual results achieved.

Keywords: gridshell, active bending, timber, pneumatic formwork, prototyping, form-finding

1. Introduction

In shell and gridshell architecture, analytical surfaces, as well as reverse hanging models and other form-finding methods have been used for decades, if not centuries, as the main driver of the design process. However, although the structural forms that result from these methods are intrinsically faithful to the nature - and behaviour - of construction materials, they do not necessarily translate into built forms straightforwardly or in a rational way.

1.1. Interfaces between conception and implementation

Heinz Isler's projects are prime examples of distance between the conceptual design of structural forms and their execution into built forms; despite his concrete shells were theoretically clear on paper, they required a complex, labour-intensive actualisation through the preparation of doubly curved formworks and curved steel reinforcement meshes. The concrete bridge over the Basento River, designed by Sergio Musmeci, is another project of this kind; where the shape of the bridge itself is the perfect representation of a minimal surface, the lack of elegance in the final construction reveals a missing synergy between conceptual design and the practical implementation of an idea.

But that is not always the case. A strong relationship between aesthetics and technology, or better an interface between "art and science of building", is present in Pier Luigi Nervi's projects, where the development of a construction technique accompanies the emergence of architectural form.

Félix Candela’s work can be read from a similar perspective. His structures primarily use geometric forms, in particular hyperbolic paraboloids. As ruled surfaces, these geometries are describable as a set of straight lines that ‘rule’ a surface, and can therefore be erected using simple formwork that does not require the presence of curved elements.

This relationship - or better interface - between engineering and architecture was pushed even further by Frei Otto’s timber gridshell project for the Multihalle in Mannheim; in this case, physical models form finding was used not only to design the structure, but also to reproduce, to a certain degree, the actual building erection principle. It is a well-oiled synergy – or better interface – between theory and practice that also characterises the *Binishell* system patented by Dante Bini. Similar to Isler’s pneumatic models, Bini managed to find structural form by means of an inflatable membrane; on top of it, most importantly, he successfully scaled up the concept to bend a flat slab of concrete and steel reinforcement mesh into a three-dimensional thin shell. The *Binishell* architecture is clearly based on geometric intersections and cuts of pneumatic structures, and represents another example where low-end technology and construction processes allowed ideas to emerge - not vice-versa.

In this framework, the project described in this paper takes inspiration from Frei Otto’s and Dante Bini’s work and proposes a new interface between the design and construction of timber gridshells. Applications of pneumatic formworks to shell structures date back to the 40s with the early works of Wallace Neff; however, applications to active-bending gridshell structures were only envisioned in literature (Otto et al. [5], Quinn and Gengnagel [7], Liuti and Pugnale [3], Quinn et al. [8], Liuti et al. [4]). A prototype, called *Airshell*, was erected in Pesaro in December 2016 by means of an inflatable membrane and an Arduino board to monitor the erection process. Details about the technique and results are discussed in the following sections.

2. A design-and-construction framework for bending-active gridshells

The overall design of *Airshell* (Figure 1) replicates the geometry of an existing timber gridshell, called *Woodome1*, which was designed and built in Lecce in 2009 by *Gridshell.it* (Pone et al. [6]). This structure measured 7.5m x 7.5m x 3.3m and was erected through a “push-up” method consisting of props and ropes – eventually braced by a double set of steel cables. The flat grid of orthogonal laths was assembled on site from nine macro-moduli, made of four layers of timber, two per each direction. These layers were connected with M6 zinc-plated bolts, so to realise hinged connections. The gridshell edges were constrained using soil-filled 0.5m x 1.4m flowerpots.

Figure 1: the built *Airshell* prototype. [Image: A. Liuti]

With a budget of approx. AU$8,000, the authors were granted access to the *Woodome1* documentation drawings, and obtained feedback on the final structure behaviour, as well as issues related to erection, from the designers. This opportunity permitted directed focus to the implementation of a pneumatic erection technology, and to make a direct comparison between the two construction methods – push-up vs. pneumatic – applied on structurally similar gridshell structures.

Airshell's design-and-construction workflow was based on D'Amico et al. [1], Liuti et al. [4], Pone et al. [6], so that design, manufacturing and construction could iteratively inform one another throughout the process (Figure 2). By embedding the pneumatic formwork at both the design and construction scales, form finding could be implemented and replicated with accuracy.

The gridshell wireframe was digitally modelled in the parametric CAD *Rhinoceros® – Grasshopper®* environment, where also the erection simulation was performed. By using the interactive physics/constraint solver *Kangaroo2*, the gridshell was modelled as a spring system made of two orthogonal mats of parallel polylines; these were given a bending stiffness adjusted according to an equivalent section and then connected at the nodes with hinge-like joints. In parallel, the pneumatic membrane was modelled from a closed mesh sphere as a spring system; form finding was adjusted to match the archetypical shape of *Woodome1*, but also considering the contribution given by the pneumatic formwork (Liuti et al. [4]).

Setting the diameter of the pneumatic formwork to 5.20m offered a dual benefit. On the one hand, it allowed reaching the target maximum rise of 3.3m while maximising the area of contact between pneumatic membrane and gridshell. On the other hand, it permitted manufacturing a regular, well-known geometry, this avoiding collateral manufacturing problems and costs (Figure 4).

To monitor prototyping and strengthen the critical interface between the analogical and digital domains, a feedback system using control sensors was implemented. The erection height and pressure were therefore recorded in real time using two Arduino boards (Figure 5).

Of note, within this research project, a relevant aspect was to use prototyping as a technical tool for seeking, testing and validating a proof of functionality for the initially envisioned system (Stark et al. 2009 [9], Kamrani and Nasr 2010 [2]).

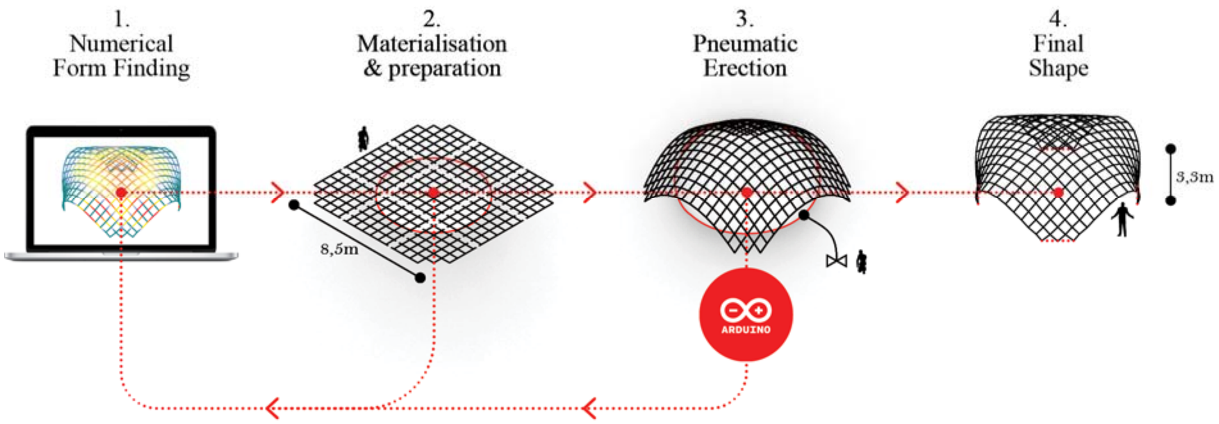

Figure 2: Keeping an open-ended design to construction framework allowed the form finding process to inform, and at the same time to be informed, by pneumatic inflation simulations. [Image: A. Liuti]

3. Prototyping

Prototyping was implemented sustainably, in accord with the philosophy that underpins the nature of timber gridshells. A "lightweight" impact on the planet should also minimise the overall energy consumption involved in the process – thus preference was given to local markets for sourcing materials and facilities.

Woodome1 was built using a *Sweet Chestnut* typical of southern Italy. An extensive market research, aimed to seek a compatible timber breed with little nodes, high durability and good elasticity, led to pick *European Silver Fir* or *Abies Alba* – a Pine breed which commonly grows in central and southern Europe. Bending resistance tests were performed prior to construction, to get information on the allowable radius of curvature, given that 1.4m was the minimum radius detected in *Woodome1*.

Given the high repetition of cutting, drilling and slotting to be repeated for over 250 laths, manufacturing was divided in two steps. First, raw planks were visually selected to avoid knots and defects, sectioned and cut to length in 250 laths with artisanal workshop tools – such as saw tables and table planners; tolerance of ± 2mm. Second, due to the need for a ± 0.1mm precision, these laths were processed in an industrial workshop by means of CNC milling machines (Figure 3).

Where the main focus of the first step was to assess the quality of the material, precision could be looser; oppositely, in the second step it became pivotal to provide manufacturing precision and rapid processing times, so that a large number of operations could be carried out while minimising error propagation – namely between 7 and 12 holes or slots per lath, times 250 laths.

In order to bypass the slight differences in size of the many laths during the CNC milling, each lath was lodged in a template jig, so to register to a single milling origin. This way, the relative position of the holes and slots was univocally determined. After drilling and slotting, each lath was rounded and sanded to ease painting and finishing.

In parallel, custom-designed steel ground connections were fabricated being steel-and-rod shoes (anchored with nuts and bolts to the corner nodes of the gridshell) and a fixed system of plates, forks and rails (strapped with filleted rods to the foundation slabs). These were designed to perform a dual function: first, to act as a horizontal linear roller during the forming process; second to interlock the supports with pinned joints once reached the final position (Figure 7).

Figure 3: preliminary and industrial processing; right, the milling of two laths in the jig. [Image: A. Liuti]

Respectively, the steel shoes were secured to the Ω profiles rails to create roller joints; such a bond was secured through a cable-and-pulley system anchored to the foundations. Once in their final position, the rod of the shoes could slide in the fork of the ground plate and lock in position as a hinged support; after this, winged fastenings would act to prevent vertical displacements, while still allowing potential rotations related to active bending.

It is worth mentioning that the system features polar-symmetric quadrants; this permitted carrying engineering design for supports on the single, most penalised, condition and extend it to the rest of the ground connections. Such forces were extrapolated from a FEA carried in parametric FE solver *Karamba*®, and processed, according to Eurocode 7, assuming good founding material.

In parallel, a cable system made by inextensible cables was engineered to allow a smooth transition from the initial to the final geometry. Hereafter, a specific focus is made first on the engineering and manufacturing of the pneumatic formwork and, second, on the development of the feedback system.

3.1. The pneumatic formwork

The pneumatic formwork engineering was premised by seeking to minimise fabrication time and overall cost. These objectives suggested to minimise the sphere volume, while optimising the number, distribution and length of welds. For this reason, a regular discretisation of a spherical shape was chosen over more irregular solutions.

Given such premises, the area of contact between the sphere and the gridshell had to be maximised throughout the whole erection process, making sure the membrane pressure could act homogeneously and constantly on the gridshell laths. Iterative trial-and-error simulations allowed the selection of a sphere with 2.6m radius.

It then became relevant to determine the amount of pressure required to perform the actual gridshell erection. Such a pressure (P) had to overcome the combination of the gridshell self-weight (P_w) and the necessary bending actions (P_b), while not exceeding the maximum pressure (P_{max}) at which the membrane would fail: $P_w + P_b < P < P_{max}$.

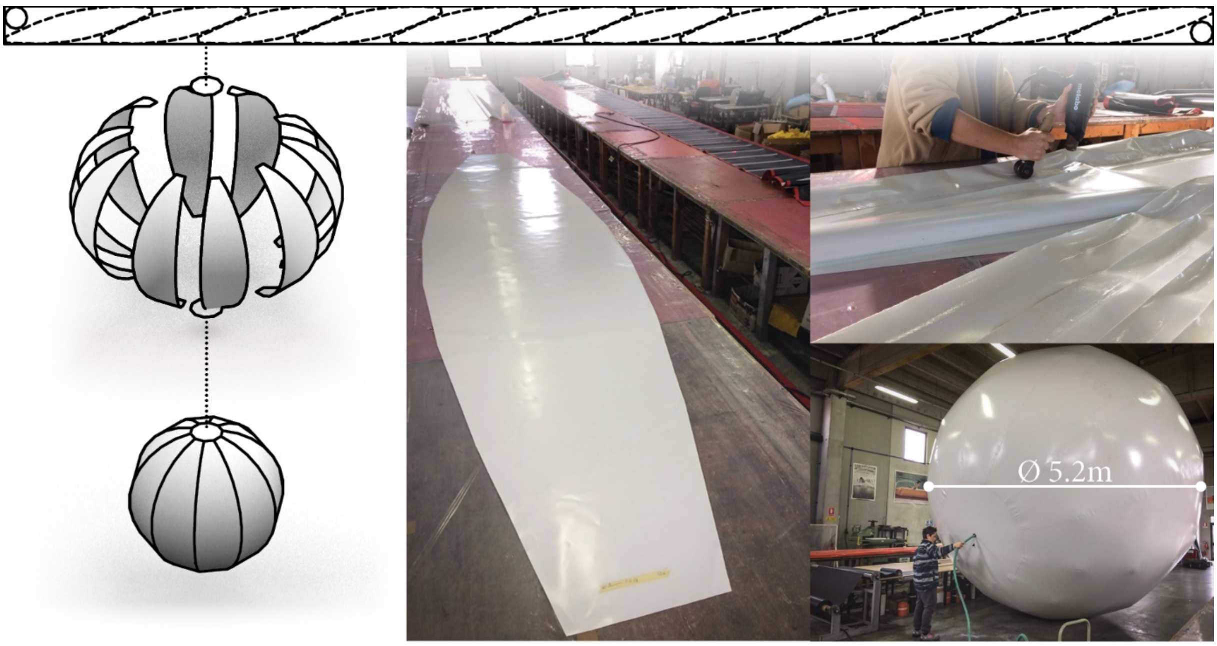

Figure 4: The membrane was virtually discretised into equal slices and unrolled for manufacturing – so that the flat patches could be cut and welded together; swelling test at the bottom right. [Image: A. Liuti]

Assuming a minimum contact area equal to the projection of the sphere on the ground level, the first action to contrast (P_w) was evaluated as the sum of the distribution of the gridshell's dead weight over the contact area to the membrane's dead weight, as per (1):

$$P_w = \frac{W_{GRD}}{\pi \cdot r^2} + \delta_{pneu} = 0.13\,\frac{kN}{m^2} \tag{1}$$

Conservatively, the contribution related to the bending actions (P_b) was evaluated by reductive means to avoid uncertainties related to the simulation procedures; this simplified system was modelled in the FE platform *Karamba®*, under Euler-Bernoulli assumptions, as a grid of elements subject to a linear load q. A prescribed displacement was imposed to the four free edges, to meet the target rise of 3.3m on such static system, the distributed load was found by imposing the equilibrium between internal and external actions. Finding the value of q, the pressure value could be written as per (2):

$$P_b \sim \frac{EIk^3}{2} = 10\,\frac{kN}{m^2} \tag{2}$$

P_{max} was determined as the maximum allowed pressure action associated to the maximum tensile strength of the PVC-coated membrane – a *Ferrari Précontraint 920 S2*. Prudently, the upper limit was set 20% below 1atm, so that a suitable range of erection pressure could be framed between $101\ mBar < P < 800mBar$. For practical purposes, the ideal erection pressure was assessed as $P = 120mBar$.

Hence, to optimise manufacturing, the following considerations were made: (1) minimising the waste of fabric; (2) minimising the number of welds given a prefixed welding length and, hence, reducing the overall welding time. Preliminary explorations led to discretise the sphere, according to the meridians, into 12 identical slices. Having an array of identical elements led to a reduction of the manufacturing imprecisions and a simplification of the cutting patterns to a set of planar polylines. Welds were tested against traction, resisting concentrated loads up to 250Kg.

3.2. Assembly and calibration of the monitoring system

Monitoring the erection procedure required the identification of key-parameters to describe the bending / swelling performances during the erection process. Regarding the gridshell, the position of the edge supports was mechanically controlled by means of the aforementioned system of rails and plates; the structure rise was measured at the central point (that is, the expected apex). For the pneumatic formwork, it was essential to monitor the inner membrane pressure and keep it within the admissible range of values.

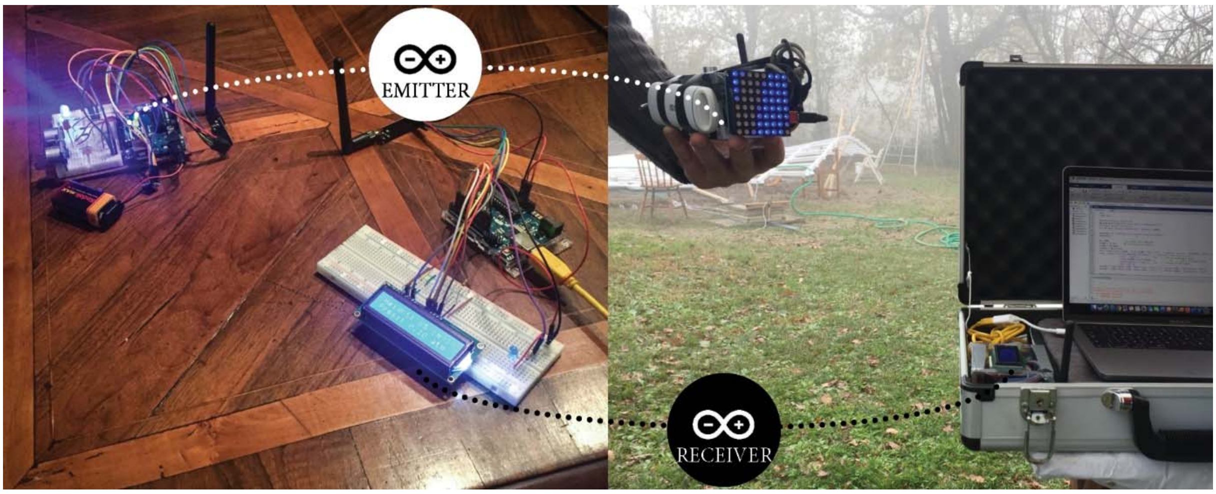

Figure 5: The *Arduino®* emitter and receiver during testing (left) and on site (right). [Image: A. Liuti]

For the monitoring system, a receiver *Arduino*® board was connected to a PC, so that the data received via Wi-Fi could be plotted on screen and stored in a *.csv format file (Figure 6). The emitting *Arduino*® board, instead, was placed inside the pneumatic membrane prior to inflation; on such a device, two sensors were embedded: a distance ultrasonic sensor, and a barometric sensor.

The pressure modulus consisted of a piezo-resistive sensor, type BMP 180. Such a sensor provides an absolute measurement of the atmospheric pressure. The distance modulus was an ultrasonic sensor, set at the centre of the deflated membrane, at the global coordinates (0,0,0). By pointing up towards the zenith of the pneumatic membrane, it was possible to coincidentally monitor the maximum rise point of the gridshell. Through echolocation, rays were cast over a relatively flat surface and reflected within an approximately 20º field of view.

As the emitter broadcast from inside a sealed space for a considerable amount of time, a Wi-Fi antenna and a 7800mAh power bank were inbred on the board. Having the emitting board inside the membrane also provided the benefit of neglecting interference in data monitoring related to variations in outdoor air density and temperature.

4. The gridshell takes shape

After the nine doubly-layered structural moduli were assembled off site, site preparation focused on laying the footings, arranging the twelve ground connection plates, the four rails and a few dead weights around the working area. Then, the membrane was aligned at the centre of the gridshell footprint and the *Arduino*® emitter was lodged inside it in the proper position (Figures 6-7).

Subsequently, the moduli were laid over the membrane and bolted together in a continuous flat configuration. Loosely bolted M6 nuts and bolts allowed, on the one hand, the orthogonal laths to rotate around the normal axis of each joint and, on the other hand, the parallel laths to slide onto each other along their main axis.

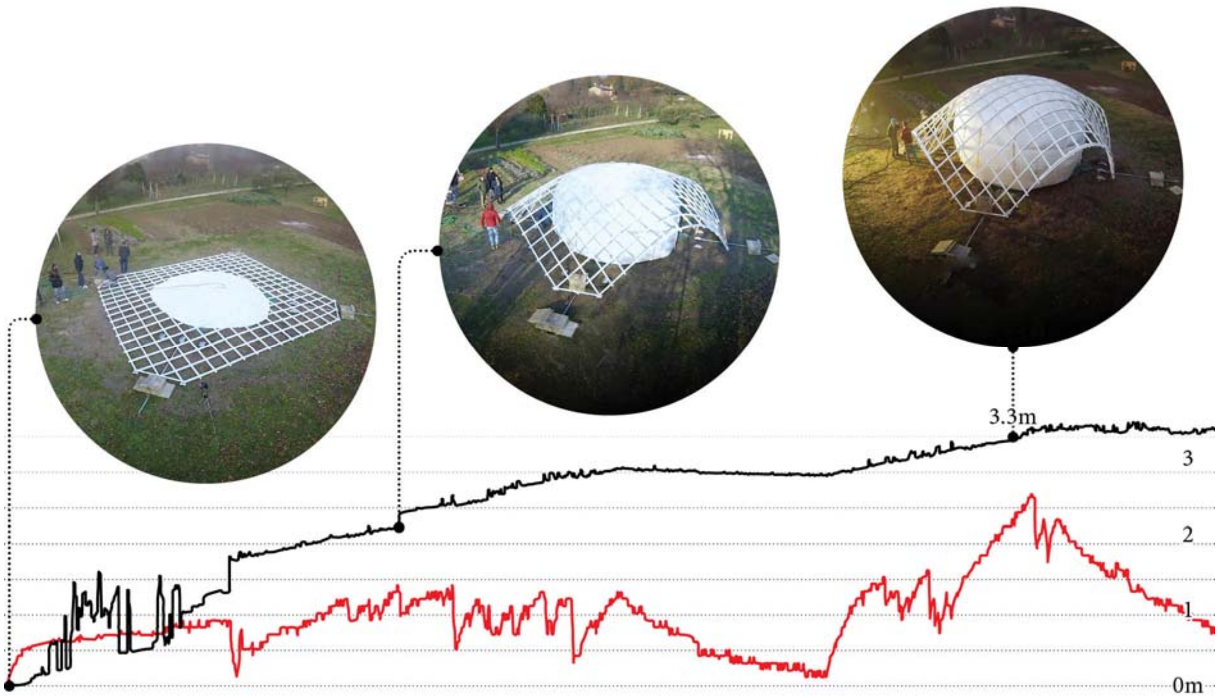

Figure 6: Bottom, trends of pressure (red) and rise (black) throughout the erection; top, key-moments: from the left, preparation, intermediate stage and final goal; the initial noise in the rise graph is related to surface wrinkles. Erection time lapse video available on: https://youtu.be/6flPMmNxUVA. [Image: A. Liuti]

After running a quick test, the actual erection took place by switching on and off the compressor at hourly intervals. Once the rise reached 1.7m, pumping was suspended to let the timber absorb and dissipate the imposed changes in curvature (Figure 6). After repeating a second swelling session for one hour, the structure was left to rest again at a rise of 2.2m. At this point, a critical curvature was reached, imposing a longer resting time before running the last swelling session. Once the goal of 3.3m was surpassed, the blower was kept going for a while to counteract marginal deflation effects.

To freeze the form-found configuration, the rod bars attached to the steel shoes were slotted in the steel plates and secured with winged flanges; this way, the roller connections were transformed into hinged ones. After this operation, the pneumatic membrane was kept in pressure for a day while tightening the joints and applying the shear blocks in the lower parts of the structure; this allowed preventing possible failures before tightening and bracing were finalised.

4.1. Comparison of the two erection methods

As in any bending-active structure, the final behaviour and stability over time of a gridshell are determined by many factors included in the forming process – such as overall geometry, connection to the ground, bracing direction and so forth; this is one of the reasons why the simulation of the construction process, as well as the determination of intermediate stages of deformation, is paramount to prevent any condition of local overstress.

In order to prevent such harmful conditions, the geometries of both *Woodome1* and *Airshell* were designed to be doubly symmetrical throughout the whole forming phase, to avoid the generation of valleys, sudden changes in curvature and local stress peaks.

Woodome1 was pushed up by means of props and ropes. Preventing humps and sags, a set of hoop tie-cables, and an orthogonal set of cables on the ground, were used to move the boundaries to their final position and to reach the requisite height. Nevertheless, once each boundary reached a 1.20m displacement towards the centre of the structure, the central area of the gridshell could not rise accordingly along the z axis. Props were used to reach the desired rise and curvature; however, given the small area suitable for the props to be arranged, these could not be placed in a symmetric layout.

On the one hand, the hoop tie-cable successfully preserved deformation symmetry throughout the process; on the other hand, however, the props induced slight dissymmetrical actions. Nevertheless, the final result was not affected by the asymmetrical pushing action, mainly because of the action and presence of the hoop tie –replaced with a bracing set of steel cables once the final shape was reached. Pushing up the lattice by means of props, also required workers to operate under the unfinished, and non-stabilised, structure. By contrast, remotely controlling the pneumatic formwork ensured a safer working environment, as well as reduced the use of manpower throughout the forming process.

For the pilot project *Woodome1*, however, the cheap and labour-intensive technologies applied, were necessary to fulfil fast actions over unexpected events, and to set up a protocol for the fast assembling of a small timber gridshell.

A second major improvement in *Airshell* was the combination of a rail system and a real-time feedback system – the first used to guide the boundaries along trajectories of imposed displacements, the second used to monitor the erection sequence easily and precisely. The manual shift operated in the *Woodome1*, on the one hand, required a constant series of time-consuming distance measurements between the four lines; on the other hand, it occurred also in minor positioning errors.

This second feature, however, can backfire since the final position of the supports must be correctly calculated and, due to material imperfections or unexpected contingencies, it becomes hard to correct such a position later in the erection process. This aspect shall be further deepened by implementing a more flexible system of ground connections.

Overall, advantages in using a pneumatic membrane to gently shape the flat grid pertain both the possibility of avoiding false deformations throughout the process, and, subsequently, avoiding overstressing the laths. Where these two factors often are responsible for fatigue cracks, in any case potential breakages can always occur during the erection phase due to timber defects, human error, or a project fail.

Furthermore, a comparison between the preparation of the two erections systems would imply more resources required for the pneumatic formwork; however, a pneumatic solution offers a good potential for replicability. It is to be considered also that a fixed pneumatic shape can only be adopted to a given scale / range of gridshell geometries; nevertheless, the technology has potential to be scaled to larger structures.

5. Conclusion

Airshell was built in Pesaro, Italy, in December 2016 as the product of a collaboration between institutions – the University of Melbourne, Politecnico di Milano and the University of Naples "Federico II" – and private companies – such as *Gridshell.it*, *Grottaroli* and *Green2*.

The use of a pneumatic erection technology allowed replicating, during construction, the form-finding simulations which were developed in the design phase; this operation was carried out with a reasonable amount of precision and reducing the number of workers and resources required on site.

A response was developed also in terms of rapid construction, as little preparation was required on site prior to erection; this was mainly related to the design choice of using a closed air-tight membrane, which could be deployed and be ready to use. Differently from the *Binishell* system, in which a foundation concrete edge ring was necessary to perform the erection, this system could more flexibly adapt to conditions where site preparation is unfeasible.

Figure 7: details of the diagonal bracing and shear blocks (left), ground connection (right). [Image: A. Liuti]

In this perspective, using a closed pneumatic membrane allows for ease of transport, deployment and construction system set up – in a way that no high-end technology, no skilled workers and no extensive times for preparation are required on site. Furthermore, this pneumatic formwork can be packed after the usage and reused on a different project, minimising the impact of such a device in the economy of a possible series of gridshells. The use of an integrated monitoring system allowed transposing analogic into digital data, so that such an interface became a resource in automating the design and erection framework.

As an endnote, the construction of gridshell structures still copes with further contingencies such as: the unpredictability of timber due to its hardly-standardisable behaviour (anisotropic and scattered with nodes); the huge amount of labour required by the joint connections (tightening and placing the shear blocks); the difficulty of providing everyday functions to such manufactures.

Acknowledgements

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