Building timber gridshells with air: Numerical simulations and technique challenges

A. Liuti & A. Pugnale

Faculty of Architecture, Building and Planning, University of Melbourne, Australia

B. D'Amico

School of Engineering & the Built Environment, Edinburgh Napier University, UK

ABSTRACT: Construction has always been a fascinating and challenging aspect of timber gridshells. So far, only three techniques have successfully been used for the erection of such structures: the so-called ‘lift-up’, ‘push-up’ and ‘ease-down’ (Quinn et al. 2015). Inflatable Membrane Technology is here proposed as a new solution and is tested by means of numerical simulations on a simple case study. As a matter of fact, IMT reduces the timber lath’s stress during erection and guarantees an optimal shape control. It also seems suitable to post-form more challenging gridshell geometries, but this aspect still deserves further investigations and experiments.

1 INTRODUCTION

It is almost paradoxical that shells and gridshells require important, expensive and sometimes complicated formworks to be erected. The principles of lightness, efficiency and sustainability, on which these structures are generally conceived, become difficult to maintain, and that is due to the conventional means of construction.

Air is a possible solution: it is light, efficient and sustainable; it is a system in which conception and construction are completely aligned. *Building with air* is the idea, and is also the title of Dante Bini’s book on his famous construction systems, which are all based on the use of pneumatic membranes, and include Binishell and Binistar (Bini, 2014). It is not a new idea overall, as it dates back to the 60s, but it has never been applied for post-forming timber gridshells. In this field in particular, the current construction techniques are known, for instance, for stressing the timber laths much more during erection than in the steady state. Therefore, possible structural and construction benefits of using pneumatic membranes for post-forming gridshells are investigated in this paper, by means of numerical simulations.

2 FIRST CASE STUDY MODELLING AND SIMULATION

Inflatable Membrane Technology (IMT) is first numerically tested, as erection technique, on a familiar case study: the Accoya gridshell. This structure was built at the University of Melbourne in October 2014 as part of the Master’s subject “Issues in technology”, which was coordinated by A. Pugnale, S. Pone and S. Colabella. The design arose as a variation of a structure which was previously constructed by “Gridshell.it” in Italy: the Alida Woodome (Pone et al. 2013). The choice of this case study permits a reliable comparison between the new construction tests and simulations, performed with IMT, and the experience already acquired using more conventional construction techniques. In fact, the original Accoya gridshell erection system did not guarantee precision in node positioning, nor allowed to control the lath stress during erection. The

simulations below demonstrate, instead, that better results are achievable by implementing a pneumatic membrane, as also argued by Quinn et al. (2015). These results complement the preliminary findings of this research work, which have already been published by Liuti & Pugnale (2015).

In this section, three numerical models are described. The first model aims to find structural form for the Accoya gridshell and is based on a multi-objective Genetic Algorithm. It provides a pareto-front of geometrical solutions to choose from, which mediate between an optimal funicular form and a shape that minimises lath's curvature. This model is developed in Rhinoceros and Grasshopper, with the aid of Kangaroo Physics 2, an interactive physic simulation software (Piker 2013), Karamba, a FE solver (Preisinger 2011), and Galapagos, the GA implemented in Grasshopper (Rutten 2013). It is worth noticing that the original form-finding of this gridshell was performed and optimised by "Gridshell.it", an Italian construction company, and was based on the use of proprietary codes (Pone et al. 2013). A new structural design procedure is developed for this specific research work, as it does not involve any staff from "Gridshell.it". The second model is developed in Rhino/Grasshopper with Kangaroo Physics 2, and simulates the erection through IMT. The third model reconstructs the second one in a more advanced commercial FE software, namely Abaqus/CAE (Hibbit et al. 2013).

2.1 Numerical model 1 – Form optimisation in Rhino/Grasshopper with Galapagos GA

The first Rhino/Grasshopper parametric model drives the Accoya gridshell form-finding process. Membrane and erection technique are excluded at this stage, while Grasshopper's plugin Galapagos, a Genetic Algorithm (GA), is used to run the multi-objective optimisation. The algorithm's objective function aims to minimise, at the same time, the gridshell curvatures and nodal displacements.

The gridshell numerical model is defined with equivalent cross-sections, allowing approximating the two layers along the x global axis with a single line set, as well as the two layers along the y global axis with a second line set. Grid spacing is constant at 0.5m and intersections between orthogonal laths define the line segments which are modelled by inextensible springs for Grasshopper's plugin Kangaroo Physics.

Post-forming is performed through Dynamic Relaxation (DR) directly in Kangaroo, where a nodal load of -1kN in the global z direction is applied at the nodes. Material properties, such as bending stiffness, are based on preliminary tests performed for the Accoya timber gridshell built in 2014 at the University of Melbourne (Liuti & Pugnale 2015).

Two groups of control points are the design variables of the GA: P_1 , which identifies the endpoints of the 4 long external laths; and P_2 , which includes the endpoints of the 2 central laths (Figure 1, top). Point groups P_1 and P_2 are also constrained as pinned joints of the DR.

As the problem presents a double symmetry, P_1 and P_2 are moved synchronously by acting on only two parameters, a_1 and a_2 . These parameters describe, respectively, the inward sliding of point groups P_1 and P_2 , considered from the gridshell flat configuration. Imposing $a_1 \leq a_2$ permits restraining the edges' concavity outwards, to provide an anticlastic curvature and, hence, a more stable structural configuration to the gridshell.

For this optimisation process, each GA individual is defined by a unique combination of two values, a_1 and a_2 . These values generate a funicular gridshell form, from which curvatures at the nodes and maximum nodal displacements are calculated and, then, aggregated as the GA fitness function. The first part of the function refers to the curvatures. It is defined as the normalised, uniform norm of the absolute curvature values $|k_i|$:

$$f_k(a_1, a_2) = \|k\|_\infty = \max(|k_1|, \dots, |k_n|) \rightarrow f'(k) \in [0; 1] \quad (1)$$

The second part of the function is, instead, calculated as the normalised, uniform norm of the beam utilisation values $|dE_i|$:

$$f_{butil}(a_1, a_2) = \|bUtil\|_\infty = \max(|bUtil_1|, \dots, |bUtil_n|) \rightarrow f'(bUtil) \in [0; 1] \quad (2)$$

Beam utilisation is calculated through Grasshopper’s FE plugin Karamba and is based, according to Preisinger (2015), on the procedure described in section 6 of the Eurocode (EC) 3, EN 1993-1-1:2005. Buckling and lateral torsional buckling are also taken in account. Material properties and boundary conditions are based on the built Accoya gridshell. Equivalent cross-sections are used, therefore two orthogonal sets of lines are modelled as beam elements with equivalent bending stiffness EI_x . Referring to D’Amico et al. (2014), I_x is calculated as:

$$I_x = c_s \frac{(h+h_s)^2}{2} bh + \frac{bh^3}{6} \tag{3}$$

where I_x = second moment of area around the x cross-sectional axis of the lath, h = cross-sectional depth; b = cross-sectional width; h_s = distance between overlapping laths; $c_s \in [0; 1]$ = dimensionless factor, also known as the *connection efficiency factor*, which allows to take into account the increase in stiffness due to the presence of shear blocks.

Figure 1. Top left: the doubly-symmetric gridshell geometry is determined by P_1 and P_2 , which are allowed to slide along the grey rails; their offset from the initial position is determined by a_1 and a_2 . Other images: sample gridshells explored by the GA show the external laths are always subject to critical utilisation and curvature values. Curvature trend is shown on the right half; beam utilisation is displayed on the left half. Red identifies positive moment areas, whereas blue is used for negative moment areas.

Equation (4) shows the aggregated function fitness minimised by the GA. Figure 1 compares the performance of different gridshell configurations.

$$f(a_1,a_2)=f'(k)+f'(bUtil)\in[0;2] \tag{4}$$

2.2. Numerical model 2 – Erection through IMT in Rhino/Grasshopper

After optimising the form, a second numerical model is developed to simulate the gridshell erection through a pneumatic structure. Grasshopper’s plugin Kangaroo Physics 2 is used for the purpose – from a computational point of view, it demonstrated to be much more performant in running dynamic simulations when compared to Kangaroo Physics version 1.

An inflatable membrane of 7.2m x 7.2m x 0.05m is first modelled as a NURBS surface, and then discretised as a smooth quad mesh. Each quad face is finally subdivided into four triangles tracing both diagonals, so that the mesh discretisation is further refined and still isotropic. At this stage, the mesh is transformed into a spring system to simulate the real membrane elastic behaviour. After setting the membrane physical properties, inflation is performed by controlling the inner volume of the mesh.

The parametric gridshell of the previous simulation is then added to this Kangaroo2 model. Gravity load is applied to the system to simulate self-weight and anchor points are constrained as roller supports.

To move the edges towards the desired position, a cable system is finally modelled, as represented in Figure 2 and described by Liuti & Pugnale (2015). The cables are considered as string elements, which are anchored to the gridshell control points P_1, P_2 , as well as to a system of ground-restrained pulleys. Tuning the cable lengths and the pulley’s positions generally requires several empirical tests.

Figure 2. Top left: With IMT, structural and curvature critical points are less likely to overlap during the erection. Top right: the acceptable discrepancy between the IMT-erected gridshell, in black, and the target shape, in red. Bottom: flat and final configuration of the cable and pulley system.

After running the simulation, the gridshell form obtained through inflation is evaluated against the fitness function (4), which was previously used by the GA. Numerical and graphical results are shown in Figure 2 and suggest an acceptable margin of discrepancy. However, the next section provides more accurate results to further demonstrate the preliminary findings.

2.3 Numerical model 3 – Erection simulation in Abaqus

This third model reconstructs the previous Rhino/Grasshopper simulation in Abaqus/CAE.

The gridshell laths are represented with *wire* parts, aligned to the x and y positive (global) axes, and joints are placed every 0.5m. Adopting the aforementioned equivalent second moment of area criterion, a cross-section of 50mm x 30mm is assigned to the *wire* parts; such an approximation was legit since the elements' thickness and depth were much smaller than the length. The two layers were staggered along the z-direction by a distance equal to the equivalent cross-sectional height in order to avoid self-intersections. Based upon the Euler-Bernoulli theory, a *beam*-type element was assigned to each *wire* part. The modulus of elasticity of the Accoya timber is here calculated on the basis of a three point bending flexural test, which was performed on three lath samples of 1m length (Figure 3). An isotropic, *linear-elastic* material is preferred over an orthotropic material, as the laths present a higher torsional and shear stiffness. This approximation still simulates accurately the general system behaviour, because the laths' deformation is mainly governed by bending stiffness. *Hinge*-type connector elements are used to link each pair of joints having the same x and y global coordinates. These connectors accurately reproduce the post-forming process by constraining the relative translation along the *hinge* axis while allowing the rotation. The 7.2m x 7.2m membrane is modelled as a 3D *solid part* of 50mm thickness; a *membrane section* is set to simulate the in-plane tensile strength/stiffness of the material whilst providing no out-of-plane bending and shear stiffness. Non-linear, visco-plastic features are approximated to a linear elastic material, as shown in Table 1.

Inflation is simulated with a *surface-based fluid-filled cavity*, to couple the membrane deformation with the pressure exerted by the air fluid contained in it. The fluid is modelled as a pneumatic, compressible, ideal gas. Due to the rapidity of inflation, the fluid temperature cannot be determined from the conservation of energy assumed in an adiabatic process. The energy equation comes from the first law of thermodynamics - by neglecting the kinetic and potential energy, equations (5) to (10) provide the energy for the fluid cavity. Air parameters are here retrieved from literature (Hibbit et al. 2013), and internal pressure is set as the only degree of freedom associated to the fluid cavity. Structural displacements and fluid pressure are the primary variables of the mixed-formulation problem. The pressure, temperature, and density of the gas are obtained by solving the ideal gas law, the energy balance and mass conservation. Frictionless *wire* and *slipping* elements model the manner in which cables run through the pulleys. Collision between membrane, laths and cables is implemented with a *contact*-type interaction. Starting boundary conditions impose a null pressure to the cavity reference node. A gradual increase of pressure from 0 to 1000N/m² is then applied during step 1. Due to the high non-linear nature of the model, an *explicit dynamic simulation* is required to recreate and analyse the collision between pneumatic membrane and gridshell. Design bending stresses are calculated referring to *Building Science* formulae (11) and (12). A local axis system u_1, u_2, u_3 is oriented along the grain for the purpose. Figure 3 illustrates the trend over time of the design stress σ_d of critical point j^* ; stress peak $\sigma_{d,max}$ occurs when the cables are tensioned. The system inertias generate an oscillatory trend for stresses, and σ_d eventually converges towards a constant value below $\sigma_{d,max}$. It is worth mentioning the contribution of $\sigma_{3,d}$ seems negligible.

Table 1. FEM material properties.

Material	ρ (kg/m ³)	ν	E (N/m ²)
Accoya timber	460	0.25	$8.16 \cdot 10^9$
PVC membrane	1400	0.4	$3.00 \cdot 10^6$

Figure 3 Top: Post-forming stages at times t_0 (flat rest condition), t_i (cable tensioning and $\sigma_{d,max}$), t_r (final post-formed configuration).

$$\tilde{p} = \rho R(\theta - \theta^Z) = p + p_A \quad (5)$$

$$\rho(p, \theta) = \frac{\tilde{p}}{R(\theta - \theta_A)} \quad (6)$$

$$\frac{d\bar{V}}{dp} = -\frac{m}{\rho^2} \frac{d\rho}{dp} = -\frac{mR(\theta - \theta_A)}{\tilde{p}^2} \quad (7)$$

$$V_M = \sum_i \bar{V}^i(p, \theta, m) = \sum_i \frac{m^i}{\rho(p, \theta)} = \frac{m}{\rho(p, \theta)} \quad (8)$$

$$\delta\Pi^* = \sum_i [\delta\Pi^i - p\delta V^i - \delta p(V^i - \bar{V}^i)] \quad (9)$$

$$\frac{d(mE)}{dt} = \dot{m}_{in}H_{in} - \dot{m}_{out}H_{out} - \dot{W} - \dot{Q} \quad (10)$$

$$\frac{\sigma_{2,d}}{f_{2,d}} + \frac{\sigma_{3,d}}{f_{3,d}} \leq 1 \quad (11)$$

$$\sigma_d = \frac{M_{2,d}}{S_2} + \frac{M_{3,d}}{S_3} \quad (12)$$

where $\tilde{p}$ = absolute pressure; R = gas constant; θ^Z = absolute zero temperature; $\rho(p, \theta)$ = fluid density at p pressure and θ temperature; θ_A = ambient temperature; θ_I = initial temperature; $d\bar{V}/dp$ = volume-pressure compliance; V_M = membrane volume; $\delta\Pi^*$ = augmented virtual work; $\delta\Pi$ = virtual work for the system without the cavity; $d(mE)/dt$ = energy equation for the fluid cavity; $\dot{W} = p\dot{V}$ = work done by the fluid cavity expansion; $\dot{Q}$ = heat energy flow rate due to the heat transfer through the surface of the fluid cavity; H = specific enthalpy; $\sigma_{i,d}$ = design bending stress about the i^{th} (cross-sectional) axis; $f_{i,d}$ = design bending strength, $M_{i,d}$ = design bending moment about the i^{th} axis; $S_i = bh^2/6$ = lath section modulus about the i^{th} axis.

3 FURTHER CASE STUDIES DESIGN AND MODELLING

As already shown by Dante Bini's work, an intrinsic problem of using IMT relates to the limited family of geometries to which it can be applied to. However, this should not represent an issue for timber gridshells, where the final form is always constrained by the flat grid design and the post-forming phase. Figure 4 illustrates two preliminary tests of erecting more articulated gridshell geometries through IMT. The first experiment replicates the Downland gridshell, and grid and membranes are both modular. In the second case, a square grid is used and the final shape finds supports in the four corners. Further case studies are still under development.

Figure 4 IMT post forming simulations applied to the reverse engineering of two existing projects: at the top, the Weald and Downland Gridshell by Buro Happold and Edward Cullinan Architects is post-formed by means of 3 modular cushions; at the bottom, the Toledo gridshell by Gridshell.it is post-formed by means of a single square cushion.

4 CONCLUSIONS

Inflatable Membrane Technology is proposed in this paper as a promising erection technique for post-formed timber gridshells.

A system that combines a pneumatic membrane with cables and pulleys is described and tested on a simple case study: the Accoya gridshell, which was built in Melbourne in September/October 2014. The flat grid of laths is post-formed into the desired shape through two different numerical simulations: first, using Rhino/Grasshopper and Kangaroo Physics; second, with the commercial FE software Abaqus/CAE. The final gridshell geometries and structural stresses, which are calculated throughout the erection process, are then compared with the results of another analysis, which simulates post-forming through the more conventional “lift-up” method. As a matter of fact, IMT reduces the timber lath’s stress during erection and guarantees an optimal shape control.

IMT is finally tested, numerically, on two other gridshell case studies: Toledo2 in Naples and Downland Museum. These simulations show the system seems capable to adapt to post-form different gridshell geometries. However, further experiments are required to properly investigate this issue.

REFERENCES

- Adriaenssens, S., Block, P., Veerendaal, D. & Williams, C. 2014. Shells for Architecture: Form Finding and Optimization. Routledge.
- D’Amico, B., Kermani, A. & Zhang, H. 2014. Form finding and structural analysis of actively bent timber grid shells. *Engineering Structures* 81: 195-207.
- D’Amico, B., Kermani, A., Zhang, H., Pugnale, A., Colabella, S., & Pone, S. 2015. Timber gridshells: Numerical simulation, design and construction of a full scale structure. *Structures* 3:227-235. Elsevier.
- Hernández, E., Baverel, O., & Gengnagel, C. 2013. On the design and construction of elastic gridshells with irregular meshes. *International Journal of Space Structures* 28(3-4): 161-174
- Hibbit, K., Karlson, H. & Sorensen, P. 2013. ABAQUS: User’s Manual: Version 6.13.
- Liuti, A. & Pugnale, A. 2015. Erection of post-formed gridshells by means of inflatable membrane technology. *Proceedings of the 49th International Conference of the Architectural Science Association, Melbourne; Living and Learning: Research for a Better Built Environment*.
- Otto, F., Henniscke, J., & Matsushita, K. 1974. Gitterschalen Grid shells. Institut für Leichte Flächentragwerke. *IL* 10, 340.
- Piker, D. 2013. Kangaroo: Form finding with computational physics. *Architectural Design* 83(2): 136-137.
- Pone, S., D’Amico, B., Colabella, S., Parenti, B., Lancia, D. & Fiore, A. 2013. Construction and form-finding of a post-formed timber grid-shell. *Structures and architecture. Concepts, Applications and challenges*, 245-252.
- Quinn, G., Gengnagel, C., Williams, C. 2015. Comparison of Erection Methods for Long-Span Strained Grid Shells. *Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2015, Amsterdam; Future Visions*.
- Rutten, D. 2013. Galapagos: On the logic and limitations of generic solvers. *Architectural Design* 83(2): 132-135.
- Preisinger, C. (2011). Karamba: Parametric Structural Modeling *Computer software*.
- Preisinger, C. (2015). Karamba User Manual 1.1.0.

Minerva Access is the Institutional Repository of The University of Melbourne

Author/s:

Liuti, A;PUGNALE, A;D'Amico, B

Title:

Building timber gridshells with air: Numerical simulations and technique challenges

Date:

2016-07-29

Citation:

Liuti, A., PUGNALE, A. & D'Amico, B. (2016). Building timber gridshells with air: Numerical simulations and technique challenges. Cruz, PJS (Ed.) STRUCTURES AND ARCHITECTURE: BEYOND THEIR LIMITS, pp.251-258. CRC Press. <https://doi.org/10.1201/b20891-32>.

Persistent Link:

<http://hdl.handle.net/11343/113931>

License:

[Publisher's own licence](#)