Comparison of Erection Methods for Long-Span Strained Grid Shells

Conference Paper · August 2015

3 authors:

Gregory Charles Quinn
Swinburne University of Technology

Christoph Gengnagel
Universität der Künste Berlin

Chris J K Williams
Chalmers University of Technology

Proceedings of the International Association for Shell and Spatial Structures (IASS)
Symposium 2015, Amsterdam
Future Visions
17 - 20 August 2015, Amsterdam, The Netherlands

Comparison of Erection Methods for Long-Span Strained Grid Shells

Gregory C QUINN*, Christoph GENGNAGEL, Chris JK WILLIAMS [a],

*Department for Structural Design and Technology [KET], University of Arts Berlin
Hardenbergstrasse 33, 10623 Berlin, Germany
quinn@udk-berlin.de

[a] Department of Architecture and Civil Engineering, University of Bath, UK

Abstract

In this paper, a detailed comparison is carried out between established ('lift up', 'push up' and 'ease down') as well as novel ('inflate') erection methods for strained grid shells by means of FE simulations and a 3D-scanned scaled physical model in order to evaluate key performance criteria such as bending stresses during erection and the distance between shell nodes and their spatial target geometry. These investigations were carried out on a case study of a dome with a 30m span, 10m pitch and constant double curvature. A detailed description is provided of the developed simulation approach, which makes particular use of contact springs for a structural system subject to large deformations, in the SOFiSTiK FE software environment. It is shown for the 'lift up' and 'push up' methods, that maximum bending stresses are most likely to occur during the erection process and not during end-state static load cases. This risk of beam-overstressing for existing erection methods along with challenges caused by modern safety restrictions, scaffolding costs and build duration can be drastically reduced or even eliminated by making use of inflated pneumatic cushions for the erection of strained grid shells. Furthermore it is argued that the use of pneumatic falsework has the potential to once again facilitate large-span ($L \geq 30m$) strained grid shell structures such as have not been realised since the likes of the extraordinary "Multihalle Mannheim" (Happold and Liddell [1]). It is claimed that the overriding constructional benefits of strained grid shells, such as low material usage and fabrication simplicity, are undermined by the methods typically used for their erection.

Keywords: grid shell, erection, pneumatic, falsework, formwork, FE, non-linear, simulation, physical modelling

1. Introduction

In this paper reference is made to 'strained' grid shells, while in literature the term 'elastic' grid shells is also used often. While both are valid and interchangeable terms, the high probability of creep relaxation after erection means that the amount of elastic recovery can be very limited and subsequently 'strained' is deemed a more accurate engineering description for the behaviour. There are three tried and tested ways to erect a strained grid shell: 'lift up', 'push up' & 'ease down'. The practicality of each method and the effect on structural behaviour varies. While the benefits and caveats of each erection method have been compared qualitatively (Quinn and Gengnagel [2], Harris et al. [3]), so far no quantitative comparison of the erection methods exists. This paper provides a detailed write-up of a series of finite element simulations developed in order to compare said established erection methods. Although the idea of pneumatic falsework for the erection of strained grid shells ('inflate') has been considered before (Otto [4, p. 245]), the work presented in this paper presents the first ever practical experiment of the proposed method.

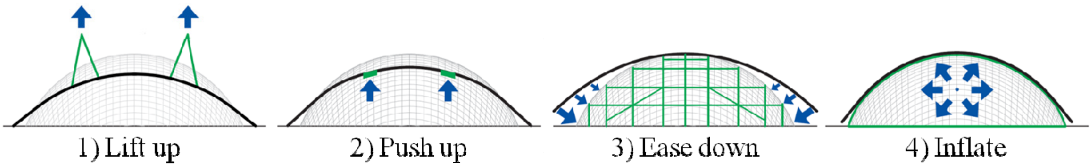

Figure 1: Schematic representation of three established (1-3) and one novel (4) methods of erecting strained grid shells.

The complex challenge of finding meshes suitable for strained grid shells of equal edge lengths with controlled curvatures has been well investigated and documented. Viable approaches include the compass method (Otto [4]), the variational method (Hernandez, Baverel, and Gengnagel [5]), dynamic relaxation (Adriaenssens et al. [6]) and variations thereof (D'Amico, Kermani, and Zhang [7]). Finding the most suitable approach for the complex interaction between a strained grid shell and an underlying pneumatic falsework raises many similar questions. A primary challenge lies in the development of a simulation approach which is able to establish force equilibrium between a pneumatically loaded cushion interacting with an actively bent grid of laths with embedded strain energy. This novel challenge combines principles of form-finding and large deformations. Simulation of contact in particle spring systems can be achieved by defining proximity limitations between particles or by manipulating their acceleration to zero when close to another body. The approach presented in this paper using FE and contact springs has proven successful however investigations by the author are ongoing.

2. Dome case study

A case study was performed on dome with a 30m span and a 10m pitch. The dome has constant synclastic double curvature (i.e. spherical) and a grid member spacing of 1m. The dome is made of a single layer of timber laths (assumed Young's Modulus, E = 7970 N/mm2) with a square cross section of 50x50mm (same as the Hemlock Pine laths in the Multihalle Mannheim). This dome represents a stiff shell shape which was consciously chosen for its simplicity and the subsequent freedom it grants to focus on other test parameters. The simple mesh grid topology was generated manually using the compass method (Otto [4]). The assumed node weight of 400kg (3.92N) is based on a slightly modified and lighter version of the steel bolt and plate node from the Downland grid shell (Harris et al. [3]). For the pneumatic falsework also being investigated, only large spans are of interest financially and practically. A span of 30m is judged to be the minimum span suitable for when considering erection via pneumatic falsework.

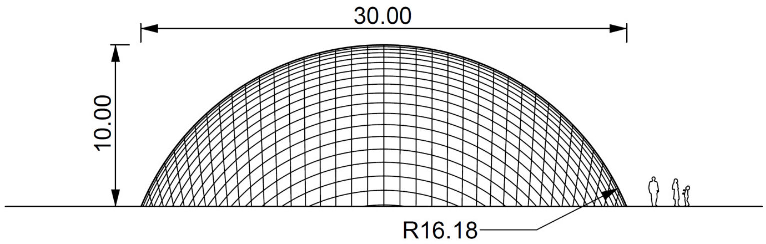

Figure 2: Span and pitch of case study test dome made from a single layer of 50x50mm timber laths.

While the number of lifting points for cables in the 'lift up' method or spreader beams in the 'push up' method is arbitrary and dependent on subjective design choices, a sensible total of 12 lifting points were defined in order to ensure a fair comparison between the erection methods.

2.1 FE modelling approach

In order to achieve an accurate simulation of the erection of grid shells, a defining behavioural characteristic is the occurrence of large deformations and rotations as well as the generation of residual stresses (or strain energy) in the laths during forming. In order to simulate these 2nd and 3rd order effects accurately, the software package SOFiSiTiK was used. In order to increase speed and stability of the calculation in the case study, only a quarter of the grid shell was simulated by means of appropriate support conditions (Figure 3).

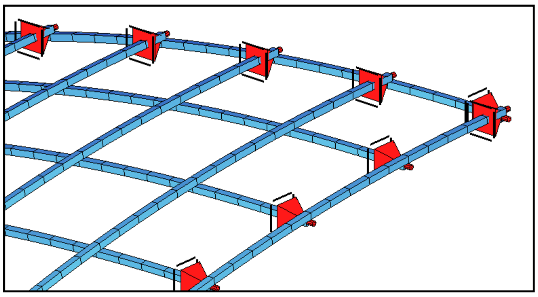

Figure 3: Vertically unrestrained but rigidly connected boundary conditions for the quarter model of the case study geometry.

2.1.1. Erection Stages

For both the computational and physical models, the erection was divided into three separate stages: 1) Erection, 2) Beam ends to supports, and 3) Relax. In the second phase the beam ends are pulled to their respective support coordinates in the simulation by means of single-element cables with very low transient stiffness properties such that under increasing load increments of pre-stress they shorten in length; i.e. the elastic cable approach (Lienhard, La Magna, and Knippers [8]). A convergence to null for all cables was not computationally feasible. The average geometric deviation between the beam-ends and the target support points after cable contraction was 77mm (0.26% of 30m span) for the 'lift up' method and 42mm (0.14% of span) for the 'push up' method. Such small deviations of the support positions are considered to have negligible effect on the global stiffness of the structure. For 'ease down' the cables are not used and so there was zero geometric error at the support points. So, given the near-identical boundary conditions for the different erection methods, it was shown that the final shape of the grid shell after erection still varies depending on the erection method used. This is due to the fact that during erection, the grid shell nodes are still free to rotate and so the system is a very soft mechanism for which multiple states of equilibrium can be found. The 'relax' phase of the erection procedure allows the grid shell to find a new equilibrium after the beam ends have been fixed and the erection aids have been removed. In order to evaluate larger differences between the simulations, the shell was not stabilized (by cables or a third layer of timber laths) in the final 'relax' stage as would normally be the case for grid shells.

The key processes of the simulation approach are illustrated as a flow chart in Figure 4 with reference to SOFiSiTiK's specific programming modules such as "ase" and "sofimsha". This process varies slightly for the different erection methods.

The erection process was simulated in full only for the established erection methods ('lift up', 'push up' and 'ease down'). For the 'inflate' method, the complexity of simulating an initially deflated and arbitrarily crumpled cushion that inflates while making indiscriminate contact with a grid of laths subject to large deformations proved too high within the constraints of SOFiSTiK. However a successful approach was developed to simulate the final end-state interaction between a pre-inflated cushion and the self weight of an actively bent grid with embodied strain energy. Furthermore the erection of the grid shell was simulated separately in a scaled physical model.

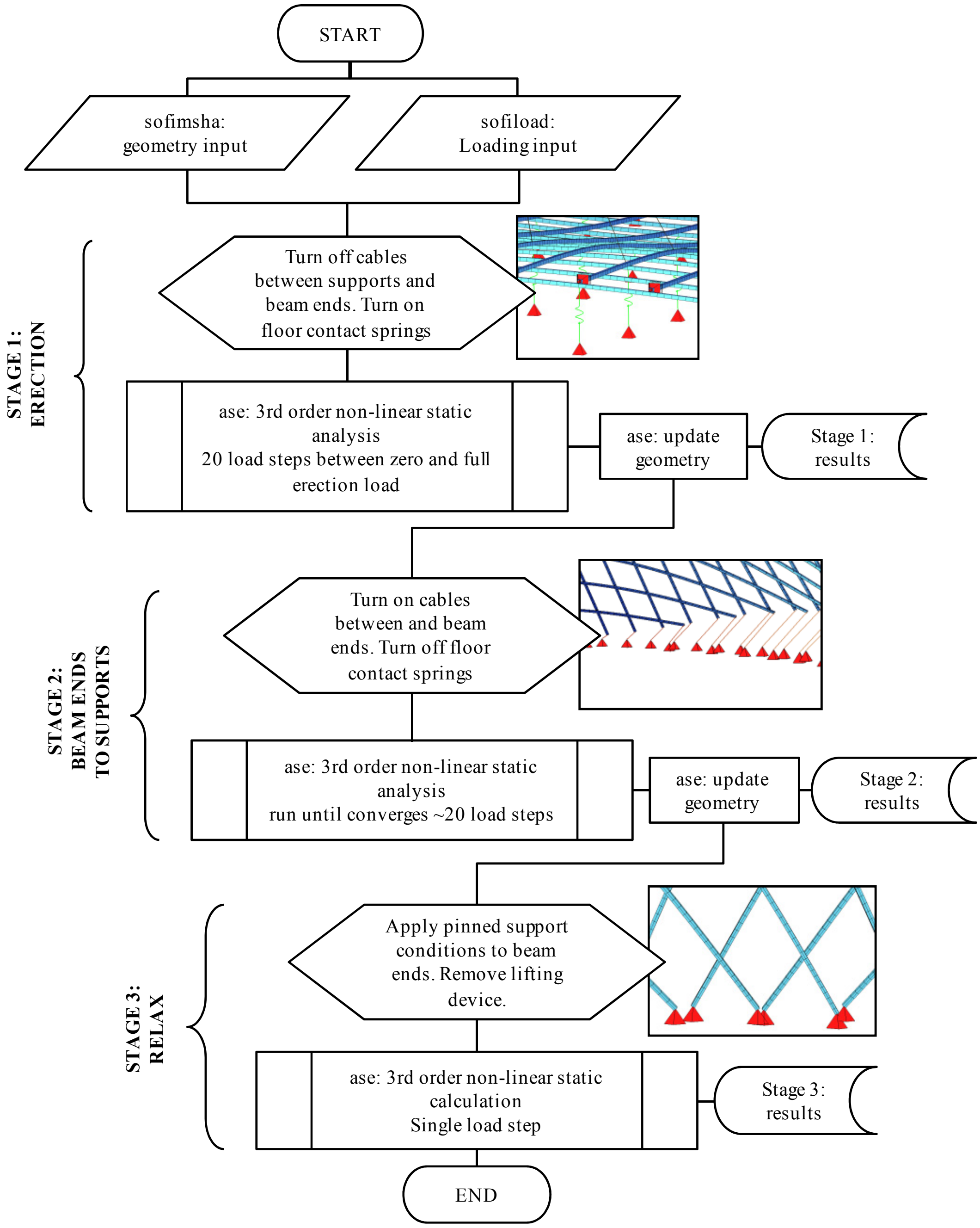

Figure 4: Flow chart representation of the simulation approach using SOFiSTiK for “lift up” method.

2.1.2. Coupling Elements and Contact Springs

Unlike most structural elements in SOFiSTiK, the geometric orientation of springs and coupling elements does not update after each iteration step. Instead their originally-defined orientation is maintained. Subsequently coupling elements cannot be used to simulate the pinned connection between the beam layers. Instead custom cross section properties (with very high bending stiffness and very low torsional stiffness) are defined for connecting beam elements

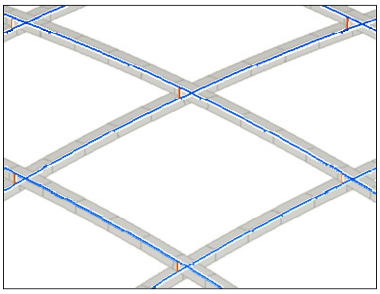

Figure 5: Custom section properties for ‘pin’ beam connector elements between timber lath layers.

During the simulation of the erection it is important that the laths make contact with the ground in order to accurately recreate the draping effect. Without this effect, incorrect curvatures would be generated for the beams. A custom working law was defined for the contact springs which are very stiff under compression but inactive under tension (Figure 6, left). The orientation of the floor contact springs is defined vertically (Figure 6, centre) and, for the contact between grid and pneumatic falsework, a local orientation is defined (Figure 6, right). Since the orientation of spring elements is not updated after each iteration in SOFiSTiK, the contact between pneumatic falsework and grid shell can be simulated with accuracy only if small deflections occur.

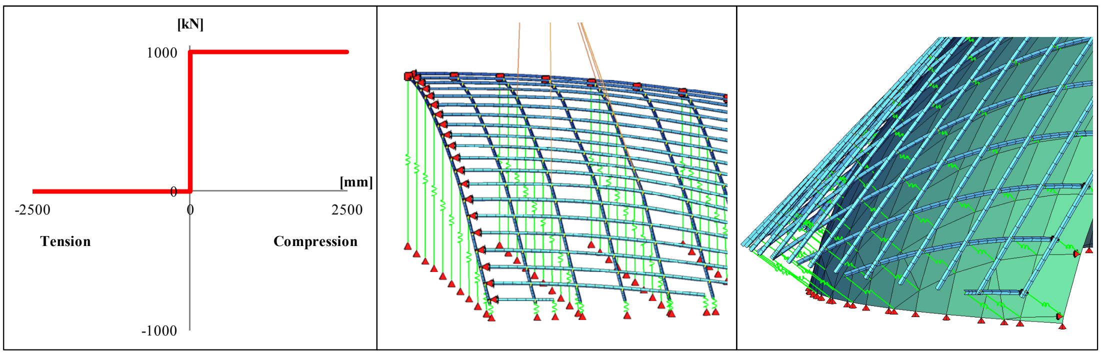

Figure 6: Contact springs described with a custom compression-only working law (left), with a positive orientation

2.1.3. Volumetric pressure

Another justification for the suitability of SOFiSTiK for simulating the interaction between actively bent grid shell systems and an underlying support from inflated pneumatic falsework is its accurate definition of volumetric loadings which follow Boyle's law of proportionality between pressure and volume. The 'VOLU' definition (Bellmann [9]) accurately modifies the pressure matrix applied to the mesh elements of the cushion depending on incident loads. In this case the initial volume definition of 985m^3 reduces minimally to 984m^3 and the surface pressure increases by 0.07kN/m^2 under self weight of the grid shell.

3. Comparison of Erection Methods

As can be observed in Figure 7, the simulations show categorically that, of the established erection methods, the 'lift up' method is most likely to result in overstressing of the laths during erection. The maximum stress of the laths for the 'lift up' method is significantly higher than in the shell's final state. So much so, that the ultimate strength of the material is exceeded which can lead to breakages or permanent damages of the laths; a phenomenon that was documented to have occurred in the Essen grid shell (Otto [4]), in the Multihalle Mannheim (Happold and Liddell [1]) and even to a small extent in the Downland & Weald grid shell (Harris et al. [3]). The results also demonstrate clearly that the 'ease down' method is the most controlled, the most precise but also the least strenuous on the laths. The bending stresses do not peak during erection, but instead rise in a controlled manner. Multiple contact points from the scaffold are much more effective at spreading forming loads than singular point loads from lifting cables and pushing platforms.

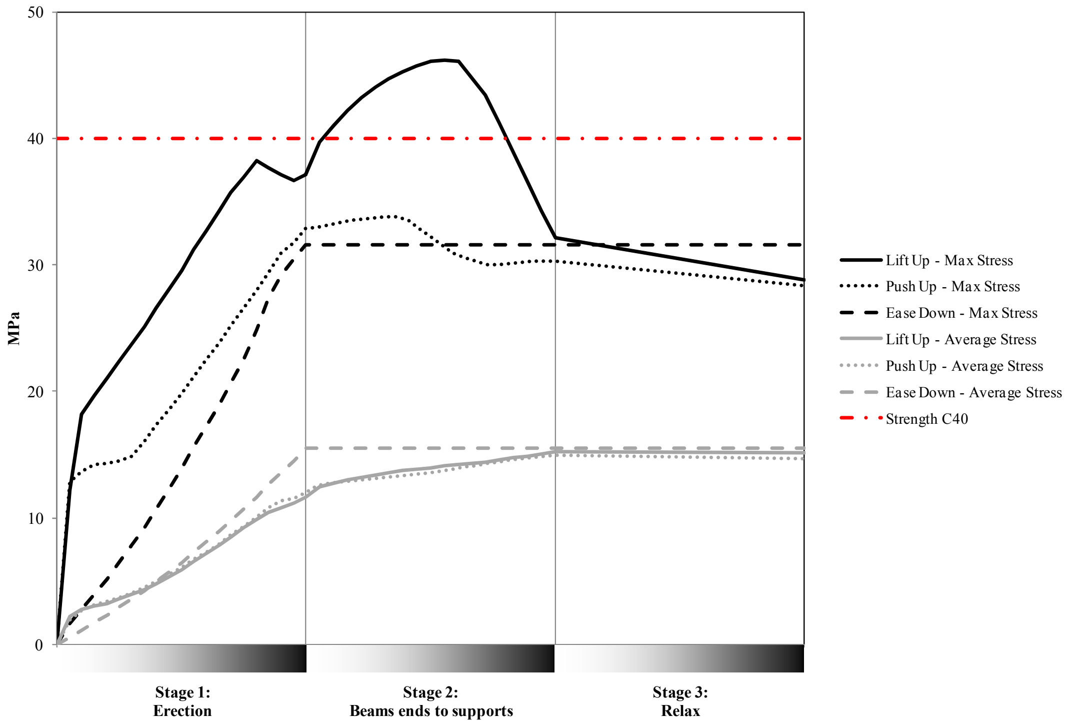

Figure 7: Maximum (black) and average (grey) surface stress in the timber laths for three different erection emthods. Ultimate strength cut-off line for C40 timber shown in red.

4. Pneumatic Falsework

4.1 Physical model

In parallel with FE simulations, a physical model was used to perform a first ever erection of a strained grid shell by means of pneumatic falsework. The scaled model makes use of acrylic beams with an 8mm square cross section. The scale of the physical model is one tenth (1:10) of the full scale structure, subsequently it has a span of 3m. Dimensional Analysis which makes use of the Buckingham Pi theorem is a method for establishing dimensionless variable groups in order to reproduce physical behaviour in scaled models. This method is well documented in literature (Simitses and Rezaeepazhand [1], Sonin [10, p. 6], Happold and Lidell [11]) and so will not be elaborated upon here. The dimensionless group used for the scaling of this model was:

$$\frac{\omega S^3}{\left(\frac{EI}{a}\right)}$$

Where ω is the load per unit area, S the span, EI the bending stiffness of the members, and a the member spacing (Adriaenssens et al. [6, p. 93]). The above dimensionless group prioritises bending stiffness which, during the erection, is the dominant behavioural property. Other dimensionless groups can be found for analysing other behavioural properties in the shell such as lateral stiffness from bracing members however this is not of relevance during the erection.

A detailed description of this physical model and its results are documented by the author in a paper for the 2019 Design Modelling Symposium in Copenhagen. This section of the paper makes reference to that work.

The erection by means of pneumatic falsework for this shell geometry worked extremely well. Both the flat lattice and the uninflated cushion were positioned in the centre of the circular test area before inflation. During inflation the shell remained almost perfectly central with negligible sideways deviation. This is due to the distribution of self weight loading and the inherently stable form of the rotationally symmetric cushion. For asymmetric shapes, the degree of horizontal deviation (and potential need for restraint) during erection it is yet to be investigated. Figure 8 shows a snapshot of the erection process in elevation photos (below) as well as 3D coordinates from the photogrammetric scan (above).

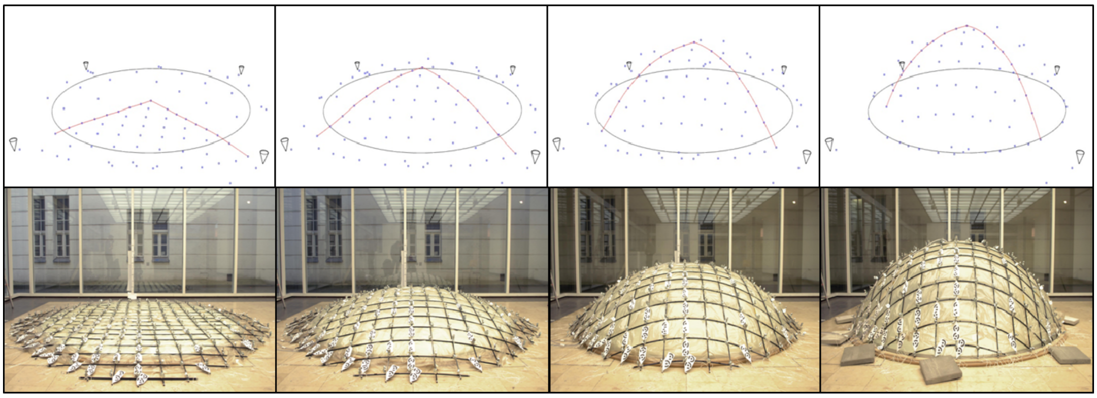

Figure 8: Four snapshots from the inflation process with elevations photos (below) and photogrammetric 3D point cloud data (above).

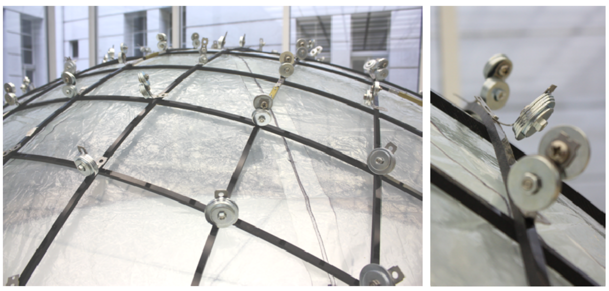

Figure 9: Increased self weight of the grid shell by means of an additional 104g at each node to account for scaled physical properties according to dimensional analysis

4.1.1. Uplift

During the final stages of the inflation as the air pressure increased, the ring beam began to lift up from the ground due increasing surface tension in the membrane resulting in an uplift force along the perimeter edge. Figure 10 (right) shows the perimeter edge lifting up during erection and then being weighed down with paving slabs to resist uplift (left). In early FE simulations using SOFiSTiK, the vertical uplift force along the edge was shown to be around 0.14kN/m. This uplift will have an effect on the design and detailing of the perimeter foundations which have to perform under upward and inward uplift during the erection and then downward and outward pressure from the laths in the end-state.

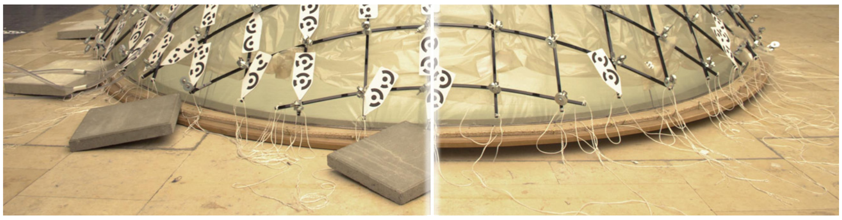

Figure 10: Uplift at membrane edge-restraint due to internal pressure. Left: ring beam loaded and restrained against uplift. Right: Unrestrained lifting of edge beam.

4.1.2. Air pressure

The physical model revealed that the internal air pressure ranges from 0 to about 2mbar (0.2kN/m^2) when considering only self weight of the system. This is slightly lower than typical pressures necessary for air-supported membrane structures (0.25-1.0kN/m^2) and significantly lower than pressures required for air-supported falsework for concrete shells (3.5-10kN/m^2) (van Hennik and Houtman [12]). These initial findings show that, as long as the shell volume remains large, internal air-pressures for the pneumatic erection of strained grid shells are low and subsequently easily produced and maintained.

Despite the low air pressures in this system, leakages still occurred. In this experiment, as soon as the pump was switched off, gradual loss of air pressure occurred meaning that procedures which took a prolonged period of time (such as fixing the beam ends to their support points) lead to separation between pneumatic falsework and the grid shell. While not critical under self-weight alone, this effect is undesirable because the grid shell has yet to be stabilised and in absence of the air pressure from the falsework, is subsequently prone to large deformations. For concrete shells supported by pneumatic falsework, maintaining a constant internal air pressure while hardening has been shown to be of critical importance due to shells' inherent sensitivity to geometrical deviation from force thrust paths (Levy, Salvadori, and Woest [13, p. 39]). Over- or under-inflating the cushion could result in global stability failure.

4.2 FE simulation of pneumatic falsework in combination with a strained grid

4.2.1. Initial results

The simulation process shown in Figure 4 was modified in order to accommodate the integration of pneumatic falsework modelled with quad meshes (membrane elements). First the beams are bent into their precise target position by means of nodal displacement, and then the offset membrane elements as well as the locally-oriented contact springs are activated. Finally the system is calculated under self weight such that the embedded strain energy in the laths from erection cause the laths to lift up along the edge creating a skirting effect (Figure 11, left). The separation between the laths and the pneumatic falsework occurs at around 30% of the structure's height for the case study in question (Figure 11, right).

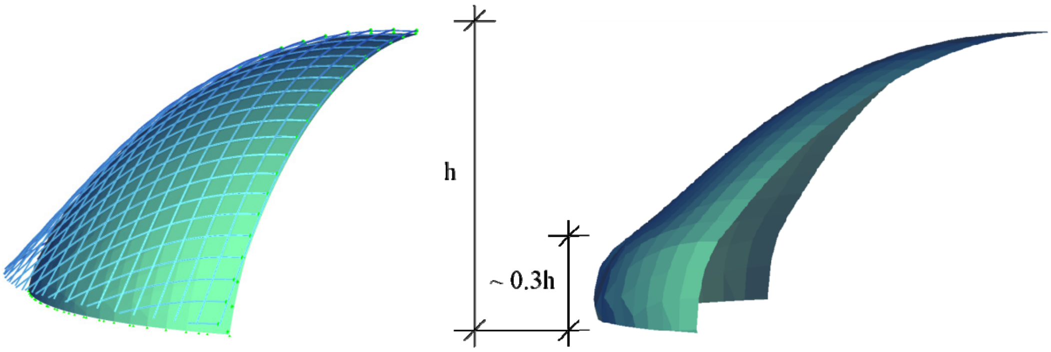

Figure 11: Left: Combination between actively bent grid shell with embedded strain energy on top of supporting pneumatic falsework. Right: Separation zone between falsework and laths (i.e. the bulge) shown to occur at around 30% of the total height of the structure (3x magnification).

5. Conclusion

Within the context of a geometrically simple strained grid shell, it has been shown that the 'lift up' and 'push up' erection methods are likely to cause overstressing of the laths during erection and that 'ease down' is the most geometrically precise and the least structurally demanding method. However, an alternative method of using pneumatic falsework offers comparable precision but at a fraction of the speed and cost necessary in the 'ease down' method resulting from high scaffolding demands. An accurate and viable simulation approach in SOFiSTiK is detailed and discussed for the established erection methods as well as the contact interaction between a strained grid and underlying pneumatic falsework.

Generally it is shown that despite equal boundary conditions in the end-state, the erection path that the strained grid shell takes to meet its target geometry has an impact on the final position and subsequently the global stiffness of the shell. This simply means that because the grid shell is a soft mechanism during erection, multiple states of equilibrium can be found depending on the erection method.

By means of a scaled physical model it was shown that the method of pneumatically erecting a strained grid shell is feasible and practical for simple shell shapes and curvatures. Important behavioural phenomena such as membrane uplift and separation zones are remarked upon. Further investigations are underway in order to better understand which varieties and extremities of shell sizes and shapes are compatible with the pneumatic erection method.

References

[1] E. Happold and W. I. Liddell, "Timber Lattice Roof for the Mannheim Bundesgartenschau," *Struct. Eng.*, vol. 53, no. 3, pp. 99–135, Apr. 1975.
[2] G. Quinn and C. Gengnagel, "A review of elastic grid shells, their erection methods and the potential use of pneumatic formwork," *Mob. Rapidly Assem. Struct. IV*, vol. 136, p. 129, 2014.
[3] R. Harris, J. Romer, O. Kelly, and S. Johnson, "Design and construction of the Downland Gridshell," *Build. Res. Inf.*, vol. 31, no. 6, pp. 427–454, 2003.
[4] B. B., Jugen Hennicke Frei Otto, *IL 10 - Grid Shells (10)*. Institute for Lightweight Structures, University Stuttgart, 1974.
[5] E. L. Hernández, O. Baverel, and C. Gengnagel, "On the Design and Construction of Elastic Gridshells with Irregular Meshes," *Int. J. Space Struct.*, vol. 28, no. 3, pp. 161–174, 2013.
[6] S. Adriaenssens, P. Block, D. Veenendaal, and C. Williams, Eds., *Shell Structures for Architecture: Form Finding and Optimization*. London ; New York: Routledge, 2014.
[7] B. D'Amico, A. Kermani, and H. Zhang, "Form finding and structural analysis of actively bent timber grid shells," *Eng. Struct.*, vol. 81, pp. 195–207, Dec. 2014.
[8] J. Lienhard, R. La Magna, and J. Knippers, "Form-finding bending-active structures with temporary ultra-elastic contraction elements," *Mob. Rapidly Assem. Struct. IV*, vol. 136, p. 107, 2014.
[9] J. Bellmann, "Air Volume Elements For Distribution of Pressure in Air Cushion Membranes," in *Structural Membranes 2011*, International Center for Numerical Methods in Engineering (CIMNE), 2011, pp. 77–85.
[10] G. Simitses and J. Rezaeepazhand, "Structural Similtude and Scaling Laws for Laminated Beam-Plates," Aerospace Engineering and Engineeering Mechanics, University of Cincinnati, CINCINNATI, OHIO 45221, Technical Report NASA Grant NAG-1-1280, 1999.
[11] A. A. Sonin, "Dimensional analysis," Technical report, Massachusetts Institute of Technology, 2001.
[12] P. C. van Hennik and R. Houtman, "Pneumatic formwork for irregular curved thin shells," in *Textile Composites and Inflatable Structures II*, Springer, 2008, pp. 99–116.
[13] M. Levy, M. Salvadori, and K. Woest, *Why buildings fall down: how structures fail*. New York: W.W. Norton, 2002.