SHELTAIR PAVILION

AEDES METROPOLITAN LABORATORY IN BERLIN, GERMANY

This pavilion investigates the use of air-filled cushions to rapidly, safely and cheaply erect beautiful and structurally efficient elastic gridshells for events and humanitarian causes. Scientifically developed by Gregory Quinn as part of his doctoral thesis at the Berlin University of the Arts at the department of Structural Design and Technology KET (Prof. Christoph Gengnagel) and exhibited in the summer of 2017 at ANCB The Aedes Metropolitan Laboratory in Berlin.

Figures 1 - 2. Inside and outside view of the SheltAir pavilion

Introduction

The importance of large shelters for medical treatment, social convalescence and religious gatherings in refugee or disaster stricken areas remains underserviced due to the necessary focus on smaller family dwellings but also due to the cost, time, complexity and energy demands associated with their construction. Based on rigorous research, this holistic solution facilitates the fast, safe and low-energy erection of elastic gridshells by means of pneumatic falsework i.e. air-filled cushions. Benefits are found in the ability to generate large, stiff and beautiful doubly curved shells from slender and straight beams with very little material or embedded energy. This 13m pavilion in the garden of the Aedes Metropolitan Laboratory Berlin was built to test and validate the researched method but also to demonstrate its architectural potential. The biomimicry of the shell curvature and repeating patterns of the grid complement the sustainability aspects of the solution and offer a refreshing contrast to typical planar shelter systems (Figs. 1 - 2).

A novel method

Elastic gridshells such as Frei Otto's Multihalle in Mannheim are highly efficient structures, able to cover large spans with very little material or embedded energy. The simplicity of these structures lies in their ability to generate beautiful doubly-curved shell surfaces from slender and initially straight beams. While elastic gridshells are efficient in their built-state, the existing methods with which to erect them are usually associated with significant complexity, cost and time. This novel method, which makes use of pneumatic falsework (i.e air-filled cushions), has the potential to greatly increase the speed of construction for large-span shells (i.e. up to 100m in a matter of days), which would have groundbreaking implications on construction costs and efficiency with promising potential for application in rapidly deployable event covers and shelters (Fig. 3).

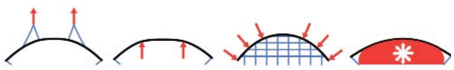

Figure 3. Schematic representation of erection methods for elastic gridshells:, left to right "lift up", "push up", "ease down" and "inflate".

The erection methods for elastic gridshells can be grouped into the following four categories: "lift up", "push up", "ease down" and now also "inflate". Various technological methods for pneumatic falsework and formwork are well established in the context of continuum shells made from reinforced concrete (e.g. Wallace Neff's bubble houses and Dante Bini's work). Using pneumatic falsework to erect concrete shells presents technical challenges relating to large dead-loads, maintaining pressure during curing and minimisation of displacements.
The pneumatic erection of elastic gridshells presents its own set of unique challenges. A key advantage of elastic gridshells is their ability to be assembled as a flat grid on the ground however this means that a vertical repositioning of the kinematic grid into its final shape is necessary. In this intermediate state of erection, the grid is extremely soft and flexible due to the slenderness of the rods and the single degree of rotational freedom at every node making the system highly susceptible to overstressing from bending and tricky to restrain effectively. Furthermore, the erection process of elastic gridshells is hindered by modern health and safety legislations which forbid working underneath a partially-restrained structure. Also, scaffolding platforms and safety measures are usually necessary when adding grid stabilisation elements (such as struts or cables). As such, this puts into question the claim of rapid deployability often associated with elastic gridshells. The use of pneumatic falsework offers an interesting answer to this question, particularly for large elastic gridshells with spans over 30m. Further benefits include: the distributed support of the soft gridshell during forming, the support and restraint of the shell during the addition of shell stabilisation elements and the provision of a safe walk-on working surface during construction and finally the reuse of the cushion membrane as an architectural envelope. The reuse of the erection membrane can also be considered for the stabilisation of the grid shell.

The SheltAir pavilion

For the SheltAir pavilion, the target shape or base geometry for the shell was a digitally form-found funicular surface. This surface is then re-meshed using a Chebyschev discretisation which defines the geometry of the gridshell. Funicular shell surfaces are inherently well suited to resisting evenly distributed compression forces and as such were deemed a highly suitable target geometry for the gridshell. A surface with plenty of double curvature and curvature changes (from convex to concave) was selected due to the aesthetic appeal from such curvature changes but also due to its stiffening effect on the shell.
The method proposed here sees the cushion being removed before the gridshell is stabilised (in this case by means of bracing cables); as such the resultant shape of the gridshell in the end-state is in fact the relaxed elastica despite the target shape being defined as a funicular. For this to work the gridshell must be stiff enough to support its own self-weight without stabilisation once the beam-ends have been secured in place and the cushion is no longer supporting the gridshell.
The cushion design proposed here is a passive (no shape compensating) cushion which is

identical to the target shape of the gridshell. It comprises an upper doubly-curved part and a flat ground sheet which, when clamped together at the perimeter edge, form a closed volume which is fully restrained. This perimeter restraint ensures that the cushion stays in the correct position during and after erection. Once the gridshell has been erected, demounting the perimeter clamps results in immediate deflation of the cushion. Further shape manipulation could be achieved with internal tethering cables.

The presence of only one small opening was conscious and intended to minimise the shell-weakening effects of large and multiple openings.

Figures 4 - 5. Construction details - connections

Figures 6 - 7. Interior impressions

Erection sequence

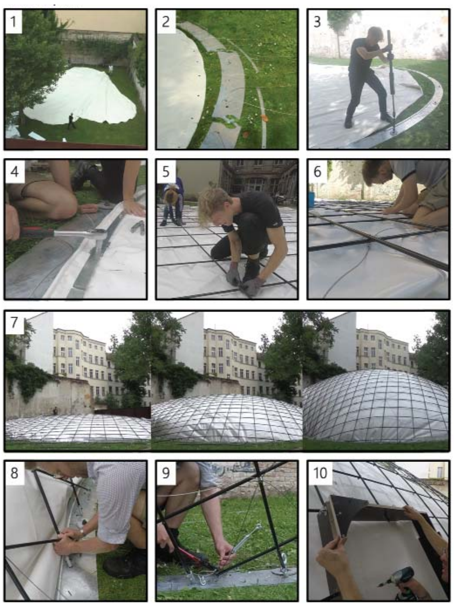

Figure 8. Erection sequence

1. *Flat ground sheet is positioned in desired shelter location. No measuring or marking of site required.*
2. *Steel anchor plates are positioned and interlocked with one another as well as the membrane ground sheet. Ground sheet acts as template. No measuring or marking required.*
3. *Anchors are driven into the ground, securing the steel plates.*
4. *The upper cushion membrane is added and the clamping plate is secured.*
5. *The grid is assembled on top of the deflated cushion.*
6. *Bracing cables are fed through the appropriate nodes with a generous amount of slack.*
7. *Cushion is inflated.*
8. *Beam ends are positioned into their corresponding support sockets in the base plate.*
9. *Bracing cables are pretensioned.*
10. *Doors and details are added.*

Low-tech implementation: high-tech simulation

The implementation & construction for the proposed solution is purposefully and necessarily low-tech. However the physical interaction between the elastica curves of the beams with residual stresses and the pneumatic form of the cushion in relation to the architectural target shape is particularly complex. Bespoke simulation methods have been developed based on a novel dynamic relaxation solver which is insensitive to the system's transience between dynamic (inflating) and static (inflated) states. Simulations and physical prototypes have produced a breadth of results which determine, for example, which spans, curvatures and pressures are feasible and suitable with this method. The amount of design freedom permitted within the constraints of the solution is considerable.

In order to simulate the proposed erection method, bespoke simulation pipelines were developed in the Rhinoceros 3D / Grasshopper software environment making use of the Kangaroo Dynamic Relaxation (DR) solver alongside substantial customisations using Python and C# programming scripts. A series of 2D and 3D mechanically calibrated case studies were conducted which simulate the incremental inflation of a membrane cushion of high tensile stiffness but zero bending stiffness in combination (colliding) with a grid featuring significant bending stiffness and relatively low self-weight. The method features low membrane utilisation stresses and bending stresses climb gradually such that overstressing of the beams is avoided entirely, demonstrating the effectiveness of the method. The importance of external and internal tethering cables for restraint and the significance of an initial 'trigger' pressure were also investigated.

Computation

In structural engineering implicit integration methods are more common, typically featuring a full six degrees of freedom (DOF) at each node which can accurately describe mechanical stresses and displacements in a discretized continuum under the assumption of small deflections. If equilibrium is being sought in a system where deflections are large, the stiffness matrix must be updated over multiple iterations in a non-linear analysis which can be computationally demanding and often unstable. Generally, a prerequisite for implicitly integrated methods is that the systems must be statically determinate or indeterminate. Mechanisms cause numerical instability and are harder to solve. Initial simulations were carried out into the pneumatic erection of elastic gridshells using implicit global stiffness based solver simulation methods in SOFiSTiK (Fig. 9).

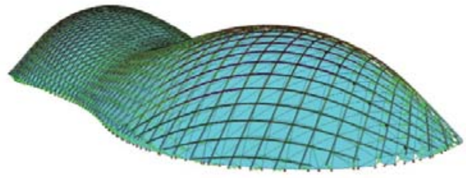

Figure 9. Initial FE simulations using implicit global stiffness-based solver with SOFiSTiK. Contact between the grid and cushion was simulated by means of compression-only springs but the method has significant limitations relating to the particular computational challenges presented by this erection method (i.e. large deformations, sliding contact, mechanisms).

Dynamic relaxation (DR) on the other hand, does not require the computation and inversion of a global stiffness matrix, but instead seeks equilibrium in each node explicitly and simultaneously by assigning mass, acceleration and a method of damping to the nodes. This means that DR methods are insensitive to the static determinacy of the structural system such that mechanisms and large deformations are not an issue, provided the solver is able to remain stable (as is the case with Kangaroo). Furthermore, collisions can be quite easily achieved using Kangaroo.

In order to be able to use the DR solver in Kangaroo for the simulation of structural systems with accurate stiffness properties, development and calibration of Kangaroo was carried out by the Kangaroo's creator Daniel Piker together with Gregory Quinn and a team of experts (Anders Holden Deleuran, Cecilie Brandt-Olsen, Will Pearson). The latest release of Kangaroo and its ability to model mechanically accurate systems has implications and application potential that reach far beyond the scope of the studies presented here.

At the time of writing, the Kangaroo solver is based on the manipulation of vertices with three degrees of freedom and a 6DOF version is in BETA stages. This has certain implications on which mathematical models can and can't be used for the simulation of structural behaviour. For the modelling of beams in Kangaroo, axial and bending stiffness are defined by goals based on Hooke's Law and the Barnes / Adriaenssens model respectively. The bending model defines bending radii on a plane of three sequential nodes and does not account for orientation or anisotropy of cross sections. Nor is beam torsion accounted for. As such the beam model is simple and fast to compute. While more accurate 4 and 6 DOF solutions exist to describe beam behaviour using DR their increased computational demands significantly reduce their speed and hence suitability for this method. The graphical display of internal forces was scripted using native Grasshopper components as well as custom Python scripts.

A great strength of the latest Kangaroo (2) is the ability to script custom 'goals' in C# or

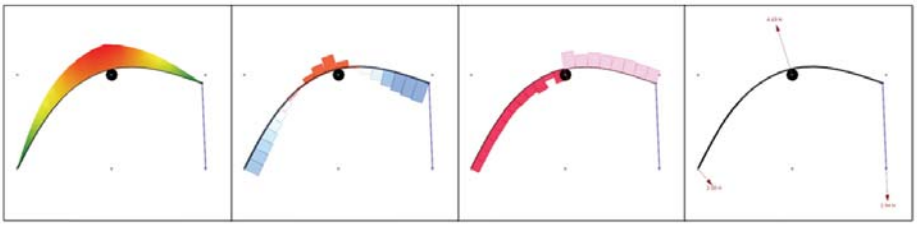

Figure 10. Custom GUI and visualisation of internal and external forces. From left to right: bending moments, axial force, shear force and reactions.

Python which define move vectors and weightings for particles in the system to be solved.

The methods here make use of predominantly native Kangaroo goals in combination with some custom goals scripted by the author.
The DR solver in Kangaroo seeks equilibrium for a user-defined threshold of the root mean square of particle velocities or 'VSum' in Kangaroo terminology. For the 2D simulations, the default value of 1e-15m/s was increased to 1e-10m/s since during inflation the semi-inflated cushion, by its very nature, struggles to find equilibrium as the membrane folds and slides. These low-resolution convergence steps are essentially snapshots of an instable system during inflation. Only when the cushion is fully inflated, and the structure sufficiently restrained, can precise equilibrium be found. More suitable convergence criteria could be the particles' acceleration or residual energy, which are likely to be available in later Kangaroo releases.
Custom GHPython scripts monitor the VSum output and flag when the solver has converged. Convergence then triggers logging of result data (such as bending stresses and screenshots) and then the Grasshopper slider for the internal air pressure is signalled to progress to the next increment. Manipulating sliders is made possible by accessing the Grasshopper software developer kit (using GH-Python). Sending data upstream (i.e. disrupting GH's directed acyclic data-flow) is made possible by accessing the RhinoPython "sticky" variable (a dictionary hash-table data structure) which can be accessed from anywhere in the current Rhino session using either of the Python editors (Edit- PythonScript or GH-Python). For easy access to a basic and custom GUI, the GH remote panel was used extensively. The stored result data (.csv format) is finally loaded into a second GH file which automates the drawing of graphs.

Funicular Pneumatic Elastica

The funicular, pneumatic and elastica forms lie at the very heart of this thesis. Gaining a robust understanding of these individual shapes and, when combined, their influence on one another is central to developing solutions for the proposed method.

For the gridshell geometry, the SheltAir prototype make use of a funicular target shape or base geometry. Digital studies have shown that the deviation between the funicular, pneumatic and elastica forms is minimal for shells with a span-to-height ration less than 3:1 but more significant as the height increases. Funicular shell surfaces are inherently well suited to resisting evenly distributed compression forces and as such were deemed a highly suitable target geometry for the gridshell (Fig. 11).

The funicular target surface for the ANCB pavilion was generated by means of a digital hanging model. This surface was then re-meshed with a Chebyshev subdivision such that all mesh edges are the same length: a key requirement for the functionality of an elastic gridshell. For the funicular form-finding step, the initial mesh and method of loading has an influence on the shape of the funicular surface. The starting mesh for a funicular surface can be either quadrilateral or triangular.
While regular quadrilateral chains are a perfectly valid means of surface form-finding for elastic gridshells, they are subject to directional bias along their orthogonal axes particularly for irregular or asymmetric shapes. A regular quadrilateral chain lattice hanging chain can be simulated digitally by applying a length-dependent vertical load at the beginning and end of each element. The elements may be given an arbitrary spring stiffness (albeit proportional to their lengths) allowing them to extend under applied load. This results in an approximate catenary surface which is very much subject to directional bias relative to the mesh orientation. By using a triangulated configuration for the initial form finding mesh, it is possible to apply barycentric loads to the corner nodes which, if

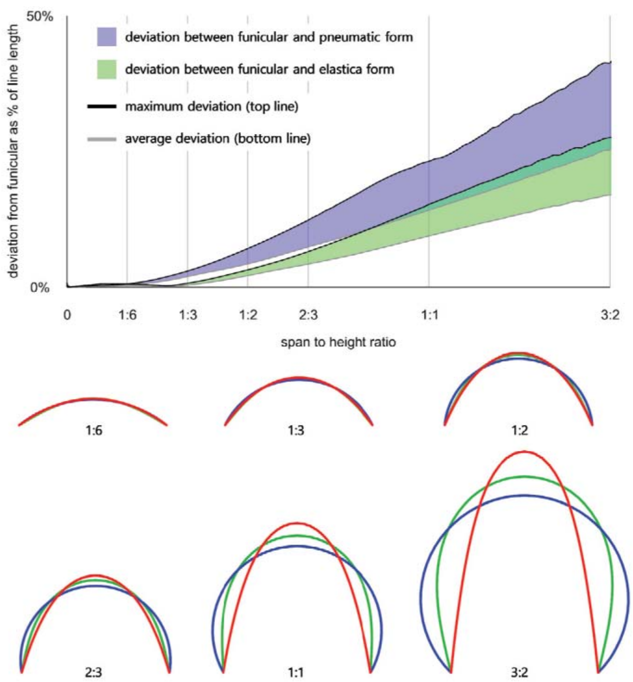

Figure 11. Deviation in 2D for different span-to-height ratios between the three forms central to this method: funicular, pneumatic, elastica

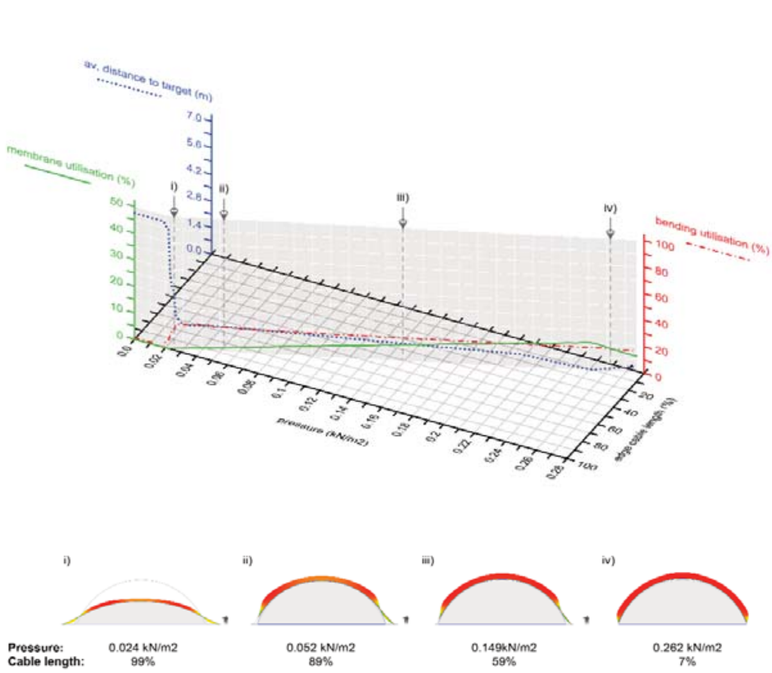

Figure 13. Sample of 2D erection analysis results. Erection of 30m dome with edge cable length initially at full length and then progressively shortened at a constant rate after the trigger pressure has been reached.

the elements are given stiffness proportional to their length, will result in a uniform funicular shape without directional bias. A custom Kangaroo goal (based on existing goals from Daniel Piker) was written for the barycentric vertical loading of triangulated meshes.

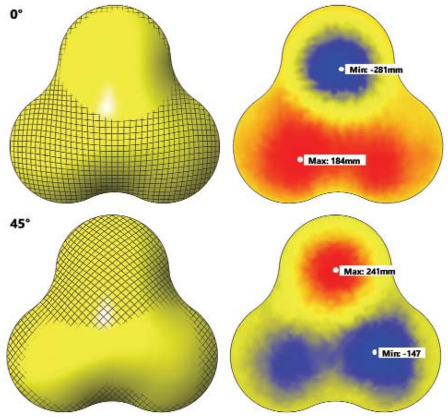

Figure 12. Directional bias of digital hanging chain model using a mesh quadrilateral subdivision (black) compared with a triangular mesh (yellow). Deviation shown right.

Experimental results

Generally, it was proven that the erection method is very gentle to the rods in terms of bending stresses. The results help to quantify with precision which curvatures, spans, shapes and material choices are feasible and sensible for the proposed method which, in light of the successful prototype, is proven to offer a viable solution for rapidly-deployable, structurally efficient and architectually elegant dwellings ideal for application in event or disaster shelters.

During inflation bending stresses in the beams remain null until the trigger pressure is reached, after which a rapid increase can be observed. Crucially however, the bending stresses climb gradually and overstressing, as can occur with other erection methods such as 'lift up' and 'push up', is avoided entirely demonstrating the effectiveness of the method.
The membrane stress is also very low throughout the inflation process. Larger spans result in lower curvature and subsequently higher membrane strain for a given pressure. However even for the weakest type (I) of PVC coated polyester membrane, the membrane stresses are uncritical. Overall, exhibited membrane stresses are even low enough to satisfy typical safety factors accounting for long term effects, temperature and environmental degradation, however due to the very temporary demands on structural performance, membrane utilisation stresses up to 90% are deemed acceptable for the proposed erection method.
The need for external tethering cables is twofold. Firstly, external tethering cables can prevent excessive lateral sliding of the beam/grid on the cushion. Secondly, when the cushion is fully inflated, the beam/grid ends cantilever out and must be pulled towards their support points before the grid shell can support itself independently of the cushion. The external tethering cables can be shortened (by hand or winches) in order to pull the beam ends to their target support points. The shortening of these edge cables can occur at different stages during (or after) the inflation process. The strategic value and structural impact of when to shorten the edge cables has been investigated in detail revealing that it is most sensible to shorten the external tethering cables after full inflation (Fig. 13).

Trigger Pressure

An important aspect of being able to pneumatically erect elastic gridshells is knowing how much pressure is required to do so. Low pressures are desirable because they are easy to supply (with low-cost blowers) and because they have simpler and more affordable demands on detailing for the membrane. The pressure required to inflate a gridshell (trigger pressure) can be defined as:

$$\text{trigger pressure} = g_{membrane} + f_{Area} \cdot g_{gridshell}$$

Where $g_{membrane}$ is the distributed self-weight of the membrane, $g_{gridshell}$ is the distributed self-weight of the gridshell and f_{Area} is a factor for area compensation between the footprint of the gridshell in its end-state and the gridshell footprint in its initial and flat state. This area factor will increase for higher height to span ratios and is also dependent on the shape of the gridshell (Fig. 16).

Physical Mock-up

In parallel with FE simulations, a scaled physical model was used to perform a first ever erection of an elastic gridshell 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 a full-scale 30m span equivalent structure, subsequently it had a span of 3m.

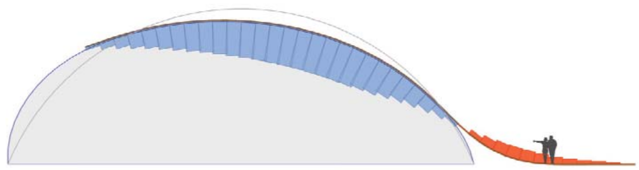

Figure 14. Demonstration of lateral sliding of beam along membrane surface highlighting the need for external tethering cables. Notice the change in axial forces from predominantly tension (blue) to compression (red).

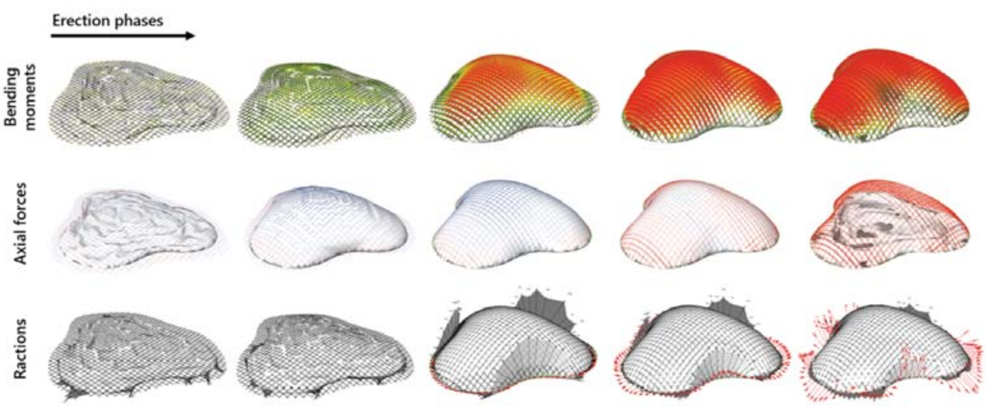

Figure 15. Sample of 3D erection analysis results.

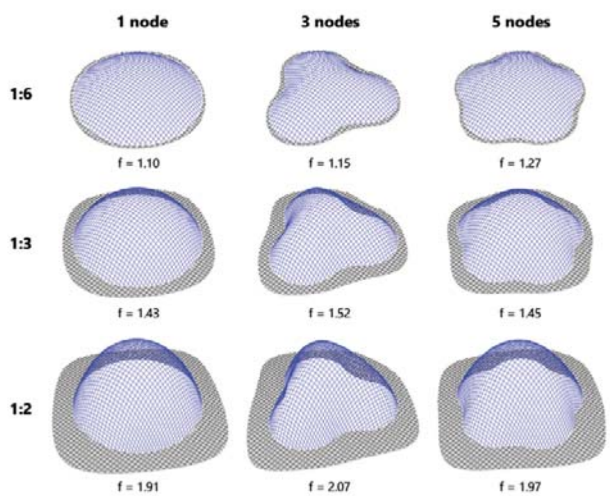

Figure 16. Influence of span-to-height ratio and shell shape on area compensation factor in calculating the trigger pressure required to initiate pneumatic erection of an elastic gridshell. Shown in blue is the end-state gridshell and in black the initial and flat configuration.

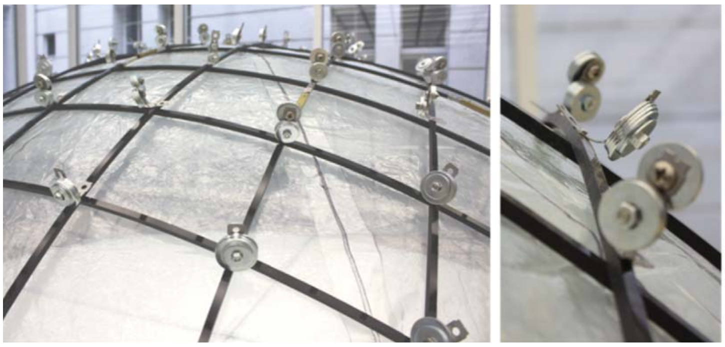

Figure 17. Increased self-weight of the grid shell by means of an additional 104g at each node to account for scaled physical properties according to dimensional analysis.

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 and was used here (Figs 17-18).

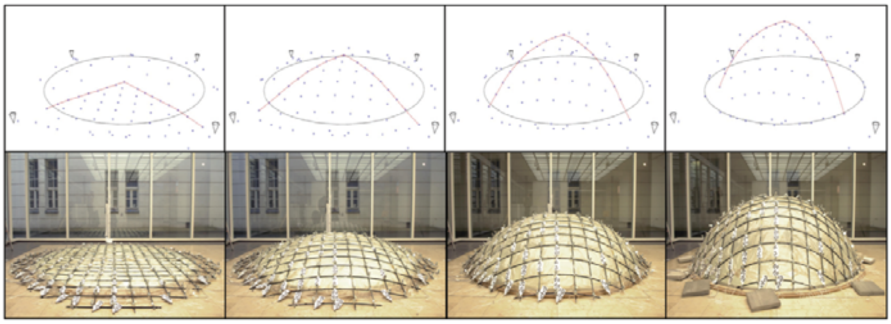

Figure 18. Four snapshots from the inflation process with elevation photos (below) and photogrammetric 3D point cloud data (above).

Fitness Criteria

It was found that the range of materials, spans and shapes can and must be selected very specifically in order to ensure the method's success. If the rods are too stiff, the grid mechanism will not deflect sufficiently under its own self-weight and will subsequently reduce its contact area with the cushion, requiring much higher air pressures and membrane detailing in order to achieve successful erection. Conversely if the rods are too soft, the gridshell will not be able to support its own self-weight in the transition phase after erection (including removal of the cushion) and before the gridshell has been stabilized (e.g. with bracing cables) (Fig. 19).

At higher rod diameters, the self-weight component from the membrane (0.0111kN/m^2 in the case of typical PVC coated polyester fabric) to the trigger pressure is dominated by the gridshell self-weight component meaning the cushion must crumple and deflect downwards in order to ensure sufficient contact area between the grid and the volume of air. Gridshells with smaller rod diameters are less stiff and so deflect more under self-weight and in doing so make contact with the cushion which means that the cushion must not deflect to ensure sufficient contact area. Similarly, gridshells with higher rod diameters are stiffer and will deflect less under self-weight meaning that unless the cushion deflects, only a small area of contact would be available between it and the cushion (Figs. 20 - 21).

Simply increasing the air pressure to compensate for this phenomenon is only a feasible solution within strict limitations. Higher pressures result in overstressing of the membrane, adding to the demands of the membrane details (welds in particular) and will be much more difficult to effectively seal at boundaries.

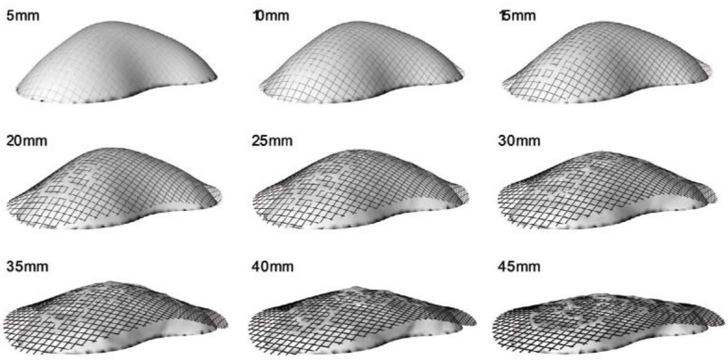

Figure 19. For GFRP rod diameters ranging from 5mm to 45mm, the interaction between the grid and cushion, under its respective trigger pressure, is shown.

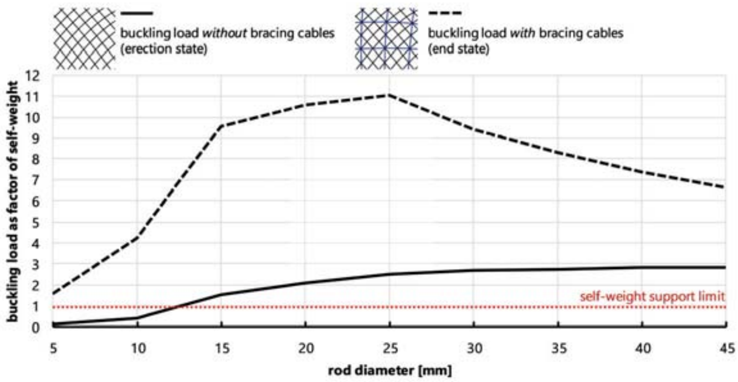

Figure 20. Here the buckling load of elastic gridshells without bracing cables (erection-state) and with bracing cables (end-state) is shown for a variety of rod diameters. This shows how smaller rod sections are not stiff enough to support the gridshell's self-weight while large diameters are too stiff and inefficient.

rod diameter	5	10	15	20	25	30	35	40	45	mm
gridshell UDL	1,9	7,6	16,8	29,8	46,6	67,2	91,4	119,4	151,1	N/m2
trigger pressure	0,01	0,02	0,04	0,06	0,08	0,11	0,15	0,19	0,24	kN/m2
deviation from target	13	61	150	307	446	579	711	812	939	mm
manual anchorage load	0	3	8	16	27	42	60	86	114	kg
beam utilisation	5	9	13	18	22	27	31	36	40	%
membrane utilisation	10	16	26	40	58	80	106	137	171	%
buckling load no cables	0,1	0,4	1,5	2,1	2,5	2,7	2,8	2,8	2,9	SW factor
buckling load cables	1,6	4,2	9,6	10,6	11,1	9,4	8,3	7,4	6,6	SW factor

viable

failure | undesirable | desirable

Figure 21. Range of experimental results which show the bandwidth of viable specifications for the SheltAir prototype.

Enabling and sustainable technology

The practical benefits of elastic gridshells, such as low material usage and fabrication simplicity, are undermined by the existing methods for their erection (lift up, push up & ease down) which are time-consuming, costly and can overstress the system. This novel method has extremely low demands on energy, material consumption and construction. Only very simple blowers for low temporary pressures (under 5mbar) are required. Architectural skins and/or insulation can be erected simultaneously with the gridshell, further reducing construction time and complexity. Repetition and simplicity of predominantly linear construction elements is extremely high and all manual labour is conducted at ground level. The method proposed here has been shown to be effective and viable. The simulation methods developed to validate the method technically have wider reaching implications for the speed and accessibility of engineering simulation tools.

A second prototype, modified for application as a humanitarian disaster relief shelter, is planned for the summer of 2018 in collaboration with the Universities of Bath and Cambridge under the umbrella of the research project *Healthy Housing for the Displaced.*

Acknowledgments & material sponsorship:
Pultrex, Hightex, Serge Ferrari, Spirafix

Gregory Quinn
quinn@udk-berlin.de
Pneumatic erection video: https://youtu.be/OKe14VF03RM
Design & Build Video:https://youtu.be/y56PkC7tpU8

Figure 22. Rendering of a pneumatically erected elastic gridshell for a highly suitable application of the novel method: large-span, rapidly deployable disaster-relief or event shelter.

Name of the project:		SheltAir
Location address:		The garden of ANCB, Christinenstr. 18 - 19, 10119 Berlin
Client (investor):		Berlin University of the Arts, Department of Structural Design and Technology KET (Prof Gengnagel) / Aedes Metropolitan Laboratory Berlin
Type of application of the membrane:		Shelter
Year of construction:		2017
Structural engineers:		Gregory Quinn
Contractor for the membrane:		Hightex
Manufacture and installation:		Gregory Quinn / KET
Material:	Rods:	nylon-sheathed glass fibre reinforced plastic (pultruded)
	Membrane:	PVC-coated polyester fabric
	Foundation plate:	Hot-dip galvanized and laser cut steel (6, 8&10mm)
	Cables:	7x19 strand steel wire 3mm
	Cable-Rod connectors:	thread-tapped trellis wire connectors /
	Ground anchors:	ram-driven steel screws
	Membrane-tensioning:	Nylon rope 8mm