A review of elastic grid shells, their erection methods and the potential use of pneumatic formwork

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Abstract

The evolution of elastic grid shells has observed significant progress in the fields of computational form-finding, structural analysis and to some extent buildability since their inception in the 1960s. While the engineering precision of built elastic grid shells has increased on the whole (most notably Chiddingstone Orangery Savill Gardens), the size and span of modern elastic grid shells has decreased. Furthermore, building costs per square metre for such structures have also increased. Despite an increase in the frequency of elastic grid shells built in Europe over the last two decades, fuelled in part by academic curiosity, the low sample makes interpreting trends in their adoption rate difficult. Nonetheless the failure for more widespread adoption in the built environment of this low-tech, large-span building technology may be attributable to the increased serviceability demands of modernised building codes coupled with limitations or apprehension caused by health and safety legislation.

While the idea has been considered before, it is argued in this paper that the use of air-inflated membrane cushions for the erection of elastic grid shells has the potential to significantly reduce the demands on structural performance of the nodes and beams when compared with the crane and cable erection method and that when compared with the scaffolding erection method, the air-inflated cushion approach can offer paralleled safety but at a fraction of the time and cost. It is believed that this technique offers a way to once again facilitate large-scale, low-cost elastic grid shell buildings in the modern built environment such as have not been since the likes of the Multihalle Mannheim.

Keywords: elastic grid shells, pneumatic formwork, active bending, erection.

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1 Introduction

Elastic grid shells are structures made from long continuous beams and employ the principals of active bending [1] to achieve their target shape. Regular grid shell structures on the other hand are made from elements of varied and finite lengths. This paper is concerned with elastic grid shells only. The economic advantages that arise from using elastic grid shells (low material quantities, cost effective transportation, large spans and low-tech assembly of linear elements) are undermined by the cost and complexity of the temporary formwork and labour which are necessary for their erection.

This paper reviews in detail the most important western elastic grid shell buildings since their inception in the 1960s. A literature review is also presented of buildings and projects that have made use of pneumatic formwork. Until now, the authors are unaware of pneumatic formwork having been used for the erection of an elastic grid shell. The final sections of the paper make a case for the use of pneumatic formwork for the erection of elastic grid shells, considering both benefits and caveats. Finally, a simple prototype from a student workshop is shown.

It is fair to say that the erection phase is usually a major, if not dominant, load case for an elastic grid shell due to high bending stresses induced by tight curvatures and point loads in the laths. This effect is dependent on the method of erection as well as the shape and size of the shell. The main reasons for minimizing bending-induced stresses are to prevent breakages of beams during erection and to ensure that sufficient stress reserves are available in the beams under external load cases. While every major grid shell project has experienced breakages during erection, the number of breakages has progressively reduced. For example: "...during the assembly of project Essen: due to inherent stresses, several grid rods directly next to joints were broken" [2, p. 219]. At Manheim "... quite a number of finger joints broke on site during handling and erection" [3, p. 126]. In the Downland grid shell "of the 10 000 joints in the structure, there were approximately 145 breakages during forming. Almost all were failures of the finger joints" [4, p. 437]. Finally, in the Savill Garden grid shell, which had extremely low curvatures and a fully scaffolding-supported erection there were only "two fractures during the construction process" [5]. While this progressive reduction of breakages is very positive, it comes at the cost of increasingly slow, precisely measured and costly erection. It is supposed that pneumatic formwork may facilitate a reduction of labour and cost during erection while simultaneously further reducing the risk of localised bending-induced stresses and breakages during erection.

Another main reason to limit bending stresses during the erection of elastic grid shells is that for both GFRP and wood, creep can be accelerated by high internal stresses. Various sources recommend limiting the internal stresses of GFRP to between 30% and 60% in order to prevent worsening of this effect.

2 Review of pneumatic formwork for dome-like structures

Making use of pneumatic formwork for dome structures has intrigued engineers and researchers for some time. As early as 1940, Californian architect Wallace Neff developed a system of using inflated sailcloth cushions to support flexible reinforcement which is then sprayed with shotcrete in increasing thicknesses to create a strong and stable shell structure [6, p. 38].

Figure 1: Wallace Neff's bubble houses.

Developed in the 1960s, the Bini method [7] facilitates concrete shell erection using un-stiffened formwork whereby wet concrete and sprung length-changing reinforcement are all contained within an upper and lower membrane in which concrete curing occurs in-situ after inflation. The Bini system enjoyed a strong burst of adoption for small to mid-span structures during the 70s and 80s. More than fifteen hundred Bini shells have been built in twenty-three countries with spans from 7.5m to 90m [6, p. 38], proving without a doubt the potential for success of pneumatic formwork. While the double membrane system coupled with anchored foundations cleverly restrains the load-bearing wet concrete shell during erection, the same system could not be applied to elastic grid shells since when flat, they occupy a much larger footprint than when erect.

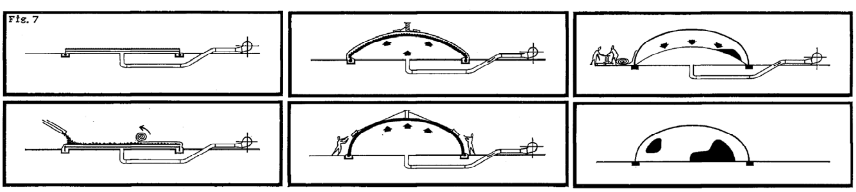


Figure 2: The Bini method for erecting concrete domes with pneumatic formwork [7, p. 190].

In the 1980s Sobek [8] explored the use of pneumatic formwork for the erection of concrete shells citing the same justification as the authors in this paper i.e. the ever increasing expense of labour-intensive formwork. A focus of Sobek's work was on how to limit concrete strains during erection by stiffening the formwork by partially filling the enclosed membrane with a fluid or by strengthening the membrane with circumferential steel cables as previously patented by Wallace Neff [9].

More recently Dallinger and Kollegger [10] used pneumatic formwork to erect domes made out of prefabricated concrete panels as well as ice sheets (fig. 3). Two methods for stabilising the kinematic system during erection were developed: firstly by combining pneumatic formwork with radial and circumferential tendons which are shortened during erection (polyhedron method) and secondly by combining pneumatic formwork with a rigid central mounting tower (cloister-vault method). Kokawa *et al.* [11] have also developed ice shells built on temporary pneumatic formwork. Water is sprayed on in the same fashion as shotcrete in Harrington/Neff shells (fig. 4).

Figure 3: Pneumatic formwork for the erection of prefabricated concrete panels [10].

Figure 4: Ice shells created by pneumatic formwork and sprayed water [11].

The largest known project to have made use of pneumatic formwork for its erection is the train car maintenance dome for the Union Tank Car Company in Wood River, Illinois designed by engineer Richard Lehr working for Buckminster Fuller's company Synergetics with Chicago architects Battey Childs [12]. The steel dome with a span of 114.4m [13, p. 1137] was the world's largest clear span building at the time. Using a "huge pneumatic nylon bag" [14, p. 216], the crown of the rigid (non-elastic) shell structure was raised to its target height while the perimeter skirt was attached. This project demonstrates that large and heavy dome-like can be lifted in a controlled and safe manner with pneumatic formwork.

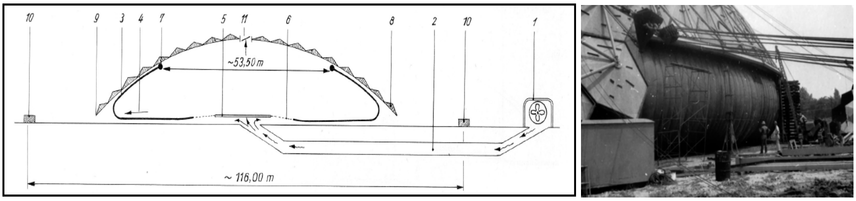


Figure 5: Left: Pneumatic formwork system for the large Union Tank Car Dome in Wood River [15, p. 267]. Right: The large nylon bag [12].

3 Review of relevant elastic grid shell projects

The following tables collate the most significant and relevant western elastic grid shell buildings built since the 1960s. While many comparison tables on elastic grid shells exist in published work, none have been as thorough or as the detailed documentation provided by Otto *et al*. in the 1974 IL13 publication from the University of Stuttgart [2, pp. 268–309]. The following tables performs a similar task but are populated by modern projects. It can be observed that since 1975, the clear span of western elastic grid shells has never since achieved nor exceeded the 60m clear span of the Multihalle Mannheim.

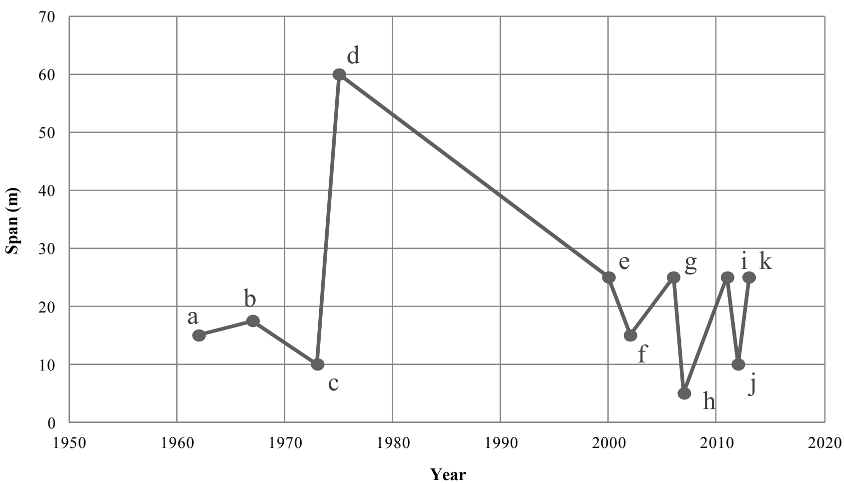


Figure 6: Clear span of grid shell buildings: a) Essen Pavilion, b) German Pavilion, c) Seibu, d) Multihalle Mannheim, e) Japan Pavilion, f) Weald and Downland, g) Savill Garden, h) Chiddingstone Orangery, i) Soliday Pavilion, j) Flying Dome, k) Creteil Church.

Table 1: Comparison table part 1.

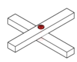
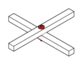
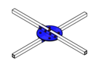
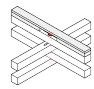
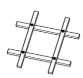
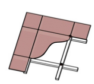
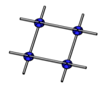
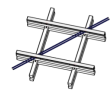
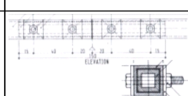
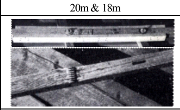
	Essen Pavilion	German Pavilion	Seibu	Multihalle Mannheim
Year	1962	1967	1973	1975
Location	Essen, Germany	Montreal, Canada	Tokyo, Japan	Mannheim, Germany
Client	-	BRD	Seibu Construction Co.	Bundesgartenschau Mannheim GmbH
Architect	Frei Otto	Rolf Gutbrod, Frei Otto mit IL	Kazunori Matsushita	Mutschler + Partner (Atel. Warmbronn)
Engineer	-	Leonhard + Andrä	Toshiyuki Shirayanagi	Ove Arup + Partners, IAGB Stuttgart
Node detail				
Node description	Single bolted connection.	Single bolted conenction.	Circular plate with flanges for beam alignment. Upper and lower plates connected by M6 bolt	Single 8mm bolt. Upper two layers with slotted hole to enable radial slip during erection.
Formfinding method	Hanging model	Hanging model	Hanging model	Hanging model
Erection method	"lift up" mobile crane + light auxilary columns	"lift up" cable hoists from existing cable net	Unknown	"push up" horizontally unrestrained scaffolding towers
Material	Hemlock Pine laminated from three 1.3mm layers	Hemlock Pine	Aluminium	Hemlock Pine
Cross section	 60x40mm	 42x35mm (big shell) 42x28mm (small)	 20x20x2mm	 50x50mm
Grid size	 0.482m	 0.5m	 0.5m	 0.5m
Cladding	Transparent plastic sheet nailed to grid with cover strips.	Insulation + PVC coated fabric.	None.	PVC coated polyester grid fabric (30% translucancy)
Shear stability	Rigid nodes.	Shell action from nailed plywood boards.	Rigid nodes. Upper and lower aluminium circuluar plates. Four bolts for rigid joint. Holes in lower plate drilled after erection.	Wood friction joint (Bellville washer) & two 6mm 19 wire strand ties every 6th node
Grid type	Regular	Regular	Regular	Regular
Span	 15m x 15m	 17.5	 10m x 10m	 60x60m & 50x50m
Pitch	4.85m	4m		20m & 18m
End-to-end connection	N/A	N/A		
pre-fab	Dove-tailed wedge joints.	Unknown	At least two joints necessary for each grid beam. 150mm long aluminium scarf joint with four M5 bolts on horizontal plane.	Finger joints every 4m for 30-40m long lath lengths. Finger joint 20mm long with a 6mm root. Made in the Poppensieker factory.
on site	None	Unknown	None	Long laths joined by 50x25mm lapping pieces. 16 nails each side. Also used to repair finger joints.
	[2], [16]	[2], [16]	[16, p. 246]	[16], [3]

Table 2: Comparison table part 2.

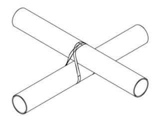
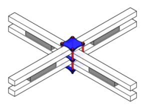
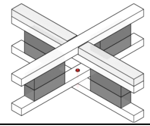
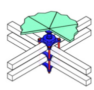
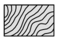
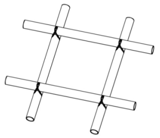
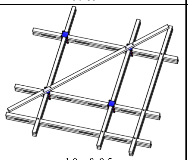
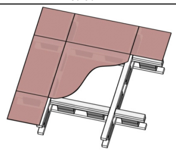
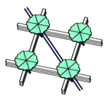
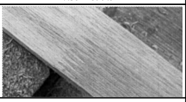
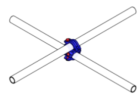
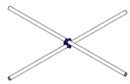
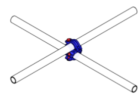
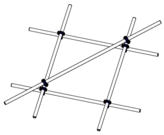
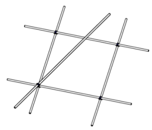
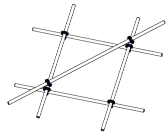
		Japan Pavilion	Weald & Downland	Savill Garden	Chiddingstone Orangery
Year		2000	2002	2006	2007
Location		Hannover, Germany	Sussex, England	Berkshire, UK	Kent, UK
Client		Expo 2000	Weald & Downland Open Air Museum	The Crown Estate	Trustees of Chiddingstone Castle
Architect		Shigeru Ban	Edward Cullinan Architects	Glenn Howells Practice	Peter Hullbert
Engineer		Buro Happold	Buro Happold	Buro Happold	Buro Happold
Node detail					
Node description		Fabric tape wrap around	Patented three-plate node. Central plate with locator pin. Two exterior with four bolts for clamping.	Single bolt on bottom layer only. Top layer laid up manually on scaffolding supported structure.	Precision engineered stainless steel node.
Formfinding method		Mathematical definition	Mathematical definition	Chebyshev net	Unknown
Erection method		"ease down" Peri Up hydraulic scaffolding + formwork girders	"ease down" Peri Up hydraulic scaffolding + formwork girders	"ease down" Peri Up hydraulic scaffolding + formwork girders	"lift up" slow lifting from scaffold over several days, wetting of laths with water
Material		Paper / Cardboard	Oak	Larch	Green Chesnut
Cross section		 Round: 120mm x ?mm	 50x35mm	 80x50mm	 40x35mm
Grid size		 1m	 1.0m & 0.5m	 1.0m	 unknown
Cladding		Fireproof paper with glass fibre reinforcement and laminated PE film.	Crown: RoofKrete, Shoulder: Polycarbonate, Sides: Western Cedar	Stiffeneing plywood boards + 160mm insulation + aluminium standing-seam skin + oak laths.	12mm toughened frameless glazing.
Shear stability		Glulam ladders, Steel wires.	"Fifth layer" lath	Two layers of nailed birch plywood boards.	Doubled steel cables on every second node.
Grid type		Regular	Regular	Regular	Regular
Span		 74 x 25 m	 48m x 15m	90m x 25m	12m x 5m
Pitch		16m	7.35m & 9.5m	5m & 8,5m	-
End-to-end connection		N/A			
	pre-fab	None	Finger jointing in 6m lengths. 65% moisture content of the green oak managed in finger joint with special adhesive (Purbond HB 530).	Finger jointing in 6m lengths.	Finger jointing
	on site	"20m lengths for transport and then connected using a wooden splice rather than a joint"	On site the 6m lengths were joined with scarf joints (slope 1:7)	On site the 6m lengths were joined with scarf joints (slope 1:7)	None
		[17][18]	[4]	[19]	[20][21]

Table 3: Comparison table part 3.

	Soliday Pavilion	Flying Dome	Creteil Church
Year	2011	2012	2013
Location	Paris, France	Berlin, Germany	Creteil, France
Client	Solidays' Festival	UdK Berlin	Eglise catholique du Val de Marne
Architect	-	-	-
Engineer	Olivier Baverel	E. Lafuente, C. Gengnagel	Esmery Caron / Olivier Baverel
Node detail			
Node description	Standard swivel scaffold connectors.	"Double clamps" from sailing industry.	Standard swivel scaffold connectors.
Formfinding method	Compass method	Sphere + VaryLab mesh	Compass method
Erection method	"lift up" crane & cable	"push up" by hand	"lift up" crane & cable
Material	GFRP from Topglass (polyester resin from DSM & Owens Corning glass fibre)	GFRP (Fibrolux GmbH)	GFRP from Topglass (polyester resin from DSM & Owens Corning glass fibre)
Cross section	 Round: 41,7 x 3mm	 Round: 20mm x 2mm	 Round: 41,7 x 3mm
Grid size	 1m	 0.66 - 1.27m	 1m
Cladding	Polyester fabric, double sided PVC coated, 750 g/m2 + glass fibres	None.	Polyester fabric, double sided PVC coated, 750 g/m2 + glass fibres
Shear stability	"Third layer" GFRP tube.	"Third layer" GFRP tube.	"Third layer" GFRP tube.
Grid type	Regular	*Irregular*	Regular
Span	 25m x 15m	 10m	 25m x 15m
Pitch	7m	5m	7m
End-to-end connection			
pre-fab	Two scaffolding swivel connectors. Limited bending stiffness in joint.	80mm aluminium tube, diameter 30mm, 5mm wall thickness. M5 bolts clamp fit against outer wall of GFRP tube. No penetration.	Threaded steel bar into steel sockets. Steel sockets with three through-bolts to resist bi-directional bending and torsion.
on site	None	None	None
	[22]	[23]	[24]

4 Erection methods

The authors acknowledge four main viable means of elastic grid shell erection: “pull up”, “push up”, “ease down” and “inflate”. All but one of these methods have so far been employed for the erection of elastic grid shells. At the time of writing, the authors are unaware of elastic grid shells that were erected by means of pneumatic formwork.

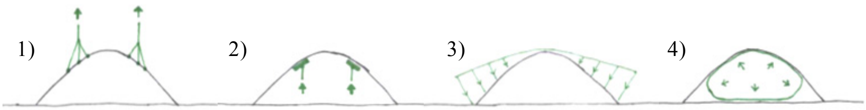


Figure 7: Erection methods for elastic grid shells: 1) “pull up”, 2) “push up”, 3) “ease down”, 4) “inflate”.

4.1 “Pull up” (crane and cables)

The first known example of a *timber* elastic grid shell was the experimental prototype by Frei Otto built in Essen in 1962. This 15m grid shell was erected by means of a single mobile crane (fig. 8, left) but also wooden stilts were used to support the perimeter. The German Pavilion at the 1967 Expo in Montreal was also erected by cable hoists suspended not from a crane but instead from an existing cable net structure (fig. 8, right). More recent examples of cable and crane erection are the Soliday Festival and Creteil Church grid shells by Baverel (fig. 9).

This erection method has the benefit of speed, however there are several disadvantages. Cables, even when branched off into clusters of fixing points introduce large point loads and subsequent stress concentrations into the structure. While clusters of wires will better distribute the applied vertical loads (out-of-plane), they introduce compressive membrane forces (in-plane) which will increase buckling risk for the laths.

Furthermore the crane erection method can only apply force in the vertical direction and is not restrained in the horizontal direction. The lack of horizontal restraint from the cables is beneficial due to the necessary grid distortion during erection. However global horizontal restraint of the grid shell itself or at least its edge must be provided by separate means. Typically crane erection requires very calm weather and is only practical for small shells.

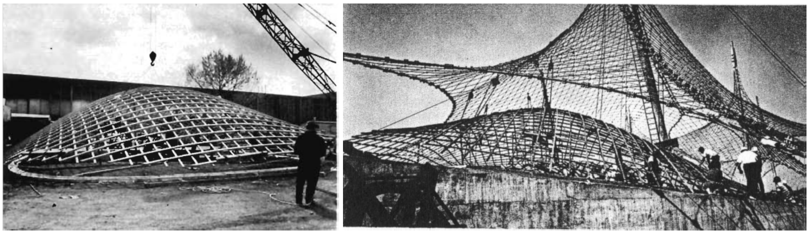


Figure 8: Left: crane erection of the Essen Gridshell [3, p. 101], right: cable hoists from existing cable net lifting the German Pavilion [2, p. 247].

Figure 9: Crane erection of the Soliday Pavilion left [25, p. 10], and the Creteil Church right [26].

4.2 "Push up" (static formwork/jacking towers)

Originally, the Multihalle Mannheim was planned to be erected using four 200 tonne cranes but eventually a system of jacking towers was devised by the contractors and engineers in order to cut costs [3, p. 131]. 3.5m by 2.5m H-shaped spreader beams were connected via ball joints to the 1m square scaffolding towers which were up to 17m tall. These towers were jacked up vertically using fork lift trucks which were able to accommodate the necessary lateral translations of the lifting points.

A key feature of the erection process was that "the lattice was anchored with cables at certain key points to prevent collapse". The spacing between the towers was 9m such that the laths themselves deflected by 200mm under bending from self weight. This deflection had to be gradually reduced to around 50mm by progressive stiffening of "strips" along the grid shell followed by height adjustment of grid zones.

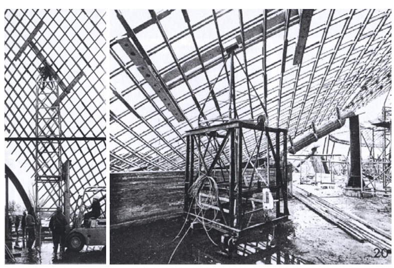


Figure 10: Horizontally unrestrained jacking towers as used for the erection of the Multihalle Mannheim [2, p. 312].

4.3 "Ease down" (hydraulic/mechanical formwork)

The three most recent *timber* elastic grid shells built by Buro Happold (Japan Pavilion, Weald and Downland Centre, Savill Garden) were erected by means of scaffolding support underneath the entire grid shell area coupled with incremental and controlled displacement of the laths. Under the UK's 1994 Construction Regulations, the hazards of working at height under a temporarily supported structure, as was the case at Mannheim, are no longer permitted [4, p. 440]. The erection of these three projects all made use of the modular scaffold system PERI-UP, including the MULTIPROP jack. The unique aspects of this method is the high layout level for the flat grid, from which gravity is harnessed and the laths are gradually displaced downwards (allowing also for lateral movements). Scaled physical models played a crucial role in planning, predicting and checking the erection process [4, p. 443]. Detailed labelling and measuring of the structures during deformation was carried out to monitor and control the process. Additional straps and ratchets were required to initiate further "scissoring" in order to successfully form the crowns and valleys of the Weald and Downland Centre.

Figure 11: The Savill Garden grid shell was lowered into position gradually with vertically adjustable formwork [27].

5 Pneumatic formwork for elastic grid shells

One of the most comprehensive and relevant works on pneumatic formwork for dome-like structures is the chapter "Pneumatic Formwork for Irregular Curved Thin Shells" by Hennik and Houtmann from the book "Textile Composites and Inflatable Structures II" [28, pp. 99–116]. While the work focuses on the application for concrete shells, many of the findings and references are relevant and applicable to elastic grid shells. Guidelines on permissible sag for pneumatic structures are available from Herzog *et al.* [29] as well as various building codes. The level of sag is dependent on the following factors: Internal static pressure, external vertical load, membrane stiffness, curvature of the pneumatic formwork and aspect ratio of the cushion (height/width). Flatter zones of a pneumatic cushion are better able to resist vertical external loading with low static pressures than "steep" surfaces and small horizontal contact areas (fig. 12). And yet, small curvatures while beneficial for erection are undesirable for the final shell geometry due to the resultant low shell stiffness. Therefore the shape of the pneumatic formwork and the final grid shell must be developed in unison.

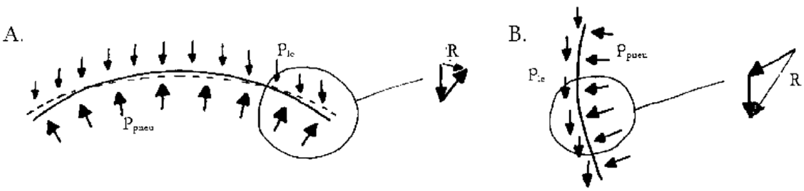


Figure 12: Free body diagram for static pressure and dead load for flat (A) and steep (B) zones [28, p. 108].

The self weight of wet concrete for a “thin” 100mm shell is 2.5kN/m^2. Comparatively, the self weight of a typical timber elastic grid shell will be in the range of 0.1 to 1.0 kN/m^2. As such the self weight applied by the grid shell and subsequent sagging will be significantly less problematic than for concrete shells. Furthermore, during curing concrete shells are extremely sensitive to deformations and strains. By their nature, actively-bent grid shells on the other hand can comfortably sustain large deflections (as long as stress concentrations and utilisation are managed). However it is important to remember the role of air moisture and speed of erection for certain timbers. The Chiddingstone Castle Orangery grid shell experienced high ambient temperatures and low humidity during erection such that the laths were regularly wetted to maintain moisture levels [21]. Furthermore, over or undershooting the target shape due to air temperature changes can lead to incorrect curvatures in the final shape which could result in stability failure. While Neff and Sobek showed that rotationally symmetric pneumatic structures can be stabilised by circumferential reinforcement or by the addition of fluid, more recently in 2014, design group “Numen” have shown through empiric prototypes that precise shape manipulation and sagging control can be achieved by means of extensive internal tensile bracing [30]. However, the concept of form stabilisation for inflatable structures by means of internal cable bracing was patented as early as 1987 [31].

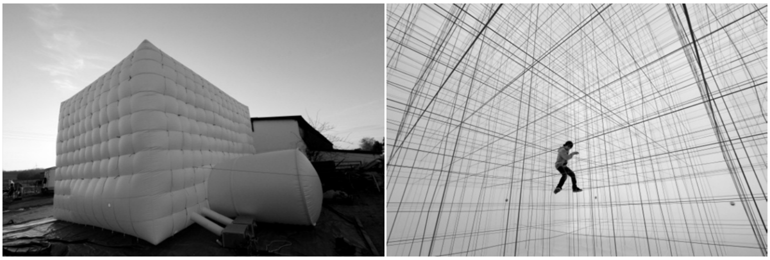


Figure 13: Precise shape and sag control via internal tensile bracing [30].

The most critical challenges for the erection of elastic grid shells by means of pneumatic formwork are concerned with the following major issues: stability and restraint of the grid shell mechanism during erection and ensuring that the target surface geometry is achieved despite sagging of the cushion. It is proposed that regardless of cushion type, the grid shell should be raised to a height higher than its final destination such that the beam ends can be lowered to their supports via deflation in a controlled manner.

6 Student workshop tests

To trial the proposal, a 2 x 3m grid shell made from 5cm strips of 7mm thick flexible plywood was erected by means of a pneumatic cushion within the context of a student workshop at the Department for Engineering Design and Technology at the University of Arts Berlin. The grid shell geometry was form found by means of the educational software tool "Push Me Pull Me 3D" [32]. The experimental erection of the model grid shell demonstrated a successful trial highlighting the potential for the method as well as some of the difficulties such as controlling the shape and sag of the cushion. Additional simulations have been begun by the authors but were not ready for publishing at the time of writing.

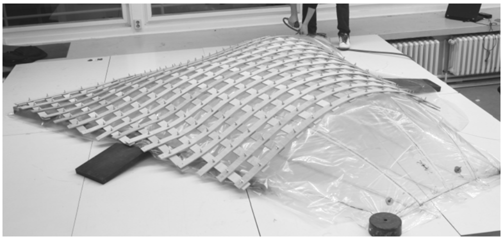


Figure 14: Initial experimental trial of pneumatic formwork for the erection of scaled model elastic grid shell.

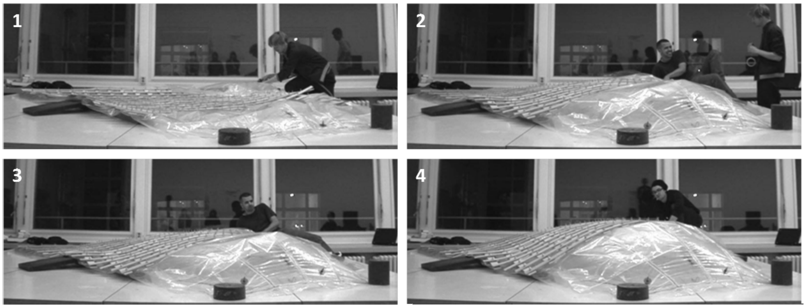


Figure 15: Inflation sequence of scaled model.

7 Conclusion

A review has been presented of historic uses of pneumatic formwork for the erection of dome-like structures. A review has also been presented of the most relevant and recent elastic grid shell structures. A review and discussion has been presented of known erection methods for elastic grid shells including: "pull up", "push up" and "ease down". The benefits and caveats of each method were discussed, highlighting in particular the bending stress concentrations and subsequent breakage risk induced by the point supports of cables or jacking towers as well as the slow and costly alternative of using a fully scaffold-supported bed. A case is made for the use of pneumatic formwork for the erection of elastic grid shells, highlighting speed, safety, control and cost as drivers. Technical challenges are predicted in the areas of calculating sag of the cushion, restraining the shell mechanism during erection and designing for irregular shell shapes. Finally an initial small scale prototype is presented. The authors are planning further tests, simulations and prototypes to explore this novel method.

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