Modeling of bending-torsion couplings in active-bending structures. Application to the design of elastic gridshell.

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1 A neat way to build free-form architecture

1.1 Review

Ted Happold (1930–96), founding partner of Buro Happold, worked on the Mannheim gridshell in Germany (Architect Frei Otto, built 1975), when he was with Ove Arup & Partners. For many years after its completion, Happold promoted the benefit of the timber gridshell as a construction technique and stated that he could not understand why it had not been adopted more widely. He perceived the benefits to be in the efficiency of the construction method to enable doubly curved (shell) structures to be constructed quickly and cost effectively. A doubly curved structure offers the benefits of a minimal use of materials and therefore an efficient coverage of space. Such a structure can be made either in situ in the case of concrete or in a factory in the case of steel or aluminium. Except in the case of a spherical gridshell, the repetition of the ele- ments is very limited and the shell is made from a com- plex set of components. In contrast, a timber gridshell enables doubly curved structures to be formed from a set of straight, prefabricated, identical components. A number of Happold's partners at Buro Happold had worked with him on the Mannheim gridshell and, when the opportunity arose to design a series of small land- scape structures at the Earth Centre, near Doncaster, UK, in 1994, gridshells were proposed. [Har+03, p. 2]

"The key to the modern use of timber gridshells is the development of computer methods in modelling complex three-dimensional shell structures. " [Har+03, p. 2]

At present, the architectural significance of grid shells can hardly be fully envisioned. Too little experience has been gained as yet. However, the first signs of a grid shell architecture are already apparent. The projects planned and executed to date and the results of this research work indicate possibilities that open up a wide field of applications for grid shells. Two things stand out above all. The first is the nearly unlimited variety of forms that can be realized with grid shells, the second is the fact that there is no closed shell surface, but rather a simple, spatially curved grid composed of rods. Both features are of fundamental significance. They fully characterize the architectural essence of the grid shell support structure. [BHS74, p. 250]

The beginings

F. Otto and its team started their experimentations in the later 60's. On of the first elastic gridshell known was made in a workshop with students at Berkeley, USA, in 1962 [BHS74, p. 270]. Actually, this gridshell was not a timber gridshell but was made of twin steel rods. The technics started to expands with the construction of a timber gridshell at Essen, Germany the same year. Five years latter, in 1967, he designed two gridshells in wood that served as auditoria inside the German Pavilion for the 1967 exposition in Montreal, Canada. At this time, the IL had somme deep links with a Japanese contratctor called Seibu. This company was partly funding the research at the IL. They built an experiental structure made with tubes of hollow square section in aluminium in 1973 [Bur+78, p. 245]. Somme links were setted up with India too and a quite large bamboo grishell was built there in 1974 [BHS74, p. 304].

Mannheil

Tous ces projets racontent une prise en main progressive (1962-1973), aussi bien technique que constructive, de cette technologie. Ce n'est qu'à l'issu de ce cheminement fait de recherche, d'enseignement, d'expérimentation, en relisant de manière critiques les expériences réalisées, que l'IL se donne la capacité à intervenir en amont d'un processus de conception habituel, et peut pousser sa technology. C'est l'avènement du projet de Mannheim, qui marque l'histoire comme le premier gridshell élastique en bois de grande ampleur (toujours un reccords de surfafce et de portée pour cette typologie structurelle.

Dans l'IL13, on trouve également de nombreuses références à des projets étudiés qui sont restés inconstruit, signe que F. Otto était très solicité pour ce type de struictureS. L'expérience de Mannheim est fondatrice pour l'ingéniérie européne des structures légères. Vont s'y croiser Lehonardt (chez qui commencera) et T. Happol qui fondera plus tard sont propre bureau à Bath et concevra le reste des gridshells iconics.

EN particulier, une experience constructice très riche. Chaque nouveau séminaire, est l'occasion d'expérimenter une nouvelle méthode de mise en forme, un système d'assemble nouveau, une autre façon de contreventer, un autre matériau, une autre façon de couvrir, une forme nouvelle, etc.

The desert

Après Mannheim, il y a un creux de 25 ans. A la lecture de l'IL13 on percoit que les outils développés par F. Otto sont très avangardistes et ne peuvent pas s'"appliquer à des contextes plus courant (écomie, temps), recherhce de form sur des maquettes physiques à divers échelles, mesures élaborées par photogramétrie, calculs informatiques (les premiers pour l'époque). Celà est mis en valeur par T. Happold dans son article de Dowland, le manque d'outils numériques.

Néanmoins, cette espérience aura été formatrice pour un grand nombre d'ingénieurs ayant travayé sur ce projet, en témoigne la richesse et la diversité des articles regroupés dans l'IL13. C'est d'ailleurs le propre de tels projets : une expérience collective qui amène un saut technique, une rupture, au sein de la profession, en ce sens qu'il plante les graine pour la diffusion d'un savoir nouveau. Lorsque de tels projets commenceront à refaire surface, le B. Happold aura l'exculsivité sur la conception de la grille.

De pettis projets se font ci et là, en continuant d'explorer les système constructifs et en particuler la question de l'enveloppe. Sous l'impulsions des héritiers directes de l'expérience de Mannheim. On rappemle qu'à Mannheim, le gridshell n'était pas isolé. Par exemple un projet avec du FerroCement. Une activité effective jusque à la fin des années 70. Puis s'en suit une vrai periode de trou. Il faut attendre 1995 pour voir réapparaitre ce qui resseble à un gridshell (tissé sur son cintre) à Hooke Par, pour la Westminster Lodge. On retrouve sur ce projet, centré sur la valorsation des thinnigs, F. Otto et T. Happold [BDH98]. En 1998, Happold renoue avec les GS à l'occasion de la construction du Earth Center.

Le renouveau

Avec les nouveau logiciesl de calcul, celà ouvre des portes. EN 2000 Shieru Ban, assisté de F. Otto propose un gridshell en tubes de carton pour l'expo de Hannover. Le bureau sera Happold (T. H étant décédé).[MBO06]. Le projet rencontrera de nombreuses difficultrées techniques (des problèmes de creep dans les tubes nécéssitreons un renforcement par des arches un bois, qui serviront également au contreventement du gridshell en carton). Et des difficultées avec le controleur technique allememand. Donc toile PVC transparent supplémentaire par dessus la toile en papier, spécialement développé.

En 2002, c'est le grand retour du gridshell bois avec Downland [Har+03]. Confirmé avec Savill [HHR08]. Projets tous effectués avec le même charpentier Green Oak Carpentery, signe de l'importance de la sinérgie entre architecture, conception et construction. Cette équipe réitère pour l'orangerie en 2006 avec une couverture en verre. Ce sont les premiers bâtiments de ce nom, qui assurent plus qu'une couverture, mais un véritable clos couvert, avec de l'isolation.

Ces projets restent dans le ligne historiuque dessinée à Mannheim par F. Otto et ses collègues.

Des pistes ouvertes

Les méthodes numériques de Day, Barnes, Adriaenssen, Douthe, Lefevre, Tayeb

Le formfinding vs. grid finding (COmpas Lionel, Compas Baptise, GFFT, Compas Yannick singularité)

Les matériaux composites

Les méthodes de montage. L'inflatable(Otto, Pugnale, Quinn)

La simplification (gridshell.it => ZA, UTSA, Cluj, quaternion + Navier, Navier)

La robotisation de la production (ENPC)

Une reflexion sur l'enveloppe (booby ENPC).

N	Nickname	Year	City	Country	Type	Architecte	Enginneer	Ref
1	Berkeley	1962	Berkeley	USA	Prototype	F. Otto	F. Otto	[BHS74]
2	Essen	1962	Essen	Germany	Pavilion	F. Otto	F. Otto	[BHS74]
3	German Pavillion	1967	Montreal	Canada	Pavilion	F. Otto	F. Otto	[BHS74]
4	Seibu	1973	Tokyo	Japan	Prototype	K. Matsushita	T. Shirayanagi	[Bur+78, p. 245]
5	Ahmedabad	1976	Ahmedabad	India	Building	G. Sarabhai	G. Ramaswamy	[Bur+78, p. 249]
6	Bamboo	1976	London	England	Workshop	J. Park	B. Oleiko	[Bur+78]
7	Mexico	1973	Tokyo	Japan	Protorype	J. Hennicke	J. Hennicke	[Bur+78]
8	Mexico	1973	Tokyo	Japan	Workshop	J. Hennicke	J. Hennicke	[Bur+78]
9	Mexico	1977	Zitacuaro	Mexico	House	F. Montero	F. Montero	[Bur+78]
10	Mannheim	1975	Mannheim	Germany	Building	C. Mutschler	Arup + F. Otto	[Bur+78]
11	Japan Pavilion	2000	Hannover	Germany	Pavilion	S. Ban + F. Otto	Buro Happold	[]
12	Downland	2002	Singleton	England	Building	E. Cullinan	Buro Happold	[Har+03]
13	Savill	2006	Englefield	England	Building	G. Howells	Buro Happold	[HHR08]
14	Chiddingstone	2007	Chiddingstone	England	Canopy	P. Hulbert	Buro Happold	[]

Table 1.1 – Key numbers.

N	Year	Nickname	Type	City	Country	Architecte	Engineer	Page	Citation
1	1962	Experimental structure	Workshop	Berkeley	USA	Students	F. Otto	p. 270	[BHS74]
2	1962	Exhibition pavilion	Pavilion	Essen	Germany	F. Otto	F. Otto	p. 272	[BHS74]
3	1967	German Pavilion	Pavilion	Montreal	Canada	F. Otto	Lehonardt	p. 274	[BHS74]
4	1973	Seibu	Experiment	Tokyo	Japan	IL	IL	p. 245	[Bur+78]
5	1974	Basket shell	Experiment	Amehabad	India	G. Sarabhai	IL	p. 304	[BHS74]
6	1974	Experimental structure	Experiment	London	England	Students	Arup + IL	p. 306	[BHS74]
7	1975	Mannheim Multihalle	Building	Mannheim	Germany	C. Mutshler	Arup + IL	p. 308	[BHS74]
8	1973	Ferrocement gridshell	Building	Ahmedabad	India	G. Sarabhai	G. Ramaswamy + IL	p. 248	[Bur+78]
9	1976	AA Bamboo Latice Shell	Workshop	London	England	Students	J. Park + B. Oleiko	p. 255	[Bur+78]
10	1976	Test structure of a gridshell	Experiment	Stuttgart	Germany	Students	J. Hennicke	p. 298	[BHS74]
11	1977	Small Pavilion	Workshop	Mexico City	Mexico	Students	J. Hennicke	p. 258	[Bur+78]
11	1977	Small Greenhouse	Workshop	Zitacuaro	Mexico	Students	F. Montero	p. 260	[Bur+78]
12	1977	Experimental structure	Workshop	Mexico City	Mexico	Students	F. Montero	p. 270	[Bur+78]
13	1977	Experimental structure	Workshop	Mexico City	Mexico	Students	F. Montero	p. 270	[Bur+78]
14	1995	Westminster Lodge	Building	Dorset	England	E. Cullinan	F. Otto + Happold	p. 90	[BDH98]
15	1998	Earth Center	Building	Doncaster	England	Grant	Happold		
16	2000	Japan Pavilion	Pavilion	Hannover	Germany	S. Ban + F. Otto	Happold		[MBO06]
17	2002	Downland	Building	Downland	England	E. Cullinan	Happold + C. William		[Har+03]
18	2003	Life Science Centre Trust	Building	Pishwanton	England				
19	2006	Savill	Building	Savill	England	G. Howells	Happold + C. William		[HHR08]
20	2007	Chiddingstone Orangery	Roofing	Kent	England	P. Hulbert	Happold		
21	2007	ENPC	Experiment	Noisy-Champs	France	Navier	Navier		[DBC06]
22	2011	Solidays	Pavilion	Paris	France	ENPC	Navier + T/E/S/S		[Bav+12]
23	2012	Toledo	Workshop	Naples	Italy	gridshell.it	B. D'Amico		[DKZ14]
24	2013	Créteil	Building	Créteil	France	T/E/S/S	T/E/S/S + Navier		[dPel+16]
25	2014	Toledo 2.0	Workshop	Naples	Italy	gridshell.it	B. D'Amico		[DAm+15]
26	2016	JPO	Pavilion	Toulouse	France	Quaternion	Navier + Terrell		
27	2016	FAV	Pavilion	Montpellier	France	Quaternion	Navier + Terrell		
28	2016	CLC	Workshop	Noisy-Champs	France	ENPC	Navier		
27	2016	Trondheim	Workshop	Trondheim	Norway	Students	NTNU		[Had+16]

		Project		Structure		
Year	Nickname	Country	Duration	Material	Layer	Pitch
1975	Mannheim	Germany	LT	hemlock	double	0.5 m

Table 1.3 – Key numbers.

[1] [2]

1.2 Building free-forms

1.2.1 Non-standard forms

1.2.2 Importance of free-forms in modern architecture

1.2.3 Canonical approaches to build free-forms

1.2.4 Main challenges

1.3 Gridshell structure : definition and classification

1.3.1 Historic overview

1.3.2 Rigid gridshell

1.3.3 Elastic gridshell

The invention of the gridshell concept is commonly attributed to Frei Otto, a German architect who devoted several years to gridshells. In 1975 he achieved the famous *Mannheim Multihalle* [HL75], a wooden shell of 7500 m^2, in collaboration with the engineer Edmund Happold (Arup). Literally, the word "gridshell" refers to grids behaving like shells : from a mechanical point of view that means stresses acting on the structure are mainly transmitted through compression and traction. These structures can cross large-span with very little material.

However, according to the historic evolution of the concept, characterizing a gridshell as the combination of a structural concept – a grid behaving like a shell – and a specific construction process – using the bending flexibility of the material – seems to be more accurate. The Mannheim project (in which a wooden regular and planar grid, lacking shear stiffness, is elastically deformed up to a targeted shape with the help of stays, and then braced and covered) is regarded as the starting point of this new concept.

The Mannheim project is regarded as the starting point of this new concept for which a wooden regular and planar grid, lacking shear stiffness, is elastically deformed up to a targeted shape with the help of stays, and then braced and covered. This type of gridshell, known as elastic gridshell, offers a very elegant manner to materialize freeform shapes from an initially flat and regular grid, which obviously has many practical benefits: planar geometry, standard connection nodes, standard profiles and so on.

[1] German pavilion 1967 : https://www.youtube.com/watch?v=Z0mtFMoseUk
[2] German pavilion 1967 : http://www.uncubemagazine.com/magazine-33-15508949.html/page1

(a) Forum Café, Solidays (2011).

(b) Prototype (2007).

(c) Prototype (2008).

Figure 1.1 – Prototypes and projects of GFRP elastic gridshells.

1.4 Elastic gridshells : revisiting Mannheim

1.5 Elastic gridshells : the benefits of composite materials

Glass fiber reinforced polymer (GFRP) tubes are at the heart of the presented technology. They can favorably replace wood where both resistance and bending ability of the material is sought [DCB10].

The tubes are made by pultrusion, “a continuous molding process whereby reinforcing fibers are saturated with a liquid polymer resin and then carefully formed and pulled through a heated die to form a part. Pultrusion results in straight constant cross section parts of virtually any shippable length”.[3] This process is very economic and its standardization guarantees very stable material and mechanical properties. It frees designers from the problem of joining wood pieces with finger joints to obtain long and continuous members and of wood durability.

[3] Video explaining the pultrusion process : https://www.youtube.com/watch?v=4MoHNZB5b_Y

(a) Mannheim (1975).

(b) Mannheim (1975).

(c) Downland (2002).

(d) Downland (2002).

(e) Savill (2006).

(f) Savill (2006).

Figure 1.2 – Major permanent projects of elastic wooden gridshells built since 1975.

1.6 Gridshells

1.6.1 Recent projects

In 2000, Shigeru Ban innovated by shifting from wooden materials to cardboard for the construction of the Japan Pavilion at the Hanover Expo [**McQuaid2006**]. More recently, with the development of numerical tools, two new projects were carried out: the wooden gridshells of Downland in 2002 (Weald and Downland Gridshell, Chichester, UK) [Har+03] and Savill in 2006 (Savill Garden Gridshell, Wick Ln, UK) [HHR08]. The principles of these projects are similar to that of Mannheim; however, new construction methods were used for the newer gridshells.

The first research works on elastic gridshells are attributed to Frei Otto, founder of the *Institute for Lightweight Structures* (IL, Stuttgart, Germany). Probably one of his first elastic gridshell was built in 1962 with students at Berkley, USA, and was made with steel rods and not wooden elements. During the 60's, he built several experimental structures including one at Essen in 1962 and two at Montreal in 1967 [Lid15]. In 1975 he completed the famous Mannheim Multihalle, a wooden shell of 7500 m^2, in collaboration with the engineer Edmund Happold [**Otto1976**, HL75]. This project is generally regarded as the starting point of this new concept.

In 2000, Shigeru Ban innovated by shifting from wooden materials to cardboard for the construction of the Japan Pavilion at the Hanover Expo [**McQuaid2006**]. More recently, with the development of numerical tools, new projects were carried out : the wooden gridshells of Downland, UK, in 2002 [Har+03] and Savill, UK, in 2006 [HHR08]. The principles of these projects are similar to that of Mannheim. However, new construction methods were used for the newer gridshells. The flat lattice of the Downland gridshell was built on a modular scaffold platform, which height was altered progressively to deform the lattice. The grid was braced by a third direction of laths. The lattice of the Savill gridshell was built on a fixed scaffold platform. Small jacks where used to deform the lattice, pushing from below. The grid was then braced with plywood panels, which also served as the first cladding layer.

The Orangery roof at Chiddingstone Castle is a smaller gridshell built in 2006. The lattice is very similar to the one employed in Downland. But this time the grid is braced with a diagonal cable network and the cladding is made of triangular glass panels (the first of this kind). To this end, the steel connection includes a cable clamping system and is equipped with a threaded hole to accept fixing parts for the glazing.

1.6.2 Recent developments

Based on this groundwork, the Navier laboratory has developed a research program on gridshells for the last decade, focusing on both the use of new materials and the development of more efficient numerical methods [Dou07]. These developments have been validated by the construction of two prototypes (Figures **??**a and **??**b) whose areas were about 150 m^2.

In 2011, the laboratory used its expert knowledge for a large-scale project [Bav+12], the forum of the Solidays festival (??c). This achievement, built by voluntary workers, has been the first composite material gridshell to house public.

In 2012, the context is favorable for a new achievement named *"Temporary Cathedral of Créteil"*. Although this gridshell has an area very similar to the Solidays one, the project raised new challenges, in particular the challenge of reliability. Indeed, its period of use is at least two years. Additionally, the skills coming from T/E/S/S company made possible important developments such as for doors, lacing edge beam, anchorages and sleeves.

Unlike the two first prototypes, the gridshells built for Solidays and at Créteil are based on a new approach regarding shape-structure relationship. Indeed, thanks to a numerical tool performing the compass method, the geometry of the object is no longer defined as the reversal of a hanging net – in this case, only the flat geometry could be mastered [Add13] – but now the flat geometry is straight deducted from the one proposed by the architect. This new approach opens up new architectural horizons, making possible the exploration of new shapes for gridshells.

The Faraday Pavilion : [NLG13] The Pishwanton / lothian : [**Pishwanton2003**] The laboratory Navier tested various numerical methods to generate such grids [BBC09] Masson : [MM17].

1.6.3 Gridshell in composite material

The benefits of GFRP gridshells have been covered previously. We just recall the main aspects.

The gridshells built in composite material, being at the heart of this paper, are consistent with the framework defined previously, that is to say :

Glass fiber reinforced polymer (GFRP) tubes are at the heart of the presented technology. They can favorably replace wood where both resistance and bending ability of the material is sought [DCB10].

The tubes are made by pultrusion, “a continuous molding process whereby reinforcing fibers are saturated with a liquid polymer resin and then carefully formed and pulled through a heated die to form a part. Pultrusion results in straight constant cross section parts of virtually any shippable length”.[4] This process is very economic and its standardization guarantees very stable material and mechanical properties. It frees designers from the problem of joining wood pieces with finger joints to obtain long and continuous members and of wood durability.

[4]Video explaining the pultrusion process : https://www.youtube.com/watch?v=4MoHNZB5b_Y

Structural Typology

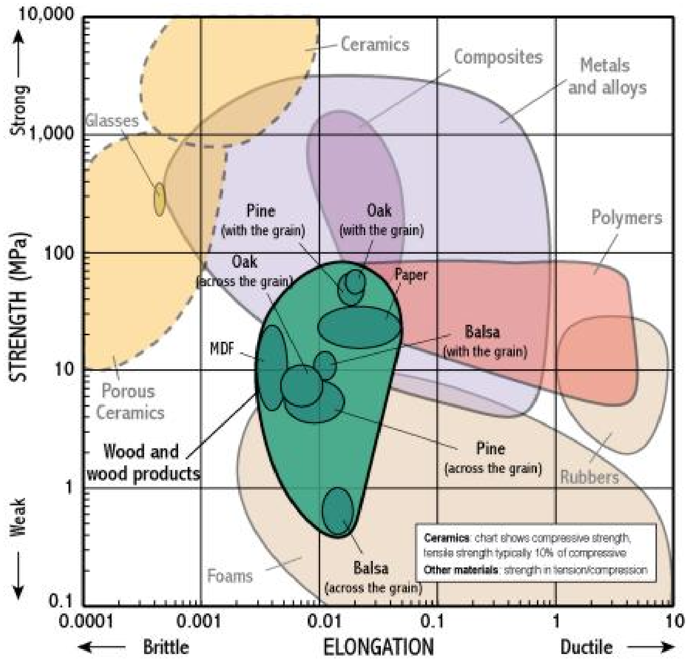
Their mechanical behaviour is very similar to the one of real shells even if the material is discrete and located in a grid more or less open. In spite of that, gridshells benefit from the same advantages as the ones showed by an eggshell : they can cross large span using a low amount of material. Their stiffness is mainly linked to their double-curved shape.

Material Flexibility for Structural Rigidity

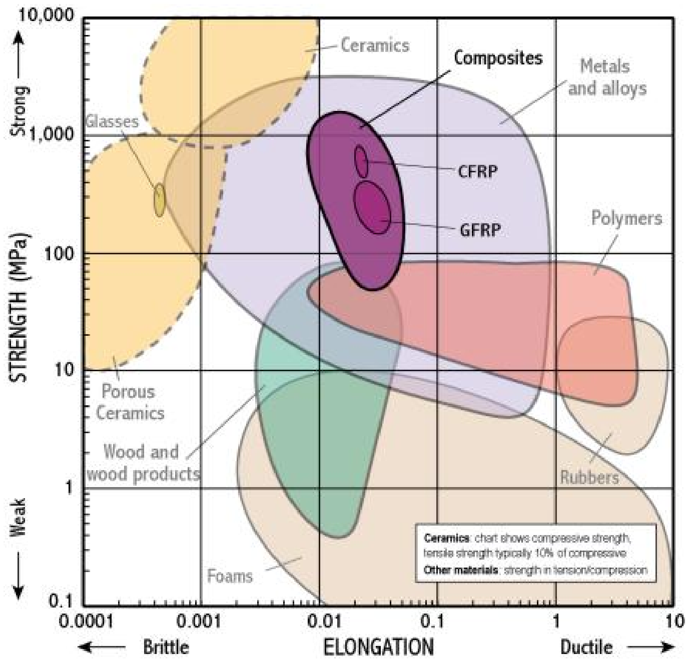
In this field of application, composite materials like glass fibre reinforced polymer (GFRP) could favourably replace wood, where both resistance and bending ability of the material is sought [DCB10]. The stiffness of the structure does not derive from the intrinsic material rigidity but principally from its geometric curvature. Ideally, the composite profiles are produced by pultrusion, an economic continuous moulded process. The standardization of the process guaranties very stable material and mechanical properties. It frees designers from the painful problematic of wood joining and wood durability. The characterization of this material is presented further in the paper.

Erection Process

Usually, the grid morphology is not trivial and leads to design numerous costly and complex joints. To overcome this issue, an original and innovative erection process was developed that takes advantage of the flexibility inherent to slender elements. A regular planar grid made of long continuous linear members is built on the ground (Figure 1.5a). The elements are pinned together so the grid has no in-plane shear stiffness and can accommodate large-scale deformations during erection. Then, the grid is bent elastically to its final shape (Figure 1.4). Finally, the grid is frozen in the desired shape with a third layer of bracing members (Figure 1.5b) and the structure becomes a shell.



(a) Forum Café, Solidays (2011).



(b) Prototype (2007).

Figure 1.3 – Prototypes and projects of GFRP elastic gridshells.

Figure 1.4 – Erection of the primary grid by two cranes

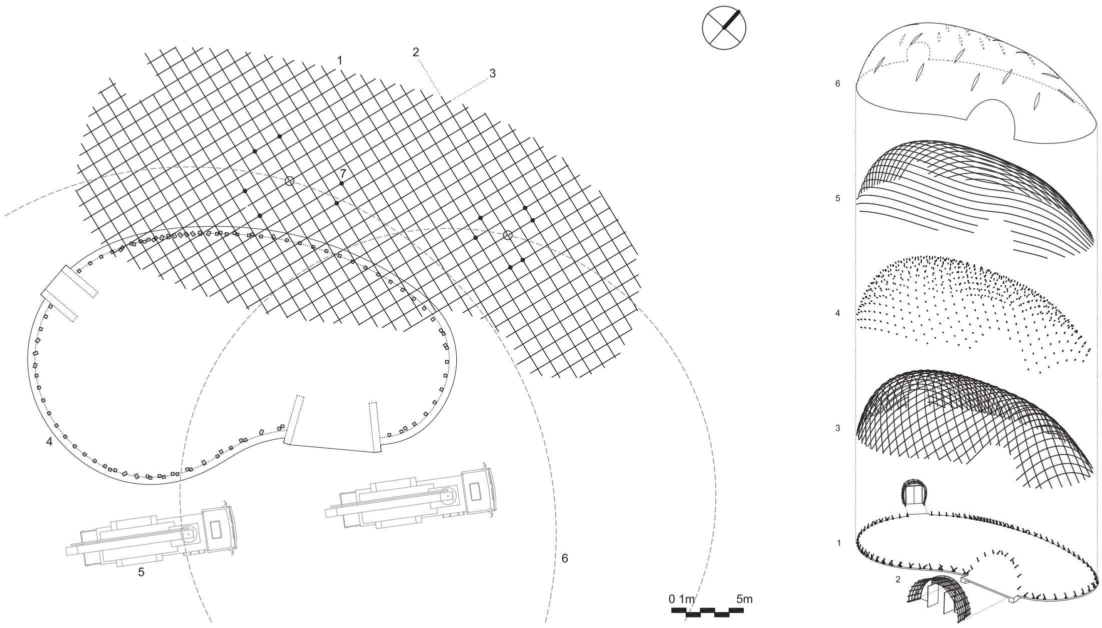


Figure 1.5 – Erection plan and construction stages

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