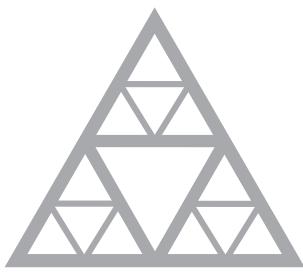


Modeling of bending-torsion couplings in active-bending structures. Application to the design of elastic gridshell.



École des Ponts
ParisTech

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par

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2 Ephemeral cathedral : the first GFRP gridshell building

2.1 Introduction

The Ephemeral Cathedral of Créteil, France, is an elastic gridshell structure made of composite materials. Built in 2013, this 350 m² religious edifice was initially a temporary church meant to gather the parishioners during the two year (2013 - 2015) renovation of their permanent cathedral (see [fig. 2.1](#)). At the time of writing, this building is still in activity and has been erected for almost five years. Although this structure is no more a church it has been converted to a space for community activities and is now the property of the city of Créteil.

This large-scale prototype represents a first in the building industry which still shows excessive apprehension for the use of non-traditional materials such as composites, especially when it comes to structural applications. This is emphasized by the fact that only pre-norms or professional recommendations exists for composite materials, which is quite insufficient when one has to deal with insurers and legal technical controls.

Although this structure is not the first elastic gridshell ever built in *Glass Fiber Reinforced Polymer* (GFRP) composite material, it should be regarded as the first true building using this technology. Indeed, this prototype – which can legally accommodate up to 500 people – complies with all the required performances : structural stiffness, fire safety, waterproofness, lightning, thermal comfort, etc. To our knowledge, this building is still the only one of this kind ever built.

It is worth to mentionne that this project arises thanks to a long-term collaboration between T/E/S/S atelier d'ingénierie¹ and the laboratory Navier² and marks the accomplishment

¹A structural design firm based in Paris, France : <http://tess.fr>

²Architected Materials and Structures (AMS) research team, specializes in the field of mechanics of materials and structures : <http://navier.enpc.fr/Materiaux-et-Structures?lang=en>

of a ten years research project in this field.³ More over, this challenge was both technical and human as the structure was built by the parishioners them selves.

In this chapter, we present the main aspects of the design and construction of this structure. This project was at the heart of the motivations of this thesis as it acted as a proof of feasibility and as a validation of the design tools and methods developed until then ; and the gained experience has highlighted further research directions that are presented in this manuscript.

2.2 Project overview

2.2.1 Context and challenges

Créteil is a city of 90.000 inhabitants in the southeast suburb of Paris. Its urbanization began in the late 50's, impelled by the French architect Charles-Gustave Stoskopf. In 1976 he designed Notre Dame of Crêteil, a modest catholic church made of concrete, which became a cathedral 10 years later (see item 2 in [fig. 2.1](#)). Recently, the diocese of Crêteil has undertaken a major architectural redevelopment project of its cathedral, including a timber shell covering the religious area and the creation of a new cultural area. Once transformed, the edifice shall be more visible, more hospitable and livelier for citizens. Inevitably, such a molt takes time and a temporary place of worship was required to ensure liturgical services during the two-years work. In November 2011, T/E/S/S, the structural design office in charge of the cathedral renovation project, made an ambitious proposal to the diocese : based on a previous successful experience – the construction of a composite gridshell for the festival Solidays [[BCTdP12](#)] – T/E/S/S suggested that rather installing a basic tent, the parishioners should construct themselves a temporary cathedral.^{4,5}

2.2.2 Architectural considerations on the form

The origin of this building form was driven by two objectives, that is, to provide a variety of appropriate internal spaces within which the community could assemble, and to provide an externally welcoming and visually interesting form. According to the architect Tom Gray, today, the internal organization of a roman catholic church is in large part driven by the post Vatican II vision of a religious celebration being a collective gathering of the community around the Eucharist, center of spiritual life. A circular seating arrangement is often considered the most convivial form to create a sense of belonging while minimizing a sense of hierarchy. However the community is not only using the building for religious celebration but also for encounters on a more informal manner, for example spontaneous gatherings after religious ceremonies. In the early Roman church, such gathering of the

³Note that I developed this project in 2012 while I was a structural engineer at T/E/S/S, using the knowledge I had previously gained on the gridshell project for the Solidays music festival in 2011 while I was a research engineer at Navier. I started this thesis in octobre 2014, 18 months after the opening of the temporary cathedral to pursue my research on this topic started in may 2010.

⁴See the video of the construction of Solidays' gridshell here : <https://youtu.be/24LLfcVIZWw>.

⁵See the video of the construction of Crêteil's gridshell here : <https://youtu.be/jLq-UfOdnQQ>.



Figure 2.1 – Situation map. The temporary gridshell (1) was built very close to the permanent cathedral (2). Remark that the two buildings cover a quite similar projected area.

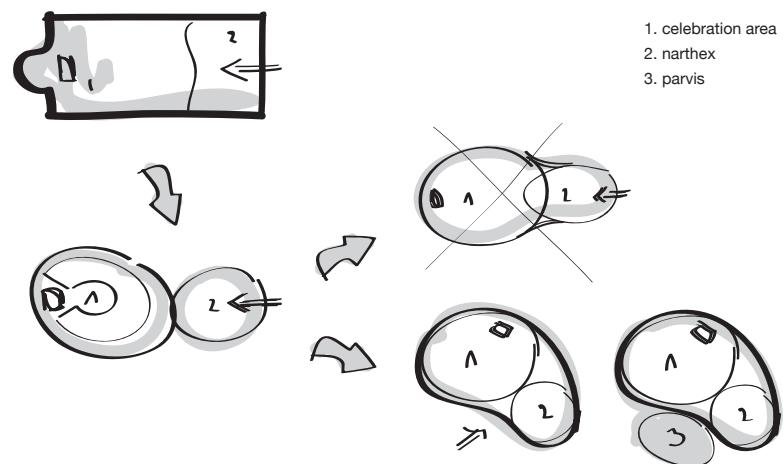


Figure 2.2 – Architectural sketch. Major and minor volumes are agglomerated into one volume. Here, the morphological register allowed by elastic gridshells appears to be relevant.

community was facilitated by the presence of an anti-space to the main space called a *narthex*, through which one passed on entering the church. It was therefore felt appropriate that the formal freedom which the gridshell system offered would be used to explore forms composed of an agglomeration of major and a minor volumes which contain the two functions : formal and informal gatherings (see item 1 and 2 in [fig. 2.2](#)).

Formal explorations were undertaken using modeling clay. The final form is based loosely on two adjacent semi spherical volumes of different size, which are merged into one complex form. Externally the fear of the design team was that the totally convex blob form could look intimidating. It was therefore decided that the two spherical virtual forms, which would be joined to make the final form, would be arranged not in a symmetrical axial manner, but in an asymmetrical curved composition. The resulting form seen in plan is convex on one side and concave on the other. The concave form in plan allows for double curvature to be introduced into what would be otherwise a simpler blob and gives sensuality and visual interest to the building.

2.2.3 Placing of the building on the site

The temporary cathedral is located on a land owned by the municipality, which is used for sporting and other communal gatherings. The curve in the building defines an external area where the church community could meet in the open air and this is where the entrance to the church is situated. The building was positioned on the site so that the entrance addresses a grass planted area forming a garden forecourt or “parvis” (see item 3 in [fig. 2.2](#)). A service building housing plant, toilets and vestry are housed in a portacabin positioned to the rear of the building.

2.2.4 Entrance

It is formally quite difficult to integrate doors, which must be verticals, into a complex geometry. Either the gridshell could be deformed to accommodate the geometrical requirements of doors, or the doors could be integrated into an independent form. The latter approach was chosen. In looking for forms to house the doors, reference was made to the conical monumental doorways with rings of concentric decoration, which welcome the faithful to romanesque and gothic churches in France. The conical forms were found to be coherent to the overall geometry of the building. The entrance doors were therefore inserted into a conical hooded form made of rolled steel plates and stiffened by concentric steel tubes, which not only make reference to historic precedence but also refer to the gridshell to be discovered inside (see [fig. 2.5b](#)). The cone of the entrance doors was positioned in the concave side of the building giving access directly to the narthex part of the internal volume. To the rear of the church is situated a service door. The steel hood, which houses this door, is curved tightly around the door and takes up an ovoid form.



Figure 2.3 – Exterior view. The connections mark the fabric suggesting the interior grid structure. This texture enriches the perception of the building viewed from the outside and creates effects with the light reflections – © L. du Peloux for T/E/S/S.



Figure 2.4 – Interior view. The grid pattern highlights the lightness of the structure and gives its tempo to the internal space. Lines converge to the altar, the heart of the liturgical area where the mass is offered on – © C. Moissinac for T/E/S/S.

2.2.5 Daylight

The gridshell is covered in a PVC membrane, which is opaque. How to introduce daylight into the interior was a major subject of reflection. The simplest way found was to use transparent membrane placed occasionally on the membrane. A small amount of light was required in the interior to create a contemplative atmosphere. The lights would in consequence glow and would be seen as luminous insertions in the vault, like stars in the celestial vault or the apse of some Romanesque churches. The stars were patterned on the joints of the PVC membrane. The almond shape came from simplification of the cutting into the panels either side of the joints and to avoid stress concentrations around cuts in the membrane. This shape, known as Mandela, is frequently used in Marian religious imagery. The distribution of the transparent insertions is quite uniform but gets denser above the pinnacle.

2.2.6 Technical description

The gridshell structure is made of long glass-fibre tubes (42 mm diameter) fastened together with scaffold swivel couplers (see, [fig. 2.6a](#)). The structural members of the grid, all of different lengths, are built from one, two or three composite tubes connected with steel sleeves (see [fig. 2.6b](#)). The length of the tubes is limited to 12 m to enable transportation through standard trucks. The tubes are organized in three layers. During assembly, the first two layers are first placed perpendicular to one another on the ground. They form the *quadrangular primary grid*. The distance between the tubes of these two layers is constant, resulting in a regular grid. This primary grid is elastically deformed to obtain the final shape. The third layer of tubes acts as bracing. It gives the structure a shell-like behavior. The tubes are fixed to the primary grid once the shape has been obtained

The structure is anchored to a concrete strip footing with a special steel system, which ensures transfer of loads from the composite structure to the ground (see [fig. 2.6c](#)). A similar system enables fixation of the structure to the doors (see [fig. 2.5a](#)). A PVC coated fabric (see [fig. 2.3](#)), tailor-made for the purpose, covers the structure. The transparent portion of the structure allows daylight inside the gridshell. The fabric is stretched on the peripheral edge of a dedicated beam with a double-lacing system (halyard and strap, see [fig. 2.6d](#)). At the ground level, the lacing edge of the beam is made of a bent, composite rod nailed to the concrete slab. At the grid-door junction, a steel arch is welded to the doorframe (see [fig. 2.5a](#)).

The PVC fabric is waterproof and, since it is a continuous membrane, has no joints except at the perimeter. At the perimeter, a continuous strip of membrane is prefixed to the internal surface of the membrane and fixed to the ground slab. At the doors, a flexible strip of the membrane is riveted to the doorframe.



(a) Exterior.

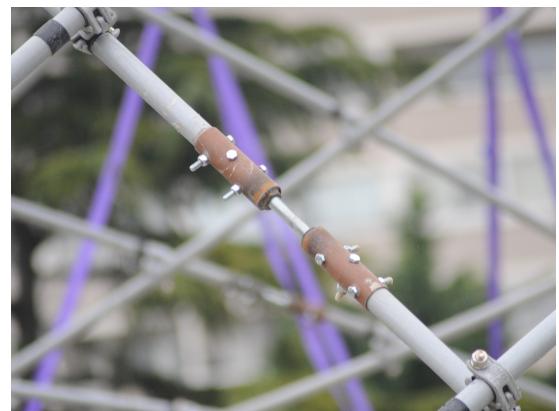


(b) Interior.

Figure 2.5 – Entrance. Two steel doors allow the entrance inside the building.



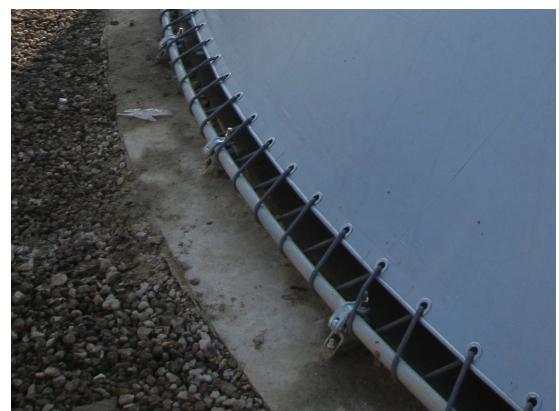
(a) Scaffold swivel coupler.



(b) Steel sleeve.



(c) Ground anchorage.



(d) Edge beam.

Figure 2.6 – Standard elements that composed the structural system.

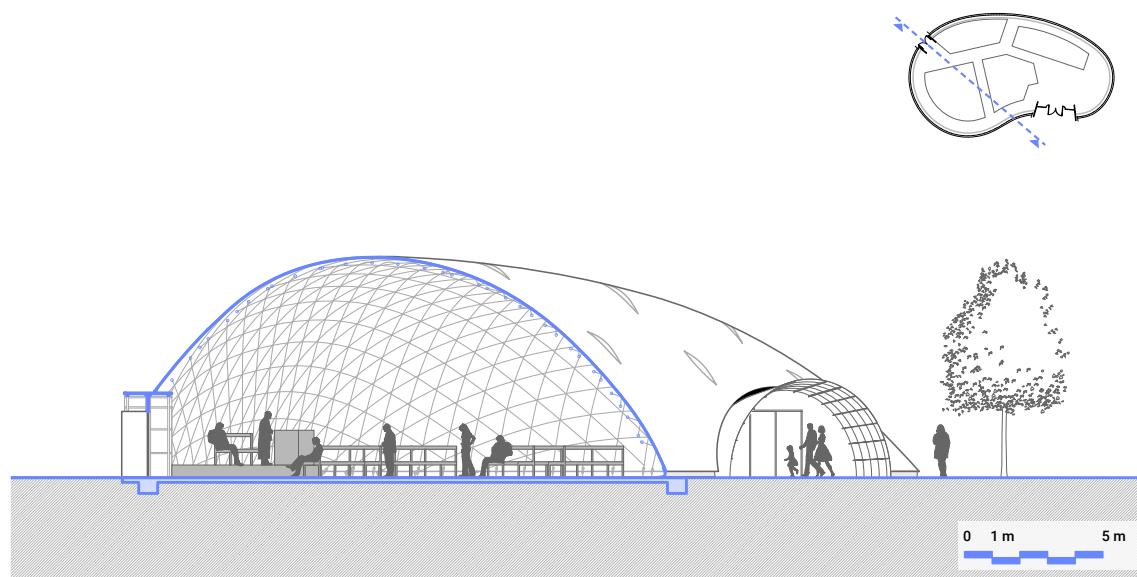


Figure 2.7 – Transversal section of the building. Observe how the grid gets denser at the choir. Two doors give access to the building. The height at the pinnacle is about 7 m.

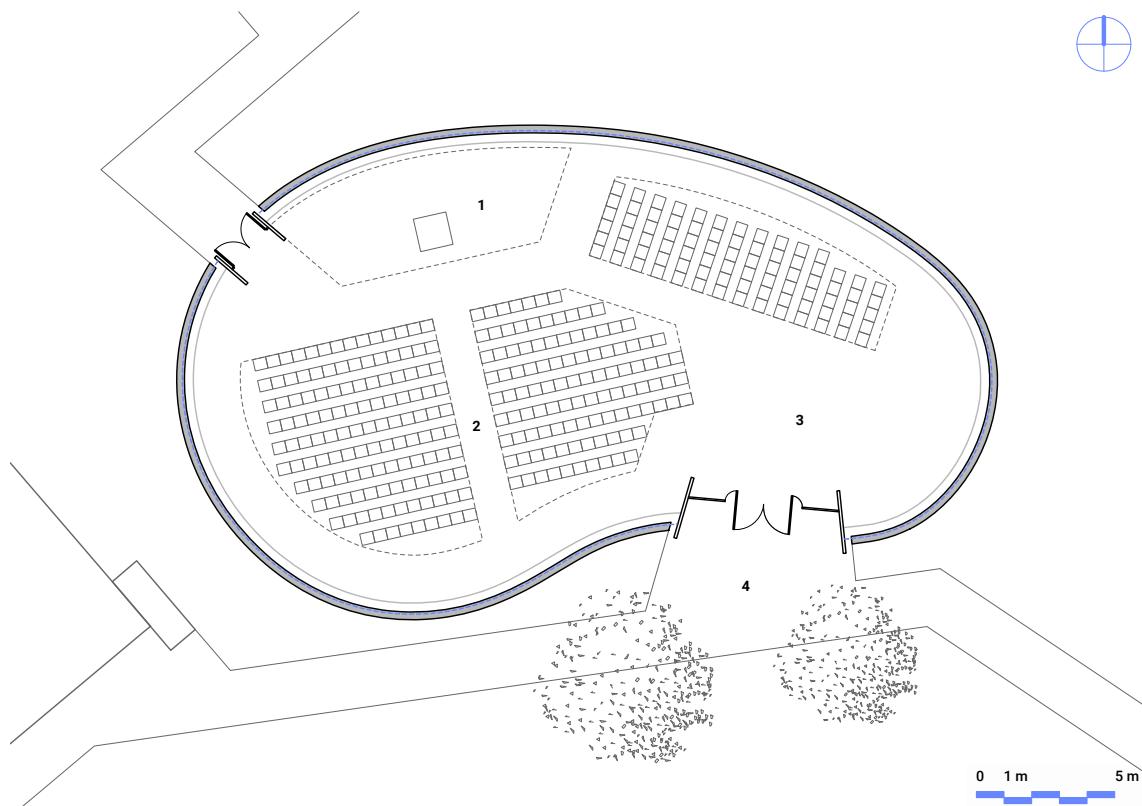


Figure 2.8 – Top view of the building. The interior space is composed of a choir (1), a place of assembly (2) and a narthex (3). The main entrance overlook the parvis (4). The shell spans about 29 m in the longitudinal direction and about 17 m in the transversal direction. The covered area is about 350 m². The space can accommodate 360 seating people or 500 standing people.

Category	Item	Unit	Quantity
Public	seating	p	360
	standing	p	500
Dimensions	length	m	29
	width	m	17
	height	m	7
	contour	ml	75
	area	m^2	350
	volume	m^3	1600
Gridshell	tubes (x176)	ml	1775
	connections		1130
	sleeves		125
	anchorages		127
	<i>ground (single)</i>		77
	<i>ground (double)</i>		16
	<i>door (single)</i>		18
	weight	kg/m^2	5
Fabric	opaque	m^2	530
	transparent	m^2	12
	lacing rod	ml	67
	weight	kg/m^2	1

Table 2.1 – Key numbers.

2.3 Cost analysis

2.3.1 Overall cost for the client

The overall cost of the project is \$500.000, approximately 30% more than the rental for a standard tent of the same size for over 2 years. The overall cost for the client is estimated to € 350.000 (excluding V.A.T). Puis on donne la ventilation générale. It includes design stages, production works and fittings such as the heating system and the electrical network. It does not include the man-hours of the volunteers. The real cost of the design and production studies was higher and was considered as an investment by the design company T/E/S/S.

2.3.2 Detailed cost of the building

2.3.3 Strengths and weaknesses

In this project the prefabrication process represents almost half of the cost in man-hours (see [fig. 2.13](#)). The manufacturing of the grid (cutting pipes, marking nodes, preassembling swivel couplers, sleeves and anchorages, etc.) could easily be automated. Composite materials such as GFRP are easy to cut, mill and drill. Small robot arms can do the job quickly with a better accuracy. This idea has been tested in a workshop at the Ecole des Ponts ParisTech in september 2016.⁶ More over, a numerical production process would allow to answer quickly to a variety of forms with the same equipment and industrial process.

Lots of man-hours are spent in the installation of the sleeve system (88 h) – which represents 35 % of the man-hours spent in the grid prefabrication. This part should be reimplemented to allow a simpler and faster installation. Similarly, the connection should be redesigned to avoid the application of the EPDM protection layer and to allow a faster positioning and fastening as it represents 23 % of the man-hours spent in the prefabrication of the grid. This would also be a preponderant factor of improvement in the bracing stage although this cost is not detailed in [table 2.2](#).

At first sight it seems that the time spending assembling the grid on the construction site – which represents 22 % of the man-hours – can not be easily reduced. However, the grid system could be divided into transportable modules. These modules would be preassembled in the factory to increase the speed and quality of the production and to minimize on-site works. Thanks to the intrinsic grid kinematic, modules can be folded for transportation. Once on site, modules are unfolded and connected to each other to form the primary flat grid. This idea was tested successfully in two wooden gridshell projects of 50 m² each, with students of the Ecole National d'Architecture de Toulouse and Ecole National d'Architecture de Grenoble in June 2016.⁷

⁶See the video of the construction of a 50 m² wooden gridshell in the workshop “Building Free Froms” : <http://thinkshell.fr/freeform-wooden-gridshell-2016/>.

⁷Construction of two wooden gridshell pavilions : <http://www.lemoniteur.fr/article/a-toulouse-les-architectes-se-rassemblent-sous-le-meme-pavillon-32398196>.

2.3. Cost analysis

Bracing is yet another costly stage as it accounts for almost 30 % of the man-hours (see [fig. 2.13](#)). This work is not easily parallelizable as it requires working at height with proper lifting equipments such as cherry pickers. Thus almost a small and qualified team can do the job. For instance, on the gridshell of Crêteil, the team was composed of 6 workers using two aerial lifts. This team spent three full days to complete this task, that is the same amount of days required to assemble the grid and lift it up. Several attempt have been made during this thesis to answer this problematic. The first attempt was to use a bidirectional cable network to brace the grid.

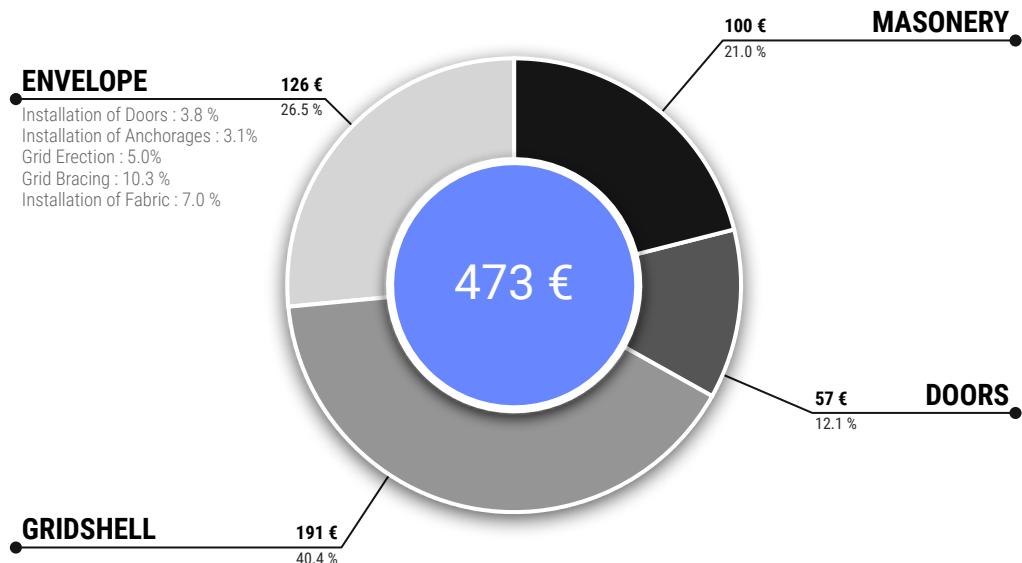


Figure 2.9 – Costs per square meter of covered area. Prices are given excluding taxes (V.A.T is 20 %).

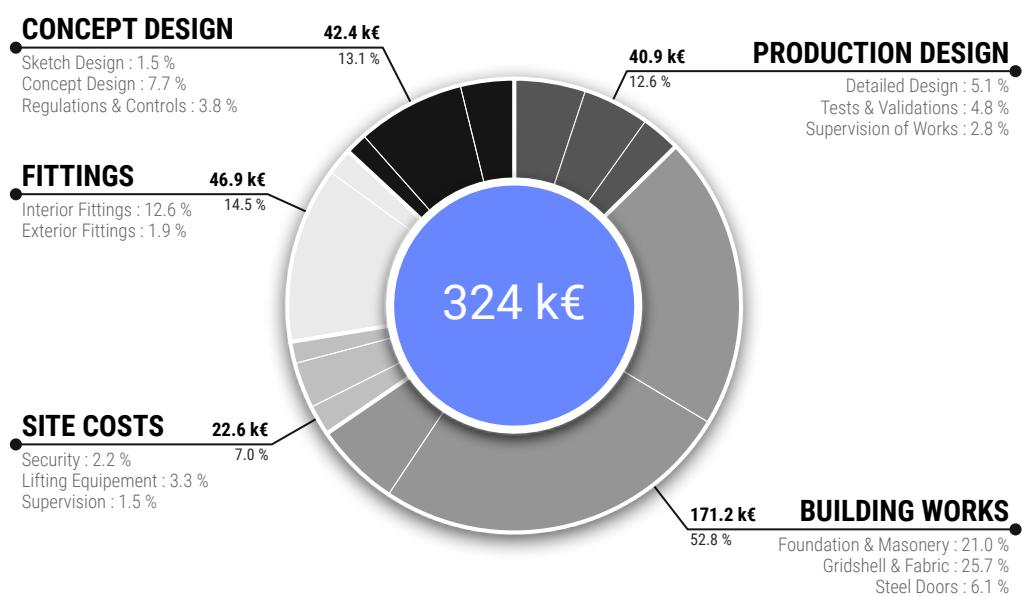
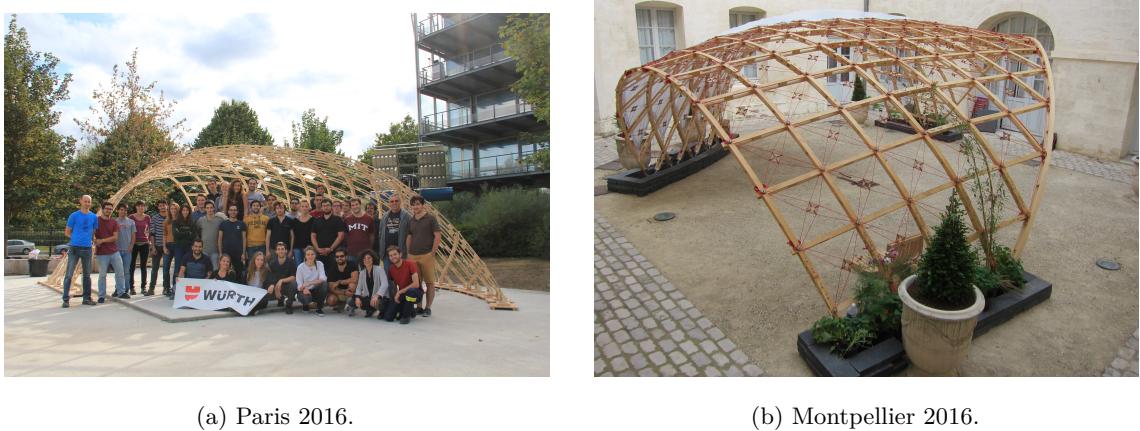


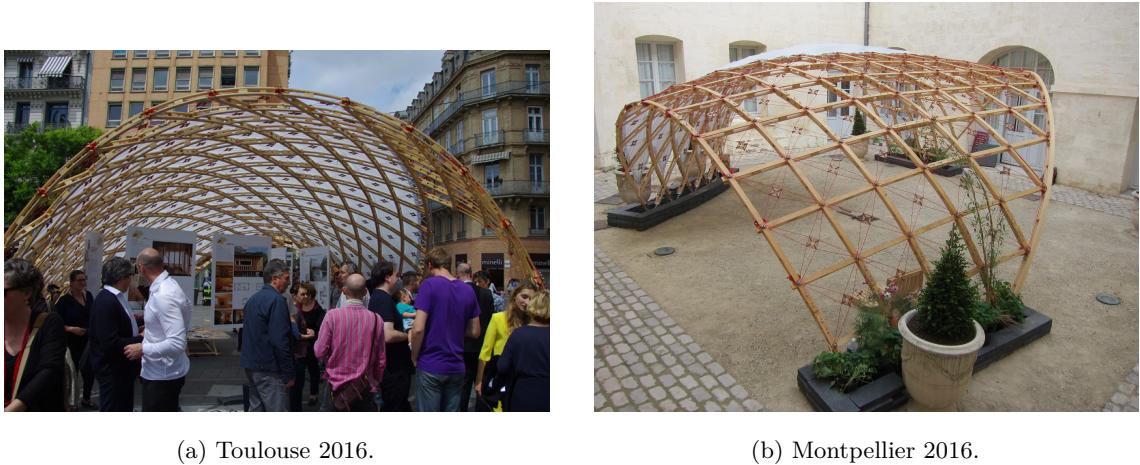
Figure 2.10 – Project's budget. This is the estimated overall cost for the client. Prices are given excluding taxes (V.A.T is 20 %).



(a) Paris 2016.

(b) Montpellier 2016.

Figure 2.11 – Wooden gridshell built during the one-week workshop “Building Free Forms” at the Ecole des Ponts ParisTech.



(a) Toulouse 2016.

(b) Montpellier 2016.

Figure 2.12 – Modular wooden gridshells.

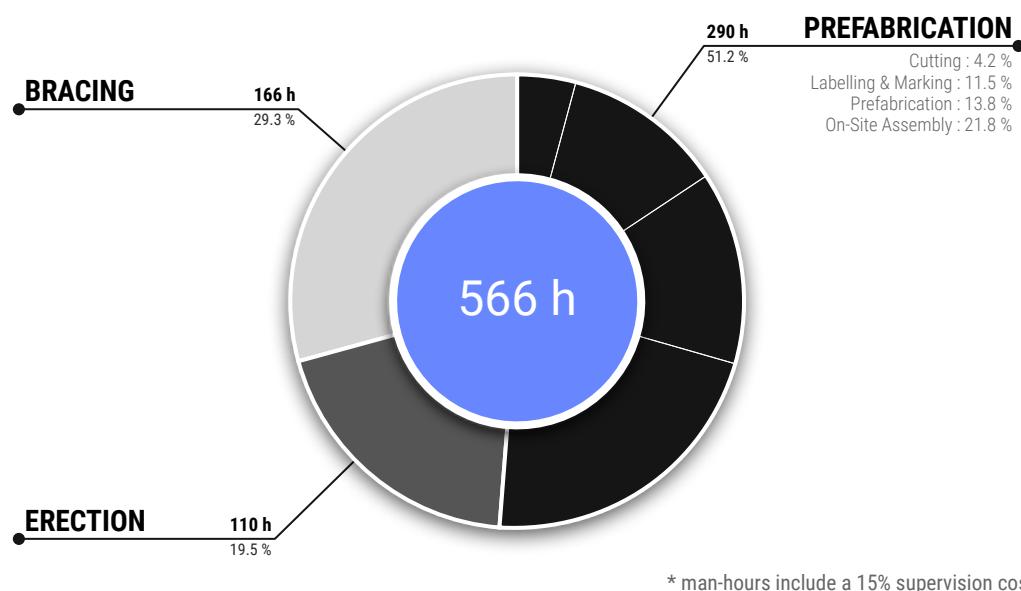


Figure 2.13 – Volunteers man-hours spent on the gridshell fabrication. A 15% increase is considered to take into account coordination and supervision of the individual tasks. See [table 2.2](#) for detailed data.

2.3. Cost analysis

Item	Unit Task		Man-Hours	
	Worker	Duration	Quantity	Hours
Workstation “Cutting”	4			20.53
Pick a raw tube from the stock	2	1' 00"	176	5.87
Mark it and cut it at right length	2	2' 00"	176	11.73
Put it into the labelling stock	2	0' 30"	176	2.93
Workstation “Labelling”	5			56.64
Pick a tube from the labelling stock	2	1' 00"	176	5.87
Label it at start and end	2	1' 00"	176	5.87
Mark the position of connection collars	1	0' 30"	2260	18.83
Mark the position of sleeves	1	0' 30"	250	2.08
Mark the position of anchorages	1	0' 30"	127	21.06
Put it into the prefabrication stock	2	0' 30"	176	2.93
Workstation “Prefabrication”	6			67.75
Pick a tube from the prefabrication stock	2	1' 00"	176	5.87
Put the EPDM ribbon	1	0' 30"	2260	18.83
Prefix the swivel collar on the tube	1	0' 30"	565	4.71
Glue the sleeves	3	2' 00"	250	25.00
Drill pin holes for the sleeves	1	1' 00"	250	4.16
Fix sleeve pins	1	1' 30"	250	6.25
Put it into the final stock	2	0' 30"	176	2.93
Workstation “Site Assembly”	12			107.34
Connect the sleeves with steel rods	5	5' 00"	125	52.08
Pick a tube and position it in the grid	2	3' 00"	176	17.60
Install swivel couplers (HV)	1	2' 00"	565	18.83
Controlled tightening of couplers (HV)	1	1' 00"	1130	18.83
Workstation “Grid Erection”	12	8:00' 00"	1	96.00
Workstation “Grid Bracing”	6	8:00' 00"	3	144.00
Grid prefabrication				252.00
Grid erection				96.00
Grid bracing				144.00
Cost of supervision (15%)				74.00
Total				566.00

Table 2.2 – Volunteers man-hours spent on the gridshell fabrication. A 15% increase is considered to take into account coordination and supervision of the individual tasks. See fig. 2.13 for a graphical representation of these data.

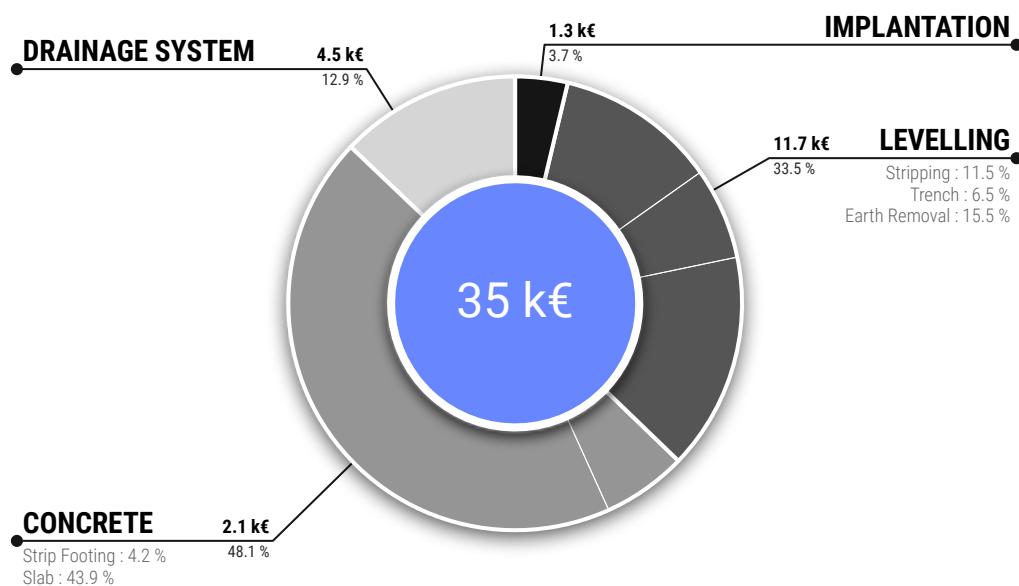


Figure 2.14 – Volunteers man-hours spent on the gridshell fabrication. A 15% increase is considered to take into account coordination and supervision of the individual tasks. See [table 2.2](#) for detailed data.

2.3. Cost analysis

Item	Unit	Quantity	U.P. (€)	Price (€)
Building implantation		1	1 300.00	1 300.00
Leveling works				11 680.00
Top soil stripping	m ²	400	10.00	4 000.00
Trench for concrete strip footing	ml	76	30.00	2 280.00
Earth removal	m ³	180	30.00	5 400.00
Concrete				17 400.00
Concrete strip footing (200 kg/m ³ steel)	ml	70	30.00	2 100.00
Concrete slab (x2 welded wire mesh)	m ²	340	45.00	15 300.00
Drainage systems				4 500.00
French drain (x2 Ø100 mm pipes)	ml	70	30.00	2 100.00
Precast concrete inspection chamber		1	400.00	400.00
Drain line (PVC Ø125 mm pipe)	ml	30	30.00	900.00
Pre-assembled channel drain	ml	10	110.00	1 100.00
Masonry works	€/m ²	350	100	34 880.00

Table 2.3 – Cost details for masonry works. Prices are given excluding taxes (V.A.T is 20 %). Only costs associated to the structure are reported here (for instance the works for the equipment slab and the pathways are omitted).

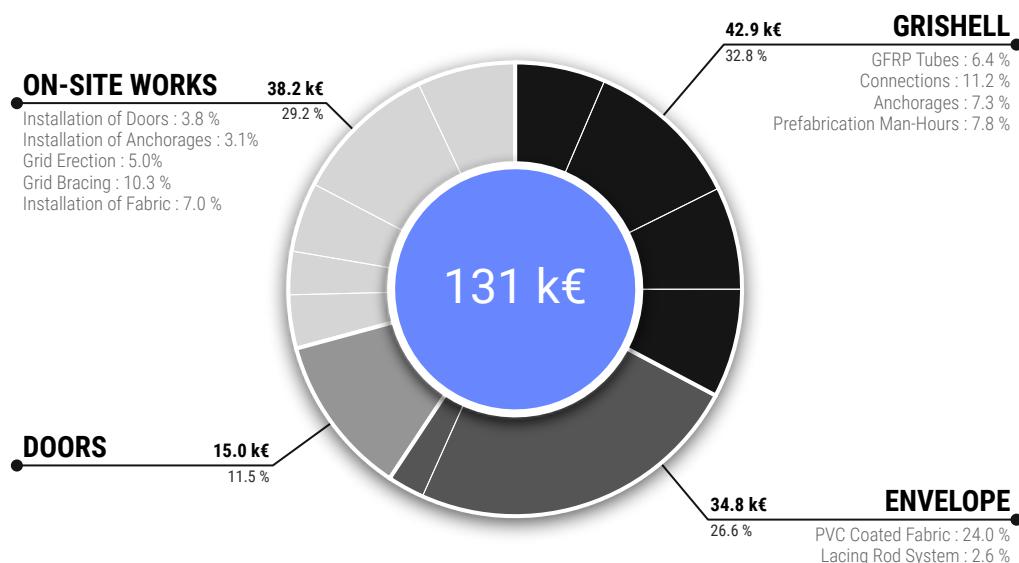


Figure 2.15 – Volunteers man-hours spent on the gridshell fabrication. A 15% increase is considered to take into account coordination and supervision of the individual tasks. See [table 2.2](#) for detailed data.

2.3. Cost analysis

Item	Unit	Quantity	U.P. (€)	Price (€)
Manufacturing of the gridshell				42 853
GRFP tube (Ø42 mm)	ml	2304	3.66	8 433
Swivel connector (42x42 mm)		1295	3.95	5 115
Swivel connector (42x49 mm)		135	4.18	564
EPDM layer (1302x40x1.5 mm ribbon)		2775	0.36	1 131
Welded steel sleeve system		150	50.00	7 500
ARALDIT 2047 glue (480 ml cartridge)		8	45.00	360
Ground anchorage (welded steel)		120	80.00	9 600
Man-hours (prefabrication)	h	290	35.00	10 150
Manufacturing of the envelope				34 769
GFRP lacing rod (Ø32 mm)	ml	96	14.00	1 134
Steel clip for the rod		125	15.00	1 875
Swivel collar (Ø34 mm)		120	3.50	420
PVC coated fabric	m ²	550	50.00	27 500
Option for transparent inclusion		12	320.00	3 840
Manufacturing of the steel doors				15 000
Main door		1	10 000.00	10 000
Small door		1	5 000.00	5 000
On-site works of installation				33 365
Installation of the doors		1	5 000.00	5 000
Installation of the anchorages and clips	h	90	45.00	4 050
Grid erection	h	110	35.00	3 850
cranes (x2 35T)	h	24	110.00	2 640
Grid bracing	h	167	45.00	7 515
aerial bucket (x2)		1	6 000.00	6 000
Installation of fabric		1	9 165.00	9 165
Total	€/m ²	374	363	130 842
Cost of structure			265	92 622
Cost of installation			109	38 220

Table 2.4 – Cost details for superstructure elements. Prices are given excluding transport costs and excluding taxes (V.A.T is 20 %). Only costs associated to the superstructure are reported here. Spare quantities are included.

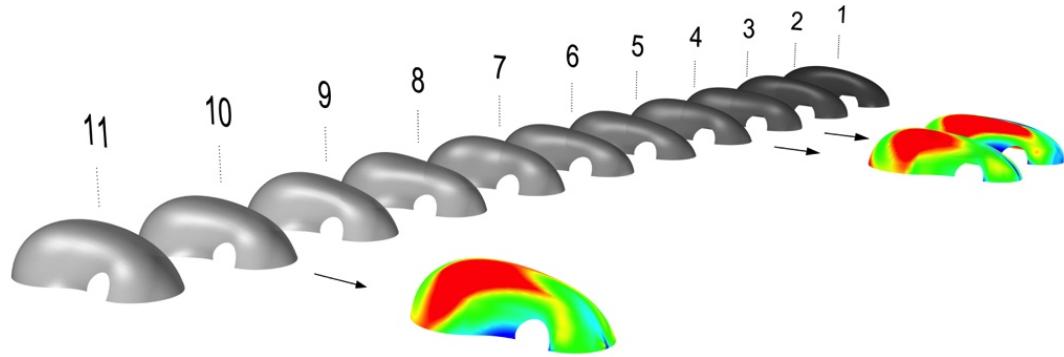


Figure 2.16 – Evaluating the mechanical potential of shapes regarding principal curvatures

2.4 Design Process

2.4.1 Overall design process

The goal of the design process is to identify a gridshell structure that works and respects as faithfully as possible the architectural project – a shape and a program. It represents “the path from shape to structure”. Its progress, sequential and iterative, revolves around three major stages: shape, mesh and structure. It is not trivial to go through this complex process. Indeed, for each step, the method, the tool, the criteria, that offers both a sufficient explorative richness to find out enough candidate solutions, and the means to evaluate and compare the suitability of those solutions, have to be found.

2.4.2 3D modelling of the intended shape

The first step of the process consists in building a precise geometric model from the sketch of the architect and to evaluate its mechanical potential ([Figure 2.16](#)). At this stage, the goal is to estimate the probability a given shape would lead to the generation of a structurally feasible gridshell.

Stresses in the grid are mainly due to the bending of the profiles. They derive directly from their geometric curvature. Thus, the principal curvatures of the surface – because they give a qualitative measurement of the local curvature of any curve drawn on a surface – are relevant indicators to evaluate the stress rate of a grid laying on it. Particularly, one should ensure the following condition is satisfied everywhere, where r is the pipe’s outer radius, R_{min} is the minimum principal radius, E is the flexural modulus, $\sigma_{k,flex}$ the characteristic flexural strength and γ_{lt} the long-term partial coefficient of material resistance :

$$E = \frac{r}{R_{min}} < \frac{\sigma_{k,flex}}{\gamma_{lt}} \quad (2.1)$$

Ideally, the shape is controlled by few key parameters. Thus, it can be adapted and

optimized through an iterative process, towards this criterion.

2.4.3 Mesh from the compass method

During the second step, the candidate surface is meshed and the mechanical potential of the resulting grid is evaluated. At this stage, we try to estimate the probability a given mesh could lead to the generation of a viable gridshell structure. Simultaneously, meshes are compared according to their architectural relevance.

This time, the geometric curvature of the polylines drawn on the surface is the criterion to characterize the mechanical potential of the grid. In particular, one should ensure the following condition is satisfied everywhere, where R_{spline} is the spline's local curvature radius :

$$E = \frac{r}{R_{spline}} < \frac{\sigma_{k,flex}}{\gamma_{lt}} \quad (2.2)$$

The mesh is obtained by the compass method, described in [OSHH74], which develops a regularly spaced grid on a surface from two secant directrix. For a given shape there are an infinite number of meshes. The aim is to identify at least one grid, suitable towards architectural and structural criteria. The laboratory tried various numerical methods to generate such grids [BBC09]. Here, a specific software [dPBCT11], developed for rhino & grasshopper, allows generating this kind of mesh on any NURBS surface.

2.4.4 Formfinding and bending prestress

From now on, the initial form has been optimized and promising meshes for the materialization of the future gridshell have been identified. However, they do not take account of any true mechanical reality, because only geometric rules have led to their generation. The formfinding step consists precisely in finding the geometry of the grid at mechanical equilibrium, and the corresponding permanent bending stresses. The calculations, performed numerically thanks to a dynamic relaxation algorithm with kinetic damping [Bar75], is composed of the following steps:

1. The grid is bent by a set of applied displacements from rest to compass position
2. The grid is then relaxed through its mechanical equilibrium
3. Bending stresses of the triangulation are calculated relative to the relaxed geometry
4. Geometry and bending stresses of the triangulation are reinjected in the model

Two analysis models are built during this process to study the structure with or without bracing tubes. Note that the algorithm has been improved to take account for the eccentricity due to connections [DBC06].

2.4.5 Structural analysis

A full structural analysis is performed on the gridshell, using the two mechanical models created previously during the formfinding stage. The non-braced model is used to check the grid's behavior during the construction stages. In particular, it must be verified that the primary grid - the one with no triangulation tubes - has no risk of buckling, both for obvious safety reasons and to ensure the accuracy of the final geometry. Indeed, the more the form is likely to buckle, the more it can be triangulated in a buckled geometry different to the targeted geometry. The model with the triangulated grid is used to confirm the gridshell complies with all the structural requirements during its lifetime. Its behavior under standard loadings is evaluated.

2.5 Construction details

In this project, one can identify 4 major structural details : the swivel coupler for connecting composite tubes to assemble the grid (??a); the steel sleeve for connecting several composite tubes to make long members from initially short piece of tubes (??b); ground anchorages for fixing the structure to the concrete slab (??c) and the lacing edge beam of the fabric (??d). Note that the tricky issue of connecting steel and composite parts is solved in a similar way through sleeve and anchorage details.

2.6 Codes for composite materials

Beyond the technical difficulties related to both design and structural analysis of the shell, the regulatory framework was a vital issue for the project's success. Because it was the first time a structure of this kind would host regularly a large number of people in a long-term period, the question of its reliability over time was a major issue. To be built the gridshell had to comply with existing standards, which do not take into account such an innovative edifice, all in composite material. The strategy adopted to bypass this obstacle consisted in making the most of the existing regulatory framework to justify the compliance of a structure that would not, at first sight, be taken into account by standards that does not include composite materials. As far as possible, the design was led in compliance with the Eurocodes, where the structural design is made according to limit states under normalized loadings (self-weight, snow, wind, etc.). Despite the Eurocodes do not directly take into account composite materials, they propose some probabilistic methods to introduce new materials (Annexe D). As far as possible, the mechanical properties of the GFRP pipe were determined by tests in conformance with these methods. Otherwise, values were taken according to the Eurocomp [Cla03]. In some cases, as the sleeve, the design of the construction details has also benefited from this approach.

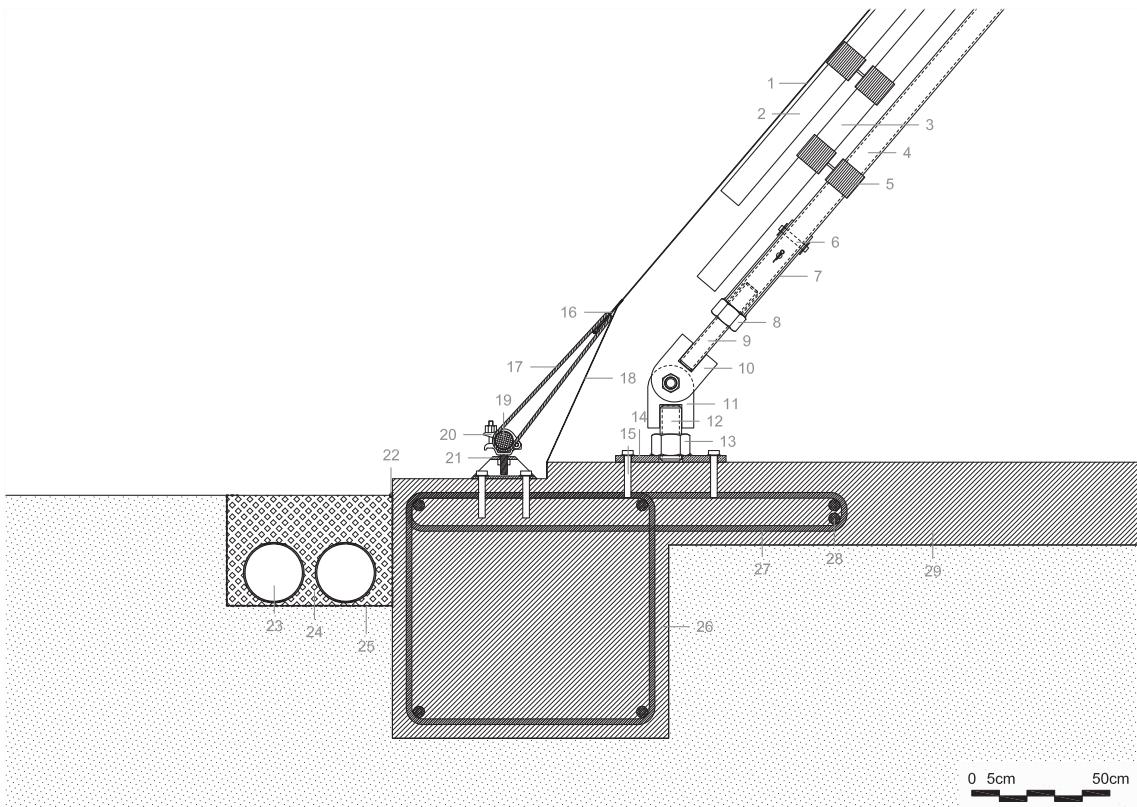


Figure 2.17 – Section on the footer

2.6.1 Flexural strength of the tubes

The characteristic flexural strength ($\sigma_{k,flex}$) of the GFRP tube has a critical impact on the structure's reliability because in this particular application stresses in the tubes are mainly due to bending. Thus, it was important to confirm the manufacturer's value by assays. Three-point flexural tests were led with and without connexions (tightening torque set to 20Nm) to determine the characteristic strength according to the protocol of the Eurocode (Annex D) :

$$\sigma_{k,flex} = \bar{\sigma}(1 - k_n \sigma_x) \quad (2.3)$$

For five tests, the factor $k_{n,5\%}$ is 1.80 , assuming a normal distribution. One can note that the connections scatter the results more (Table 1). Finally, the manufacturer value of 400MPa (ASTM D790) was confirmed and retained for further calculations.

Connections	σ_1	σ_2	σ_3	σ_4	σ_5	$\sigma_{k,flex}$
Without	456	441	445	460	477	430
With	444	478	434	479	427	408

Table 2.5 – Three-point flexural tests of the GFRP tubes (results in MPa)

2.6.2 Partial safety factors

The partial coefficients of material resistance used in the project are calculated according to the Eurocomp (Table 2). The short-term coefficient proposed in the Eurocomp ($\gamma_{st} = 1.3$) was raised to consider the critical stage of erection, where the deformations are not controlled accurately.

Impact	Partial coefficient	Design flexural strength
Short-term	$\gamma_{st} = 2.0$	200 MPa
Long-term	$\gamma_{st} = 3.0$	133 MPa

Table 2.6 – Short-term and long-term values for material resistance.

Note that designers should take care about long-term effects in permanently loaded pultruded composite materials subjected to creeping and relaxation [KW12]. Here, it is reflected in a high partial coefficient for long-term effects.

2.7 Conclusions

This paper has presented the different steps for the design of a gridshell in composite material : a Temporary Cathedral at Créteil, in Paris suburb, in 2013. The first step was the optimization of the shape in order to avoid local concentrations of curvature. The second step showed a tool to automatically mesh a surface using the compass method. With this tool, the orientation of the mesh is studied according to structural and architectural criterions. The last steps showed the structural analysis of the gridshell and how to get the as-built geometry from the analysis model. Architecturally, the structure offers a very interesting space where the textual richness of the tubes against the membrane accentuates the reading of the complex curved surfaces.

This project demonstrates that gridshells in composite material are suitable for constructing freeform buildings. However, the long-term behavior of these materials needs to be better characterized to extend their lifespan.

At the moment, further developments are conducted by the laboratory to take account for torsional effects and non axisymmetric sections in such structures, as it is studied in [BAK13].

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Bibliography

- [Add13] Bill Addis. 'Toys that save millions' - A history of using physical models in structural design. *The Structural Engineer*, 91(4):12–27, 2013.
- [BAK13] Michael Barnes, Sigrid Adriaenssens, and Meghan Krupka. A novel torsion/bending element for dynamic relaxation modeling. *Computers & Structures*, 119:60–67, apr 2013.
- [Bar75] Michael Barnes. Applications of dynamic relaxation to the design and analysis of cable, membrane and pneumatic structures. In *International Conference on Space Structures*, Guildford, 1975.
- [BBC09] Lina Bouhaya, Olivier Baverel, and Jean-François Caron. Mapping two-way continuous elastic grid on an imposed surface : application to grid shells. In *IASS 2009*, pages 989–998, Valencia, Spain, 2009.
- [BCTdP12] Olivier Baverel, Jean-François Caron, Frédéric Tayeb, and Lionel du Peloux. Gridshells in composite materials : construction of a 300 m² forum for the solidays' festival in Paris. *Structural Engineering International*, 22(3):408–414, 2012.
- [Cla03] John L. Clarke. *Eurocomp design code and handbook : structural design of polymer composites*. 2003.
- [DBC06] Cyril Douthe, Olivier Baverel, and Jean-François Caron. Formfinding of a grid shell in composite materials. *Journal of the IASS*, 47:53–62, 2006.
- [DCB10] Cyril Douthe, Jean-François Caron, and Olivier Baverel. Gridshell structures in glass fibre reinforced polymers. *Construction and Building Materials*, 24(9):1580–1589, 2010.
- [Dou07] Cyril Douthe. *Etude de structures élancées précontraintes en matériaux composites : application à la conception des gridshells*. PhD thesis, Université Paris Est, 2007.
- [dPBCT11] Lionel du Peloux, Olivier Baverel, Jean-François Caron, and Frédéric Tayeb. From shape to shell : a design tool to materialize freeform shapes using gridshell structures. In *Design Modelling Symposium*, Berlin, Deutschland, 2011.
- [HHR08] Richard Harris, Steve Haskins, and Jonathan Roynon. The Savill Garden gridshell : Design and construction. *The Structural Engineer*, 86(17):27–34, 2008.
- [HRKJ03] Richard Harris, John Romer, Oliver Kelly, and Stephen Johnson. Design and construction of the Downland Gridshell. *Building research and information*, 31(6):427–454, 2003.

Bibliography

- [KW12] Natalia Kotelnikova-Weiler. *Optimisation mécanique et énergétique d'enveloppes en matériaux composites pour les bâtiments*. PhD thesis, Université Paris-Est, 2012.
- [MO06] Matilda McQuaid and Frei Otto. The Japanese pavilion. In Phaidon, editor, *Shigeru Ban*, pages 8–11. 2006.
- [OSHH74] Frei Otto, Eda Schauer, Jürgen Hennicke, and Takeshi Hasegawa. *IL10 Grid shells*. 1974.