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Construction of a Large Composite Gridshell Structure: A Lightweight Structure Made with Pultruded Glass Fibre Reinforced Polymer Tubes

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Abstract

The Ephemeral Cathedral of Créteil at Paris, France, is a gridshell structure made of composite materials. Built in 2013, this 350 m^2 religious edifice is a temporary church meant to gather the parishioners during the two year renovation of their permanent cathedral. 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.

Keywords: gridshell; composite; glass fibre reinforced polymer; freeform; double curvature; large span.

Introduction

The invention of the gridshell concept is commonly attributed to Frei Otto, a German architect who devoted several years to gridshells. In 1975 he completed the famous Mannheim Multihalle,[1] a wooden shell of 7500 m^2, in collaboration with the engineer, Edmund Happold.

Literally, the word "gridshell" refers to grids behaving like shells: from a mechanical point of view this means that stresses acting on the structure are mainly transmitted through compression and tension. These structures can span large distances with very little material. At Ephemeral Cathedral of Créteil, the whole structure spans 17×29 m^2 and weighs only 5 kg/m^2.

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 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.

After a brief description of the structure, this paper gives an insight into the field of elastic gridshells and discusses the benefits of composite materials in such structures. The overall design process employed, from the three-dimensional (3D) shape designed by the architect to a full structural shell, is then explained. Finally, complexities due to the connections are highlighted and solutions are presented.

Building Overview

Architectural Considerations

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. The interior view of the Ephemeral Cathedral is shown in *Fig. 1*. The chosen form provides under a single roof, a religious space with a circular arrangement and an area for more informal gatherings after ceremonies (*Fig. 2*). Based on a previous successful experience (see video in Ref. [2]), the gridshell was prefabricated and erected (see video in Ref. [3]) by the parishioners themselves.

The building can accommodate up to 500 people and complies with all the essential requirements for such a building: structural stiffness, fire safety, waterproofness, lightning protection, thermal comfort and others.

Technical Description

The gridshell structure is made of long glass-fibre tubes (42 mm diameter, see *Fig. 3a*) fastened together with scaffold swivel couplers. The structural members of the grid, all of different lengths, are

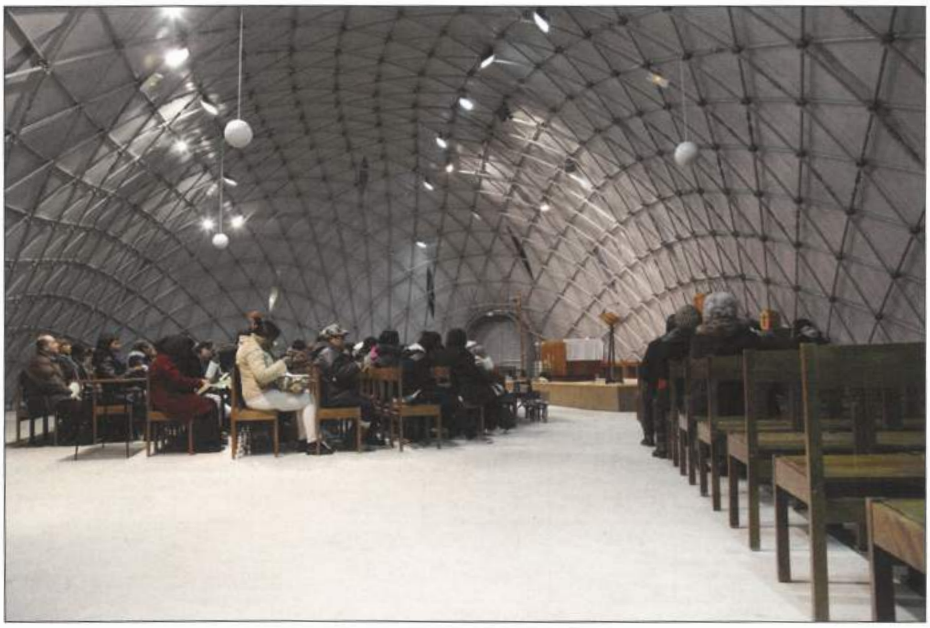

Fig. 1: Interior view of the Ephemeral Cathedral in Paris

the forum of the Solidays festival (*Fig. 4c*). This structure, built by voluntary workers, has been the first composite material gridshell used by the general public.

In 2012, the temporary cathedral of Créteil provided the opportunity to extend this new concept. Although the area of the Créteil gridshell is almost the same as the Solidays gridshell, this project raised new challenges—in particular the challenge of reliability, since its intended duration of use was at least 2 years. Additionally, the skills from the builder made possible important developments such as the addition of doors, a 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 the shape–structure relationship. Indeed, owing to a numerical tool applying the compass method,[9] the geometry of the structure is no longer defined as the reversal of a hanging net—earlier, only the flat geometry could be mastered[10]—but now the flat geometry is deducted from the geometry proposed by the architect.

This new approach opens up new architectural horizons, making possible the exploration of new shapes and new meshes for gridshells.

Gridshell Composed of Composite Material

Gridshells built using composite material (the topic of this paper), are consistent with the framework defined previously.

Structural Typology

Their mechanical behaviour is very similar to the one of real shells even if the material is distinct and the structure is built in a grid pattern. In spite of that, gridshells benefit from the same advantages as the ones enjoyed by an eggshell: they can span large distances using a minimum amount of material. Their stiffness is mainly linked to their doubly curved shape.

Material Flexibility for Structural Rigidity

In this field of application, composite materials like glass fibre reinforced polymer (GFRP) can favourably replace wood, where both resistance and bending ability of the material is sought.[11] The stiffness of the structure is not derived from the intrinsic material rigidity, but principally from its geometric curvature. Ideally, the composite profiles are produced by pultrusion, an economic, continuous moulding process. The standardization of the process 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. The characterization of this material is presented in detail in this paper.

Erection Process

Usually, the grid morphology is not simple and leads to the design of numerous costly and complex joints. To overcome this issue, an original and innovative erection process was developed (*Fig. 5*) that takes advantage of the flexibility inherent to slender elements. A regular planar grid made of long continuous linear members was built on the ground (*Fig. 6*). The elements were pinned together such that the grid has no in-plane shear stiffness and can accommodate large-scale deformations during erection (*Fig. 7*). Then, the grid was bent elastically to its final shape (*Fig. 8a*). Finally, the grid was frozen in the desired shape with a third layer of bracing members (*Fig. 8b*) and the shell structure was achieved.

Other ways to triangulate the grid, for example, through the use of cables, can be investigated.

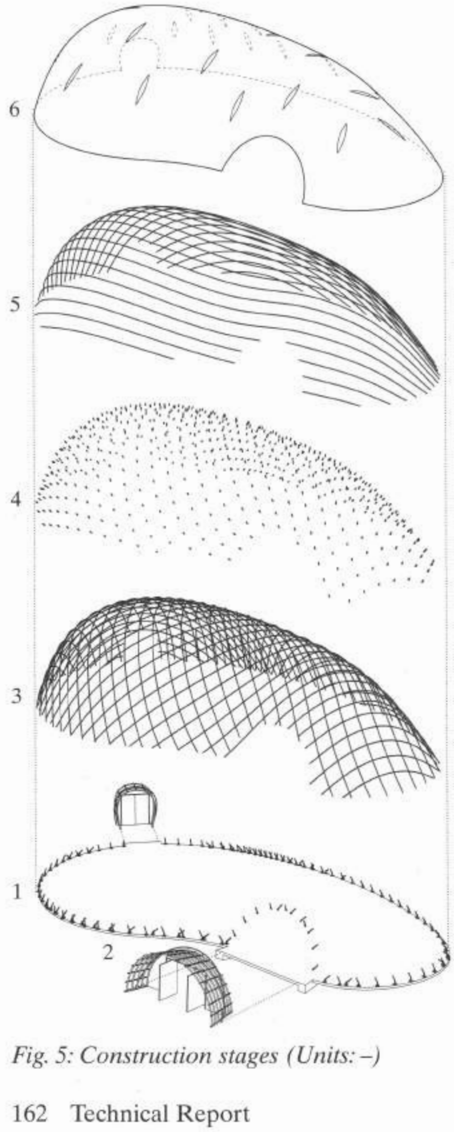

Fig. 5: Construction stages (Units: –)

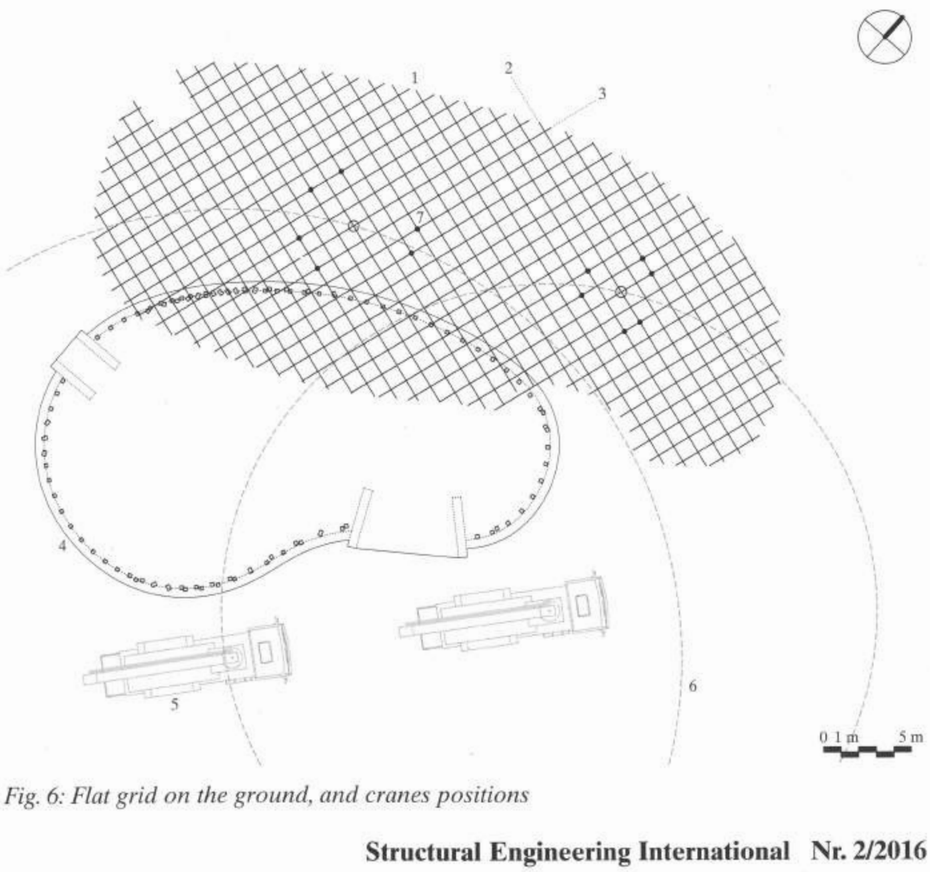

Fig. 6: Flat grid on the ground, and cranes positions

Design Process

Overall Design Process

The goal of the design process was to identify a gridshell structure that works and respects as faithfully as possible the architectural project with respect to the shape and program. The design of the gridshell represents "the path from shape to structure". Its progress, sequential and iterative, revolves around three major stages: shape, mesh and structure. Developing this structural design was a complex process. Indeed, for each step, the method, the tool and the criteria that offer both a sufficient explorative richness in order to find potential candidate solutions, and the means to evaluate and compare the suitability of those solutions, had to be found.

Fig. 7: Grid during erection

In the next part of this paper, the studied options and the selected evaluation criteria for each previously mentioned stage are presented.

3D Modelling of the Intended Shape

The first step of the process consisted in building a precise geometric model from the sketch of the architect and evaluating its mechanical potential (*Fig. 8*). At this stage, the goal was to estimate the probability a given shape would lead to the generation of a structurally feasible gridshell.

(a) (b)

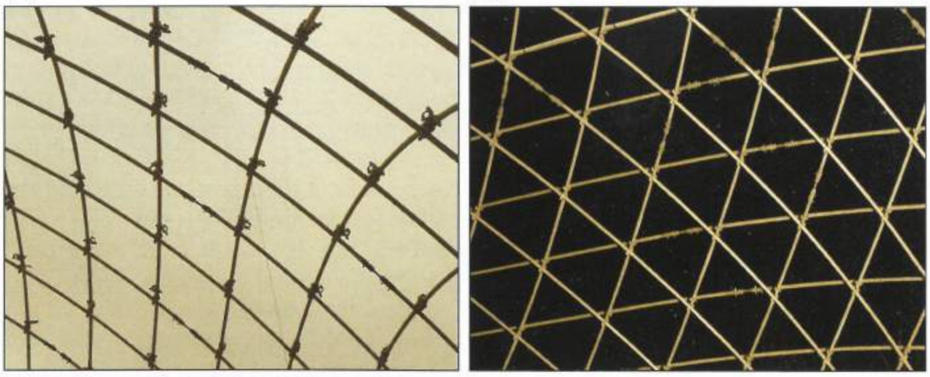

Fig. 8: (a) Erected grid, (b) braced grid

Stresses in the grid are mainly due to the bending of the profiles. They are derived directly from their geometric curvature of the profiles. 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 laying a grid on it. Particularly, the following condition had to be satisfied everywhere:

$$E\frac{r}{R_{\min}} < \frac{\sigma_{k,\text{flex}}}{\gamma_{\text{lt}}} \qquad (1)$$

where, r is the pipe's outer radius, $R_{\min}$ is the minimum principal radius, E is the flexural modulus, $\sigma_{k,\text{flex}}$ the characteristic flexural strength and γ_{lt} the long-term partial coefficient of material resistance.

Fig. 9: Candidate 3D shapes are selected regarding their minimum principal radius of curvature

Ideally, the shape is controlled by few key parameters. Thus, it can be adapted and optimized through an iterative process, towards the above criterion (1).

Mesh from the Compass Method

During the second step, the candidate surface was meshed and the mechanical potential of the resulting grid was evaluated. At this stage, the probability of a given mesh leading to the generation of a viable gridshell structure was estimated. Simultaneously, meshes were compared according to their architectural relevance.

In this step, the geometric curvature of the polylines drawn on the surface was the criterion to characterize the mechanical potential of the grid. In particular, it had to be ensured that the following condition was satisfied everywhere:

$$E\frac{r}{R_{\text{spline}}} < \frac{\sigma_{k,\text{flex}}}{\gamma_{\text{lt}}} \qquad (2)$$

where, R_{spline} is the spline's local curvature radius.

The mesh was obtained by the compass method, described in Ref. [12], which develops a regularly spaced grid on a surface from two secant curves lying on the surface and called "directrices". For a given shape, there are an infinite number of meshes (*Fig. 10*). The aim was to identify at least one grid, which satisfies both the architectural and the structural criteria.

Navier laboratory had tested various numerical methods to generate such grids.[13] Here, a specific software,[14] developed for Rhinoceros and Grasshopper, allowed generating this kind of mesh on any non-uniform rational B-spline (nurbs) surface. It performed the following elementary operations: surface meshing with the compass method, trimming, control of the geometry's integrity and flattening of the grid. The tool also generated automatically a text file, which could be imported into a structural analysis software, containing all the required information to perform the form-finding of the structure. An add-on feature facilitated loads application of various complexities (snow, wind, etc.), which was otherwise difficult for freeform structures.

Form-Finding and Bending Prestress

In the previous steps, the initial form was optimized and promising meshes for the materialization of the future gridshell were identified. However, the meshes do not take into account any of the mechanical reality, because only geometrical rules had been used in their generation. The form-finding step consisted precisely in finding the geometry of the grid at mechanical equilibrium, and the corresponding permanent bending stresses (*Fig. 11*).

The calculation, performed numerically thanks to a dynamic relaxation algorithm with kinetic damping,[15] comprised the following steps:

1. The grid was bent, by a set of applied displacements, from its resting position to the compass position.
2. The grid was then relaxed through its mechanical equilibrium.
3. Bending stresses of the triangulation were calculated relative to the geometry of the equilibrium.
4. Geometry and bending stresses of the triangulation were re-injected into the model in step 2.

Two analysis models were built during this process to study the structure with and without bracing tubes.

The algorithm was improved to take account of the eccentricity due to the connections.[16]

Structural Analysis

A complete structural analysis was performed on the gridshell using the two mechanical models created during the form-finding stage.

The non-braced model was used to check the grid's behaviour during the construction stages. In particular, it had to be verified that the primary grid—the one with no triangulation pipes—had 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 from the targeted geometry. The model with the triangulated grid is used to confirm that the gridshell complies with all the structural requirements during its lifetime. Its behaviour under standard loadings is evaluated.

As-Built Geometry Regarding Eccentricity of Connection

The previous geometric and structural models employed during this project did not take into account the eccentricity between the three layers of pipes, due to the connectors (*Fig. 12*). Although the mechanical consequences of this eccentricity could be neglected to a first-order approximation, this is

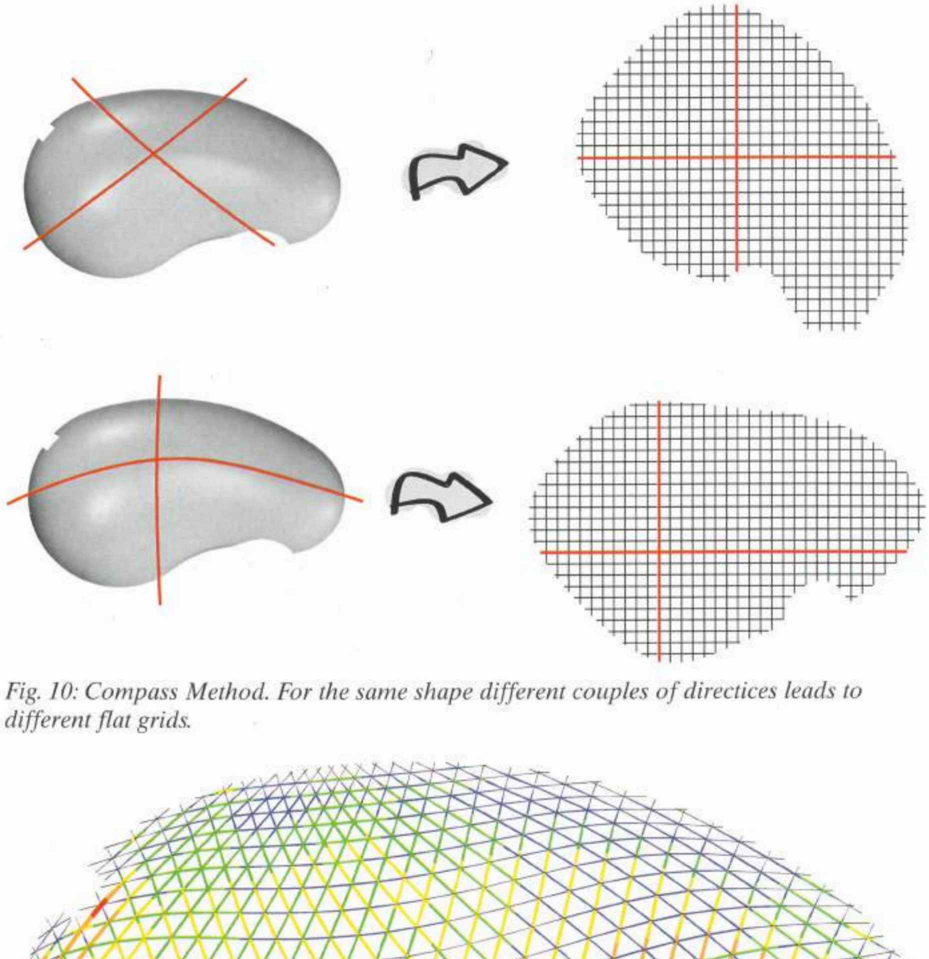

Fig. 10: Compass Method. For the same shape different couples of directices leads to different flat grids.

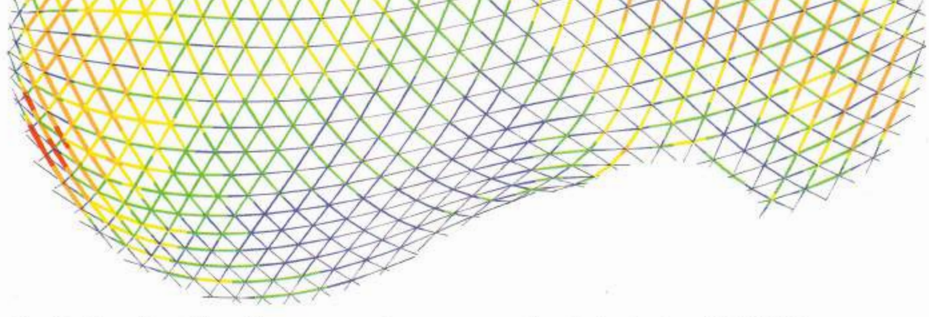

Fig. 11: Combined bending stress under permanent loads (red pipes:130 MPa)

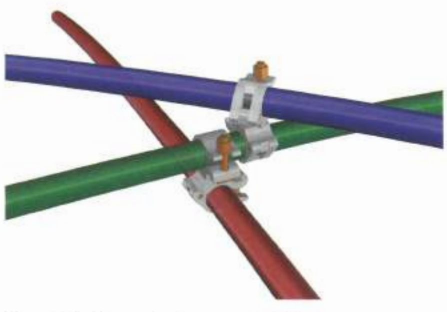

Fig. 12: Geometric eccentricity

not the case for the geometric consequences it induces. Indeed, the eccentricity remains small compared with the span of the shell, but it is not negligible compared with the mesh size (e = 80 mm; l =17 m; w = 1 m). Thus, the pipe lengths and anchorage positions (*Fig. 13*) could not be determined with sufficient accuracy without taking into account the thickness of the structural grid due to this excentricity. The employed method, purely geometrical, assessed that the neutral fibre of the shell is equidistant from the first two layers of pipes. The form-finding was performed only with those two layers. Connection axes had to be parallel to the local normal of the shell surface. This assumption was not exact, but, in this case, gave sufficient accuracy. The red pipe was offset by $-e/2$, the green by $+e/2$ and the blue by $+3e/2$ along the normal (*Fig. 12*).

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 success of the project. As it was the first time a structure of this kind was going to host a large number of people for over two years, the question of its reliability over time was a major issue. In order 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 is presented later in the paper.

First Level: Administrative Classification of the Building

The first level, administrative activity consisted of obtaining from the French authorities an appropriate classification for the building, taking into consideration the project's real-time requirement: a light-weight structure with a short lifespan. As expected, the structure was classified as a "building open to the public" from the category "big tops and tents".[17] In this classification, construction procedures and regulations are adapted to the short lifespan of buildings.

Second Level: Compliance with Existing Standards

The second level, normative activity consisted of ensuring that most of the existing regulatory framework justified the compliance of a structure that would not, at first sight, be considered by standards that do not include composite materials.

As far as possible, the design was made in compliance with the Eurocode, where the structural design is done according to the limit states under normalized loadings (self-weight, snow, wind, etc.). Although, the Eurocodes do not directly take into account composite materials, they propose some probabilistic methods to introduce new materials (EN1990, Annexe D). The mechanical properties of the GFRP pipe were determined as far as possible by tests in conformance with these methods. Alternatively, values were taken according to the Eurocomp.[18] In some cases, such as for the sleeve, the construction design also benefited from this approach.

The Eurocomp is a kind of pre-standard intended for the structural design of buildings and civil engineering works using GFRP composites, consistent with the Eurocode approach. It is considered as the reference design code for GFRP material.

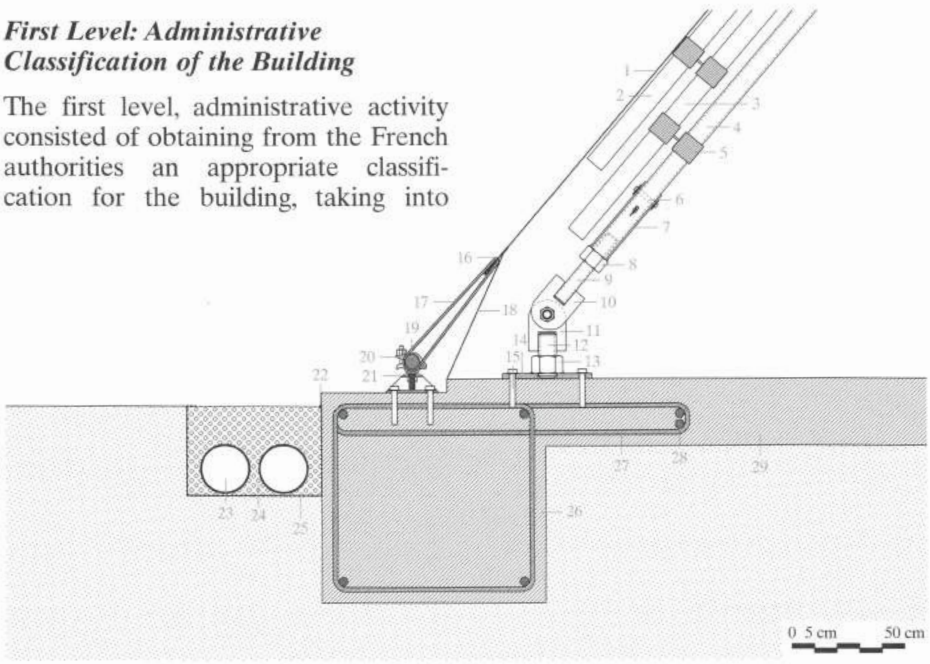

Fig. 13: Ground anchorages (Units: –)

Flexural Strength of the Tubes

The characteristic flexural strength ($\sigma_{k,flex}$) of the GFRP tube was used to verify if the structure complied with the Eurocode. This parameter had a critical impact on the structure's reliability, because in this particular application, stresses in the tubes were mainly due to the bending. Thus, it was important to confirm the manufacturer's permitted value through testing.

Three-point flexural tests were carried out with and without connections (*Table 1*; tightening torque set to 20 Nm) to determine the characteristic strength according to the Eurocode protocol (Annex D):

$$\sigma_{\text{k,flex}} = \bar{\sigma}(1 - k_n \sigma_x) \quad (3)$$

For five tests, the factor $k_{n,5\%}$ was 1.80 assuming a normal distribution. It could be noted that the connections caused more scattering in the results. Finally, the manufacturer allowed value of 400 MPa (ASTM D790) was confirmed and retained for further calculations.

Partial Safety Factors

The partial coefficients of material resistance (*Table 2*) used in the project were calculated according to Eurocomp.

The short-term coefficient proposed in Eurocomp (γ_{st} = 1.3) was increased to consider the critical stage of erection, where the deformations could not be controlled accurately.

When dealing with long-term effects in permanently loaded, pultruded composite materials subjected to creeping and relaxation designers should be

σ_1	σ_2	σ_3	σ_4	σ_5	$\sigma_{k,flex}$
456	441	445	460	477	430
444	478	434	479	427	408

Table 1: Three-point flexural tests of the GFRP tubes with (second row) or without (first row) connectors (results in MPa)

Impact	γ	σ_d
Short-term	2.0	200 MPa
Long-term	3.0	133 MPa

Table 2: Short-term and long-term values for partial coefficient and corresponding material resistance

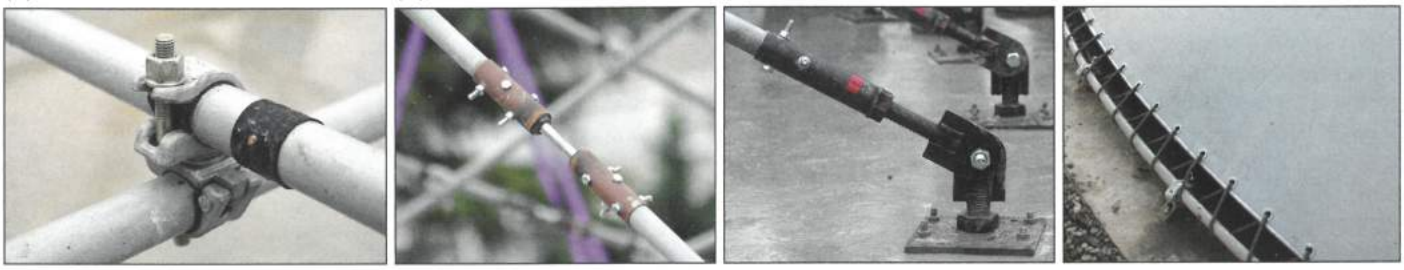

Fig. 14: (a) Swivel coupler, (b) steel sleeve, (c) ground anchorage, (d) lacing edge beam

careful.[19,20] In this project, this was reflected in the high partial coefficient for long-term effects.

Construction Details

Overview

In this project, it was possible to identify four major structural details: the swivel coupler for connecting composite tubes to assemble the grid (*Fig. 14a*); the steel sleeve for connecting several composite tubes to obtain long members from initially short pieces of tubes (*Fig. 14b*); ground anchorages for fixing the structure to the concrete slab (*Fig. 14c*) and the lacing edge beam of the fabric (*Fig. 14d*).

The challenging issue of connecting the steel and composite parts was solved similarly through sleeve and anchorage details.

Sleeve: Description

Sleeves are major components in the structural system. The component presented is an important innovation compared with the composite gridshells built previously, where members were simply interrupted or overlapped. By establishing mechanical and architectural continuities between tubes, the sleeve brought the real behaviour of the shell closer to its theoretical behaviour.

The sleeve is a steel system that provides mechanical continuity between two adjacent composite tubes for both tension and bending. It is made of three parts: two connectors linked by a threaded rod. Each connector is a 48.3 × 2.9 mm tube, slightly larger than the composite tubes it connected, with a welded M20 nut at one end. The connector was pinned to the composite tube with three 10 mm bolts. Some structural adhesive was also employed to fill the gaps and to guarantee good rigidity of the assembly. However, the sleeve was designed to ignore the contribution of the adhesive to the mechanical strength of the system.

A M20 threaded rod linked the two connectors. It allowed tension forces and bending moments to pass from one tube to the other. It did not transfer any torsion.

Sleeve: Mechanical Behaviour

Tension forces were transferred from the composite tube to the connector through shear in the pins. Owing to a lower bearing resistance in the composite than in the steel, each of the three pins could be gradually loaded. When loading the system, initially, only one of the three pins was in contact with both the steel tube and the composite tube, because of inevitable minor manufacturing gaps. When the axial load was increased, this pin started to "eat" (*Fig. 15*) into the composite tube until the second pin also came in contact. Thus, the axial load was transferred equally between the two pins. This scheme could work for more until another failure mode occurs.

For this mode of composite failure, which prevailed in this case, the total bearing capacity of the assembly was thus three times the capacity of a single pin. This total bearing capacity can be calculated from the compressive strength, the composite thickness and the pin diameter:

$$F = 3 \times f_{u,c}\, dt = 3150 \text{ daN} \quad (4)$$

In the next section, tests carried out at the Navier laboratory to confirm the predicted value are presented.

Bending moments were transferred through the threaded rod of the sleeve. This part was designed to reach the two following qualitative criterions simultaneously:

Firstly, the bending stiffness of the rod should be roughly equivalent to the composite bending stiffness to preserve the curvature's continuity along the system. This continuity was of prime importance from an architectural point of view.

$$EI^{\text{rode}}/EI^{\text{pipe}} \approx 1 \quad (5)$$

Secondly, the steel quality of the rod should be adjusted such that plastification begins when the composite tube tends to approach its maximum design stress (a third of the yield stress). Thus the rod acted as a "fuse": if the curvature of the system reaches the maximum allowed curvature, the steel rod starts to plastify. The plastic hinge accumulates the rotation thus preventing the curvature to increase in the composite tubes.

$$M^{\text{rode}}_{\text{elastic max}} \,/\, M^{\text{pipe}}_{\sigma\ =133\text{ MPa}} \approx 1 \quad (6)$$

In this project, the numerical values for the ratios (5) and (6) were 0.79 and 0.96, respectively.

Test: Load-Bearing Capacity of the Pinned Connection

Figure 16 shows the tensile test of a three-pin connection between a connector and the corresponding

Fig. 15: Local bearing failure due to pin pressure

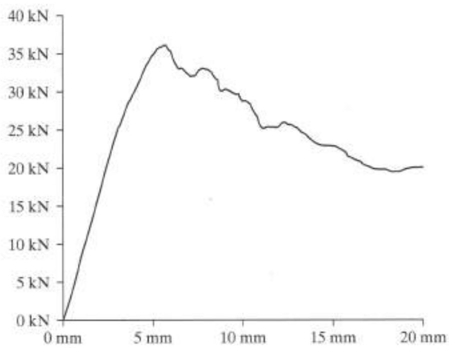

Fig. 16: Tensile test of the pinned connection

composite tube. The graph reflects the elastic behaviour of the composite tube up to 35 kN, with slight deviations corresponding to the rearrangement of the pins. The compressive stress applied by each pin to the composite tube exceeded its compressive strength. Progressively, the pins were pulled through the tube under a residual force that tended to stabilize at around 20 kN.

Conclusions

This paper presented the different steps in the design of an elastic gridshell structure composed of composite material, the temporary cathedral at Créteil, a Paris suburb. The first step was the optimization of the shape in order to avoid local concentrations of curvature. The second step involved a tool to automatically mesh a surface using the compass method. With this tool, the orientation of the mesh was studied according to structural and architectural criteria. The last steps comprised the structural analysis of the gridshell and how to achieve the as-built geometry from the analysis model.

Architecturally, the structure offers a very interesting space where the textural richness of the tubes against the membrane accentuates the complex curved surfaces.

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

At present, further developments are being conducted by the Navier laboratory to take into account torsional effects and non-axisymmetric sections in such structures.[21] The interaction between the structure and the fabric is also a vast research field that needs to be explored.

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SEI Data Block

Public	360 seats/500 people
Cost:	$500.000
Date of completion:	February 2013
Contractor:	Association Diocésaine de Créteil
Dimensions:	
$S = 350$ m^2/$V = 1600$ m^3	
$h \times l \times L = 7 \times 17 \times 29$ m	
Gridshell:	
Tubes	1775 m
Connections	1130
Sleeves	125
Anchorages	123
Fabric:	
Opaque	530 m^2
Transparent	12.5 m^2
Weight	5 kg/m^2