CONSTRUCTION OF GRIDSHELLS COMPOSED OF ELASTICALLY BENT ELEMENTS AND COVERED BY A STRETCHED THREE-DIMENSIONAL MEMBRANE

STRUCTURAL MEMBRANES 2013

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Key words: Gridshell, Composite materials, dynamic relaxation, form-finding, prototypes.

Summary. This document deals with the gridshells built by the Navier laboratory in the last ten years. The numerical conception is developed, from the draft made by architects up to the final structure. To design a gridshell several numerical tasks have to be performed. The geometry of the gridshell is first considered. Then, an iterative step mixing geometry and mechanical considerations is important. In particular, it is explained how the naturally straight beams are bent to form the final shape. This active bending provides many interests like high stiffness for a light weight structure. After the numerical design of the grid, the geometry of the membrane is drawn from the numerical final geometry of the gridshell. The improvements of gridshells, including safety considerations as well as practical considerations are then developed, trough the four gridshells recently built.

1 INTRODUCTION

In the last twenty years many applications of composite materials in the construction industry were made. The main field of application concerns the reinforcement of concrete beams with carbon fiber plates [1] or post tension cables. More recently, a footbridge with carbon fiber stay-cable was build in Laroin (France, 2002 [2]), another footbridge, all made of glass fiber composites, was build in Aberfeldy (Scotland, 1993 [3]) and a movable bridge (the Bonds Mill lift bridge in Stonehouse, England, 1995 [4]). Nevertheless applications using composite materials as structural elements remain exceptional. Although the qualities of their mechanicals properties are obvious (low density, high strength and high resistance against corrosion and fatigue), their relatively low elastic modulus is a disadvantage against steel. Indeed most slender structures in structural engineering are designed according to their stiffness and rarely to their strength. In addition, the elastic instabilities depend linearly on the Young modulus, so that again, having a low Young modulus is a real disadvantage when a designer tries to calculate structures based on conventional design structure. In order to take advantages of every characteristic of composite materials, new structural concepts have to be found.

The Architected Structures and Materials research unit of Navier laboratory is working on the development of innovative solutions for composite material in civil engineering. Four design principles guided the conception of the structures:

- Optimal use of the mechanical characteristics of the fibers;
- Simple connection between components of the structure;
- Optimal design according to its use;
- Use of components already available in the industry for cheap material costs.

Several structures were investigated such as an innovating footbridge [5] and several experimental gridshells [6] [7] [8] [9]. The purpose of this paper is to explain the method used to design gridshells, up to the fabrication of the membrane and then to emphasis the improvements of the building process. The first section gives a proper definition of gridshell and emphasis the specificity of their construction process. Then, the numerical aspects of the project are developed. Finally the steps of construction and the improvements made through the salvo of projects are approached.

2 GRIDSHELLS: DEFINITION AND PROCESS OF CONSTRUCTION

The name of gridshell commonly describes a structure with the shape and strength of a double-curvature shell, but made of a grid instead of a solid surface. These structures can be made of any kind of material - steel, aluminum, wood… Generally, the metallic structures are made of short straight elements defining a cladding made of plane triangular or quadrangular element. The complexity of this geometry requires the development of many clever and expensive assemblies. In order to avoid these complex joints, a very specific erection process was developed using the ability of slender components to be bent [10]. Long continuous bars are assembled on the ground, pinned between them in order to confer on the grid a total lack of plane shear rigidity what allows large deformations. The grid is elastically deformed by bending until the desired form is obtained and then rigidified. With this process, the initially straight beams are bent to form a rounded stiff surface. Only few gridshells were built using this active bending method, among which the most famous are: the Mannheim Bundesgartenschau (arch: Mutschler and Partner and Frei Otto, Str. Eng: Arup, 1975 [11]), the carpenter hall of the Weald and Downland Museum (arch. E. Cullinan, Str. Eng. Buro Happold, 2002) [12] and the Japanese pavilion for the Hanover 2000 Exhibition (arch: Shigeru Ban, Str. Eng. Buro Happold) [13]. In addition, the Navier research unit has already participated to the construction of four gridshells in glass fibre reinforced polymer (GFRP), increasingly large. The gridshell for the Solidays' festival was 300 m² large [8] but very recently a 350 m² gridshell called "Cathedrale Ephemere de Creteil" has been constructed to replace the Creteil cathedral during its renovation which should last at least two years.

Construction steps: the main building steps are illustrated figure 1: the grid is assembled flat on the ground (figure 1a), then erected by two cranes (figure 1b) and gets its final form when attached on anchorages.

Figure 1. Cathedrale Ephemere de Creteil. a. Primary grid made flat. b. Primary grid deformed elastically and attached to boundary conditions.

3 COMPOSITE MATERIALS TAILOR MADE FOR THIS TYPE OF STRUCTURES: FLEXIBILITY FOR STIFFNESS.

Most of the gridshell structures have been made of wood because it is the only traditional building material that can be elastically bent without breaking. This flexibility generates curved shapes which generates structural stiffness. However looking at other industrial fields (sport and leisure, nautical...), it can be noticed that every time high strength and high deformability are required, composite materials is replacing wood (ship masts, skis, rackets). To study accurately the question of the best material for gridshells, the authors adopted the method proposed by M. Ashby [14]. In this method, indicators characterising the object to be designed are defined. In the case of gridshells, it is necessary to have a material with:

- High elastic limit strain in order to be able to bend the element and obtain a curved shape.
- High Young modulus to confer to the gridshell its final stiffness after bracing.

The Ashby method drawn for these two characteristics provided several materials potentially better than wood for the gridshell application. These materials are titanium, CFRP, GFRP and technical ceramics. In addition, this study showed that steel or concrete can not be better than wood for such an application: these materials can not deform as much as wood. To choose between the four families of material, other aspects have to be considered. In particular, materials shall not be too brittle to be easily handled on site by workers and therefore ceramics are not suited. Because of cost limitation, titanium and CFRP can not suit for the gridshell application.

The most valuable alternative to wood is hence glass fibre reinforced polymers (GFRP). They have higher elastic limit strain (1.5 % at best for GFRP and 0.5 % for wood) so large curvature synonymous of freedom of shape is possible. Their Young modulus also is higher (25-30 GPa against 10 GPa for wood). This is an advantage to make a stiff structure. In addition, supposing that for a given geometry, the buckling load of a gridshell is linearly dependent from the young modulus, one can expect the buckling load of a gridshell in composite materials to be 2.5 to 3 times higher than one made of wood. Moreover, as composites are industrially produced, the reliability of their mechanical properties is much higher than that of natural materials like wood. Finally, while wood beams have to be made of several pieces of wood stuck together, GFRP profiles can be made continuously, as long as necessary.

Concerning costs, if one takes into account the mechanical properties and the ability of composites to be formed into efficient sections like tubes, GFRPs become very interesting challengers, especially if pultrusion production is used. Indeed, hollow sections make possible the use of light beams optimized for each application (stiffness and curvature). Moreover, the polymer chosen for the GFRP can resist to corrosion, UV and other environmental attacks, whereas wood materials need maintenance.

At this point, the gridshell concept is explained. The type of materials chosen is GFRP for flexibility, cost, stiffness and reproducibility reasons. The process of construction can be developed.

4 CONCEPTION OF A GRIDSHELL: FROM A GEOMETRY TO A FINAL SHAPE.

At the beginning of the process, the architects have to define a shape. To be well suited with the process of the gridshell, the shape has to be a rounded shape with curvatures as homogeneous as possible. Then, according to the range of curvatures, the engineers have to choose the geometric properties of the beams (mainly the outer radius – this is explained in equation 1). Then, the engineers have to do first a geometric mesh of the shape before relaxing it mechanically to get the final form of the gridshell. After this form-finding step, the engineer adds the third layer numerically (bracing layer) and evaluates the stresses in the structure under serviceability limit states (SLS) and ultimate limit states (ULS) loads, according to construction codes [15]. They might have to modify the mesh, or the shape of the gridshell, in agreement with the architects to reduce the stresses. Once the form-finding has converged and the stresses are suitable, the engineers can design the membrane according to the three-dimensional shape numerically obtained. The method summarized here is developed in the following.

Geometrical step: The method used for the forming of the grid is "the compass method". This method consists in constructing a network of regular quadrangles on any surface, plane or not. This method was described in IL10 Gitterschalen of Frei Otto 1974 [11]. The figure 2 shows the different steps of the method on surface which can be three-dimensional. The task is to construct a grid using only a compass. First, two curves that intersect each other are laid down on the surface to mesh. Then, a mesh size is chosen and serves as the compass radius. The spacing of the grid is marked along each axis, from the point of intersection of the axes. The knots are determined by the intersection of two circles as shown on the figure 2. Gradually, new points are determined.

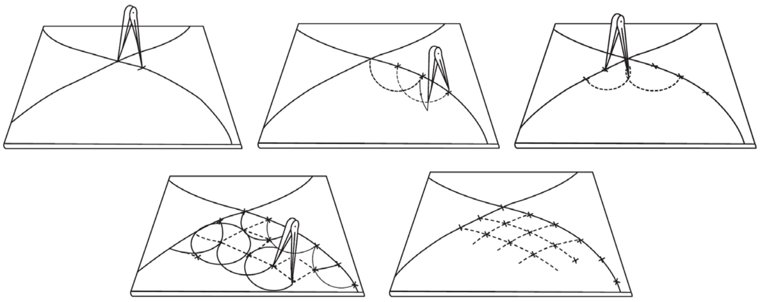

Figure 2: Construction of the grid using the compass method (Otto 1974)

So, to generate the grid of the gridshell, a 3D compass method is performed on the surface. Obviously, the grid obtained has no mechanical meaning. The real shape of the gridshell is obtained later when the mechanical properties are considered. This method was used for the design of the gridshell for the Solidays festival (June 2011) and for the one of the “Cathédrale Ephémère de Créteil” (February 2013).

An implementation of the geometrical method has been developed at Navier laboratory, using Rhino NURBS modeller. This modeller makes possible the modification of a surface through control points. This is very interesting because the compass method is also performed under the same numerical environment. Thus, modifications of the surface to mesh - but also modifications of the curves defining the mesh - are easy to do and the process of meshing is immediately auto-updated.

To sum up the process, first a shape of a structure is proposed by the architects. Secondly, the surface is extended and two main axes for the construction of the grid are drawn (figure 3a). Thirdly, the mesh is automatically generated (figure 3b). The mesh might either cover all the functional shape or cover only a part of it. In the first case, the mesh can be more or less homogeneous. Among meshes covering the entire functional surface a mesh has to be chosen. It is then trimmed to get the final mesh (figure 3c).

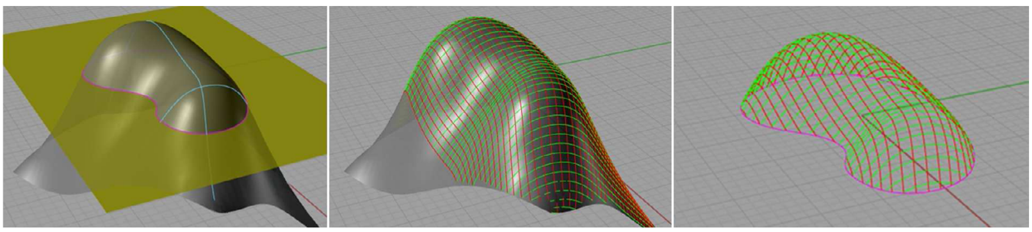

Figure 3: meshing process of a 3D surface. a. extension of the surface and drawing of the two curves. b. meshing of the extended surface. c. cutting of the useful part of the mesh.

Mechanical step: the final shape is obtained by performing a non linear structural analysis of the structure with real mechanical properties. This non linear algorithm is based on dynamic relaxation algorithm [10], [16].

If the shape proposed by architects is suitable with the gridshell process, the geometry of the grid provided by the compass method is very slightly modified by the dynamic relaxation process. Once the real shape is found, classical structural analyses are performed with the standard loads. Obviously, the stress due to form-finding is taken into account in the structural analysis: the main source of stress is linked with the bending of the beams during the erection process. In other words, the stress σ is proportional to curvature of the beams 1/R, (equation 1), and the curvature is mainly due to forming: even under critical loads, its shape (and so the curvature of beams, and also stress) does not change significantly. This is the main advantage of the active bending which provides high stiffness in this case.

$$\sigma = \frac{E\,y}{R} \qquad (1)$$

where E is the Young Modulus and y the outer radius of the beam.

Designing a grid shell is a difficult task. As a guideline, the designer has to check that:

- The curvature in each bar is not too high, to avoid the break of beams even with relaxation and fatigue phenomena. In practice, according to Eurocomp [15], the maximal stress in the bar must not exceed 30% of the strength of the beam. To this limit stress corresponds a limit curvature under which the risk of break is low enough to be acceptable (equation 1).
- The entire surface is meshed
- The mesh does not get too concentrated locally

If the grid is too weak to support the external loads, the designers have to reinforce it by reducing the size of the mesh and/or modifying the geometry of the cross section of the beams. If the outer radius is increased, the stress due to the form-finding gets higher as the maximal stress in a beam is proportional to both the curvature and the outer radius of the cross section of the beam. So the engineers have to be cautious.

The consideration of wind and snow loads presupposes that the gridshell is covered by a membrane. The membrane is made according to the geometry obtained through the dynamic mechanical process. From this geometry, the surface is partitioned in pieces of plane surface (according a tolerance which depends to the material of the membrane). Then the pieces are sewed to form the three-dimensional membrane. Some pieces of membrane (the yellow ones) can be easily seen thanks to colouring, on the gridshell, figure 4. The membranes are PVC coated sheetings.

Figure 4: Long term erected composite gridshell. Some planar parts (yellow) of the membrane can be seen.

5 PROTOTYPES

Prototypes: to demonstrate the feasibility of composite gridshells, four full scale prototypes of composite material gridshells have been built. The two first ones were built on the campus of the *Université Paris-Est.* The first prototype was a purely experimental structure which was tested under several loading conditions in order to investigate the behaviour of gridshell structures and to compare it with the numerical models (figures 4 and 5a). Detailed results of these tests can be found in [9]. The behaviour of the prototype is very close to simulations performed numerically, with the dynamic relaxation algorithm presented in [14]. This gridshell is now serving as a shed for equipment and has a great importance since it is the one that was erected the first (around five years ago). It is still erected and serves as testing for long term damage (mainly creep and fatigue). The second prototype was build to cover a wind tunnel, figure 5b.

Figure 5: a. First experimental gridshell under testing. b. Second experimental gridshell used as a shelter for a wind tunnel.

Prototypes sheltering people: as previously written, two gridshells built to house people have been recently made. The first one for the Soliday's festival (June 2011) and the last one built to temporally replace the Creteil Cathedral (February 2013 for at least 2 years of use). More details about the context of this gridshell and about the project can be found in [17]. Compared to the two first experimental gridshells, these two are larger and had to take into consideration many aspects for public safety.

These two last gridshells have got several improvements regarding the previous ones. First, their size was larger. So large that most of the tubes of the structure was to be built from several tubes joined up together. Second, the gridshells had to obtain an attestation from administrative authorities to house people for a specified period. This attestation was given after a committee had studied the structures, that is to say the project on the paper as well as the execution on the building site.

The shapes: the Solidays Gridshell was looking like a half peanut (two domes) while the Ephemeral Cathedral looks a little more like a stretched one dome structure. The dimensions of these structures are quite similar: around 7 m high, 25 m long and 15 m wide. They are constituted of about 2 kilometres of pultruded unidirectional tubes from Topglass (polyester resin from DSM + Owens Corning glass fibres) with a Young modulus of 25 GPa and a limit stress of 400 MPa. The available length and diameter of the tubes are respectively 13.4 m and 41.7 mm; the wall thickness of the tubes is 3 mm.

As said before the stress is limited to 30 % of the limit stress to avoid severe creep and damage effects like progressive rupture of the fibres.

Unlike the former gridshells and as written previously, given the short period for the project, the geometries of the membrane of these two gridshells were drawn from the numerical shapes.

Computation: the computation has been performed for different sizes of mesh. It appears that a mesh size of one meter was acceptable to resist to the loads studied (dead weight, wind, snow). Under these loads, it is important to check that the stress remains acceptable in all the structure, but since the stress in the bars is mainly due to the form-finding if the structure has been cautiously designed – that is to say if it does not buckle under considered loads - the stress might not reach too high values. In this case, the stress can be drawn from the study of the gridshell without any load applied (figure 6).

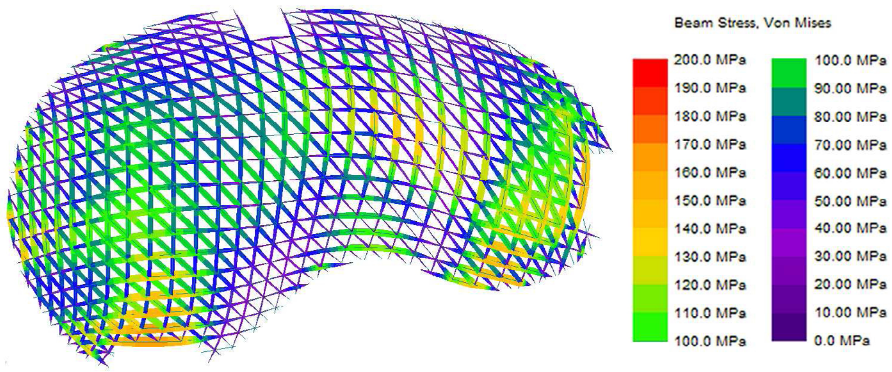

Figure 6: Stress resulting from forming in the Soliday's gridshell

Fabrication: once the form of the structure is defined, the coordinates of the extremities are picked up and precisely reported by geometers on site and stakes are positioned. Then, the grid is assembled flat on the ground: tubes has been cut to the right dimensions with hacksaws and connected to the others with standard swivel scaffolding elements (figure 7a). These scaffolding elements allow rotation around their axis. They are chosen for their low cost due to industrial production.

Then the grid is deformed and shifted by two cranes that hook up the grid in several places (figure 1b). The final form is reached when the extremities of the beams are fixed on the anchorages. The erection phase requires only a few hours work for about ten people whereas the preparation of the grid can take many days.

The following structural step is the bracing. This step is essential, as before bracing, the grid still holds its shear degree of freedom. To behave like a shell, the bracing will transform every deformable quadrangle into two rigid triangles. The third direction of beam is installed as shown in figures 7b and 7c with the use of new scaffolding elements. Once the bracing is installed, the gridshell gets its full mechanical properties and its stiffness gets about twenty times the stiffness of the grid before bracing [8]. The bracing step does not apparently change the form of the gridshell, but since the bracing can't be done everywhere in the same time, it may modify the shape a little. This step is the most fastidious one because the third layer of beams has to be set up in the deployed geometry. Thus the operators have to adjust each connector and tighten the beam inside it, generally in a basket, a few metres over the ground.

Figure 7: a. Joint detail. b. Mesh before bracing. c. Mesh after bracing.

The structural part being finished, the positioning of the membrane can be started. First the PVC coated membrane is pulled above the gridshell (figure 8a). In order to fix the canvas, a girder is set up 10 cm from the soil (figure 8b). The girder follows the contour of the gridshell. For the Creteil gridshell, this girder was a pultruded rod able to support a large amount of shear stress as well as high curvatures (here hollow cross-sections are not suited and the outer radius has to be smaller than for structural beams). The canvas is then positioned and stretched. This step was supposed to be critical as polypropylene-PVC coated canvas is almost not stretchable, and was manufactured according to the geometry of the numerical model. So a mistake during the numerical design or during the building phase could have led to a situation where the canvas would not really fit to the structure. As the gridshells were accurately set up, the canvas fitted to their shape. No wrinkle was observed (figure 8c). The membrane might play a part in the structural behaviour of the grid but given the high dependence to modelling (in particular to friction between beams and membrane and also between connectors and membrane), it is very difficult to evaluate accurately the real stiffening effect of the membrane.

Figure 8: a. Positioning of the PVC coated membrane (Creteil). b. Continuous beam for border during tightening (Creteil). c. Membrane without winkle (Solidays gridshell).

Improvements: to deal with the fact that these last gridshells are made to shelter people many improvements have been added to the previous prototypes. In particular, fire, waterproofness, lightening and thermal considerations have been added to the primary mechanical considerations. Nevertheless mechanical properties have been considered with much more attention to assure the public safety. The reference construction guide - named Eurocomp, for composite materials – guided the construction. In particular, the way of production of beams, their constitutive materials as well as the duration of solicitations acting on the structure were taken into account. On the other hand, many assays were performed to get the real properties of the beams (mean strength, variation coefficient).

In addition, a robustness study has been performed on the Solidays gridshell [18]. This study showed that the gridshell can undergo accidental situation such as vandalism without risking collapse. Indeed, thanks to redundancy, the stress from a break would spread largely and the stress in the neighbouring beams would not get too high. In the same time, large displacement of broken beams would be visible and the evacuation of public could be launched. This kind of ductility is named pseudo-ductility in this case when fragile materials are mainly used. This study has also showed that the buckling of the gridshell must be avoided at any cost: if bucking starts, the curvature of some beams will increase a lot and the stress will increase in the same time, up to breaking and then to the ruin of the structure.

Other improvements were done, relating to the connection of the grid with the soil (figure 9a) and also to assembling of 13 m pipes to form long beams up to 35 m (figure 9b). The difficulty is to make connections able to transmit stress in a way that the assembled beams keeps mechanical properties of the primary GFRP beam. In particular, the joining up of two beams have to:

- transmit normal stress for structural stiffness
- have similar bending stiffness for the continuity of the global shape

Thus, to combine these faculties, the system the system presented on the figure 9b was chosen. Each beam is assembled with a sleeve slightly larger with three pins. This assembly can undergo axial forces up to 30 kN. This theoretical value (obtained with the help of [15]) has been experimentally validated thanks to a salvo of assays. In addition, some extra glue is put inside the assembly to prevent from relative movements and thus fatigue phenomena. Then, between the sleeves of the two beams to connect, a M20 threaded rod is screwed inside bolts welded to the sleeves. This threaded rod is adapted to behave like the structural beams, under bending stress.

Figure 9: a. Pin anchorage for beams. b. Assembly used to join two beams.

6 CONCLUSION

This article first explained the choice made by the Navier laboratory to use composite materials, and in particular the choice of GFRP. Then, the process of conception of these composite material gridshells is presented. In particular, the active bending of the gridshell is illustrated, on a numerical aspect as well as during the building stage.

The development of the prototypes can be seen as the prototypes got larger, with safety standards getting higher and higher because of their use as a shelter for public and also to make possible longer periods of use. In particular, assembling devices and anchorages have been largely improved. The critical points are also approached. The most fastidious one is the bracing which can last a long time. Another one is linked with the membrane covering the structure, which is sewed according to the numerically obtained geometry. That does not leave much room for error during the construction step.

Nonetheless it is important to remind the qualities of such structures. Due to suitable process of construction, the structures shows light weights (around 5 kg per m²), as well as high strength. Another advantage is the fact that most of the stress in elements is due to forming, and that extra loads like wind and snow add very little stress, under acceptable load cases. This behaviour is observed since in these cases, bucking is not generated. Finally from an architectural point of view, this technology provides new horizons. The gridshell built in Creteil is a good illustration, for the global exterior shape (figure 10a) as well as from an interior view (see figure 10b).

Figure 10: Gridshell built in Creteil. a. Global view. b. Inside view.

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