Gridshells in Composite Materials: Construction of a 300 m² Forum for the Solidays' Festival in Paris

Olivier Baverel, Dr.; **Jean-François Caron,** Prof.; **Frederic Tayeb,** Eng.; **Lionel Du Peloux,** Eng.; UR Navier, Université Paris-Est Ecole, Ecole Nationale des Ponts et Chaussees, France. Contact: baverel@lami.enpc.fr

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Abstract

Composite materials are well known for their low density, high strength and high resistance against corrosion and fatigue; but so far only few constructions have been built with these materials. This article shows how composite materials might be an original and profitable solution for lightweight structures called gridshells. In this paper, the principal characteristics of gridshells are recalled first and a demonstration that glass fiber reinforced polymers are suitable for these structures is shown. Then the concept is applied to a functional structure built to house people in a festival. The form-finding of the structure, as well as the construction and some improvements are included.

Keywords: gridshell; composite materials; dynamic relaxation; form-finding; prototype.

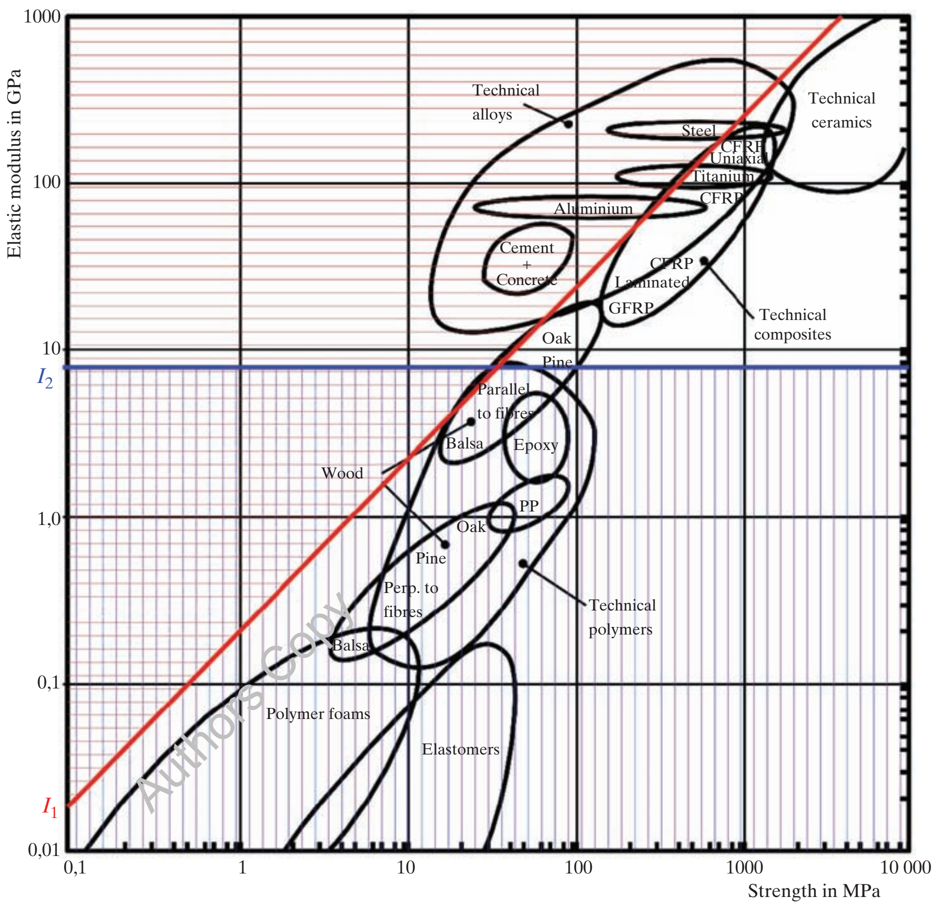

Fig. 1: Selection of materials suited for the construction of gridshells

Introduction

In the last 20 years many applications of composite materials have been made in the construction industry. 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 built in Laroin, France, in 2002[2], another footbridge, all made of glass–fiber composites, was built in Aberfeldy, Scotland, in 1993[3] and a movable bridge—the Bonds Mill lift bridge in Stonehouse—in England in 1995[4]. Nevertheless, applications using composite materials as structural elements remain exceptional in comparison with concrete, steel or even wood. Although the benefits of their mechanical 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. Moreover, the elastic instabilities depend linearly on the Young's modulus, so that again, having a low Young's modulus is a real disadvantage when a designer tries to calculate based on conventional design structure. In order to take advantage of every characteristic of composite materials, new structural concepts have to be arrived at.

The Architecture 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;
- Cheap material cost toward use of components already available in the industry.

Several structures were investigated, such as an innovative footbridge[5] and an experimental gridshell.[6, 7, 13] The purpose of this paper is to illustrate the development of the latest project of composite gridshell, built for the Solidays' festival in June 2011. This project was developed by the students of the Ecole des Ponts Paris tech. Two firms supported the project financially and technically. They also took care of the calculations and the students on-site. The first section gives a proper definition of gridshell and emphasises the specificity of the construction process. It is then demonstrated how certain composite materials are suited for this type of construction. Then, the numerical aspect of the project is developed. Finally, the steps of construction and the possible improvements for future projects are approached.

Gridshell: Definition and Process of Construction

The term 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 or even cardboard tubes. 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 ingenious 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.[9] Long continuous bars are assembled on the ground, and pinned between in order to confer on the grid a total lack of plane shear rigidity, which allows large deformations. The grid is elastically deformed by bending until the desired form is obtained and then rigidified. Only few gridshells were built using this method, among which the most famous are: the Mannheim Bundesgartenschau in 1975,[10] the carpenter hall of the Weald and Downland Museum in 2002[11] and the Japanese pavilion for the Hanover 2000 Exhibition.[12] In addition, the research unit has already built three gridshells in glass fiber, increasingly large. The gridshell for the Solidays' festival is the biggest.[13]

Composite Materials Tailor-Made for this Type of Structure: 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 etc.), it can be noticed that every time high strength and high deformability are required, composite materials are replacing wood (ship masts, skis, rackets). To study accurately the question of the best material for gridshells, the method proposed in Refs. [14,15] was adopted. In this method, indicators which characterize the constraints of 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 (given by the ratio elastic limit stress over Young's modulus). For instance, the material must have an elastic limit stress over Young's modulus ratio better than the typical ratio of woods which is the reference material for gridshells.
– High Young's modulus to confer to the gridshell its final stiffness after bracing. Roughly, it has to be higher than typical woods' Young's modulus.

A typical log–log graph is used in Ashby's method as shown in *Fig. 1*. The x-axis represents the elastic limit stress in MPa and the y-axis the Young's modulus in MPa. The oblique line I_1 on this graph represents the limit between materials that have a good and a bad elastic limit strain/elastic modulus ratio in respect with a wooden reference such as oak or fir (the woods chosen for construction of the Mannheim and Downland gridshells). The horizontal line I_2 represents the limit between materials that have a Young's modulus higher than wood. Hence the materials isolated in the upper right corner between the two lines (titanium; fibre reinforced polymer, CFRP; glass fibre reinforced polymer, GFRP; and technical ceramics) will have better mechanical properties than wood and their application for gridshell structures will thus be interesting to study. It appears clearly that traditional materials (like iron or steel or concrete) exhibit much lower deformability than wood, confirming the choice made for the gridshells until then.

To choose between the remaining materials (wood, titanium, CFRP, GFRP and ceramics), several comparisons of seven parameters relevant for gridshell design were made with a similar graph (for details see Ref. [13]). First of all, the material shall not be too brittle in order to enable easy handling on-site by workers and therefore ceramics are not suited. Cardboard which was used for the Japanese pavilion in Hanover has for sure interesting environmental properties and attractive price but its low strength makes it unsuitable. Compared to GFRP, Titanium and CFRP have handicaps such as their price and their embodied energy. Nevertheless, these materials could be interesting because they have very high Young's modulus, in comparison with the other materials studied.

The most valuable alternative to wood is hence GFRP. They have higher elastic limit strain (1,5% at best for GFRP against 0,5% for wood). As a result GFRP resist larger curvature synonymous of freedom of shape for architects and rigidity for structural engineers might be obtained. Their Young's modulus also is higher (25–30 GPa against 10 GPa) and thus, supposing that for a given geometry, the buckling load of a gridshell is linearly dependent on the Young's 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.

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 is used. Moreover, the polymer chosen for the GFRP can resist corrosion, UV and other environmental attacks, whereas wood materials need maintenance.

Several tests were carried out to compare two types of GFRP tubes: the pultruded and the pullwound tubes. The pultruded tubes are made from unidirectional fibres in a profile line, whereas the pullwound have an extra layer of circumferential fibres.

The evaluation was based on three and four points' flexion tests. The test is presented in *Fig. 2*. This test was used to get the Young's modulus of the beams, their elastic limit stress and also to run permanent flexion tests.

The results show that the rupture of the pullwound tubes leads to a full rupture of the beam. On the other hand, the pultruded beams break

Fig. 2: Four points' flexion test

	Young's modulus (GPa)	Elastic limit stress (MPa)	Comment
Pultruded tubes	32,7	458	
Pullwound tubes	46,7	488	Ruin when breaking

Table 1: Intrinsic results from experiments

more softly and keep part of their tensile mechanical properties. For this reason, pultruded beams were chosen. Nonetheless, the results show that the pullwound tubes have a better Young's modulus as well as a better elastic limit stress (*Table 1*).

The research unit is currently studying the durability of GFRP. Several aspects were studied in Ref. [13]. The study comes to the conclusion that GFRP and wood gridshells have similar costs. Indeed, it is important to keep in mind that GFRP make possible the use of hollow beams. And hollow beams can easily have a second moment of inertia without using much material. Moreover, GFRP is much easier to use insofar as GFRP beams can be manufactured almost as long as necessary, and with a high mechanical reproducibility. Finally, the GFRP have better durability than wood.

Nonetheless, concerning the durability of GFRP under bending loads, the Solidays' structure was designed according to the recommendations given in the Structural Design of Polymer Composites, Eurocomp[8] that recommends not to exceed 30 % of the elastic limit stress.

Form-finding of Gridshells

The method used for the forming of the grid is "the compass method". This method consists of constructing a network of parallelograms on any surface, plane or not. In a study[9] performed in 1974, this method was described. *Figure 3* shows the different steps of the method on a plane surface. The task is to construct a grid using only a compass. The steps of this method are summarized as follows: Two curves that intersect each other are laid down. Then, a mesh width is selected and serves as the compass radius. The spacing of the grid is marked along each axis, starting from the point of intersection of the axes. The knots are determined by the intersection of the two circles drawn around each of the neighbouring points. Then, gradually, new points are determined in the same way. Finally, the net knots are connected rectilinearly.

For nonplane surfaces, the principle of the construction of the grid is the same as previously explained. A 3D compass method is performed on the surface. This method yields a grid that fits to the 3D shape. At this point the grid has no mechanical meaning as the compass method is only a geometric process. The real shape of the gridshell will be obtained later when the mechanical properties are considered. This method was used for the design of the gridshell for the Solidays' festival in June 2011. An implementation of the algorithm has been made at Navier laboratory, using NURBS modeller. Non-uniform rational basis spline (NURBS) is a mathematical model commonly used in computer graphics for generating and representing curves and surfaces, which offers great flexibility and precision for handling both analytic and modelled shapes. In particular, the model makes possible the modification of a surface through control points, which is interesting. First a shape is proposed by the designer (*Fig. 4*). Second, the surface is extended and two main axes for the construction of the grid are drawn (*Fig. 5*). Third, the mesh is automatically generated (*Fig. 6*). Depending on the two main axes chosen, the mesh can either cover a part of the shape or cover entire shape. In this last case, the mesh can be more or less regular. Among meshes covering the entire surface, the most regular mesh is chosen. It is then trimmed to get the final form (*Fig. 7*).

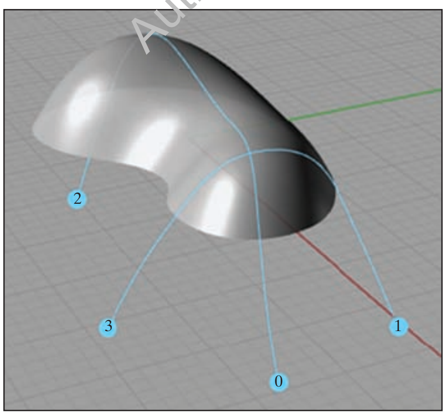

Fig. 4: Surface to mesh

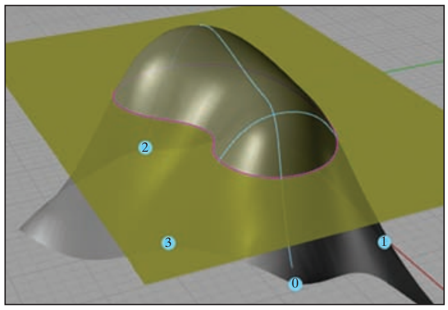

Fig. 5: Main direction of the mesh

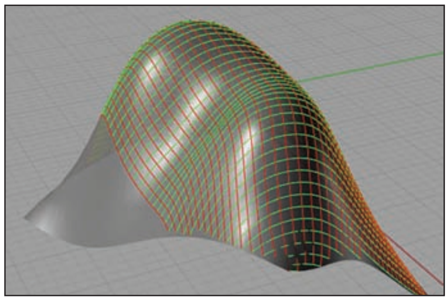

Fig. 6: Surface meshed

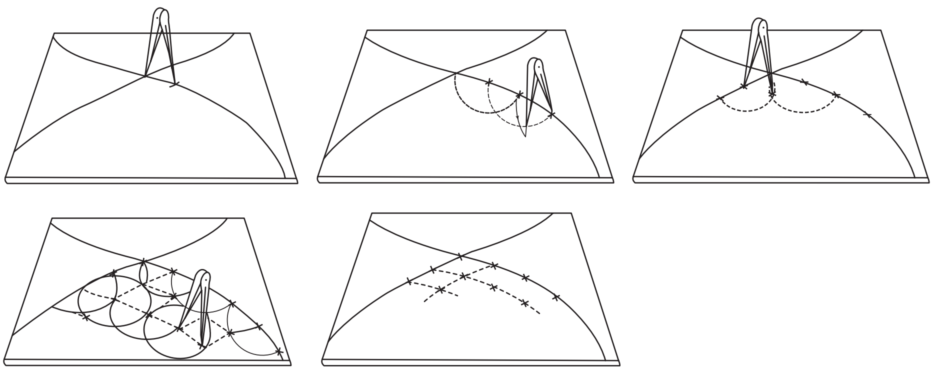

Fig. 3: Construction of the grid using the compass method[9]

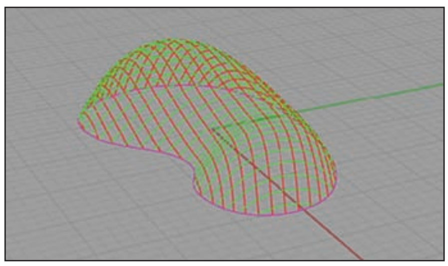

Fig. 7: Resulting surface

The final shape is obtained by performing a nonlinear structural analysis of the structure with real mechanical properties.

If the shape proposed by architects is suitable for the gridshell process, the shape provided by the compass method will have very little modification with the consideration of the mechanical properties of the beams (at this new stage, the grid is not forced to stay in contact with the initial surface anymore). The initial stress due to the form-finding has to be taken into account in the structural analysis.

Once the final form is found, classical structural analyses are performed with standard wind and snow loads.

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, in order to avoid breakage even with relaxation and fatigue phenomena. In practice, according to Eurocomp,[8] the maximal stress in the bar must not exceed 30% of the breaking stress. Upto this limit, stress corresponds to a limit curvature under which the risk of breakage is low enough to be acceptable.
– 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 designer has to reinforce it by reducing the size of the mesh and/or modifying the cross section of the beams. If the cross section is modified, the stress due to the form-finding might cause high stresses as the maximal stress in a beam is proportional to both the curvature and the outer radius of the cross section of the beam.

Construction of the Prototypes

To demonstrate the feasibility of composite gridshells, three full scale prototypes of gridshell in composite material were built. The first prototype was a purely experimental structure which was tested under several loading conditions in order to investigate the true behaviour of gridshell structures and to compare it with the numerical models (*Fig. 8*). Detailed results of these tests can be found in Ref. [7]. The behaviour of the prototype is very close to simulations performed with the numerical model, based on the dynamic relaxation algorithm presented in Ref. [16]. The second prototype was built to cover a wind tunnel. The sheeting was a PVC coated membrane as shown in *Fig. 9*.

This section will now focus on the third gridshell, built to house visitors at the Solidays' festival (24–26 June 2011 at the hippodrome Longchamp, Paris). This gridshell has several improvements over the two previous ones. First, its size is larger. Such that most of the tubes of the structure were built by joining up several tubes. Second, given the very short duration for building, the canvas was manufactured according to the simulated numerical model of the gridshell and not to the real measured geometry. Third, the gridshell had to obtain an attestation from administrative authorities to house up to 500 people.

The shape is that of a half peanut obtained by elastic deformation of a flat grid under the upward loads of two cranes.

The dimensions of the structure are: height 7 m, length 26 m, and width 15 m with an approximate covered area of 280 m^2. It is constituted of pultruded unidirectional tubes in GFRP, with a Young's 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. The stresses in the prototype are limited to approximately 30 % of the limit stress to avoid severe creep and damage effects like progressive rupture of the fibres. Although standards do not exist yet, recommendations can be found in the literature, for example in Eurocomp.[8]

The computation has been performed with the software GSA, for different sizes of mesh. A nonlinear analysis based on dynamic relaxation algorithm[13] is performed to get the shape of the grid after fitting or under the loads. The model is based on 1D elements bent in a 3D shape and linked with each other through joints. The beams have only elastic mechanical properties until they crack. It appears that a mesh size of 1 m was acceptable to resist the loads studied. These loads correspond to wind loads coming from North, South, East or West. Finally the maximal stress obtained during computation is around 28% of the breaking stress (113 MPa), except adjacent to the openings where stresses are higher but the beams can be reinforced easily (*Fig. 10*). It is important to note that the stress in the bars is mainly due to the form-finding, and that external loads have little effect on the stress in the beams (at the most 6% more in the most unfavourable cases, the stress being evaluated at a few nodes chosen at random). As a consequence, the forming stress is a key issue in the design and has to be cautiously evaluated. In practice, the initial forming stress is evaluated using the software. It is directly linked with the curvature of the beams. As the loading mode is only bending, the formula is: $\sigma = Ey/R$ where σ is the stress, E is the Young's modulus of the beam, y is the distance to the axis of the beam, and R is the curvature radius of the beam. So, the stress is maximal when y is equal to the outer radius of the beam.

The considerable benefit of this behaviour is that the forming stress has to be studied cautiously to ensure that the structure will resist all the environmental stress whatever they are.

Fig. 9: Second experimental gridshell

Fig. 8: First experimental gridshell

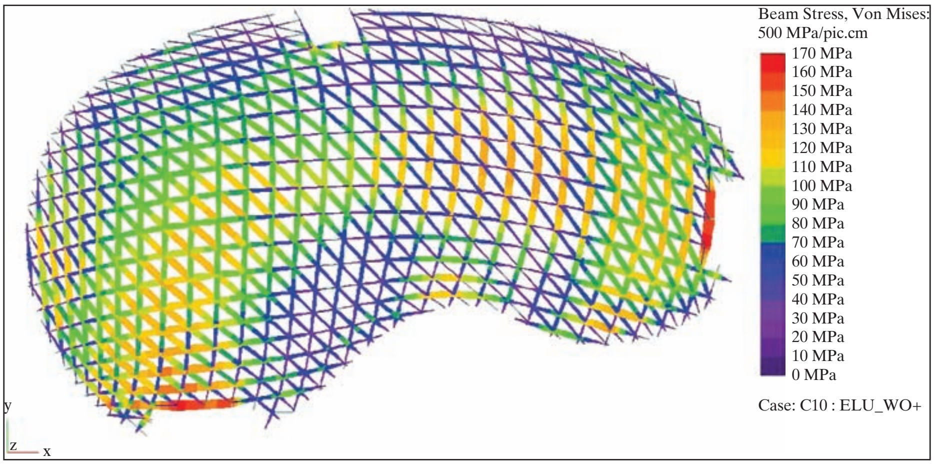

Fig. 10: Stress resulting from both prestress and a bottom wind load

Fig. 11: Initial grid assembled next to the final place of the gridshell

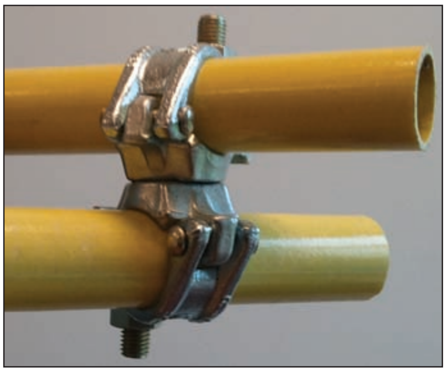

Fig. 12: Joint detail

Fig. 13: Lifting of the prototypes by the two cranes

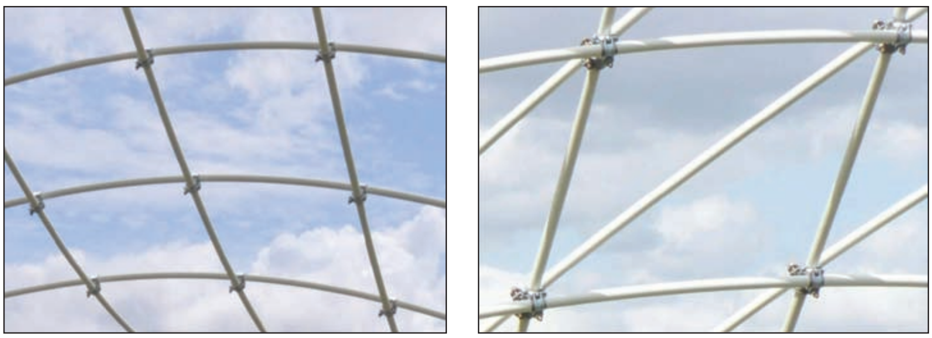

Fig. 14: Meshes before bracing (left). Mesh after bracing (right)

Once the form of the structure was defined, the coordinates of the extremities were picked up and precisely reported by the geometers from the Ecole Nationale des Sciences Géographiques on-site where stakes were positioned into the ground with the help of hammer drills. The grid was

Fig. 15: Continuous beam for border

then assembled flat on the ground: tubes were cut to the right dimensions with hacksaws and connected to the others with standard swivel scaffolding elements (*Fig. 11*). These scaffolding elements allow rotation around their axis (*Fig. 12*). They were chosen for their low cost, which was due to large-scale industrial production.

The grid was then deformed and shifted by two cranes that hooked up the grid in several places around the two domes of the structure. The extremities of the beams were fixed on the posts with other scaffolding elements. The erection phase required only a few hours work for about ten people in addition to the cranes (*Fig. 13*).

The final structural step is the bracing. This step is essential, because without bracing, the grid still holds its shear degree of freedom. To behave like a shell, the bracing will transform every quadrangle into rigid triangles. The third direction of the beam is installed as shown in *Fig. 14*. New scaffolding elements were placed on the second layer of beams, where the first and the second layers of beams cross each other. Once the bracing is installed, the gridshell achieves its full mechanical properties. Its stiffness is about 20 times the stiffness of the grid without bracing.[13] The bracing step does not apparently change the form of the gridshell.

In order to fix the canvas, a continuous beam was set up about 200 mm from the ground (*Figs. 15 and 16*). Once again, the beam used was the same as the beams used for the grid. The continuous beam follows the outlines of the gridshell. The canvas was then positioned and stretched. This step was critical as polypropylene-PVC coated canvas, almost not stretchable, was manufactured according to the numerical model. The canvas and the membrane were manufactured to industry standards. As the gridshell was accurately set up, the canvas fitted

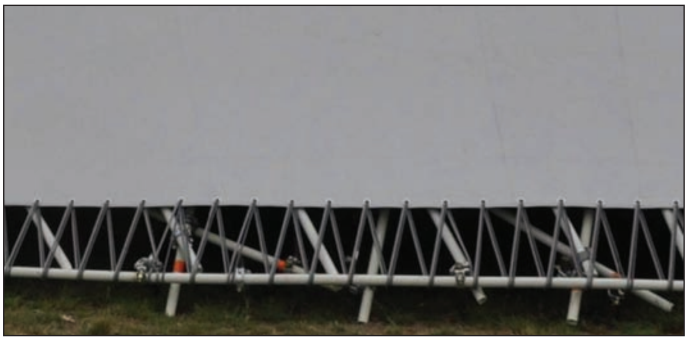

Fig. 16: Canvas laced on the beam

Fig. 17: Peanut shape of the gridshell for Solidays festival

Fig. 18: Inside view of the gridshell

Fig. 19: Bird view of the structure during the festival

Fig. 20: Cracks on the continuous beam where the canvas was laced

Fig. 21: Poor connection between two beams

Fig. 22: Connection bolt that can damage the canvas

to its shape. No wrinkle was observed (*Fig. 17*).

An inside view of the structure is proposed in *Fig. 18* and a bird's eye view of the gridshell during the festival is shown in *Fig. 19*.

Improvements for Future Gridshells

In this section, improvements for three different technical aspects are proposed.

Continuous Beam for the Border

On the continuous beams, several cracks were observed. The continuous beam has a disadvantageous load combination (*Fig. 20*). This beam does not work as the others are purely bent. It is also sheared by local transverse concentrated forces, which explains these unexpected disorders.

However, these beams have been made of composite materials for practical reasons. The use of more conventional and resilient material as steel or aluminium is therefore recommended.

Length of the Elements

For a structure as large as the Solidays' one, beams cannot be continuous because of the limited size of trucks used for transportation. Therefore, most of the beams have to be linked on-site. The linking solution chosen did not behave as expected. Indeed, when the structure was set up in its final form by the cranes, a rotation of the scaffolding elements around the beams reduced the local curvature of the beams, fostering a risk of damaging the canvas (*Fig. 21*).

However, it must be noticed that from a structural behaviour point of view, how the bars are connected has little influence on the shape or rigidity.

Connection and Canvas

The scaffolding connectors of the bracing layer can damage the canvas. To prevent any damage the screws of the couplers were shortened but the nuts damaged the canvas (*Fig. 22*). For a durable application, this detail should be improved by designing a specific connector.

All these aspects make gridshell structures perfectible, but none of these aspects is unsolvable. Nevertheless, gridshells have many advantages as a variety of shapes can be achieved at a reasonable cost.

Conclusions

This paper shows the building processes of a 300 m^2 gridshell made of composite materials. First, a method for selection of materials shows that composite materials are well suited for the construction of such structures: *flexibility for structural stiffness*. Economical aspects of the use of GFRP as well as durability are discussed "GFRP appears to be better than wood" they are easy to use, inexpensive as wood, and are durable.

The numerical design of the Solidays' structure is then approached. In particular, the reasoning used to design the gridshell is explained: after the choice of the geometry, a geometrical gridshell is designed. This geometrical gridshell is then relaxed according to dynamic relaxation and a mechanical shape is obtained. From this point, the curvatures in the beams as well as the stress can be calculated. Then, according to Eurocomp[8] and other experiments carried out on materials constituting the beams, the mesh size as well as the geometry of the beams is chosen.

The steps of construction are then detailed and it is shown how simple the erection step can be: the erection of the grid took a few hours, with the help of two cranes. The bracing is then set up. Finally, technical improvements are proposed. No measurement was made during the construction and the errors have not been evaluated. As the canvas was set up without any wrinkles, it showed that the errors were insignificant. The same structure will be set up next year as well and an accurate evaluation of the error can be made.

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Further Information

Video in French: http://vimeo.com/31341461

SEI Data Block

Owner:
Solidarité Sida

Client:
Solidarité Sida

Structural designers:
UR Navier/Ecole des Ponts/TESS

GFRP components:	1600 m of pultruded tubes
PVC coated membrane:	500 m^2
Structure weight:	5 kg/m^2, able to support more than 100 kg/m^2 with a span longer than 10 m

Estimated cost (EUR)	
For materials only:	Approx. 150 €/m^2
For the whole gridshell:	45 000
Service date:	24–26 June 2011