From shape to shell: a design tool to materialize freeform shapes using gridshell structures

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ABSTRACT This paper introduces and explains the design process of a gridshell in composite materials built in Paris in 2011 for the festival Soliday. A brief introduction presents the structural concept and the erection methodology employed. It explains why composite materials are relevant for such applications. Following this practical case, the whole process from 3D-shape to real-shell is then detailed. Firstly, the shape is rationalized and optimized to smooth local curvature concentrations. Secondly, a specific computing tool is used to mesh the surface according to the compass method. This tool allows designers to look for optimal mesh orientations regarding the elements curvature. Finally, a full structural analysis is performed to find the relaxed shape of the grid and check its stability, strength and stiffness under loads. The authors conclude on the overall relevance of such structures.

KEYWORDS gridshell, composite material, GFRP, grasshopper, compass method, freeform, double curvature

INTRODUCTION

The emergence of gridshell structures – intensively studied by the German architect Frei Otto – is a major step in the development of complex shapes in AEC (Architecture, Engineering and Construction). Since the 70's this structural concept has led to emblematic realizations (Mannheim [Happold and Lidell 1975], Downland [Harris et al 2003], Savill, Hanovre [Ban 2006]). They have shown that beyond their architectural potential, gridshells are well suitable for complex shape materialization because of their intrinsic geometric rationality.

However, the very few number of gridshells constructed up to now attests that they are quite tricky to design compared to standard buildings. Architects and engineers would face both demanding conceptual knowledge (3D geometry, form finding techniques, non-linear behaviour, large scale deformations, permanent bending stresses, etc.) and real lack of tools dedicated to their design.

This paper presents a computing tool based on Rhino & Grasshopper that aims at meshing NURBS surfaces with the compass method. This tool also includes a one-way interface for GSA (a structural analysis software from Oasys) to perform the structural analysis of the resulting grid. Thereby, this tool introduces shape-driven design of gridshells. Following a case study – the construction of the first composite gridshell to host people – a methodology to design these shape-driven structures is proposed. Finally, future prospects to their development are discussed.

Gridshell: concept, erection process, materials

CONCEPT A gridshell is a structure which behaves like a shell but is made of a grid. Thus, the material is not spread continuously as shells, but it is organized in a discrete grid pattern. Like shells, gridshells derive their stiffness from their double curvature shape. These structures can cross large spans with very few materials. They offer a rich and voluble lexicon to express blob-shapes.

ERECTION PROCESS Usually, the grid morphology is not trivial and leads to design numerous costly and complex joints. To overcome this issue, an original and innovative erection process was developed that takes advantage of the flexibility inherent to slender elements.

A regular planar grid made of long continuous linear members is built on the ground (Fig. 1). The elements are pinned together so the grid has no in-plane shear stiffness. Thus, the grid can accommodate large scale deformations during erection (Fig. 2). Then the grid is bent elastically to its final shape (Fig. 3). Finally, the grid is frozen in the desired shape with a third layer of bracing members (Fig. 4). The grid becomes a shell and the structure's stiffness is multiplied by about 15.

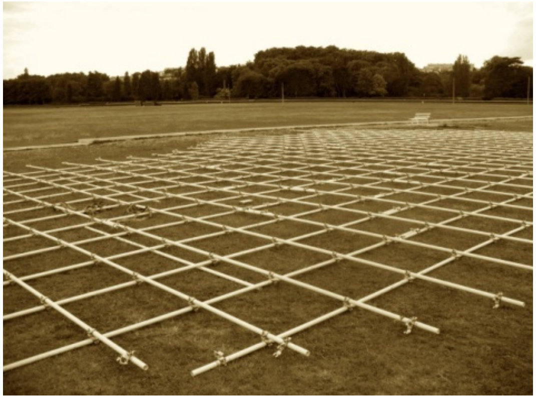


Figure 1: Regular grid on the ground.

Figure 2: Grid erection.

Figure 3: Erected grid.

Figure 4: Grid triangulation.

MATERIAL FLEXIBILITY FOR STRUCTURAL RIGIDITY Composite materials like glass fibre reinforced polymer (GFRP) could favourably replace wood in this case where both resistance and bending ability of the material is sought. Thus, structure's stiffness derives from its geometric curvature and not from the material's intrinsic rigidity. Moreover, using synthetic materials free us from the painful problematic of wood joining and wood durability [Douthe, Caron and Baverel 2010].

HIGH TECH & LOW COST Though gridshells require high-tech design techniques, they seem to be a low-cost way to materialize non-standard morphologies (200€/m^2), because of their geometric rationality. The project complexity is shifted upstream.

From-finding versus Grid-finding

One can identify two different ways of designing gridshells: those with a given outline and those with a given shape. The first approach considers the final shape a consequence of a form-finding process, driven by the supports of a grid which is thought to be an input data. The second approach consists of deriving a grid from a given shape. When erected on its supports, the grid should give back the intended morphology.

FORM-FINDING A physical or numerical grid-model is handled until a structural shape is found, in compliance with the architectural intents. This way, Frei Otto designed the Multihalle of Mannheim using hanging funicular nets and photogrammetry [Otto and Hennicke 1974] (Figs. 5-6). Nowadays, this form-finding stage would probably be done by computer, relying on numerical methods such as dynamic relaxation or force density.

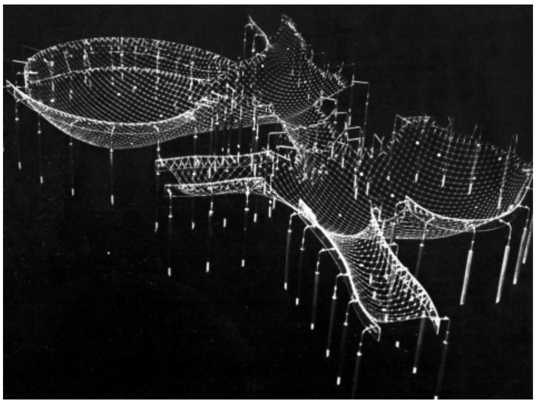


Figure 5: Hanging net.

Figure 6: Resulting structure.

An alternative method has been proposed by the Navier laboratory to achieve this form-finding stage by computer. Based on a dynamic relaxation algorithm which considers the elements bending stiffness, it leads to new shapes where free outlines express the grid natural stiffness [Douth, Baverel and Caron 2006 & 2007].

GRID-FINDING The compass method is used to develop the initial shape in a quadrangular mesh. Rebuilt on a plane, the mesh leads to a regular grid suitable to materialize the studied shape by a gridshell. An alternative method, taking into account the grid's mechanical properties, was also proposed by the Navier laboratory [Bouhay, Baverel and Caron 2009]. This method uses explicit dynamic algorithms to pin an initially flat grid on a given shape, with a system of fictive forces.

CASE STUDY

The project

In June 2011 six students from the École des Ponts ParisTech (French engineering school), supported by the Navier laboratory, gave birth to a structure for the association "Solidarité Sida": a tent unlike any other, reminding blob architecture with its curved and rounded shape (Fig. 7).

DESCRIPTION This structure of 300m² was the first gridshell in composite materials (GFRP) to receive an audience. It had to get a certificate of approval that involved administrative requirements and EUROCODE justifications, a first for such a structure. Beyond the technical performance, this large scale project designed to house up to 500 people at a time has shown the economic relevance of this concept. It became reality thanks to key partnerships including T/E/S/S and Viry.

SOLIDAYS FESTIVAL Each year in June, Solidarité Sida organizes the Solidays festival. It is a music festival that has attracted around 160 000 people during 4 days and has raised about 1.7 million Euros in 2011. It is also a forum. Its purpose is to raise awareness about AIDS, and raise funds for medical research and outreach initiatives. The gridshell structure was designed to house the forum during the festival.

Figure 7: Photo of the final structure (http://vimeo.com/31341461).

Design Process

The following diagram summarizes the design process from the initial architectural intent (a 2D sketch) to the final gridshell. Each step is then detailed.

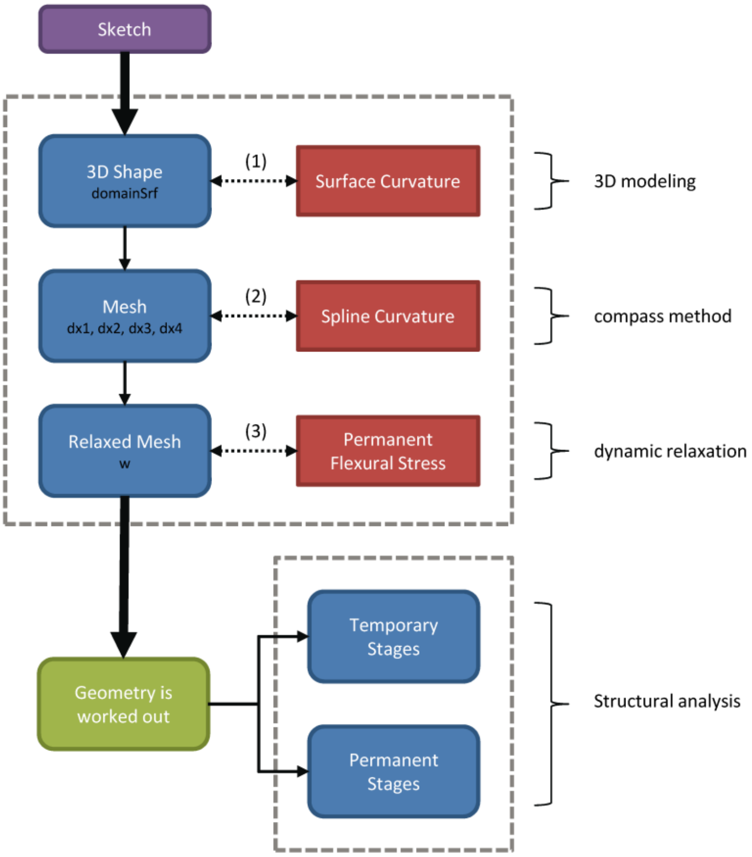


Fig. 8: Step by step design process including different levels of structural control, based on curvatures and stresses checks (1,2,3).

3D Modeling

From the initial architectural intent we have modelled the shape as a wireframe (Fig. 9), including the outline and some sections. With those curves we can control the shape in-plane and drive its volumetry. The surface is then derived from the wireframe using a NURBS interpolation (Fig. 10). All along the design process adjustments were carried out on this surface until it reached the architectural and structural requirements. In this process, the initial surface was mostly deformed or sculpted by handling its control points.

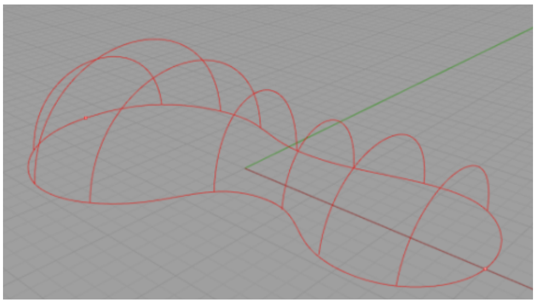


Figure 9: Wireframe geometry.

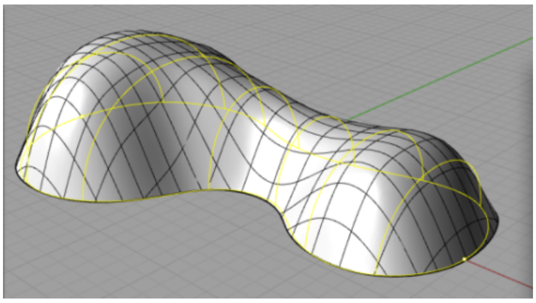


Figure 10: NURBS patch.

Shape Optimization

For now, we built a «space sketch» of the project. However, this NURBS surface has no reason to lead directly to a structural shape. Thus, the structural elements have to be checked to make sure they will support the stress field induced by grid shaping.

STRESS & CURVATURE Stresses in elements are mainly due to grid bending, that is to say geometric curvature imposes the grid stress state (Eq. 1). Thus, principal curvatures of the surface describing the shape are good indicators to evaluate if the structural members have the required mechanical properties. This preliminary control can be completed by an analysis of the curvature of the mesh elements. Finally, nothing but a true structural analysis considering members mechanical properties will allow us to find the exact relaxed shape and the stress field in the structure.

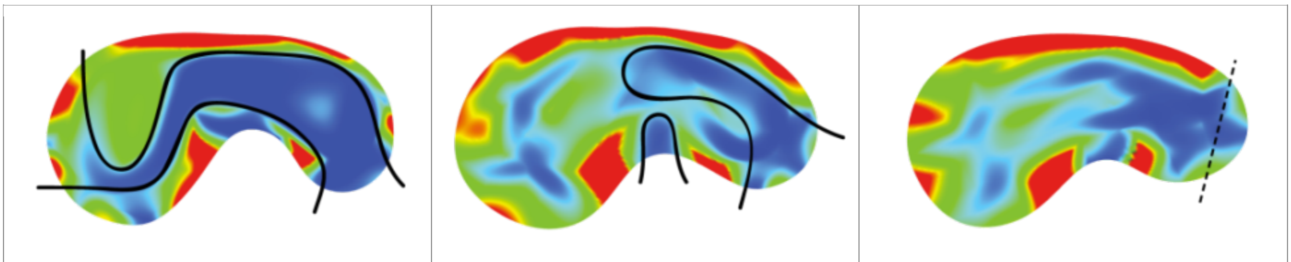
$$\sigma = \sigma_{comp} + \sigma_{bend} \cong \sigma_{bend} = \frac{M}{I/v} = E.\frac{v}{R_{curvature}} \qquad (1)$$

Where σ represents the total stress (compressive plus bending) induced by the shaping. E, v and I are respectively the longitudinal young modulus, the radius and the bending inertia of the profile. R is the radius of curvature of the profile.

SURFACE OPTIMIZATION Before any attempt to mesh the shape, it is recommended to optimize the sketch shape regarding its minimal principal curvatures (Eq. 2). Using the curvature-analysis built-in function in rhino, it is easy to identify and smooth areas that are initially too curved (Fig. 11).

$$R_{min} > \frac{E.v}{\sigma_{max}} \qquad (2)$$

Different sketches are compared according to this criterion to smooth areas where curvature is excessive.



Sketch n°1	Sketch n°2	Sketch n°3

Figure 11: Geometric curvature minimization in three steps. Rmin ∈ [blue = 3,00m ; red = 10,00m].

Shape Meshing

Following a decade of research on this topic at the Navier laboratory, a specific tool has been developed on Rhino & Grasshopper for the design of such shape-driven gridshells (Fig. 12). This tool gathers several components that process basic operations (meshing with the compass method, grid-processing, structural analysis) required for the generation of a suitable grid for the materialization of a 3D shape by a gridshell structure.

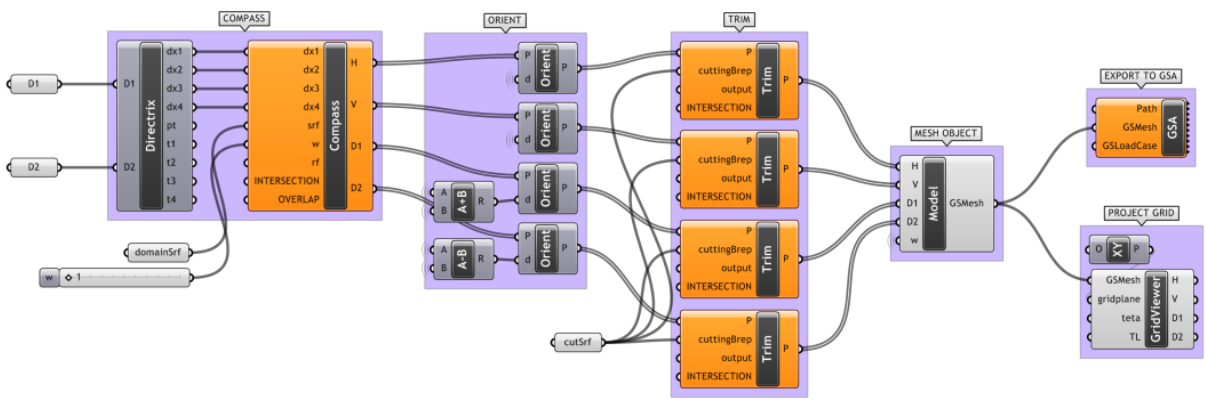


Figure 12: Grasshopper canvas (compass method, grid processing, structural model generation).

Compass Method This process propagates a two way mesh of constant pitch on any NURBS surface.

Two crossing guide-curves are drawn on the surface to mesh. These curves mark the boundary of 4 quarters. Each half guide-curve is then subdivided with a compass of constant distance w (the pitch). Finally, from two consecutive half guide-curves, quadrants are meshed with the same compass distance (Fig. 13).

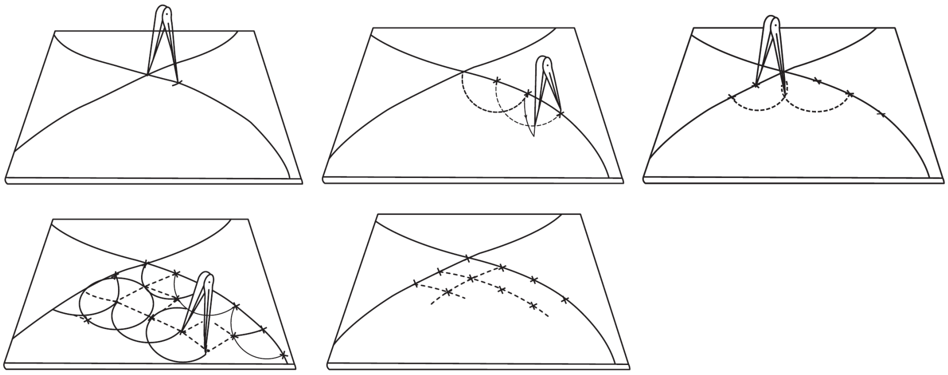


Figure 13: Compass method principle.

Meshed Surface The compass method doesn't allow to mesh the entire meshing domain. Only a smaller part could be meshed and its area varies according the chosen set of guide-curves (Figs. 14-15). Thus, it is not possible to rely exclusively on the shape to be realized with the lattice. An extended surface –chosen carefully - has to be considered as the meshing domain.

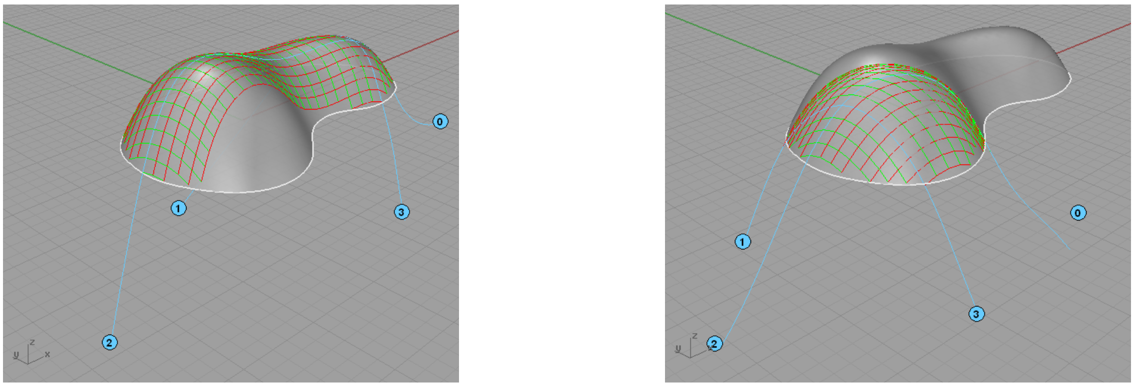


Figure 14: Two different meshes are obtained from two distinct sets of guide-curves. The meshed area never takes on the whole surface. Convergence phenomena could be observed (right picture).

Overall Process To overcome this difficulty, we propose a methodology which relies both on the creation of a meshing domain (domainSrf) from the targeted surface to materialize (gsSrf) and on the identification of a suitable set of guide-curves.

First Step. We consider the gridshell surface (gsSrf) a part of a larger surface (domainSrf). Trimmed by a clipping plane or surface (cuttingSrf), this domain surface should give back the intended shape to build (Figs. 15-16).

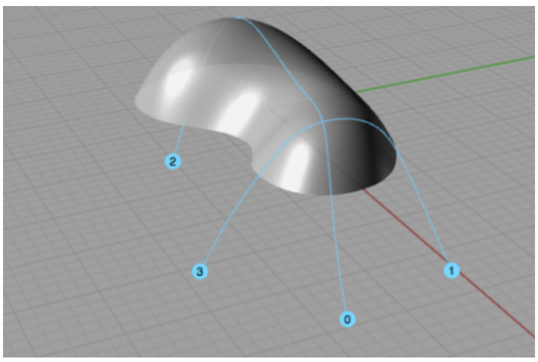


Figure 15: gsSrf.

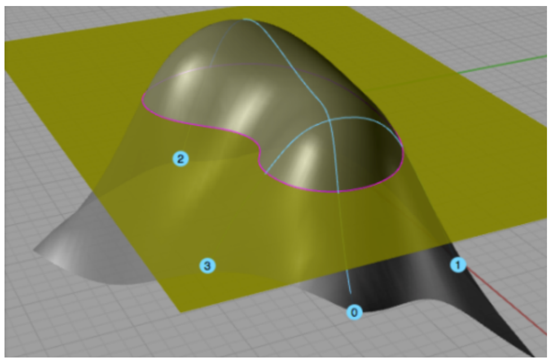


Figure 16: domainSrf and cuttingSrf.

Second Step. A set of guide-curves is chosen (Fig. 17) and the mesh is propagated on the domain surface according to the compass method (Fig. 18). The guide-curves have to be chosen so that the whole gridshell surface (gsSrf) is meshed. Several trials can be necessary to get a suitable mesh.

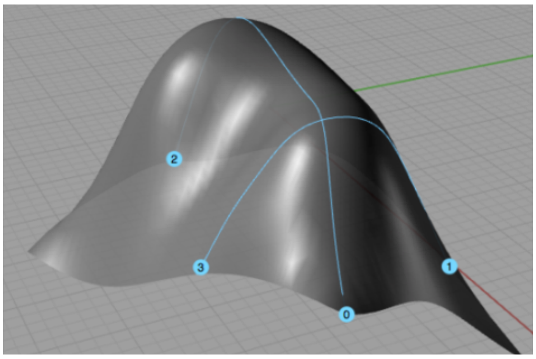


Figure 17: Guide-curves set.

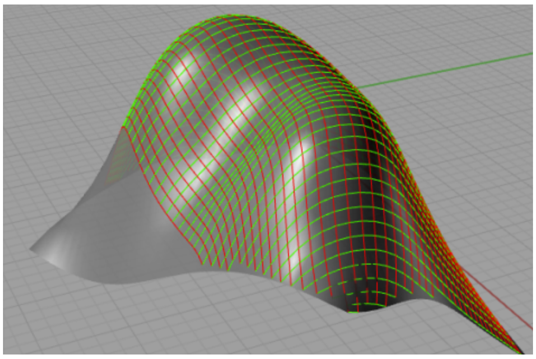


Figure 18: Resulting mesh on domainSrf.

Third Step. The mesh is trimmed by the clipping surface (Fig. 19). The resulting mesh lays on the whole initial intended surface to mesh. The gridshell support-outline is given by the intersection of the clipping plane and the domain surface (Fig. 20).

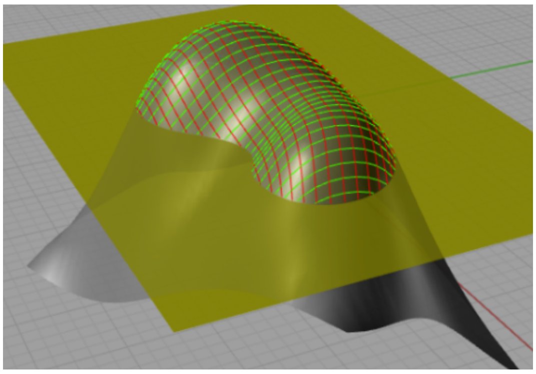


Figure 19: Trimmed mesh.

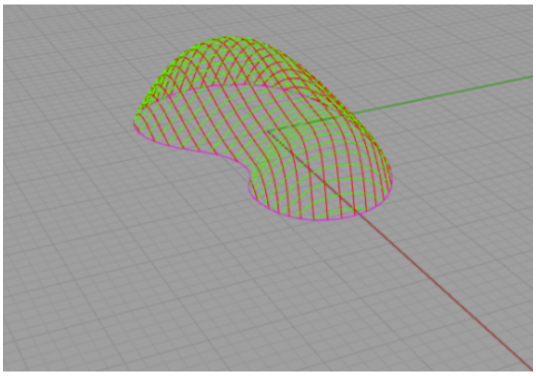


Figure 20: Final mesh and support outline.

MESH OPTIMIZATION As the form is known and the procedure to mesh the surface is now known, an optimization of the mesh can be performed (Fig. 21). The aim is to find a mesh that can mesh the entire surface and that creates acceptable stresses in the beams. To this end the curvature of the elements is checked using the following equation (Eq. 3) :

$$C_{mesh} > \frac{\sigma_{max}}{E.v} \qquad (3)$$

Different sets of guide-curves are chosen and the resulting meshes are compared according to this criterion:

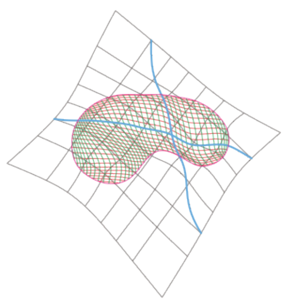
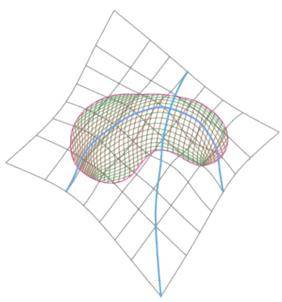
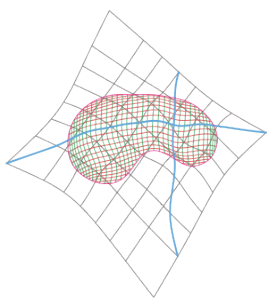
		
Mesh n°1	Mesh n°2	Mesh n°3

Figure 21: Mesh testing.

GRID-PROCESSING The generated mesh can be shaped in a matrix. This allows both its transformation in a planar grid of regular pitch (Fig. 22) and automatic definition of triangulation elements for bracing.

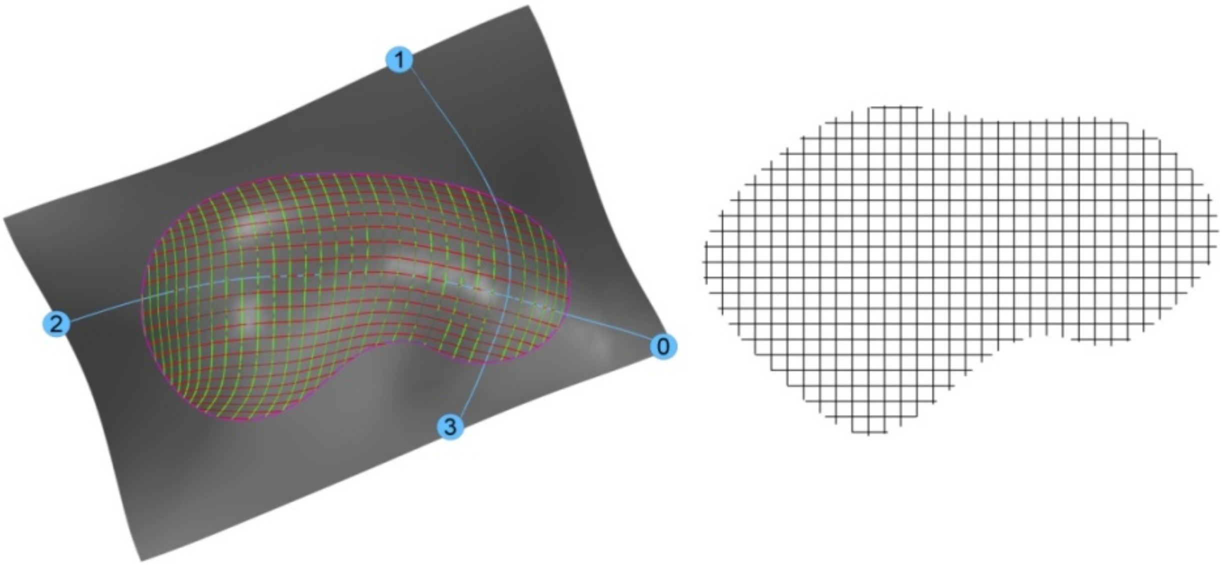


Figure 22: Developed surface and derived grid.

<u>GENERATION OF ANALYSIS MODEL</u> A procedure gathers and processes all the geometric information. It creates an import file for the automatic generation of an analysis model in GSA, a third-party software dedicated to structural analysis. Additional components assist the designer in the definition of complex load cases, such as non-uniform wind and snow loads, directly in Rhino & Grasshopper.

Structural Analysis

Once the structural model is built by our tools, it can be loaded in the structural analysis software to perform:

- Computation of the permanent flexural stress and the relaxed shape using a dynamic relaxation algorithm (Fig. 23).
- Loading analysis according to the Eurocode (self-weight, snow, wind, ...).

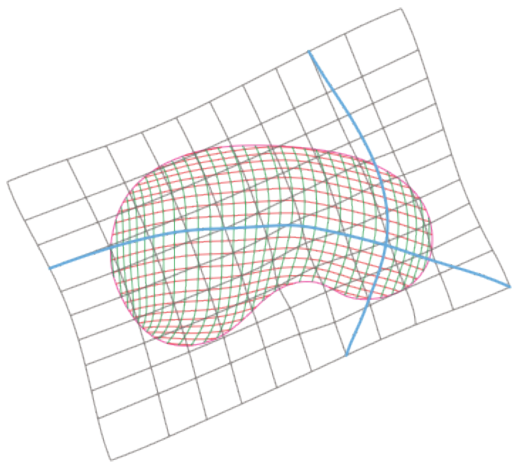
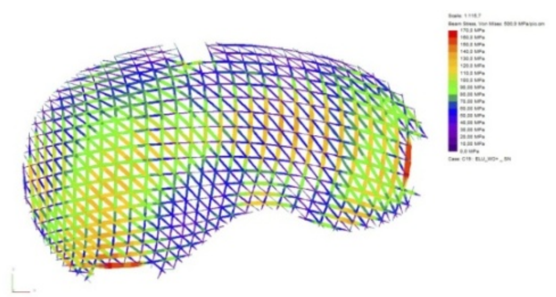
	
Final mesh	Permanent bending stress

Figure 23: Final compass mesh and corresponding relaxed mesh (stress diagram).

CONCLUSION

This paper has presented the different steps for the design of a gridshell in composites materials built for the Solidays festival in 2011 in Paris. The first step was the optimization of the shape in order to avoid concentrations of curvature locally. The second step showed a tool to automatically mesh a surface using the compass method. With this tool, the optimum orientation of the mesh is studied. The last step showed the details of the structural analysis of the gridshell. This construction demonstrated the technical feasibility and also the economical feasibility of the gridshell in composites materials.

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