INTRODUCING PASCALIAN FORMS TO A LARGE SCALE PHYSICAL MODEL

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ABSTRACT

The paper describes the experience of the design and construction of a complex double curved shell that was constructed during a one week workshop, organised in October 2007. This pedagogical workshop was organised by the Free Form Design group, a sub-Working Group of Working Group 15 "Structural Morphology" (IASS).

As the workshop was a first attempt to construct a large scale model based on a numerical model designed with Pascalian Forms, initialised by professor Marty, basic constraints were set in order to secure simplicity of the design and construction. Finally, a double-curved shell (with anticlastic and synclastic segments) was constructed. The result of the experiment entailed interesting remarks which will be discussed in this paper.

KEYWORDS

Interdisciplinary, free form design, learning by experimentation, large scale physical model, geometric generation.

INTRODUCTION

This paper describes the experience of the design and construction of a complex double curved shell that was built during a one week workshop, organised in October 2007 at Les Grands Ateliers in l'Isle d'Abeau in France, by the Free Form Design group, a sub-Working Group of Working Group 15 "Structural Morphology" of the International Association of Shell and Spatial Structures (IASS). The international and multidisciplinary team was formed by French students from the School of Architecture in Montpellier and by Dutch students from both the Faculty of Architecture and the Faculty of Civil Engineering and Geosciences of the Delft University of Technology.

The intention of the workshop was to gain better control in generating free form shapes, since an increasing desire for these shapes has developed over the last decades. This includes the aim to introduce a geometric methodology to the design and construction of complex shapes. Based on these intentions, the presented approach in this paper has the possibility of allowing continuity from the first design sketches to the final materialisation of a large scale physical model.

1. PASCALIAN FORMS: FROM THEORY TO PRACTICE

The workshop started with introduction lectures providing the theoretical base necessary for the subsequent practical work of designing and constructing the free form shape. General theory and background issues about the conceptual design [1], structural design [2], materials [3], and perception of doubly curved shapes [4] were presented during the lectures. Finally a more detailed presentation introduced the parametric tool, the Pascalian Forms [5][6], which was used during the design process.

1.1 Objectives of the workshop

Numerical tools have stimulated architects' audacity for spatial representation and invited them to generate forms that were hitherto inaccessible through the simple use of ruler and compass. This resulted in geometrically complex projects which are driven by aesthetic intentions, but may remain disconnected from other design parameters. Considering the materialisation and realisation of such complex forms, questions associated with architectural, structural and constructive aspects make the emergence of an ideal compromise difficult. These questions specifically concern the prospective function of the design object, how it is perceived (symbolism), the composition and organisation of components, or materials and their mechanical behaviour as well as production technology.

Behind graphic interfaces of modelling software, families of forms like Bézier, B-Spline, or NURBS curves and surfaces are easily manipulated on the computer screen without allowing any deeper understanding of the algorithms behind them. Shapes generated with these free form curves and surfaces escape the immediate comprehension which a direct analytical approach would allow. Thus, non-standard geometry finally results in an increased visual complexity rather than in a genuine tool for mental representation as enabled through drawing by hand. The merely visual then predominates over materiality. Also, most complex forms hitherto realised have exploited traditional techniques to generate new aesthetics which, however, should require new technologies. The emergence of a new architectural approach clearly is hindered by the confusion between a definition of the "non-standard", often expressed in purely visual terms, and the means of realisation as such, which are far more diagnostic. This confusion, which is probably the consequence of a certain "immaturity" of non-standard design, leads to bring down complexity to mere complication.

As the profession is facing new paradigms in the design process, education in engineering and architecture must be adapted by exposing students to innovative methods and tools. The pedagogical objective of the "Free Form" workshop relates to this idea as its goal was the study of the design process of forms characterised by complex geometries. Additionally, in order to contribute to the debate on free form design the main question dealt with during the workshop was:

How to ensure greater coherence in the design process of complex shapes, from the first sketches to the effective realisation?

This paper focuses on the coherence between design, engineering and construction in terms of methods chosen at different stages of the process leading from conception to realisation. It is necessary to develop new geometric tools that allow the generation of complex forms and keeping the link between geometry and physics of the processed form. It was proposed to test the choice of a common vocabulary, the one of "pascalian forms" proposed by professor Alain Marty [5].

1.2 An introduction into Pascalian Forms

Pascalian forms are nothing but Bézier forms approached from a recursive geometric point of view. And as such, they inherit all their properties. Pascalian forms are parametric based on a gestural approach since the most fundamental one simply returns the middle of two points. Consequently this method offers the advantage to represent the generation of complex forms according to a few basic transformation rules. This differs from the complex mathematical methods usually found in literature. This particular case of parametrics is based on a systematic application of the De Casteljau algorithm (Fig.1). The name is justified by the use of the coefficients of Pascal's triangle in linear combinations of points, and by the particular geometric approach.

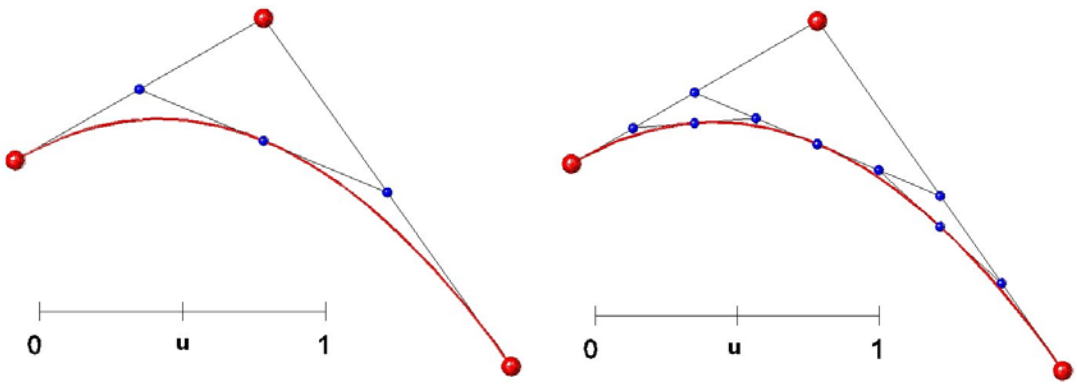

Fig.1 – Visualisation of the recursive De Casteljau Algorithm

In order to secure simplicity of the design and construction, the simplest curved element was used as design tool: the parabola, named "pL3", defined by three control points. Figure 1 illustrates its construction using the recursive De Casteljau algorithm. It is visible that intermediate control points does not belong to the resulting curve.
By combining three parabolas, a double curved surface is obtained: the biquadrate, named "pS33", the simplest non ruled curved surface in the family of pForms (Fig.2). According to the construction logic, the intermediate parabola does not belong to the resulting surface. The curvature properties of the resulting surface (anticlastic or synclastic) depend on the positioning of the control points.

The "pS33" is built by three parabolas each defined by three control points. To generate the surface, the *De Casteljau* algorithm has been used twice:

- the control points of the parabolas belonging to the surface: starting from the three initial parabolas; one first builds the parabola medium, then the parabolas at 1/4 and at 3/4, and continues this process until obtaining the number of parabolas entailing the desired smoothness in direction V.

- the current points of each parabola : one first builds the point medium, then the points at 1/4 and at 3/4, and so on until obtaining the number of points entailing the desired smoothness in direction U.

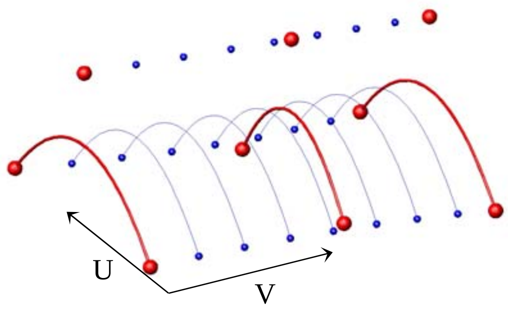

Fig.2 – "ps33" generation

1.3 Student's design exercises

After the introduction lectures, the students, organised in teams of two or three, made preliminary designs for the double curve shell, using diagrams, sketches, and physical models. The main purpose of this exercise was to apply the pForm concept to the design of a realisable large scale model of a pavilion devoted to experimentation on shape perception.

The proposed designs had to respect a number of imposed constraints, in order to fabricate and construct the double curved shell within the available time including the assurance of simplicity of assembly. Main constraints concerning the design were the maximal external dimensions of 25m² in plan and a 4m maximal height, as well as the demand for the combination of two surfaces, synclastic and anticlastic, each defined by three parabolas.
Based on these constraints, ten groups of students elaborated different proposals (Fig.3) of which one was chosen for realisation (Fig.4).

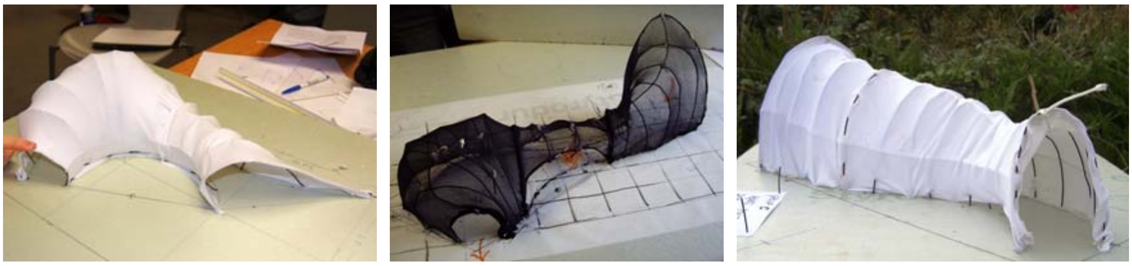

Fig.3 – Several proposals

The chosen project related fully to the constraints that had to be respected and was suitable to be realised within the available construction period (Fig.4).

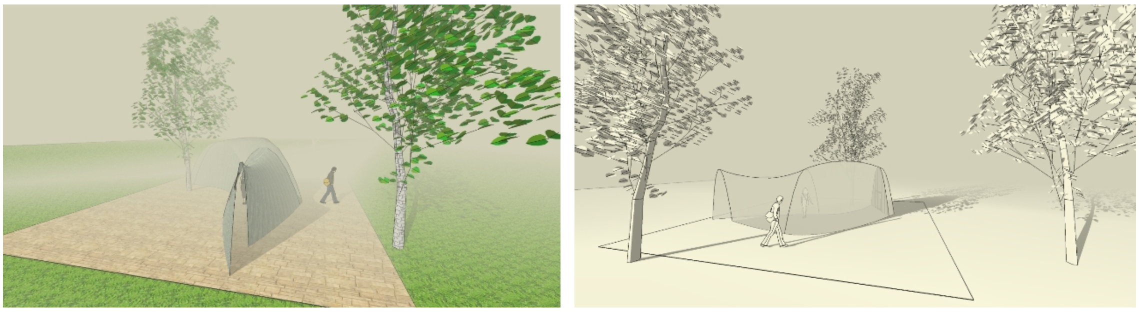

Fig.4 – The winning project

In order to optimise the preliminary design for the large-scale realisation, the project was then numerically modelled using a design software application linked to a plug-in developed by Alain Marty. As a result, the geometric outline of the design could be determined exactly, making it possible to draw the projection of every segment and to construct the parabolas accordingly.

2. CONSTRUCTION OF THE LARGE SCALE PHYSICAL MODEL

Based on a sequential process of the fabrication of wooden parabolic segments and cardboard surfaces, the used construction methodology was derived from earlier experimentations.

2.1 General methodology of construction

Following the geometry as described by the numerical model, thirty-three parabolas supporting thirty-two shell sections were built. For the construction of the parabolas, segmented timber frames were assembled, each consisting of sixteen linear elements geometrically defined by the pForm discretisation. By connecting the two parabolas of every odd shell section with two cardboard sheet layers – on the inside and outside of the parabolic frames –, sixteen stiff self-supporting shell segments were created. These were joined together with connecting cardboard sheets to finally complete the whole large scale physical model.

2.2 Building step by step

Using the 3D numerical model as a basis, groups of three or four students projected the parabolic segments for construction in full scale on the floor of the workshop. This was necessary due to the dimensions of the project. The projection was outlined using simple tools, such as rope and scotch tape, and the *De Casteljau* principle. Utilising this principle, students defined the parabola by recursively drawing points in the middle of a line segment between two previously fixed points – initially based on the control polygon of the parabola –, and repeating this operation four times. By mirroring these points for symmetric parabolas and recursively determining points on the other side for non-symmetric segments, this resulted in a curved shape defined by nine coordinates for eight wooden elements.

Once a parabola was drawn with rope, pieces of wood with a square cross section of 27mm by 27mm were used to reproduce these curves physically. By cutting the wooden pieces under an appropriate angle, a larger contact surface and smooth transition was obtained between the pieces to transfer the arch self weight and external loads. The pieces of wood were then connected by metal plates and screws (Fig.5). The base points of the arches were connected with a string for easy transportation during the assembly process, because otherwise the horizontal loads from self weight could not be transferred.

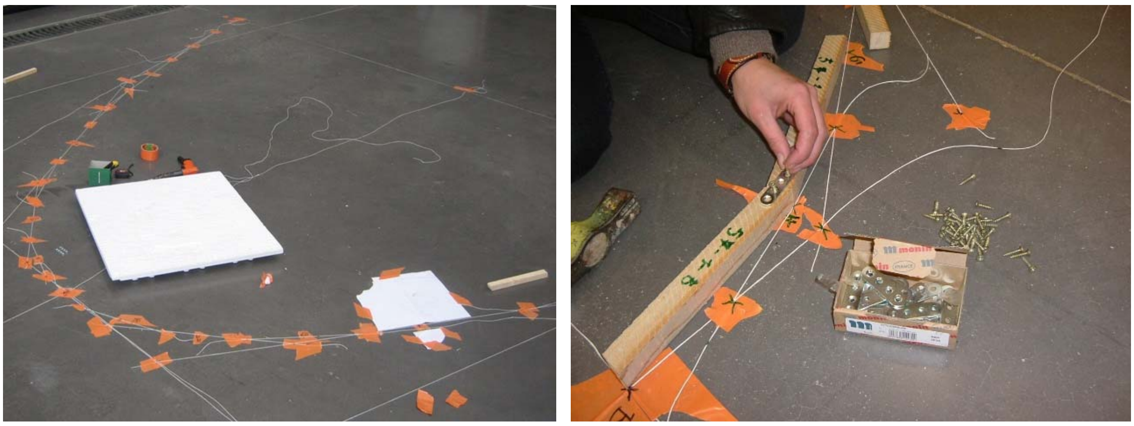

Fig.5 – Drawing of the parabolas and wooden work

The outline of every single cardboard panel was projected on a flat surface with a system of triangulation, according to the 3D virtual model. Due to the triangulation the resulting surface could be described by planes and straight lines. Each cardboard panel was made twice, one for the exterior surface, and one for the interior surface covering the wooden structure in the interior. The cardboard acted as a ruled surface in the construction of the segments. Due to the properties of the material, the cardboard performed an important function by giving the stiffness necessary to make each section stable in itself.

One of the biggest difficulties was to maintain the appropriate distance between the two wooden parabolas. Subsequently, the inner and outer cardboard panels were stapled to the two wooden parabolas, making the sixteen odd shell segments (Fig.6).

Fig.6 – Assembly of wooden parabolas and cardboard panels

The final assembly of the full scale model was initiated by connecting the stiff self-supporting shell segments with cardboard sheets of the even shell segments. An embedded flexibility of the wooden parabolas was guaranteed by the assembling method. Combined with the possibility to remodel the connecting cardboard sheets, it was possible to prevent some deviations due to the construction method (Fig.7).

Fig.7 – General assembly of the cardboard free form

After three intensive days of work, the initially designed free form shell was not fully realised, but the built part was for a good representation of the original sketches and computer models (Fig.8).

Fig.8 – The free form after three intensive days of work

2.3 Utilising the free form shell as a form work

The workshop at Les Grands Ateliers was not only an opportunity to apply Pascalian Forms to large scale physical models. The model that was built in timber and cardboard was also very suitable to serve as a formwork for testing an innovative application of glass fibre reinforced composites: Fibre reinforced composite sandwich shells [3].

Before the workshop the composite sandwich material had only been used for flat surfaces. The goal was to see how the material would behave when producing surfaces with high curvature. Small scale models were therefore made in which a single curvature arch was created using the sandwich material (Fig.9).

Fig.9 – Small scale models of the composite sandwich material

The experiments showed that due to the large curvature in combination with the steep sides of the arch resulted in flat areas in the composite. The flattening was a result of the fact that the imposed difference in length between the top and bottom layer, due to the curvature, becomes too large. During construction the resin that was supposed to fill the interlayer of the glass fibre weave could hardly collect in the flattened areas. This severely weakened the arch.
A practical solution was to make a cut across the width of the arch in the top layer of the fibre glass weave By choosing the locations where the tensile force in the top layer was interrupted, flattening was prevented. After filling the cut, the weave can be repaired with a single layer glass mat. This procedure was used in the large scale model.

The final composite used to create the shell acts as a sandwich material. The sandwich was created by a 3D weaving of glass fibres resulting in stiffs two layers interconnected by loops of fibres. When the interlayer was filled with an epoxy resin a stiff composite was created. This way the material is not only stiff as a membrane structure, but also some small bending moments can be transferred. The outer glass fibre mats will transfer the bending moments and the inner layer can transfer shear forces. This way a thin but stiff structure is obtained.

The fabrication of the composite itself was phased. First, the 3D-weave was evenly filled with resin and then the resin-filled fabric was placed on a formwork. The filling and the placement needed to be completed within a small timeframe to prevent hardening of the resin before the final position was obtained.

It was the goal to use part of the timber-cardboard shell as a formwork for the composite sandwich shell structure. Since there was only a limited amount of glass fibre weave available it was important to find an interesting part of the shell. Furthermore, the double curvature could not be very large in order for the composite to follow it. The low and narrow side of the shell structure fitted this description.

Due to the relatively small height and width it would be possible to place the composite by hand. In order to support the weight of the composite without sagging, the shell section was reinforced with timber. The glass fibre weave and resin were taken outside and there the glass fibre weave was filled. To get a good and even fill the weave was flipped and resin was applied from both sides (Fig.10). Within the limited time span available for filling and placement the non-hardened composite was lifted onto the formwork.

Fig.10 – Application of the resin on the weave

To prevent the flattening effect, the cut and patch technique was used which worked well on the large scale model (Fig.11).

Fig.11 – The cut was repaired with a single layer glass mat

The next day the composite had not completely hardened yet due to the low temperature outside. Still, it was visible that the filling of the resin had worked out well. The sandwich was clearly visible (Fig.12, left). After a longer period of hardening the shell was transported to Montpellier. There, it could be concluded that the composite had become a stiff structure that could easily support itself (Fig.15, right).

Fig.12 – The composite sandwich material

The shape of the formwork had been followed well by the composite, even double curvature had clearly been transferred from the formwork (Fig.13). At the same time the surface quality was good, even though the conditions in which the composite was created were simple.

Fig.13 – The final model created with the composite material

3. DISCUSSION

The workshop focused on the geometrical aspect of free form architecture and engineering on a pedagogical level. The implementation of a more direct algebraic description, such as the pForm method, replacing for instance NURBS modelling with basically the simple recursive method of determining the mid-point of two points, provides an improved control over the geometric generation. It can be affirmed that the pForm method constitutes a very effective geometrical language for a quick understanding of the geometry of non standard shell shapes and a relatively easy method for building large scale physical models.

Although the goal of geometrical understanding and manipulation leading from the virtual design to real physical model was reached, the workshop revealed two other issues about non-standard practice as well: the technical and aesthetical aspects, which add to the complexity of this new tendency in the building practice. Consequently, some disappointments were felt at the end of the workshop. In other words, some technological issues as the roughness of the real materials (wood and cardboard), the accumulated imprecision, and the weakness of the chosen connecting technique caused a high level of imperfection in the final built form. In order to fully utilize the Pascalian language and the presented pForm method in the realisation process of for instance large scale models, refinements of some of the technological solutions are necessary to reach a better structural coherence in the whole design process.

In relation to the fabrication of the composite shell, other issues can be discussed. As the experiment was done on a small part of the full scale physical model, which was not highly double-curved, most of the major problems were minimised. These mainly concern the question on how to cover a non-developable surface with plane fibre glass surfaces. Within another design project, problems, such as wrinkles, different lengths of the top and bottom layers, flat areas, local accumulation of the resin, assembly of different panels, etc. might result in less satisfactory results than during this workshop.

4. CONCLUSION

Since they seem to be an effective geometrical language to assure continuity during the different phases of the design process, Pascalian forms were proposed as the main tool of the design of a shell structure. The pedagogical target was finally reached in terms of geometrical understanding of the structure and its spatial layout. Above this initial goal, Pascalian method also provided the students with a tool to build what usually remains on a computer screen, with the additional notion of the model being full scale. This step from the virtual to the real enlightens the difficulties generated by these new architectural tendencies.
And, although several controllable and non-controllable difficulties arose during the design and construction period, the final realisation of the large scale physical model demonstrates the usefulness and interest of this kind of geometrical approach to the design and construction of complex shapes.

ACKNOWLEDGEMENTS

The workshop’s venue was Les Grands Ateliers, a scientific and pedagogic research centre, located near Lyon in France. The Atelier was founded in 2001 by several higher educational institutions in France and can be used for research and experimentation in the fields of architecture and structural engineering and it has excellent conditions for constructing large scale models.

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