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Free-form, form finding and anisotropic grid shell

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Abstract

The new geometrical developments open new perspectives for free-form design, making it possible to escape from planar triangular or quadrilateral discretizations. Recent advances in theory algorithms allow for the discretization of any surface using only single curvature panels thus allowing the realisation of smooth double curvature glazed envelops of any form.

Grid shell structures usually present a nearly in plane uniform behaviour, but previous realisations have shown that grid shells can be designed also according to an anisotropic in-plane arrangement. The control of principal direction and the fine tuning of the stiffness of the different structural elements (arcs, cables etc.) is a tool for adjusting the form-finding thus controlling the resulting geometry. Moreover, the form-finding can also be performed without researching a constant stress (self weight); in this case an even wider range of forms become possible.

These new geometrical and structural approaches have been coupled together and tested in re-designing, as a case study, the glazed roof of the Neumunster Abbey in Luxembourg. Such approach allowed for the conception of an efficient structure supporting a smooth double curvature glass skin, made out of only single curvature panels, perfectly coherent with the perimeter of the courtyard i.e. matching all the edges without any gaps.

Keywords: free-form, form finding, grid shell, glass, single curvature panels, surface discretization.

1. Introduction

RFR have been involved in the design of double curvature transparent skin for more than a decade (Baldassini [3], [4]). The realized projects present a different approach from the ones characterizing the architectural debate lead by bars-assembled structures: they are based on the rationalization of the geometry, the standardization of the connections and the utilization of cold-bent glass panels. This approach resulted in a limited vocabulary of possible forms but has however minimized the associated technological complexity. This renders possible the realization of small projects of this type which could not otherwise sustain the extra cost of the development of special production techniques.

From the structural point of view projects like the Avignon TGV Station, the Glazed Roof for the Neumunster Abbey (Baldassini *et al.* [1]) and the St Lazare Metro Station Entrance (Edwards *et al*. [9]) are based on continuous circular arches. This solution simplifies the constructional issues as well as improving the structural behaviour, mostly the buckling resistance. Further to this, the studied approach to the setting out of the arches disguises the regularity of the geometry which disappears in the global view.

The coupling between the structural layout and the transparent envelope for the skin of the "Lentille" St Lazare is rendered possible. This results in the possibility of the production of varying sizes of glazed panels from a very limited quantity of oversized moulds.

Figure 1: Lentille St Lazare Metro station entrance

In the case of the Avignon TGV Station the coupling between the flat double glazed panels and the structure is assured by the cold-bending technique. The flat glazed panels are elastically twisted on site during installation thus adapting the shape of the panel to the geometry of the support. Such an approach allowed a pannelisation which is not aligned with the parallel and meridians of the torus reference geometry, thus giving a dynamic appearance to a rational and regular geometry.

Figure 2: Avignon TGV Station

2. Strasbourg and cold bending

The approaches developed in the above two projects converged in the Strasbourg TGV Station (Blassel [7], Blassel *et al.* [8]) where a smooth non-facetted envelope is achieved by developing to the highest extent the cold bending technique.

The new glass shell, created in front of the existing building, is a combination of tangent tori inclined with respect to the horizontal plane in order to give a dynamism to a classical form. The glass panels are organised radially and elastically bent into a cylindrical shape to suit the regular geometry of the section. The panels are long and narrow in order to maximize their longitudinal flexibility while the transversal span is relatively short in order to minimise the glass thickness thus enhancing the bendability.

Given the different families of glass curvature, the cold-bent technique has been optimized with respect to different radii. On-site cold-bent glass would have been possible for the majority of the skin, with the exception of the tightest radius where the locked-in stress due to the cold-bending would have been too high with respect to the climatic stresses. In order to minimize the locked-in residual stresses in such critical areas, the glass panels are cold-bent before, and not after, lamination. Finally all the glass panels are fabricated according to this technique for reasons of simplicity of installing pre-bent panels.

This project proved to be very successful from the technical and aesthetical point of view showing how the discretization of a double-curvature surface can result in an imperceptible discontinuous surface that is perceived as being smooth.

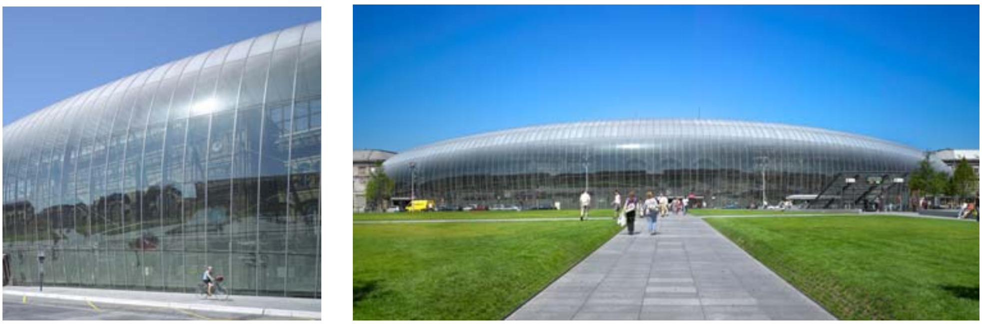

Figure 3: Strasbourg TGV Station

3. Free-form from single curvature panels

The architectural interest is to create smooth (continuous) double-curvature surfaces without the limitation of using double curvature glass or being limited to simplified geometries. The utilisation of double-curvature glass can be envisaged only for special projects, free from economical constraints. The Strasbourg project proved to be effective in creating a smooth double curvature envelope using single curvature glass panels. However, the project was limited to a revolutional surface, far from being a real free-surface.

The concept of extending the single curvature discretization to any surface was a challenge which was not possible to undertake using standard tools and goes well beyond the possibilities of the most sophisticated and powerful drawing packages such as CATIA. Sophisticated drawing packages even if implemented with specifically written scripts (as we are used to do for more than a decade) are still not a breakthrough in terms of geometrical thinking and are not appropriate in dealing with the complexity envisaged nowadays by the architectural community nor are they useful for discretizing any surface according to single curvature panels.

On the other hand, research on mathematical algorithms allow for an approach to issues of geometry from the point view of the properties of the surface. This shifts the interest from the tool and design strategy to the theory and understanding of the geometrical properties.

On this basis, the current research program developed by RFR, TUW and Evolute has been successful in the goal of discretizing any arbitrary free form surface in layouts of single curved panels, creating "developable strip" models, or D-strip models, which can be seen as a semi-discretizations of the double curved surface; i.e. discretization in one direction only, the other direction remaining curved (Pottmann et al.[11], Baldassini [5], Schiftner et al.[12]).

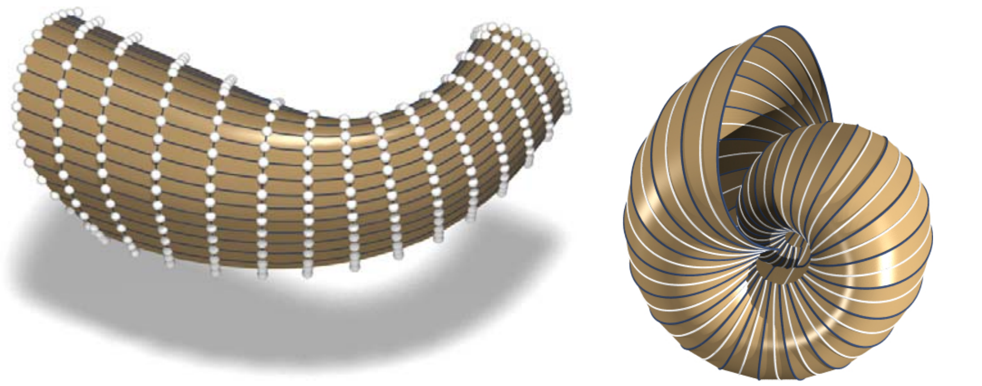

Figure 4: Examples of single curvature panels discretisation

On an arbitrary surface, several D-strip models solutions are possible, such as Conical/Circular and Geodesic strip model allowing flexibility for the design process.

Among them some are of particular interest due to their inherent properties. The duality between the Conical and Circular D-strip models imply that the constant offsets of Conical D-strip models still generate Conical D-strip models and that the offsetting surface, defined by the offset vectors, is also developable. Consequently the structural or glazing profiles members, when aligned with the boundary of the D-strips, will not present any twisting along their length. This results in great simplification of the construction process.

Geodesic strip models are orientated along geodesic lines of the surface thus minimizing the in-surface curvature of the strips.

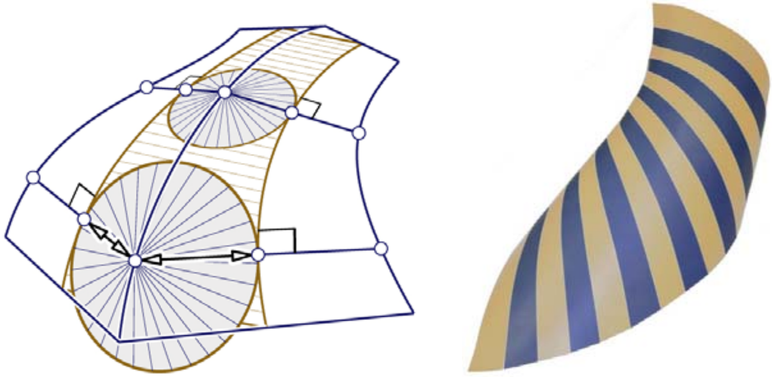

Figure 5: Conical/Circular and Geodesic strip mode

When approaching a design according to this new strategy, the resulting pattern of the single curvature glazed panels is coherent with many technical issues explored in past projects (Baldassini [2],[3],[6]). All these experiences come together to constitute a technical and aesthetical corpus coherent with the architectural application of transparent double curvature skins. A skin discretized according to single-curvature glass panels is perfectly complementary with:

- *Cold bending techniques*: This production technique (both before and after lamination) creates curved glass at a sustainable cost with better optical qualities compared to hot-bent glass.
- *Continuous arcs*: The homogenous bending resistance along the entire length of the arc improves the structural behaviour.
- *Glass posed directly over the arcs*: This glass fixation system reduces, by default, the problems of the offset between the structural axis and the skin working point.
- *Orientation of panels according to maximum radius curvature lines*: The strategy of matching the curvature of the glass panels with the maximum radius curvature allows for a discretization which is barely visible: the visual impression is one of a smooth continuous double-curved free-form surface.

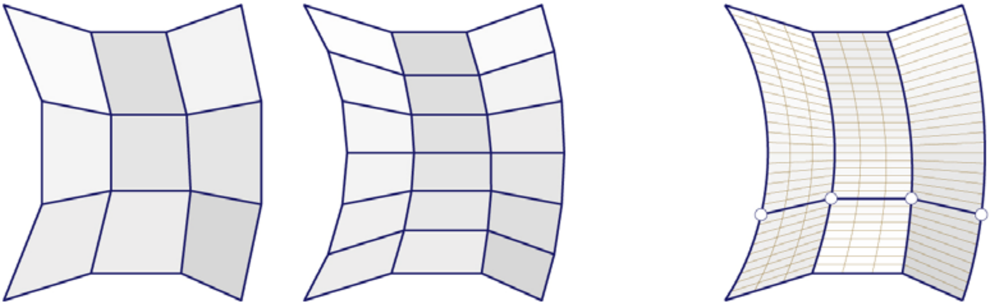

Figure 6: Semi-discrete mesh as limits of discrete mesh

Single curvature panel discretization offers the possibilityof extending the design dominium of single curvature discretization well beyond the translational/revolutional surface achieved in the past in the Strasburg TGV Station with a technological coherence that open new design horizons.

3. Case study: the glazed roof of the Neumunster Abbey

In order to assess the architectural possibilities of such an approach, the previous project of the Neumunster Glazed Roof in Luxembourg (Baldassini *et al*. [1], [2]) has been re-studied and re-engineered. This project is a relevant case study since the reference scheme presents important constraints which make the design particularly challenging:

i. The roof is aligned with the four sides of the courtyard, (history has shown that shells present a problem in adapting to straight boundaries).

ii. The structure is a hybrid grid-shell characterised by a strong anisotropy, an unusual and innovative structural scheme.

iii. The geometry presents a relevant singularity, i.e. a fold of the surface diagonally axed on two opposite corners, as result of the choice of a diagonal grid finalised to increase the corner curvature.

Figure 7: Glazed Roof over the main courtyard of the Neumunster Abbey

The design of the revised solution start from this basis and is developed with respect to the following principles:

a. Geometry - Sealing the four sides of the courtyard, (as in the original design), removing the fold and having a continuous double curvature surface.
b. Meshing - Using single curvature glass panels, (according to the scope of the re-designing exercise).
c. Technology - Organising the structure coherently with respect to the glass joints in order to support the glazing on at least two sides.

3.1 The anisotropic grid shell

As in the case of the original scheme, the grid is anisotropic but at a lesser extent since the grid is not composed of arcs, (only in one direction) and cables: it is composed both by primary arcs and secondary bi-articulated bars (of different section), braced by cables.

As in the reference case the grid is not orthogonal to the perimeter, it is oriented at 51° approximately in order to achieve, in the corner, a consistent curvature for assuring the out of plane stability of the grid shell.

With the aim of improving the buckling behaviour, the form-finding process is not developed with the mean of researching a state of constant forces in the arcs and in the bars under self weight. The form-finding is performed with respect to a variable state of forces in order to achieve an optimal curvature, (optimisation of the maximum and minimum radii and orientation of curvature lines) which is important for controlling the buckling modes of the structure.

The form-finding has been realised using a Dynamic Relaxation solver according to the density force method. The different state of forces of the different arcs has been controlled applying a different pre-stress to each arc during the form generation process.

Different configurations have been tested varying the orientation of the arcs as well as changing the parameters of the form finding and normalising the results with respect to the surface of the skin which still has the same area as the reference case.

The optimal configuration resulting from the different cases studied was shown to be one in which the length the arcs were minimised for a maximised overall curvature.

3.2 The geometry definition

The form-found grid was not directly exploitable since the structural development was not directly coupled with the geometrical research. In order to match together these two issues the form-founded grid has been transformed in a discretized/faceted surface. This surface has been interpolated in order to obtain a new reference continuous smooth surface.

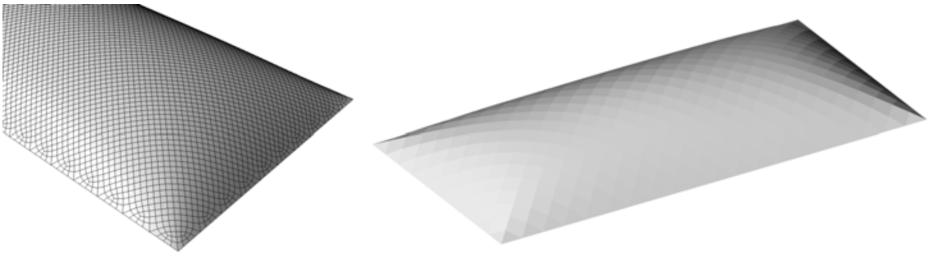

Figure 8: b) initial discontinuous surface, a) smooth reference surface

Such a reference surface is the base for the pannelisation and has been decomposed in single curvature strip. In order to correctly resolve the edges without incurring into numerical singularities, the reference surfaces have been extended beyond the limit of the roof. The exceeding part of the strips is cut only after that the meshing operation is finished.

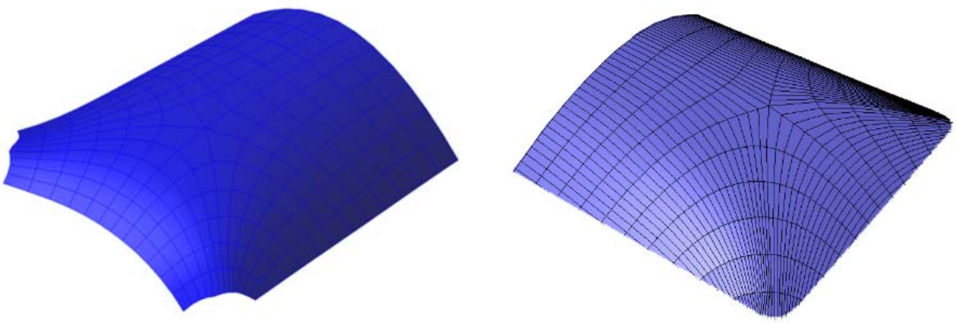

Figure 9: a) Extended meshed surface, b) exceeding surface, c) single curvature strip model

Such a configuration represents the first intermediate step, a first possible single curvature glass pattern, in the process of generating the final structural geometry and the base for the optimisation of the structure.

3.3 The structural definition

The reference surface and the associated pattern are used for reorganising the structural lay-out with the aim of matching the structural layout with the strip discretization layout in order to support the single curvature glass panels directly over the arcs. This positioning would therefore avoid the necessity for point fixing devices, (used in the original project). The modifications of the original layout, (orientation of the arcs) are minimal in the central part of the vault as well as in the corner where the arcs have the same spring but bend inwards. On the other hand the original pattern results in being strongly altered in the intermediate parts which present a singularity where three arc branches converge together. The modification to the structural lay-out does not modify substantially the direction of anisotropy in the four corners whereas in the centre of the structure the arcs now result in being nearly orthogonal to the two long sides with the advantage of reducing the span of the arcs. This adaptation of lay-out presents an important feature in that the pattern of the single curvature panels corresponds to the maximum and minimum curvature lines: the arcs correspond to the maximum curvature lines therefore ensuring a shorter and stiffer path for transferring the loads to the supports.

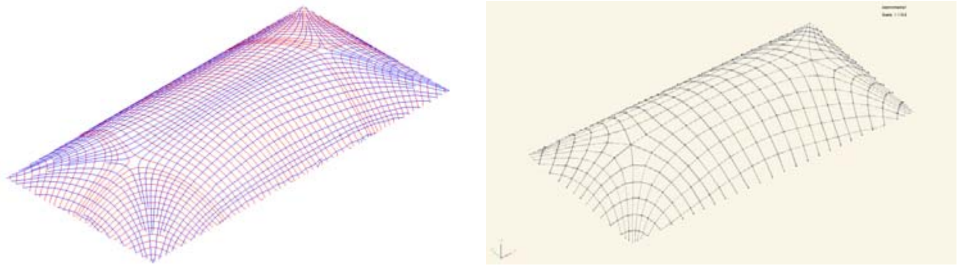

Figure 10: a) minimum and maximum curvature line, b) structural lay-out consistent with surface discretization according to single curvature strips

In terms of constructional technology, the arcs directly support the glass which is therefore efficiently held on it's two opposite long sides. Consequently, the transverse bars have only a global structural role, are dissociated from the glass lay-out and can be re-organised with the aim of seeking, as much as possible, a uniform efficient grid.

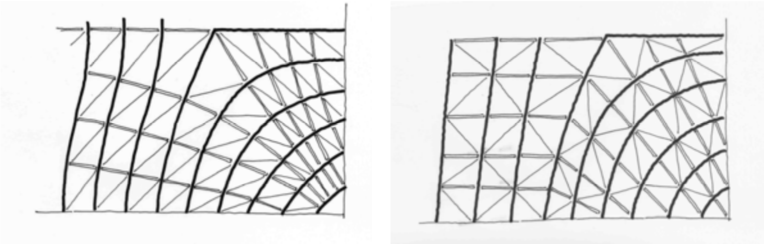

Figure 11: Sketches showing the modifications to the secondary elements.

3.3 The fine tuning

Since the orientation of the re-organised structure presented a relevant mismatch with the form-found structure it was not sure that there were no repercussions on the structural behaviour. Therefore the new structural disposition has been form-found a second time. The new form differs from the original one by only a several millimetres thus proving that the first initial geometry generation process was very efficient and that the change in the orientation of the anisotropy was only minor and insignificant from a structural point of view. Moreover the resulting small change in geometry has no effect on either the strip layout or the glass pattern which in any event, has been recalculated in order to have a full coherence between geometrical and structural variables.

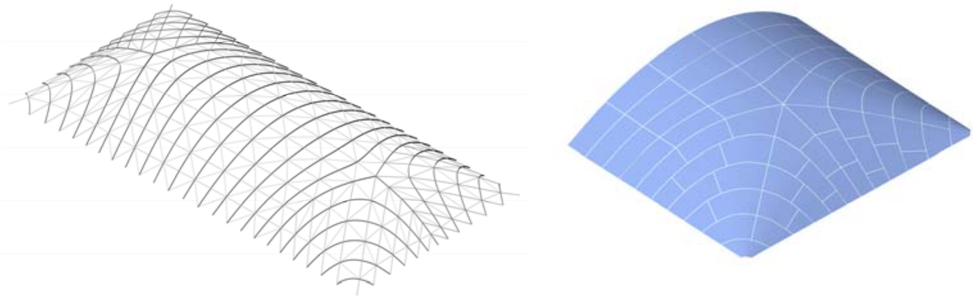

Figure12: Final structural layout and the associated glass panes.

4. Conclusion

The exercise of re-design for the Glazed Roof of the Neumunster Abbey proved that the combined strategy of conceiving the roof while coupling together the skin and the structural issues was powerful. The revised project represents a step forward with respect to the realised project since:

- The structure is more efficient, its weight has been reduced by 25%.
- The surface is (of course) smooth and does not present the discontinuity which was characteristic of the original project.
- The production of glazed panels is consistent with the cold bending technique and/or adjustable circular moulds.
- The utilisation of “conical” meshing results in free-twist arcs.

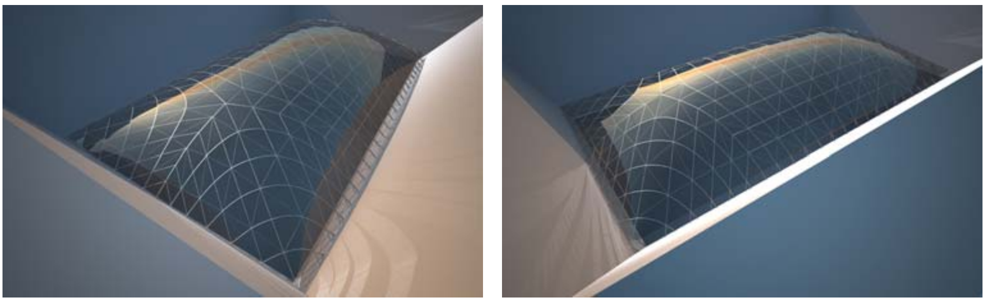

Figure 13: Rendering showing the glazing and the supporting structure

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