Forming process of façade panels by curved folding with combined geometric and mechanical optimisation.

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Abstract

The generation of 3D surfaces based on curved foldings is a time and cost-efficient process, avoiding the use of moulds. In this paper we demonstrate that by using the mechanical behaviour of materials and folding kinematics we can expand the possibilities of this fabrication technique. Parametric Design is combined with simplified structural analyses of finite element models in order to develop a robust form-finding process and optimise geometries. A non-linear finite element model simulating the step-by-step deformation of the panel from flat to deformed is then used to validate this simplified method. Finally, a series of prototypes at 1:4 scale are built to verify the feasibility of the fabrication pocess in real conditions and the resulting appearance of the finished panel.

1 Introduction

Current building façade design practice is transitioning to include specific components for each specific function. This multi-layer approach to opaque envelopes allows for higher performance requirements (mechanical, thermal, acoustic, aesthetic) [1]. The outer cladding, due to its external position, performs two important roles: an initial barrier against the rain and the principal visible element of the façade [2]. It is common practice to improve the form and aspect of these external elements to guarantee the architectural quality of the façade.

The current study is undertaken in the context of a significant façade project that consists of large doubly-curved panels (6m x 1.2m) with a reflective finish. The initial proposed solutions incorporated the commonly used procedure of moulded fibre-reinforced concrete (UHPFRC / GFRC) or pressed sheet metal. Both methods require the use of heavy and costly machinery that restrict the possible forms to repeatable elements. In this paper, a new method that requires simpler machinery and lighter elements whilst increasing the range of possible panel forms is proposed. This novel fabrication method uses curved folding on standard construction plate elements (metal sheets, composite panels) [3].

In this case the sheet metal is considered as a surface of null thickness with infinite stiffness in its plane. The deformation generated by the curved folding produces a « piece-wise developable surface » with well-known limits on the range of possible forms (from a geometrical point of view) [4], [5], [6]. However, in this article, elastic deformation in the plane [7], [8] is utilised to increase number of possible forms.

The structure of the report is as follows : Section 2 - form-finding using a simplified mechanical analysis ; Section 3 - validation and comparison of these simplified methods to advanced finite element models ; Section 4 - fabrication of a ¼ scale model (1.5m x 0.3m) to validate the design methodology.

Fig. 1 3D view of the rainscreen panel.

2 Form Finding

The first step of the design process is to find a form of panel as close as possible to the architectural intention but incorporating the geometrical constraints of the construction method and the mechanical constraints of the fabrication technique. The panel is discretised into a quad mesh wherin each quadrangle is represented by 4 points. The position of these points, limited by the mechanical and geometrical contraints, are used as the parameters for a dynamic relaxation process to find the final form. Grasshopper and 3D Rhinoceros software are used as the interface to implement this method.

2.1 Geometrical constraints

The first constraint applied is to ensure that the final geometry is as close as possible to the intial form proposed by the architects. This constraint is established by minimising the absolute distance between the points of the intial form and that produced by the curved fold method.

Secondly, the boundary conditions of the panel element are set. These conditions ensure the alignement of the panels on the façade and the continuity of the curved motif along the façade in order to reduce the deformation of light reflections.

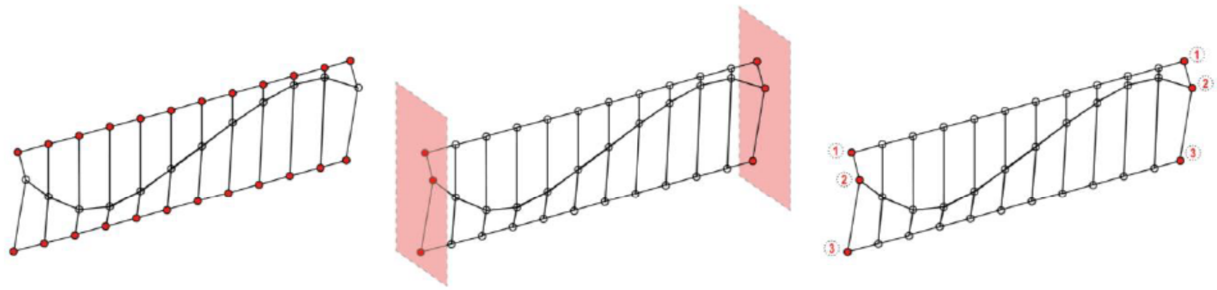

Fig. 2 The boundary conditoins imposed on the geometry: (Left) The long edges are perfectly straight and parallel. (Middle) The short edges must be included in a vertical plane. (Right) The short edges are symmetrical. 1 and 2 facilitate the assembly of the panels and 3 ensures the visual continuity.

Thirdly, the foldability of the surface is modelled by introducing the constraints that the sum of all angles generated by arcs converging to a vertex in a 3D fold must be equal to 2π.

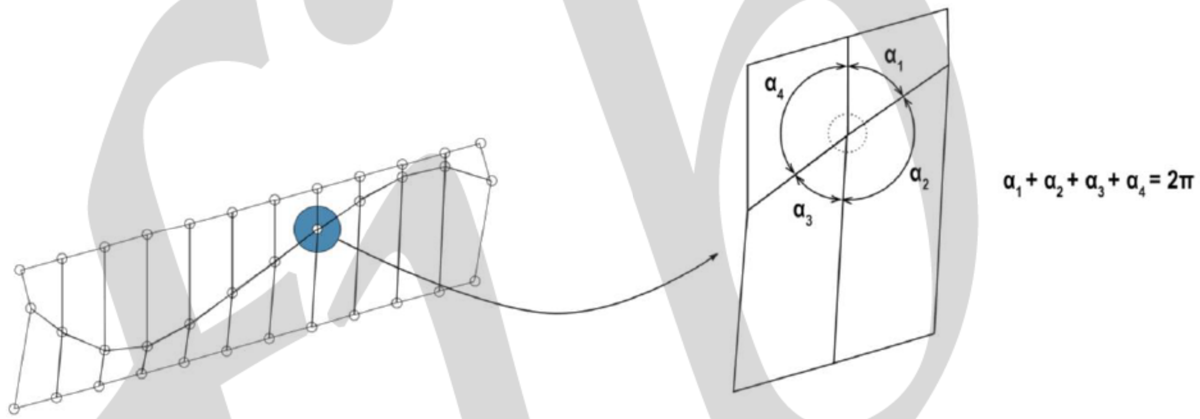

Fig. 3 The folding criteria is introduced using the sum of all angles generated by folds converging to a vertex.

Finally, the in-plane stresses of the surfaces are minimized in order to produce a quasi-developable surface. As shown in [9] the global developability of the surface can be modelled by the individual planarity of the quad elements.

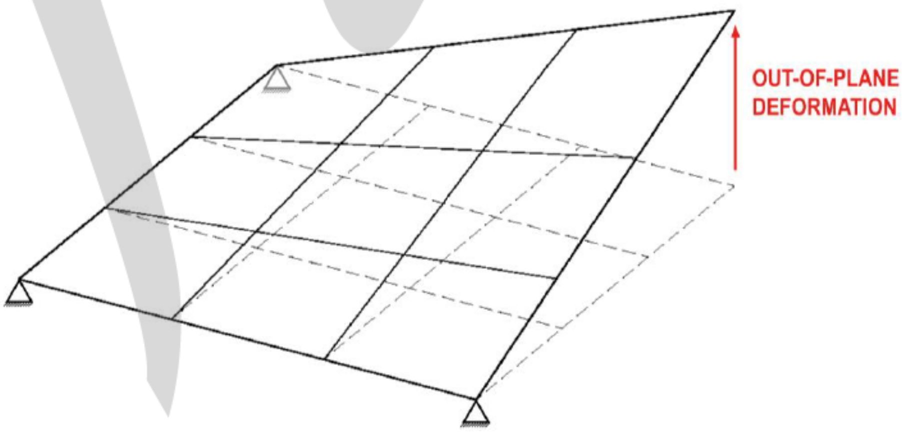

Fig. 4 The out-of-plane deformation of each quad elements is minimised (local constraint) to produce a quasi-developable surface (global constraint)

The geometrical constraints are each pondered by a weighting specific to the importance of the contraint in the optimisation process. The different weighting applied to each constraint can lead to different solutions. It is necessary for the design team to decide on the balance between the technical constraints and the fidelity to the intial form (these are unfortunately usually in conflict). The weighting chosen is to remain in the elastic domain of the metal whilst staying faithful to the initial architectural form.

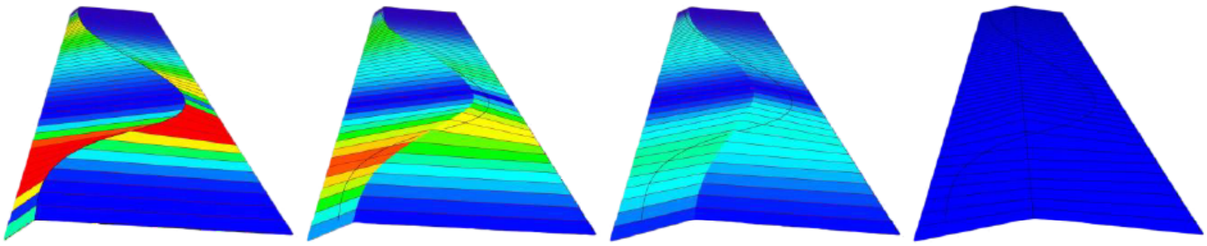

Fig. 5 Evolution of the form with a variation in the weighting on the closeness to the initial architectural form (decreasing from left to right). In this instance, the geometry converges to a straight fold.

2.2 Mechanical constraints using a simplified method

In order to evaluate if the surface remained within the elastic range it is necessary to calculate these surface stresses in real-time. Given the large number of iterations resulting from the dynamic relaxation method, it is impossible to evaluate each form in an external finite element software. The proposed solution involves the pre-processing of the internal stresses in fixed-width quad elements for a range of lengths and out-of-plane displacements before the use of a bi-linear interpolation in real-time.

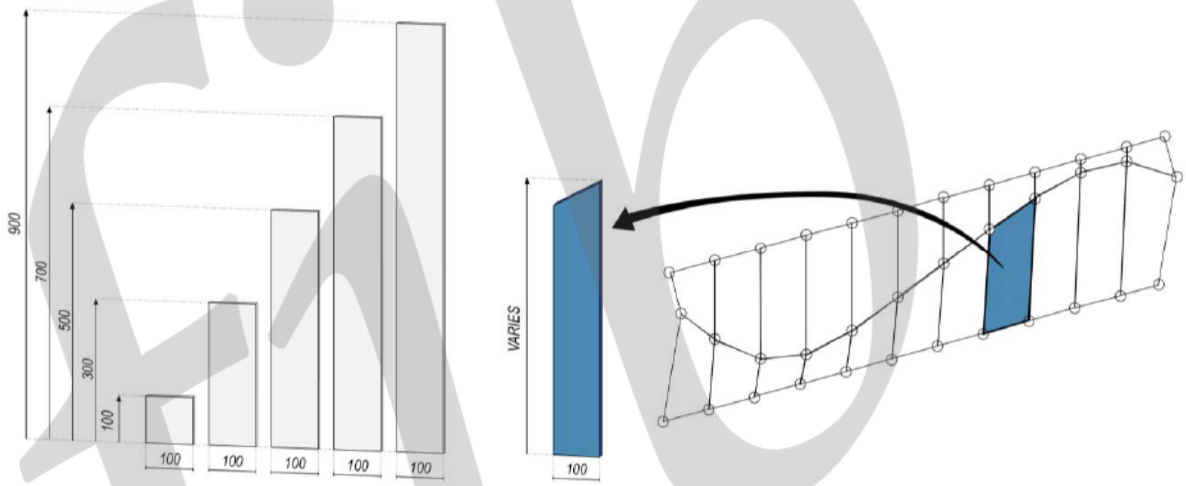

Fig. 6 A set of plates is analysed in a FEM to evaluate the local stresses due to various out-of-plane displacements. The maximal stress in each quadrangle is then interpolated from these results.

The interval of quadrangles lengths is varied between 100 and 900mm and the out-of-plane displacement between 3 and 15mm. The plates width corresponds to the width of the mesh quad elements and is fixed at 100mm. The quad elements are modelled as aluminium plates (E = 70 GPa) with a nominal thickness of 4mm. For each combination of length and displacement a finite element analysis is performed and the maximum Von Mise stress is found and tabulated. These values are used to perform a bi-linear interpolation of the stress values for each quad element in the panel mesh to approximate their local stresses. The interpolated values are outputted directly in the visual interface to give real-time feedback of the stress conditions (Fig. 11). In effect, the mechanical stress of the plate is deduced from the geometrical warping of the element; by limiting this warping the stresses can be kept within the elastic range.

Table 1 Von Mises stresses in the set of plates.

Maximum Von Mises stress [Mpa]					
Length (mm) / Deformation (mm)	100	300	500	700	900
3	51	15	9	6	5
6	130	35	19	13	10
9	237	58	30	20	15
12	362	81	40	27	20
15	494	105	51	34	25

3 Mechanical modelling of forming and stability

However, having found an optimised surface that satisfies the geometrical constraints whilst resting in its elastic domain, it is now necessary to perform a more precise stress calculation on the surface. This calculation is performed using a non-linear finite element software. The curve folded fabrication process is simulated by applying the required 3D deformation to a thin 2D plate and the resulting stress distribution is calculated.

3.1 Definition of the cutting pattern used as the input geometry (unfolded pattern)

The output of the form finding process is the 3D geometry of the deformed panel that best satisfies the applied contraints. It is necesssary to derive the form and the folding pattern of the flat plate element that produces this 3D geometry when folded. This pattern is used as precise fold introduced into the finite element model and as the cutting pattern that will be used when machining the scale model. Developable surfaces are characterised by an isometric relationship between their 3D form and their unrolled geometry. However, in this case the double curvature of the panel introduces small in-plane deformations that make the surface not perfectly developable. The generation of the initial flat plate is therefore non-trivial. In order to derive the intial flat plate geometry it is necessary to flatten each twisted quadrangle of the mesh onto a horizontal plane whilst conserving as much as possible their surface area. In addition, the difference in length and rotation of each quadrangle should be minimised to ensure the best isometry relationship between the 3D geometry and its unfolded pattern.

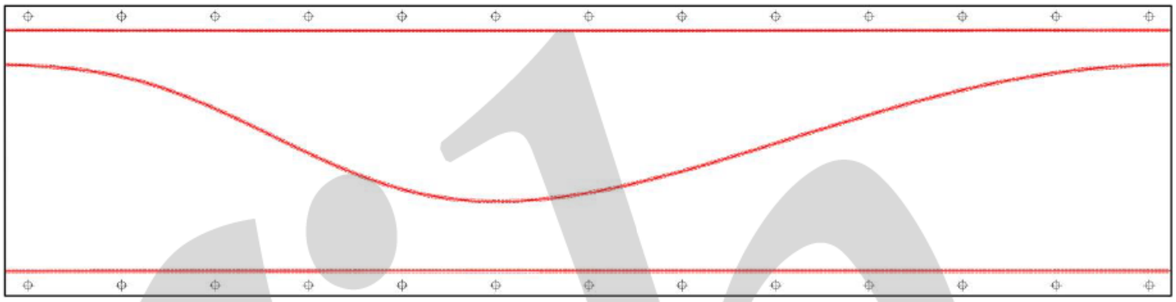

Fig. 7 Cutting pattern with folds along the red lines.

3.2 Kinematic of the folding

Now that the flat plate geometry has been obtained it is possible to input this into the finite element model and apply a prescribed displacement along the long edges. This displacement is coupled with a nominal out-of-plane force applied along the curved fold in order to simulate the folding process. The fold is modelled as a plastic hinge while the rest of the panel stays in the elastic domain.

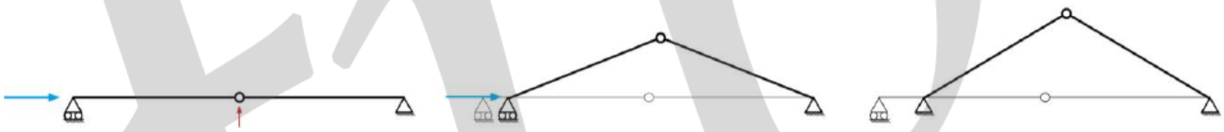

Fig. 8 Kinematic of the deformation in the FEM.

The software used is Straus7 version 2.4.6 and the calculation method is an incremental non-linear geometrical and mechanical analysis. The geometry is modelled as as series of linear quad shell elements. The results obtained from this finite element method can then be used to validate the initial results obtained using the simplified mechanical method. The comparison is performed by using two local surface parameters, the Gaussain curvature and the Von Mises stresses, and one global parameter, the 3D position in space of the surface.

Initially the geometrical differences between the form obtained from the form finding process and the finite element analysis are quantified. The comparison is performed by calculating the absolute deviation of 8,500 points on both surfaces. A mean absolute deviation of 0.67mm and a local maximum of 2.1mm are obtained between both surfaces. This global geometrical comparison is now complemented with an analysis of the local Gaussian curvature. The figures below demonstrate qualitatively the similarity in the Gausssian curvatures obtained in both models. The similarity of geometry and curvatures allows for the finite element model to validate the form obtained using the simplified mechanical approach.

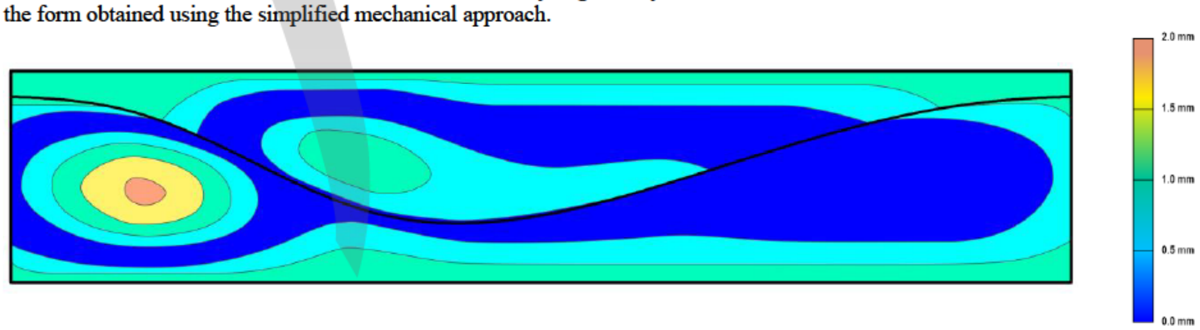

Fig. 9 Absolute deviation between the form obtained from the form finding process and the finite element analysis.

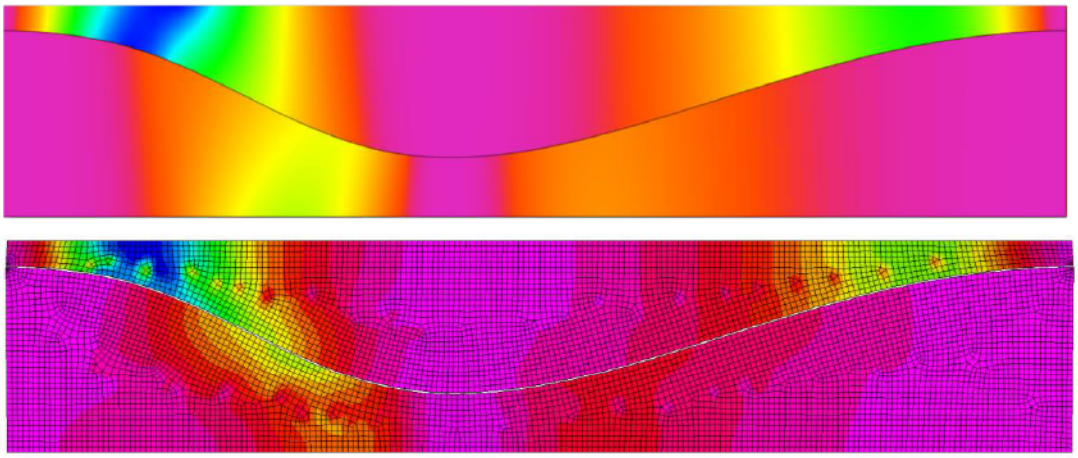

Fig. 10 Gaussian curvature of the form obtained from the form finding process (upper figure) and the finite element analysis (lower figure).

Finally, the Von Mises stresses obtained using both methods are compared. Figure 11 demonstrates quantatively the similarities between both analysis methods, confirming the pertinence of using the simplified mechanical analysis during the form-finding process.

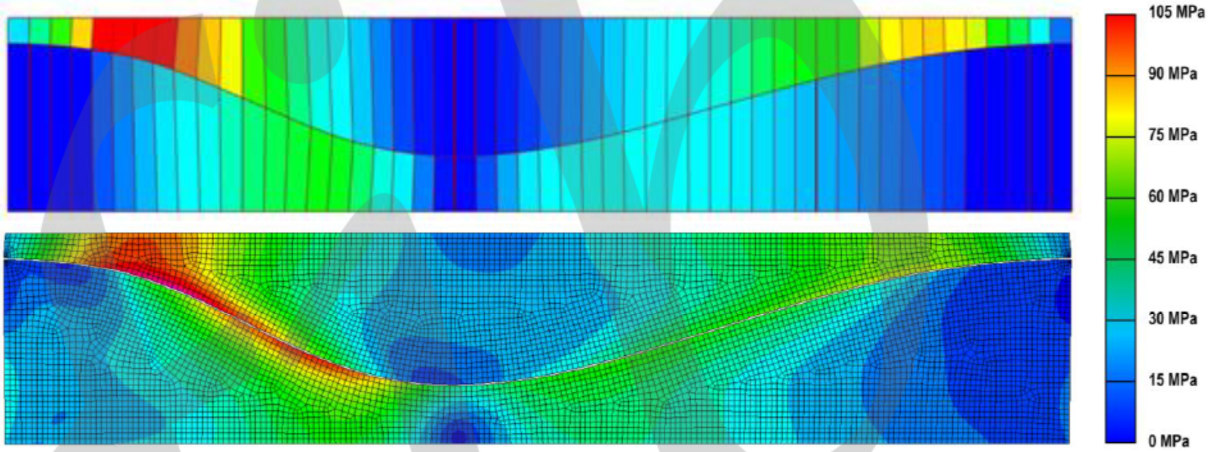

Fig. 11 Von Mises stresses calculated with the simplified method (upper figure) and with the FEM (lower figure).

4 Prototyping

The final stage of this project involves the fabrication of a ¼ scale model in order to verify the feasabillity of the fabrication process using the curved folding method and to examine the quality and finish of the panel obtained. The prototype was fabricated at the design office using basic hand tools and standard materials. A composite metal panel of 4mm, composed of a polymer core sandwiched between two aluminium sheets of 0.3mm, was used as the intial flat sheet. Three grooves were machined in the surface of the panel to mark the two straight edges and the curved central fold. A V-groove was carved along these lines at a specific depth to allow the formation of a plastic hinge within the aluminium. The panel was folded and mounted on a fixed wooden frame to keep its final form.

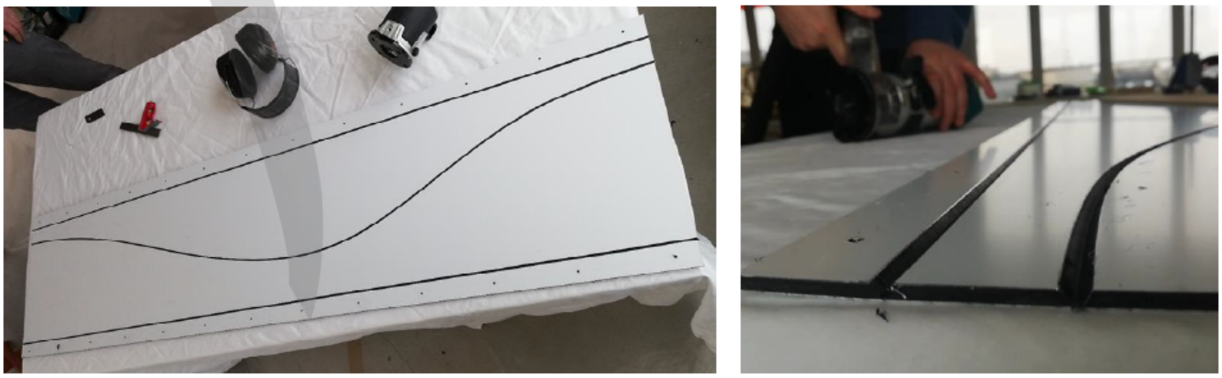

Fig. 12 Machining of the composite sheet to generate both straight and curved folds.

The quality of the surface finish and reflections from the powder coated panel are very satisfying and are coherent with both theoretical models described in this article. The curved image of straight elements formed on the panel, in the photo below, demonstrates the double curvature of the surface.

Fig. 13 Pictures of the prototype. The finish is very smooth and the reflections highlight the double-curvature of the panel.

5 Conclusion and further researches

We have demonstrated through the design and fabrication of this prototype the advantages of the curved-folding method; reducing the amount of material and simplifying the fabrication process when compared to traditional methods.

Furthermore, the curve-folding method, in contrast to other technologies, does not degrade the surface of the panel during the deformation process. This allows finishing treatments, such as polishing or specific coatings to be applied to the flat plate before performing the fold. Other fabrication methods, such as metal pressing, introduce surface cracks and other imperfections requiring treatment. The treatment of curved surfaces as opposed to flat surfaces has two important disadvantages ; firstly, the range of possible finishing is reduced. Secondly, the methods that can be applied are more laborious and costly, requiring manual labour or 3D machinery.

Finally, it has been demonstrated that by controlling the elasticity of the matieral it is possible to enlarge the range of possible forms generated while minimizing the energy used to deform the panel. In order to do so, simplified but robust design tools were created.

In order to further validate this design method, it is necessary to quantatively compare a 1 :1 scale prototype with the theoretical models using a precise measurement tool (laser of photogrammetry). This model should also integrate the real thicknesses of the metal sheets and reduce the fabrication imperfections by using CNC cutting tools.

Finally, an analysis of the sucessive energy states within the panel, both bending and membrane, would allow the precise characteristics of both developability and double curvature of the surface to be derived.

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