ORIGAMI – Folded Plate Structures, Architecture

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Summary

This research proposes new methods to generate rapidly complex folded plate structures that can be built with cross laminated timber panels. Composition and dimensions of these panels as well as the possibility to mill them by Computer Numerically Controlled machines, show a great potential for surface structures. The aim of this research is to reveal this potential in the domain of folded plate structures. An interdisciplinary team investigates architectural, structural and mathematical aspects of folded plate structures built from cross laminated timber panels.

The main concern of the architectural part is the form finding process witch is inspired by Origami, the Japanese art of paper folding. Based on a simple technique, Origami gives birth to an astonishing formal richness and variability. Complex geometries are generated in an economic way and this research aims at transposing these principles to construction with timber panels.

1. Introduction

Paper folding gives a very direct and intuitive perception and comprehension of geometry and rigidity of folded plate structures. By folding and manipulating paper, hands and eyes elaborate in a dialog a spontaneous understanding for the potential of such forms. Friederich Fröebel used paper folding in kindergartens to teach comprehension of geometry and to foster the sense of aesthetic of his pupils [1]. Later Joseph Albers used similar methods in the preparation class of the Bauhaus to make discover his students the relationship between materiality, geometry and structure [2]. Driven by the same curiosity as Albers and Fröbel and convinced that hands-on experience can lead to scientific conclusion, we use this intuitive approach to discover the universe or folded forms. A series of folded paper models explore the formal and spatial potential of this technique. The goal of this first part of our research was to identify some interesting folding patterns that have potential to be transposed to folded plate structure made with cross laminated timber panels.

The second part of the study aims for an analytic understanding of the chosen geometries which results in their generation by computer aided design. Thereby the generation method of the geometry should be close to architectural design processes and use devices as section and plan to define the folded plate structure. The so defined method allows creating rapidly a great number of various forms that can adapt to specific project conditions.

Finally the building of models and prototypes transposes the geometries to construction with cross laminated timber plates. In close collaboration with a civil engineer design of connections and assembling methods are experienced. Deformability and rupture of the structure is evaluated by loading tests. Results are the source for the engineering development of the research.

2. Folding patterns

2.1 Basic Technique

Three patterns are identified to be particularly interesting for architectural and structural applications: Yoshimura pattern, Miura Ori pattern and Diagonal pattern. The three of them are based on a combination of simple accordion folding and reverse fold: A series of straight valley and mountain folds are bent by the reverse folds to form simple curved surfaces.

The reverse fold is one of the base techniques of Origami [3]: A single parallel fold can be bent by a diagonal crease across the parallel fold. The straight parallel fold bends and reverses from mountain to valley fold (Fig. 1). At the inversion point two diagonal side creases run to the edge of the parallel fold. All four creases meet at the inflection point K. The angle of inflection Φ depends on the opening of the main crease δ and the angle α between the inversed main fold M^- and the diagonal side crease S^+ (fig.2). It varies between $\Phi=180°$, $\delta=180°$ and $\Phi=180-2\alpha$ ($\delta=0°$). In the first state the paper strip is open and flat in the second one it is completely folded. The acuter α the bigger Φ.

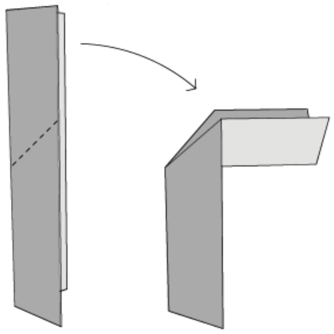


Fig. 1 *Reverse fold [3]*

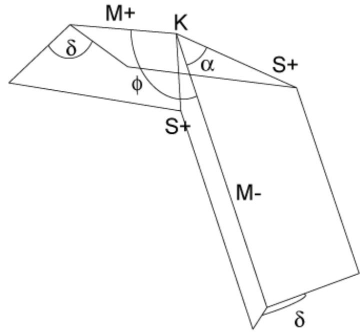
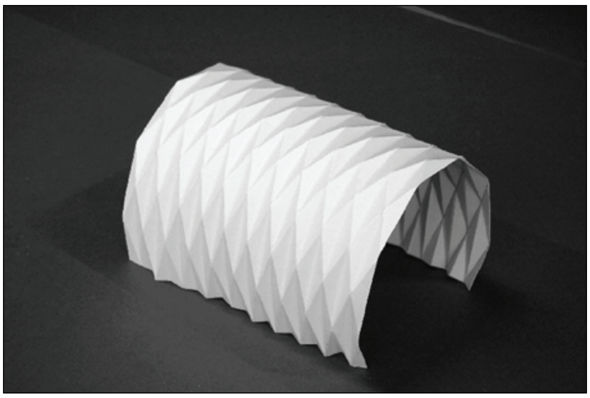


Fig. 2 *Reverse fold*

2.2 Yoshimura Pattern (Diamond Pattern)

The basis of this pattern is a diamond shape fold in one of its diagonals. It is named after a Japanese scientist who observed that thin walled cylinders show this kind of buckling pattern under axial compression [4]. If in a regular diamond pattern all parallel diagonals of one direction are fold as valley folds and the edges as mountain folds one get a cylindrical shape. This pattern can be obtained by mirroring a reverse fold at its inflection point K and on the base point of its side creases S. The diagonals of the diamond are equivalent to the main crease of the reverse fold and the edges of the diamond to the side creases. The curve of the folded pattern is designed by the shape of the diamonds. The acuter the angle α between the diagonal of the diamond and its edge, the flatter the bending of the pattern. A distortion from diamond to kite shape changes the inflection of the curve. This allows approximating any continuous curve (circle segment, parabola…). Another variation of this pattern can be obtained by splitting the diamond or kite shape and stretch it along the folded diagonal. The result is a hexagonal pattern formed by symmetrical trapezoids.



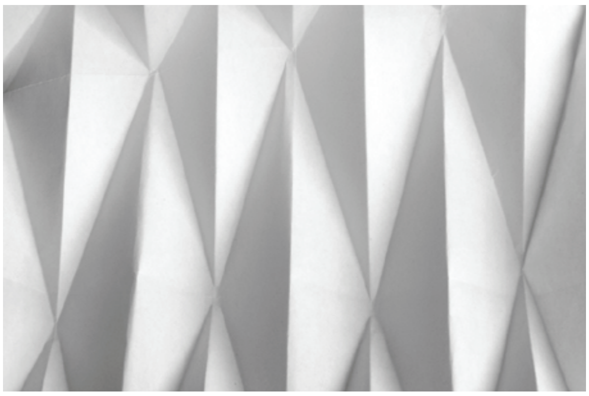
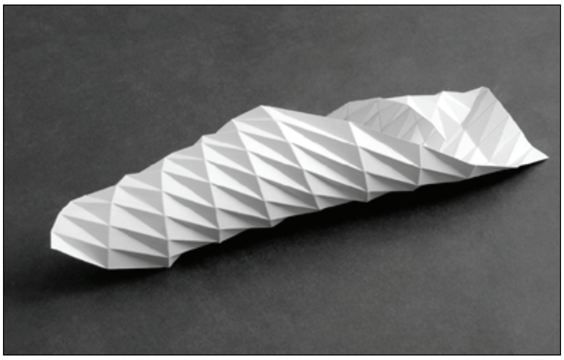


Fig. 3 *Yoshimura Pattern*

2.3 Diagonal Pattern

Basis of this pattern is a parallelogram folded in its diagonal. Out of a parallel position the edges are turned up diagonally. A series of so folded parallelograms form a helical distorted folding. A similar buckling pattern appears when a thin walled cylinder shell is compressed with a distortion [4]. Yoshimura- and diagonal- pattern are close to each other. They mainly differ by the fact that valley folds of diamond pattern form a plane polygonal line whereas the valley folds of the diamond pattern form a helical polygonal line.



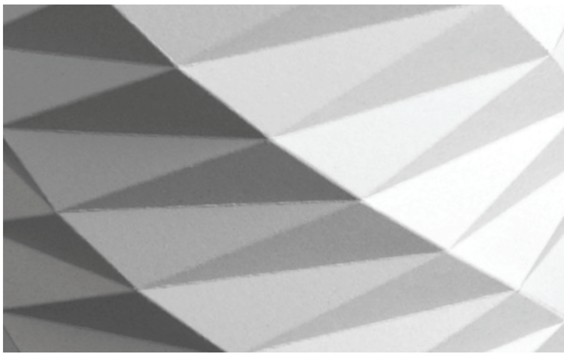


Fig. 4 *Diagonal Pattern*

2.4 Miura Ori Pattern (Herringbone Pattern)

As the diamond pattern, this pattern can be obtained by a repetition of reverse folds. Instead of mirroring the reverse folds they are repeated in line so that the main crease describes a zigzag line. Therefore the folded pattern has a characteristic zigzag corrugation in two directions. This allows extending and retracting the pattern in both directions. Miura [5] used this capacity to build solar sails for satellites that could be packed in very compact way and once unfolded, have maximum extension. The pattern is composed of symmetric trapezoids that form a herringbone tessellation. The legs of the trapezoids (non parallel sides) are inclined in the same direction. In general the zigzag line of the main fold follows a curve. This is due to the difference of inclination of the legs. If the legs are parallel so that the trapezoid forms a rhomboid, the zigzag line extension of the manifold is straight. If on of the bases (parallel sides) of the trapezoid is reduced to zero the pattern is composed of symmetrical triangle that form a dart. This is only possible when the legs of the trapezoid are not parallel.

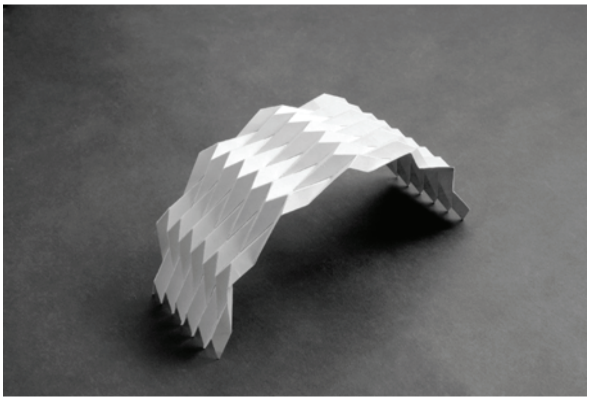


Fig. 5 *Miura Ori Pattern (Herringbone Pattern)*

3. Geometry of the Folds

3.1 Parallel Corrugations

The most basic folding is a corrugation of parallel mountain and valley folds. It can be described as an extrusion of a zigzag line along a straight line (Fig. 6). The zigzag line (plane yz) is characterised by the extension and the amplitude of its segments. The projection of the corrugation to the vertical plane xz shows a series of parallel lines defined by the amplitude of the segments whereas in the horizontal plane xy the extensions of the segments define a series of parallel lines.

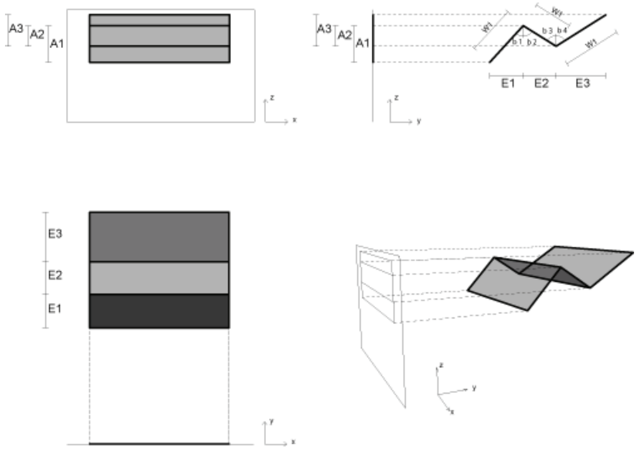


Fig. 6 *Extrusion of a zigzag line to parallel corrugation*

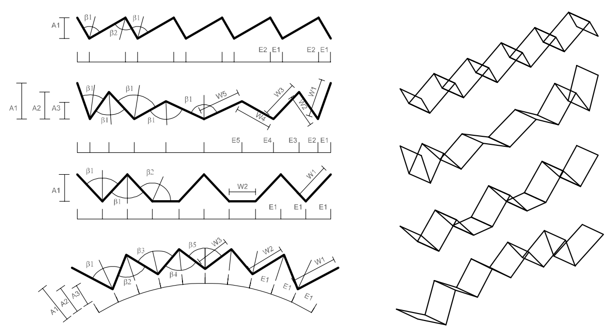


Fig. 7 *Typical profiles of parallel corrugations*

The form of parallel corrugations can be manifold. Extension is the main parameter characterizing a series of parallel folds. It defines direction and magnitude of the deploying creases. Its direction can either be straight, bent or take an arbitrary curvilinear or polygonal form. Magnitude varies between an entirely closed and a completely opened state. Extension length and amplitude vary with magnitude. Amplitude of valley and mountain folds outlines the shape along the extension line. Resulting shapes of amplitude variation can be multiple. Outcome of constant amplitude is a parallel line to the extension direction. Other typical variations are constantly growing or diminishing of amplitude. Local or general variations of amplitude can be used to adapt folded plate structures to stress. The higher the amplitude, the stronger the resistance of the folded plate structure. The order of mountain and valley folds does also strongly qualify the appearance of a series of parallel folds. Usually valley and mountain folds alternate. Other corrugations used in metal sheet industry are a suit of two mountain and two valley folds or a suite of one mountain and two valley folds (Fig. 7).

3.2 Reverse Fold

A single crease can be more or less opened. The sum of the positions the two flaps of the fold can take is a cylinder around a central axis, the crease. In case of the reverse fold the axis is broken in two sections. The flaps turn around each section. The sum of all their positions is two intersecting cylinders. They have a horizontal and a vertical intersection of elliptic form. The flaps of the reverse fold must intersect on the horizontal ellipse so that the edges of the reverse fold conserve their initial length. The horizontal ellipse represents all possible edge-intersections the reverse fold can take by changing its opening. The size of the cylinders and their intersection varies in function of the width of the reverse fold flaps. The sum of all possible cylinder intersections is a horizontal plane that is perpendicular to the angle bisector of the main fold. The side creases are located in this plane. In the front view and in the perspective it appears clearly that reverse fold can be considered as a reflection of the initial single fold on a horizontal plane. The line of the main crease and the edges are parallels and reflect on the perpendicular to the angle bisector (external angle bisector).

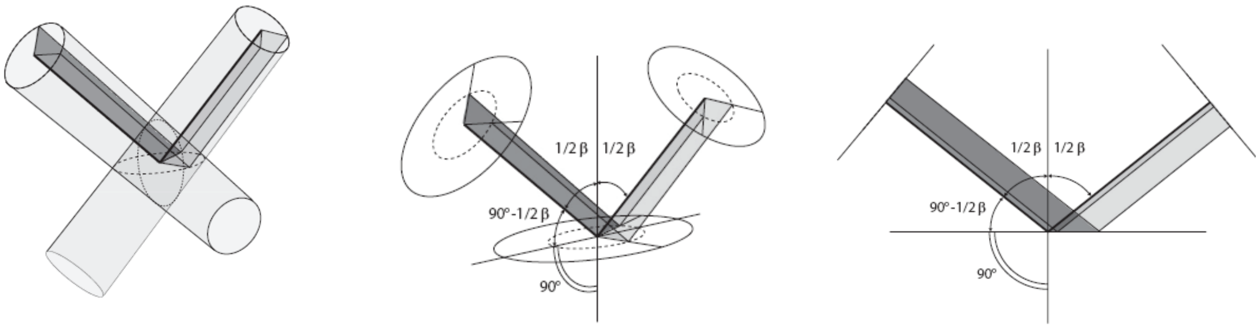


Fig. 8 *Reverse fold*

3.3 Generating Complex Folding Patterns

It has been shown that diamond pattern and herringbone pattern can be fold out of a parallel fold by use of the reverse fold. The straight line of the main crease is broken and outlines the new shape of the corrugation. For every pattern the line of the main crease has a characteristic form: convex polygonal line for a diamond pattern and a zigzag line for the herringbone pattern. By drawing a polygon line we can outline the general form of a folded pattern. The edges of the folds are parallel to this form-generating line. They reflect on the external angle bisector of the polygon segments. The distance between the centreline and the edge lines marks the amplitude of the folds (Fig. 9, 11, 12). As long as all the lines stay in the same plane this represents a completely closed pattern. In order to deploy the edge lines, they have to be projected in a certain distance to the centre line: the extension of the folds (Fig. 10).

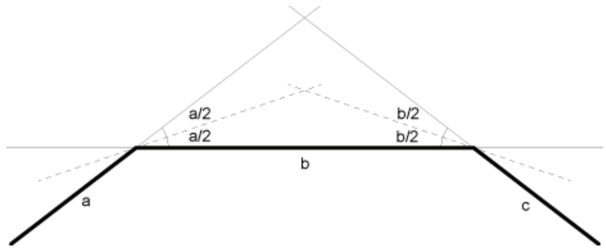


Fig. 9 *Generating polygonal line and external angle bisectors*

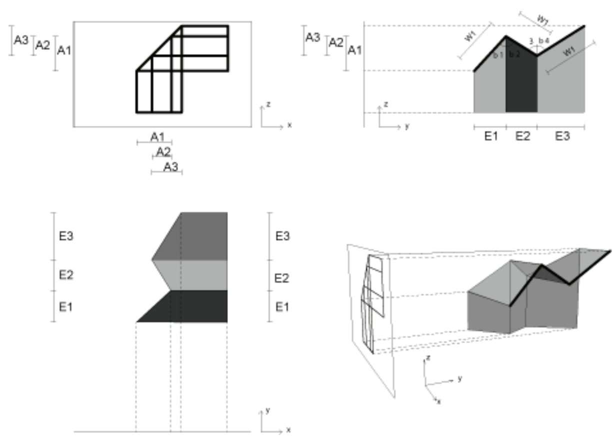


Fig. 10 *Deploying of the two dimensional reverse fold*

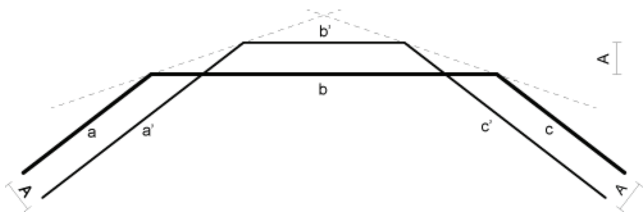


Fig. 11 *Edge line parallel to the form generating line*

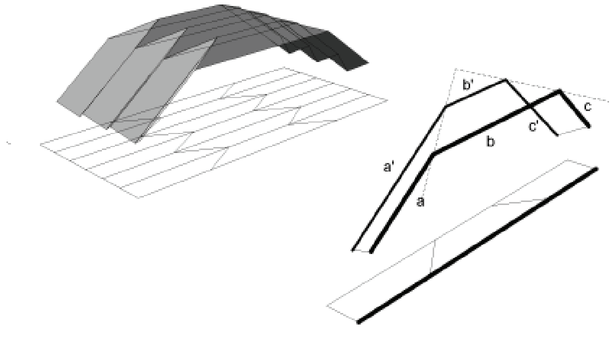


Fig. 12 *Perspective of the generated fold*

Two lines define the folded plate structure:

- A polygonal profile designs the general shape in section. The initial accordion folding follows this line and reverses at each inflexion point. All lines reflect on the external angle bisectors of the segments.

- A second profile designs the corrugation of the accordion folding. It defines amplitude and extension of the parallel folds.

This method allows generating rapidly various different geometries for folded plate structures. General shape and corrugation can be adapted to specific boundary conditions of a project. For example, amplitude of corrugation can be increased at the edge to reinforce the border of the folded plate structure.

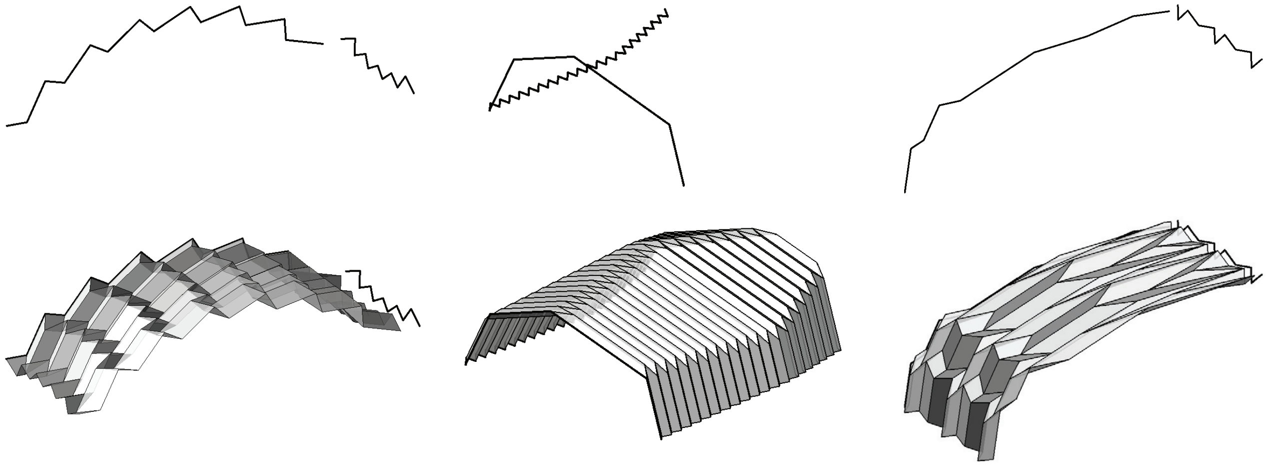


Fig. 13 *Variations of folded patterns generated by a section profile and a corrugation line*

4. Prototype

4.1 Small Scale Prototype

The construction of a prototype had the following goals: demonstrate the feasibility of timber panel structures based on the proposed geometries, get some first experience with connections and assembling methods and compare the deformation of the prototype with a numerical model.

The folded plate structure was based on a regular herringbone pattern. Two symmetrical trapezoids compose the whole structure. The 21mm thick plywood elements are cut in mitre and connected in pairs by self drilling screws. Twelve pairs form an arch with a span of 6,7m and a clearance width of 2,6m. The structure is composed of six arches with a total width of 2,8 m. A jig was used to join the base elements and allowed a precise assembling.

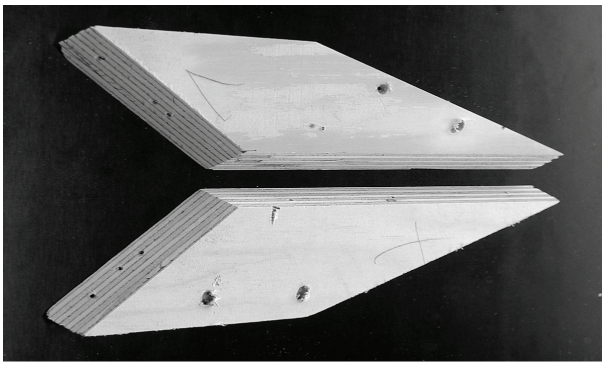


Fig. 14 *Basic elements*

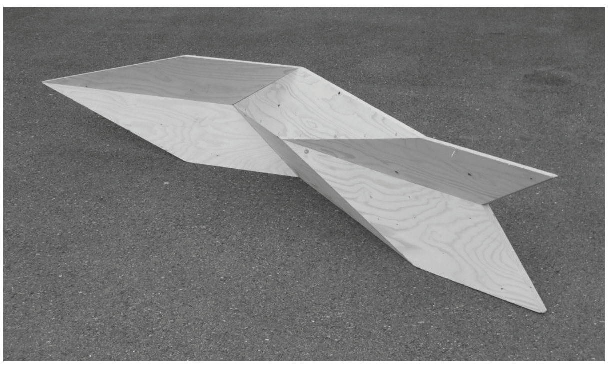


Fig. 15 *Three pairs of connected basic elements*

The static load test showed important deformations of the structure particularly on the open sides. Failure of the structure was due to the opening of the connections with a charge of 2,7 kN. The results showed the importance of the connections in the proposed structures. The goal of the research of Marcel Haasis (IBOIS) is to improve the connections and to enhance our understanding of the general stiffness of the structure in relationship to the stiffness of the connections.

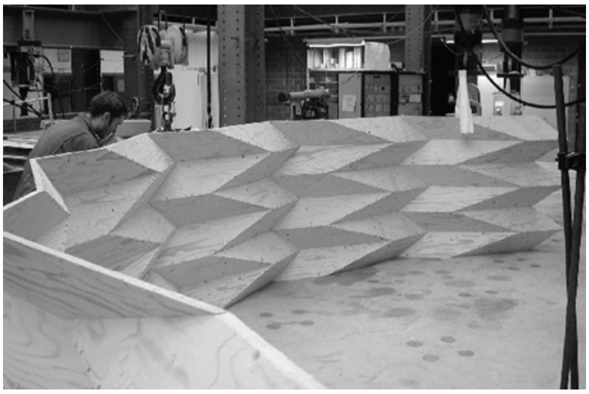


Fig. 16 *Assembling of the prototype*

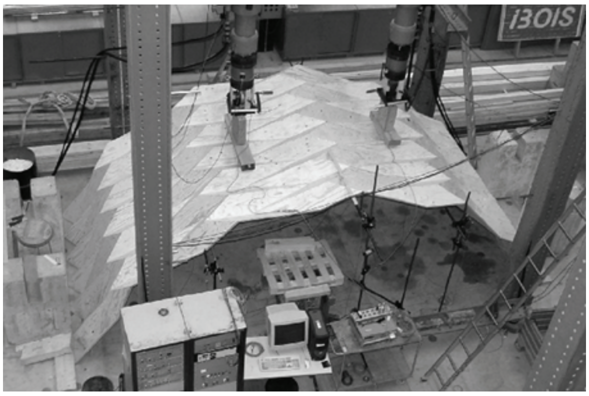


Fig. 17 *Static load test of the prototype*

4.2 Chapel

In collaboration with Local Architects in Lausanne, we actually design a small chapel. A convent for protestant nuns has to be renovated. During the construction the nuns need a temporary chapel. Local Architects proposed collaboration with the IBOIS to design a folded plate structure. The building is planned for about hundred persons. The architects wanted the chapel to remember the form of a basilica with one rounded nave. Two symmetrical, slightly bent, zigzag lines, define the form in plan. The basic corrugation is irregular such as the light reflection in the final shape is different on every panel. The section profile is a simple trapezoid. Due to the curve form of the basic corrugation the roof is compressed and rises up to a tip that recalls a little belfry. Some simple manipulations gave birth to a somehow familiar but discrete and original form.

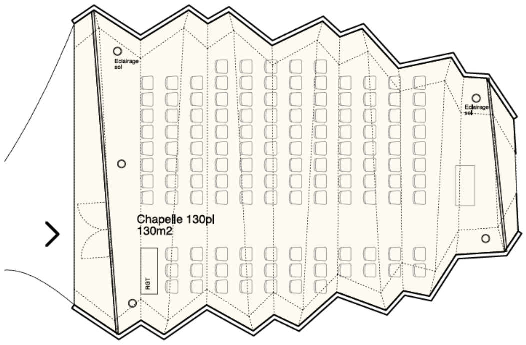


Fig. 18 *Plan of the chapel*

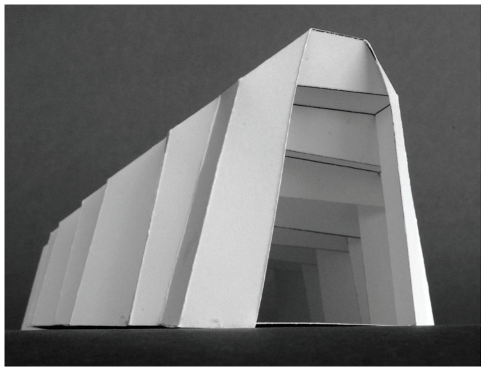


Fig. 19 *Paper model*

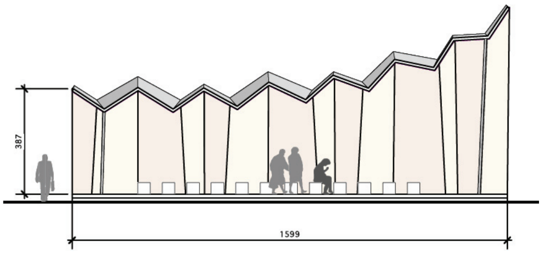


Fig. 20 *Section of the chapel*

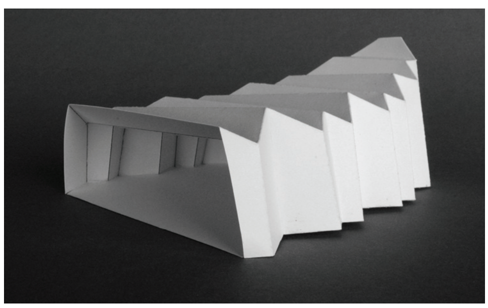


Fig. 21 *Paper model*

5. Conclusion

In an intuitive approach, hands-on experience by paper folding allowed identifying three patterns particularly interesting for construction with cross laminated timber panels. Geometrical analysis showed that the folded patterns can be generated by two polygonal lines. This allows representing rapidly complex folded plate structures in space as well as unfolded. A great variety of forms can be generated. For the moment the type of form is limited to simple curved surfaces. In paper folding some patterns can easily be deformed to double curved surfaces with radial or spherical form. Further investigations will show if it is possible to extend the method to such forms.

Feasibility of folded plate structures based on Origami patterns was shown by the construction of a small scale prototype. The results of the load tests were the source of the engineering part of the research.

A first real scale project is planed in collaboration with an architecture office. This collaboration shows the interest of architects and clients for proposed structures and the ability of the generation method to react on project specific conditions.

Fig. 22 *Detail of the prototype*

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