Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2009, Valencia
Evolution and Trends in Design, Analysis and Construction of Shell and Spatial Structures
28 September – 2 October 2009, Universidad Politecnica de Valencia, Spain
Alberto DOMINGO and Carlos LAZARO (eds.)

The application of folded plate principles on spatial structures with regular, irregular and free-form geometries

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Abstract

The two main folding plate principles of pointed folding plates forming an facet texture and longitudinal folding plates forming the typical fold texture imply different fields of application in architecture and structural engineering. This Paper presents a method of developing the folding plate principles on spatial structures also with irregular and free-form geometries. Hereby algorithms of triangulation, originally applied in finite elements analysis, are used for discretisation and form-finding of the textures of folded plate shells.

Keywords: folded plate, free form geometries, form finding method, metal spatial structure, triangulation, tessellation

1. Introduction

The principle of folding as a tool to develop a general structural shape has been known for a long time. Folded structure systems which are analogous to several biological systems such as found at broadleaf-tree leaves, petals and foldable insect wings, are adopted to be employed in a new, technical way (Nachtigall [6]). The aerospace and the automotive industry, e.g. apply this principle to create self-supporting wall, mould and slab elements with a high load capacity out of flat and thin semi-manufactured metals. This stands in contrast to the building industry, where the principle of folding has played a secondary role so far.

1.1. Folding systems in nature

In flora and fauna, the principle of folding is often found to create widespread, structural surfaces. It generates not only a stabilisation of flat and delicate shapes, it is also necessary to exercise complex and reversible movements (Nachtigall [6]).

1.1.1. Rigid folding systems

Thin-walled structures such as blades of grass or palm tree leaves are structurally stiffened in one or even two axis because of their embossed folding structure. The leaf of Chamaerops hunilis has a radial zick-zag-ribbing which is the reason for its stability, especially during changing wind forces.

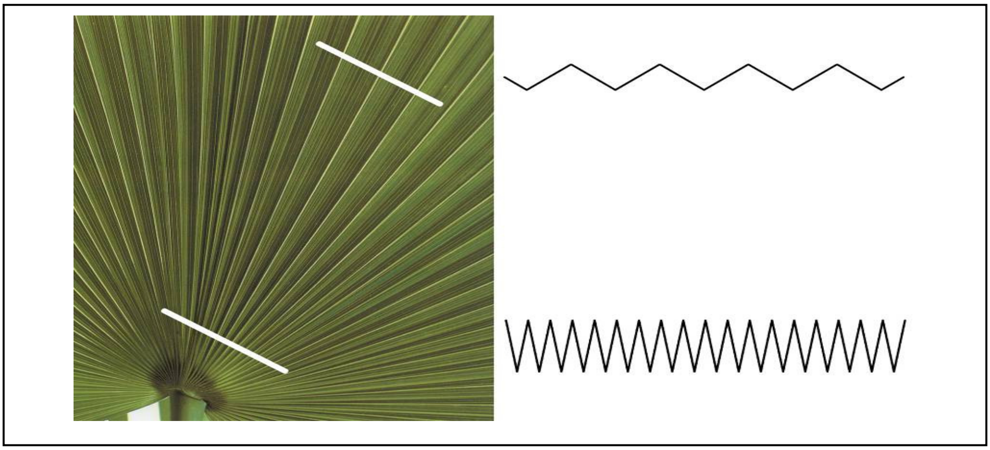

Figure 1: Leaf of Chamaerops humilis . Das große Buch der Bionik, Nachtigall, Kurt G. Blüchel; Deutsche Verlags-Anstalt, Stuttgart/München, 2000; Page 128.

This example demonstrates how the flora uses a highly effective building structure to generate plane structural surfaces and also shows the process of optimization of the employed folding principle.

In correspondence to the load, the stiffening due to the folding decreases from the caulis to the edge of the leaf. The elevation of the folding decreases continuously towards the edge of the leaf and the frequency of the folding is reduced. According to this adaptation, the structural cross section of the leaf shows that it is always equally used to its capacity (isostatic status).

1.1.2. Kinematic Folding systems

The structural characteristics of kinematic folding are analogical to the ones of the rigid folding. The complex movements and folding processes will not be examined in this essay.

1.2. Transmission of the examples from nature to the buildings

Natural folding as light weight structure could be of high interest for engineering and architecture. It is a material-saving and efficient method of construction because it supplies the load bearing structure and the building envelop at the same time.

2. The principle of folding

Folding systems represent one category of plane structural surfaces, alongside with plates and slabs. Their special structural behaviour is due to their structural subdivision arrangement in pairs which correlate with each other and so they are connected through a shear connection. The structural characteristics of folding structures depend on the shape of the folding (longitudinal or pyramidal), on their geometrical basic shape (plane, hoppit, cupola, free-from), on its material (concrete, timber, metal, synthetics), on the connection of the different folding planes and on the design of the bearings. The characteristics of the folding structures are interactiv related to each other.

2.1. Structural behaviour of folding

The inner load transfer of a folding structure happens through the twisted plane, either through the structural condition of the plate (load perpendicular to the centre plane) or through the structural condition of the slab (load parallel to the plane) (Leitner [5]).

At first, the external forces are transferred due to the structural condition of the plate to the shorter edge of one folding element. There, the reaction as an axial force is divided between the adjacent elements which results in a strain of the structural condition of the slabs. This leads to the transmission of forces to the bearing.

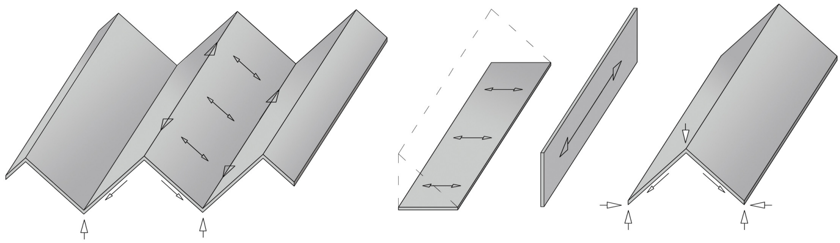

Figure 2: Structural condition of folding structures/ Künstler, Chair of structures, RWTH Aachen University.

2.2. Different general types and styles of folding

The structural characteristics can be reduced to two general types. Either the structural system is equivalent to a linear load bearing structure or it can be traced back to a pyramidal load bearing structure (Leitner [5]).

2.2.1. Longitudinal/ prismatic folding

Longitudinal folding is characterized through uninterrupted and linked folding edges where parallel and skew up folds and down folds alternate.

Single-layered longitudinal folding corresponds in their load bearing structure to a linear load bearing system whereas a double-layered folding with different directions of their folds can create the structural condition of the plate.

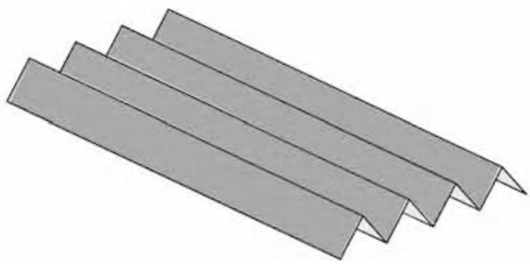

Figure 3: Sketch longitudinal folding/ example in the architecture.

2.2.2. *Spot or facet folding*

Spot or facet folding requires that several folds intersect like a bunch in one single spot. This results in pyramidal folds with crystalline or facet-like planes. Facet folding can either be based on a triangular shape (figure 6, The Kaiser Hawaiian geodesic dome, Buckminster Fuller) or on a quadrangular shape. A single or double-layered facet folding resembles the load bearing structure of a plate and can be compared to space frameworks (Hachul [2]).

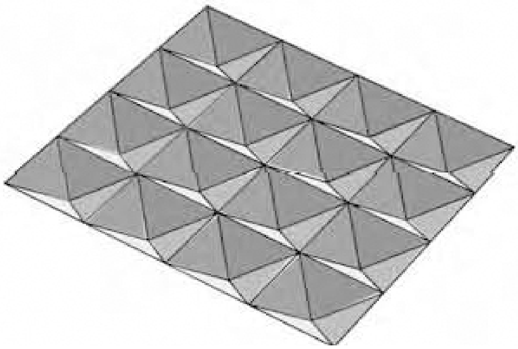

Figure 4: Sketch pyramidal folding, Herkrath, Chair of structures, RWTH University

3. Regular Folding structures

3.1. The principle of structural shaping at the example of folding textures in engineering

The increase of stiffness through the folding texture of a plane, filigree semi-finished product leads to a higher load capacity while the material input stays alike. With this principle to structural shaping it is possible to generate plate-like or slab-like building elements out of extremely thin semi-finished products which are the load bearing structure and the building envelope at the same time.

The size, the characteristics of the material and the deformation behaviour of the semi-manufactured product (e.g. concrete, timber plates or metal) are directly related to any possible folding typology and its scale and span (Engel [1]).

This relation becomes apparent when built folding structures of concrete (P.L. Nervi) are compared to folding structures of metal by Buckminster Fuller or to the synthetic folding structures by Renzo Piano.

This is also a principle of light weight engineering, highly efficient in terms of use of material and in terms building process due to modularity. Until now this structural principles were just applied on regular structure geometries.

3.2. Regular structures

Folding structures have been used quite rarely in architecture so far. The first examples for built folding structures occurred as concrete structures at the beginning of the 20th century and resulted from the new constructive opportunities of reinforced concrete. They were folding structures in a large scale, made of in-situ concrete out of longitudinal folding with a constant frequency based on orthogonal plans.

In addition to concrete folding structures, other plane-like folding structures made of materials such as steel, timber or synthetics have been realised as well. Due to the limited size of the elements available, the spans were much smaller.

In contrast to any free-form and scalable concrete folding structures, the basic requirement for the utilization of plane-like materials is the description of their surface in mathematical or geometrical terms. This leads directly to the multiple repetitions of the same shapes and building elements which result in a highly efficient production and processing of the building elements (Trautz [7]). For plane-like parallel foldings and facet-like foldings based on radial-zylindric areas the fragmentation in triangular or rhombical shapes of the same geometire is relatively easy to realise.

Figure 5: IBM Travelling Pavillion/ roof for industrial use, Pomezia, Italien, Architect: Renzo Piano.

This fragmentation and segmentation (tessellation) of hemispherical or ellipsoid dome structures into triangular shapes was the idea of the architect Richard Buckminster Fuller. He used the obtuse icosaedron as a modified platonic body to describe the radial sphere with a spatial polygonal network structure (Trautz [7]). The geometry of platonic bodies and the regular polygons which could be drawn from this were known and so it was possible to calculate them exactly. Based on this, the geodesic Dome Kaiser Hawaiian was broken down into a facet-like structure which was based on nine different triangular shapes.

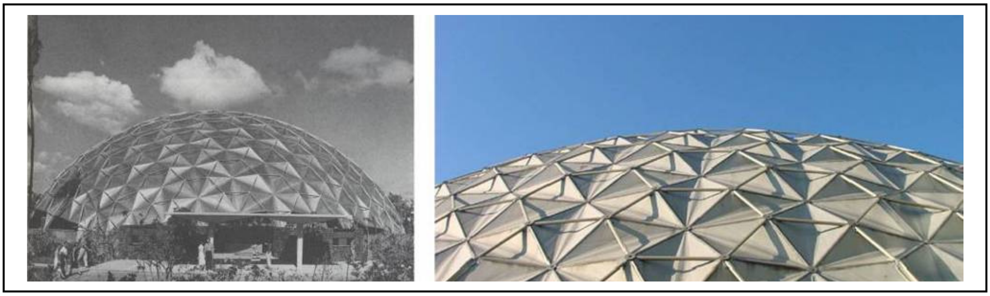

Figure 6: The Kaiser Hawaiian geodesic dome, Architect: Buckminster Fuller, Buckminster Fuller´s universe, an appreciation, Norman Cousins, Plenum Press New York and Landon.

Based on Fuller's ideas, numerous hemispherical domes and shells were built as bar skeletons or as a combined structures consisting of bars and metal facets. The Colourdome built in 2002 by Helmut Hachul and Wilfried Führer (Chair of Structures and Structural Design, RWTH Aachen) was a prototype of a single-layered facet-like structure which was exclusively composed of profiled and folded metal sheets and based also on a modification of icosahedrons (Hachul [2]).

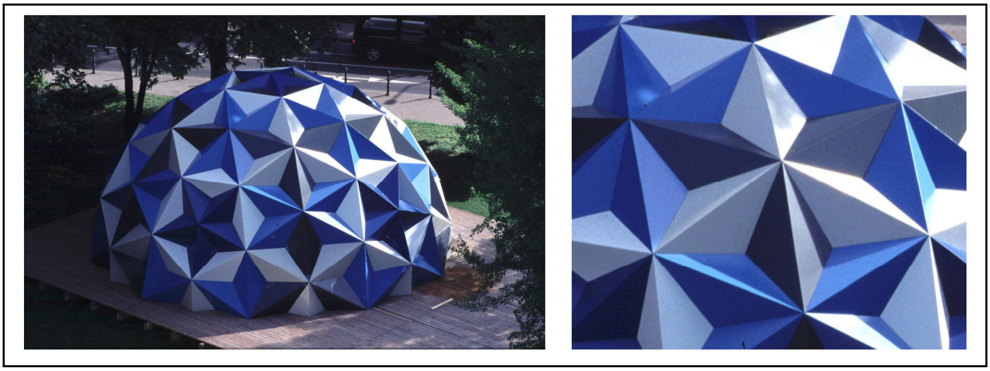

Figure 7: Colourdome, Aachen, Hachul, Führer, 2002.

4. Irregular Folding structures – Application of the principle of structural shaping for free-forms

The number of projects using free-forms has enormously risen. The realisations of these projects show that there is an immense gap between the conventional building system and the innovative design strategy. There is often no coherent general design concept which includes the manufacturing.

For these design projects it is therefore necessary to develop very complex and thus expensive and material-consuming construction methods which seem to assure an effortless manufacturing because of their two dimensional shape.

4.1. Irregular Folding structures

Regular folding structures can be described mathematically and geometrically and are therefore easy to tessellate and based on this easy to unfold. If the tessellation of bodies and areas is related to the existence of more or less complex mathematical descriptions the canon of shapes which can be described by this method is limited. This is in particular relevant when congruence or geometrical affinity of the net structure or the facet-like shapes is necessary, e.g. for the production of different building elements.

With the help of computers and numerical methods of describing geometries (CAGD) it is possible to classify and categorise arbitrary geometrical shapes with different tessellations. The outcomes are primitive shapes such as rectangles or triangles which describe the free-form as a net. Based on this tessellation, free-form bodies or areas can be transformed into longitudinal or facet-like folding textures (Trautz [7]).

A software tool was developed at the Chair of Structures and Structural Design, RWTH Aachen to atomise the process of form modifications. The tool enables the design of folding structures for free-forms. After the design of the different folding textures, the data is processed for the production and the erection. The numerical description of free-forms solves the problem of the tessellation indeed but it also leads to different sizes of the rectangles and the triangles of the mesh. With modern methods of sheet metal forming (functional Rapid Prototyping) it is however possible to produce these different building elements by a maximum of cost-efficiency. Because steel as a ductile material is extremely suitable for the realisation of folding structures, a complete, digital series for metal folding structures could be developed starting with the design process by the architect and ending with the computer-processed production of the modules.

4.2. Softwaretool

4.2.1. The Design and a digital model

The design process and the optimisation of the structures were done digitally and analogue. On one hand it is possible to generate digital models out of an analogue model with the help of a 3d-scanner, on the other hand it is also possible to materialize the digital 3d model with a 3d printer. Through a parametric structure of the design in a CAD programme the different stages of the procedure of the planning and the generation of alternatives was simplified.

Figure 8: Form finding and the digital model of an example design, Herkrath, Lohmann, Pofahl, Chair of structures, RWTH University.

4.2.2. Tessellation of a free-form

Hereby, algorithms of triangulation, originally applied in finite elements analysis, are used for the discretisation and the form-finding of the textures of folded plate shells.

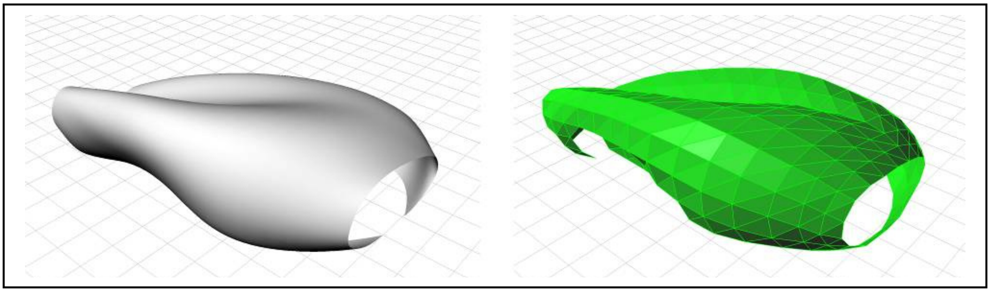

Figure 9: Triangulation of free-forms, Herkrath, Lohmann, Pofahl, Chair of structures, RWTH University.

4.2.3. The fragmentation in to facet-like textures of a free-from

Based on the tessellation, the free-form is unfolded while the constitution of the folding structure (longitudinal or pyramidal), the height of each fold and the frequency of the different folds are arbitrary. The interface with a FEM Programme gives the possibility of a detailed analysis of the folding structure. Through this method, the general folding structure can be optimised. This can happen through a variation of height and frequency of the folding or the use of a thicker metal element at points which are subject to high stress.

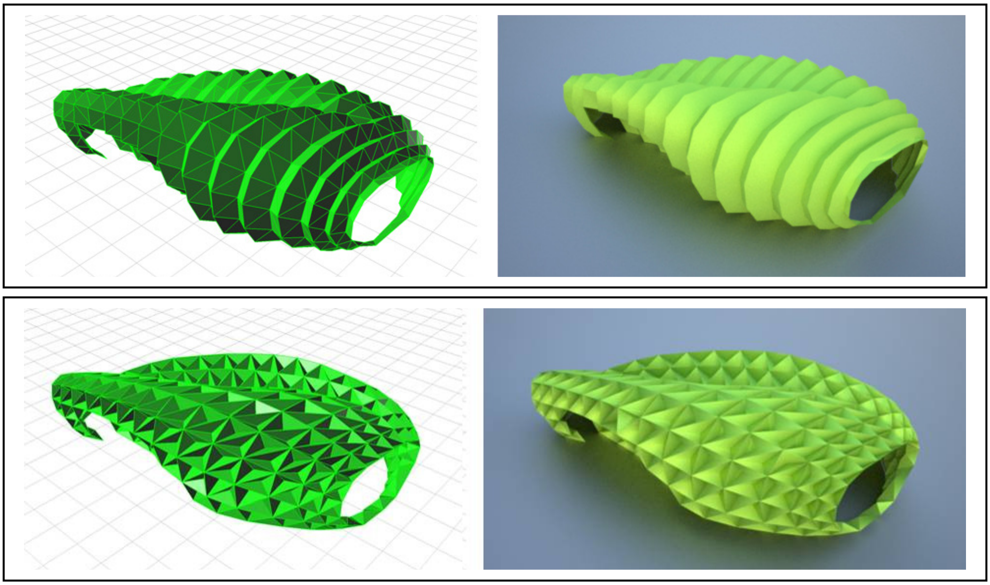

Figure 10: Longitudinal and facet-like folding structure based on triangulation, Herkrath, Lohmann, Pofahl, Chair of structures, RWTH University

4.2.4. Pre-elementing and conditioning fort he production

The pre-elementing happens according to the chosen folding structure (longitudinal or facet-like). Metal pyramids with a hexagonal base area on the outer and a triangular base area on the inner site evolve from a double-layered facet-like folding. The softwaretool processes the individual metal pyramids for the CNC controlled sheet metal forming with the help of software that translates the geometry of the free-form into the data to control the CAM production (computer aided manufacturing). All different parts are labeled to assure a correct typological erection.

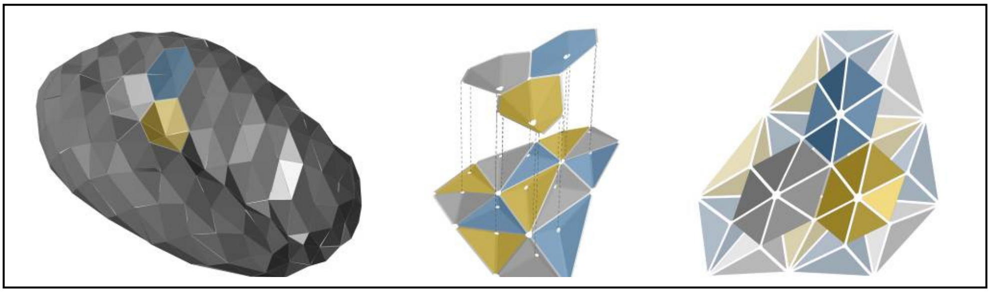

Figure 11: Pre-elementing of a double-layered facet-like folding structure, Herkrath, Lohmann, Pofahl, Chair of structures, RWTH University.

4.2.5. CNC-Incremental Sheet Forming

The incremental sheet forming with a CNC-controlled forming header is an innovative step to manufacture cost-efficiently complex shaped metal building elements for prototypes and small series (Hirt [3], Jeswiet [4]). This process makes it possible to produce the different elements of the folding structure with minimized tool costs. The sheet is clamped in the blank holder. The forming tool moves down a small increment in the z-direction and traces a contour in the x-y-plane (tool level curves).

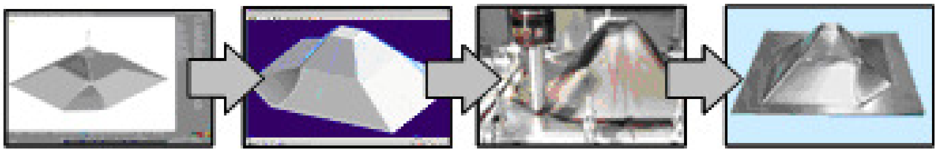

Figure 12: Process of incremental Sheet forming, Cad Model, Generation of the tool path, shaping and the completed element, Institute of Metal Forming, RWTH Aachen University

These first attempts of the sheet metal forming process show metal pyramids based on triangular and hexangular area plans for the construction of a double-layered facet-like folding structure.

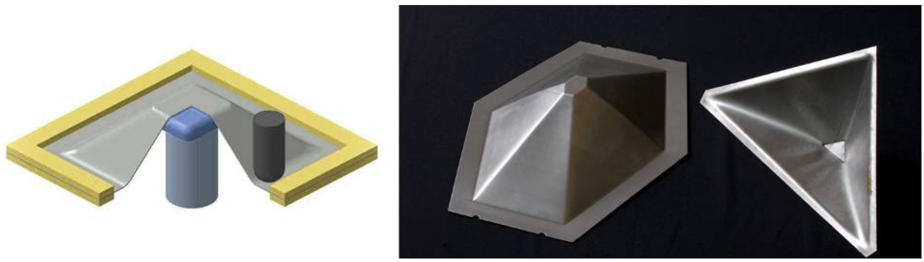

Figure 13: steel elements formed by of incremental Sheet forming / Chair of Structures and Structural Design with Institute of Metal Forming, RWTH Aachen University

4.2.6. Erection and building construction

The different metal pyramids are assembled to buildings elements which are to be erected on site. The assembling of the elements is guaranteed by overlapping of the different metal sheets.

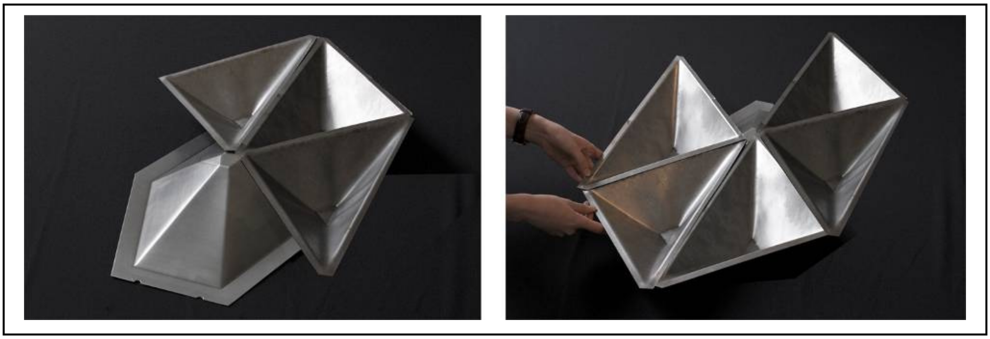

Figure 14: metal pyramids are assembled into a 2-layered folding structure, Herkrath, Lohmann, Pofahl, Chair of structures, RWTH University.

4.3. Conclusion and prospect

The principle of folding structures is an established principle of construction in nature whose potential has rarely been used in architecture. Based on folding structures, high-stressed and wide-spanning light weight structures can be realised. More than the complex requirements for their constructive detailing, the limited possibilities to describe them geometrically with mathematical geometrical functions have constraint their realisation.

Numerical digital methods annul this limitation by making the tessellation and triangulation of arbitrary shapes possible. Due to this method, almost any folding structure can be constructed (Trautz [7]).

After the development of the software tool and after the first successful shaping, the research has now the aim to approach the application of folding structures in context of the sustainable use of material and to gain new impulses for this principle of structural shaping. Additionally, new ideas of the building process for free-forms should be generated which could also serve as helpful suggestions for other engineering disciplines.

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