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SOFT.SPACES _ new strategies for membrane architecture

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Summary. *The desire for new mostly fluent "soft spaces" in architecture cannot be overseen any more. Therefore new tools and approaches are tried out to create architecture with special spatial qualities. Spatially curved membrane structures and especially anticlastic Minimal Surfaces offer one possible approach to this topic. This paper presents the overview of the research on spatially curved Minimal Surfaces that considers the infinite possibilities of membrane forms as elements in architecture in combination with common building-technologies and shows the manifold possibilities of this approach and technology*[1]*. Further on this paper partly reveals new correlations between Minimal Surface and boundary conditions and so far unknown rules in its self organizing processes. Case studies document new capabilities in designing and creating space in architecture. Latest approaches are dealing with alternative boundary-conditions and with software implementation in terms of scripting found rules*[2]*.*

1 INTRODUCTION

On the basis of the research of Frei Otto and his team at IL (University of Stuttgart) and the resulting exceptional pioneer constructions, building with textiles as an alternative to traditional materials like wood, stone, steel, glass, and concrete was rediscovered during the last decades. Deriving from self organizing forms of Minimal Surfaces, prestressed, spatially curved Membrane Structures were up to today mainly used for wide span, lightweight-structures. For this reason membrane structures tend to be seen from a structural or material point of view only. In contrast to our right-angled, conventionally built environment the desire for fluent "soft" spaces in architecture cannot be ignored any more. The possibility to create light and fluent spaces as a symbiosis of form and structure offers new qualities and chances in the design of residential or office buildings.

2 SUBJECT

This paper presents the overview of the research on spatially curved Minimal Surfaces that considers the infinite possibilities of membrane forms as elements in architecture in combination with common building-technologies and shows new capabilities in designing and creating spaces. Seen as an element in the design of architecture these anticlastic, fluent forms caused by structural conditions, follow the rules of FORMFINDING in its initially (by Frei

Otto) defined sense. Very often we misuse the term „formfinding“. What Architects mostly mean and do is a man controlled process of SHAPING - a process that happens on a consciously controllable and formal level. In contrast to the man-controlled process of shaping, forms that are arising from self organizing processes can only be influenced by the design of their boundaries. The form itself can only be found and represents the result which cannot be manipulated. The architect finds himself in the unusual position of a creative “formfinder” instead of the “shaper”. The fluent forms of Minimal-Surfaces are fascinating by their variety, structural performance, reduction to the minimal in terms of material use and resources and their special fashion-resistant aesthetics. Together these parameters represent the common basis of a potential design or design concept and characterize its grade of sustainability.

3 OBJECTIVES

Since self organizing processes follow precise rules and contain optimization by their nature descriptions and especially in architecture illustrations of these rules can be used as design tools. To find out about the chances for an architecture between „hard“ and „soft“ morphology, basic research on the systematic determination of very different boundaries - the interface between membranes and common construction technologies - enables the opportunity to analyze anticlastic Minimal Surfaces regarding form and curvature. Vice versa we get an idea of the correlation between 3d-curvature, deflection and determined boundary and further on an idea of formal and structural behavior. In this context the assessment and visualization of the Gaussian curvature, which were adapted especially to this research, played an important role.

4 SPECIAL SPECIFICATIONS

4.1 MINIMAL SURFACE

All experiments are restricted to forms that can be derived from the results of soapfilm models – the Minimal Surface. As long as boundary conditions are not changed, Minimal Surfaces can be arranged as a unity arbitrarily in space without changing its form/geometry.

4.2 INTERFACE

Linear, maximal 2dimmensionally curved, bending resistant, line supported boundaries turned out to be the ideal interface between membranes and common construction technologies. All further experiments were restricted to boundaries of that kind.

4.3 MEMBRANES AS AN INTEGRATIVE ELEMENT

Membranes are seen as an integrative component of architecture and are directly connected to other elements of common construction methods. In terms of structural effectiveness the surfaces themselves are considered to be highly efficient by their spatial curvature but not to be load bearing elements for other structural members although newest approaches in the author`s research are dealing with this possibility.

5 INVESTIGATION

The range of exploration covers wall-like elements, T-shaped connections, solutions for vertical, horizontal and free corners and tubular entities – the so called Catenoid.

6 METHODS

Besides physical (Fig. 01) and soapfilm models (Fig. 02) mainly digital experiments (Fig. 03) were used for the interpretation and the verification of results. Soapfilm models were mainly considered to fulfill a control function. Digital models were essential for the analysis and evaluation of forms (section curves, their diagrammatic overview, analysis of angles in space,…) of Minimal Surfaces. In this context the assessment and visualization of the Gaussian curvature (Fig. 04), which were adapted especially to this research, made it possible to compare and to draw one`s conclusions on different forms and their structural behavior.


Fig. 01 Physical study model showing catenoids between shifted circular rings


Fig. 02 Sequence of Soapfilm Models

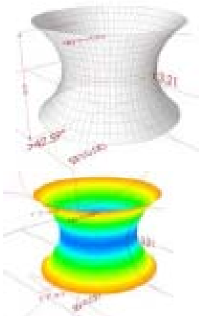


Fig. 03 Digital model of a catenoid between circular rings and Visualization of Gaussian Curvature

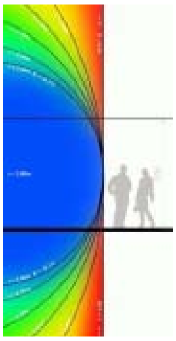


Fig. 04 Special unification of assessment and visualization of the Gaussian curvature for this research

7 RESULTS OF INVESTIGATION

The results of physical, soapfilm and mainly digital experiments show surprising and partly new correlations between form and boundary proportions and so far unknown rules of the self organizing processes of Minimal Surfaces – especially in the field of the Catenoid. The overview and the comparison of the results as well as the possibility of a targeted selection can now be the basis for creative applications.

7.1 MINIMAL SURFACES BETWEEN STRAIGHT LINES AND BOUNDARIES CONSISTING OF SEGMENTS OF A CIRCLE

All experiments related to this series (Fig. 05) show, that for this boundary condition it is not possible to find a fully anticlastic curved Minimal Surface. Those surfaces which show few flat areas are generated within a relatively small spectrum of boundary conditions. They concentrate on boundary conditions consisting of semicircles with a diameter that corresponds to the distance of the boundaries. Independent of the amplitude of the curved boundary Minimal Surfaces tend to be flat in the near of the straight line boundary. Experiments show that in average up to 96% of the horizontal deflection that was given by the curved boundary is disappearing halfway between the upper and lower boundary. Horizontally shifted boundaries (Fig. 06) can be interesting from the architectural point of view. But in terms of anticlastic Gaussian Curvature this always means a further increase of flat areas.

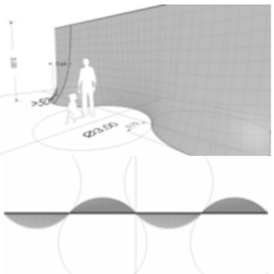


Fig. 05 Minimal Surfaces between straight lines and boundaries consisting of segments of a circle

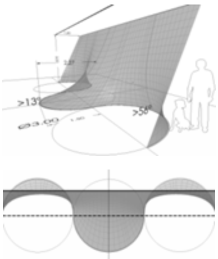


Fig. 06 Horizontally shifted boundaries

7.2 MINIMAL SURFACES BETWEEN BOUNDARIES CONSISTING OF SEGMENTS OF A CIRCLE

In this case the boundaries of wall like Minimal Surfaces can have the **same direction** or they can be **arranged inversely**. Horizontally shifted boundaries represent special cases and show interesting architectural effects. The horizontal offset can be in longitudinal, cross or diagonal direction.

7.2.1 Minimal Surfaces between boundaries consisting of segments of a circle in the same direction

Boundaries that are curved in the same direction (Fig. 07) generally effect strong anticlastic curvature of Minimal Surfaces. Boundary conditions consisting of semicircles with a diameter that equals the distance of the boundaries can be qualified as 100% spatially curved. Section lines show the smallest circle of curvature exactly on half height and harmonic development of the surfaces (Fig. 08).

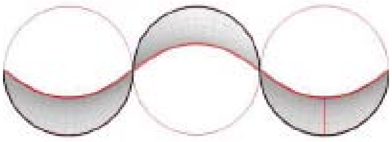


Fig. 07 Boundary configurations consisting of segments of circles having the “same direction”

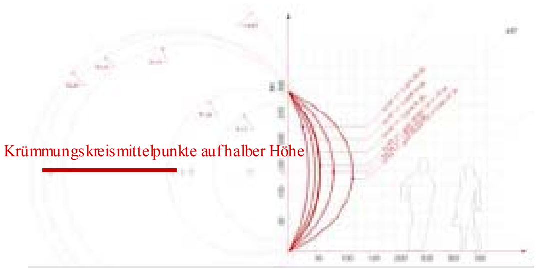


Fig. 08 Vertical section of digital models and their circles of curvature

7.2.2 Minimal Surfaces between boundaries consisting of inversely arranged segments of a circle

Curved and inversely arranged boundary conditions effect anticlastic curvature covering most of the surface, even if the boundaries have little oscillation from the longitudinal axis. The mostly curved surface can be developed with boundaries consisting of semicircles with a diameter of 2/3 of the distance of the boundaries (Fig. 09).

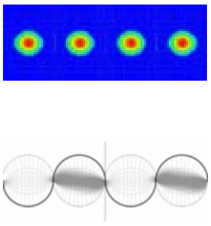


Fig. 09 EM KK 2/3 _ 1,00HK ggs

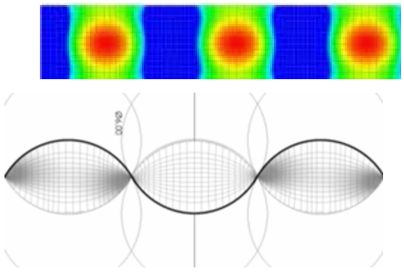


Fig. 10 EM KK 2/1 _ 0,50HK ggs

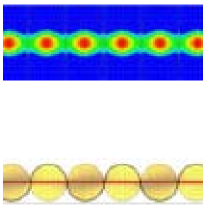


Fig. 11 EM KK 1/2 _ 1,00HK ggs

Areas with little spatial curvature can first of all be found exactly at the maxima of boundary curvature and on half height. Starting from the ideal case these flat areas increase with increasing as well as with decreasing diameters of the base-circles. Surfaces arising from boundary conditions with base-circles bigger than the height show flattened vertical stripes (Fig. 10) whereas flattened horizontal stripes (Fig. 11) appear with boundaries consisting of segments of circles with less than the height.

7.3 MEMBRANE CORNERS

Regarding corner solutions, boundaries can be arranged horizontally (Fig. 12) or vertically (Fig. 13). The free corner (Fig. 14) describes a special case and will not be described in this paper.

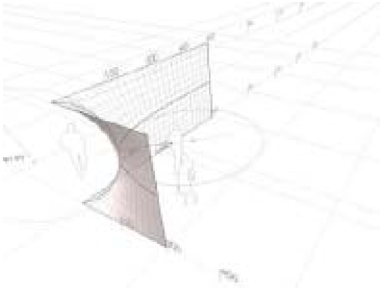


Fig. 12 Horizontal Corner

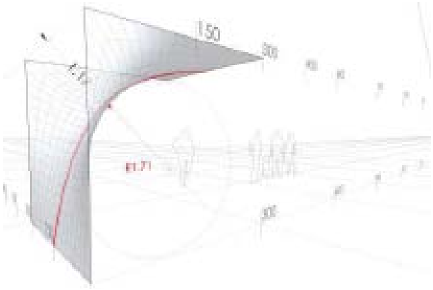


Fig. 13 Vertical Corner

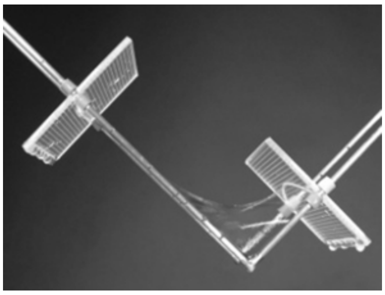


Fig. 14 Free Corner

7.3.1 Horizontal Membrane Corner

All executed experiments with horizontal right-angled corners show almost constant surface curvature (Fig. 15) and deflection in the area of the corner (Fig. 16). This happens independently form the leg length and from being arranged symmetrically or asymmetrically. The section lines of digital models are congruent (Fig. 17). Leg length being shorter than the height cause surfaces with little anticlastic curvature. Surfaces of maximum spatial curvature in all areas can be achieved with a ratio 1/1 to 3/2 of leg length/height. Increased leg length causes areas with little anticlastic curvature at the end of the legs.

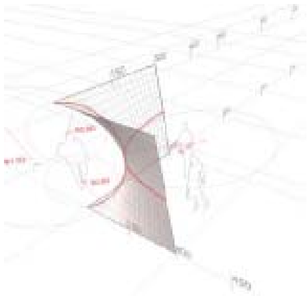


Fig. 15 Horizontal corner with ratio of 1 1 1 (leg/leg/height)

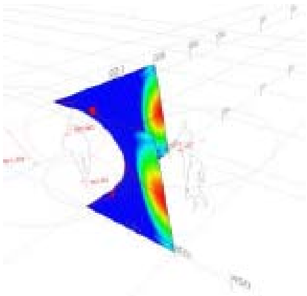


Fig. 16 Horizontal corner with ratio of 111 Gaussian Curvature

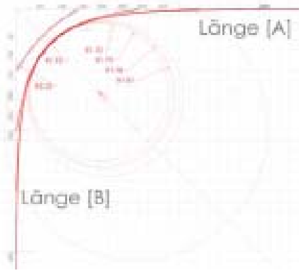


Fig. 17 Horizontal section lines „Horizontal Membrane Corner“ – in comparison

7.3.2 Vertical Membrane Corner

The configuration of the vertical, right-angled corner can be used to explore different element length [EL] or different wing length [FL] and their effect on the spatial curvature of the surface. The analysis of section lines, circles of curvature and Gaussian curvature illustrates the interrelationship of surface and boundary proportions. For predominantly curved surfaces these proportions can be located at a ratio of 1/1/1 (element length/height/wing length) whereby even distribution of curvature and harmonic, fluent transitions of surface curvature can be achieved (Fig. 18 to Fig. 20).

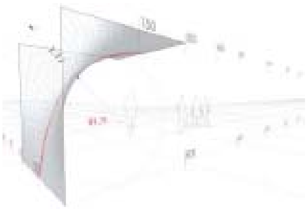


Fig. 18 EV 1 1 1 FL var

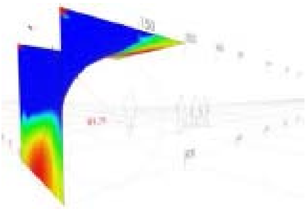


Fig. 19 EV 1 1 1 FL var

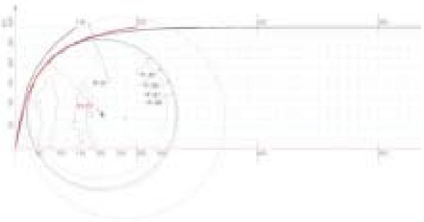


Fig. 20 Overview and comparison of vertical section lines from models with different wing length [FL]

7.3.2.1 Vertical Membrane Corner – variable wing length

Variable wing length (Fig. 21) cause change of form of Minimal Surfaces until the wing length is 1,5 times longer than height. From this point the Minimal Surface stays constant in terms of form and curvature. Further increasing of wing length leads to flattened areas at the end of the wing. Wing lengths which are shorter than the height generate strong anticlastic curvature in the area of the corner but the vertical part of the surface looses spatial curvature at the same time.

7.3.2.2 Vertical Membrane Corner – variable element length

Elongating the element length (Fig. 22) means a decrease of curvature in the midspan of the element, while the strong anticlastic curvature in the corner region stays unchanged.

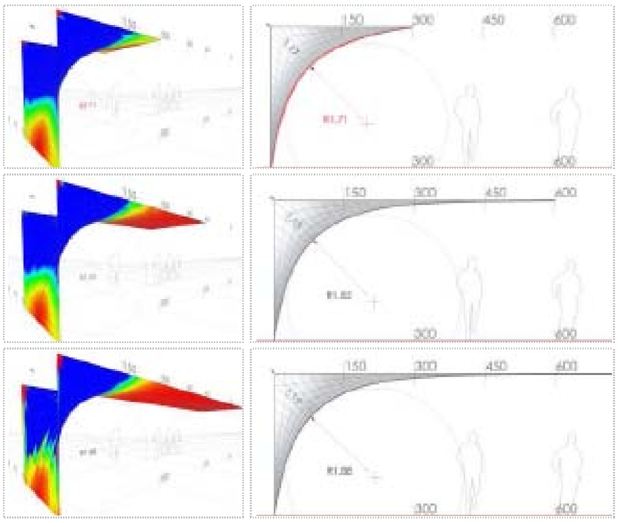


Fig. 21 Overview vertical corner [FL] variable length, Gaussian Curvature and longitudinal section

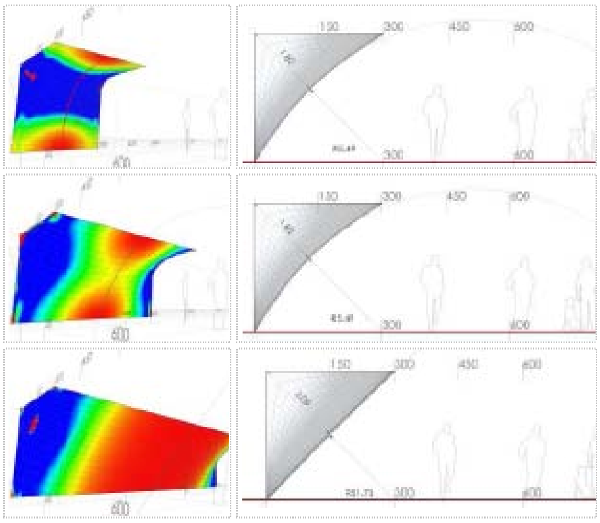


Fig. 22 Overview vertical corner [EL] variable length, Gaussian Curvature and longitudinal section

A square geometry in plan, meaning that the element length equals the wing length, offer the possibility to attain larger areas with sufficient anticlastic curvature. These curvatures are characterized by soft transitions and even distribution of curvature.

7.4 T-CONNECTION

Surfaces meeting in a T-connected boundary (Fig. 23) generate a Y-intersection (Fig. 24). This happens independently from the angle of the boundary connection. The 3 different parts of the Minimal Surface meet with 120° and form an arch-like intersection. This arch is less curved at its angular point and more curved the closer it is to the T-connection of the boundary. *„In very special cases only, a circular intersection can be formed."*[3] These special cases were used to form pressure resistant arches for real structures.

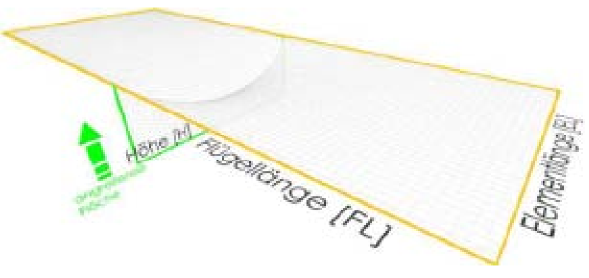


Fig. 23 Geometry of right angled T-connection

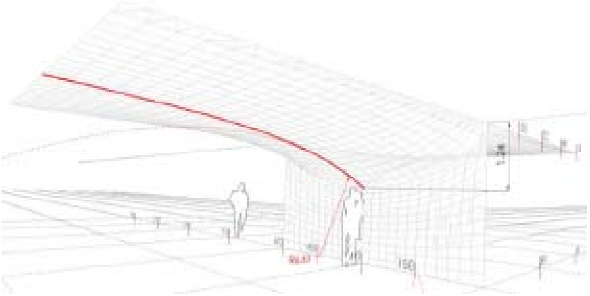


Fig. 24 Minimal Surface generated from a right angled T-connection

7.4.1 Right-angled T-connections

In terms of right-angled configurations the leg length of H (Fig. 23) has no influence on the form of the generated Minimal Surface as long as it is longer than the deflection of the Y-intersection. This happens to be the same, independently from the wings being arranged symmetrically or asymmetrically.

7.4.1.1 symmetric wing length [FL]

For symmetric wing length [FL] one can determine that the magnitude of the Y-intersection is directly connected to the ratio of wing length and element length. For all boundary conditions with FL ≥ EL/2 the magnitude of the Y-intersection equals 20,6% of the element length. For wing length shorter than the element length, a nonlinear behavior of the Y-intersection can be determined. So the boundary condition **FL=EL/2** represents the borderline between linear and nonlinear development of displacement in the direction of H (Fig. 25).

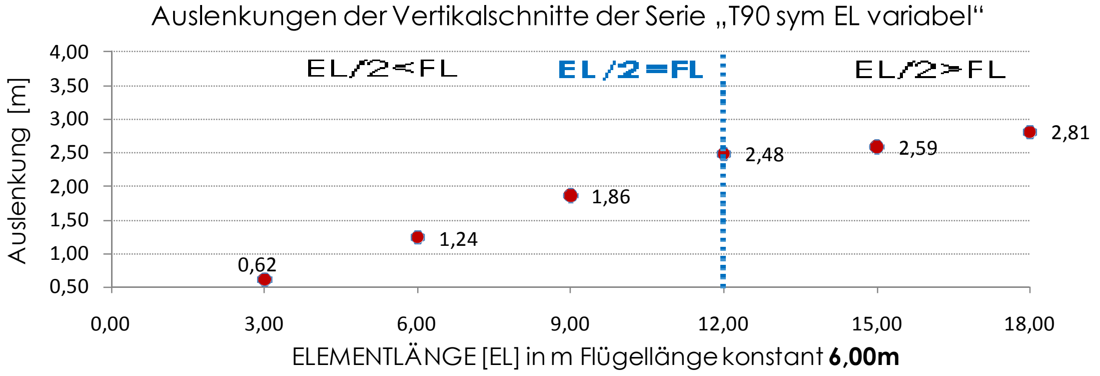


Fig. 25 Displacement of vertical section lines from right angled T-connection with symmetric wing length and different element length [EL]

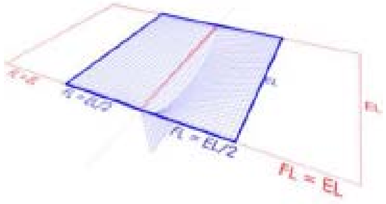


Fig. 26 T-connection with square boundary geometry FL = EL/2

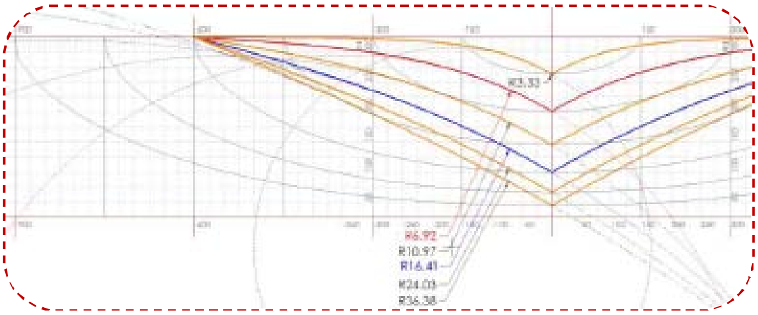


Fig. 27 linear increase of displacement at increasing element length up to EL/2=FL, then nonlinear

A square geometry in plan causes evenly distributed curvature in the surface (Fig. 26). The curved Y-intersection is similar to a basket arch (Fig. 27). Starting from a square geometry in plan increased wing length results in the generation of insufficiently curved areas at the ends of the wings. On the other hand there are no effects on the form, radii of curvature of the Minimal Surface and the transitional zone with anticlastic curvature to insufficiently curved areas does not move. The enlargement of the element length which corresponds proportionally to a reduction of the wing length causes insufficiently curved areas which are merged together in the element middle. Strong anticlastic curvature is limited to the areas of the T-connection of the boundary.

7.4.1.2 asymmetric wing length [FL]

Spatially curved Y-intersections and spatially curvature of all partial areas are generated by asymmetric wing length. The horizontal component of the deflection always occurs in direction of the larger wing.

7.4.2 Non-right-angled T-connections

When using T-connected boundaries with angles different from 90° the surface of H (Fig. 28), which is totally flat for the 90° case, will be spatially curved too. Increasing deviation of 90° goes along with increasing anticlastic curvature of surface H (Fig. 29).

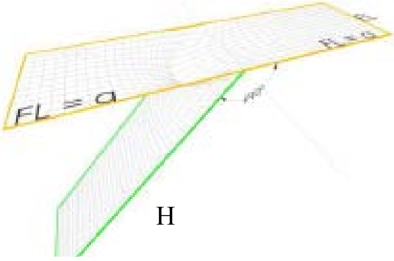


Fig. 28 T-connections different from 90°

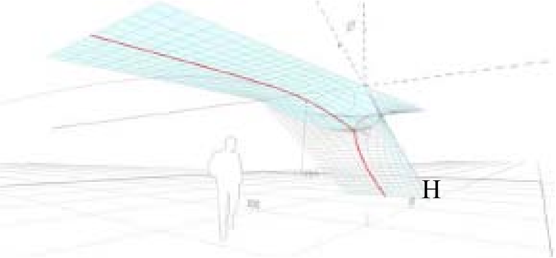


Fig. 29 T-connection with an angle of 60°

The formally interesting Minimal Surfaces which develop as a result of a T-connection with a not at right angles deviating surface H show spatially curved intersection lines. The more the angle differs from 90° the more the anticlastic curvature of H increases. At the same time the vertical deflection of the former horizontal parts decreases.

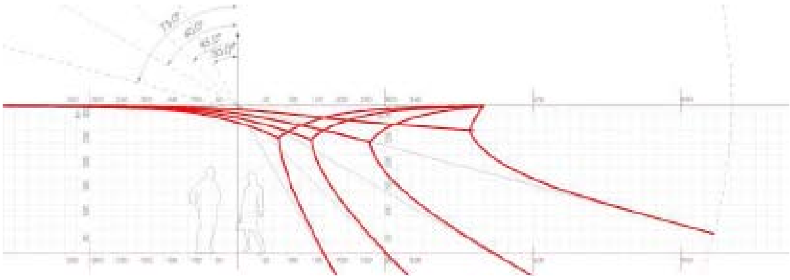


Fig. 30 vertical section lines T30°, T45°, T60°, T75°

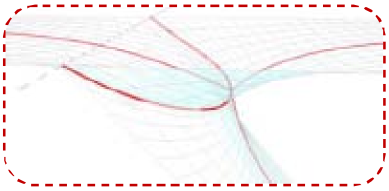


Fig. 31 spatially curved intersection line for T60°

7.5 CATENOID

The shape of the catenoid is basically generated by a catenary that rotates around a longitudinal axis. It is the only rotational body that can be minimal surface at the same time. As we know from SFB230 the maximum attainable height of a catenoid spanning two circular rings is *approximately 1,3 times the radius of a ring.*[4] For conceptual designs in architecture, boundaries different from two identical circles but with different diameters, not being arranged in one axis and/or not being symmetrically arranged are needed. So the maximum attainable heights of catenoids with different boundary geometries and arrangements were examined. New rules could be found for major boundary configurations. The resulting diagrams can be scaled at will.

7.5.1 Catenoids between circular rings of different diameters

Starting from the extreme of 1,3 times the radius of a ring the maximum height of a catenoid is decreasing if one of the rings diameter is decreasing (Fig. 32). Fig. 32 also illustrates that upper rings smaller than 1/5 (upper ring /lower ring) effect very little maximum attainable height and surfaces with little Gaussian Curvature at the same time.

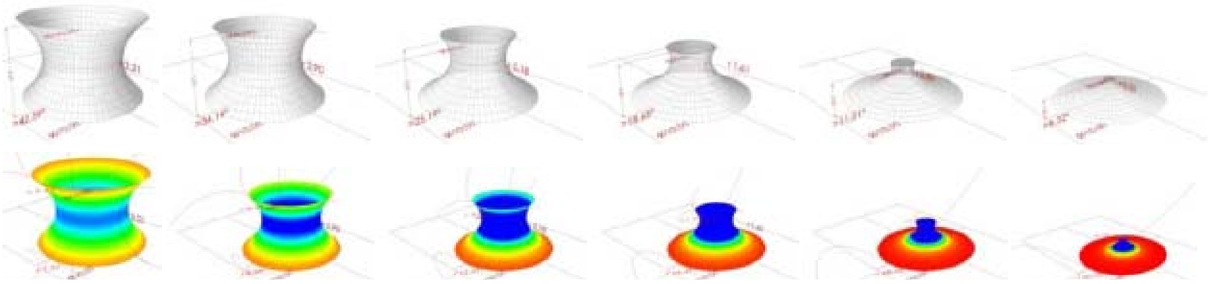


Fig. 32 Change of form and change of Gaussian Curvature of a Catenoid with decreasing diameter of upper ring and therefore decreasing height

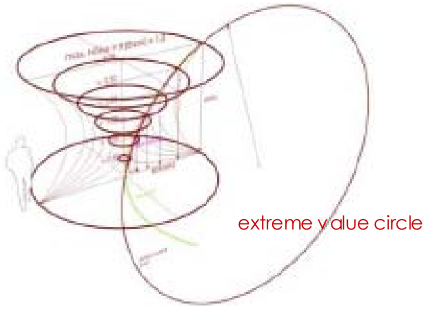


Fig. 33 3dimensional diagram for catenoids between circular rings of different diameters

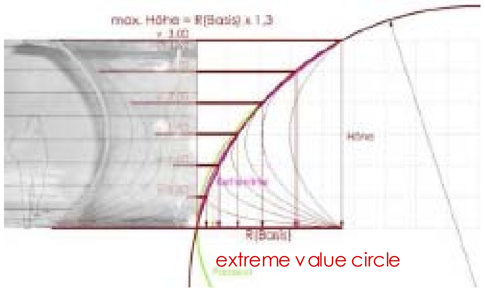


Fig. 34 Soapfilm model and diagram for catenoids between circular rings of different diameters

Several experiments showed that all the attainable maxima in dependence from the given diameters are located on a common circle - the extreme value circle. This circle again is in direct proportion to the circular base ring. (Fig. 33) The developed diagram allows a determination of the maximal attainable height when the diameters of the two rings are given. The other way round the maximal diameter of the upper ring can be found by predefining the desired height and the diameter of the base ring. (Fig. 34)

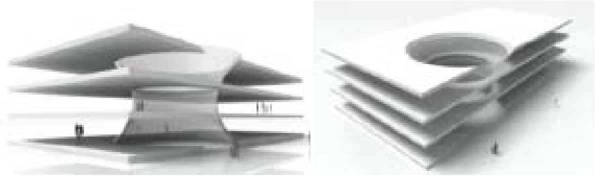


Fig. 35 Case-Study A

Case-Study A

A catenoid is perforating several floors and creates a courtyard situation. Its position is chosen the way that the ground floor gets a spatial incision whilst the other floors are still connected by a catwalk between catenoid and facade.

Fig. 36 Case-Study G

Case-Study G

The form of the catenoid is intersected with a rectangular building. In this case the catenoid was tilted in the direction from (left) and towards (right) the building. For this reason the opening in the façade opens on top and narrows to the sky inside the courtyard (left) and vice versa (right).

7.5.2 Catenoids between shifted circular rings

A displacement of the boundary rings effects lower maximum heights of catenoids. (Fig. 37) This correlation also follows precise rules. The interrelation of displacement of boundary rings and maximal attainable height of the catenoid can be found on circular movements defined by the center of the base ring and the diameter of the rings. (Fig. 38) At the same time we can observe that a displacement of more than ¾ of the diameter of the rings effects areas with little Gaussian Curvature. Strongly curved areas can always be found at half height of the catenoid. A displacement of 1 diameter of the boundary rings cannot be attained with a catenoid but forms two separated surfaces within the rings.

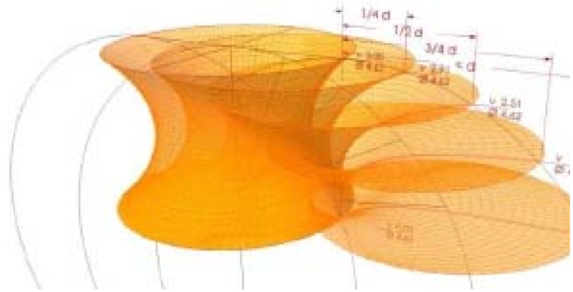


Fig. 37 3d view of overlayed catenoids between shifted circular rings showing the circular movement of the upper ring and the dependence of horizontal displacement of the rings and the loss of height.

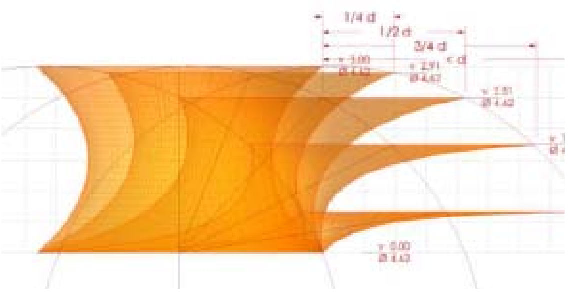


Fig. 38 Side view of overlayed catenoids between shifted circular rings showing the circular movement of the upper ring and the dependence of horizontal displacement of the rings and the loss of height.

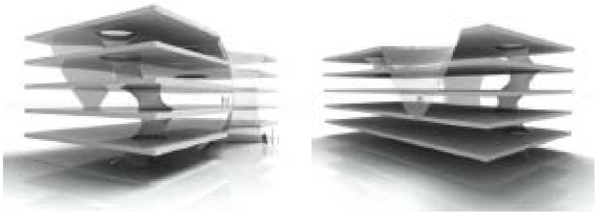


Fig. 39 Case Study K

Case-Study K

A horizontal displacement of one of the boundaries of the catenoid enables a spatial movement. For the fact that the base rings of displaced catenoids have equal diameter they can act like swivel plates. This way vertical connections or orientation to natural light can be solved.

7.5.3 Catenoids between square rings of the same side length

Compared to catenoids generated by two circular rings, catenoids between two equal square rings (Fig. 40) are having their maximum height at 1,44times of the side length of the square (Fig. 41) In analogy to catenoids between circular rings the maximal attainable height or the smallest possible upper square can be found on a common extreme value circle too.

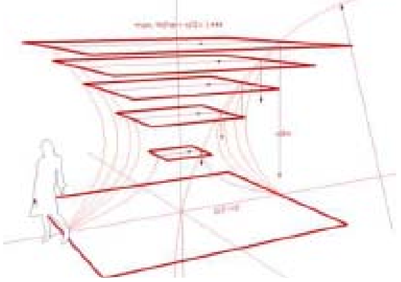


Fig. 40 3dimensional diagram for catenoids between square rings of the same side length

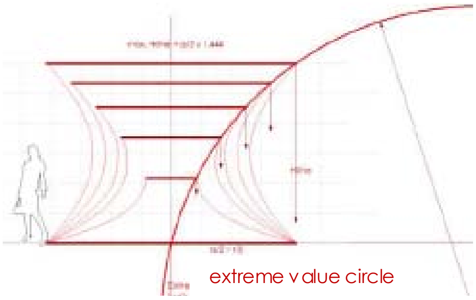


Fig. 41 diagram for catenoids between square rings of the same side length

7.5.4 Catenoids between a square and a circular ring

Catenoids between a square and a circular ring don`t follow an extreme value circle but a catenarylike line starting from the center of the square and going through the quadrant of the upper circular boundary. The maximal attainable height equals 1,39times the radius of the inscribed circle of the square respectively half of its side length. This is valid for configurations where the circle is the incircle at the most.

7.5.5 Congruent cut-outs from Minimal Surfaces of Catenoids

All executed investigations have shown that each randomly selected cut-out from a Minimal Surface of a catenoid will be a Minimal Surface with equal position in space and equal curvature of the surface itself. This can be explained by the absolute identical stresses in all directions of Minimal Surfaces. The example in Fig. 42 is showing a randomly selected closed curve that is projected on the surface of a catenoid. For this reason this curve is exactly matching the surface of the initial catenoid. By defining this curve as a new boundary line the new surface within this boundary is also matching the surface of the initial catenoid.

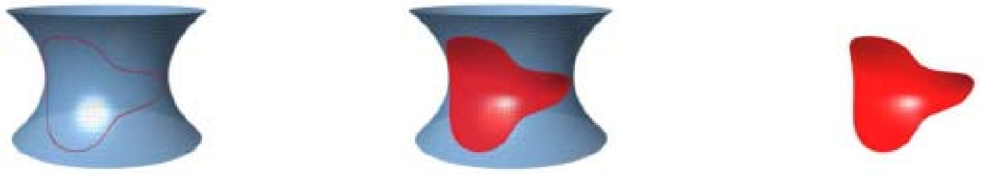
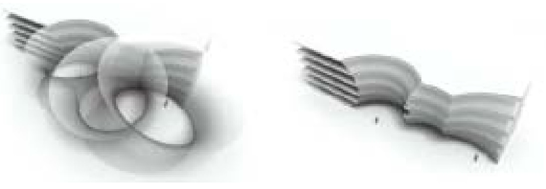


Fig. 42 Congruent cut-outs from Minimal Surfaces of Catenoids



Case-Study M2

The intersection of several catenoids is possible without changing of form of the different parts. This way 3dimensionally curved ridges are developed by the intersection line.

Fig. 43 Case Study M2

The definition of the new boundary can be found as described before, but it can also be found by intersecting different independent catenoids or by intersection with other forms. As shown in case-study M2 (Fig. 43) catenoids even don`t need to have the same position in space or the same size. This way a lot of possibilities are open for a potential design in architecture.

8 CONCLUSION ON RESEARCH, CASE-STUDIES AND EXPERIMENTAL STRUCTURES

The characteristics that Minimal Surfaces can be proportional scaled and that a predefined cut-out of minimal surface keeps unchanged multiplies the possibilities for the design. Using the found rules case studies give an idea of the infinite possibilities that are open to create very special „soft spaces", with new architectural qualities like shown in case studies and experimental structures (Fig. 44 to Fig. 46) and furthermore.

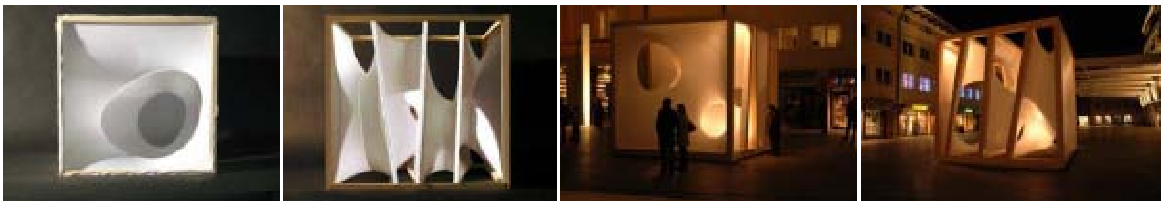


Fig. 44 "Cube of Clouds" experimental structure in model and in scale 1/1
exhibited and published at Premierentage 2005, Best of 2005 and Ziviltechnikertagung 2005

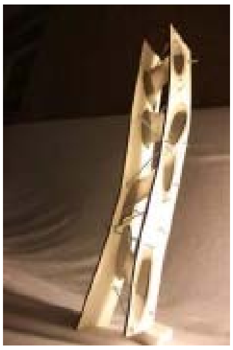


Fig. 45 "Cut.enoid.tower" - experimental structure with a height of about 13meters in scale 1/1. The distorted appearance is generated by the interaction of pin-joint columns, which work on compression and different versions of prestressed catenoids.

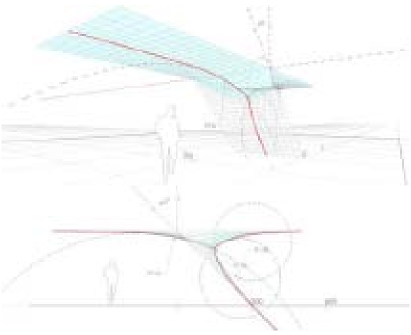


Fig. 46 "minimal T"–structure shows the possibility to deflect surfaces that were flat before being assembled by using special geometries in arrangement

9 PERSPECTIVE

Latest approaches are dealing with alternative boundary-conditions and with software implementation in terms of scripting found rules (Fig. 47). An investigation on the correlation of self organizing forms, their close relation to nature and their aesthetic values also seems to be interesting questions for the future.

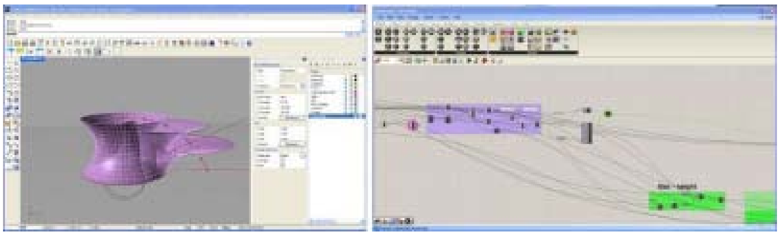


Fig. 47 Grasshopper script "Catenoids between horizontally shifted circular rings"

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