Transformable Cladding Systems: Research, Design and Fabrication

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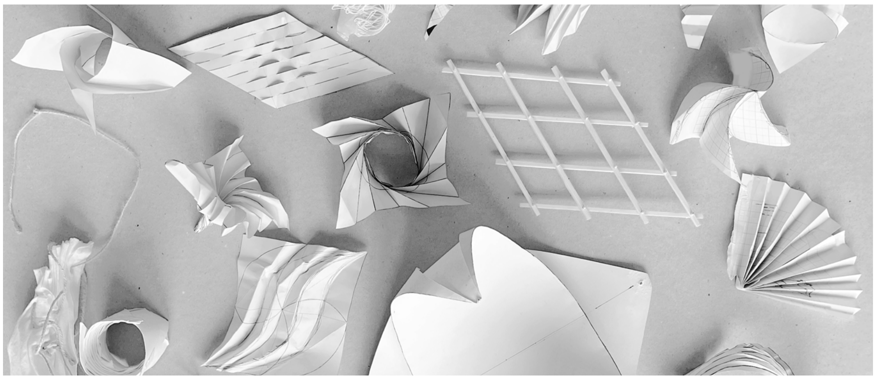

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Bachelorthesis
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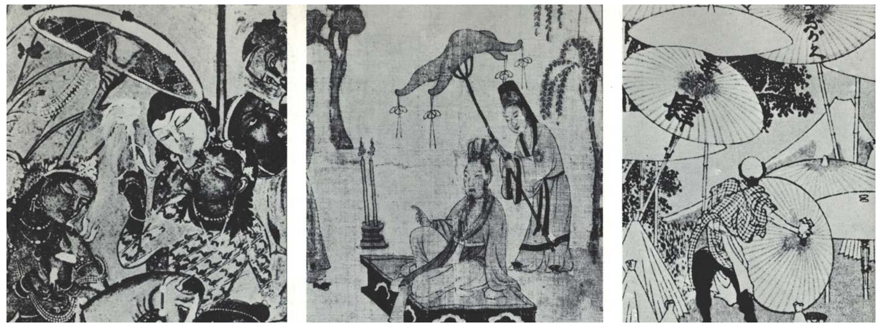


Fig. 1: Historical cladding systems (chinese umbrella)

Research

Introduction

“Convertible roofs are designed so that their form can be changed as often as desired and in a relatively short time.” (Blümel & Pankoke, 1972)

The ability to transform is also transferred to the corresponding cladding system. The traditional concept of architecture in the 20th century took durability and solidity as the most important characteristics of building as a given. This was gradually replaced by a concept that was characterised by functionality, practicality, utility and movement. (Blümel & Pankoke, 1972) These principles were pioneeringly explored by Frei Otto and his colleagues at the Institute for Lightweight Structures of the University of Stuttgart. Tents, awnings, street canopies, umbrellas, folding roofs and the Roman theatre velum have established themselves in various forms in our everyday lives worldwide over thousands of years (see Fig. 1). The fact that movement had previously played only a secondary role in architectural history has resulted in a lack of research in this area. This has led to the relevance of its research in recent years, as there are increasingly technical methods to parametrically simulate and statically calculate such technically highly complex constructions. This paper focuses on the research, design and digital fabrication of transformable cladding systems using the example of the Kinetic Umbrella project by Jonas Schikore from the Department of Technology/Structural Design at the Technical University of Munich.

Related work

An extensive research of typologies until the end of the 20th century is provided by the Institute for Lightweight Structures under the direction of Frei Otto in the book “Convertible Roofs IL 5” from 1972. Many different membrane constructions, their constructional details, and classification into different typologies are described based on the examples of built structures or concept designs (see Fig. 2). (Blümel & Pankoke, 1972)

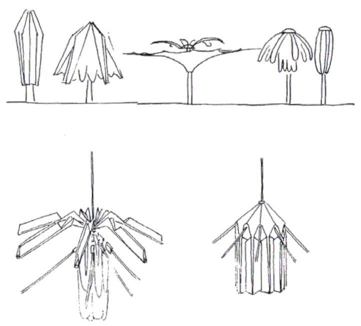


Fig. 2: Umbrella-like structure

The doctoral thesis „Deployable Tensegrity Structures for Space Applications“ shows different reflector antennas for space applications. The work also introduces several complex folding mechanisms (see Fig. 3) of transformable cladding systems for space applications. (Tibert, 2002)

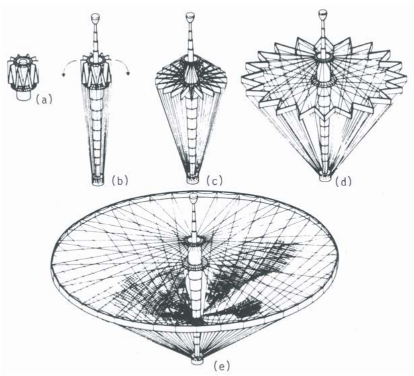


Fig. 3: Deployment sequence of antenna

„Construction Manual for Polymers + Membranes“ presents an overview of materials that can be used for transformable cladding systems, planning aids and built examples (see Fig. 4). It also lists convertible cladding systems with membrane systems. (Knippers, 2010)

Fig. 4: Trichterschirm

In his doctoral thesis, Motoi Masubuchi describes transformable foldable membrane roofs and their application and advantages. He explores different typologies, different materials, the historical background and carries out two case studies (see Fig. 5). (Masubuchi, 2013)

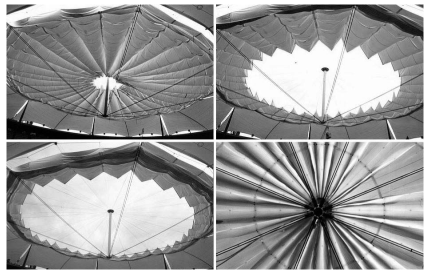


Fig. 5: Sequential view of membrane roof

In his work „Bending-Active Structures“, Julian Lienhard describes the form-finding process for kinetic load-bearing systems with the help of elastic deformation (see Fig. 6). In particular, he examines the elasticity of different materials. (Lienhard, 2014)

Fig. 6: Wind tunnel tests

The dissertation by Zoran Novacki deals with a comprehensive overview and analysis of transformable linear load-bearing systems and the development of a new system (see Fig. 7) by combining existing typologies. (Novacki, 2014)

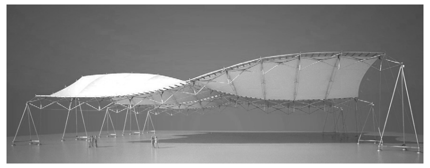


Fig. 7: Transformable load-bearing system

Andrej Mahovič examines rectable roof structures in stadiums and sporthalls and compares different systems and compares the opening and closing mechanism (see Fig. 8). (Mahovič, 2015)

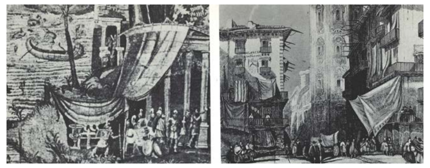


Fig. 8: Tennis stadium Qizhong

Transformability has relevance in nature, as adaptation to the environment is essential for plants to survive. Numerous research projects explore the transformation and simultaneous adaptation of plants at different scales. Simon Schleicher shares his research report on bio-inspired compliant mechanisms for architectural design. He is inspired by flexible structures from nature and generates proposals for mechanisms with joint-free bending (see Fig. 9). (Schleicher, 2016)

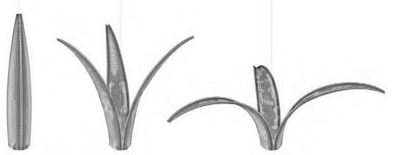


Fig. 9: Kinetic model of the lily bud

„The geometry of unfolding tree leaves“ mathematically describes the parallel folding method of leaves of hornbeam and beech from the blossom to the fully opened leaf. This complex folding method allows the very large leaf to be minimally folded (see Fig. 10). (Kobayashi et al., 1998)

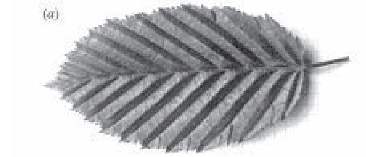


Fig. 10: Hornbeam leaf

The hind wings of the bamboo weevil are similar to a convertible cover system are (see Fig. 11). Xin Li et al study this microstructure and simplify the principles of the folding mechanisms, thus providing a basis for reproducing them. (Li et al., 2019)

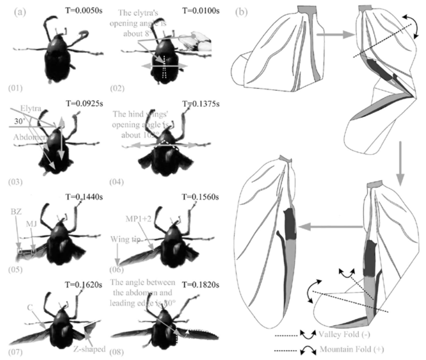


Fig. 11: The video sequence of wings

„Structural, Deployable Folds - Design and Simulation of Biologically Inspired Folded Structures“ focuses on the parametric calculation and translation of biologically inspired folded structures using earwigs, maple and hornbeam leaves as examples (see Fig. 12). (Baerlecken et al., 2014)

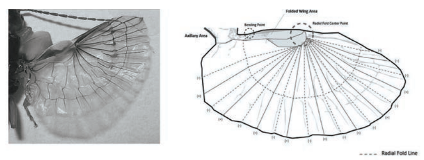


Fig. 12: Diagram of folding mechanism

In the paper „Self-Organized Origami“, the folding mechanism of the hornbeam leaf is compared with the artificially generated Mira-ori folding pattern and its efficiency and mathematical derivation is described. (Mahadevan & Rica, 2005)

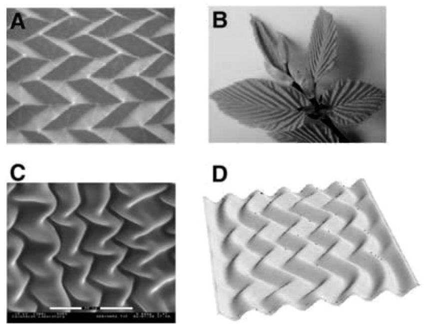


Fig. 13: Miura-ori pattern

Sebastien J.P. Callens and Amir A. Zadpoor deal with the mathematical calculation and fabrication of curved geometries from flat sheets using origami and kirigami approaches. The resulting transformable systems all have the ability to shrink spatially. (Sebastien J.P. Callens & Amir A. Zadpoor, 2018)

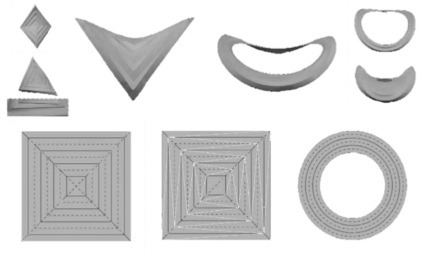


Fig. 14: Concentric pleating origami

Guidelines for the parametric modelling and simulation of curved foldings are provided in the paper „Modeling Curved Folding with Freeform Deformations“. The principles and geometric framework of curved folding are explained mathematically (see Fig 15). (Rabinovich et al., 2019)

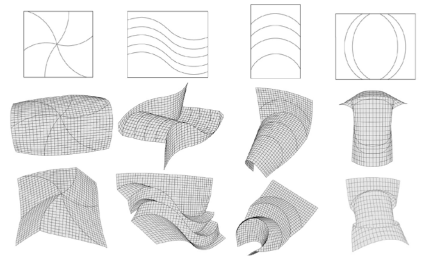


Fig. 15: Comparison of the folding

Learning from mechanisms found in nature, Kathy Velikov et al. describes pneusystems as highly flexible structures that can be applied in architecture in a kinetic context. By inflating pneu cushions, structures can be designed which are not only extremely light and flexible, but also extremely controllable in their overall appearance (see Fig. 16). (Kathy et al., 2014)

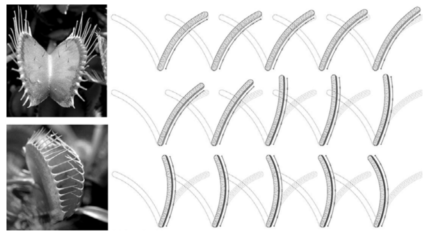


Fig. 16: Nastic movement

Categorisation

The transformable structure and the associated transformable cladding system are proportionally dependent on each other. Therefore, we assume that they can be structured in the same way.

Based on the classification system (see Fig. 17) by Frei Otto of the Institute for Lightweight Structures in the book „Convertible Roofs IL 5“ from 1972, our cladding system can also be categorised in this way. Ignoring the column construction system, convertible cladding systems can also be classified according to their type of movement: bunching, rolling, sliding, folding and rotating. These in turn can be classified according to their direction of movement: parallel, central, circular and peripheral.

In addition, it is important to note that these categorisations are not the only options. A combination of type of movements and type of directions can be made, which in turn creates new categories. New scientific findings can further add to the categorisation. For example, a pneu movement can be added as a new type of movement.

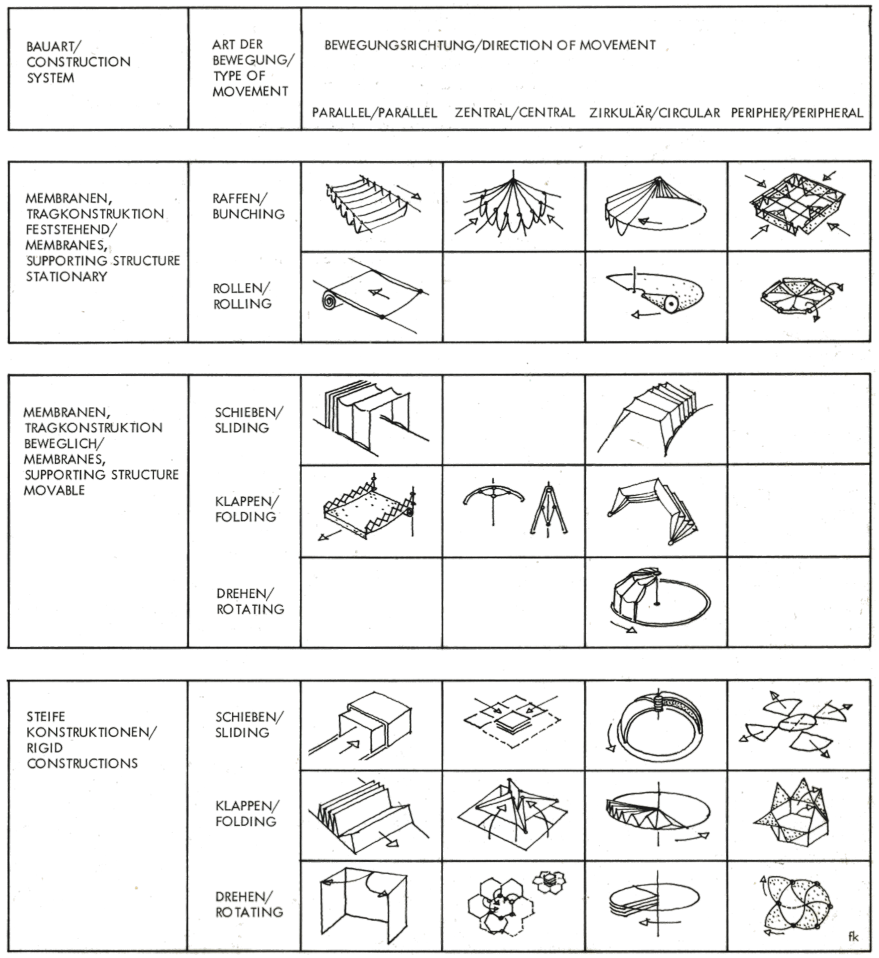


Fig. 17: Transformable structure classification

The aforementioned examples in the related work can be classified in the same way with the categorisation by the Institute for Lightweight Structures (see Fig. 17).

The built and concept designs by Blümel / Pankoke (see Fig. 2), the structure described in “Deployable Tensegrity Structures for Space Applications” (see Fig. 3), the „Trichterschirme“ by Rasch+Bradatsch (see Fig. 4) as well as the roof of the Bull-fight ring in Jaén can be categorised as membrane-based cladding systems with bunching and folding movements.

The examples of Julian Lienhard and Zoran Novacki showed in the figures 6 and 7, explored the possibilities of a new system achieved a covering system using a combination of folding and sliding movements.

In nature, folding surfaces mechanism can be found in both plants and animals. “The geometry of unfolding tree leaves” (see Fig.10) and the paper “Self-Organised Origami” (see Fig. 13) showcase the naturally occurred rigid folding mechanism of the leaves of maple and hornbeam. Meanwhile, the non-folding joint-free flexible bending structure through the pneumatic cell movement found in plants (see Fig. 9) such as venus flytrap (see Fig. 16) suggest a new mechanism outside the categorisation of the Institute for Lightweight Structures. While in the realm of animals, the fan-shaped folded wings of earwigs and bamboo weevil (see Fig. 11 and 12) are investigated by Xin Li and Baerlecken et al.

Through advancements in the field of computational design, new possibilities for folding mechanisms have been invented and therefore expand the field of this research with complex curved folding mechanisms (see Fig. 14 and 15).

Transformable Cladding Systems


Fig. 18: Rendering of the Kinetic Umbrella

Scientific Context

The work, which has an interdisciplinary approach from architecture and structural engineering, focuses thematically on transformable cladding systems. Based on in-depth research and analysis, the fabrication is exemplified using the Kinetic Umbrella project by Jonas Schikore.

With the Kinetic Umbrella, an innovative construction method is investigated. Straight lamellae are joined together to form a spatial grid structure by means of elastic deformation. Under consideration of geometric-mechanical rules, a grid structure is created which allows clearly defined deformations. When locked, the grid forms a highly efficient load-bearing structure. The aim is to generate a spatially changeable load-bearing structure by simple means and with little use of materials.


Fig. 19: Sequence of the umbrella opening and closing

The Kinetic Umbrella changes shape from a 6.5 m high cylinder to an 8 m diameter umbrella (see Fig. 19). The supporting structure made of 32 GRP elements is activated by a cable system (actuation system).

Students are closely involved in the development, production and construction of the Kinetic Umbrella project and learn about the relationships between spatial geometry, elasticity, tension and weight in a practical way.

The construction is part of a „research-by-design“ process and will be put into operation on the event grounds of the Kreativquartier München after completion in summer 2021.

Design

Exploratory research

Based on the typologies of the previously identified structural systems and the geometric restrictions of the Kinetic Umbrella (see Fig. 8), first preliminary designs and concepts of transformable cladding systems are presented and compared in the categories:

- Weight (the cover system should be light in order not to add unnecessary additional loads to the supporting structure, which could limit the transformability).
- Environmental (the covering system should provide protection against environmental influences such as wind, solar radiation and, if applicable, rain)
- Fabrication (the fabrication should be universally modular and digitally or easily fabricable, as a very large number is to be produced)
- Aesthetics (from an architectural point of view, the covering system should complement the supporting structure and unite it aesthetically).

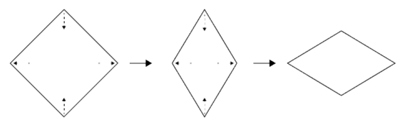


Fig. 20: Form change of rhombus

In this preliminary study, one unit of the Kinetic Umbrella is analysed individually (see Fig. 20). When closed, that module is a rhombus and is formed into a square by deforming the corner points. The resulting dependencies are complex and will be used in the following to create an efficient covering system.

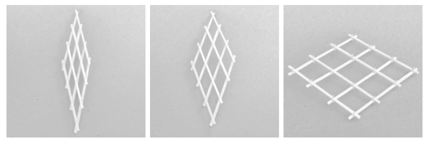


Fig. 21: Form change of test model

In order to compare the different variations of this preliminary study from a qualitative point of view, a model was created which simulates the mechanical relationships of the Kinetic Umbrella in a simplified two-dimensional space (see Fig. 21).

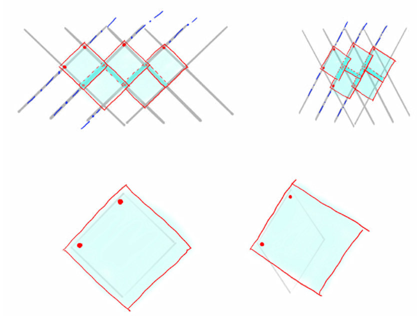


Fig. 22: Sketch: shingles, two points

Shingles - two points connected

The covering system with module-sized elements is adapted to the shape of the module when the umbrella is opened to the maximum. During the closing process, the shingles overlap more and more, but always remain connected to the structure at two points. (see Fig. 22)

Rainwater can drain off well as it is very overlapping in every opening position of the umbrella.

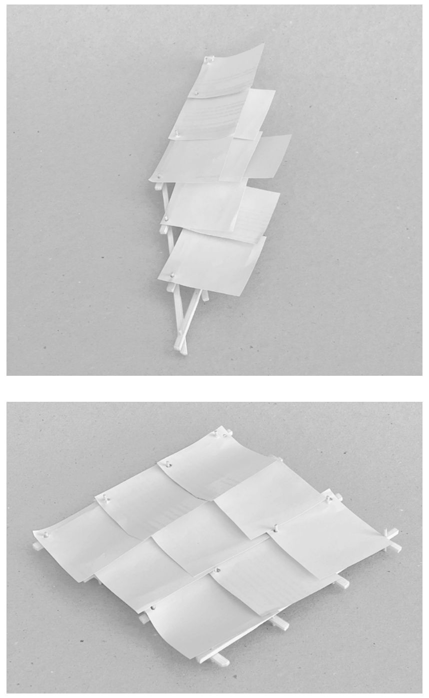


Fig. 23: Photo: shingles, two points

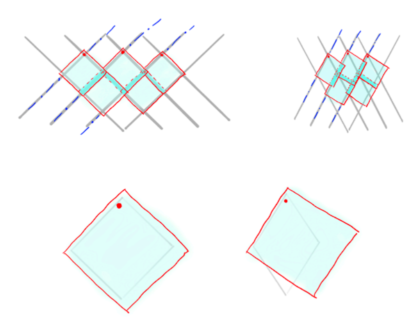


Fig. 24: Sketch: shingles, one point

Shingles - one point connected

The covering system with module-sized elements is also adapted to the shape of the module when the umbrella is opened to the maximum. During the closing process, the shingles overlap more and more, but always remain connected to the structure at one point. (see Fig. 24)

Rainwater can drain off well as it is very overlapping in every opening position of the umbrella.

The connection to the construction must be very durable, as it must be able to withstand several forces impacting the connection point.

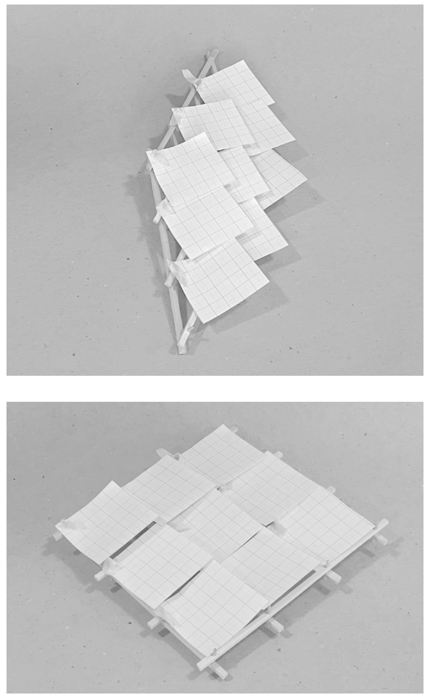


Fig. 25: Photo: shingles, one point

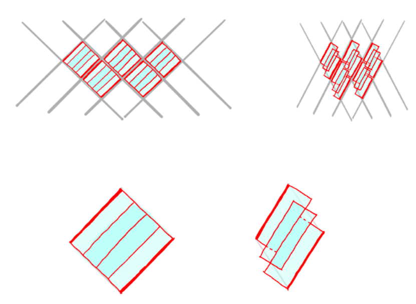


Fig. 26: Sketch: sliding, parallel

Sliding - parallel

The cover system with module-sized elements is adapted to the shape of the module when the canopy is opened to the maximum. During the closing process, the shingles overlap more and more, but always remain connected to the construction on two sides. (see Fig. 26)

Overlaps impale themselves to some extent with the construction and adjacent modules.

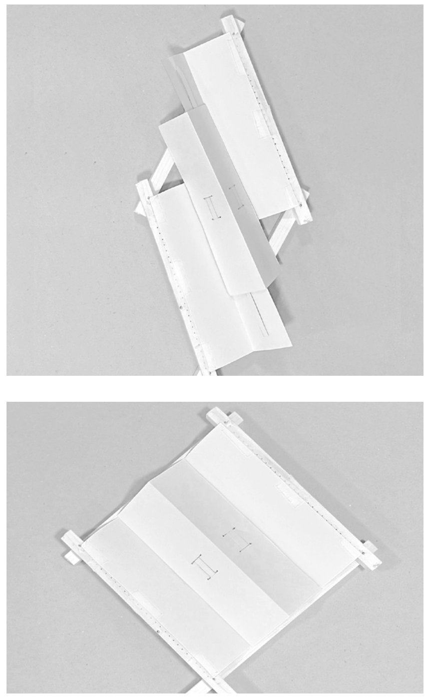


Fig. 27: Photo: sliding, parallel

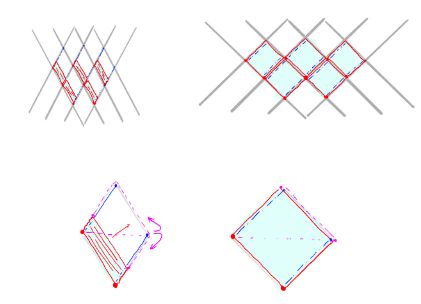


Fig. 28: Sketch: mechanical bunching

Bunching - automatic closing

The cover system with module-sized elements has a „curtain" that covers or opens the module proportionally to the opening and closing of the construction (see Fig. 27).

The variation is only sun protection.

The cable construction is mechanically interesting but complex and would therefore cause significant problems in everyday usage.

Fig. 29: Photo: mechanical bunching

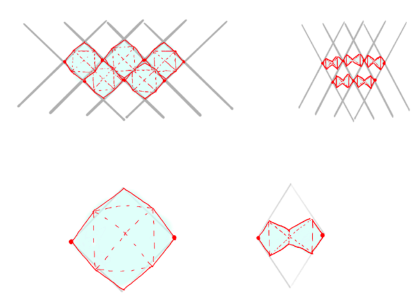


Fig. 30: Sketch: folding, origami

Folding - Origami

The cover system consists of modular foldable elements. Each element has a relatively small thickness when folded and is positioned in the centre of each rhombus (see Fig. 29).

However, in the unfolded state, it only provides sun protection, not rain protection.

There is a higher vulnerability of the parts because they consist of a small-part folding mechanism.

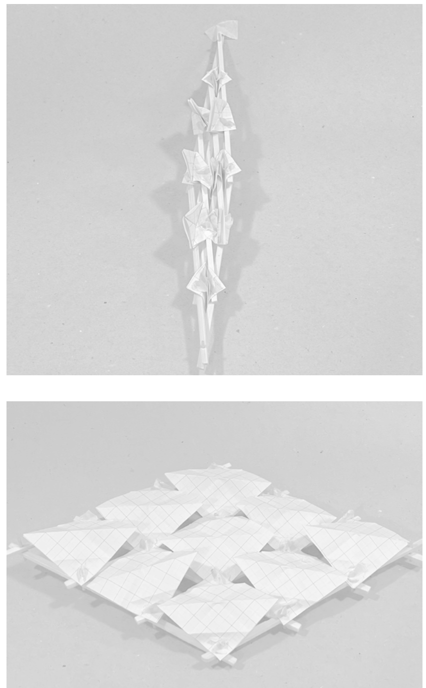


Fig. 31: Photo: folding, origami

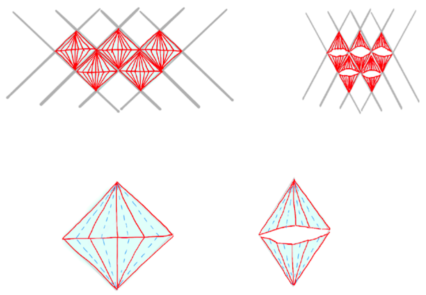


Fig. 32: Sketch: folding, fan shaped

Folding - Fan shaped

The cover system consists of modular foldable elements. The folding mechanism consists of two overlapping compartments that close simultaneously with the construction (see Fig. 31).

In the unfolded state, it provides sun protection, but not reliable rain protection.

There is a higher vulnerability of the parts because they consist of a small-part folding mechanism.

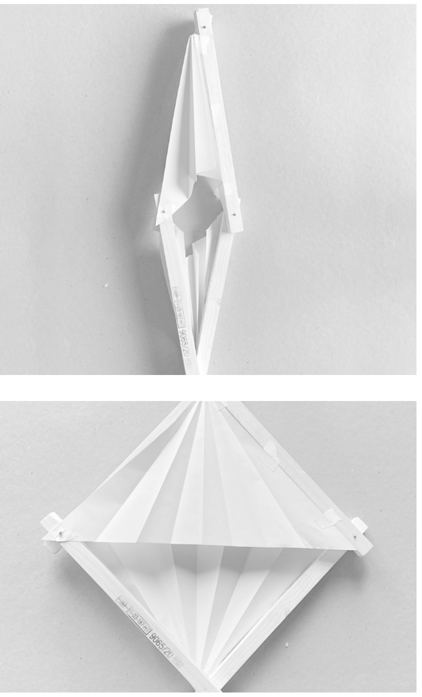


Fig. 33: Photo: folding, fan shaped

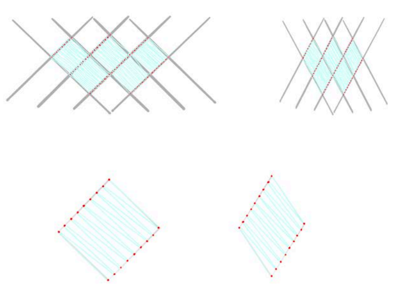


Fig. 34: Sketch: cable, linear

Cable - Linear

The covering system with module-sized elements is covered with threads (see Fig. 33).

Therefore, no rain safety can be guaranteed.

It is possible to experiment with distances between the cables and with different cable-colours. In this way, complexity can be created.

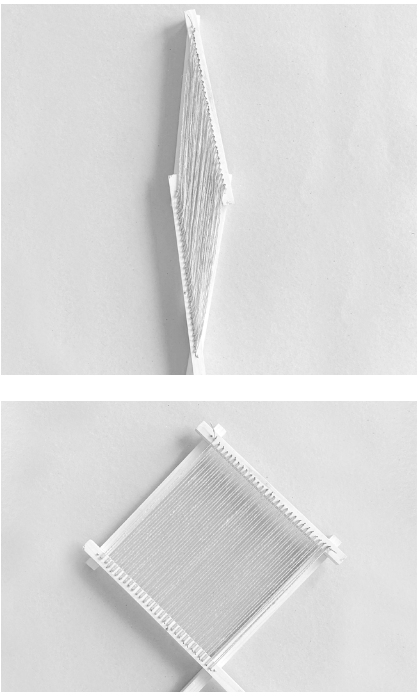


Fig. 35: Photo: cable, linear

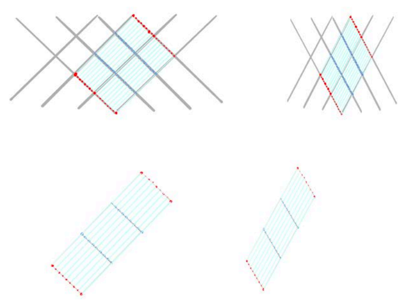


Fig. 36: Sketch: cable, cross-module

Cable - cross-module

The covering system with cross-module elements is covered with threads (see Fig. 35).

Therefore, no rain safety can be guaranteed.

It is possible to experiment with distances between the cables and with different cable-colours. In this way, complexity can be created.

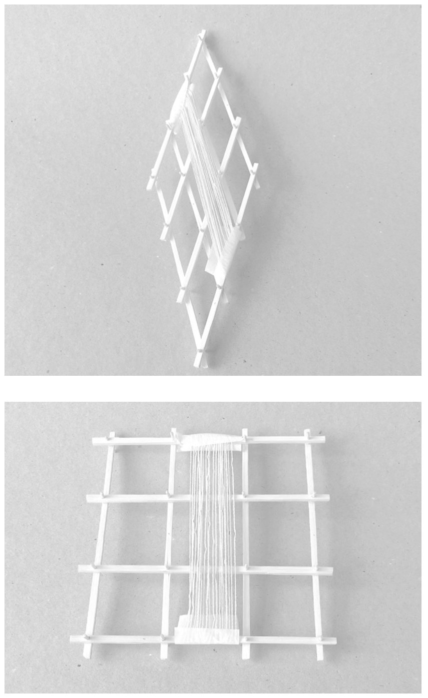


Fig. 37: Photo: cable, cross-module

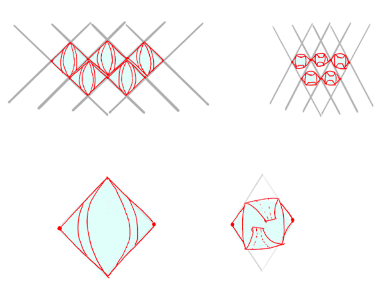


Fig. 38: Sketch: curved folding I.

Curved folding I

The covering system consists of modular foldable elements. Each element is relatively thin when folded and is located in the centre of each diamond (see Fig. 37).

In the unfolded state, however, it only provides sun protection, not rain protection.

There is a higher vulnerability of the parts because they consist of a small-part folding mechanism.

Curved folding means that the edges are not folded in a straight line but in a curved shape. This requires the use of machines or a very high amount of work.

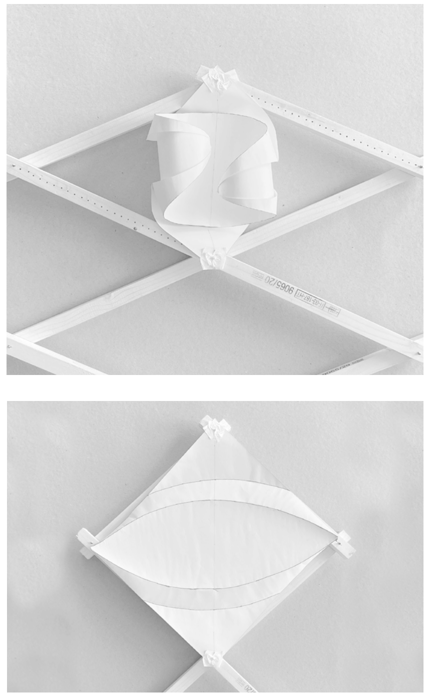


Fig. 39: Photo: curved folding I.

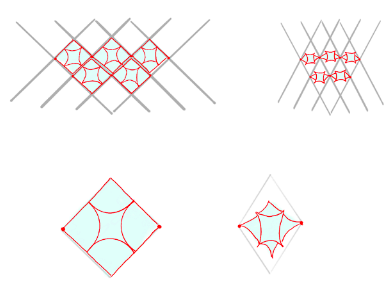


Fig. 40: Sketch: curved folding II.

Curved folding II

The covering system consists of modular foldable elements. Each element is relatively thin when folded and is located in the centre of each diamond (see Fig. 39).

In the unfolded state, however, it only provides sun protection, not rain protection.

There is a higher vulnerability of the parts because they consist of a small-part folding mechanism.

Only possible on every second module due to overlap.

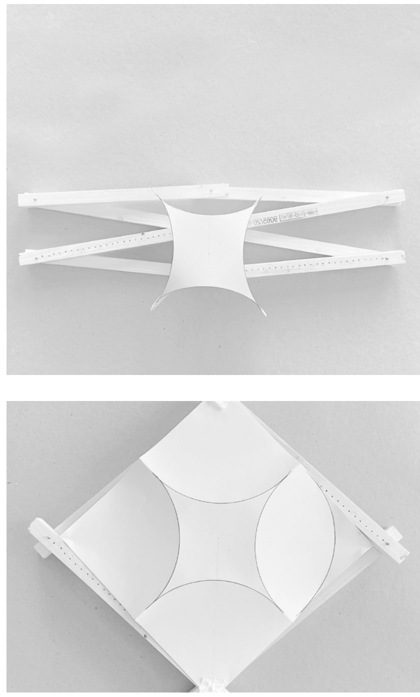


Fig. 41: Photo: curved folding II.

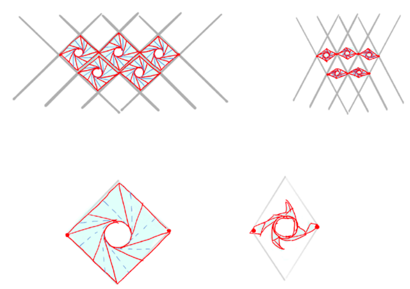


Fig. 42: Sketch: curved folding III.

Curved folding III

The covering system consists of modular foldable elements. Each element is relatively thin when folded and is located in the centre of each diamond (see Fig. 41).

In the unfolded state, however, it only provides sun protection, not rain protection.

There is a higher vulnerability of the parts because they consist of a small-part folding mechanism.

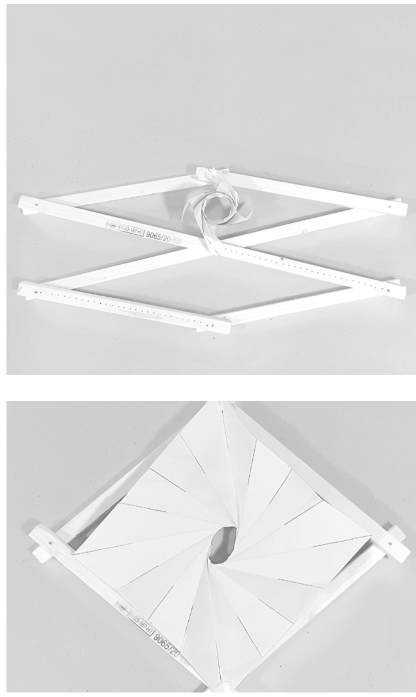


Fig. 43: Photo: curved folding III.

Concept	Weight	Environmental	Fabrication	Aesthetics
Shingles *two points connected*	medium	sun + /rain + /wind 0	easy	clean
Shingles *two points connected*	medium	sun + /rain + /wind -	easy	not matching structure
Sliding *parallel*	heavy	sun + /rain + /wind -	difficult	not matching structure
Bunching *automatic closing*	heavy (mechanism)	sun + /rain - /wind -	difficult	sophisticated
Folding *Origami*	heavy	sun + /rain 0 /wind -	difficult	sophisticated
Folding *Fan shaped*	medium	sun + /rain - /wind -	difficult	not matching structure
Cable *Linear*	light	sun 0 /rain - /wind +	easy	clean/matching structure
Cable *cross-module*	light	sun 0 /rain - /wind +	easy	clean/matching structure
Curved folding *I*	heavy	sun + /rain + /wind -	difficult	sophisticated
Curved folding *II*	heavy	sun + /rain - /wind -	difficult	sophisticated
Curved folding *III*	heavy	sun + /rain - /wind -	difficult	sophisticated

Fig. 44: Overview of different cladding systems

Evaluation of the results

After the first preliminary study, all results are compared in an overview (see Fig. 44) on the basis of previously determined subjective and objective factors.

The shingle variants (with two and one connection point to the structure) (see Fig. 22, 24) are not considered as interesting, as they cannot withstand the wind forces on the Kinetic Umbrella due to their large-area covering.

The sliding solution (see Fig. 26) was not considered, as it was too complicated to build during the prototype test, as the sliding mechanism is very complex to construct and is too susceptible to long-term use.

Likewise, the bunching mechanism (see Fig. 28) is too sensitive to environmental factors. The mechanism is very sophisticated and aesthetically very interesting. It considers the dependencies of the geometric relationships of the rhombus during deformation of the Kinetic Umbrella.

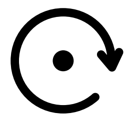
The folding mechanisms (origami and fanshaped) (see Fig. 30, 32) are too susceptible to wind forces due to their large-scale closure when the umbrella is open, but they are too time-consuming to fabricate. It is also a disadvantage that, despite their large-area covering, they do not offer any rain protection.

The curved folding variants (see Fig. 38,40,42) are also not interesting to develop further for the Kinetic Umbrella, as they cannot be manufactured in such a high quantity due to both their complex construction and high susceptibility to wind forces. In addition, a heavy material is needed for the folding mechanism to ensure that the geometry folds back again.

The cable system (see Fig. 34,36) is the most interesting to develop because it is simple to manufacture and also light. Moreover, from an aesthetic point of view, it corresponds to and complements the Kinetic Umbrella. As this concept is simple at its core, it can be made more complicated in further steps, as there are many parameters that can be modified.

Some of the other concept ideas presented can also be developed further, but in our work we focus on cable systems exemplified on the kinetc umbrella project.

Transformable Cladding Systems

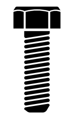


01. Orientation

- parallel to lamellas
- perpendicular to the lamellas

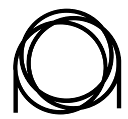
02. Layer for cable system integration

- bolts fixture
- upper lamella edge
- in lamella (outside)
- centre
- in lamella (inside)
- lower lamella edge



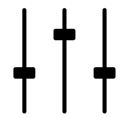
03. Mounting method

- profile
- drilling
- punctual mounting
- cut-in



04. Cable Properties

- stretchable
- stiff
- foldable
- flat
- round



05. Parameterisation

- cable thickness
- cable colour
- cable distance

Fig. 45: Parameter overview

Targeted research: cable system

Cable systems on the Kinetic Umbrella have numerous parameters, most of which are dependent on each other or complement each other. Figure 45 shows an overview of all parameters: orientation to the lamellae of the Kinetic Umbrella, layer for the cable system integration, the mounting method, the cable properties and the parameterisation.

The design is based on a compilation of all parameters and a subjective consideration as well as consideration of the geometric constraints for installing the cover system on the Kinetic Umbrella. Taking all the above factors into account, an architectural concept is then developed and fabricated in the next step.

The orientation of the Kinetic Umbrella allows two directions: parallel to the outer lamella and perpendicular to the outer lamella (see Fig. 46). The outer lamellae were specifically considered as a reference, as the cabel system can follow or oppose them for an outside observer.

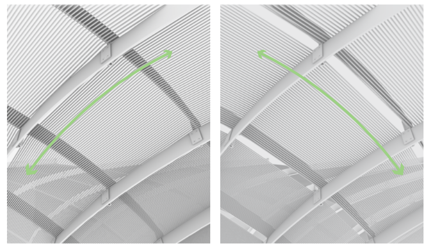


Fig. 46: Orientation comparison

The second parameter is the layer in which the cable system is integrated into the structure of the Kinetic Umbrella. For this purpose, a junction point is used at which the different layers can be identified exemplarily: bolts fixture, upper lamella edge, in lamella (outside), centre, in lamella (inside) and lower lamella edge (see Fig. 47).

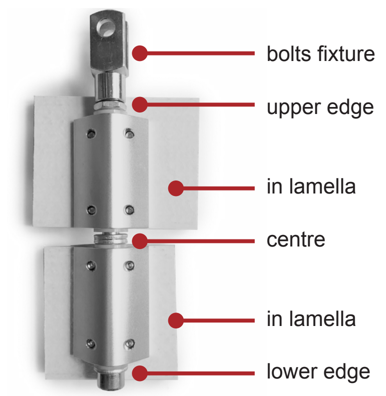


Fig. 47: Mounting positions

The third parameter is the mounting method, which is closely related to the previous parameter. Cables can be spanned or guided from lamella to lamella by numerous methods. The following have become established: profiles, drilling, punctual mounting and cut-in (see Fig. 48).

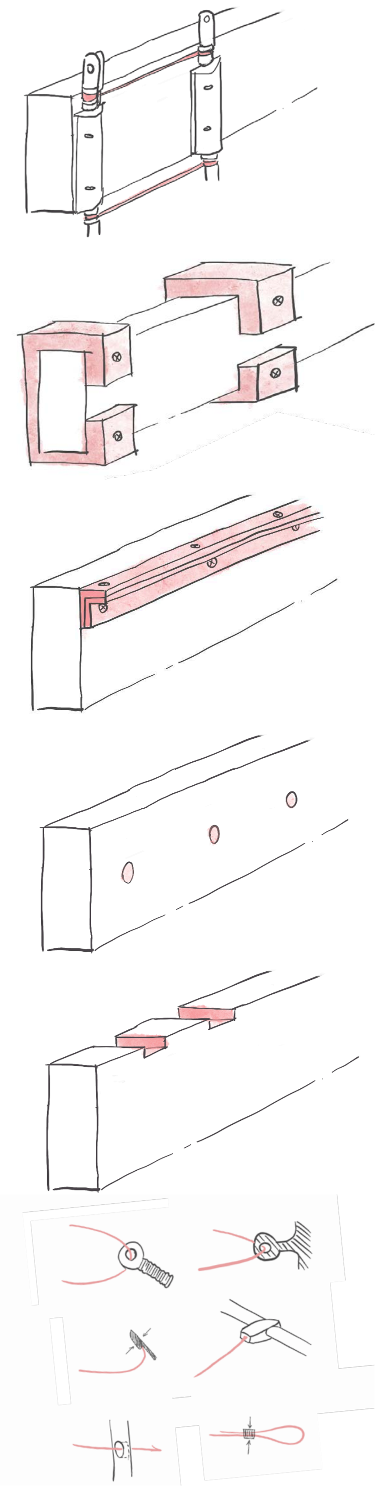


Fig. 48: Mounting methods

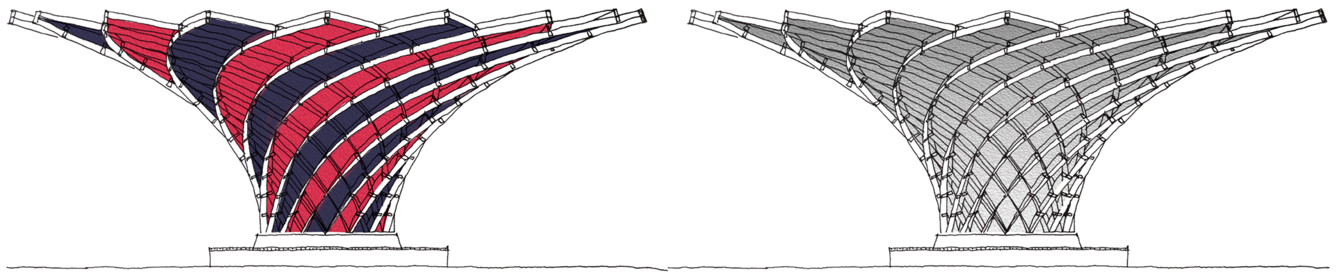


Fig. 49: Pattern / colour study using water colour

Another important parameter is the properties of the cable. On the one hand, it can be distinguished by its properties: stretchable, stiff and foldable. On the other hand, it can have different geometric cross-sections. The most common are flat and round.

In the final step, the cable system can be parameterised. This is closely related to the other parameters. For example, the cable thickness, the cable colour and the cable distance can be used to create an interesting pattern. Conceptual watercolour drawings were made to visualize this (see Fig.49).

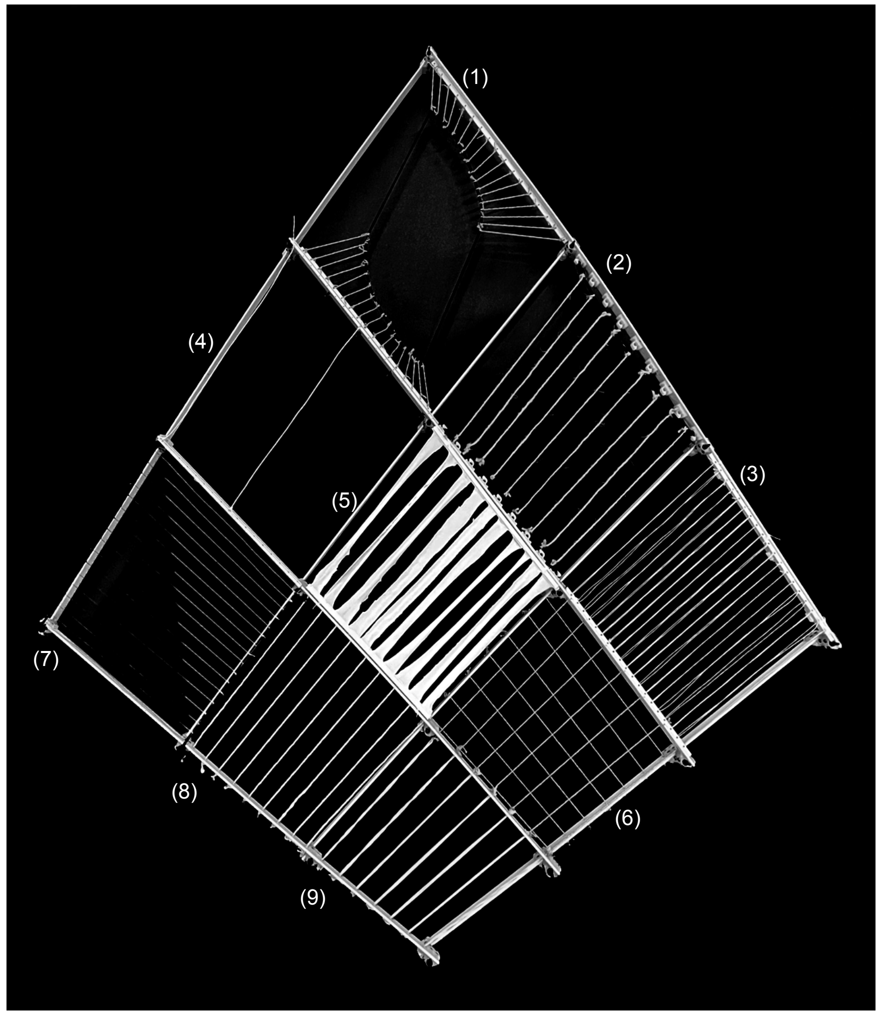


Fig. 50: Pattern / colour study on the 1:3 model cut-out

In an experimental form-finding study, numerous possibilities were tested in a 1:3 segment of the Kinetic Umbrella. The figure on the left (see Fig. 50) shows the following configurations: elastic tensioned opening (1), cables fixed with single hooks (2), cables tensioned over profile (3), cable tensioned over L-profile (4), elastic tensioned textile (5), cables tensioned in two directions (6), coloured cables (7), drilled connection (8) and stretched rubbers (9).

Design selection

The preceding list of possible parameters allows a subjective selection for the implementation of the Kinetic Umbrella. In the following, the individual parameters are presented. These were determined in an iterative design process with consideration of the geometric project-specific factors.

The orientation of the cladding system will therefore be parallel to the outer lamellae in order to make the construction more readable from the outside.

The layer for the cable system integration will be in the centre, as this hides the rear lamellae, which increases the effect of the parallel cladding system. Furthermore, the cover system does not interfere with the actuation system on the inside.

A discreet profile is preferred so that the cover system is not perceived as a new structure. Drilling or other manipulation of the lamellae will damage them and hinder the opening and closing mechanism. The profile should also be easy to install.

A flat cable is selected in order to ensure a wide-area coverage with cable. This can provide more shade. In addition, fewer cables need to be installed to achieve the same effect, which can be financially beneficial. In addition, a slight stretching of the cable is required to compensate for certain inaccuracies.

The parameterisation is done by changing the density of the cables. This again reduces the cable length and has financial and aesthetic advantages at the same time. Moreover, parameterisation with colours makes the covering system more complex and corresponds to the phenomenology of the cable, as it is very easy to dye textiles.

Subsequently, all parameters can be summarised:

- parallel to outer lamellae
- centre layer cabel system integration
- discreet profile
- flat, strechable cable
- density and colour parameterisation

This example is only one possible variation of the Kinetic Umbrella's cover system, but it is used to illustrate the whole design process from concept to fabrication. It is developed in close collaboration with Jonas Schikore, Prof. Pierluigi D'Acunto (Technical University Munich) and Prof. Eike Schling (Hong Kong University).

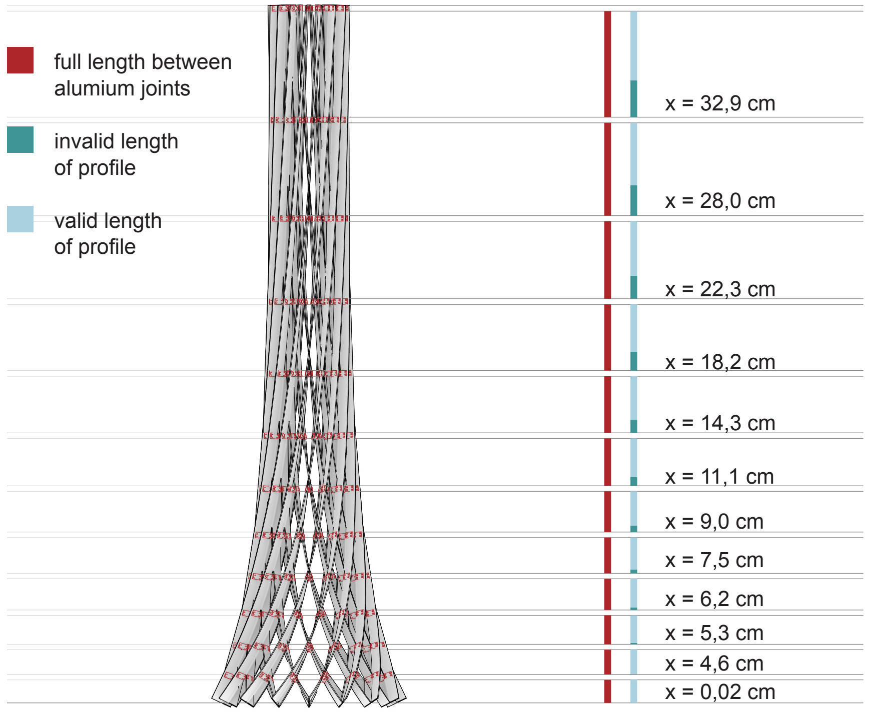


Fig. 51: Valid profile length

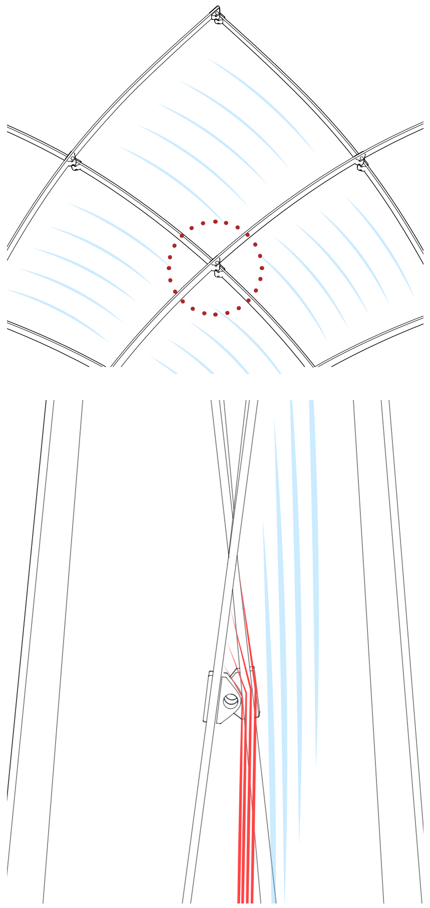


Fig. 52: Gap issue

Geometric constraints

The defined parameters lead to geometric constraints, which are described and solved in the following.

During the prototyping process of the profiles, a geometric problem occured. If the bands are evenly distributed on the existing area along the lamella, the eccentricity of the node points causes the bands to be squeezed in the peripheral area (see Fig. 52).

Figure 51 shows the resulting distances from the lamella to the profile. It can be as much as a third of the total coverage (especially in the top modules) and is therefore problematic as it results in insufficient protection from the sun.

A possible solution to this problem is to move the position of the profile away from the eccentricity and towards the position of the node points. This has the consequence that the profiles have to be mounted with distance to the lamellae, but has the freedom to mount the cables freely on the entire profile.

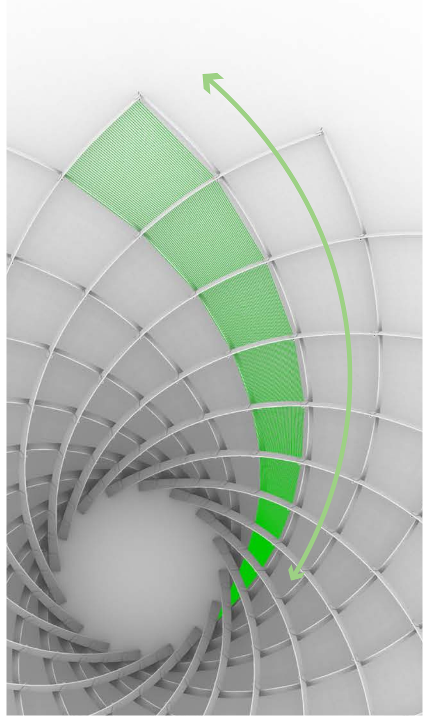


Fig. 53: Stripe-wise fixation

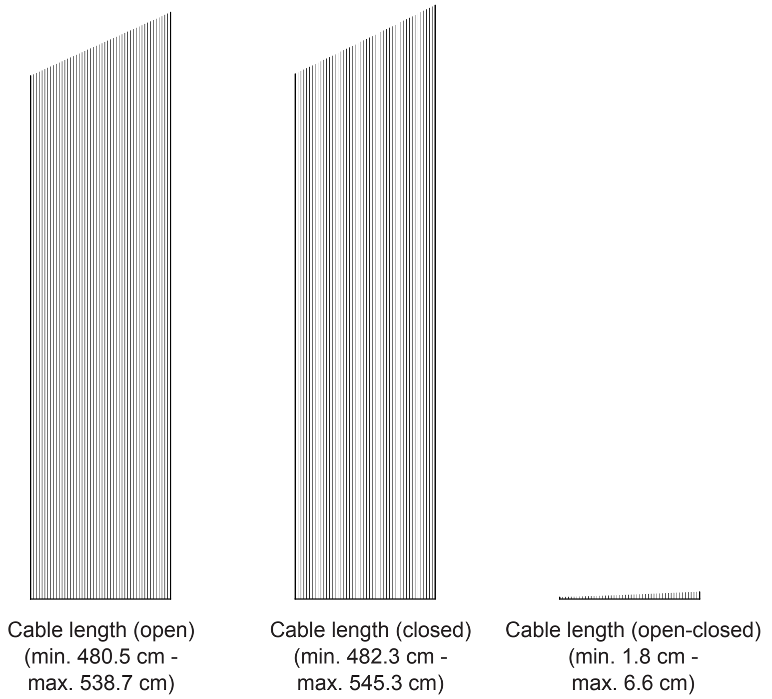


Fig. 54: Stripe-wise length comparison

Another problem is that by opening the Kinetic Umbrella structure, the length of the cables differs. Since the profiles are intended to guide the cable, the cable is not precisely parallel to the lamellae, but instead follows a polyline with a second-degree curvature and does not have a third-degree curvature like the lamellae of the structure.

As an example, one module of the Kinetic Umbrella is analysed (see Fig. 53) and the length variation is compared in relation to the opening and closing of the structure.

The analysis shows that if the rope runs parallel to the outer lamellae, it must stretch by a maximum of 6 cm in the closed position of the Kinetic Umbrella (see Fig. 54).

This is not out of proportion, but cannot be ignored. A cable with a length change of at least 1cm per metre must be found to compensate for the calculated tolerance.

This also applies to the cable direction perpendicular to the front lamellae (see Fig.55, 56).

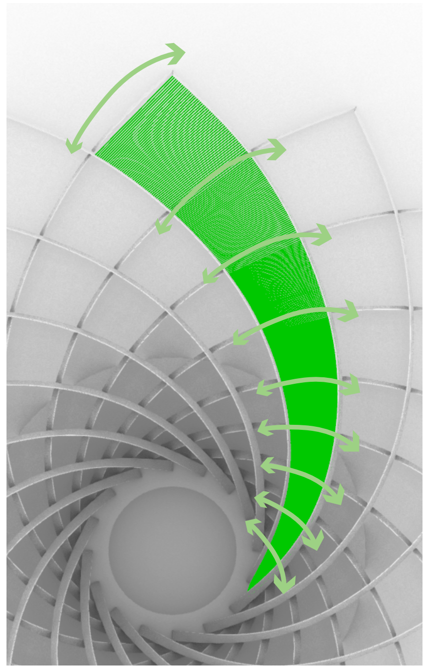


Fig. 55: Unit-wise fixation

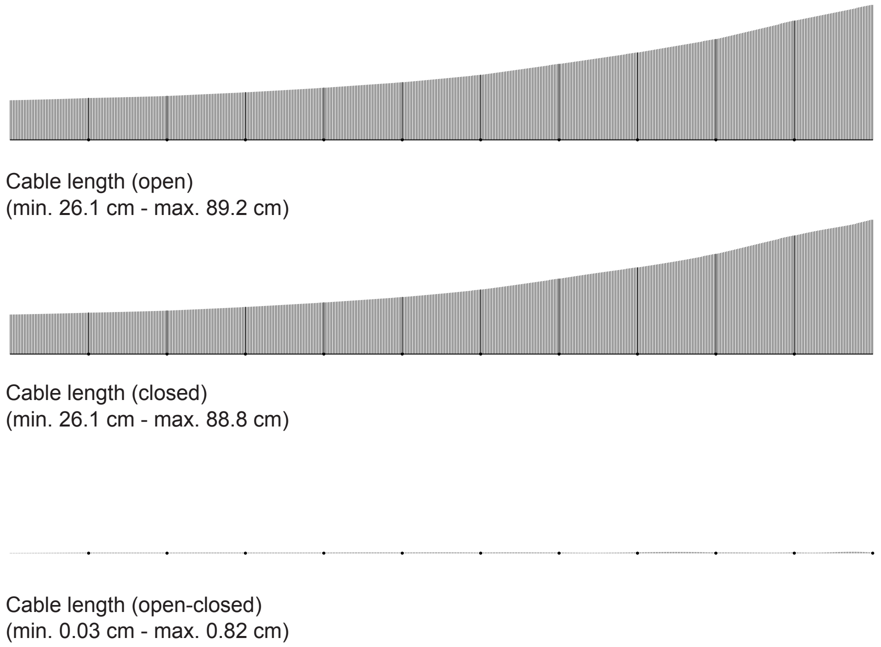


Fig. 56: Unit-wise length comparison

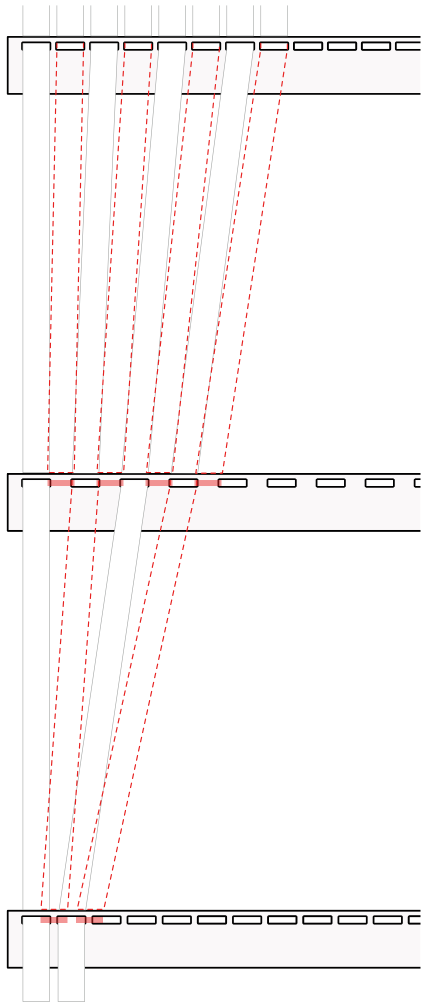


Fig. 57: Cull pattern diagram

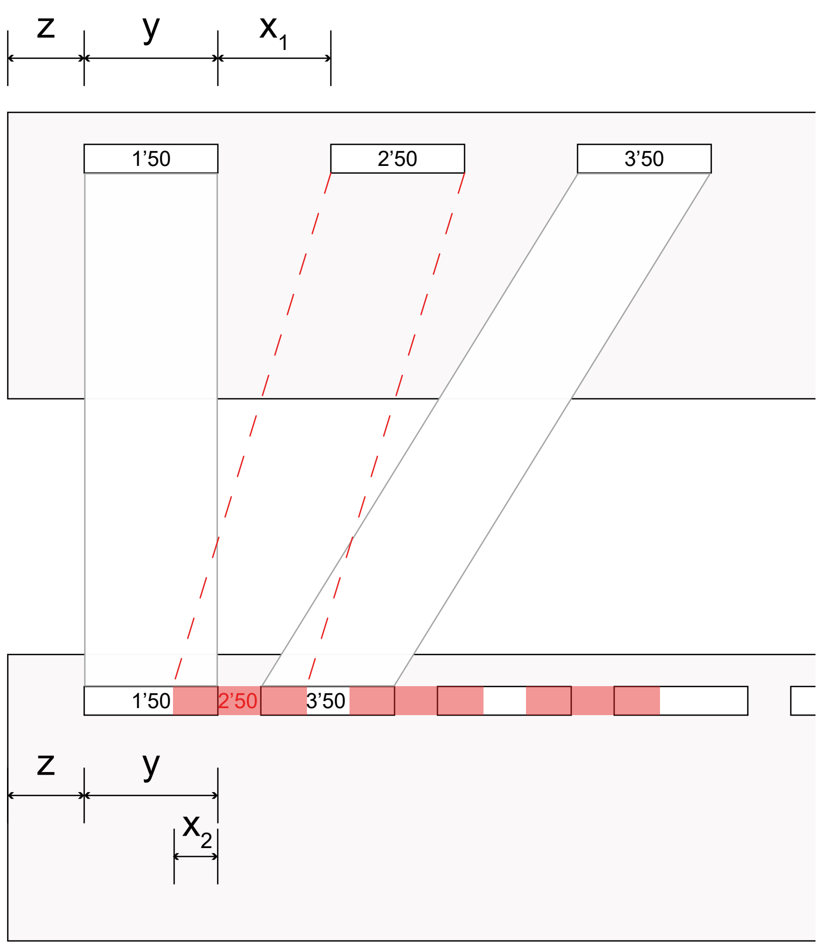


Fig. 58: Tolerance issue

When creating a parameterisation with different densities, further problems occur on the profile, which lead to additional geometric constraints.

The width of the cable always remains the same and the cables must always be evenly distributed due to the geometry of the rhombus in the transformation process when opening and closing the Kinetic Umbrella and must not run diagonally, but always have a correlation point at the corresponding position on the profile. Due to this, when the modules become smaller, the cables overlap on the profile (see Fig. 57).

Figure 58 shows how a tolerance between the profile openings can be maintained by skipping every second cable. As a result, only a cull pattern of „0-1" („delete every second cable") can be applied and cables cannot be selected randomly, as it is easier from a fabrication point of view to have cables start and end as few as possible.

The final resulting pattern is shown in figure 59.

This means that in the lower modules there is a low density, as it goes up the cables become denser, and the cover system protects more from the sun. Since the sun shines in more from above, this makes sense. This effect is ideal, as it not only makes sense, but also makes the Kinetic Umbrella aesthetically appealing.

The resulting cables of different lengths, which always alternate on the profile, can then be coloured in different shades of grey and thus complete the desired design. The design is thus a combination of aesthetic subjective choices, geometric constraints and project-specific requirements (see Fig. 59).

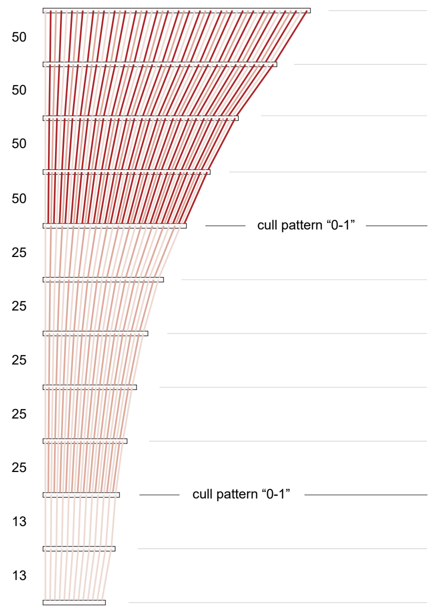


Fig. 59: Cull pattern

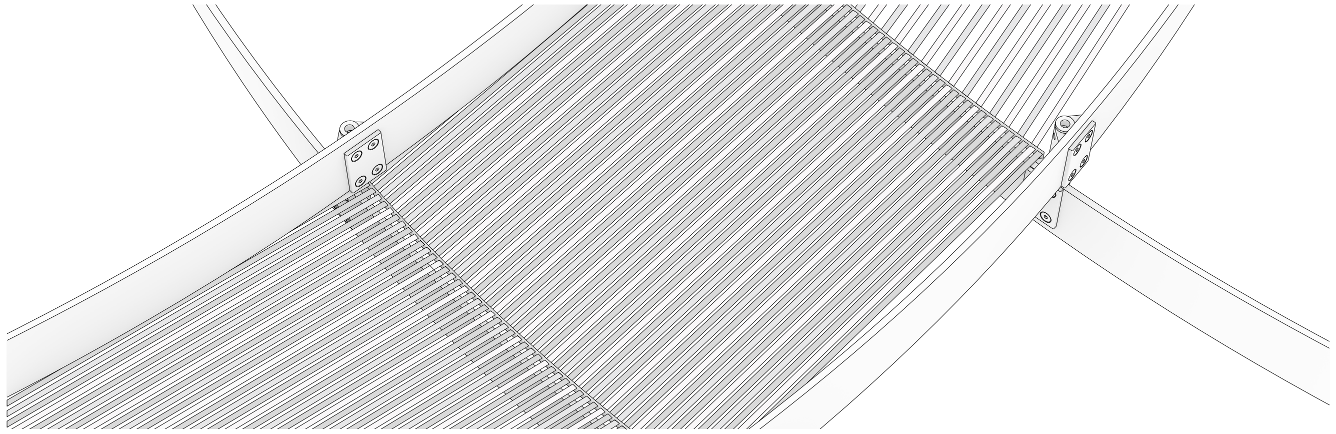
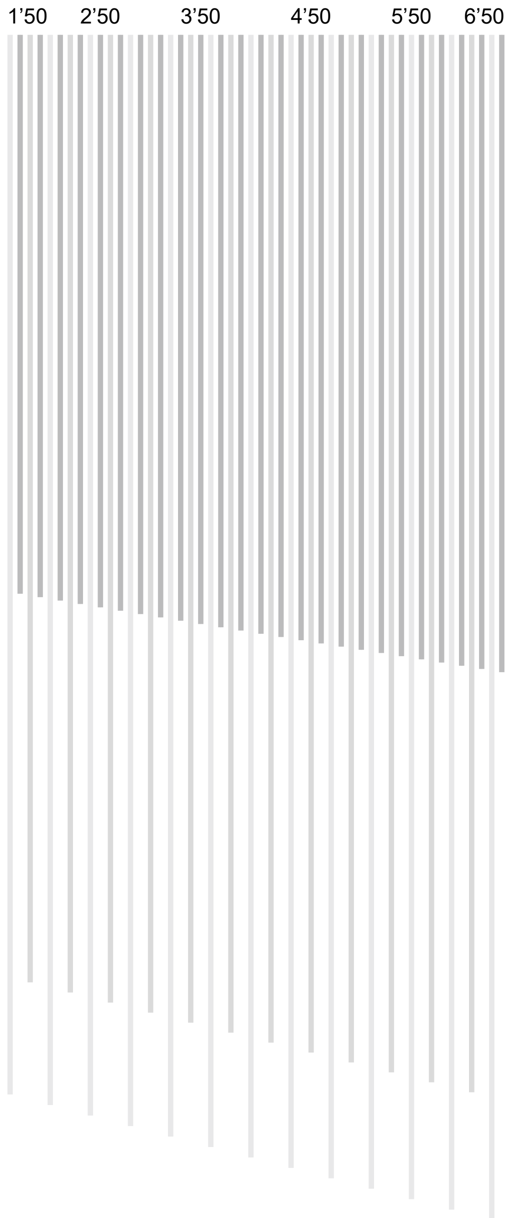


Fig. 60: Isometric view of the resulting design



light grey
1'50 = 4.80m
5'50 = 4.85m
9'50 = 4.90m
13'50 = 4.94m
17'50 = 4.99m
21'50 = 5.04m
25'50 = 5.09m
29'50 = 5.13m
33'50 = 5.18m
37'50 = 5.23m
41'50 = 5.27m
45'50 = 5.32m
49'50 = 5.37m

medium grey
3'50 = 4.29m
7'50 = 4.34m
11'50 = 4.38m
15'50 = 4.43m
19'50 = 4.47m
23'50 = 4.52m
27'50 = 4.56m
31'50 = 4.61m
35'50 = 4.65m
39'50 = 4.70m
43'50 = 4.74m
47'50 = 4.79m

dark grey
2'50 = 2.53m
4'50 = 2.54m
6'50 = 2.56m
8'50 = 2.58m
10'50 = 2.59m
12'50 = 2.61m
14'50 = 2.62m
16'50 = 2.64m
18'50 = 2.65m
20'50 = 2.67m
22'50 = 2.68m
24'50 = 2.70m
26'50 = 2.71m
28'50 = 2.73m
30'50 = 2.74m
32'50 = 2.75m
34'50 = 2.77m
36'50 = 2.78m
38'50 = 2.80m
40'50 = 2.81m
42'50 = 2.83m
44'50 = 2.84m
46'50 = 2.86m
48'50 = 2.87m
50'50 = 2.89m

total length (module): 188.61 m
total length: 3017.76 m

Fig. 61: Cable groups and the individual lengths.

Once all the constraints and parameters have been applied, a final segment of the largest module is created, as can be seen in Figure 60.

In Figure 61, an overview of the unrolled appearance of a strip of the Kinetic Umbrella is given. That will serve as a reference for the planning of the fabrication.

Transformable Cladding Systems

Fabrication

In the following, the previous theoretical solution is put into practice.

Profile

The profile, which contains all the geometric constraints, will now be designed in such a way that it is easy to manufacture, cost-effective and easy to mount.

In a first step, different cut-outs are compared in a physical mock-up, which are lasered out of plastic (see Fig. 62).

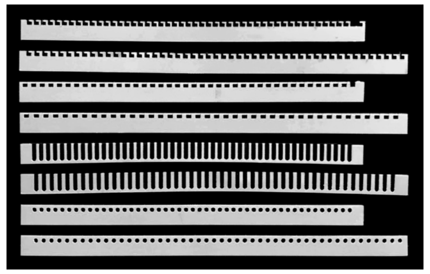


Fig. 62: Laser-cut test profiles

An instability was detected when testing the lasered profiles. The expected flexibility of the profiles was too intense. In addition, fragile cut-outs can break off very easily.
In a next attempt, profiles were milled out of aluminium (see Fig. 63). This requires digital fabrication, as the geometry must be highly precise (see Fig. 64). These profiles are also 1 mm thick, as this allows the desired flexibility. In addition, the cut-out with a rectangular cross-section is the most robust, although it requires the cable to be threaded.

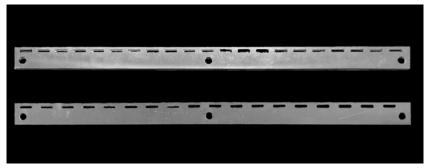


Fig. 63: Milled test profiles

Fig. 64: Milling process

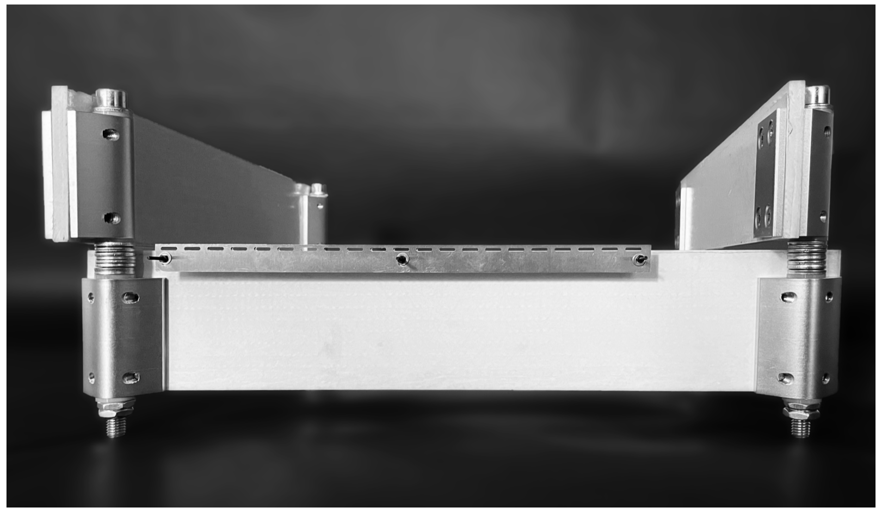


Fig. 65: Elevation of 1:1 model cut-out

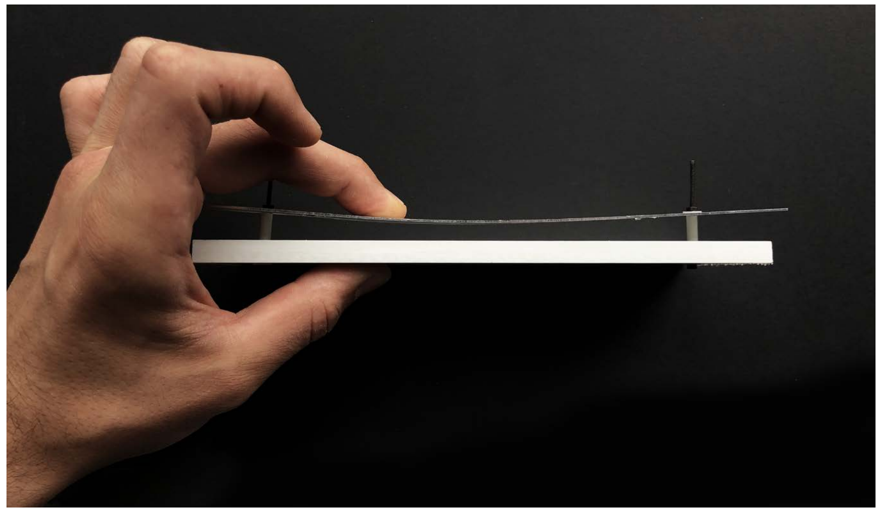


Fig. 66: Profile test model

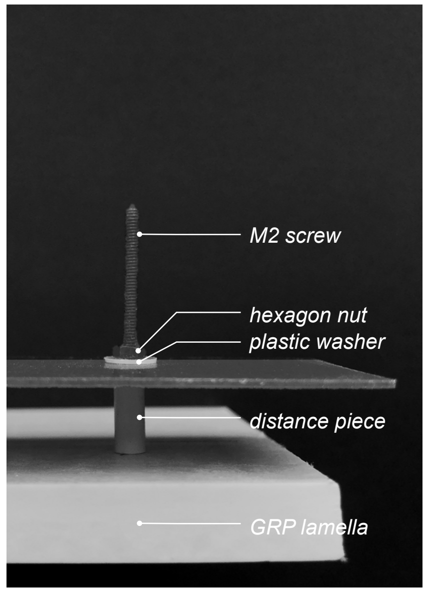


Fig. 67: Mounting detail of profile

The profile corresponds to the ideas and is tested on a 1:1 cut-out of the Kinetic Umbrella (see Fig. 65). With the help of distance pieces and M2 screws, the profiles are offset to the lamellae so that they are no longer eccentric (see Fig. 67).

Since the cover system experiences a certain tolerance due to both the mechanism of opening and closing the Kinetic Umbrella and due to construction inaccuracies, it is important that the profiles can be bent under load. This was tested in a small mock-up with the size of the smallest module, as this is the most difficult to deform (see Fig. 66).

Cable

As discovered in the design section, the cable has some aesthetic and geometric specifications.

Project-specific requirements are high UV protection and weather resistance, as the Kinetic Umbrella will be exhibited outdoors for an indefinite period of time. Material research has shown that polypropylene (PP) and polyethylene (PE) are very common in such an application. Natural materials are not as efficient in this regard.

Since a very large quantity of 3200 metres (includes a surcharge for cutting) is needed, the cable should be cost-effective.

In order to be able to save more material and at the same time provide more protection from the sun, a wider cable is preferred. It also requires a pre-calculated elasticity of at least 1cm per 100cm to allow elongation of the cable when opening and closing the Kinetic Umbrella and to prevent too much stress to the cable system.

First, commercially available cables were compared and benchmarked in Figure 69.

An evaluation of the results showed that none of the cables met all the necessary requirements. Most favoured was the „plus 400" baler twine from AGRI, but it was eliminated because it did not meet the desired aesthetics (see Fig. 68).

The „Umreifungsband" from Umreifung-24 is too rigid and cannot be steered as desired.

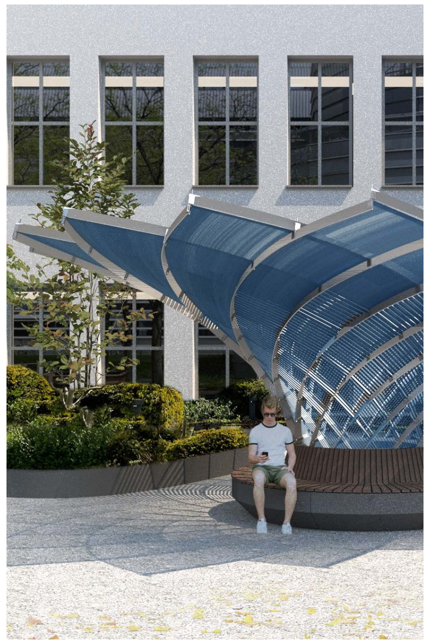


Fig. 68: Colour test

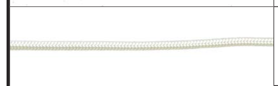
Image	Name	Price	Material	Diameter / Width	Property
	**Gummiseil** *STABILIT*	1,85 €/m	rubber, PES	6 mm	highly elastic, UV+
	**PP-Seil** *STABILIT*	0,80 €/m	PP, multifil	6 mm	non-elastic, UV++
	**PP-Seil** *STABILIT*	0,90 €/m	PP, multifil	15 mm	non-elastic, 45daN, UV+++
	**Stahlraht-Seil, verzinkt** *STABILIT*	0,80 €/m	zinc, steel	2 mm	non-elastic, 45daN, UV+++
	**Starterleine** *STABILIT*	0,60 €/m	PA	3 mm	non-elastic, 28daN, UV+++
	**Reepschnur** *STABILIT*	0,65 €/m	PP, multifil	3 mm	non-elastic, 19daN, UV++
	**Stahlraht-Seil, PVC** *STABILIT*	0,99 €/m	zinc, steel, PVC	2-3 mm	non-elastic, 45daN, UV+++
	**Polyester 8** *ROBLIN*	0,59 €/m	PE	4 mm	non-elastic, 310daN, UV+
	**Orion 500** *ROBLIN*	1,39 €/m	PE	6 mm	non-elastic, 800daN, UV+
	**plus 400** *AGRI*	0.01 €/m	PP	4 mm	non-elastic, 400daN,UV+
	**Umreifungsband** *Umreifung-24*	0.03 €/m	PE	7 mm	non-elastic, 350daN, UV+

Fig. 69: Cable overview

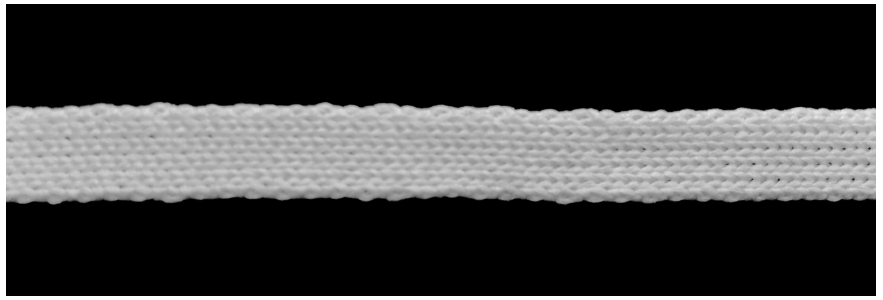


Fig. 70: Cable close-up view

In close cooperation with manufacturers from the textile industry, the next step is to customise a cable to meet all requirements. The Bavarian company Gepotex has offered to participate in the development of the cable. This resulted in a custom-made woven cable with the desired width of 7mm and UV and weather resistance (see Fig. 70).

Fig. 71: Elasticity test

The cable is woven from the material Diolen. It is characterised by its high tensile strength and its resistance to oxygen, light and high temperatures. It was woven in a special process so that it has the required elasticity. In an experiment, a 50 cm long piece could be stretched 59 cm with a force of 11.3N (see Fig. 71). When released, the cabel returns to its original state.

Afterwards the cable was tested on the 1:1 model in combination with the previously milled aluminium profiles (see Fig. 72). A metal clamper was used to fix the cables. The advantage of this is that it can be installed quickly and is stable at the same time.

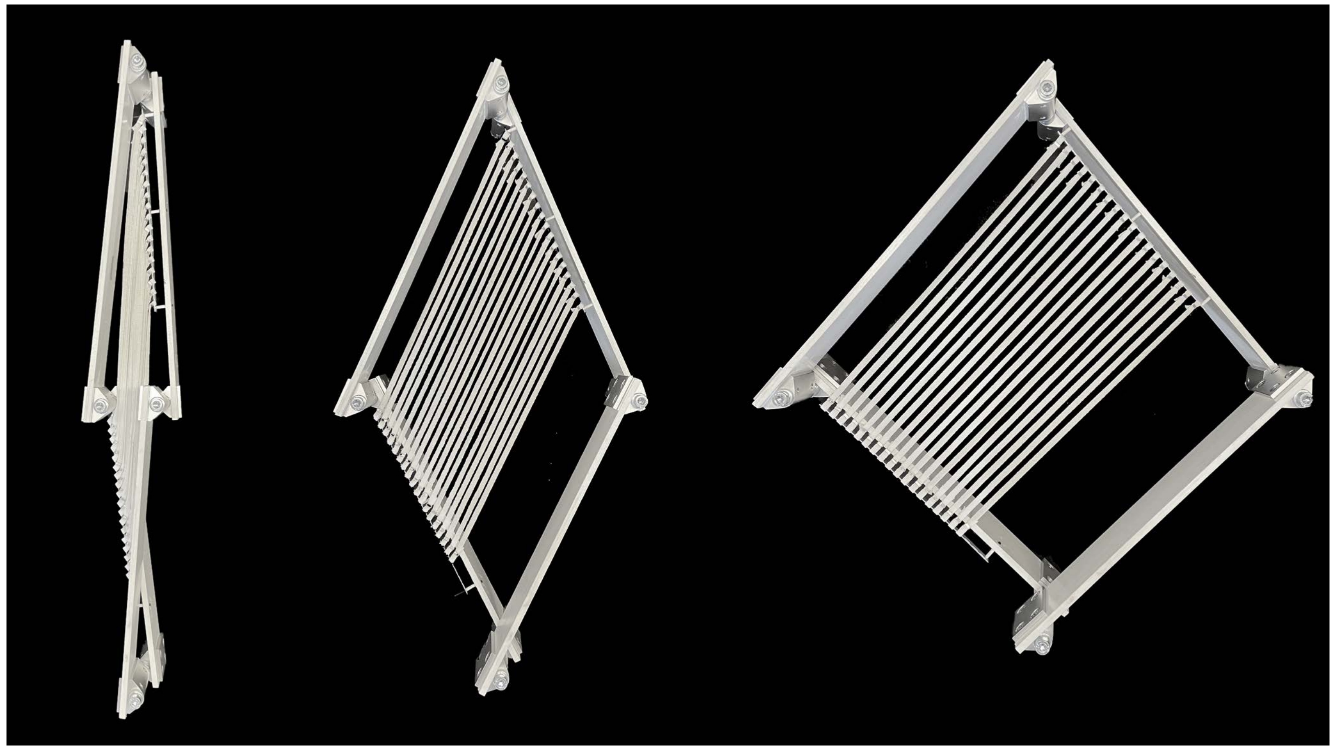


Fig. 72: Form change of 1:1 model cut-out

Parametrisation

The final step of the fabrication is colour parameterisation. Each cable was dyed using the previously created pattern (see Fig. 61).

Half of the cables are coloured with dark grey, a quarter with light grey and the rest remains white. The individual cables can be cut to the correct length in advance and then bathed in dye. The colour must also guarantee weather and sun protection.

A colour prototype study is made on the same 1:1 module as in figure 72 to test the overall appearance (see Fig. 73).

The play of colours during the day creates a homogeneous colour gradient across the structure of the Kinetic Umbrella, thanks to the parameterisation. It is not just this that makes the project aesthetically outstanding, but also the fact that in the dark, the Kinetic Umbrella stands out by its varied use of light. While the white cables reflect more light, the darker ones reflect less. In this way, the homogeneous, parameterised colour gradient can also be perceived in the dark. An art installation by Jeongmoon Choi can serve as a reference for this (see Fig. 74).

Fig. 73: Colourisation on the 1:1 model cut-out

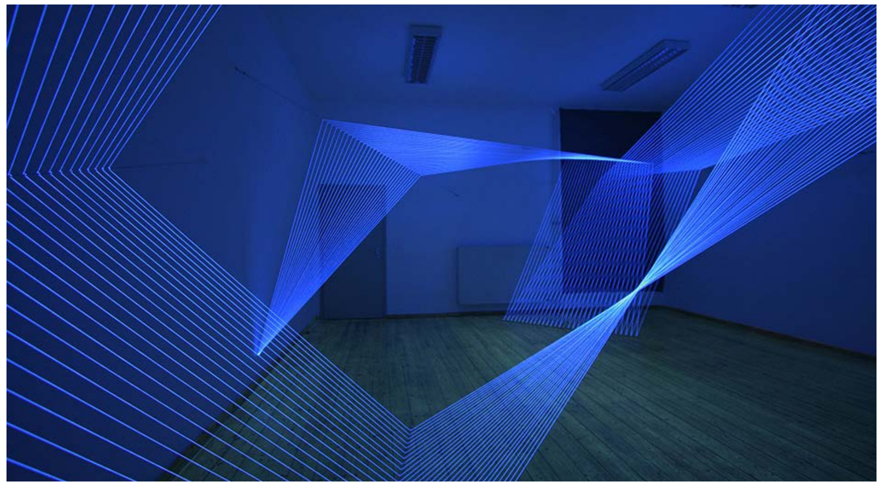


Fig. 74: LINESCAPE by Jeongmoon Choi

Insights

Potentials

The resulting cladding system for transformable structures, using the example of the Kinetic Umbrella, can be universally seen as a cladding system for transformable structures, as it can be applied in a variety of configurations.

Due to its linearity, the flexible cable system is particularly suitable in combinations with grid structures, as they can emphasise their structure in this way. In the case of the Kinetic Umbrella, it also corresponds to the design language of the actuation system.

The simplicity of the manufacturing process and the easy installation in particular should give architects and clients confidence for transformable structures. The transformable cladding system turns the Kinetic Umbrella into an architectural structure that offers solar protection and invites visitors to linger beneath it.

Weaknesses

One weakness of the transformable cladding system is that it only protects against the sun and not against rain. However, this was explicitly taken into account.

It should also be mentioned that transformable structures result in numerous geometric constraints due to their complex geometry. However, this is also an advantage for the planner, as they can utilise them to their advantage in the planning process.

Furthermore, it must be mentioned that due to the small-scale nature of the designed concept, vandalism is very likely to occur.

In conclusion, however, it can be said that the advantages clearly outweigh the disadvantages.

Application

Since the construction of the Kinetic Umbrella is still in the planning stage and has not yet begun when this paper is published, the application is shown on a 1:3 model.

However, all individual steps have been tested on the 1:1 module and the construction can begin.

As can be seen in figure 75, 76, 77 and 78, the cladding system complements the Kinetic Umbrella very well and completes its overall appearance.

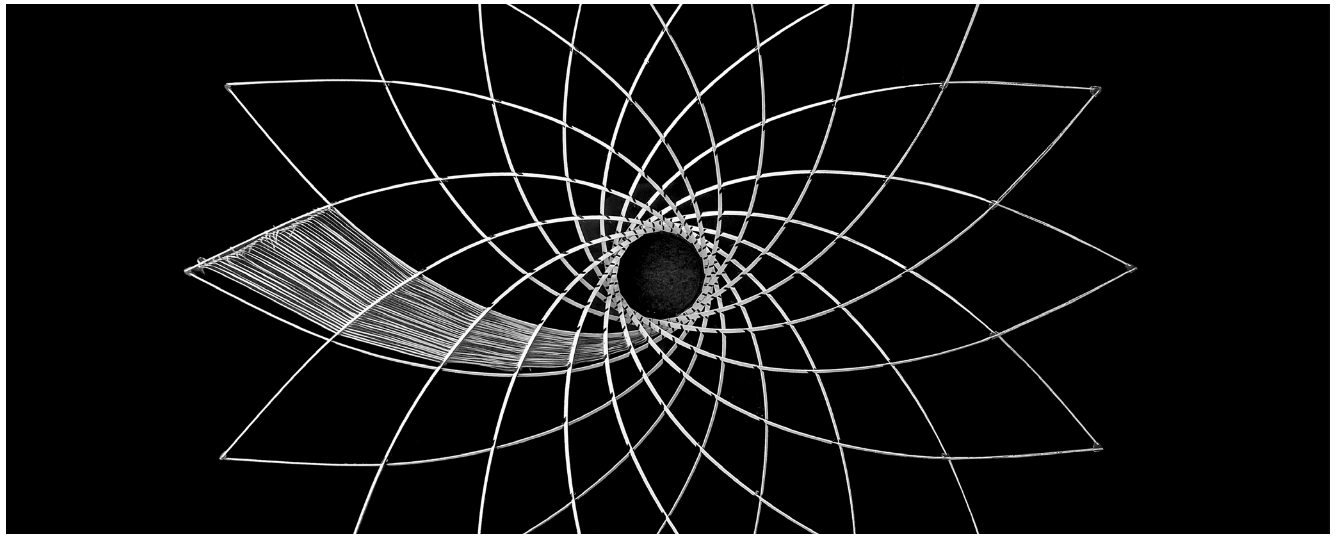


Fig. 75: Top view 1:3 model, open

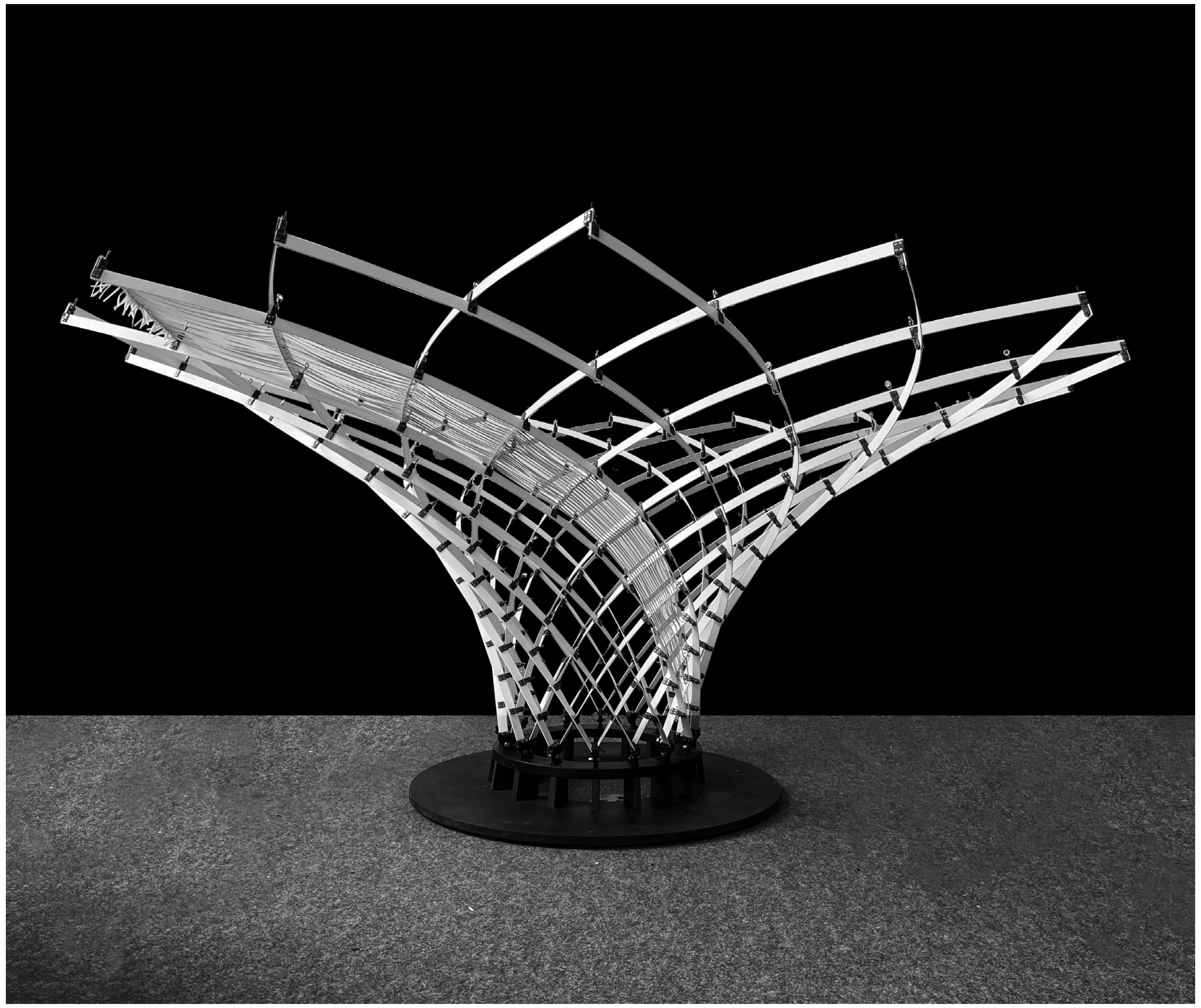


Fig. 76: Front view 1:3 model, open

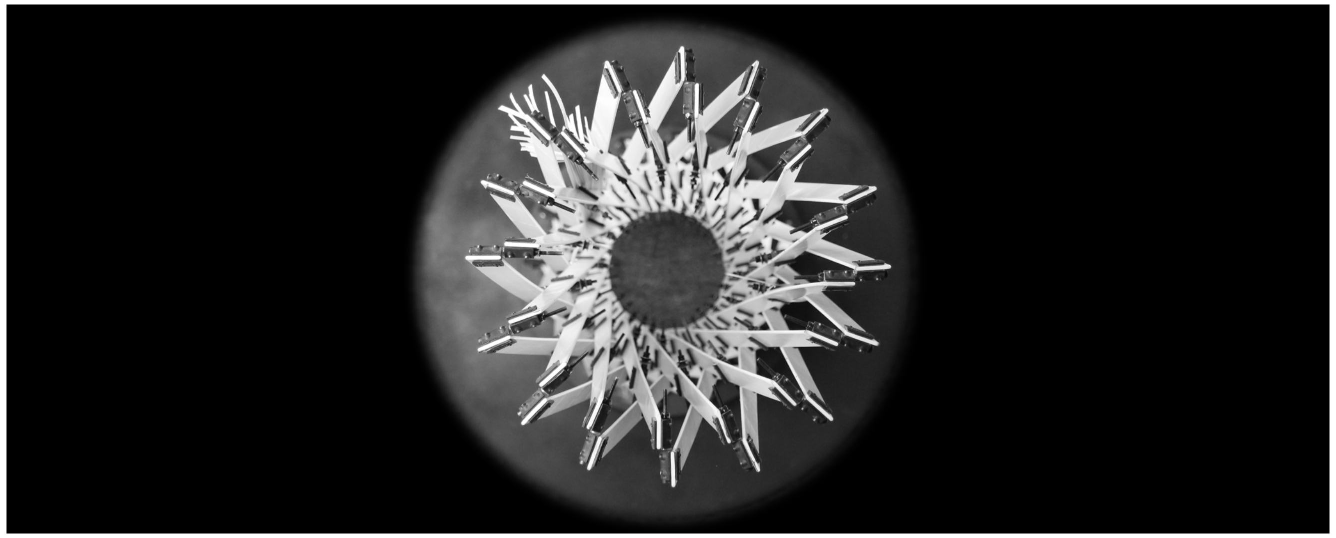


Fig. 77: Top view 1:3 model, closed

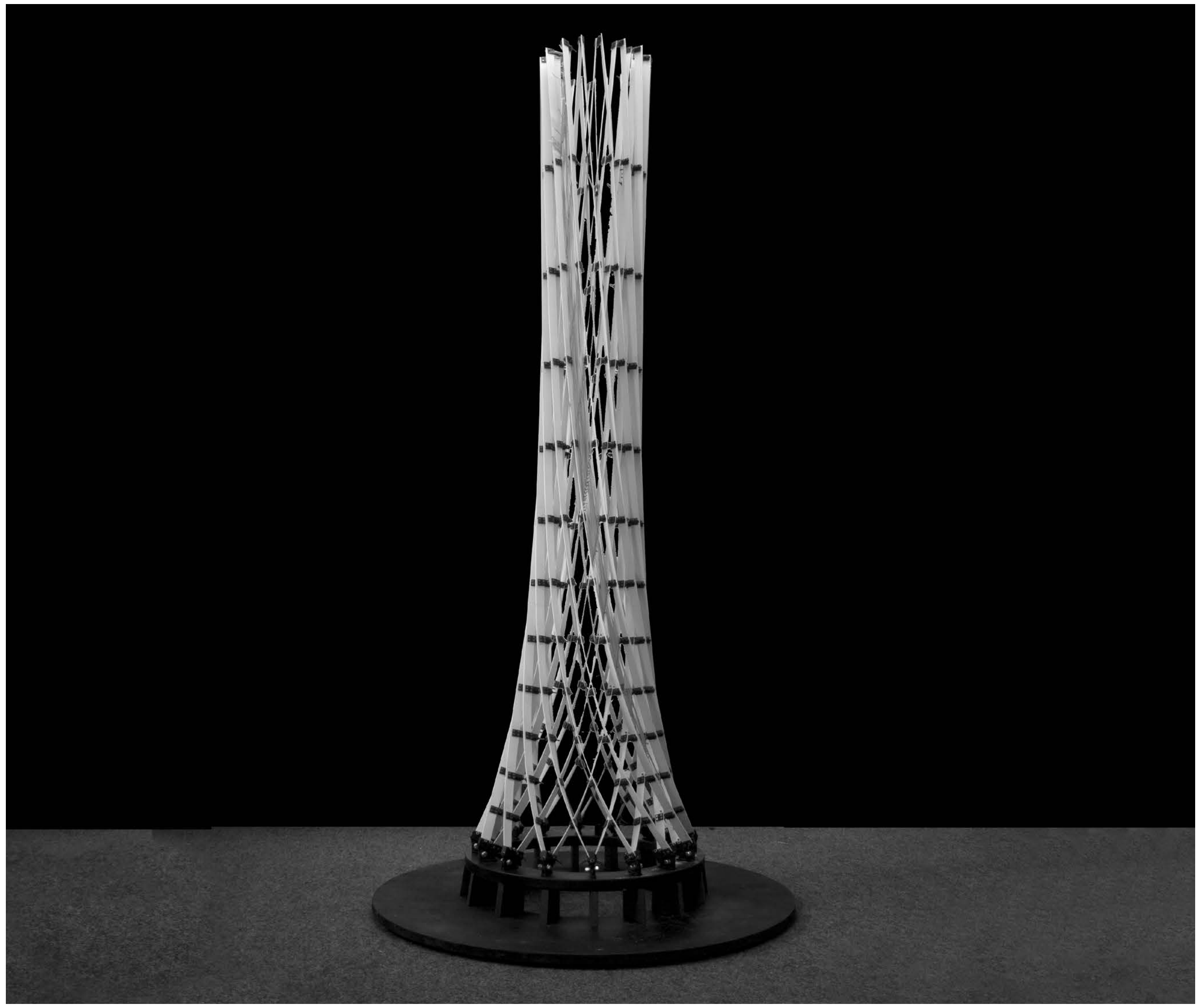


Fig. 78: Front view 1:3 model, closed

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Acknowledgement

We would like to say a big thank you to Jonas Schikore for making this work possible as part of his dissertation and for his constant support throughout the semester. We really appreciate this unique mentoring and had tremendous joy developing and realising the project.

Many thanks also go to Prof. Eike Schling (University of Hong Kong) and Prof. Pierluigi D'Acunto (Technical University Munich), who were always available for us and helped us a lot with valuable feedback and professional input.

Furthermore, we would like to thank the company Gepotex for their competent consultation in the field of textiles and their generous sponsoring, which made the realisation of the work possible.

Many thanks also go to the workshop of the Faculty of Architecture of the Technical University Munich, who advised us at all times with their technical know-how.

Transformable Cladding Systems

This thesis is about the cladding systems of transformable structrues, and is divided into three parts.

The first part gives comprehensive background information to understand the current relevance of the work and its context.

In the second part (design), numerous studies on different systems of cladding are explored. In particular, systems are designed based on the Kinetic Umbrella, a research project of the Technical Universty Munich, Germany. Using an architectural iterative design process, geometric constraints and project specific factors, a cladding system is designed.

In the third part, the fabrication, a detailed design of the cladding system is carried out in order to be able to realise it with the help of digital fabrication.

Following this, the potentials and weaknesses of this design with regard to transformable cladding systems are assessed and an analysis will be created by constructing a 1:3 model of the Kinetic Umbrella.