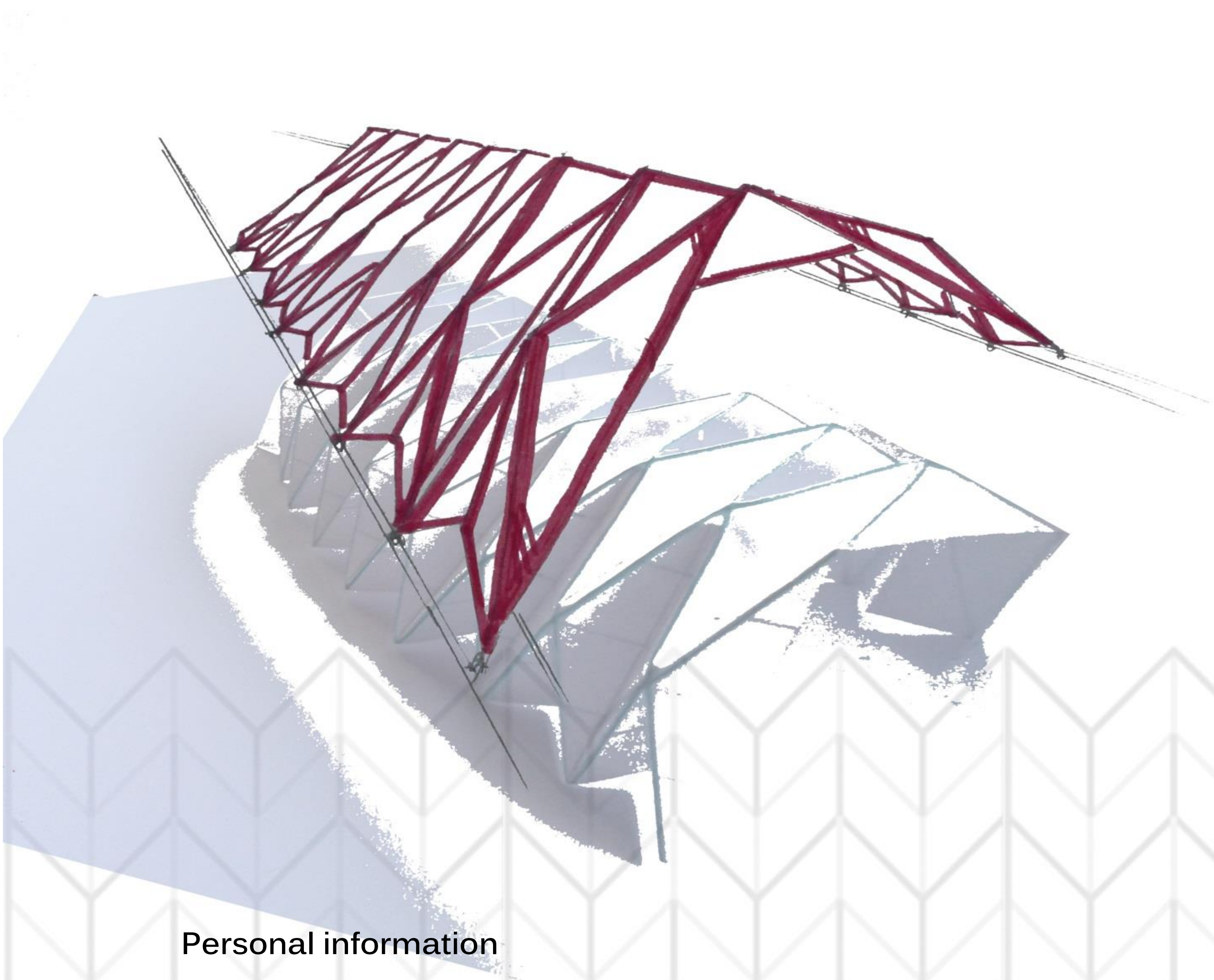
Folded Glass Plate Structure: deployable cover

Graduation plan - Alkistis Krousti 4420705



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Graduation project title: Folded glass plate structure: Retractable cover

Background

Folded plates as a way of increasing stiffness in large-span structures have been around since the 1950s, when it was quite extensively applied in concrete roofs. For a very long time this type of construction has been realized in practice only in of reinforced concrete and made on site, which conditioned the use of a very complicated shell. Development of prefabricated building led to improvements of this type of construction so that the folded structures could be derived by the making of prefabricated elements and their assembly on site. Since then, folded plate structures have reappeared in the engineering and architectural scene the past fifteen years, as new materials have been considered, especially fiber-reinforced plastics and glue laminated timber. A great inspiration was drawn from Japanese origami structures, which provide a good topological background for the evolution of developable and foldable surfaces. Recently, a lot of emphasis has been put on the potential of folding as a transformable mechanism, leading to kinetic structures. In recent studies, a lot of different crease patterns, dimensions and mechanisms have been tried as far as the geometry constants are concerned, and as a result, different transformation concepts were developed, on directional rails, linear, or radial, one or two directional, on a planar or a spatial configuration. Of course the additional challenge was the third dimension of engineering applications, as opposed to the ideal zero thickness origami surfaces. Extensive research has been done in this direction, especially from Tomohiro Tachi, to tackle the obstacles introduced with panel thickness, without, however any structural verification.

Why glass?

There has been an increased interest in structural glass including its application in high-end projects and extended research on its potentials and restrictions. In this respect, there has recently been an interest in the use of glass on plate structures, and especially on shells, mainly for architectural reasons. A common problem of folded spatial structures usually is natural light, as openings compromise the structural integrity of the structure. Glass can efficiently address this problem, as it provides for full transparency, while still applicable as a load bearing material, unlike other alternatives as ETFE foils, which require a full supportive structural system.

Using structural glass in a folded plate configuration allowing for full transparency combined with a stable three dimensional structural system is a very interesting contemporary topic with extended architectural applications.

Problem statement

While the benefits of folding in light-weight structure are certain, as stiffness is considerably increased, folding patterns and joint types are still under research as built examples in new materials have been restricted to a scale of a pavilion. However, despite the original concept of folding as a means of improving structural behavior, few steps have been made in this direction, especially when it comes to kinetic structures. It appears that different approaches have been used so far, facing folding either as a technique of enhancing structural performance and increasing the spans, or as a method of deployment. As a result, the different potentials of a folding geometry in structures have not been holistically addressed, and thus not full advantage has been taken on the spatial and structural benefits of folding.

Challenge

Given the complexity of folding geometries as far as form and structure are concerned, making use of the capacity to resist external loads by form, in combination with a transformable mechanical system still remains a challenge for architectural applications. It needs to be noted that the structural and kinematic are in reality two conflicting aspects of folding structures, as the degree of freedom between implied by the necessity to deploy, drastically reduces the load-bearing capacity of the structure. Especially as far as glass folded plate structures are concerned the increased material weight further adds to the complexity.

Research question

The objective of this research by design project is set to produce a kinetic system in combination to a folded glass plate structure in the purpose of fully or partially opening up an enclosed space.

Sub-questions:

- To experiment on different folding systems and produce a comparative research of their geometric and structural potentials and restrictions.
- To design and calculate an optimized frameless glass folded plate structure with the ability to fully or partially deploy and demonstrate on a mock-up under scale.
- To develop an innovative hinged connection using PURE composite[1] (http://www.ditweaving.com/) which meets the deployment requirements of the final structure and evaluate its performance through a series of tests.
- To further explore the extent to which such a system would be feasible without resulting in cost, material use or mechanical complexity excesses.

Case study

In the scope of this research by design project, the final architectural product will be developed for the specific needs of covering in an adjustable way the area of a small outdoor swimming pool of dimensions 21m width x 50m length. The proposal needs to address the need for high

[1] More information on the material in the website: http://www.ditweaving.com

architectural quality in order for the space to be used as a sport and leisure facility with natural light, for retractability of the whole or part of the structure for both functional and climate purposes, during summer season, turning the pool from closed to outdoor and for a large span without supplementary support mechanism. A design proposal like this would be suggesting an easily adjustable generic system for sport facilities of small dimensions.

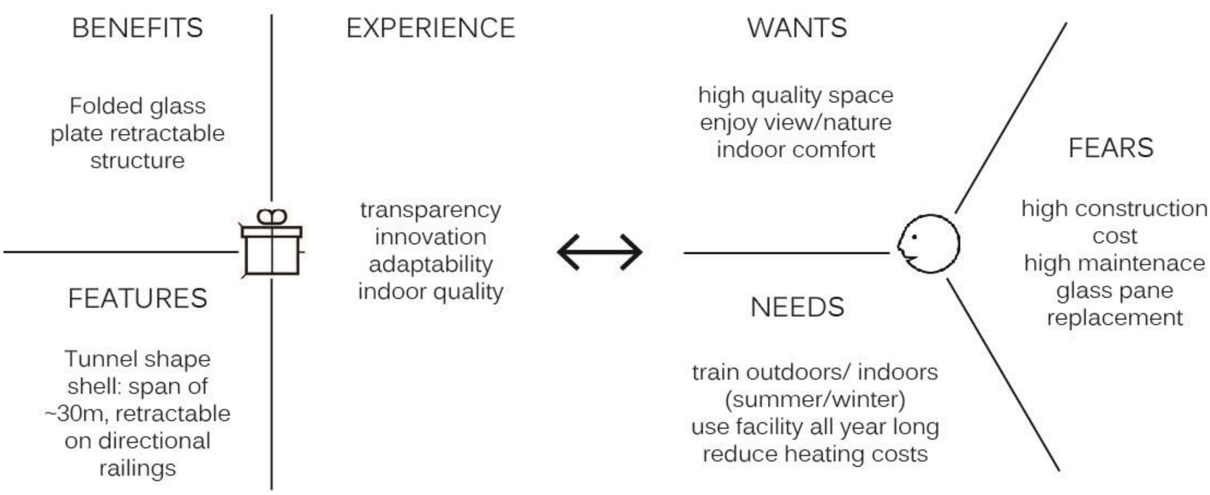
Focus and research boundaries

The focus of this research is primarily set on the architectural form deriving from structural optimization on folded glass plate geometries, and the detailing of deployment mechanisms and plate connections, according to the outcome of the research.

Aspects concerning thermal comfort and resulting micro-climate, such as solar control, heat losses and acoustics on the roof as a building envelop element will not be addressed during this project. Although building physics matters are of great importance especially in the case of structural glass, these are considered solvable by further study on the glazing elements themselves and additional mechanical equipment.

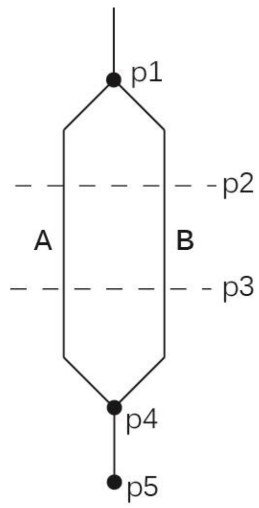
Relevance

Validation of the proposed architectural product is elaborated through the method of value proposition canvas, forming part of Business model canvas, which is a contemporary strategic product management tool[2].



[2] The Value Proposition Canvas, forming part of the Business Model Canvas (BMC) is a strategic management tool proposed by Alexander Osterwalde in 2004. It is first elaborated in his thesis book "*The business model ontology: A proposition in a design science approach*", for the University of Lausanne.

Research methodology



This project will follow a research by design methodology based on experimental testing and form-finding optimized for structural performance.

1. **Initial phase:**

First, a specific architectural scenario has been chosen, so that the spacial and functional specifications for the structure are given. On the given scenario, different types of folding plate shell structures will be developed based on existing origami geometries. Through literature study, fundamental design decisions have been taken, essentially the ones mentioned under “Case studies’”.

2. **Elaboration phase:**

During this phase, two parallel research routes will be followed:

- One on the form-finding of the folded plate structure, based on its structural analysis , and
- One on the hinge detail development and testing, using PURE composite.

A. Form-finding on the structure:

- Through literature study and physical scaled paper models, geometry of folded and deployable shapes, their potentials, challenges and structural properties are defined and compared. The product of this process will be a comparative table of patterns and geometries, which will help the design decision.
- One folded geometry will be selected and proceeded further with. Starting from a very simplified one-fold model First, physical models on paper and thick materials will be made for better understanding of the properties. Then, a first FEM analysis will be performed to draw some first conclusions, Then, a parametric model will be set and the design solution will be gradually elaborated by adding parameters, which will eventually result in the optimization process.
- A finite element analysis will be run on the geometry, with the goal of optimizing the curvature of the desired structure surface and the folding pattern size, based on structural performance, for the specified span. For the structural analysis, different stages of deployment need to be taken into account, given the kinetic aspect of the project.

B. Hinge connection detail:

- “Bend and Break”: In the course of this Minor in Civil Engineering, three different glass pane connection types have been tested in the laboratory for tension, compression, in plane shear stress and out of plane bending, as well as prototypes of different folded plate glass shells. The results of those tests will be further used as reference.
- Forces and moments which the connection between panels of the final structure will undergo need to be specified in advance, to provide a reference point for all laboratory tests. This will result from a preliminary FEM analysis on a series of folded geometries for

the specific span, in combination with data from past studies on structural glass connections.

- During the development of the connection detail, research will be focused around the PURE composite sheet, and tests will be performed on the material itself, as some property values are unknown and as part of one or more proposed connection components.

  Tests on the material itself include:
  1. Shear strength
  2. Fatigue
  3. Creep

  Tests on the connection principle(s):
  1. Buckling under compression
  2. Shear strength in plane (around holes)
  3. Shear strength out of plane
  4. Peel (glass on glass glue)

3. Finalization:

- The connection principle, as developed in stage B, will be embedded to the final design and a general check will be performed for any unpredicted conflicting aspects.
- The final model of the structure will be defined and finite element analysis will be performed on:
  1. the final structure for different phases of deployment
  2. Individual glass plates
  3. Connection elements

  Feedback from the analysis will be taken into account to improve the final design on a dimensioning and detailed level.
- If feasible within the time limit, a scaled physical model of the final design, with the specified connection type will be fabricated, demonstrating the deployment of the structure and the material properties.
- Last updates will be made on the final design and presentation and report material will be produced, including architectural and detailed drawings, FEM calculations and visualizations.

Research tools

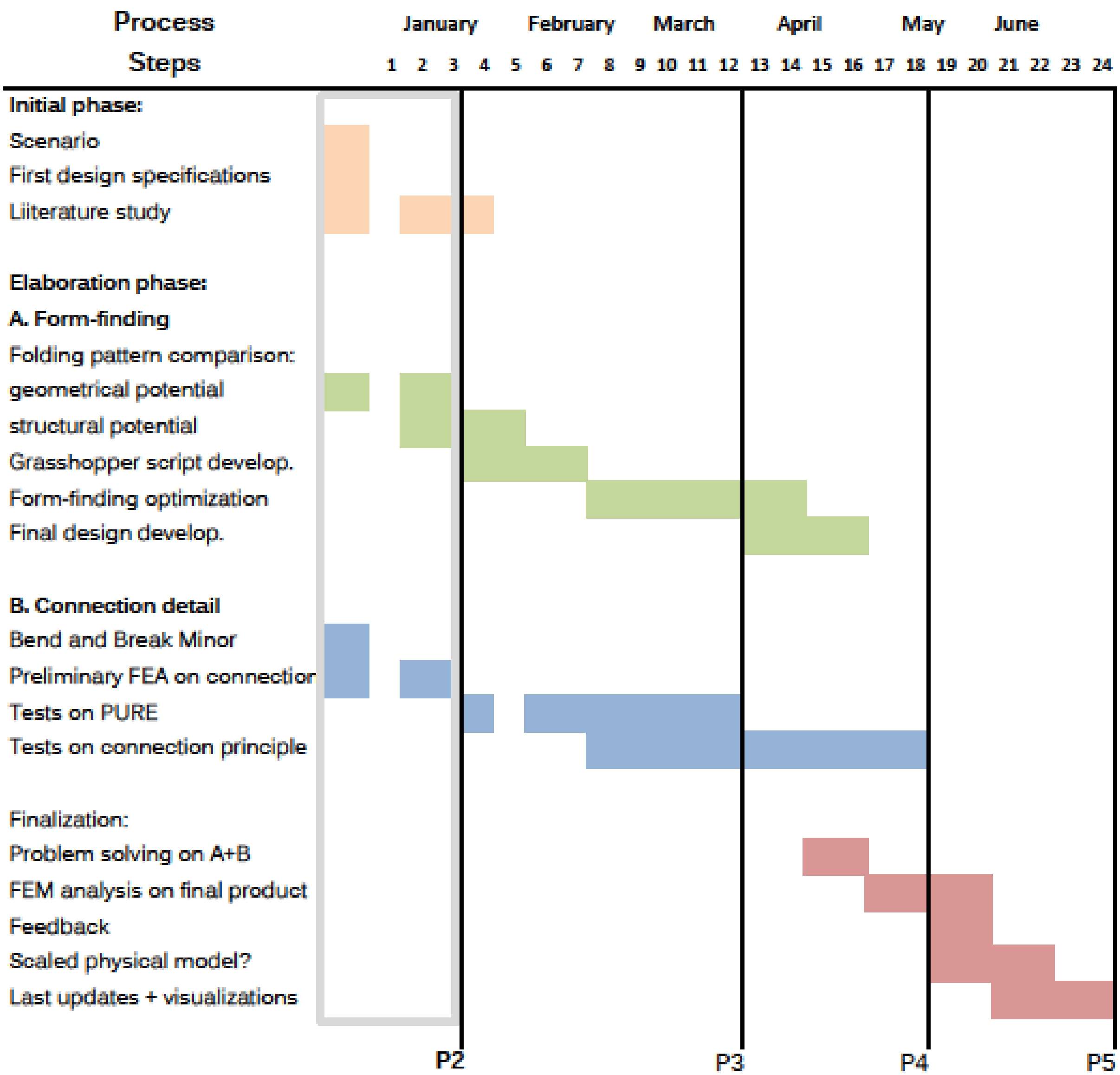
In the course of the project both digital and physical tools will be used parallel or in turns.

Phase A (form finding): In the beginning, first folding ideas will be developed on paper model, followed by 3D digital models in Rhinoceros to be output for structural analysis as dfx. Draft finite element analysis for comparison purposes will be done in TNO Diana, while the main model will be developed in Grasshopper, including its complex geometry and deployment steps, parallel to

Karamba plug-in for simultaneous structural analysis feedback. Given the degree of freedom of the hinged structure, additional structural analysis tools need to be explored for accurate results.

Form-finding might be enhanced at the final steps with some optimization engine, such as Galapagos or Octapus, on very specific parameters. Further tools for simulation of kinetic structures and folding patterns might require some further looking into either using mathematic definitions, such as Matlab, Mathematica-Tesselletica, or more elaborate CAD tools, such as Catia.

Phase B (connection principle): First draft calculations on the connection principles, with different element sizes and configurations will be simulated in Karamba and TNO Diana, previous to physical testing. As soon as some conclusions can be drawn and some configurations chosen, specimen testing will take place in the 3ME campus building laboratory. Fatigue, creep, pull out tests, and possibly a speckle test will be held.



References

On structural glass:

Jan Wurm, *Glass Structures: Design and construction of self-supporting skins*, 2007, Birkhauser

Ulrich Knaack, Tillmann Klein, *Special issue: Glass*, Journal of façade design and engineering, Volume 2, 2014

On folded structures:

Tomohiro Tachi: *Rigid-Foldable Thick Origami*, as found in the website of Origami Lab-Tachi Lab, http://origami.c.u-tokyo.ac.jp

Pierluigi D'Accunto, Juan Jose Castellon: *Folding Augmented: A design method to integrate structural folding in architecture*, 2015, pre-publication

H.Kobayashi, B.Kresling, J.F.V.Vincent, *The geometry of unfolding tree leaves*, The Royal Society 1998

Nenad Šekularac, Jelena Ivanović Šekularac, Jasna Čikić Tovarović, *Folded structures in modern architecture*, 2011, University of Belgrade, Faculty of Architecture, Serbia

Robert J.Lang, www.Langorigami.com

Wolfram Demonstrations Project

On folded glass plate structures:

Anne Bagger: *Shell plate structures of glass, studies leading to guidelines for structural design,* 2010, DTU Civil engineering report R-221 (UK)

Stefan Trometer, Mathias Krupna, *Renaissance of paper models and folded plate structures in glass,* International Journal of Structural Engineering (IJSTRUCTE), Vol. 1, No. 3/4, 2010

M. M. El-Shamia, K. S. Kandeelb, *Structural behaviour of glass folded plate curtain walls*, The IES Journal Part A: Civil & Structural Engineering, Volume 4, Issue 2, 2011

Stefan Marinitsch, Christian Schranz , Martien Teich*, Folded plate structures made of glass laminates : a proposal for the structural assessment,* Springer, October 2015

International Association for Shell and Spatial Structures (IASS) documentation:

Kai Schramme, Annette Boegle, Jose M. Ortolano Gonzalez: *The challenge of rigid foldable structures,* as published for IASS symposium 2015.

Jose Carrasco, Sandra Gonzalez: *Ori-ssors: Research proccess in between vegetal crease patterns, expandable scissors and miura-ori solutions*, as published for IASS symposium 2015

Pierluigi D'Accunto, Juan Jose Castellon, Alessandro Tellini, Shibo Ren : *foldKITE: an ultra-light-weight folded structure*, as published for IASS symposium 2015

Valentina Beatini: *Polar method to design foldable plate structures*, as published in the IASS journal 56(2)-184, pp125-136

Valentina Beatini: *Translational method to design foldable plate structures*, as published in the journal Space Structures 30(2)

Stefan Trometer, Mathias Krupna: *Development and design of glass folded plate structures*, as published in the IASS journal

M. Trautz, A. Kunstler, *Deployable folded plate structures: folding patterns based on 4-fold mechanism using stiff plates*, as published in the Proceedings of the IASS Symposium 2009