Folded Glass Plate Structures: deployable roof system

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1. Research Proposal

1.1. 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.

1.2. Problem statement

Folded plate structures have been around since the 1920s. Since the introduction of new materials, such as wood, composites, glass, there has not yet been a full exploration of the new potentials deriving from different material properties and innovative manufacturing techniques. Glass is a material that has been increasing in popularity, ever since the technological developments made it possible to use load bearing glass elements of complex geometries. More specifically, the structural behavior of folded plates is highly compatible with glass as a material, given its high compressive but brittle behavior. So far, folded plate structures are being designed and researched upon as either kinematic-deployable geometries, using an additional structural support, or as a beneficiary structural system. These two distinct properties provide a very strong potential, if combined, for a self-supported deployable structural system, which needs to be further investigated and glass provides a very interesting and beneficiary material for this purpose.

1.3. Research question

To which extent can the kinematic qualities of folded geometries be combined with the structural benefits of glass plates and more specifically, how can these be applied in the case of a deployable glass roof system?

Sub-questions:

- What are the criteria for selecting a folding pattern that provides both stiffness and deployment potential?
- How do the geometrical parameters of the folding pattern affect the structural properties of the system?
- What kind of mechanism enables the specified deployment movement and what restrictions does this present for the design?
- What types of connections are required between plates and in the structure supports to ensure that the load transfer is done as expected and also to allow the necessary degree of freedom for the deployment?
- What is the potential of an innovative polypropylene material in a hinged connection principle between panes and how does the material behave in this application?
- How can those connections be designed to be as invisible as possible, while providing the required tolerances and envelope properties, such as waterproofing, etc.?

1.4. Case study

In the scope of this design by research project, the final architectural product will be developed for the specific needs of covering in an adjustable way the area of an outdoor swimming pool of Olympic dimensions (21m width x 50m length). The proposal needs to address the need for high architectural quality in order for the space to be used as a sport and leisure facility with natural light, for retraction of the structure for both functional and climate purposes, during summer season, turning the pool from closed to outdoor and without supplementary support mechanism. A design proposal like this would be suggesting an easily adjustable generic system for sport facilities of small dimensions.

1.5. Focus and 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,
1.7. Research methodology

This project will follow a design by research methodology based on experimental testing and geometry evolution based on structural performance. The geometry development aspect, directly linked to the structural performance and the hinge connection development aspect will be proceeded separately and in parallel. The goal is to bring the two aspects together in the final phase of the project and with the feedback from the connection properties, explore what modifications are needed and to which extent the design is feasible in the current conditions, in order to make necessary alterations leading to the final product.

1. Initial phase:

First, a specific architectural scenario has been chosen, so that the spatial and functional specifications for the structure are given. On the given scenario, different types of folding plate shell structures have been developed based on existing origami geometries. Through literature study, fundamental design decisions have been taken as a first approach.

2. Elaboration phase:

During this phase, two parallel research routes will be followed:
- One on the general geometry of the folded plate structure, based on its structural analysis, and
- One on the hinge detail development and testing, using PURE composite.

A. Design and structural performance:

- 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

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1. The Value Proposition Canvas, forming part of Business Model Canvas (BMC) is a strategic management tool proposed by Alexander Osterwalder 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.
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decision.
• One folded geometry will be selected as a basis and proceeded further with. Given the increased complexity of the structural and kinematic behavior of folded shapes, a process will be followed from a simplified version to more complex ones, each time using form parametrization and finite element analysis to define the geometrical parameters of the design step by step.
• Starting from a very simplified one-fold model, physical models on paper and thick materials will be made for better understanding of the properties. Then, following hand calculations as a first approximation to draw some first conclusions, a parametric model will be set for the simplified design and the finite element structural analysis will help define the optimal geometrical parameters for the specified span and glass type.
• The design solution will be gradually elaborated by adding parameters, which will eventually result in the final product with specified plate sizes, angles, glass thicknesses, etc. A finite element analysis will be run on the final geometry. For the structural analysis, different stages of deployment need to be taken into account, given the kinetic aspect of the project and additional loading situations, such as lateral wind load and suction need to be taken into account.

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-pull out
2. Fatigue

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

3. Finalisation:
• 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 limit loads and other restrictions deriving from the material as well as connection properties need to be taken into consideration and the criteria for the structural performance will be reevaluated. Some changes and reconsiderations on the final shape will probably occur at this point.
• 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.
• A scaled physical model of one fold element of the final design, with the specified connection type will be fabricated and imposed to distributed load, to be used as a reference in comparison to the used finite element model.
• 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.

4. A step further:
• The developed system will be applied on a free-form geometry, showing the architectural potential and design adaptivity of the specific system as an incentive of further research. The aspects of the developed product that are applicable to a free-form design as well as the extra necessary steps will be thus defined.

1.8. Research tools
In the course of the project both digital and physical tools will be used parallel or in turns. Phase A (geometry): 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 dxf. 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.

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, parallel 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.

1.9. Criteria definition
As a first step, a set of criteria has been set regarding both aspects of the problem, which will be used as guidelines throughout the project. A different chapter will be devoted to each of the different categories of criteria, in order to make the evaluation as well as the explanation of the design and research process easier. The same criteria will be used to assess the final product after the finalization of the research process.

DESIGN CRITERIA
1. Provide natural lighting and maximum transparency
2. Self-supported glass plate structure (no frame)
3. Deployable on one side (fully adaptable)
4. Feasibility (as related to cost and sustainability)

STRUCTURAL CRITERIA
1. Controlled element deformation + stress levels (all phases of deployment)
2. General shape stability (all phases of deployment)
3. Glass element redundancy
4. Damage sensitivity - Fracture mode – Safety factors
5. Fire protection - thermal stress?

**DETAILING CRITERIA**

1. Discrete design - Invisible connection
2. Tolerances
3. Restriction of gaps - waterproofing
4. Repair work facilitated
5. Structural behaviour enhanced by connection detailing

### 1.10. Time planning

The weekly planning of this research project is graphically shown in figure 1.3. As shown, tasks included in processes A and B are often executed simultaneously, as progress is required on both subjects, which is expected to provide with mutual feedback and inspiration. It needs to be noted that all planning of testings is purely speculative as progress is highly dependent on the availability of the laboratory as well as the outcome of the first tests, resulting in potential changes in this part of the schedule.
2. Literature study

2.1. A brief history of folded plates

2.1.1 The 1950s

There are different ways of constructing folded structure in terms of their forms and the application of different materials they are made of. Based on the research and analysis of the formal potential of the folded constructions the systematization of folded structures was done in terms of shape and geometry. The term folded structure defines a folded form of construction, including structures made of plates and structures made of sticks which make a folded form by their mutual relationship in space. Some authors also call a folded structure the origami construction.

Design and construction of folded structures occurs at the beginning of the twentieth century, and is associated with the development of reinforced concrete. The main goal originally was to reduce the net weight of the structural element, by adding structural height and rigidity, by shape, without adding extra material. The strength and stiffness of folded construction is achieved primarily by proper design of the structure, and to a lesser extent, by thickness and dimension of the elements that form it. This is an interesting quality, as opposed to the heavy frame structures in which the net weight is very great and that are cost-effective only for ranges up to 25 m. At the time, folded structures were an innovative example of cost-effective constructions and became feasible due to the development of structural systems and the use of reinforced concrete.

The first roof using structural folding was constructed in 1923 by Engineer Eudene Freyssinet, as an aircraft hangar at Orly Airport in Paris. This roof used pre-fabricated, pre-stressed elements, which is a remarkable engineering undertaking of the time. Based on the application of this pre-stressed structure Eudene Freyssinet has been called “the father of pre-stressed concrete”.

Since then, in the modern-movement era, folded structures, made in reinforced concrete have been broadly used in buildings of different scale, in the form of a roof, wall or spatial structures. The largest number of examples of folded structures refers to roof structures. The need for acquiring the larger range and more cost effective structure led to the emergence of this type of structure. The development of spatial structures led to the exceptional formal solutions which directly influenced the aesthetics and visual identity of the building. One of the most significant buildings constructed as folded form is the Chapel at the Air Force Academy in Colorado Springs, in the USA.

2.1.2. Types of folded plates

Folded structures are spatial structures formed by the elements in the plane, different in form and materialization. Folded structures differ in: geometric form, the form of a base over which they are performed, the manner of performance, methods of forming stiffness, function and position in the building, and the material they are made of. By using folded structures different spatial forms can be made. The straight elements forming a folded construction can be of various shapes: rectangular, trapezoidal or triangular. By combining these elements we get different forms resulting in a variety of shapes and remarkable architectural expression.

Based on geometric shape folded structures can be divided into:

- folded plate surfaces:
  Folded structures in the plane are the structures in which all the highest points of the elements and all the elements of the lowest points of the folded structure belong to two parallel planes.
- folded plate frames:
  Frame folded structures represent constructional set in which the elements of each segment of the folds mutually occupy a frame spatial form. This type of folded structure is spatial organization of two or more folds in the plane.
- spatial folded plate structures:
  Spatial folded structures are the type of a structure in which a spatial constructive set is formed by combining mutually the elements of a folded structure.
2.2. From origami patterns to thick panels

Since the beginnings of the use of folding as a building element, the Japanese art of origami has been a major source of inspiration, providing a vast library of examples of folding patterns. Some of the origami patterns can indeed successfully be applied to folded structures and cellular modular kinetic structures. These are repeatedly encountered in architecture and structures literature and have been largely investigated on. The most common is the Tachi-ori pattern, Miura-ori pattern, the diamond pattern and the egg box pattern. A more thorough comparison of their properties follows in chapter 3.

In terms of geometry, most commonly types of folded structures are referred to based on the number of folds that meet on one node of the folded shape. Thus, a distinction is made between 1-fold, 4-fold and 6-fold patterns, which present different characteristics as far as their structural and kinematic properties are concerned.

In general, 4-fold structures present extreme compactness, which also implies planar and spatial deployment possibilities, in comparison to 1-fold and 6-fold patterns, which is why they are often preferred in structural applications. Nevertheless not all 4-fold mechanisms and their combinations are applicable with the use of stiff plate materials and need to be designed as deployable folded plate structures.

Most origami patterns do not involve cutting, with the exception of the ‘eggbox’ pattern. This condition, central in origami, is referred to as the ‘loop closure constraint’ and it means that all final folded shapes derive from a flat surface, which makes them developable surfaces. A folded surface is developable when all angles defined by the vertices around a node add up to a full circle, so that:

\[ a_1 + a_2 + \ldots + a_n = 360^\circ \]

Developability also implies some deployment possibilities, related to the specific geometry of the pattern. Another interesting property of folding surfaces is the degree of freedom.

2.1.3. Modern approaches and new materials

In more contemporary examples, there has been a strong reappearance of structural folding in the past twenty years, in modules enhanced by the use of parametric design. Excited by the efficiency of such structures, more recently research teams began to adapt them for a variety of alternative materials, including fiber-reinforced plastics, glued laminated timber, and laminated glass plates. The use of folded plates is expanded from roof structures to shells, often featuring complex cellular geometries.

New fabrication techniques contributed significantly to this direction, making it feasible to produce customized elements.

As a result, more irregular folding patterns, computationally derived, are being tried, mostly as a tessellation method for free-form shell geometries. While regular folding structures can be described mathematically and geometrically and are therefore easy to tessellate and based on this easy to unfold, when the tessellation of bodies and areas is based on more complex mathematical descriptions the canon of shapes which can be described by this method is limited. With the help of computers and numerical methods of describing geometries it is possible to classify and categorize arbitrary geometrical shapes with different tessellations. The outcomes are primitive shapes such as rectangles or triangles which describe the free-form as a net. Based on this tessellation, free-form bodies or areas can be transformed into longitudinal or facet-like folding textures. In this case of course, the folding is not primarily used as a structural element nor a deployment method, but rather a means of effective tessellation of a non-repetitive cellular surface. An example can be seen in pic.2.3.

Some definitions:

- Rigid foldability: refers to the continuous folding of an origami structure which doesn’t result in facet deformation.
- Compactness: refers to the potential of an origami structure to fully fold on one or more directions.
- Developability: refers to the property of a surface to have zero Gaussian curvature, to be able to be flattened onto a plane without distortion.

2.2. From origami patterns to thick panels

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Another interesting property of folding surfaces is the degree of freedom. The degree of freedom...
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(DOF) of a folding pattern reflects the number of possible deployment directions and is at maximum equal to the number of vertices on the surface boundary for triangulated facets. As defined by Schenk, in the example of a 4-fold surface with an array of \( n \times n \) quadrilateral facets:

\[
N = 2n(n-1), \\
M = (n-1)^2, \\
\text{where } N \text{ the number of creases and } M \text{ the number of vertices on the surface boundary.}
\]

The degree of freedom is thus defined by redundant constraints, meaning the nullity of the \( 3M \times N \) matrix of every vertex constraints:

\[
\text{DOF} = N-3M = (n-2)2 + 1 \quad \text{Note: For } n > 2, \text{ DOF} < 0.
\]

According to Schenk, finding multi-vertex crease patterns that supply the singular configuration is the challenge of rigid foldability. Comparing DOF of different patterns helps getting some information about the geometry in motion and adjusting the span direction in the case of a structure.

Origami shapes have successfully been applied for architectural proposes for monolithic structures made mainly in concrete. However, a great challenge appears in the process of turning origami shapes into rigid systems. This is mainly because the lack of a 3rd dimension is essential to origami folding. In origami concepts, paper is considered as an ideal surface, while this is not the case when designing structures out of thick panels. Additionally to this, many origami patterns require small twisting of the paper, which means that the plate surfaces can no longer be assumed as planar. This is not a problem for thin paper models, but is crucial for rigid thick panels. Naturally, thickness constraints also greatly affect the level of potential compactness of a deployable structure. Some very interesting outcome on geometry solutions is given by Tomohiro Tachi, in the example of a 4-fold and 6-fold pattern respectively.

This lack of structural background is a serious concern, as usually, in designs explorations, the interplay between design and structure is not considered since the beginning of the process. As a result, some structural evaluations are inconclusive and not full advantage is taken on the potential of folding.

2.3. Structural behavior of folded plates

The structural advantages of folding have been largely investigated since the beginnings of the 20th century and a thorough understanding of their function has been attempted. However, the structural behavior of folded plates, and especially of hinged folded plates remains a subject of great complexity and its approximation can be quite challenging. According to Trautz, folding systems represent one category of plane structural surfaces, alongside with plates and slabs. Their special structural behavior is due to their structural subdivision arrangement in pairs which correlate with each other and so they are connected through a shear connection.

The folded plate structure can be considered as a middle ground between a slab and a shell. They are rigid systems that consist of thin planar structural surfaces. Depending on the height to depth ratio of the folding, their structural behavior can be described as beam action or plate action. Plate action implies a significant structural depth 50-100% higher than that of a beam action. Usually a combination of the two actions exists in the structural behavior of folded plates. The external loads are first transferred due to the structural condition of the plate to the shorter edge of one folding element. There, the reaction as an axial force is divided between the adjacent elements which results in a strain of the structural condition of the slabs. This leads to the transmission of forces to the bearing. Pure plate action can only be achieved when the structural height is half the span in dimension. A very important quality is therefore the moment of inertia, \( I \), at each section transversally to the span. Areas where structural height is reduced to plate thickness basically act as hinges.

CHAPTER 2 • Literature Study

2.4. Glass: Potential and restrictions of an innovative structural material

Glass is a material with fascinating architectural qualities. It is the only material which so effectively combines absolute transparency with structural strength. This duality in its nature makes it at once a façade and a structural element, which allows a self-supported structure to also be "invisible". The basic molecule of glass is siliciumquatrooxide, SiO₄. This is comprised of silicium dioxide, sodium carbonate and calcium carbonate. The microscopic structure of glass is comparable to that of a liquid in which the individual constituents form an irregular network without a long range order. Glass is a strong but brittle material. Its main characteristics, as far as the building industry is concerned, are transparency, heat resistance, pressure and breakage resistance and chemical resistance. Glass is melted at a temperature between 1000 and 2000° C.

Since its discovery in ancient times, various manufacturing techniques have been developed, leading to the introduction of float glass, one of the most standard production methods still, which also leads to low surface finishing and restricted dimensions. In Europe, maximum dimensions remain to 6.0 x 3.2m, while the range of thicknesses is quite limited. Production techniques have been greatly enhanced in the last decades, allowing structural glass to become widely used in the building industry. Originally, there have been some important issues preventing the use of glass in structural elements. The ductile behavior of glass, which breaks suddenly after slowly reaching the limits of its load bearing capacity, could prove fatal for a building and its users. This problem has been tackled in two ways.

First, toughened glass has been produced, by artificially introducing compression to the outer surface of the glass. In this way, the amount of cracks and other defects in the surface of glass, compromising its integrity were significantly reduced. Moreover, the compression of the outer skin results in a much better reaction to impact. A special effect is also the manner of breaking. Toughened glass, as opposed to float glass, breaks into thousands of small fragments, due to the sudden release of inner stresses, caused by the breaking. There also exist semi-toughened glasses, made with the same
procedure.

Second, the laminate of glass was introduced as a safety mechanism but also a way to produce more easily customizable building elements. Lamination is essentially the gluing together of two or more layers of glass together. For the invisible connection of the layers, most commonly a two-component resin is used. Alternatively, a transparent foil, PVB, a flexible polymeric material, can be used as an interlayer between panes, thermally fused together. Laminated glass also offers better thermal and acoustical performance, which is why it is largely preferred in structural design. Performance of course can vary, according to the type of glass used for lamination, annealed, toughened, low-e.

### 2.4.1. Safety

Because of the peculiar structural behavior of glass, a meticulous set of regulations is under constant development to determine safety measures. The use of glass in buildings. Despite the insufficiency of regulations regarding structural glass, there are some admitted safety aspects to be considered. The first one is redundancy, meaning that the structure needs to have a surplus of load bearing capacity to account for the loss of a major part of the structure and avoid damage. Therefore, an increase in the number of building elements is often required. For example in the case of laminated glass, an outer layer of each pane needs always be considered as supplementary, in case of breakage. The same logic goes for entire building elements. A structural scheme needs to be designed so that in case of failure of one load bearing element, a beam, or a column, neighboring elements can carry the load long enough for the lost element to be replaced.

Secondly, in order to increase performance and guarantee safety during breakage, the use of toughened and/or laminated glass with an interlayer is implied. Toughened, or semi-toughened glass, breaks into small and relatively harmless pieces, while in the case of the interlayer, the adhesive keeps the broken pieces together even after the integrity of the structure is compromised, protecting from lateral damage.

Finally, a very high safety factor is usually set for glass structures. According to Bos\(^7\), a material factor of 1.8 is attributed to glass elements for structural calculations.

### 2.4.2. Design challenges

When applied in roof structures of course, glass faces the same challenges as in any façade element. Insulation is a key issue that might be handled by Insulated Glass Units (IGU), but also result in an unwanted greenhouse effect in summer. A variety of coatings and additional systems can provide solutions to this issue, but that is not the purpose of this specific study. For the flat material glass, folded-plate structures seem an ideal candidate when in need for an appropriate design-language. A key hurdle to master is not the load bearing capacity of the glass itself. Research conducted by Englarth (2007) and Luible (2004) has proven the suitability of the material for substantial in-plane loading. The search for an appropriate connection detail that safely transfers loadings from one plate to the other (Warm 2007), appreciating the material characteristics of the used components is the most challenging aspect of glass construction.

### 2.5. Kinematic structures: an introduction to deployment systems

Transformable structures are defined by Pellegrino (2001), as structures that are capable of executing large configuration changes in an autonomous manner. The configuration of such structures changes between a compact-packaged state and a large-deployed state. The most interesting aspect of folded plate structures is their combination of a wide span performance with kinematic properties, thanks to their articulated design. Designing a deployment mechanism using folded plates and hinged connections is very relevant in an engineering context, particularly in architecture in the following reasons, according to T.Tachi\(^8\):

---

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

---

Table 2.11 (left): Laminated glass material properties and sizes

<table>
<thead>
<tr>
<th>Property</th>
<th>Value Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>2300-2450 kg/m(^3)</td>
</tr>
<tr>
<td>Young's modulus</td>
<td>67 GPa</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>33-38 MPa</td>
</tr>
<tr>
<td>Yield strength</td>
<td>33-38 MPa</td>
</tr>
<tr>
<td>Tensile strain to failure</td>
<td>0.05 %</td>
</tr>
<tr>
<td>Compressive modulus</td>
<td>638-70.4 GPa</td>
</tr>
<tr>
<td>Compressive strength</td>
<td>370-410 MPa</td>
</tr>
<tr>
<td>Flexural modulus</td>
<td>70-74 GPa</td>
</tr>
<tr>
<td>Flexural strength</td>
<td>40-45 MPa</td>
</tr>
<tr>
<td>Shear modulus</td>
<td>27-29 GPa</td>
</tr>
<tr>
<td>Bulk modulus</td>
<td>37-40 GPa</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>0.22-0.24</td>
</tr>
<tr>
<td>Hardness (acc. To Vickers)</td>
<td>438-483 HV</td>
</tr>
<tr>
<td>Fatigue strength at 10(^7) cycles</td>
<td>26.5-31.8 MPa</td>
</tr>
<tr>
<td>Fracture toughness</td>
<td>1-13 MPa/m(^2)</td>
</tr>
<tr>
<td>Melting point</td>
<td>1000-2000 °C</td>
</tr>
<tr>
<td>Thermal expansion coefficient ((20^\circ C \rightarrow 100^\circ C))</td>
<td>9.1-0.5 μstrain/°C</td>
</tr>
<tr>
<td>Thermal conductivity coefficient</td>
<td>0.625-1.11 W/m.K</td>
</tr>
<tr>
<td>Specific heat capacity</td>
<td>850-950 J/kg°C</td>
</tr>
</tbody>
</table>

Picture 2.13 (top right): Comparison of breakage patterns between tempered and heat-strengthened glass.

Picture 2.14 (bottom left): Laminated glass pane, with an interlayer of PVB.

Picture 2.15 (bottom right): Breakage pattern of laminated glass.
1) Its structure based on watertight single surface is suitable for constructing an envelope of a space; 2) its purely geometric mechanism that does not rely on the elasticity of materials can contribute to a design of robust, repeatedly usable deployable structure.

Essentially defining for the folding process are the conditions on rigid-foldability and flat-foldability given by T.Tachi, and Schief, based on the analytical geometry of Kokotsakis meshes and Voss surfaces. Detailed analytical descriptions of folding geometries and their intermediate states have been developed which provide a valuable tool to understanding and parametrizing foldable plate structures. (see Appendix 1)

2.5.1 Kinematic mechanisms

There are two types of kinematic systems:

1. Sequential: each fold deployment occurs only after the previous one is complete, as a result of an applied force in the direction of the translation.

2. Synchronous: one fold triggers simultaneous unfolds to all, by means of a mechanical system translating the movement over the structure.

In most mechanical cases, and obviously in the case of deployable structures, a synchronous way of movement is preferred, in order to save time and energy. The key to such kinematic structures is the transmission of motion from one part of the system to the entire system. A simple example of a mechanical system achieving this transmission is a simple coupling rod. As suggested by its name, its purpose is to link two wheels into moving synchronously, as for instance in the example of train wheels.

A linkage or mechanical linkage is an assembly of bodies connected in order to manage forces or transmit movement. The bodies, or links are considered to be rigid. The connections between links are modeled as providing ideal movement, pure rotation or sliding for example, and are called joints. A linkage modeled as a network of rigid links and ideal joints is called a kinematic chain. A very typical example of linkage is a Cardan joint, which is used to transmit rotational motion. Although a single Cardan joint transmits movement non-uniformly, two joints in consequence can achieve uniform transmission of motion.

Spherical linkages are created by sets of four rigid bodies connected by revolute joints. As opposed to planar linkages, such as traditional ‘scissor’ mechanisms, the movement of spherical linkages is based on the amount of dihedral angles. In the case of 4-fold patterns, every four plates around a vertex comprise one spherical linkage. Two linkages move together when they share two out of four links. In this way, a movement can be transmitted throughout an entire three dimensional system, through consecutive transmissions between linkages sharing common links. A system of this kind becomes ‘over-constrained’ when it consists of more links than necessary for motion, which means that the system moves thanks to the special arrangement of the bodies.

From a kinematic point of view, most quadrilateral origami patterns, such as Miura-Ori, or ‘egg box’ are considered assemblies of spherical linkages.

2.5.2 Design methods

Two methods are described by Valentina Beatini9 in the direction of designing non-developable foldable plate structures with kinematic properties, the translational and the polar method.

The translational method defines three dimensional, non-developable systems that can approximate any surface made by translating a generic curve along another generic curve. The most interesting aspect of this method is its great potential in architectural application, since it evolves around the shape of the structure at a specific folding phase as the design target. Related to the degree of freedom of the pattern, it is preferable to use a system of mobility one, which means that its motion can be controlled by setting just one parameter, i.e. by one motor. The method mainly uses Kokotakis as published in the journal Space Structures 30(2).
sakis theory of meshes, to create a continuous foldable mechanism with mobility one based on a set of target curves, which define the constraint surface. In three steps, target curves are parameterized and rotation angles set, dimensions are obtained, and plates of corresponding sizes are assigned, as shown in figure.

The rotational method describes a way of producing a three dimensional grid system which approximates a translation surfaces derived from two curves, out of which one consists of straight segments. It uses perpendicular projections parallel to both target curves in order to issue a double strip of plates along one curve. Translation of this strip along the second curves produces the new grid. The procedure is performed in three steps, parametrizing the target curves and setting the rotation angles, dimensions are obtained and plate sizes and configurations derive for a strip along the projection and then translated for the full surface.

Both of these approaches are of great interest to architectural application, since they provide with a methodology and the corresponding analytical geometry background which helps deriving folded plate deployable systems out of predefined free form surfaces, without knowing a priori the degree of freedom and folded configuration. They can be used to a certain extent as a valuable guideline for understanding and parametrization of folded structures.

Figure 2.21 (left): Diagramatic explanation of the three steps of the translational method, described by V.Beatin (source:V. Beatini: Translational method to design foldable plate structures)

Figure 2.20 (top): Analytical example of polar method, described by V. Beatini (source: V. Beatini: Polar method to design foldable plate structures)
3A. Design Development

3A.1. Design Goal

The exploration of deployment possibilities of glass folded plate structures in the scope of this project will be focusing on developing a system covering an open space which requires adaptability, either because of functional or climate requirements. In this direction, spaces with high architectural standards and seasonal use were considered, added a relatively small span, in order for the structure to be feasible in glass. Sport facilities, and especially swimming pools provide an ideal example. Swimming, among other sports, is a preferably outdoor activity, also related to leisure, however highly weather dependent. As a result, swimming pools have a very discrete seasonal use, most frequently combining outdoor and indoor facilities. Moreover swimming pools are considered as leisure centers, besides training areas, which means high architectural qualities often sought for, as well as natural light.

For the above mentioned reasons, a typical outdoor swimming pool of Olympic dimensions 50x21m is chosen as a case study. An open air swimming pool will be considered, free of additional functions, which are presumed to be accommodated elsewhere. As explained in chapter 3A.3, the deployable system will be considered to cover only the area adjacent to the pool, with the addition of an entrance area on one side, as seen in diagram 3.3. According to the final pattern and deployment mechanism of choice, additional elements, such as side walls, might be added at a further stage of the design, based on architectural criteria.

In the case of selection of a form of folding unsuited for the span, a smaller, 25x10 (11, 12.5) m, pool might be considered.

The main architectural goals of the proposed system are:

1. To create a temporary climate-controlled enclosure over an outdoor sport facility, in the specific case a swimming pool
2. To create a structure allowing view to the exterior and natural lighting, providing as much transparency as possible

3A.2. A first comparison of folding patterns

As a first step in the research, prior to developing design strategies, a comparison of the basic origami structures frequently used in structures was made, in the form of the table in fig. , aiming to provide some insight to the potentials of selected folding patterns. Patterns were selected in terms of frequency of use particularly in architectural and structural research and naturally, their list is not exhaustive.

Note: in the following comparative table, mountains in the pattern are noted with a straight line and valleys with a dashed line.
CHAPTER 3A • Design Principles

1. Simple 1-fold with hybrid endings

**TYPE:** planar
**quadrilateral pattern**
**developable - 1 DOF rigid motion**
**span direction:** Y / retractable on X

This is the hybrid of a simple 1-fold pattern. It can effectively span over one direction, but is prone to bending. The extra folding around the ends helps the load distribution, avoiding large stress concentration around supports.

2. Triangular 1-fold

**TYPE:** planar
**triangular pattern**
**developable - 1 DOF rigid motion**
**span direction:** Y / retractable on X

This is a triangular version of the above. Due to the triangulations, this structure copes with bending better. It has been used in architectural applications, such as the new Terminal of Pulkovo International Airport.

3. Diamond 6-fold (single)

**TYPE:** planar
**triangular pattern**
**developable - 1 DOF rigid motion**
**span direction:** Y / retractable on X

This is one of the few triangular meshes with zero lateral expansion during deployment. This makes it ideal for rail systems. The triangulation of the surface also increases structural height, reduces the bending stresses.

4. Miura-Ori 4-fold

**TYPE:** planar
**quadrilateral pattern**
**developable - 1 DOF rigid motion**
**span direction:** Y / retractable on X

This is one of the most typical examples of folding patterns for architectural applications. Such a level of tessellation of a flat surface cannot achieve stiffness in the case of hinged connections. Unstable structure.

5. Eggbox 4-fold

**TYPE:** planar
**quadrilateral pattern**
**non-developable - no DOF rigid motion**
**span direction:** Y and X

This is one of the very few non-developable patterns, since it involves cutting it doesn’t directly fall under the definition of origami. Much like the Miura-Ori, it looses stiffness in both span directions, when hinged connections are used.

6. Simple 4-fold

**TYPE:** frame / tunnel
**quadrilateral pattern**
**developable - 1 DOF rigid motion**
**span direction:** Y / retractable on X

This is the simplest form of origami-frame structure. Folds across the span direction increase stiffness, replacing beams.

7. Butterfly 6-fold

**TYPE:** planar/ spatial (dep. on folding angle)
**triangular pattern**
**developable - 2 DOF rigid motion**
**span direction:** X, Y / retractable on Y

This is a rather complicated pattern, unsuitable for structures, as it provides very low stiffness in both span directions. Performs better if applied on a curved surface but still unstable in combination with hinged connections.

8. Diamond 6-fold

**TYPE:** frame / tunnel
**triangular pattern**
**developable - 1 DOF rigid motion**
**span direction:** Y / retractable on X

This is a simple pattern, in which, the pattern angle determines the curvature of the final surface assumed, and the element size the coarseness of the folding. Although its shape and folding provides stiffness, behavior with hinged connections is uncertain.

9. Miura-Ori (uneven)

**TYPE:** frame / tunnel
**quadrilateral pattern**
**developable - 1 DOF rigid motion**
**span direction:** Y / retractable on X

This is a version of Miura-ori with the use of two different angles. According to the angle difference, the curvature of the final tunnel shape is altered. Presents the same structural concern as the Diamond pattern.

10. Hybrid Dome

**TYPE:** spatial
**quadrilateral pattern**
**developable - 1 DOF rigid motion**
**span direction:** XY / retractable ar. Y axis

This pattern is producing a dome-like shape, which is rotationally retractable. Special folds are added around the two poles, to avoid gaps. Despite the interesting form, it presents reduced stiffness compared to a plate shell dome.
3A.3. Architectural concept

In this respect, three different design approaches were attempted, mainly based on the existing origami pattern types and their evaluation. The concepts though deriving in quite different design solutions, all try to achieve the set goals, while using a deployable folded glass plate system.

As a first step, a dome of similar shell shape was considered. However, while a glass plate dome, as already researched on 7 appears like a good solution, meeting both architectural and structural requirements, in the case of folded structures it appears quite problematic form-wise. The greatest benefit of a shell structure is the optimization of load distribution, which means that all faceted are under in-plane loading, theoretically only under compression, a result that is very favorable in the case of glass. However, in the case of a folded plate, deployable dome, the load distribution is completely altered, which makes the dome behave not as a shell but rather an uneven frame structure. The fact that multiple deployment steps are included also means that unpredictable shear forces will occur by altering geometries.

As a result, from dome geometries, focus has been shifted to frame-type structures, resulting in tunnel-shaped spatial structures, with the possibility of deploying on directional rails. This appears as a very practical scenario as it provides for maximum transparency and a large variety of relevant folding patterns, either 4-fold or 6-fold, in existing literature.

A simplified planar version of 1-fold or 4-fold patterns is also considered, as a way of minimizing complexity, both of the connections but also the deployment mechanism, while still meeting the set criteria mentioned above. This case is highly favorable for structural optimization due to the simplicity of the folding pattern, allowing for more alterations leading to efficient and aesthetically intriguing results.

3A.4. The challenge of deployment

After only a few trials on the before mentioned folding patterns, a major challenge becomes evident concerning the kinematics of the structure. The way in which most research deals with the translation of kinematic structures of this type, there have seldomly been architectural applications and even more rarely have there been specific boundaries, given for example by directional railings. Given that the design proposal for the covering of an orthogonal pool involves some form of directional railing in order to achieve uniform and feasible deployment, a major challenge arises.

The problem derives from the fact that a lot, if not all of developable structures applied in spatial structures, expand in both directions, when deployed, even though they may be flat-foldable only in one. This is best described by M. Schenk, as ‘Poisson ratio of expansion’. According to Schenk, Poisson ratio can also be used as a kinematic property of a folded surface, describing the structure’s expansion or contraction orthogonally to some applied uni-axial strain, ε1.

\[
\varepsilon_i = \frac{d x_i}{x_i} \]

Poisson ratio will then be: \( v_{ij} = \frac{\varepsilon_j}{\varepsilon_i} = - \frac{\varepsilon_j}{\varepsilon_i} \), with \( \varepsilon_i \) the resulting strain, and \( \varepsilon_i \) the applied strain in the direction of deployment.

For example, in Miura-ori, the poisson ratio can be defined as follows:

\[
v_{ij} = - \cos^2 \theta \tan \gamma
\]

where \( \theta \) the dihedral angle, the angle between folds, and \( \gamma \) the angle of the pattern.

Most patterns, as shown for the simple 4-fold frame, in fig.3.6, have a poisson ratio different than zero, meaning that there is a resulting strain in the lateral direction for the folded geometry. This results in...
3A.5. The development of geometry

3A.5.1. Concept development

As a result of the already mentioned geometry limitations, the scope of this research was focused on planar folded geometries as roof structures. It needs to be specified at this point that a “planar” folded surface only refers to the base surface of the folding mechanism and does not necessarily have implications on the complexity of the folded shape itself.

The architectural concept was further developed accordingly, into including two side loadbearing walls, enclosing the space of the pool, providing supports and allowing for the rails for the deployment of the roof. In this way, the foldable structure comprises only a roof element and there is more freedom in the way this geometry can be designed between the set boundaries. The juxtaposition of solid wall elements transparent roof will give a very appealing and impressive quality to the indoor space. Light, shadow, in combination with the effect of the water on the pool surface, will provide a very interesting aesthetic result while allowing broad natural daylight in the pool area, and a visual connection with the outside. During summer the roof will be fully deployed on the side rendering the area completely open air, while the wall elements will still allow for some sunshade, depending also on the orientation.

At this point it is of importance to be stated that this pool area, which is now presented as an isolated unit, would, in reality, form part of a larger facility, including all supportive functions. For the purpose of this research the main building is assumed to be located at the southern end of our case study area, as shown on the draft drawings (fig. 3.12-3.13).

Further investigation naturally is required in order to reach more specific conclusions on the subject, and to define exhaustive conditions to guarantee the non-expansion of folded surface.

Non-developable structures, like the ones described previously as part of V.Beatini’s research also provide a good solution to this challenge. Quadrilateral plate systems, like the ones in fig. 3.7, offer possibilities of feasible deployment systems and interesting architectural qualities. Moreover, the methods described by V.Beatini can be applied in this case, helping to identify folding patterns which result in structures deployable on parallel rails.

Further investigation naturally is required in order to reach more specific conclusions on the subject, and to define exhaustive conditions to guarantee the non-expansion of folded surface.
Fig. 3.12-3.13: Draft drawings demonstrating the poll area in an enclosed (up) and open (bottom) configuration.

**3A.5.2. Pattern selection and parameter definition**

For the next steps of design development, the case study has been simplified to a foldable roof system based on a planar geometry of a rectangle boundary 70 x 20 m. Rails and supports are considered as located on the opposite long edges of that rectangle, and parallel to each other.

Considering planar folding patterns, the six-fold planar version of the “diamond” pattern was selected (see Pattern comparison, Chapter 3A.2.), as the only one which combines a straight continuous folding line from one side to the other, with an interesting folding shape which presents further design and optimization potentials, due to its triangular elements. As mentioned before, in chapter 3A.4, the existence of a straight folding line, mountain or valley is an efficient way of determining if a folding pattern will present lateral expansion or not. In lack of a more elaborate condition, this rule has been used as a necessary attribute in the selection of pattern.

Based on those boundaries and the selected pattern, the geometry was developed on a basis of material utilization and structural performance. The structure’s span in the lateral direction was taken as a given while the span in the long direction is considered more flexible and will be precisely determined when the exact dimensions of the glass plates are decided. The limitations of the folding angle and the element sizes are gradually determined in steps, parallel to the structural analysis, as described in the next chapter. Parameters are distinguished into: givens, independent parameters, dependent parameters and time-dependent parameters. The introduction of time-dependent parameters is necessary since this is a dynamic system, in order to describe different deployment states. In the case of the selected planar six-fold pattern, the parameters are defined as follows:

**Givens**: span $S$

**number of folds** $n$
turns exported from Rhinoceros to .iges format to be input into FX Midas, and run in Diana. As there is no direct way to connect the two software, the procedure of changing the geometry and exporting the results would be quite repetitive and time consuming.

for this reason, in the purpose of being able to run fEM analysis in Diana, on geometries defined in grasshopper in an efficient way, a script has been developed by Building Technology graduate student Simon luitse, under the supervision of P.Eigenraam. The goal of this grasshopper script is to export surfaces generated in grasshopper into .dat files that can be input directly into Diana without further processing. Part of this script, with some alterations to fit the specifics of this research, has been used in the course of this project as well. This has proven a valuable tool given the repetitive nature of running certain models several times with small alterations, in sizing or thickness for example.

3A.5.3. Exporting geometries

As the results deriving from Karamba are not very precise, nor do they attribute specific numeric values to the mesh nodes, the models need to be exported to another software in order to run the conclusive finite element analysis. TNO Diana has been used for that purpose and models were in
3B. Structural analysis

Since the structural integrity of the structure is one of the main challenges of this project, an understanding of the structural properties and crucial factors affecting the system's stability and stiffness is required. Since the first design decisions, structural behavior has been central to pattern comparison and will eventually play an even bigger role during the parametrisation of the folding.

The fact that the goal is to achieve a frameless, self-supported structure, which is at once deployable is quite challenging to begin with. As already mentioned, the hinged connections between plates, which are necessary to allow for the structure to be foldable, present a big risk for the stability of the system. For this, it has to be noted, that the integrity of the structure needs to be guaranteed throughout the entire process of deployment, and not just for the two extreme states, folded and unfolded.

The problem in this case is, that given the instability of the system, as a result of the pinned boundary conditions between the plates, it is difficult to draw useful conclusions from a Finite Element Analysis for the structure as a whole. In order to approach a complex system like this one, steps need to be taken, from part to whole and from a simple geometry to more complex ones. Starting from a very simplified folding made out of two plates under an angle, as seen in fig.3.16, and moving on to increase the complexity and add more parameters, it will eventually become possible to draw conclusions on the behavior of the system and the way in which this is affected by geometry parameters, such as the pattern angle, folding angle, etc.

Different simplifications were considered, but finally the analysis was made on two steps, as shown on scheme 3.16, and also in different scales, from plates, to fold elements, to the roof as a whole. In all the steps to follow, a single folded element has been modelled as part of the full folded structure, and not the roof structure as a whole, in order to be able to draw more specific conclusions on the results. At a later step the structure as a whole will eventually be modelled and analyzed as well.

First order theory has been used primarily in the structural analysis process. The structural behavior of the geometry is assumed to be linear. Dynamic changes due to deformation and structural instability leading to non-linear behavior are not taken into account at this stage.

3B.1. Loadcases and Boundary Conditions

The loadcase considered for the final structural analysis, includes the self-weight of the structure, live loads due to snow, and a windload, assuming the least favorable direction of wind. A table presenting the assigned loadcase is shown in fig. 3.17. and has been the basis of all calculations. Initially, only vertical loads, meaning self-weight and live loads, were taken into consideration, while the wind load has been considered only for part of the connection structural analysis and will only be added in the final complete analysis. The ULS (Ultimate Limit State) was taken into account for all following preliminary analyses.

Different units and ways of applying these loads have been tried in the finite element model, for the different units and ways of applying these loads have been tried in the finite element model. For the preliminary hand calculations, loads were considered as distributed on beam elements and on the finite element model loads were applied as a combination of self-weight, automatically attributed to the model elements, and vertical pressure load on the surface elements. As different software uses different units, the distinction between Karamba and Diana input was made as seen in the table.

Boundary conditions are also an important part of the finite element model. In order to come as close as possible to the realistic conditions, while still modelling only one folded element. Points supported on the parallel rails are considered as pinned on the x and z axis on the one side, and on the z axis alone on the other side, to allow for somelateral translation, due to the shape deformation. This is given that movement on the x axis will be hindered mechanically when the structure will be in its deployed state. The long edges at the side of the geometry, where the isolated element would be connected to the rest of the shape, are considered pinned on the y axis, accounting for the
CHAPTER 3B- Structural Analysis

LOADCASE          SAFETY FACTOR   TOTAL   for hand calculation   for Karamba   for Diana
                   (N/m2)            (N/m2)              (N/m2)         (N/m2)        (N/m2)
Self weight       1.05991189  1.2  1.27094184  7.42563104  2.23094184  2230.94
Live load (snow)  0.7    1.6  1.12       0.93324327
Wind suction      -0.08  2    0.14       -0.13365677
Snow + Wind       0.2    2    0.46       0.80163704
Wind load (H)     0.2    2    0.4       0.80163704
                0.13  2    0.26       0.80163704
SLS q= 4.6724331 (N/m) ULS q= 8.427286101 (N/m)
SLS q= 4.6724331 (N/m) ULS q= 8.427286101 (N/m)

Table 3.10 (top): A presentation of load-cases applied to the structural analysis of the structure as a whole.

existence of other plate elements, not allowing them to spread open.

Finally, the connection between plates, which was required to be modeled as a hinge, has been modeled in two different ways, as will be further explained in the following chapters. It has been crucial for the accuracy of the finite element model that the hinge elements were made correctly, simulating the actual behavior of the material in this configuration. This was achieved as a combination of lab test results on the connection method and necessary simplifications on the 3D model. Also, connection properties have been tested on different scales, both in finite element method and physically, in terms of material behavior, connection between plates and the effect it has on the overall structural behavior of the structure.

3B.2. Safety measures

As mentioned in the literature study, in the design of glass structures, safety measures play a very important role. Because of the material’s brittle behavior and the sudden failure that it can present without prior warning, special regulations and factors are predicted for glass structures and more specifically for roofs. There have been several codes, developed for this purpose, such as the European code, including partial factors and the North American “Glass failure prediction model”, based on statistical theory of failure. (see Appendix) 4

Particularly in the case of plate structures like the one in this research, it is also essential that the overall integrity of the glass structure is not compromised by failure of a single element. Redundancy and fracture mode criteria need be expanded in this case to ensure that an extra, disposable layer of material is used and that there is a secondary LTM temporarily able of assuming the imposed loads in case a glass element fails completely, meaning that they possess a “residual stability”. In case of complete failure of an element, it is the connection that is required to function as a secondary LTM mechanism, for a limited amount of time, until replacement is possible. As best described by professor R.Nijss:

"If one or two in case of vandalism prone elements, layer breaks, the remaining should be able to carry the load at an arbitrary point in time, multiplied by a safety factor of 1.1, or 25% of SLS if the load is zero."

Overhead glazing as is the case in this project, under load has got to remain in place for 24h post-breakage, since the space underneath is fully accessible, to prevent people’s injury. Moreover, for the same reason, the use of laminated heat-strengthened glass is compulsory. Heat-strengthened glass and SG lamination has been chosen over PVB as it presents with higher post-failure strength. Two layers on either side of the connection, in the form of an Insulated Glass Unit were assumed. An extra layer to what is structurally needed is also added, but not estimated in calculations as a redundancy measure, so the structure has been calculated for 3 glass layers, instead of four.

The safety factor of material plays also a very important part, especially in the case of glass elements. In the preliminary design a global safety factor of 1.2 for glass was assumed, based on Dutch code EN 2608-2. Permissible deflection and architectural design stresses have been defined and used as a reference basis for all stages of structural analysis, as presented on table 3.11.

In general, a limit state approach has been used, taking into account different statistical distributions as far as material strength and loads are concerned. The combination of different safety and load factors gives the possibility of including different structural scenarios. This method can be expanded to consider multiple limit states or modes of failure, therefore providing a more holistic and accurate design tool. Safety factors have been attributed to the different load cases, resulting in the Ultimate Limit State (ULS) which has been considered the total load for calculations and the glass safety factor was attributed to the nominal allowed stress levels.
GEOMETRY

<table>
<thead>
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<th>Value</th>
<th>Unit</th>
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<tr>
<td>Glass pane thickness</td>
<td>1.06 mm</td>
</tr>
<tr>
<td>No of laminates</td>
<td>4</td>
</tr>
<tr>
<td>Plate width a</td>
<td>3 m</td>
</tr>
<tr>
<td>Structural height hi</td>
<td>1.500 m</td>
</tr>
</tbody>
</table>

Table 3.10:

| Depth of neutral axis z | 0.75000002 m |
| Distance of axis transition x | 1.299038105 m |
| Moment of inertia Iy | 0.0127 m³ |
| Beam depth b | 0.1800 m |
| First moment of area | 0.350740288 m³ |

3B.3. Structural analysis

3B.3.1. Hand-calculations and parameter definition

As a first step for the understanding of the structural behavior of the folded geometries, beam theory was used to draw some first conclusions on a simplified geometry of the same shape boundaries, as the one shown in figure 3.12. In this approximation, basic formulas, of first order linear analysis on beam elements were used and the structure was considered as a set of beams of corrugated shape. The moment of inertia was calculated accordingly, as if the plates were perfectly fixed on the edges, instead of hinged.

- Moment of inertia ly: \( I_y = 2t \cos \theta_i \cdot h_i^3 / 12 \)
- First moment of area: \( S_y = ta^2 \sin \theta_i \)
- Reaction Force: \( F = ql / 4 \)
- Deflection: \( w = 5ql^4 / 384E \)
- Bending moment: \( M = ql^2 / 8 \)
- Maximum flexural stress: \( \sigma = Mz / I_y \)
- Shear Force: \( V = ql / 2 \)
- Principle Force max.: \( F = ct \)
- Maximum shear stress: \( \tau = VQ / lb \)

,where t : plate thickness a: plate width, b: fold width \( \theta_i \): folding angle, q: distributed load as defined in table 3.10, l: structure span, E: Young's modulus for glass and \( h_i \): structural height.

Based on the above equations and on theoretical geometry constraints for folded plate structures, the first goal has been to determine the spectrum of the folding angle, \( \theta_i \). Theoretically, folded plate structures present an optimal angle of 30 degrees, meaning that \( \theta_i = 15° \) where load distribution is achieved within the plane of the plate and beam action is combined with membrane action. Within the limits of 8° and 82° of folding angle \( \theta_i \), folded plates are still operating either primarily as beam elements, when the angle is getting smaller, or as plate elements, when the angle is getting larger. After \( \theta_i = 82° \), beam action is completely cancelled out by the out-of-plane bending of the pane, and each element functions as a flat plate.

According to folded plate theory, the ratio between the span l and the fold width b is also important. More specifically, it is required that the following condition is met:

\[ 2 < S/b < 4 \]

\[ S/4 < b < S/2 \]

In the opposite case, pretension might be required as the folded shape is of no significant benefit to the structure and the element mainly operates as a beam. Those conditions have also been taken into account when defining the geometry of the folded shape (fig. 3.12).

Following those specifications and taken as given originally a span \( S = 20 \) m, a plate size \( a = 2m \) and a glass pane thickness \( t = 3 \times 0.0012 \) m, a first set of hand-calculations was done for different deployment angles \( \theta_i \) in order to specify the effect of the deployment angle on the structural performance of the one-fold simplified geometry. The results for deflection and flexural stress are presented in the graphs 3.14-3.15. From those it becomes clear that the structural behavior radically changes after approximately a 60 degree angle, presenting an abrupt pick in both graphs of deflection and flexural stress levels. This pattern was tested again for a plate size \( a = 3 \) m and a thickness of \( t = 3 \times 0.0015 \) m and for \( a = 5 \) m and \( t = 3 \times 0.0015 \) m and presented the same comparative results.

As a consequence, the folding angle \( \theta_i \) was defined between 8° < \( \theta_i < 60° \), for the purpose of this project. 8 degree angle describing the structure at the fully folded state, and 60 degrees at the fully enclosed state. All further preliminary analyses were performed for those two states.
CHAPTER 3B- Structural Analysis

Based on those first hand-calculations and using the predefined design limit stresses and deformations as mentioned in the previous chapter, different combinations of plate sizes $a$ and thicknesses $t$ were tried, for the given span $l = 20$ m and considering the most unfavorable deployment configuration, the one previously defined at $\theta = 60^\circ$.

The result has been that for a pane number of four, resulting in three panes in the calculation, which is convenient as far as the connection method is concerned (see chapter 3C-Connection principle), the difference made by increasing the plate thickness has been very subtle, while the plate size $a$, resulting in an alteration of the structural height $h_t$, is much more crucial. A minimum of $a = 3m$ appears to be required for the draft calculations to fall within premittable stresses and and deformations.

It is certain that beam theory cannot accurately be applied on the folded geometry, especially at $\theta = 60^\circ$, as it does not account for membrane action at all, but in any case those preliminary results provide a first set of parameters which were used as a first basis for the finite element analyses.

### 3B.3.2. Model Comparison

Given the preliminary results deriving from the hand-calculations, a draft comparison of finite element methods was made. The point has been to compare the general results deriving from the analysis in Karamba plug-in for Grasshopper and TNO Diana FEA software, to check if a first optimization of shape dimensions in Karamba is possible. As in Grasshopper directly, slight changes of dimensioning and angles is much faster and more efficient than exporting into Diana, the goal was to use Karamba as a first way of setting the geometrical parameters and cross checking the hand calculation results, in the case of the simplified one-fold model.

The comparison was done for a folded plate element of $S=20m$, $a=2m$ and $t\approx 0.0012$ as were the original hand calculations and for an "optimal" folding angle of 30 degrees. The same boundary conditions, as previously described have been set, and the same loadcase of selfweight plus live load was applied as element pressure. Results were compared for rigid connections between plates, and for hinged plates, which were approximated in Karamba using an interface of very small width and Young’s modulus along the edges, and in TNO Diana by use of th method of tyings. Tyings are applied between neighboring nodes of separate elements to impart that translation, but not rotational moments are transferred from plate to plate.
It can be noted that the deformation results present more accuracy and indeed appear to be closer, because the stress levels are not exported node by node in Karamba and control of numeric values across the edges is only possible visually, from the output contour levels, like shown on fig. 3.17. For this reason Karamba results have not been used as descriptive of the model behavior. Instead only the deformation results and the depiction of stress levels were used to provide a basis for narrowing down the geometry parameters to be used in the Diana model. In this respect the hand calculation conclusions were verified and the parameters mentioned before were used as the first input for the finite element model in TNO Diana.

### 3B.3.3. Simplified one-fold

The simplified model which was specified by the first hand and Karamba calculations was exported in .iges format and used in FX Midas for meshing and specifications and from there to Diana. The first model was developed in FX Midas, while the for next ones, with slight alterations the Grasshopper script mentions in chapter 3A was used.

Finite element analysis was performed at the two extreme states, at fully folded (θ = 8°) and fully unfolded (θ = 60°) state. Results are presented in fig. 3.19-3.23. As expected, the geometry appears to be behaving like a beam in the first state, presenting higher deformation in the middle of its span, and higher tensile stresses in the middle of the bottom edges. Opposite, maximum compressive stresses are located on the top edges where the plates meet. In the second, deployed, state, the elements show some plate action, and deformations appear in both directions. Same for the principal stresses, results appear more disperse, although maxima and minima are still found on the top and bottom edges. Shear stress peaks around the connection at the ends should not be taken into account, as the boundary conditions are now defined by single nodes, which will not be the case in reality. The outcome values check with the preliminary expectations, and for the given dimensioning are within the permissible design limits, as far as deformation, tensile and compressive and shear stresses are concerned.

### HAND CALCULATION TNO DIANA RESULTS

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<th>deployment angle (θ)</th>
<th>Reaction force (N)</th>
<th>Deflection (m)</th>
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<th>Shear stress (N/m²)</th>
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### SHEAR STRESS Sxy

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<th>Shear stress (N/m²)</th>
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</tbody>
</table>

It can be noted that the deformation results present more accuracy and indeed appear to be closer, because the stress levels are not exported node by node in Karamba and control of numeric values across the edges is only possible visually, from the output contour levels, like shown on fig. 3.17. For this reason Karamba results have not been used as descriptive of the model behavior. Instead only the deformation results and the depiction of stress levels were used to provide a basis for narrowing down the geometry parameters to be used in the Diana model. In this respect the hand calculation conclusions were verified and the parameters mentioned before were used as the first input for the finite element model in TNO Diana.
Having completed this simplified analysis it is assumed that the conclusions regarding folding angle limitations are applicable also to the more complex six-fold shape, since it falls within the same geometrical boundaries. For the same reason the resulting dimensioning of the one-fold model will be used as a first input for the six-fold one.

3B.3.4. Preliminary 6-fold

The six-fold model has been set as shown. The meshing has proven significantly more challenging, due to the triangular shape of the elements. Special attention has been given during mesh division and further processing, in FX Midas, so that mesh nodes in neighboring plates are found at the corresponding places and nodes are merged when required. For this model, hinged connections were simulated as they were previously on Karamba, by intersurfaces which are attributed the properties of the connection material and the expected distance between plates (see chapter 3C-Connection Principle).

As expected, results differ a lot from the ones of the one-fold structure. Although tensile stresses on the edges and shear stresses appear lower, it is easily notable that the "hanging" side flaps, which are not supported on either side present very large deformations and are compromising the stability of the whole system. This points to the conclusion that those elements need to be somehow supported as well. Supporting them would be particularly challenging, because the endpoints of those flaps are translatable on all axis during the process of deployment. However, it is necessary to provide a secondary support mechanism for those points. Assuming those elements as supported in the same way as the other ones, gives far better results, with the biggest deformations concentrating around the meeting point of the folds, at the top. This is also an area with large concentrated compressive stresses. In this direction, a geometry with chamfered edges might be a solution, providing better stress distribution. Those are improvements that still need to be tried.
3C. Connection Development

3C.1. Bend and Break

Part of the conducted preliminary research, on connection properties and structural evaluation of folded glass plates has been done in the course of the Bend and Break Minor in the department of Civil Engineering. During this course, four groups of students worked on developing a concept of a foldable glass plate structure and a connection principle, make mock-ups and perform some basic testing on both the final product and the connection. The results, although partial, already have provided some insight on the advantages and disadvantages of some connection materials, or folding techniques.

After a series of introductory lectures, students were asked to develop their own connection principle, based on suggested materials and existing research. Three different types of connections were implemented and further tested in the lab. Pull-out tests were performed on the connection principles, on a simplified configuration. Three different hinge connections were tested, a ‘traditional’ steel one, one using PUR composite and one using aluminum composite sandwich plates. Specimens were subjected to a standard tensile force, measuring strain over applied force. Data from these tests appear in the diagrams 3.16 to 3.19. Each Test were repeated for eight specimens, but here one graph will be presented per connection principle as an example. The connection principle using PUR composite, was additionally tested for strain under tensile force and for fatigue under 2500N and 3500N and over 1000 cycles. Tests were made on specimens with an engraving determining the area of the folding.

More thorough tests on the fatigue of the specific material will be conducted as part of this research project. Besides the outcome of the pull-out test, further physical experimentation proved the aluminum composite panel as inadequate for structural purposes as it is prone to fatigue.

On a next step, students were asked to design a simple folded plate structure, make a mock-up under scale, with the selected connections. The final mock-ups of the folded structures were made out of two layers of glass panes, glued together with two-component adhesive, and incorporating...
the connection. They were submitted to loading, linearly distributed over the longitudinal axis by use of a wooden beam, as it shows in the pictures.

It is interesting that although deriving results from loading a full mock-up can be quite difficult, as separate effects cannot easily be separated, it appears that these types of folded structures mostly suffer from large stresses around the fixed boundaries, where the concentration of stress can cause glass breakage, along long edges or within the connection. These weaknesses can be tackled separately by taking some precautions. First by expanding the boundary area, in order to avoid high stress concentrations, for example by ‘chamfering’ the corners of the fold at the points of fixing. The second is to optimize the design geometry so as to avoid very long free edges, as this is where the largest deformations are found and aslo where there is risk of lateral bucking under compression. Finally, extra care needs to be given to the quality of the connection detailing and a series of tests need to be done on the selected connection principle based on the expected stresses in the pinned supports between plates.

3C.2. Introducing PURE® composite

The thermoplastic composite which is found under the commercial name “PURE®” is a flexible and highly strong composite developed and patented by DWI Holding B.v. It consists of polypropylene with 70% fiber composition. As mentioned by the company in the product description: ‘The PURE® tapes are co-extruded and consist of a highly oriented, high strength and high modulus core and a specially formulated skin on both sides for welding the tapes together in a compaction process using a hot-press or continuous belt press.’

The main application fields of the material so far include consumer market, including helmet and suitcase protection, automotive and marine as well as tubes and vessels. Its material properties, as shown below demonstrate a very strong potential in its application to the building industry. Especially
in the scope of this research, PURE is investigated as an innovative alternative hinge principle, which appears to present some advantages as compared to more traditional hinge systems:

- Provides a more aesthetically integrated result
- Is very light-weight and flexible, with a high impact resistance
- Reduces weathering of the connection
- Is ecological and recyclable
- Uses a simple product method
- Offers potential sealant properties-waterproofness

The material can be found in the form of tape, sheets and sandwich panels. For this project, PURE® sheets of varying thicknesses will be used for testing and mock-ups. Given that the material has not previously been considered for structural applications, there is a broad spectrum of technical properties than require further investigation, in addition to the facts provided in the technical sheets. A full description of the suggested tests follows in chapter 3B.4.

The application of the specific material and the exploration of its potential as hinged plate connection materia has been one of the research sub-questions since the beginning, and thus a startin point of the connection development, epsecially given the positive draft results of its use in the Bend and Break Minor course.

### 3C.3. Pane to pane connection requirements

Traditional hinges and systems usually used on those cases might be sufficient enough but account for very bulky connection details which do not do justice to the elegance and transparency of the structural glass, while the same timeusing an excess of material. The PURE composite has been applied in this project as an alternative connection method, mmaking use of the flexible yet very strong properties of the material.
The connection detailing plays a very important role in the course of this project, since there is limited research performed on glass connections, but also due to the fact that hinged edges are the spots where the largest stresses are bound to occur. It is crucial that the connection allows for a smooth deployment from 80° to 60° while simultaneously preventing the glass panes from touching under compression. The way this non rigid connection behaves upon a symmetrical loading and how that affects the structural integrity of the whole is one of the main challenges.

The connections are also required to take up the tolerances when needed, given the fact that glass is a very precise material which requires equally exact measurements. The relatively large deformations allowed for folded glass plate structure means that very high stresses can be generated on the glass edges, around the connections unless tolerances in both directions are not taken into account.

In the case of folded structures the connection is additionally the means to avoiding leaks, and effectively sealing up the enclosed space. Thermal insulation will not be part of this research, as mentioned in the research boundaries, so the thermal properties of the materials and their effect on the indoor climate will not be discussed.

Finally, in case of damage on one of the plates, replacement procedure must be taken into consideration. Every one pane must be able to be detached from the structure, without the general stability being compromised, and replaced on the spot, by a new one. This means that the connection fabrication must not be entirely restricted to factory conditions, or a secondary assembly method must be considered for the case of damaged panes.

To summarize, the design aims regarding the hinge connection principle:

- Discrete design-maximum transparency
- Tolerance in both x and y direction
- Waterproofing (restriction of gaps)
- Repair work facilitated

**3C.4. Connection development**

**3C.4.1. Connection concept**

One first approach has been attempted based at a great extent to the research by Anne Bagger, The detail concept presented on the sketch 3.43 uses PURE composite as folding material and attaches the PURE sheet to the glass panes by friction, imposed externally by steel clamps. The problem with a solution like this is that in order to achieve the necessary friction level, large steel surface would probably be required along the edges, and it is possible that clamps would need to go around the glass edge, thus interrupting the continuity of the PURE sheet between panes.

A second and more interesting approach is to make use of the high tensile strength of the material and use a set of aluminum or steel disks glued between glass panels to keep the PURE sheet in place. This results in a very elegant connection detail completely embedded into the glass thickness. Replacing metal disks by glass ones would make the connection almost invisible. Further tests will be conducted on glass on glass adhesion to investigate this case. The sizing of the holes in the PURE sheet related to the actual size of the discs can account for the demanded tolerances within the plane of the plate. Additionally, this kind of connection develops along all the length of each edge and given that the material in itself is waterproof, provides a good solution for the watertightness of the full structure. Extra customized covers can be placed on the meeting points between adjacent sheets. Because of the mechanical connection of the PURE sheet with the glass unit, replacing a damaged unit is facilitated, implying that only the adhesion of the discs to the external glass pane needs to be done in place. Also, if the external pane suffers from some damage, it can be replaced without removing the entire glass element.

Since this design appeared promising and showed potential in fulfilling all set requirements, it was selected to proceed further with.

12 Anne Bagger: Shell plate structures of glass, studies leading to guidelines for structural design, 2010, DTU Civil engineering report R-221, UK
Two mock-ups have successively been made, one using aluminum discs and two-component adhesive and one using discs cut out of float glass and DELO UV curing adhesive. For both of the mock-ups, an engraving in the middle of the PURE surface has been introduced to facilitate the folding, but its effect on the material behavior has been more thoroughly investigated later on. The mock-ups were made using aluminum disks of 1.9mm diameter. This dimension has derived from a first geometry optimization of the connection design, by means of Galapagos solver, in Grasshopper.

Given the variety of disc sizes, distances and configurations that could be used, there needed to be a first optimization in order to choose the dimensions to submit to testing in the lab. In this direction, regulations and guidelines concerning steel construction were used to define the required spacing between disks and distancing from the edges as a function of disk radius, considering the disk positions working as bolts. Rhino 3D drawing software and Grasshopper in combination with Karamba FEM analysis plug-in were used to model the connection and an optimization was run using as parameter the radius of the disks for a configuration of 3+2, as shown on mockup. As fitness condition was set that the resulting principal force be the minimum. (fig. 3.50-3.52) Two different solvers were tried within Galapagos, the evolutionary solver and the annealed solver. Despite the different algorithmic optimization method that those use, they both came down to the same result.

The results point to a radius of 9mm, which for the tests was rounded up to 10mm or 20mm diameter, to facilitate production of glass discs. However the meshing of the surface still requires refining and the final results will be tested more thoroughly on FEM, using TNO Diana for confirmation, parallel to the physical testing of specimens.
3C.5. Connection detail

at $\theta_i = 60^\circ$

LAMINATED HEAT-STRENGTHENED GLASS PAN
THICKNESS: 2 X 15 mm

PURE SHEET
THICKNESS: 3 mm / HOLES OF 50 mm DIAMETER

GLASS DISK
DIAMETER: 40 mm / THICKNESS: 4 mm

RUBBER SEALANT

at $\theta_i = 8^\circ$

LAMINATED HEAT-STRENGTHENED GLASS PAN
THICKNESS: 2 X 15 mm

PURE SHEET
THICKNESS: 3 mm / HOLES OF 50 mm DIAMETER

GLASS DISK
DIAMETER: 40 mm / THICKNESS: 4 mm

RUBBER SEALANT

3C.6. Lab Tests

Following the first optimization process and building of mock-ups, a series of tests were required to specify the material’s behavior in the specific connection detail. As currently designed, there are two main load transferring mechanisms in the connection:

1. Adhesive: glass plate / glass disc
2. Mechanical: PUR sheet / glass disc, and PUR sheet / glass plate

Since the PUR composite has not previously been used in construction applications, there were not satisfactory literature data to be considered. This meant that all material and connection properties need to be thoroughly investigated. In the scope of this research, material properties included in the technical data sheets were considered, as well as technical data for the mechanical properties of DELO 6648 adhesive, which has been used for the mock-up and specimens. To determine the behavior of the material under repetitive loads which are expected in the deployable structure, fatigue tests have been conducted in the laboratory under the supervision of F. Veer.

As far as the mechanics of the connection principle are concerned, the connection has been analysed using finite element method in Diana, for tensile and shear in-plane stresses, as well as for out-of-plane compression, under vertical and horizontal loading. Limitations of time made it impossible to test all those properties in the laboratory as well, so lab testing has been in this case limited to pull out tests on the glass disc to PUR sheet connection.

For the designing of the specimens, mainly regarding the thickness of the PUR, the preliminary results of the FEM analysis on the six-fold geometry have been taken into account together with the connection optimization. Laboratory tests were done following standard protocol on the specified specimens to determine limit loads and show the manner of failure. The results of both the fatigue and pull-out tests were used as a reference of comparison to the outcome of the FEM analysis, as descriptive of limit stresses.
3C.6.1. Fatigue test on PURE®

As part of the test planning, a series of fatigue tests will be performed on the PURE composite to ensure that it can efficiently be used in a structure of an large expected life-span. Hold time is specified as the time interval between consecutive loadings. Three different hold times were tried in turn, 1 sec, 5 sec and 20 sec. The period that each cycle lasts is determined by the machine, and presents certain fluctuations.

Two sets of specimen will be used, of 10 specimen each. One is with an engraving along the middle, to define the area of the foldig and one without engraving. Sheet thickness is 1.8mm and specimens were cut on a laser cutter. Engravings were made setting the laser cutter at a speed of 180 and strength of 40, to achieve an engraving line that reaches less than half of the material thickness. In theory, since the PURE composite is basically a lamination of woven sheets melted together, the engraving shouldn’t compromise the integrity of the structure, but rather cut through a number of layers, reducing the effective thickness accordingly. A way of measuring accurately the depth of engraving and whether this depth is standard for all specimens will be investigated on further.

On these specimens, and starting with the engraved set, first fatigue tests have already been done. As a first step a tensile test was made to define the Ultimate Limit Load of the specimen. The specimen was severely damaged, although not completely detached, at 6000N. This ULL for tensile strength is used as a reference for all subsequent fatigue testing of this type of specimen. A first test on 100% of the ULL over time was conducted.

Based on this data, first fatigue testing was performed for 75% of the ULL, at 4500N, at 1000 cycles. During this test, the specimen did not break before completion of the 1000 cycles, but started to tear out along the engraving at 450 cycles. Anomalies spotted on the graph, (graph 3.41) show tearing of fibers inside the material. It can be seen for the graph, but also during the test that gradually minimum deformation increases at zero load. After the completion of the test, we notice plastic deformation even without breakage which points to material damage.

Since there has been no breakage at 75% of the ULL, the next test was one for increased load of 5500N, again at 1000 cycles. Here visible delamination and tearing out started early, at 100 cycles, while the specimen broke at 289 cycles. Given these first results, tests will be continued for a lesser percent of the ULL.

It is interesting to note that the fatigue behavior of the material is largely related to its woven fiber structure, combined with the fact that it is made of separate layers melted down together. So far it appears that our original assumption was correct, and that the engraving means a significant reduction on its nominal thickness. It can be noted that around the engraving at both tests there has been a visible ‘tearing out’ of the material which continues up to a certain length away from the engraving. This tearing indicates delamination in the material structure, which could lead to unpredictable failure and as a result, eliminating the engraving needs to be considered.

Comparing the results for the same specimens for different loads and holdtimes over time is giving some valuable insight on the structural potential of the material. By looking closely at the local maxima and minima in the strain values over time, more descriptive diagrams can be exported for the behavior of the material under different ammount of load, for the same holdtime. Respective duration of the loading cycle each time can be determined in this way as well.

By plotting strain maxima over time, it becomes clear at which point the material strength ceases to deteriorate and the behavior of the material is getting stable in the long run. A safe load is determined when the graph of strain over time tends to a horizontal line, implying no further alteration of the material condition. In this case, this can only be spotted for the load of 3500N over an area of 40mm by 1.5mm.

On a second round, another set of specimens has been tested, of the same thickness of 1.5mm this time without the engraving. In this case, all specimens were tested only at a holdtime of 1sec, due to time limitations. Increased loads were applied, as tensile strength of the first specimen proved significantly higher, as expected.
As a result, loads of 9500N, 8500N and 6500N were applied. The results have been processed in the same way and by plotting the strain maxima over time, it can be seen that for a holdtime of 1sec, the specimen can withstand a repetitive load of 6500N with its strain tending to stabilize. The green line on the graph tends to a straight line which suggests that this is a safe design load for the specific material.

Given the large difference between this value and the 3500N deriving from the previous set of tests on the specimen with the engraving, it has been decided to eliminate the engraving entirely, and work on alternatives, if needed for the folding of the PURE sheet. This load of 6500N for the specific specimen corresponds to a maximum allowed stress of 90MPa. This was used as a stress limit for the material as far as all further FEM calculations on the connection are concerned.

**3C.6.2. Pull-out test**

To determine the load bearing capacity of the connection principle, a pull-out test was carried using the same equipment as for the fatigue test, under a different configuration. A customized testing configuration has been set especially for this type of test, as it was preferable for the compressive forces to be put in plane on the glass elements, so no clamping could be used. The final piece of equipment used can be seen in picture 3.65.

Specimens like the one in picture 3.65 of 40mm width were used, consisting of one glass disc of 20mm diameter and 3mm thickness glued between glass panes of 10mm thickness, by DELO 6648 UV curing glue. Two different sets were tested, one for PURE sheets of 1.5mm and one for double 1.5mm sheets, in lack of 3mm. For the specimens of double thickness two discs superimposed were used. Four specimens of each category were made to be tested, eight in total.

Increasing load of 2N per second has been imposed on the specimen in the purpose of showing the reaction of the sheet of PURE around the glass disk. The test was set to automatically stop either when the specimen loses 80% of its tensile strength or a displacement of 40mm is reached.

Surprisingly, the results of the test have been quite largely varying for the first set of 1.5mm PURE sheet with a single glass disc. The PURE sheet was significantly deformed in two out of the four specimens, as can be seen in the descriptive results on the opposite page. Parallel or instead of the PURE deformation, there has been damage to the glass around the glass discs and adhesive failure. All types of failure occurred around the same tensile force levels, between 2129N and 2557N, which corresponds to an average of 39.70MPa given the section area of the specimen.

In the case of the double sheet specimen with the double glass disc, results are quite more consistent but not the ones expected. Instead of the PURE deformation and failure expected, all four specimens failed at the adhesive connection between glass disk and glass plate. Additionally to this, in three of the cases additional breakage of the disks occurred. On the contrary, the PURE sheet has not been deformed beyond material failure. The maximum tensile force reached varied from 3955N to 4913N, giving an average of 73MPa of allowable tensile stress. Based on the technical data of DELO-photobond 4468 UV curing glue, compressive shear strength of glass to glass adhesion is 22MPa. A combination of those results suggests that the adhesion properties are the ones indicating the allowable stress in this case.

This result was against the purpose of the test, which was to determine the material limit. It appears on the contrary that the maximum force level mentioned, refers instead to the shear strength of the adhesion between glass plate and glass disk. This points to the conclusion that the disk surface needs to be expanded to provide for a bigger adhesion surface. However, the resulting design stress limit of 73MPa will still be used as a reference for the FEM calculations, as conduction of more tests for larger disk diameters is not possible within the scope of this research.
CHAPTER 3C - Connection Principles

SINGLE 1.5mm /1 DISK

<table>
<thead>
<tr>
<th>Specimen Description</th>
<th>Standard travel</th>
<th>Standard force</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. glass breakage around disks - PURE deformed</td>
<td>8.954</td>
<td>2354</td>
</tr>
<tr>
<td>2. PURE deformed + failure</td>
<td>11.539</td>
<td>2557</td>
</tr>
<tr>
<td>3. glass breakage - glue did not fail</td>
<td>9.344</td>
<td>2129</td>
</tr>
<tr>
<td>4. glue failure</td>
<td>11.081</td>
<td>2497</td>
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</tbody>
</table>

Average force 2384

DOUBLE 1.5mm /2 DISK

<table>
<thead>
<tr>
<th>Specimen Description</th>
<th>Standard travel</th>
<th>Standard force</th>
</tr>
</thead>
<tbody>
<tr>
<td>5. glue failure+ glass disk breakage(between disks and with plate)</td>
<td>8.228</td>
<td>3955</td>
</tr>
<tr>
<td>6. glue failure disk/pane-small PURE deformation</td>
<td>14.239</td>
<td>4913</td>
</tr>
<tr>
<td>7. glue failure disk/pane-small PURE deformation-glass breakage (disk)</td>
<td>7.670</td>
<td>4132</td>
</tr>
<tr>
<td>(dif. pat)8. glue failure disk/pane-small PURE deformation-glass breakage (disk)</td>
<td>10.744</td>
<td>4207</td>
</tr>
</tbody>
</table>

Average force 4417

From technical sheet

MAX TENS. STRESS

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td></td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>Mpa</td>
</tr>
</tbody>
</table>

From fatigue testing

safe design stress for PURE composite: Unnotched

6500 N over area of 15mm x 40mm:

Max tensile stress 9.03E+07 [N/m2]

Max principal force 1.35E+05 [N/m]

Pull-Out testing

on a 40mm width

<table>
<thead>
<tr>
<th>Specimen Description</th>
<th>Standard travel</th>
<th>Standard force</th>
</tr>
</thead>
<tbody>
<tr>
<td>SINGLE 1.5mm /1 DISK</td>
<td>Average force 2383.98 [N]</td>
<td>Max. shear stress 3.97E+07 [N/m2]</td>
</tr>
<tr>
<td>DOUBLE 1.5mm /2 DISK</td>
<td>Average force 4417.37 [N]</td>
<td>Max. shear stress 7.36E+07 [N/m2]</td>
</tr>
</tbody>
</table>

Average force 2384

Table 3.71 (opp. page bottom): FEM analysis numeric results

3C.7. Finite Element Analysis

3C.7.1. Pull-out FEM simulation

With a combination of the technical data provided by the company and the outcome of the tests mentioned above used as design stress limits for the connection, a Finite Element analysis has been done on the connection under the expected loads, defined in a preliminary way on the analysis of the full structure.

More specifically, the glass disk connection principle has been tested under tension, applying the reaction in-plane tensile force expected on the bottom edge of the structure. The aim has been to determine the adequate PURE sheet thickness and check the resulting stress levels against the allowable ones, from the tests.

For the Finite Element Analysis, different meshing options have been tried, as an appropriate and relatively fine meshing between the holes is essential for the understanding of what stresses are induced in those areas. For this purpose, dodecahedrons were used instead of circles to make the meshing easier and more accurate, and a Delaunay mesh division using quadrilaterals was used as shown on fig. 3.68. Supports were modeled as half disc surface of a stiff material in direct contact with the PURE surface, in order to simulate more realistically the effect of the glass disks on the PURE sheet. The reaction force on the edges of the geometry from the six-fold FEM analysis was applied as distributed tensile force along the edge of the PURE sheet. Thicknesses of 1.5mm, 3mm and 5mm were tried and compared.

Given the results, it can be observed that 1.5mm thickness is as expected far too little to take the imposed forces effectively. On the other hand, 5mm thickness of PURE might prove to cause difficulties in folding. So a thickness of 3mm seems to be the most adequate. As presented in the
CHAPTER 3C - Connection Principles

3C.7.2. Out-of-plane compression FEM simulation

Hinge connections between folded plates suggest a certain level of instability, especially considering unevenly distributed forces or horizontal loads such as wind. For this reason, the out-of-plane compressive force generated between elements at the mountain folds is a major issue for the overall stability of the structure. There is a significant danger that the connective sheet of PUR might deform exceedingly, leading to an alteration of the structure's symmetry and a redistribution of loads. The amount of this deformation, in relation to the dimensioning of the connection and the glass plates is also critical in the sense that it might cause the glass panes to come into contact and directly transfer loads from pane to pane, thus concentrating stresses on the glass edges. In this case, a secondary load transfer mechanism would need to be developed to avoid that.

This behavior is mostly evident in the case of asymmetrical loading scenarios, such as wind load, or unevenly distributed live loads, where one plate translates in comparison to the adjacent one. So far in the process of this research the assumed loads have been considered evenly distributed on the plates and thus completely symmetrical in regards to the linear connection sheet. In order to check the effect of this asymmetrical loading with regards to the plate to plate connection, a new finite element analysis is required on a different type of model.

Moreover, it needs to be noted that this behavior is largely related to the width of the connective surface between elements, which has not realistically been considered in the preliminary calculations of chapter 3B. Because of the material stiffness, and given a PUR sheet thickness of 3mm, it is necessary to provide a minimal distance to make the folding from 60 to 8 degrees possible. The minimum distance required has been set at 50mm, as is also shown in the drawings, that follow.

For this purpose, a linear static finite element analysis was performed on plain strain elements, modeled like two facing plates with a surface of 60mm width and 3mm thickness in-between. Different loading scenarios were considered to examine distinct unfavorable loading situations. The focus has been on the resulting deformation shapes and values.

Scenario 1: Vertical load applied on one plate: self-weight and live load. For this scenario a vertical load equal to the ULS applied for preliminary calculations was applied, only on one of the two adjacent plates. Clearly, this is not a likely scenario to occur, but it is the most high-risk one and so it needs to be taken into account during the testing. The assumed load was an evenly distributed load of 2230N over a plate area of 1m².

Scenario 2: Horizontal wind load on one plate in combination with self-weight. The wind load has not yet been taken into account in preliminary calculations and is a crucial factor concerning the overall structure stability. A wind load of 400N/m² as shown in the loadcase table (3.10) has been assumed, acting on one of the two adjacent plates. In combination to that, the self weight of all elements was also added to the model.

Scenario 3: Vertical symmetrical load in both plates: self-weight and live load. This is the least challenging and yet more realistic scenario, where loads are evenly distributed over the plates and there are no horizontal forces. Even in this case, given the material properties of the polypropylene sheet, it is possible that the deformation of the material in the connection might cause the plates to clash, so it also needs to be tested in this configuration. The load used in this case is again one of 2230N/m².
SCENARIO 3

For this purpose, the connective sheet was drawn in the two-dimensional model as a curved element of 3mm thickness in the z direction, along the edges of the glass panes. The element is modeled using 2D plane strain elements, to which the material properties are attributed based on the PUR composite technical data sheet. More precisely, the properties are defined as following:

- Elastic modulus: 5.5 E09 [N/m²]
- Poisson ratio: 0.05
- Mass density: 7600 [N/m3/g]

The glass plates were also modeled using 2D plane strain elements attributed glass properties:

- Elastic modulus: 7.2 E010 [N/m²]
- Poisson ratio: 0.22
- Mass density: 24700 [N/m3/g]

The boundary conditions for the two plates were considered pinned on the one side, allowing rotation around axis z.

As shown in the numeric results, deformations are not significant, compared to the 20m span of the structure. It needs to be noted that in scenario 3, of even load distribution, the largest deformation of 15mm on scenario 1 is still a permittable result, which implies that despite the asymmetrical pane translation, the two glass plates do not come into contact and the shape alteration is not so significant to imply severe redistribution of loads, leading to instability for the plates structure as a whole. So far it appears that the stiffness of the 3mm sheet is already enough to guarantee that there are no excessive deformations around the connection.

However, despite the very small deformations this aspect is one that needs to be further investigated, since dynamic behavior of this kind is very hard to predict. For this purpose a dynamic non-linear analysis would need to be made.

Also, it is certain that finite element modelling is not a fully adequate verification when it comes to a material as complex, which includes dynamic structural and elaborate material behavior, which has not been previously tested. In order to draw more conclusive results, a physical testing of the connection in out-of-plane compression is required, with the specific geometry configuration and using a sheet of PUR composite of a 3mm thickness.

As far as the sheet of PURE is concerned, the induced stresses are still within the allowable design limits, which means that not only the glass plates are not in danger of coming in contact but the connective sheet will not fail in the process.

3C.8. Conclusions

As a result of the physical testing and the finite element analysis run both on the sheet of material itself and on the connection as a load transfer system, the main conclusions to be drawn affecting the finalization of the connection design are the following:

1. The addition of an engraving is not necessary for the folding of the PURE sheet, given the big stiffness difference between the material and glass, which causes it to bend relatively easily in the specific application. The use of an engraving only reduces the structural thickness and compromises the structural performance of the material, as shown in the fatigue results.

2. it appears that the shear strength of the adhesive connection is quite restricting. and for this purpose, the size of glass disks needs to be increased to provide a larger contact surface for the DELO glue.

3. A sheet thickness of 3mm appears to be sufficient for the connection, based on both pull-out lab tests and finite element analysis, under tensile stress.

4. The distance of 60mm assumed between plates for the connection material to fold, is satisfactory for the folding process, but is likely to create problems of glass plates coming into contact. If that is the case, measures need to be taken either by increasing the distance or by protecting the glass edges adequately.

5. A set of design limit stresses has been determined which appears satisfactory for the preliminary design, but needs to be revisited at the finalization of the design both of the structure as a whole and the connection detailing.
4. Finalisation

The most challenging part of this research project has definitely been the process of finalisation, which practically refers to the bringing together of the outcome of the geometry and the connection development. Since the two aspects of the topic, working on two very different scales, and with different methodology, have been advanced separately, the step of providing mutual feedback between the results in order to come down to a final design is of great importance.

At this stage one of the goals is to also determine whether the developed geometry, based on the selected six-fold pattern actually performs better than the respective one in the simplified version as tried before, in chapter 3. In case that the more complex and admittedly more interesting six-fold geometry does not present certain benefits that out-balance the issues due to complexity, a switch into a more simple geometry might need to be considered as an alternative.

In this direction, the correct material properties and dimensioning has been applied to the six-fold finite element model. The goal has been to compare the results of this analysis to the known properties of the glass as a material but also the strength of the connection as it derives from the process described in the previous chapter. This is in order to determine whether the application of the connection on the particular geometry is efficient and define the probable issues which arise out of this application. In turn, once the geometry is further developed and set, the resulting forces on the connections have to be compared to the ones assumed during the previous phase to ensure that the structural verification of the connection is still credible. In the opposite case it is necessary to repeat the analyses on the connection element.

4.1. Geometry development

Given the outcome of the preliminary results of the finite element analysis, in combination with the connection properties previously defined, there is a number of possible improvements in the general geometry to improve the structural performance:

- Providing extra supports at the side "flaps" as demonstrated in fig. 4.1., to prevent excessive deformation.
- Chamfering the triangular plates at the top and around the support points to reduce stress concentration.

4.1.1. Extra supports

This conclusion, combined with the need for the roof structure to be both airtight and watertight at the deployed state, when the pool space is enclosed, leads to a necessary alteration in the original geometry, as shown in the fig. 4.2. The goal is for all support points to be located on the same plane at the deployed state of 60 degrees. As this plane refers to the side wall element, this guarantees that the roof will also be perfectly aligned to the wall, rendering thus easier the waterproofing. In order to make the distinction clear, the top nodes, which are located along the rails will be referred to as nodes A and the ones located between the lateral panes, as B.

Since all the coordinates of each item of the set of points B are changing over deployment time, meaning that the points do not constantly follow any of the axis x,y,z but rather follow a more complex trajectory in space. As a result, it is only possible to support those points at the two extreme deployment stages, at 60 degrees (fully deployed) or 8 degrees (fully folded). In order for the array of points of type B to be supported an additional support railing needs to be added on the wall, with the possibility to release the pane edges when the folding or unfolding process begins. The detailing of this connection will be further investigated at a later step of the research.

Although the fact that the set of points B cannot be continuously supported during deployment appears problematic, because it leads to very large deformations of the adjacent panes, this can also be beneficial in the specific case. Once those points are no longer supported and the folding
Given the alterations in the general geometry and most importantly those on the boundary conditions, a new finite element model was required to determine the benefit of the extra supports to the structural behavior of the folded geometry.

The main differences between this finite element analysis and the preliminary six-fold one is in the additional support points and the finer meshing of the intersurfaces and the plates. The supports are divided into more nodes in order to avoid the shear stress concentration noted in the preliminary results and extra supports are added as mentioned above, around the points B. A more detailed meshing has been used for the plates, of 0.3 element size, while an even finer one was used for the intersurfaces, in order to be able to draw more specific conclusions on the behavior of the plates around the hinged connections. The applied materials, and loads are the same as before (see chapter 3) and the dimensioning is the one deriving from the preliminary analysis. Three layers of glass giving a total thickness of 45mm are being presumed, as a redundancy measure.

The results of the linear static analysis show some interesting facts. First, the asymmetry of the deformation on the different plates, which is a result of material deformation in connection as it is demonstrated in the figures, if it is not a mesh related issue, could be pointing to unpredicted changes in the geometry and possibly redistribution of force flow which might lead to instability.

Also, the shear and compressive stresses that are produced at the top are significantly larger in this case compared to the simpler scenario, while the tensile stresses in the bottom edge of the glass remain relatively similar. The big augmentation of concentrated compressive forces at the top of the connections, parallel to the tensile principal forces remaining similar, shows that the convergence of six triangular plated at the top is highly problematic. As a counter-measure, a version of this geometry with chamfered edges at the top and at the support points has been tried as well, as a hybrid between the six-fold and the one-fold. This one is a four-fold geometry and thus four folds met upon one connection point instead of six, something which also facilitates the detailing significantly.

A type of hydraulic scissor dump system, like the one in fig. 4.3, could be used, connecting the side glass plates which during deployment are hanging freely, to the supported main glass panes. A rotator needs to be added to the connection to allow for the necessary rotation. In this way, the deformation happens more slowly and until a given point when the deployment process starts and the plates are no longer supported.
CHAPTER 4 • Finalisation

4.1.2. Chamfered geometry

As a next step, in combination to the addition of supports at points B, a chamfered version of the triangular plates has been tried, as shown on fig. 4.10. The folded geometry is modeled so that the plates have straight edges at the top, instead of meeting at an angle, and avoid the sharp corners around the area of lateral supports, on the rails. This is meant to avoid stress concentration in those areas which are the ones where the highest compressive and shear stresses have been noted. In terms of design this gives more of a hybrid between the architectural and structural qualities of the complex geometry of the six-fold and the benefits of the simple one-fold.

Indeed the results of this finite element analysis are much improved in all terms to the ones of the previous six-fold geometry. In fact, the results show far less stress peaks around the connection edges, and far more dispersed deformations. The deformations still occur asymmetrically at the meeting points of the four folds, Direct comparison to the results of the simple one-fold geometry analysis which has preceded is not possible since the level of detail of the two models and the simulation of the connection are far from comparable.

In general terms, it is presumed that the tensile stresses shown are assumed by the glass panes, while the compressive stresses mainly by the PURE sheet in the connections. (see fig. 4.16-Principal stresses S2). As a result, the basis of comparison for tensile stresses are the design limits of glass, for compressive stresses at the top both the limits of glass and the connection and for the shear stresses, as shown in the connection research, the limits of the adhesive.

Maximum deformations are well below the allowable levels, and are not noted on the glass sheets themselves, but rather at the connections, because of the flexibility of the material. Still, since the deformations are relatively low (30mm) and given the positive outcome of the connection finite element analysis for out-of-plane compression, it doesn’t appear as problematic. Tensile stresses developed in the glass panes, reaching a peak at the middle of the bottom edges of the geometry,
DEFORMED SHAPE

much like in the simplified model, are within allowable limits, given the material properties and safety regulations. The same holds for compressive stresses, along the top and the side edges, where plates meet under an angle. The behavior of the connection as a sheet of material has been thoroughly examined before, in chapter 3C, as it is difficult in the general finite element analysis to isolate the results to draw separate conclusions. Concerning the connections, the reaction forces appearing between adjacent glass panes at the bottom, respectively being transferred to the adjacent PURE sheet as tensile forces, they are still within the limits determined by the fatigue test ensure that in the in-plane direction, fatigue would not be a problem in the long run.

On the contrary, it appears that the shear stresses, which reach a peak around the top and around the supported corners of the geometry can be a problem. Although they can be taken safely by the laminated safety glass, the shear stress levels exceed the shear strength of the adhesive between glass panes and glass discs. Despite the increased dimension of the glass discs, this issue requires further attention at a connection level to ensure that the structure will not fail at the adhesion points which are the primary load transfer mechanism between the laminated glass plates, that ensure that those act as one.
4.2. Wind load and wind suction effect

As defined in the previous chapter regarding the assigned loads, besides the selfweight and the live loads which are determinant for the dimensioning of the structure, another important part is the effect of the wind on the roof structure, and particularly given the specifics of the building on which it is applied. There are two distinct aspects of this effect. One has to do with the resulting wind speed, which is due to the structure’s shape in relation to the direction and magnitude of the wind, and the other with the suction pressure on the building surfaces, which is the result of the negative air pressure created by the wind flow at certain areas.

In order to determine the resulting wind speed and resulting air pressure on the structure’s surfaces, a windflow simulation was set using Autodesk Flow Design, a software developed for simulating the effect of a given wind speed and direction, on a given model, in this case the one deriving from Rhino. for this simulation a simplified 3D model made in Rhinoceros was used. The direction of the wind was assumed as least favorable for the structure, given that there is no given orientation for the roof system; the wind speed was given by considering the maximum average windload in the Netherlands, and was set at 18m/s. The choice of the Netherlands as a location was used merely as a point of reference, since the specifics of the location have not been a crucial part to the development of the retractable roof system.

Figure 4.23 is showing both the results concerning wind speed around the building volume, on a given vertical plane and the air pressure generated on the building surfaces. As can be seen, there is an area of negative pressure created next to the building volume on the side of the wind origin, which causes suction pressure on the building elements, as shown in the simulation that pressure is of approximately 60Pa applied perpendicularly to the shown surfaces. This load is very low in comparison to the loading that the structure is designed for, given that the selfweight of the glass roof structure alone is 2230 Pa. Yet it is still a force to be considered, mainly concerning the connection detailing and especially that of the railing system.

On the other hand, from the results of the simulation, the windload to be used for the finite element calculation can be extracted. On the vertical plane of fig. 4.23 set in the appointed wind direction the different colors show the difference in wind speed around the building volume as it is determined by the original wind speed and orientation, and the building’s shape. The flow around the volume determines areas of higher and lower wind speed, which also affects the airpressure on the surfaces. As seen in the fig, the maximum resulting wind speed is found on the top edge on the side of the wind’s origin and according to the color chart, it is around 23m/s, which is equivalent to 317 N/m² of windload. This is the result to be set as the final load in the finite element analysis.

Given the outcome of the windtunnel simulation in Flow Design, a Finite Element analysis was run on the finalized chamfered model, with the same configurations as described above, but under a different loadcase. In this case, a horizontal windload, again from the least favorable direction, as shown on fig. 4.25, was applied on the exposed surfaces of one structural element, in combination with the self-weight of the element, without additional live loads. The exclusion of live loads was made so as to reduce the vertical loading to the standard, permanent one, in order for the effect of the horizontal force to be clearer. In this respect a loading scenario including wind but not additional live load, such as snow is presumed as least favorable and is analyzed for. A linear static type of

ADHESIVE LIMITS

| Tensile strength from fatigue test [Mpa] | 90.28 |
| Reaction force on edge, for pull-out [N/m] | 7.76E+03 |

Fig. 4.23 (opp. page): Airflow analysis results of wind speed (on the vertical plane) and air pressure (on the building surfaces).
CHAPTER 4 - Finalisation

In the results of this analysis, as demonstrated in fig. 4.26-4.30, it can be noticed that the effect of the wind is actually very limited in comparison to the vertical loading, in this analysis the self-weight alone. The deformations and induced stresses are lower than in the previous analysis, due to the absence of live load, and the effect of the asymmetrical horizontal load does not seem to be significant for the structural integrity of the structure. As can be seen from the deformed shape in fig. 4.26 there is almost no alteration in the axis of symmetry due to the lateral load, while the maximum deformation is still noticed at the middle of the plates, as was the case in the previous analysis as well. Also, at the top connection where exceeded deformation due to asymmetrical loading is a main concern for the PURE sheet connection (see chapter 3c.7) it appears that the material deformation is quite small, as expected from the Finite Element Analysis run on the connection. There is of course a small alteration in the compressive stress distribution, but the levels of local stress in this case are still well within allowable limits.

As a result, it is safe to assume that due to its increased weight, the stability of the structure is not compromised by the horizontal wind force and that the deformations in the connection due to the asymmetrical weight are very low and present no danger to the glass plates, by contact. As far as the structural system as a whole is concerned, the horizontal wind in the given direction could force the geometry into retracting but this is prevented on a detail level through the design of the railing connection.
4.3. Kinematics

The detailing of the mechanical system of deployment enabling this roof system is a very essential and complex part of the realization of this project. Given that the kinematic aspect has been one of the driving forces of this project, the way of making this possible is very important. Due to the increased complexity of the geometry of the structure and the largely mechanical nature of the problem, the design of the railing and deployment system has been based on extensive research.

4.3.1. Reference mechanical retraction systems

There is a relatively wide range of systems which can be applied to retractable roofs, depending on the specifics of the direction of the movement, the scale and special requirements. Methods of deployment generally applied to such openable roof systems, as for example in stadiums, include three major types.  

- **Traction drive system**: that is the simplest and most economical option for such operations. It is applied only to horizontal retraction systems and uses wheels, separately motors. When the roof stops, rail clamps function as parking brakes to hold the roof in place on the rail. (fig. 4.23)

- **Cable drive system**: this includes the roof plates being moved on a path by a cable drive system mounted to the panels. Each roof panel is equipped with four cable drums that spool cable anchored to the fixed roof. Each cable drum is powered by four motors, (fig. 4.24)

- **Rack and Pinion drive system**: This system operates similar to a file cabinet drawer. It includes four pinion gears, each powered by a gearmotor, engage with racks mounted to the two-stage guide assemblies. The pinions move along the racks to extend the guides. (fig. 4.25)

Based on the specifics of the case study in question, the traction drive systems appear simpler and more suitable to be applied on a complex geometry. The parallel directional rails in this case would be placed on the lateral walls, hidden from view in an insertion on the top of a wall. Based on the example of the Reliant Stadium, where the deployment system has been developed by UniSystem

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14 Based on the systems developed by UniSystem solutions (http://www.uni-systems.com/)
solutions, the concept of a mechanical kinematic system was developed like in the sketch.

4.3.2. System requirements

The kinetic system in question requires a certain customization, given the specifics of the structure and the geometry. A set of requirements have to be met by the retraction system detail. The main goal is to ensure that movement is powered in the given direction, the detailing of the railing system guarantees that the boundary conditions remain pinned as assumed in the structural model and tolerances can be taken on at least one side to take the induced deflection.

1. Translation on y-axis allowed during folding process and hindered at the enclosed state.
2. Tolerances on x-axis, at least on the one side, to avoid moments caused by the induced deflection.
3. Increasing the area of support as much as possible to avoid stress concentration.

In this respect, the needed connection system needs to be comprised by two main parts. The bottom one, placed on the directional rails, making possible the movement along axis y, the stop at the deployed state and incorporating the motor, and one hinge system allowing the plates to fold.

In order to include tolerances, a stress release system was applied to the connection of the plates to the railing system. A four-bar linkage system, like the one in the sketch (fig. 4.26) was used to allow slight plate movement on both sides of the railings. At the same time, this system maintains wheel alignment on both rails, regardless of structural changes caused by wind, sun and other forces.

4.3.3. Waterproofing

As expected, in folded geometries such as the one in question, waterproofing is an important issue, because of all the hinged connections along the edges which account for insulating and waterproofing weak spots. In this case the waterproofing of the edge connection is not so much the challenge. Rather, the most crucial part is the covering of the sides of the folded geometry, where the
structure meets the vertical wall element.

Since the PURE sheets are linear and extend to all the length of the pane edges, the material itself guarantees waterproofing along the seams. The challenge lies mainly on the edge connections, which can be solved by adding extra caps to enclose the connection, and on the edges where the kinetic mechanism is. In order to keep the water way and protect the water from getting in the rails and the motor system, the PURE sheet connecting the bottom edges can be extend to the side, forming a channel leading the water to a duct on the wall parallel to the rails, designed with a slight inclination to lead the water into the sewage system. (see fig. 4.35)

Concerning the waterproofing as well as air-tightness on the sides, at the connection to the wall, the folded geometry is quite a challenge and requires further design steps and additional problem-solving. An extra folding element needs to be added to cover the opening created by the six-fold geometry. This element could also be made out of glass, but an aluminum frame supporting a thin PVC sheet was chosen instead as a cheaper and more light-weight option. This element has the form of a flat vertical sheet, covering the triangular areas on the side of the glass plates, which folds inwards while the whole structure is in deployment, as shown by the flat and folded shapes in fig. 4.37. An aluminum rectangle frame around the PVC sheet is keeping the material in place, while allowing for the shape to fold due to hinges found at its corners. A reference for that frame could be the foldable sunscreen panels, used for photo shootings (fig. 4.38). The two top parts of the frame are attached to the glass panels by adhesion and when the plates fold the bottom part of the frame is forced to follow. When at flat position, the sheet lays on the secondary rail placed on the wall and is sealed by means of a rubber band.

A material suggested as a reference for the transparent sheet is a Flexi-Clear double-polished clear PVC Vinyl. DAF Flexi-Clear double-polished clear PVC Vinyl is an optically clear double-polished soft PVC film, which provides Ultraviolet (UV) light protection and is fire-resistant.  

Fig. 4.37. (left): PVC and aluminum frame foldable system for waterproofing on the sides.

Fig. 4.38. (top): Example of foldable aluminum frame, used for portable sunscreen panels. (Pro-Studio Solutions)

Fig. 4.36-4.37. Waterproofing detail on the structure to wall connection and the railing system, on the deployed and undeployed state.

Fig. 4.38 (bottom): Waterproofing foldable sheet detail, on folding.
4.4. Final Design

Fig. 4.30: Section aspect of the swimming pool space with the roof.

Fig. 4.31 (bottom): Drawings of the roof structure at fully opened state ($\theta_i = 60^\circ$), scale 1:200.

Front View at Fully Covered State
Scale 1:200

Side View at Fully Covered State
Scale 1:200

Top View at Fully Covered State
Scale 1:200
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5. Conclusions

5.1. Origami geometry applications and folding potential

The selected design of the folded geometry provides an interesting complex shape with the possibility of smoothly deploying on parallel rails. As explained above, the starting point of the geometry development was a particular six-fold pattern, selected for its ability to fully fold on one side, its relative structural stiffness and the non-existent lateral expansion factor. In the process of this research, the specifics of the shape and the folding have been determined based on the needs of the case study on the one hand, but most importantly on the structural performance of the geometry as a roof system. Adjustments and alterations have been made in the final steps of the design development in this direction, leading to a design which has been demonstrated to function adequately. This outcome shows the potential of applying the folding principle of planar “origami” surfaces on roof systems, as a way to combine both kinematic and structural performance aspects. This result can be extrapolated to apply to different building systems and materials, besides structural glass. In terms of feasibility, this study has shown that it is possible to create a self-supporting structure made out of plate elements which is also directionally deployable, without this compromising the system stability.

5.2. Structural behavior related to deployment

It has been shown that the proposed design is feasible in terms of structural performance, material behavior and connection principle. It provides an architecturally interesting solution, to a system of self-supported deployable roof elements made in glass. However, as mentioned before and as it appears in the appendix 3, when standing to comparison with the simplified version which was examined in the beginning of this research, it seems that there are no clear structural benefits from using a complex spatial folded geometry like this. Rather, from a purely structural point of view, it seems that the simplicity of the one fold geometry accounts for a slightly better and more predictable structural performance, as shown in the comparison table 4.29, and further elaborated in app. 3.

This might lead to reconsidering the final design in terms of efficiency. If its structural behavior is in reality not particularly enhanced by the more complex folded geometry, it might be argued that there is no point in seeking such an elaborate and complicated solution to the deployable system. This is even more eminent given the fact that the six-fold geometry also presents more issues of airtightness and waterproofing. At this point it needs to be pointed out that the purpose of this research has been to explore the extents of developing a full-stuctural glass deployable roof system using an innovative method of hinged plate connection and not to pinpoint an optimal geometry for the purpose. In this respect it has been proven that the geometry in question is feasible and effectively combines the kinematic and structural properties of folded plates as aimed for. The choice over this or a more simple geometry is a matter of design against cost and the benefits of one of the other can be subjective.

5.3. The potential of PURE composite as a connection principle

One of the main aspects of this research has been to examine the suitability of the PURE composite material as an innovative way of connecting folded plates in a deployable configuration. As a result of the physical testing and the finite element analysis run both on the sheet of material itself and on the connection as a load transfer system, it appears that the material, under the specific connection principle is feasible and highly promising innovation.

A sheet thickness of 3mm appears to be sufficient for the connection, based on both pull-out lab tests and finite element analysis, under tensile stress. The distance of 60mm assumed between plates for the connection material to fold, is satisfactory for the folding process. Due to the relative flexibility of the material as compared to the glass panes, there is no need for a notch or any other engraving measure to help the folding. As a result, the sheet performance is expected to be close to the givers of the simulations. A set of design limit stresses has been determined after having...
been revisited at the finalization of the design. Naturally, there is a lot of room for more exhaustive research, including extensive physical lab testing, which was not possible in the short scope of this graduation research.

More specifically, the acclaimed properties included in the technical sheets need to be verified in practice, since the building construction is not the predicted area of application for the material. Furthermore, the issue of out-of-plane compression and the extent of the material deformation in this case, examined in chapter 3C, requires further attention and lab testing, as it is a crucial risk in the case of flexible connections in a kinematic structure. Finally, a set of tests would need to be performed on real scale to examine whether the attributed properties are as expected on much larger elements.

5.4. Criteria assessment

At this point, the design has been finalised, although there are certain aspects, mainly concerning the waterproofing around the edge connections and the proper enclosing of the building envelope. There are several steps in the detailing that need to be taken further, but have no effect on the general geometry and its structural behavior. Looking back to the criteria set in the first chapter, it can be evaluated that the proposed design falls within the specified criteria and combines effectively the element of folding with a self-supported spatial structural system, using light and transparent hinged connections. More specifically, the criteria were separated into three categories, each one featured and analysed in a different part of chapter 3 (A,B and C).

DESIGN CRITERIA
1. Provide natural lighting and maximum transparency
2. Self-supported glass plate structure (no frame)
3. Deployable on one side (fully adaptable)
4. Feasibility (as related to cost and sustainability)
   1. Maximum transparency and natural daylight has been a constant priority, without implying that absolute transparency or solar exposure is considered necessarily optimal. On the contrary, it is considered that the juxtaposition of a transparent roof consisting of folded glass elements with the solid walls provides an interesting relation of light and shadow, and materiality contrast which is of high architectural value.
   2. The developed system is completely self-supported without requiring any additional elements. As opposed to the usual roof glazing systems, in this case the glass panes comprise also the load bearing structure spanning over 20m of area.
   3. Full deployment from 0 to 90 degrees of folding angle has proven to be non-efficient as at the extreme cases the structural effect of the folding is cancelled. However, at the current fully opened state, of 8 degrees folding angle, the architectural purpose of the opening is still achieved. The proportion of covered and uncovered space is still very low, while with the specific architectural planning set in chapter 3A, this can also be used as an advantage, a way of covering the spectator area from sunlight and rain even in summer. If combined with some sort of glass coating the folded plates could possibly comprise a sunshading element as well.
   4. While it is certain that a structure of this scale and complexity in glass is an innovation which comes at a high cost and maintenance, it is still considered that the drawbacks have been minimized as possible. Maintenance work has been facilitated both by the connection and the railing system and the plate sizes used may be exaggerated but are still within the limits of feasibility in the contemporary market. It is implied at this point that the glass plates used will probably be cross-laminated plates of 10m length and not continuous glass sheets.

STRUCTURAL CRITERIA
1. Controlled element deformation + stress levels (all phases of deployment)
2. General shape stability (all phases of deployment)
3. Glass element redundancy
4. Damage sensitivity - Fracture mode – Safety factors
5. Fire protection- thermal stress

1. As demonstrated throughout the gradual steps into the structural analysis of the system, both the deformations and peak stresses shown are within permissible limits, and the connection detailing has been made to avoid the concentration of stresses and thus reducing potential risk.
2. Stability of the general geometry has been mainly tested in the connection development part, as it is the flexible nature of the hinged connections that is possible to compromise the stability. However, given that the width of the connection sheets has been kept as small as possible and as proven by the FEM analysis under different load scenarios, stability is not a problem.
3. Since the main load bearing elements, meaning the large full span plates are supported at both sides and on separate bearings, and the lateral smaller flaps are connected along both sides to them, damage to one of the plates, will not compromise the structure as a whole. The side flaps will be kept in place by the connections and the main plates by their supports, until repair is possible.
4. Various safety measurements for glass roof elements have been taken into account, as explained in chapter 3B. The glass used is heat-strengthened laminated and one extra layer of glass is considered disposable and is not calculated for. Safety factors have been used for glass as a material and for allowable design stresses and deformations.
5. Thermal stresses are dealt with by the use of heat-strengthened glass, and is also partially the reason of its selection. However, the issue of fire protection is a constant problem with glass, which requires further investigation and probably future research.

DETAILING CRITERIA
1. Discrete design-Invisible connection
2. Tolerances
3. Restriction of gaps- waterproofing
4. Repair work facilitated
5. Structural behaviour enhanced by connection detailing

1. The nature of the material used in the connection, its dimensioning as thin and elegant as possible combined with its white color is already enough to characterise the connection as discrete. As an extra step towards “invisibility”, the connection detail uses an array of glass discs to keep the PURE sheet in place, which increases the overall transparency around the edges.
2. Tolerances are taken by the provision of holes in PURE larger than the glass discs, thus allowing the required tolerances in the plane of the sheet. Out-of-plane a degree of tolerance is also established by the use of a disk thickness bigger than that of the actual PURE sheet, in this case 5mm over 3mm of PURE sheet.
3. Restriction of gaps is ensured by the linear geometry of the pane to pane connections, running along the full edge length and thus waterproofing all edge connections. The only issue occurs at the points where the edges meet, where extra caps of the same material should be added. On the side walls, water is led to the sewage pipes located along the walls by an extension of the sheet of PURE, as explained previously.
4. Repairwork is always challenging in the case of structural glass, especially in hanging elements. It is facilitated by the fact that the pane to pane connection is purely mechanical and does not include lamination or glass inserts. The placement of the PURE sheet in the between of the laminated sheets means that either of those laminated sheets can be replaced by detaching the adhesive and re-placing it to glue the disks on to the new surface. Although this process is indeed quite complex to be performed at such a height, it is however feasible and relatively inexpensive.
5. As checked through a series of physical tests and finite element analyses, explained in chapter 3C, the connection is suitable for the specific application, enabling the smooth deployment without being problematic to the overall stability of the system.
6. Reflection

6.1. The relationship between research and design

The methodology followed in this project was research by design oriented, and as a result, the topic revolves around a specific case study which is used in order to investigate the extents of the application of the system in question. Thus, through the development and problem solving process on a specific design, I am aiming to develop a more broadly applicable system of deployment in self-supported glass plate structures and draw some conclusions on the limits of the use of glass in this application.

In the research process, design and research, in the form not only of literature study but also of testing, have been combined in the case of the general geometry as well as in the connection detail. Starting from an extensive literature study, I have in both cases proceeded with a selected design concept, followed by a series of analytical and physical testing, which is providing essential feedback to the design process, leaning towards the final shape optimization based on the combination of the results of the two parallel processes. Bringing together the two aspects in one integrated design has been a big challenge, which, as was expected required additional problem solving at the finalization part of the research.

6.2. The relationship between the theme of the graduation lab and the case study chosen within this framework

The sustainable design graduation studio belongs to the chair of Building Technology. The aim of this studio is to explore new innovative technologies either in façade design, or in structural design or in climate with a sustainable approach. This graduation project is part of the chair of Structural Design.

In this case, looking to develop a kinetic system using structural glass plate elements I have chosen to apply this system in the case of a deployable glass roof for covering a swimming pool area. A roof structure for a swimming pool, which is used around the year, needs to be closed or outdoor depending on the weather conditions and comprises a very good example of a function which requires both a high architectural result and climate adaptability. An Olympic size of swimming pool has been selected to work on, mainly because the scale of this kind of facility justifies the application of such a cutting edge solution for the openable roof. Due to the high architectural quality which has been a goal, combined with the implied cost, I have selected the particular example of a case study in an effort to set a feasible scenario. As expected, because of the high degree of innovation in this project, it is understood that eventual scaling down of the proposed system must not be excluded and does not compromise the integrity of this research.

6.3. The relationship between the methodical line of approach of the graduation lab and the method chosen by the student in this framework

The methodical line of approach of the graduation lab can be described as technical-scientific study and is either design by research or research by design oriented. Because of the experimental and innovative nature of projects within the Structural Design chair and especially the research on glass, laboratory work forms a very important part of the research methodology, used to verify results or provide insightful information on material behaviour.

The method applied for this graduation project is research by design, including design, computational tools of geometry parametrization and structural analysis and physical material and connection testing in the lab. The purpose of this combination of methods is to create a circular process between design and structural verification on one hand, and connection concept development and physical verification on the other. These two approaches, addressing two significantly different scales of the project, in their integration provide a complete insight into the geometrical, structural and material behaviour of the system, and more specifically when applied in the particular case study mentioned above.

6.4. The relationship between the project and the wider social context

The impact of this project on a broader social context is mainly related to the introduction of an innovative structural concept, which combines the use of structural glass with a kinetic system in the purpose of making a deployable system of high architectural value. The architectural value of the product derives exactly from this integration of approaches, What is origami-shaped architecture? Most importantly, why should these very interesting aspects be dealt with separately? The most important part of structural design is providing the optimal way to combine the most effective properties of the material, the geometry, the technical background in order to make a building or a building component as integral as possible. This integrity at the time means efficiency, simplicity and in the end, beauty, in the traditional sense. This is exactly what this graduation project is aiming at.
On structural glass:

On folded plate 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
- Nenad Šekularac, Jelena Ivanović Šekularac, Jasna Čikić Tovarović, Folded structures in modern architecture, 2011, University of Belgrade, Faculty of Architecture, Serbia
- 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)

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 process 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, Shibio Ren: foldKITE: an ultra-light-weight folded structure, as published for IASS symposium 2015
- Valentina Beatin: Polar method to design foldable plate structures, as published in the IASS journal 56(2)-184, pp125-136
- Valentina Beatin: Translational method to design foldable plate structures, as published in the journal Space Structures 30(2)
- Stefan Trometer, Mathias Kruupa: 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

On steel connections:
- Roger A. LaBoube, Wei-wen Yu, Additional design considerations for bolted connections, Missouri University of Science and Technology, as published for 13th International Specialty Conference on Cold-Formed Steel Structures, 1996

On kinematic systems and mechanisms:
- UniSystem Solutions, 4600 Lake Road, Minneapolis, (http://www.uni-systems.com/)
1. Rigid-foldability and flat-foldability condition

Tomohiro Tachi in his paper further investigates the design principles of developable, flat-foldable rigid-foldable origami shapes, based on the example of the Miura-ori pattern. In this the configuration of a flat-foldable degree-4 vertex can be represented by four sector angles, $\theta_A$, $\theta_B$, $\theta_C$, and $\theta_D$, and four folding angles $\rho_{AB}$, $\rho_{BC}$, $\rho_{CD}$, and $\rho_{DA}$, between the sector angles. Angle $\rho_{CD}$ needs to be considered as negative, leading to a mountain fold, while the other three folding angles as positive, leading to a valley fold. The crease pattern of a single vertex that satisfies the developability and the flat-foldability conditions can be represented in terms of two parameters, $\theta_A$ and $\theta_B$. ($0 < \theta_A < \pi$, $0 < \theta_B < \pi$, $\pi \leq \theta_A + \theta_B$), $\theta_C = \pi - \theta_A$ and $\theta_D = \pi - \theta_B$.

As shown by Murata and Fushimi. A degree-4 single vertex rigid origami is known to have one degree of freedom. The relation between the folding angles is derived as follows using spherical trigonometry, as shown by Huffman and Hull.

$\rho_{CD} = -\rho_{AB}$ and $\rho_{DA} = \rho_{BC}$ (1)

This means that the folding angles can be represented by the two angles $\rho_{AB}$ and $\rho_{BC}$, which are dependent on each other. According to Hull, the relationship between these two angles was derived by Robert Lang as follows:

$$
\cos (\pi - \rho_{AB}) = \cos (\pi - \rho_{BC}) - (\sin^2 (\pi - \rho_{BC}) \sin \theta_A \sin \theta_B) / (1 - \cos \xi) \tag{2}
$$

where $\xi$ is the angle between $l_{AB}$ and $l_{CD}$, assuming this angle is non-zero, when the shape folds and is given by:

$$
\cos \xi = -\cos \theta_A \cos \theta_B + \sin \theta_A \sin \theta_B \cos (\pi - \rho_{BC}) \tag{3}
$$

Equation (2) gives a one-to-one map $f : \cos \rho_{BC} \rightarrow \cos \rho_{AB}$ as follows:

$$
\cos \rho_{AB} = f(\cos \rho_{BC}) = K - (1 - K^2) / (\cos \rho_{BC} + K) \tag{3}
$$

where: $K = K(\theta_A, \theta_B) = [1 + \cos \theta_A \cos \theta_B] / (\sin \theta_A \sin \theta_B)$

A general condition can be derived from Equation (3). The map $f$ represents the conversion from the rotation of the lateral foldlines to the rotation of the longitudinal foldlines. Hence, its inverse $f^{-1} : \cos \rho_{AB} \rightarrow \cos \rho_{BC}$ represents the conversion from the longitudinal to the lateral foldlines. $f^{-1}$ can be calculated from Equation (3) as follows:

$$
\cos \rho_{BC} = f^{-1}(\cos \rho_{AB}) = -K + (1 - K^2) / (\cos \rho_{AB} - K)
$$

From this conclusion drives an important condition of foldability, according to T. Tachi. “The model is rigid-foldable if and only if we can obtain $\cos \rho_{i+1} \parallel \ell_i$ and $\cos \rho_{i+1} \parallel \ell_i$ that are consistent with Equation (3) for all inner vertices. The fold angle of a segment determines the fold angle of the next segment, which in turn determines that of the following segment; this procedure is repeated until the fold angle of the original segment is once again determined. Therefore, the necessary and sufficient condition for the rigid-foldability is represented as follows. For any $x = \cos \rho (-\pi \leq \rho \leq \pi)$, and for every inner facet surrounded by $v_i,j$, $v_{i+1,j}$, $v_{i+1,j+1}$, and $v_{i,j+1},$

$$
\cos \rho_{i,j+1}(f^{-1}(f^{-1}(f^{-1}(x)))) = \text{identity,} \tag{6}
$$

This can be calculated as,

$$
(B_jx + A_j) / (A_jx + B_j) = (B_{j+1}x + A_{j+1}) / (A_{j+1}x + B_{j+1}) \tag{7}
$$

where, for $j = j, j + 1,$

$$
A_j = -K_j [i + K_i j], \quad B_j = 1 - K_j [i + K_i j]. \tag{7}
$$

This gives the following necessary and sufficient condition:

$$
(A_j B_{j+1} + A_{j+1} B_j) x^2 - (A_j B_{j+1} + A_{j+1} B_j) x + (A_j A_{j+1} + B_j B_{j+1}) = 0 \tag{8}
$$

which can be satisfied if and only if

$$
A_j B_{j+1} + A_{j+1} B_j = 0 \tag{9}
$$

Theorem 1: A quadrilateral mesh origami is finitely rigid-foldable if and only if Equation (9) is satisfied for every inner facet.
It is obvious from Theorem 1 that the pattern is rigid-foldable if the conversion coefficient $K$ of every inner vertex is constant ($K_{ij} = K_0$).

A recent study in the field of discrete differential geometry by Schief et al reveals the finite rigid-foldability of a quadrilateral mesh called discrete Voss surface. This is a planar quadrilateral mesh surface composed of degree-4 vertices, each of which satisfies $\theta_1 = \theta_3$ and $\theta_0 = \theta_2$. The Voss surface shares many characteristics including the intrinsic symmetry and kinematic mechanism. However, it is interesting to note that in its generalized form the Miura vertex will always expand in all directions simultaneously, whereas the Voss vertex expands in one and contracts in the orthogonal direction. The ‘egg box pattern’ is one well known example of a Voss surface.

Voss surfaces are part of the theory of Kokotsakis meshes, defined by Kokotsakis in 1935. A Kokotsakis mesh is a polyhedral structure, of n-sided central polygon $P_0$, surrounded by a belt of n polygons (drawing). Each vertex $V_i$ is the meeting point of 4 facets. Each facet is a rigid body and only the dihedral angles can vary. Describing the kinetic properties of this set of polygons, Kokotsakis in 1923 has defined a theorem specifying the criteria for the set to be foldable around vertexes $V_i$ without geometrical controversies.

Theorem: A Kokotsakis mesh is flexible if at each vertex $V_i$, opposite angles are either equal or supplementary.

$\alpha_i = \beta_i$ and $\gamma_i = \delta_i$

Or $\alpha_i + \beta_i = \pi$ and $\gamma_i + \delta_i = \pi$

This forms also a sufficient condition of flat-foldability, avoiding self-intersections of the surface. These conclusions are valuable when evaluating the geometrical properties of folding patterns. They demonstrate the relation between folding angles, in the simplified example of a 4-fold surface and most importantly provide conditions for rigid and flat-foldable surfaces. Although this is merely an introduction to the rather complex mechanism of the folding process, it already provides a valuable insight to the interrelation of folding angles, and original pattern geometry.

2. Glass Safety Concepts

As mentioned in the literature study, in the design of glass structures, safety measures play a very important role. As a material, glass exhibits no appreciable creep and no relaxation. Because of the material’s brittle behavior and the sudden failure that it can present without prior warning, special regulations and factors are predicted for glass structures and more specifically for roofs. There have been several codes, developed for this purpose, such as the European code, including partial factors and the North American “Glass failure prediction model”, based on statistical theory of failure. (see Appendix for more information) The Integrated Approach to Structural Glass Safety, developed by F.P.Bos 1, is presented, as a method to assess structural glass safety objectively, taking into account all relevant factors simultaneously. As a method it is more concentrated on the design of elements for safety and not of complete structures, making it easier to incorporate more than one concepts in an effective design solution.

In the case of glass structures, there can be defined different stages of failure. These can be used to minimize the effect of a potential damage for the overall structural integrity and user safety. Initial failure occurs when the element is no longer capable of transferring loads according to its primary LTM. Final failure occurs when the element is no longer capable of transferring loads through any LTM. This usually coincides with collapse. Structural damage, $D_s$ is the loss of load transferring capacity, while physical damage, $D_p$ is the physical phenomenon (e.g. fracture) that has caused the structural damage. In general, the physical damage causes of glass, are mainly defined as:

- surface damage, chemical or mechanical
- accidental impact, by a hard or soft body
- purposeful impact, in the case of vandalism
- thermal stress, normal or caused by fire

Based on those perils, the main safety concepts usually followed are focused on:

- Damage sensitivity, \( \Sigma \): vulnerability based on probabilistic failure causes
- Realtime resistance, \( r \): ratio between actions on and resistance of elements
- Redundancy, \( m \): margin between damage and failure and failure and collapse
- Fracture mode: breakage and injury potential

These properties have been chosen to address the shortcomings of a purely probabilistic approach as formulated above. The combination of more than one of those concepts, usually damage sensitivity and redundancy can eventually guarantee satisfactory safety levels for a glass structure.

Concerning damage sensitivity on material level, some ways of decreasing it include the alteration of the chemical composition or microstructure, application of thermal or chemical prestress, the application of coatings, or the use of altogether different transparent materials. Pre-stressing is the method most commonly used in this purpose, especially when three or more layers are applied. Design measures such as applying receding inner layers or protective covering can also reduce damage sensitivity.

As far as relative resistance is concerned, the obvious solution is to strengthen building elements as much as possible. Independently form the probabilistic consideration of damage potential, the safety of the element on these terms relates only to its proper characteristics. The fact that the resistance of a prestressed element may be described as the sum of an inherent strength and the level of prestress makes the analysis and prediction of the element's behavior somehow more complicated. The complex time and temperature behaviour of laminates makes an accurate failure probability analysis of such elements even more difficult than for single sheet glass. Improving edge quality has not been found to improve engineering strength as it does not remove the most severe flaws, and thus does not eliminate the low failure strength specimens from a batch.

As far as redundancy is concerned, it is necessary to determine primary and secondary load transfer mechanisms, taking into account a probable failure. Load Transfer Mechanism is the mechanism with which the element transfers loads acting on it, to its supports. An element may (latently) possess the possibility of more than one LTM. The primary LTM has the highest stiffness and will initially be addressed when the element is loaded. However, a secondary LTM may be activated after the primary LTM has, for whatever reason, lost its capacity. Determining alternative Load Transfer mechanisms is of utmost importance in order to discern damage from potential failure. (see fig. App.4.)

Finally, aside from the effort to predict and render the effect of physical damage minimal for the structural integrity of the whole structure, user safety imposes that the danger of injury in case of some element failure needs to be minimized as well. This has to do with the treatment of glass in the production phase, the type of glass used and the laminating interlayer used in case of laminated plates. Figure App.5. shows the different fracture patterns that occur by glass type. Toughened safety glass breaks into many fine pieces, while heat-strengthened glass into larger fragments. Additionally to the fracture pattern, lamination of glass panes, by use either of a PVB or a SG interlayer prevents the fractured pieces from spreading and becoming hazardous to users. For this reason, only laminated annealed or heat-strengthened safety glass is allowed to be used in over-head glazing systems.

Particularly in the case of plate structures like the one in this research, it is also essential that the overall integrity of the glass structure is not compromised by failure of a single element. Redundancy and fracture mode criteria need be expanded in this case to ensure that an extra, disposable layer of material is used and that there is a secondary LTM temporarily able of assuming the imposed loads in case a glass element fails completely.
3. Comparison with simplified one-fold model

As a basis of comparison for the final design, a complete analysis with the same specifications and level of detail of the one-fold simple model was required. The goal of this finite element analysis is to check the extents to which the developed system of this research is actually beneficial in comparison to its originally designed simpler version. For this purpose, a new finite element model of the one-fold geometry was made, using exactly the same specifications, concerning meshing, connection modelling and boundary conditions and loads as the one of the final design.

The results of this analysis show, interestingly enough, that the maximum tensile and compressive stresses are at the same levels, which is also the case of the shear stresses at the supports, with the chamfered six-fold appearing a bit more beneficial. The location of the stress peaks can be more easily anticipated in the case of the simplified version, which functions more like a triangularly shaped beam, whereas in the case of the complex model forces and stresses are not so evenly and predictably distributed. This is also dependent on the dimensions of the chamfering at the top, which has now arbitrarily been decided. The reaction forces at the supports appear to be very comparable, although there are more support points in the case of the six-fold geometry. On the other hand the support forces along the bottom edges of the plates, which denote the principal forces taken by the connection, present significantly larger values in the case of the six-fold design, and it also seems that the force flow is not evenly distributed along the edge, as is the case in the simplified design. Finally, the more obvious difference is of course in the deformations, which was to be expected. In the case of the one-fold the maximum deformation refers to the deflection of the glass in the middle of the pane, while in the case of the six fold, it refers to the translation of part of the geometry due to the flexible nature of the hinged connections.

This comparison aims to provide an insight on the structural benefits or disadvantages of the proposed system against the simpler originally tested alternative. It is certain that this is not the only basis of comparison between the two designs and a more global perspective on the matter can be found in the conclusions of chapter 4.