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Study of a Deployable Roof System

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Kinematics of Folded Glass Plate Structures: Study of a Deployable Roof System

Alkistis Krousti, Ate Snijder, Michela Turrin
Delft University of Technology, the Netherlands, alkistiskr@gmail.com

The purpose of this paper, as part of a MSc graduation project, has been to explore to which extent the kinematic potential of folded geometries can benefit from the structural and architectural properties of glass plates. Using as a case study the covering in an adjustable way an outdoor swimming pool area, the course of this paper consists of form evolution based on structural performance and development of a dual purpose connection and deployment principle developed through experimental testing. Both aspects are examined independently, in parallel processes, and the findings are combined and further evaluated. 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 compromising the system's stability and thus provides an important beginning to implementing complex structures that make use of the benefits of glass.

Keywords: Glass, Plate structures, Kinematics, PURE composite, Glass connection system

1. Introduction

Folded plates as a way of increasing stiffness in large-span structures have been around since the 1950s, when they were quite extensively applied in concrete roof structures. For a very long time this type of construction has been realized in practice only in reinforced concrete and made on site, which conditioned the use of a very complicated shell. Development of prefabricated building led to improvements on this type of construction. Since then, folded plate structures have reappeared in the engineering and architectural scene in the past fifteen years, as new materials have been considered, especially fiber-reinforced plastics and glue-laminated timber. In this process of application, 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. The structural behavior of folded plates is highly compatible with glass as a laminated material, given its high load bearing capacity in its plane. Out-of-plane forces are converted plane ones through folded structures, which makes laminated glass panes ideal for this kind of application.

As far as the folded geometry itself is concerned, a great inspiration has been 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 researched on 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. Extensive research has been done in this direction, especially from Tomohiro Tachi1 (Tachi, 2013), to tackle the obstacles introduced with panel thickness and mechanical properties, without, however any structural verification.

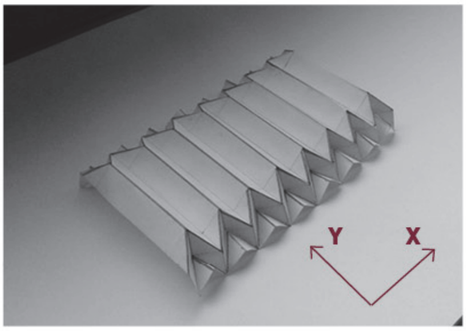
So far, folded plate structures are being designed and researched upon as either kinematic-deployable geometries, using an additional structural support, or as a beneficiary structural principle. These two distinct properties provide a very strong potential, if combined, for a self-supported deployable structural system, and glass as a material provides a very good candidate for this purpose. The goal of this paper is to examine to which extent the kinematic qualities of folded geometries can be combined with the structural benefits of glass plates and more specifically, how these can be applied in the case of a deployable glass roof system.

2. Method

2.1. Research Methodology

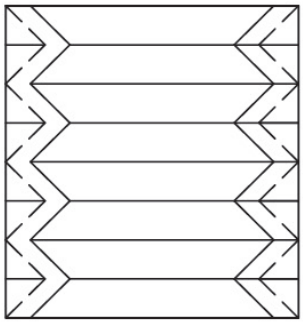
In the scope of this study, the question is researched through the development of an architectural product for the specific needs of covering in an adjustable way the area of an outdoor swimming pool of Olympic dimensions (21m width x 50m length). On a design level, the issues which need to be addressed include high architectural quality and retractability of the structure for both functional and climate purposes, without the use of supplementary support mechanism.The method followed in this paper develops in steps consisting of the form evolution based on structural performance and the development of a dual purpose connection and deployment principle through experimental testing. Based on the spatial and functional specifications given in the chosen architectural scenario, both aspects are examined independently, in parallel processes, and the findings are combined and further evaluated, leading to conclusions on the integral product.

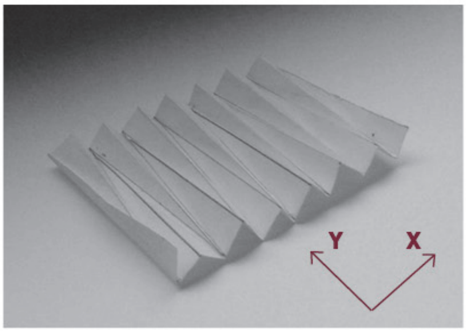
Table 1 Comparison of geometrical and structural properties of commonly used folding patterns.



1. Simple 1-fold with hybrid endings

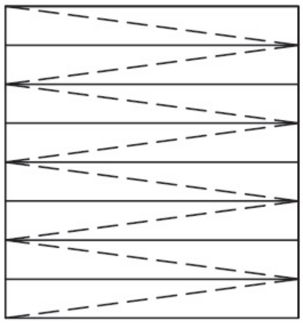
TYPE: planar
quadrilaterl pattern
developable - 1 DOF rigid motion
span direction: Y / retractable on X

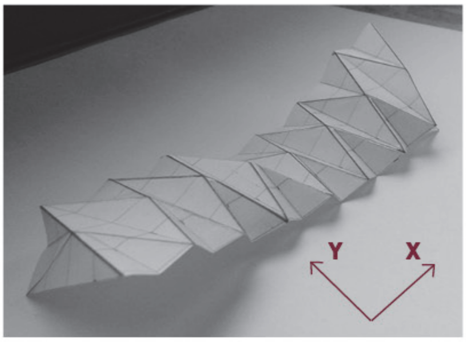




2. Triangular 1-fold

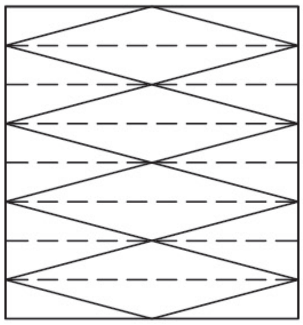
TYPE: planar
triangular pattern
developable - 1 DOF rigid motion
span direction: Y / retractable on X

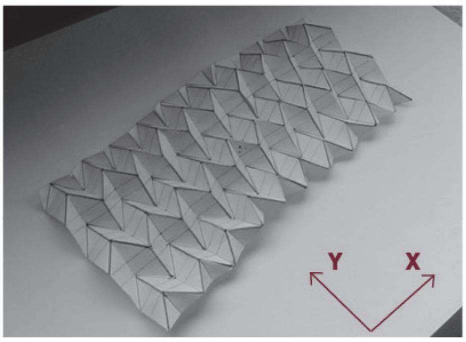




3. Diamond 6-fold (single)

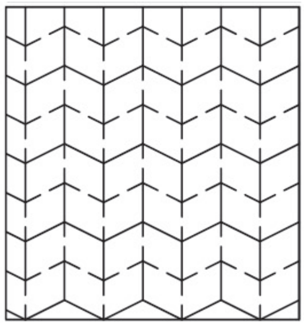
TYPE: planar
triangular pattern
developable - 1 DOF rigid motion
span direction: Y / retractable on X

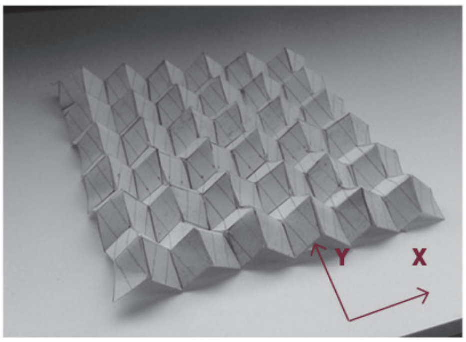




4. Miura-Ori 4-fold

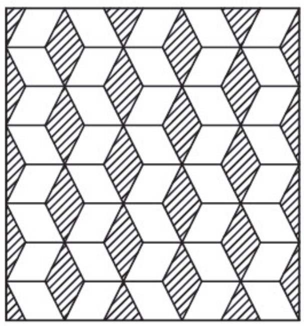
TYPE: planar
quadrilateral pattern
developable - 1 DOF rigid motion
span direction: Y / retractable on X

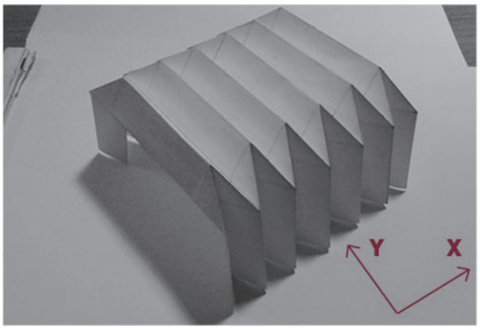




5. Eggbox 4-fold

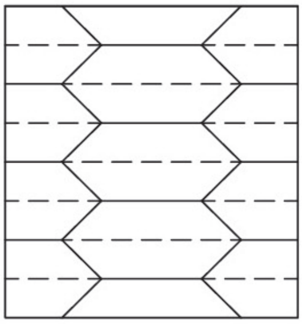
TYPE: planar
quadrilateral pattern
non- developable - no DOF rigid motion
span direction: Y and X

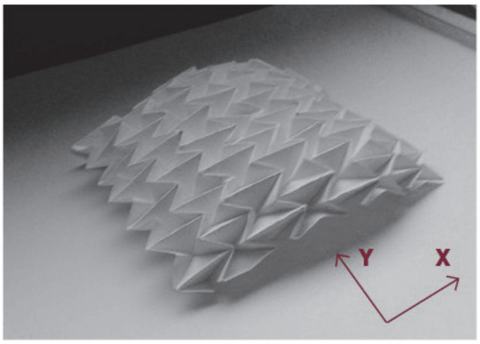




6. Simple 4-fold

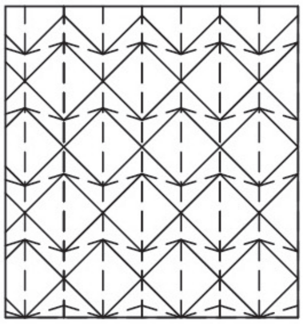
TYPE: frame / tunnel
quadrilateral pattern
developable - 1 DOF rigid motion
span direction: Y / retractable on X

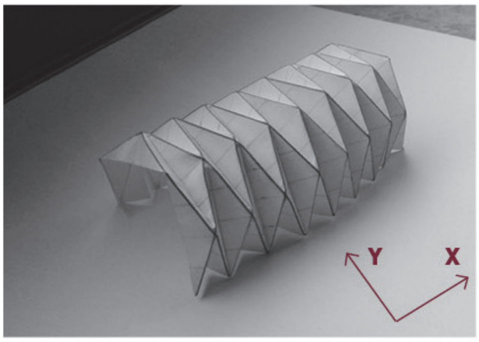




7. Butterfly 6-fold

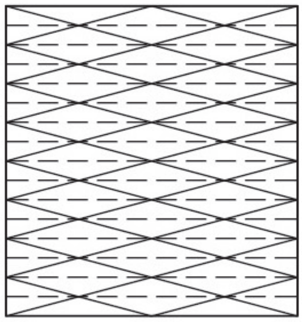
TYPE: planar/ spatial (dep. on folding angle)
triangular pattern
developable - 2 DOF rigid motion
span direction: X, Y / retractable on Y

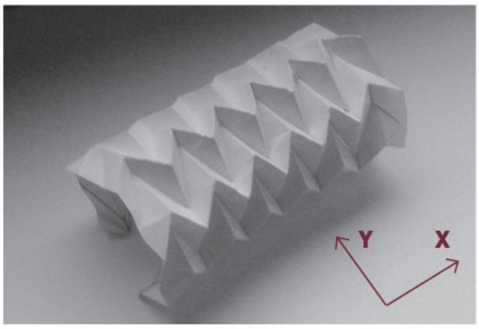




8. Diamond 6-fold

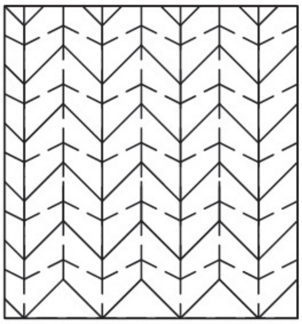
TYPE: frame / tunnel
triangular pattern
developable - 1 DOF rigid motion
span direction: Y / retractable on X

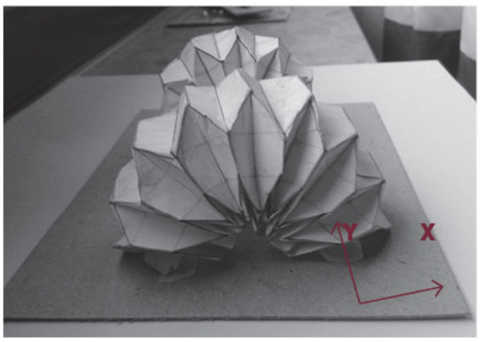




9. Miura-Ori (uneven)

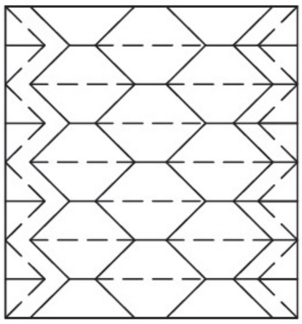
TYPE: frame / tunnel
quadrilateral pattern
developable - 1 DOF rigid motion
span direction: Y / retractable on X





10. Hybrid Dome

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



2.2. Pattern selection

Through literature study and scaled paper models, the properties and potential of a variety of common deployable shapes are defined and compared in table 1 to help the design decision. Criteria for the selection include the type, planar, frame or spatial, the rigidity of the geometry on fully open configuration, and the axis of span/retractability. Starting with the most demanding aspect of the design, the kinematic one, directional rails are considered the most efficient system for the application in question, therefore narrowing down the type of pattern to the planar ones. Given that quadrilateral patterns are not rigid unless they are fixed in a spatial configuration, triangular patterns look like better candidates.

Based on these criteria, the diamond six-fold pattern (number 3) is selected as a basis and proceeded further with. The complexity of the pattern gives room for more interesting architectural results, while the planar nature of the folding in combination with the limited number of joint edges makes it easier to analyze geometrically as well as structurally. Given the increased complexity of the structural and kinematic behavior of folded shapes, the process starts with a simplified version in steps leading to the selected diamond one, each time using form parametrization and finite element analysis to define the geometrical parameters of the design.

As a first step, the boundary conditions of the geometry are set, based on the case study. Keeping in mind the potential of implementation of a free-from structural glass system, a more basic planar and modular version is examined for the scope of this paper. As a result, a simplified bounding box is specified for the development of the structural system, of a total span of 20m. (see fig.1)

Starting from a simple one-fold model and following hand calculations as a first approximation to draw some first conclusions, a parametric model is then set for different levels of complexity and the finite element structural analysis on each of them helps define the optimal geometric parameters for the specified span. For the structural analysis, different stages of deployment need to be taken into account, given the kinetic aspect of the project and additional loading situations, such as lateral wind load and suction need to be taken into account.

2.3. Design and structural performance

Initially, only self-weight and live loads are taken into consideration, while the wind is considered only for part of the connection structural analysis (see 2.4). The ULS (Ultimate Limit State) is taken into account for all following preliminary analyses. A table presenting the assigned loadcase is shown in table 2 and is the basis of all calculations.

Points supported on the parallel rails are considered as pinned on the x, y and z axis on the one side, and on the x, z axis alone on the other side, to allow for some lateral translation, due to the shape deformation (see Fig. 1). This is given that movement on the x axis will be prevented mechanically when the structure is in its deployed state. The long edges are considered pinned on the y axis, accounting for the existence of adjacent plate elements. Moreover, it has been crucial for the accuracy of the finite element model that the hinge elements are made correctly, simulating the actual behavior of the material in this configuration. This is achieved as a combination of lab test results and necessary simplifications on the 3D model, as shown in paragraph 3.

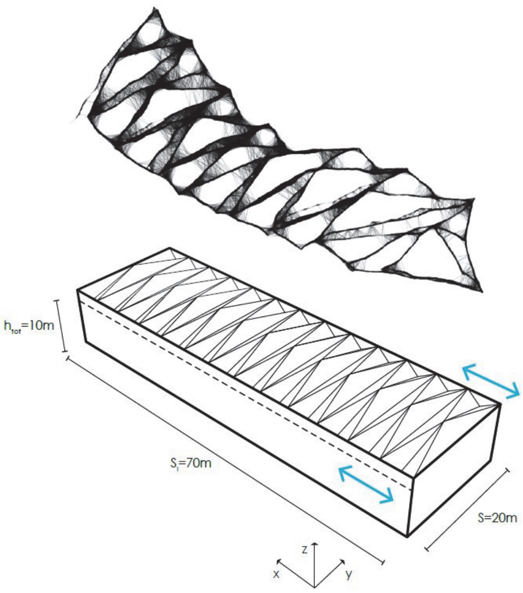


Fig. 1 Geometry boundaries for design developments and parameter description.

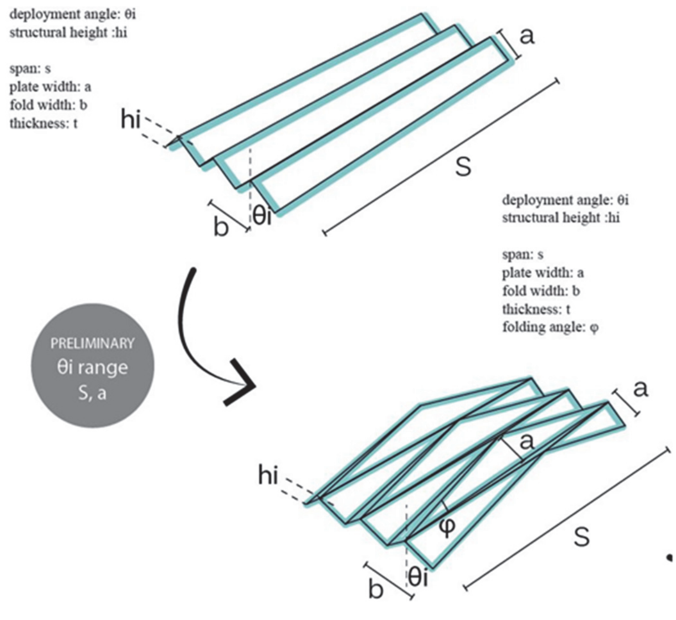


Fig. 2 Diagram of the design development process. A draft set of hand calculations and finite element analysis is performed on the simplified one-fold geometry and once some parameters are narrowed down, the analysis is made for the selected six-fold pattern.

As far as safety regulations go, this research is based on the concepts developed by F.Bos (Bos, 2009). 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. 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. For this research it is assumed that the glass plates are made out of toughened two layer laminated glass plates. 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. Safety factors are applied as shown in the table 2.

Table 2 Assigned loadcases for hand calculations and finite element analysis

Loadcase	[KN/m^2]	Safety Factor	Total [KN/m^2]	On one beam [KN/m]	For F.E.A. [N/m^2]
Self-weight (based on 1.5mm glass and vertical loading)	1.059	1.2	1.270	7.625	
Live-load (snow)	0.7	1.6	1.12	0.935	
Wind suction	-0.08	2	-0.16	-0.133	
Wind load (Horizontal)	0.2	2	0.4		
Combined wind/snow surface load			0.96	0.802	
			ULS q=	8.427	2230.94

As a first step for the understanding of the structural behavior of folded geometries, beam theory is used to draw some first conclusions on a simplified geometry of the same shape boundaries, as shown in Fig. 1. In this approximation, basic formulas of first order linear analysis on beam elements are used and the structure is considered as a set of beams of corrugated shape (see Fig.3). The moment of inertia is calculated accordingly, as if the plates were perfectly fixed on the edges, instead of hinged.

Moment of inertia Iy $$Iy = \frac{2tcos\theta i\, hi^3}{12}$$

Reaction Force $$F = \frac{ql}{4} \tag{1}$$

Deflection $$w = \frac{5ql^4}{384EIy} \tag{2}$$

Bending moment middle $$M = \frac{ql^2}{8} \tag{3}$$

Maximum flexural stress $$\sigma = \frac{Mz}{Iy} \tag{4}$$

Shear Force $$V = \frac{ql}{2} \tag{5}$$

Principle Force max. $$F = \sigma t \tag{6}$$

Maximum shear stress $$\tau = \frac{VQ}{Ib} \tag{7}$$

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

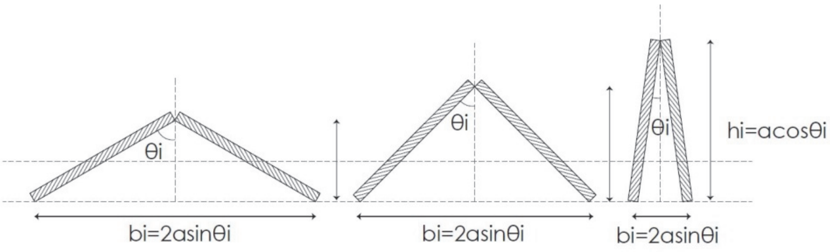


Fig. 3 Geometric description of states of deployment for one beam element

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, θ_i.

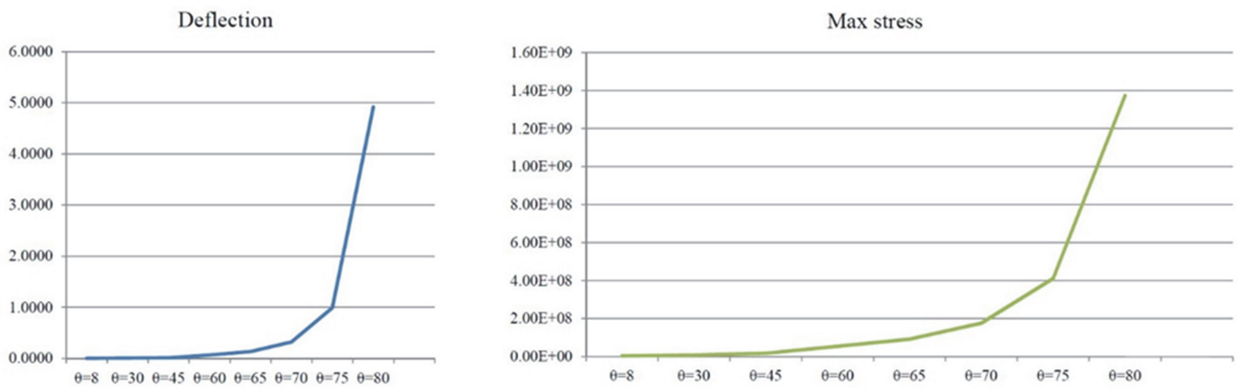


Fig.4, 5 Deflection and maximum stress calculated for one beam element under different deployment angles.Units in mm and N/mm2

In theory, folded plate structures present an optimal angle of 30 degrees, meaning that $\theta_i = 15^o$ where load distribution is achieved within the plane of the plate and beam action is combined with membrane action. Loadcases are also altered as the deployment angle changes, since the coefficient of the self-weight and live loads on the plate surface is dependent on the angle.

Following those specifications and taken as givens originally a span S = 20 m ,a plate size a = 2m and a glass pane thickness t = 3 x 0.0012 m, a first set of hand-calculations is done for different deployment angles θ_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 graphs 1, 2. From those it becomes clear that the structural behavior radically changes after approximately a 60 degree angle, presenting an abrupt peak in both graphs of deflection and flexural stress levels. This pattern was tested again for a plate size of a = 3m and a thickness of t = 3 x 0.0015 m and for a = 5 m and t= 3 x 0.0015 m and presented the same comparative results.

As a consequence, the folding angle θ_i is defined between $8^o < \theta_i < 60^o$, for the purpose of this project, with 8 degree angle describing the structure at the fully folded state, and 60 degrees at the fully open state. All further preliminary analyses are performed for those two extreme states. It is certain that beam theory cannot accurately be applied on the folded geometry, around $\theta_i = 60^o$, 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 insight on the behavior of the system.

As a next step, finite element analysis is performed at the two extreme states, using TNO Diana finite element analysis software, at fully folded ($\theta_i = 8^o$) and fully unfolded ($\theta_i = 60^o$) state. Based on those first hand-calculations 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_i, is much more crucial. A minimum of a = 2m appears to be required for the draft calculations to fall within allowable stresses and deformations (NEN 2608). As a result a plate size a=2m and a minimal thickness of t=3 *1.2mm are set as a starting point for the finite element analysis. Results are presented in fig. 4, 5, and 6.

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. Shear stress peaks around the connection at the ends should not be taken into account, as the boundary conditions are now described 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 allowable design limits (NEN 2608),, as far as deformation, tensile and compressive and shear stresses are concerned.

Consequently, the second six-fold model has been set as shown on fig.9, 10, and 11. For this model, hinged connections were modeled as intersurfaces which are attributed the properties of the connection material and the expected distance between plates (see paragraph 2.4.). 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 supported as well. This would be particularly challenging, because the endpoints of those flaps are translatable on all axis during the process of deployment.

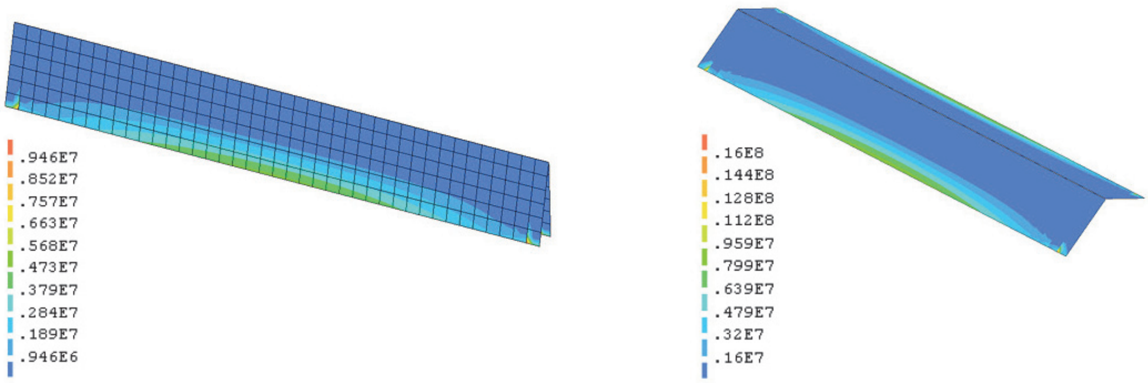


Fig. 6 Graphic representation of principal stresses S1. Units in m and N/m^2

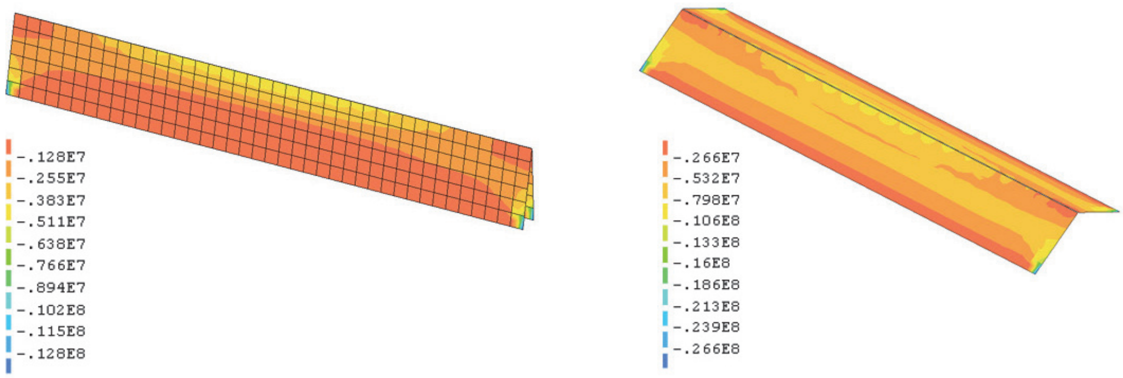


Fig. 7 Graphic representation of principal stresses S2 Units in m and N/m^2

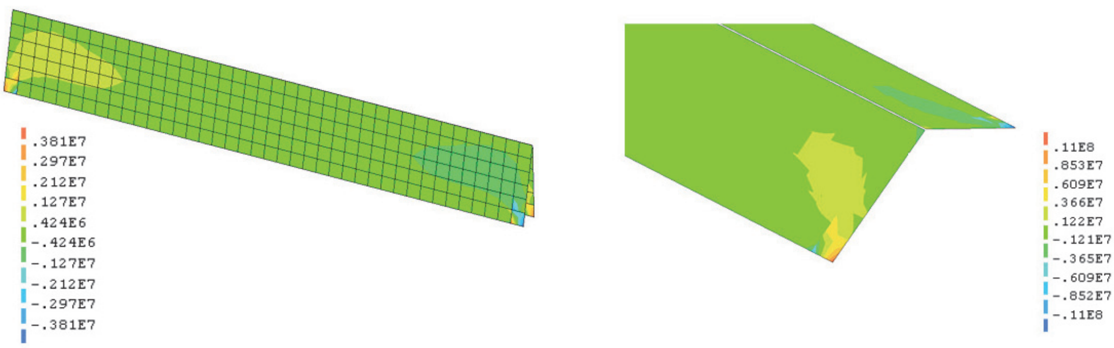


Fig. 8 Graphic representation of shear stresses Sxy. Units in m and N/m^2

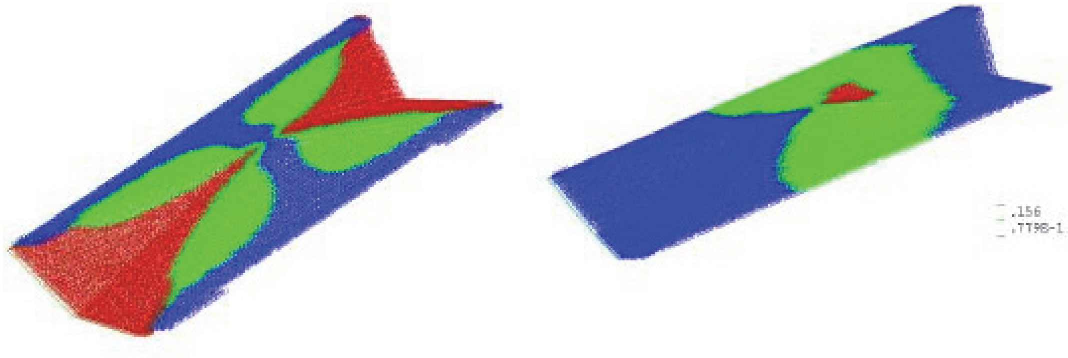


Fig. 9 Graphical representation of nodal deformations on original shape (left) and after the addition of extra supports (right)
Units in m and N/m2

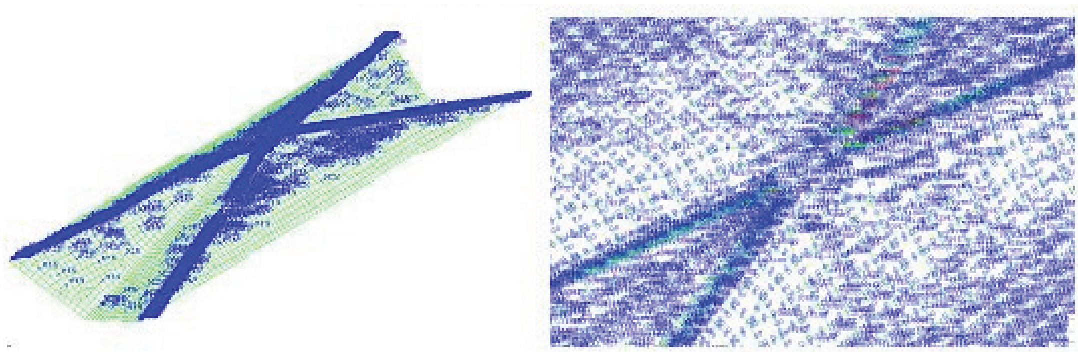


Fig. 10 Graphical representation of principal stress peaks on original shape (left) and after the addition of extra supports (right)
Units in m and N/m^2

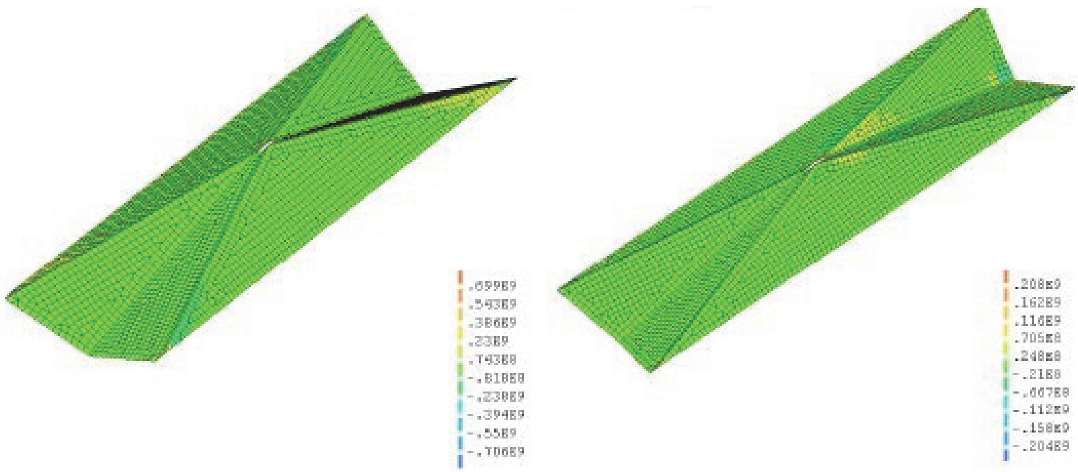


Fig. 11 Graphical representation of shear stress Sxy on original shape (left) and after the addition of extra supports (right)
Units in m and N/m2

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, geometry with chamfered edges might be a solution, providing better stress distribution. Those are improvements that still need to be tried.

2.4. Hinge connection detail

For the purposes of the preliminary structural analysis the edges between plates have been modeled as hinges. Given the nature of folded plate structures, connecting elements between the plates are of crucial importance. The connection principle needs to provide structural stability as well as flexibility allowing for deployment. The specifics of the application set the requirements for this hinged connection, in addition to the demand for extra transparency and high architectural quality. The hinge connection principle needs to provide:

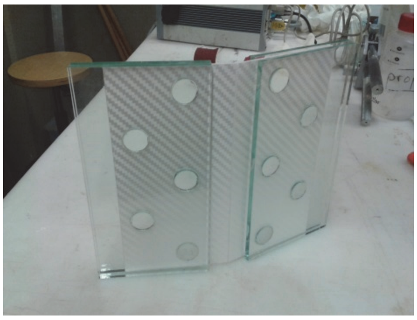
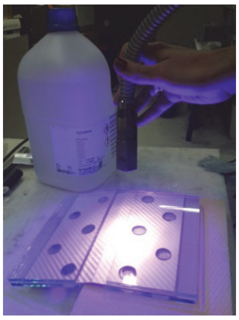
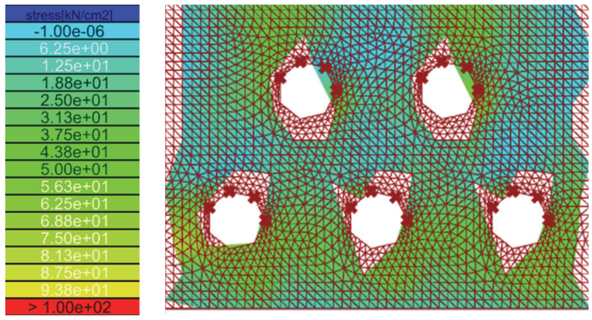




Fig. 12, 13, 14: Mock up preparation and digital optimization of the hinged connection

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

Since the beginning of this study, one of the goals has been the development of an innovative connection principle fitting these requirements. The research has been focused around the experimental application of PURE composite sheets, as a well performing and visually discrete alternative to traditional hinges. This thermoplastic composite, which is found under the commercial name "PURE®", is a flexible (E= 5.5 GPa) and highly strong (200MPa Tensile strength) composite developed and patented by DWI Holding B.V. It consists of polypropylene with 70% fiber composition. 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. More specifically, it:

- Provides a more aesthetically integral result
- Is very light-weight and flexible, with a high impact resistance, and appears fatigue-resistant
- 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 are 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. Necessary tests on the material itself include pull-out for shear strength and fatigue, and those on the connection as a system involve buckling under compression, tensile and shear strength in plane, especially around the holes, and shear strength out of plane. As part of this research, material pull-out and fatigue tests have been conducted in the laboratory, while the connection as a system has been studied computationally with the finite element analysis method.

Although the most efficient and simple connection would involve laminating the connective composite sheet between glass panes, this is rendered impossible by the surface of the material which is not favoring direct adhesion. As a result, the principle of the connection proposal is to make use of the high tensile strength of the material and use a set of glass 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. Further tests are thus 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 water tightness of the full structure. 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. The main connection detail guidelines were extrapolated from guidelines concerning steel structures (LaBoube, Yu, 1996) and tested on glass specimens.

2.5. Kinematics

Finally a very essential and complex part of the realization of this project is the detailing of the mechanical system of deployment enabling this roof system. Based on the specifics of the case, a traction drive system appears 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, as shown on fig. 13. The system in question requires a certain customization, given the particularity of the structure and the geometry. `

Fig. 15,16 Deployment on parallel rails mechanical system detail and waterproofing detail on the structure to wall connection and the railing system, on the deployed and un-deployed state.

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 are taken on at least one side to take the induced deflection.

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

As a result, the needed connection system needs to be comprised by two main parts: the directional railing, incorporating a motor, which makes possible the movement along axis y, the stop at the deployed state and the hinge system allowing for the folding of the plates. 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 was used to allow slight plate movement on both sides of the railings.

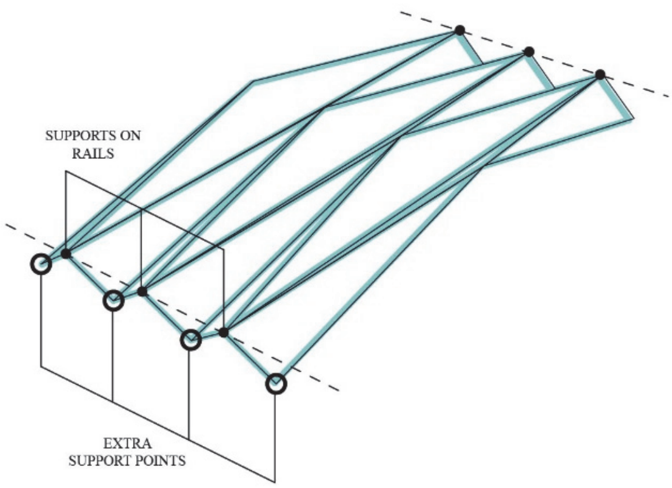


Fig. 17 Extra supports

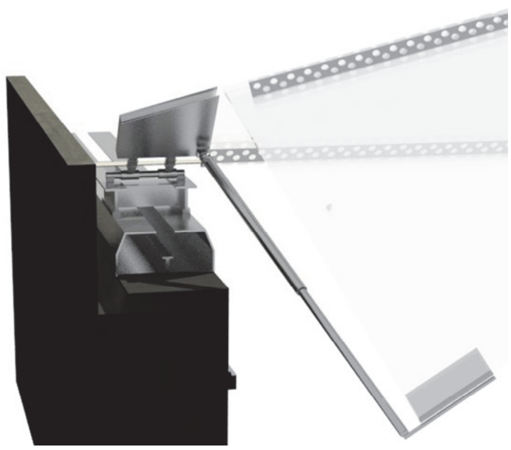


Fig. 18, 19 Example of hydraulic scissor dump system applied on the side glass panes to prevent abrupt deformation on deployment.

3. Results

3.1. Geometry Development

The most challenging part of this research project has definitely been the process of finalization, which practically refers to the bringing together of the outcome of the geometry and the connection development taking the kinetic system into account.

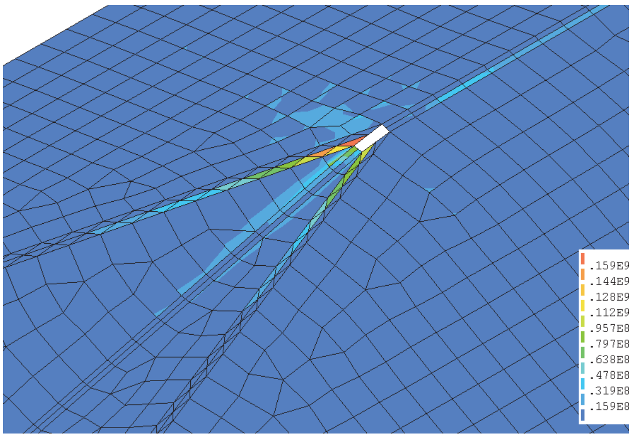
Given the preliminary results of the finite element analysis, in combination with the connection properties previously defined, there are a number of possible alterations in the general geometry to improve the structural performance. These include the provision of extra supports at the side "flaps" as demonstrated in fig. 13, to prevent excessive deformation, and the chamfering the triangular plates at the top and around the support points to reduce stress concentration. Since all the coordinates of each item of the set of points B are changing over deployment time, 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. A type of hydraulic scissor dump system, like the one in fig. 14 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 the weight of the no longer supported "flaps" assists with the deployment.

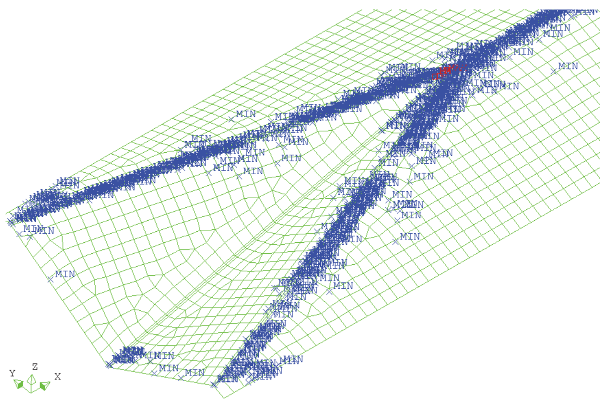
3.2. Finite element analysis on finalized geometry

Given the alterations mentioned above and most importantly those on the boundary conditions, a new finite element model is required to determine the benefit of the extra supports to the structural behavior of the folded geometry. The new folded geometry is modeled so that the plates have straight edges at the top, instead of meeting under 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. The results show far lower 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 earlier simple one-fold geometry analysis 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 concluded that the tensile stresses shown are assumed by the glass panes, while the compressive ones mainly by the PURE sheet in the connections. 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. Based on that, maximum deformations are well below the allowable levels (NEN 2608), and are not observed 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 bending, it doesn't appear as problematic.

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, are still within the limits determined by the fatigue.





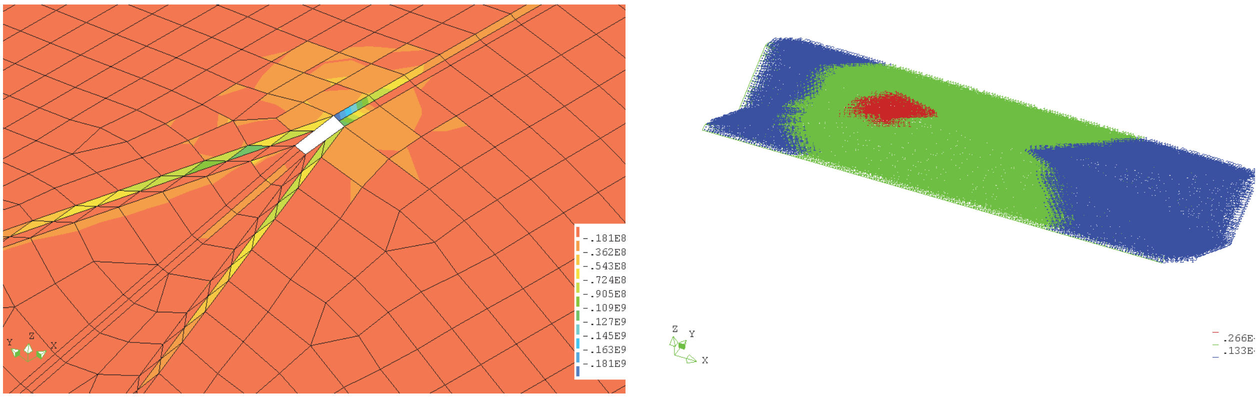


Fig. 20,21,22,23 Graphically represented principal stress S1 S2 results of the finite element analysis. Units in m and N/m2

3.3. The effect of wind load and suction

As previously regarding the assigned loads, besides the self-weight 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. 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 air pressure on the structure's surfaces, a wind flow simulation was set using Autodesk Flow Design, a software developed for simulating the effect of wind, of given speed and direction, on the final model. 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 wind load in the Netherlands, and was set at 18m/s.

Figure 22 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 self-weight of the glass roof structure alone is 2230 E9 kN/m^2. 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/m^2 of wind load. This is a fairly low wind load, so for the further structural analysis a pressure load of 1KN/m^2 is assumed as a minimum.

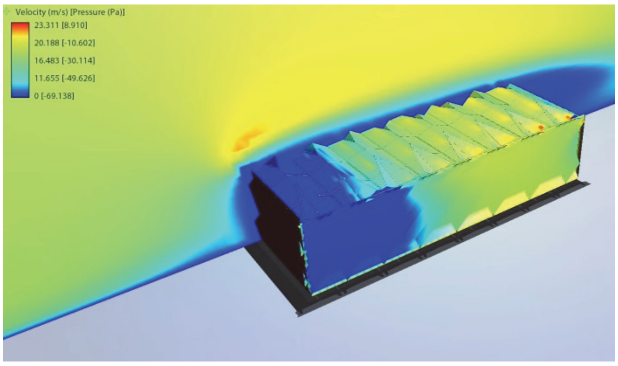


Fig. 24 Airflow analysis results of air velocity

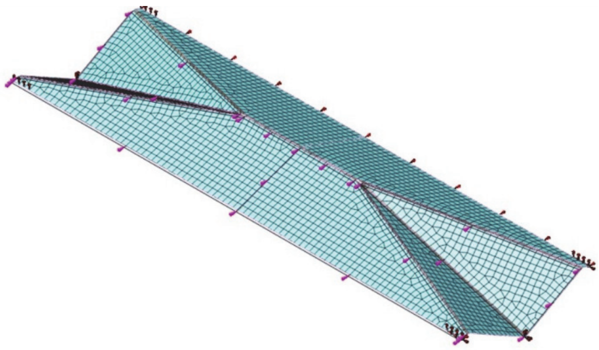


Fig. 25 Model for FEM analysis of wind load impact, in FX Midas

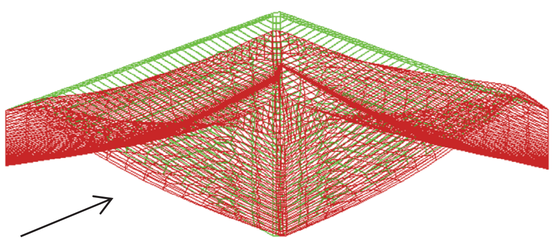
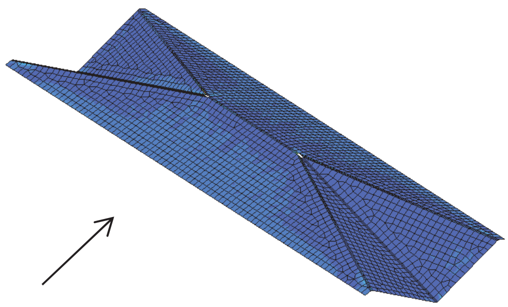



Fig. 26,27 Graphically represented deformation and principle stresses S1 results of the finite element analysis applying selfweight and windload

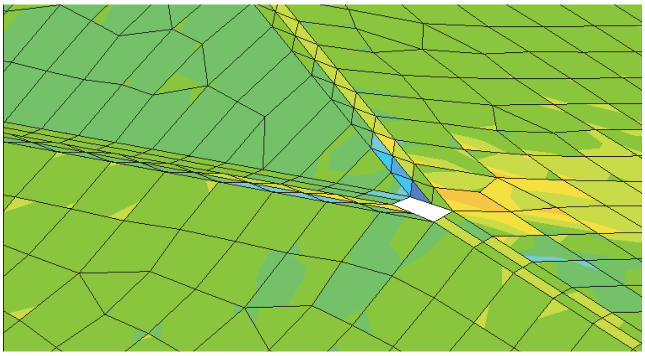
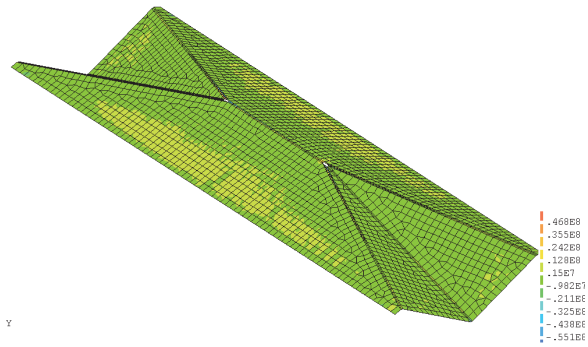



Fig. 28,29 Graphically represented principle stresses S2 results of the finite element analysis applying selfweight and windload

Given the outcome of the wind tunnel 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 load case. In this case, a horizontal wind load, again from the least favorable direction, as shown on fig. 22, 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. A linear static type of analysis was performed in TNO Diana.

In the results of this analysis, as demonstrated in fig. 24-27, 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 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. 24 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.

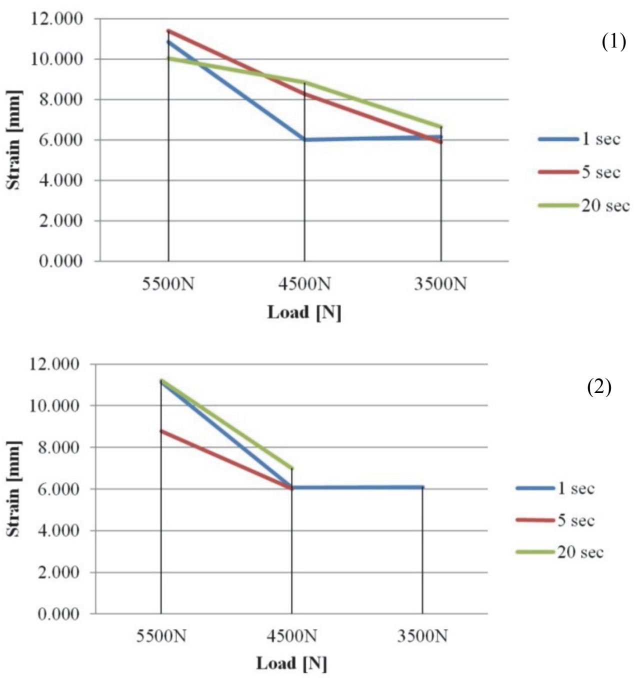


Fig 30, 31 Fatigue tests results, maximum strain over imposed load for different hold times, (1)after 1314sec and (2)220 cycles

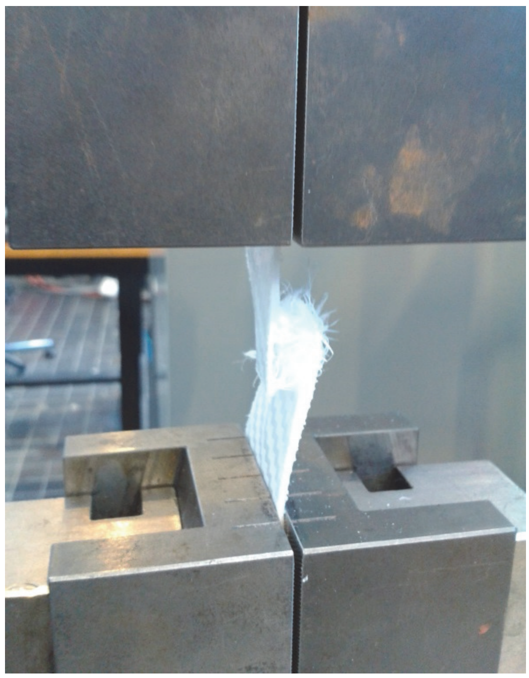


Fig 32 Fatigue tests configuration

The top connection where exceeded deformation due to asymmetrical loading is a main concern for the PURE sheet connection 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 (NEN 2608). 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.

3.4. Lab tests on the connection material and principle

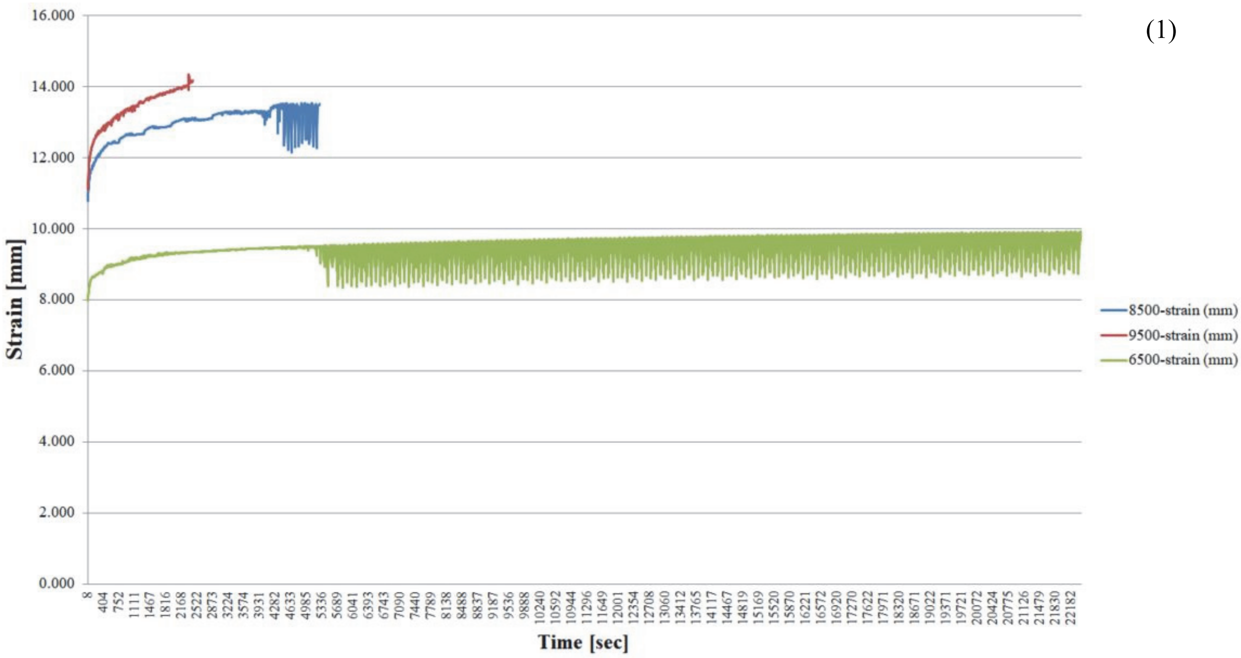
As part of the test planning, a series of fatigue tests is performed on the PURE® composite to ensure that it can efficiently be used in a structure of a large expected life-span, since the PURE® sheet effectively acts like a hinge. Hold time is specified as the time interval between consecutive loadings. Three different hold times are 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 specimens are used, of 10 specimens each. One is with an engraving along the middle, to define the area of the folding and one without engraving. Sheet thickness is 1.8mm and specimens were cut on a laser cutter.

As a first step a tensile test is made to define the Ultimate Limit Load of the specimen. Specimen is 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 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.

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.

On a second round, another set of specimens is tested, of the same thickness of 1.5mm this time without the engraving. In this case, all specimens are tested only at a holding time of 1sec, due to time limitations. Increased loads were applied, of 9500N, 8500N and 6500N as tensile strength of the first specimen proves significantly higher, as expected. 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 is used as a stress limit for the material as far as all further FEM calculations on the connection are concerned.



(1)

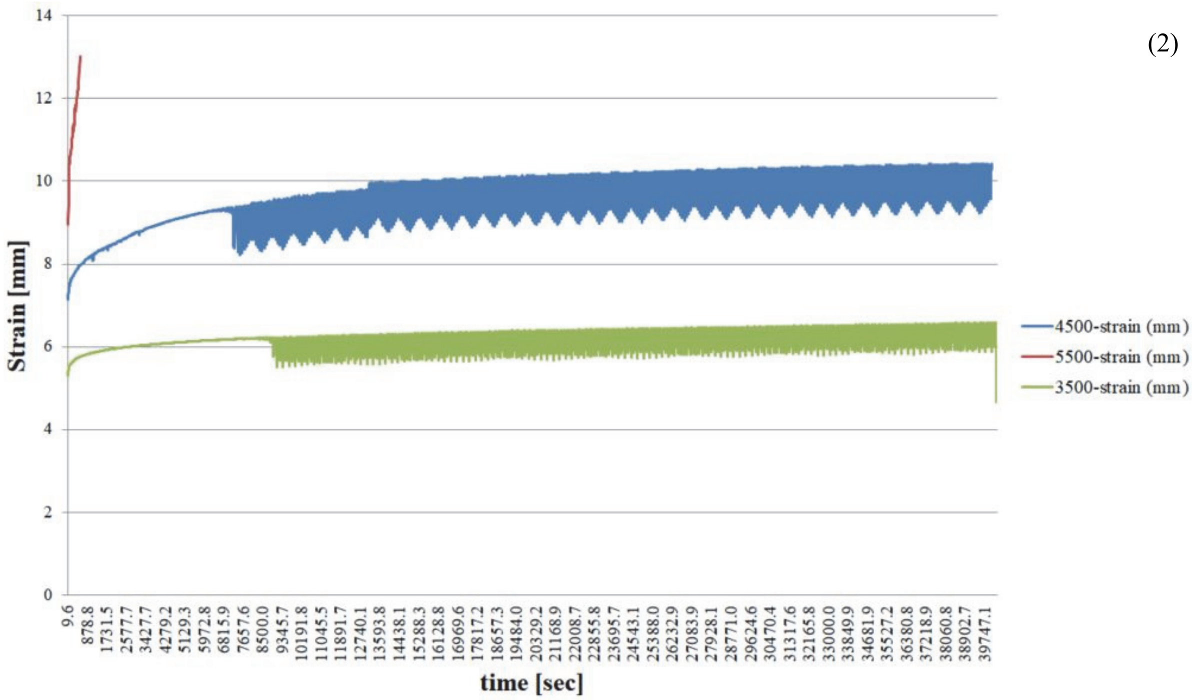


Fig. 33 Strain maxima in mm over time graph from the first testing of an engraved (1) and a non-engraved (2) specimen at a holding time of 5 sec and 1 sec respectively.

To determine the load bearing capacity of the connection principle, a pull-out test was carried out using the same equipment as for the fatigue test, under a different configuration. Specimens 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. For the specimens of double thickness two discs superimposed were used. Four specimens of each category are 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 is set to automatically stop either when the specimen loses 80% of its tensile strength or a displacement off 40mm is reached.

Surprisingly, the results of the test have been quite largely variating for the first set of 1.5mm PURE sheet with a single glass disc. In the case of the double sheet specimen, all four specimens fail at the adhesive connection between glass disk and glass plate. This result is against the purpose of the test, which has been 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

From technical sheet

MAX TENS. STRESS	200	Mpa

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]
	90.28	**[Mpa]**
MAX pricipal force	1.35E+05	[N/m]

Pull-Out testing

on a 40mm width

		N	to	N/m
SINGLE 1.5mm /1 DISK	Average force	2383.98	[N]	**5.96E+04**
	Max. shear stress	3.97E+07	[N/m2]	
		39.73	[Mpa]	
DOUBLE 1.5mm /2 DISK	Average force	4417.37	[N]	**1.10E+05**
	Max. shear stress	7.36E+07	[N/m2]	
		73.62	[Mpa]	

Fig. 34 Comparative results concerning design stresses as occurring from fatigue and pull out testing

Fig. 35, 36 Pull out test customized configuration

Fig. 36 Pull out test results

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.

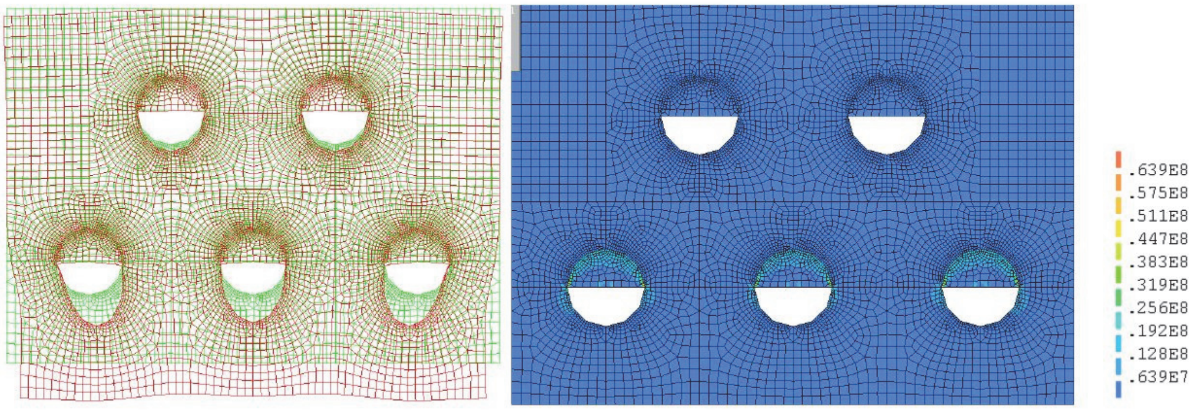


Fig. 37 Graphic representation of the 2D model of connection element of perforated sheet of PURE composite and the stress results of finite element analysis

3.5. Finite Element Analysis on the PURE® composite sheet

For the Finite Element Analysis supports were modeled as half disc surface of a stiff material in direct contact with the PURE surface. The reaction force on the edges of the geometry from the six-fold FEM analysis is applied as distributed tensile force along the edge of the PURE® sheet. Thicknesses of 1.5mm, 3mm and 5mm are tried and compared. 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. A second model is then run for larger disks, after the conclusions of the pull-out test. A disk diameter of 40mm, resulting also on a slightly bigger analysis model was selected. This version is only tested for a PURE sheet thickness of 3mm. The results are less favorable, but still within the allowable limits. (see fig. 30), (NEN 2608).

Hinge connections between folded plates suggest a certain level of instability, especially considering unevenly distributed forces or horizontal loads such as the wind. As a result, the out-of-plane compressive force generated between elements at the mountain folds is a major issue for the overall stability of the structure. For this purpose, a linear static finite element analysis is performed on plain strain elements, modeled like two facing plates with a surface of 60mm width and 3mm thickness in-between. Three different loading scenarios are considered to examine distinct unfavorable loading situations. The focus has been on the resulting deformation shapes and values. The properties of the sheet of PURE® composite are defined as following:

- Elastic modulus: 5.5 E09 [N/m2]
- Poisson ratio: 0.45
- Mass density: 7600 [N/m3/g]

As shown in the numeric results, deformations are not significant, compared to the 20m span of the structure. The deformations for the given material properties in the specific configuration are ranging between 12 and 150 mm, with the least favorable scenario being the asymmetrical vertical loading, as expected. The maximum deformation of 15mm on scenario 1 is still an allowable result, which implies that despite the asymmetrical pane translation, the two glass edges do not come into contact and the shape alteration is not so significant as 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.

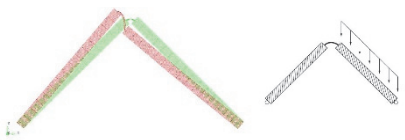


Fig. 38 Scenario 1-deformation 0.015mm

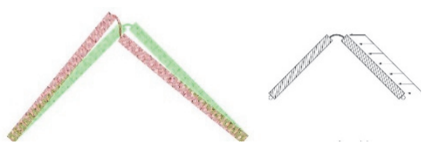


Fig. 39 Scenario 2-deformation 0.0012mm

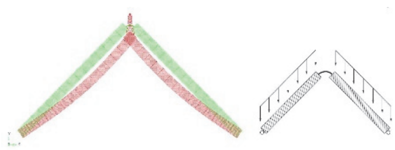


Fig. 40 Scenario 3-deformation 0.0022mm

4. Conclusions

4.1. 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. 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.

4.2. 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. However, as mentioned before 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.

This might lead to reconsidering the final design in terms of efficiency. 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-structural 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.

4.3. 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 a 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 givens 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 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 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.

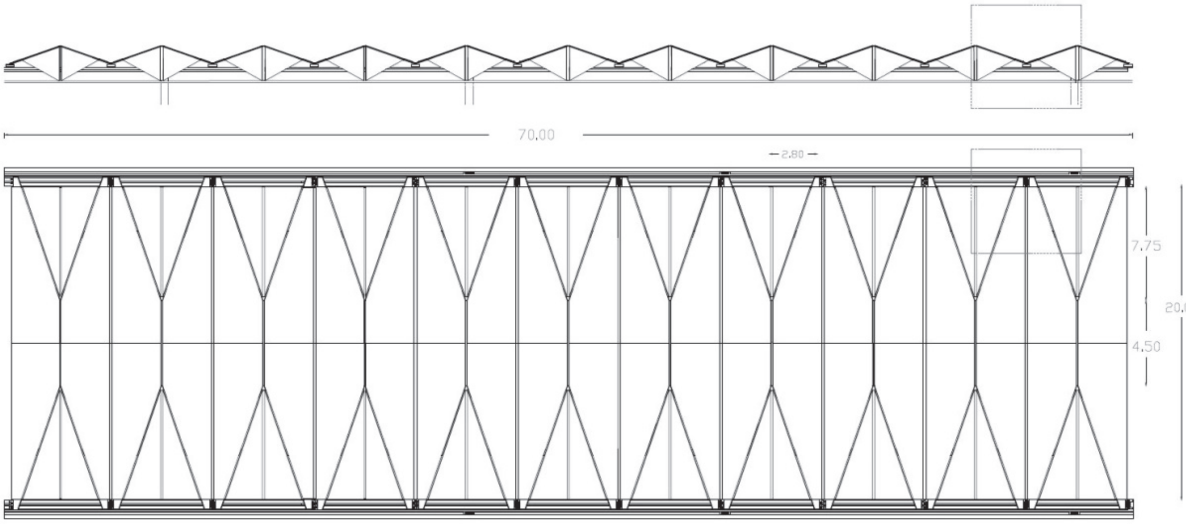


Fig. 41 Final drawings in floor plan section and cross-section of the roof system, following the specifics of the case study.

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