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The Transparent Facade of the Future

Design strategies
for maximizing transparency
with self-supporting
glass facade systems

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/// INTERNATIONAL FACADE MASTER

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/// *It wouldn't have been possible for this thesis to be realized without the valuable contribution of many people.*

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Contents

Abstract .7

Introduction .8

12 The modern movement & curtain walls

13 Latest developments

Research Definition .14

16 1.1 / Problem Definition

19 1.2 / Goals

19 1.3 / Research question

20 1.4 / Methodology

23 1.5 / Relevance

24 1.6 / Time Planning

Analysis Glass Technology .26

29 2.1 / Material properties

32 2.1.1 / Basic types of glass

34 2.2 / Design considerations

35 2.2.1 / Strength & surface condition

35 2.2.2 / Strength & loading time

35 2.2.3 / Strength & area of loading

35 2.2.4 / Strength & environmental conditions

36 2.2.5 / Failure behaviour

38 2.3 / Structural design with glass

39 2.3.1 / Mechanical quantities

39 2.3.2 / Calculating stresses and deformations

40 2.3.3 / Design & Safety

42 2.3.4 / Prestressing - Safe components

46 2.3.5 / Loadbearing glass components

48 2.3.6 / Structural systems

49 2.3.7 / Loadbearing patterns

50 2.3.8 / Established glass facade systems

51 2.4 / Constructing glass facades

51 2.4.1 / Design principles

52 2.4.2 / Stress transfer - connection types

54 2.5 / Fabrication of glass components

56 2.5.1 / Glass forms - forming processes

58 2.5.2 / Form generation

60 2.6 / Case studies

61 2.6.1 / Oversized Laminates

68 2.6.2 / Corrugated glass facades

76 2.6.3 / Cold bended glass structures

79 2.6.4 / Stacking

80 2.6.5 / Glass units

82 2.6.6 / Adhesives

84 2.6.7 / Glass welding

85 2.6.8 / Glass columns

87 2.6.9 / New design possibilities

Preliminary Concept Generation .90

93	3.1 / Oversized flat laminates
95	3.2 / Corrugated glass-curved elements
97	3.3 / Stacking
98	3.4 / Self supporting surfaces
99	3.5 / Combination
100	4 / Selection process
101	4.1 / Concept Generation
107	4.2 / Conclusions

Design Research - 3 Strategies .108

110	5 / 3 Design strategies
111	5.1 / Common Features
114	6 / Analysis of the 3 Strategies
114	6.1 / Analysis of the units
114	6.1.1 / I-profile units
118	6.1.2 / Curved units
121	6.1.3 / Tube units
124	6.1.4 / Transportation & Installation
125	6.1.5 / Summary table of unit evaluation
126	6.1.6 / Conclusions
127	6.2 / Analysis of facade design systems
129	6.2.1 / Design Strategy 1 - Flat screen (I-Profile)
140	6.2.2 / Design Strategy 2 - Glass Curtain (Curved panels)
152	6.2.3 / Design Strategy 3 - Bubble Wall (Glass tubes)
162	6.3 / Conclusions
163	6.4 / Selection of Design Strategy

Final Design Development .164

166	7 / Final Steps
167	7.1 / Form optimization
170	7.1.1 / Simulation inaccuracies
170	7.1.2 / Conclusions Scan & Solve
172	7.2 / Final Design
174	7.2.1 / Structural Design
174	7.2.1.1 / Safety - Reducing risk of failure
177	7.2.1.2 / Structural Design of the facade
194	7.2.3 / Safety factor of the Facade
198	7.2.4 / Performance simulations
198	7.2.4.1 / The model
199	7.2.4.2 / Ultimate limit state
201	7.2.4.3 / Serviceability limit state
203	7.2.4.4 / Simulation conclusions
204	
206	8 / Conclusion and recommendations

Literature .208

210	Literature
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Appendices .212

214	Appendix Drawings
224	Appendix Calculations

"Should we wish to lift our culture to a higher level, then we are obliged, for better or worse, to transform our architecture. We shall only succeed in doing this when we remove the element of enclosure from the rooms in which we live. We can only do this, however, with glass architecture, which allows the light of the sun, moon, and stars to enter not merely through a few windows set in the wall"

< Paul Scheerbart, Glasarchitektur, 1914 >

The demand of the architects and engineers for maximizing transparency in glass facades has become more and more evident during the recent decades. Pioneering architectural offices such as OMA (Office of Metropolitan Architecture) are experimenting in their projects with new technologies that can facilitate the development of dematerialized envelopes. This research has been done in several levels with main aim to create innovative glass façades that are using the minimum amount of steel structure and integrating efficient climate regulating strategies, such as translucent insulation.

The research is focusing on the development of strategies to accommodate the structural design of an all – glass façade. This façade will be designed for one of the projects currently ran by OMA. Through the research it will be attempted to organize and systemize all the different aspects that one must consider when designing with glass and end up with alternative proposals that integrate the programmatic functional requirements of the glass façade. The concepts will focus on the structural performance of the façade. Alternatives for the design of a façade of 30 m height and 15m width will be developed with focus on erecting an all – glass façade where no metal components to transfer the loads are present. Finally the combination of glass with other transparent or translucent materials will be explored in joining methods as well as in functional components that are introduced in the glass in order to enhance its tensile strength and built up a ductile behavior that is absent in normal float glass

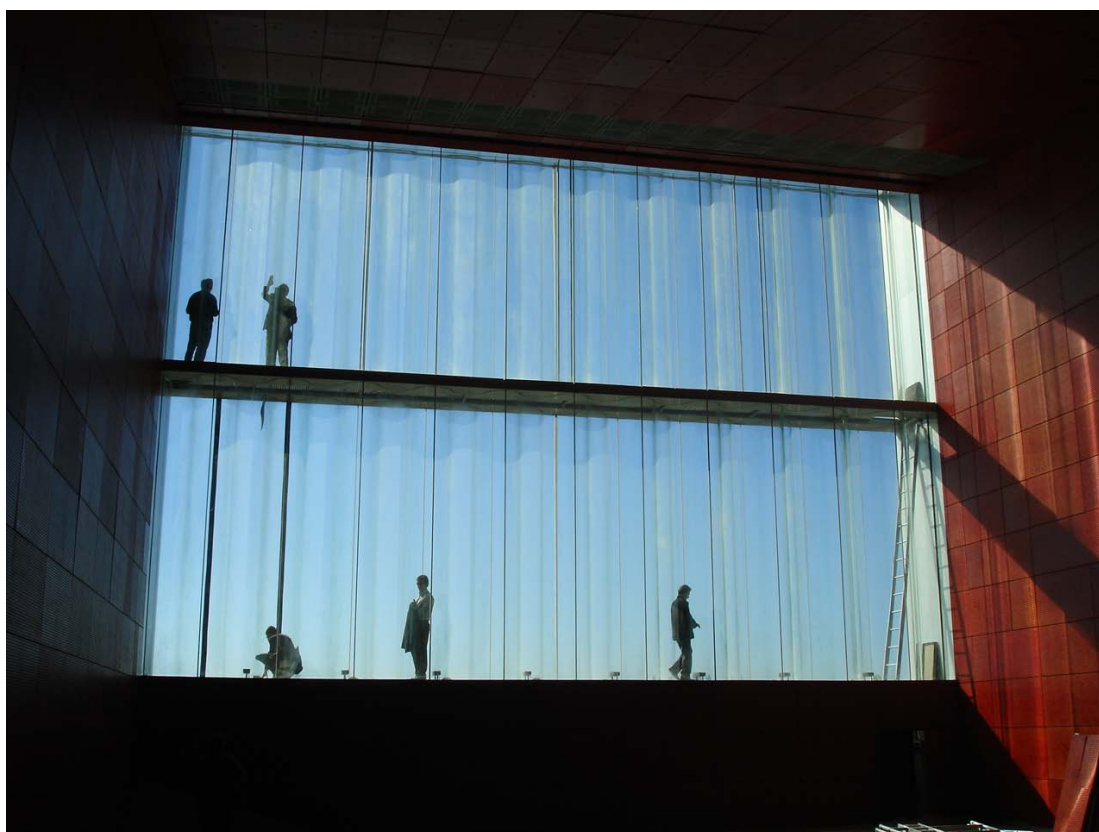


Fig. 1_ Interior view of the corrugated glass facade, Casa da Musica, Porto, by OMA < renatocilento.blogspot.nl >

Introduction

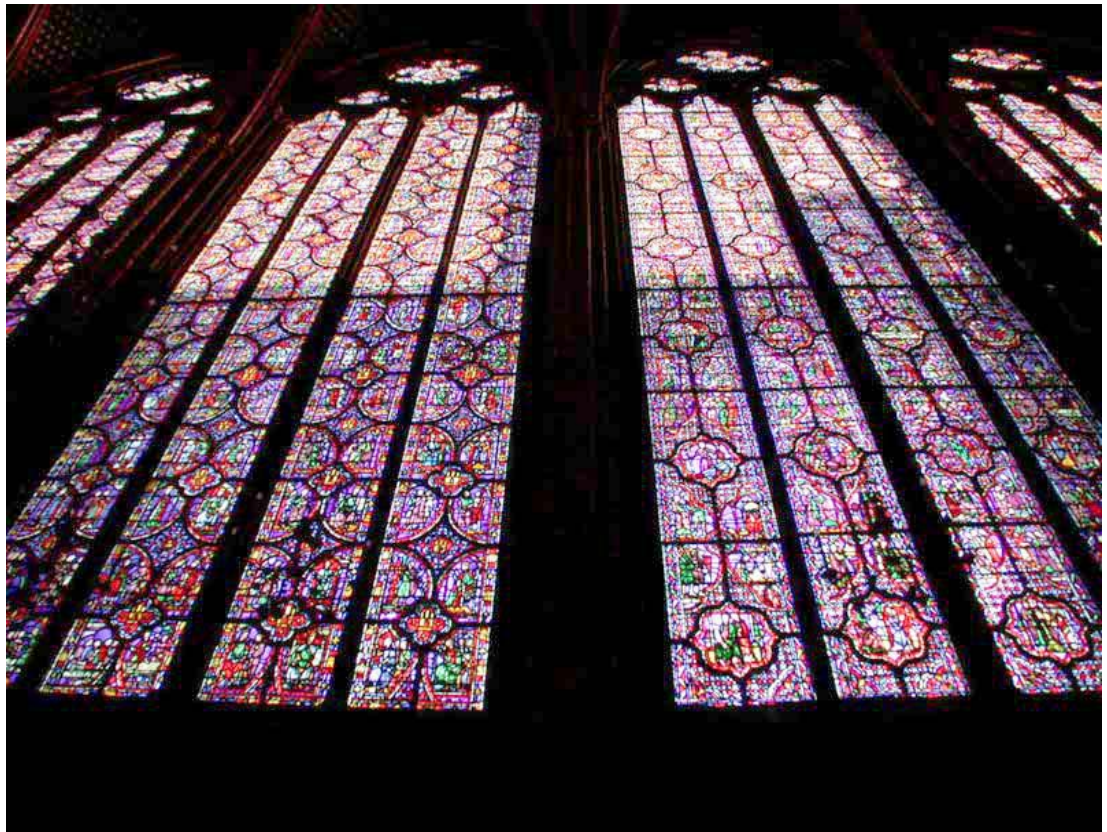


Fig.2_Vitraux art at the Upper Chapel Gothic cathedral of Saint Louis



Fig.3_ Palm house, Bioton Park gardens 1930 < www.redbubble.com >

"The word glass is derived from glaza, the Germanic term for "amber", "glare" or "shimmer". <Glass Construction Manual, 1999, p.9>

Glass as a material has, since its early use, a significant meaning and close relation with openness and light in the architectural expression. A good example of this statement is the symbolic large and colorfully glazed openings in the gothic cathedrals. The size of these openings and their special filigree like construction of lead – frames allowed for a majestic openness that can embrace a symbolic connection of the occupant with the divine.

Since the time of the Victorian glasshouses and Crystal Palace of the 1830 the need of the architects to express a dematerialized envelope that will create an ultimate connection between interior and exterior is even more profound. The very special properties obtained by the material glass were responsible for establishing it as the main material used in the building construction and led engineers and architects to constantly think of ways to use it in larger extent and scale.

The steps toward dematerialization of the façade are strongly connected to the principle of relieving the enclosure more and more from its load bearing function. This has been assisted by the ability of a structural frame to carry loads of the façade and transfer it to the floors. Finally the shield against the outside weather conditions is provided by a glass skin that fills this frame.

The modern movement & curtain walls

The modern movement was the one to find a more solid theoretical and practical framework for increasing the use of glass in architecture. Since the envelope was released from the primary structure is now assigned with fewer loads and therefore allows for smaller profiles and load bearing structure for the glass. Architecture after that would no longer be determined by the mass and the introversion of the brick and stone, but by the lightness and transparency of the steel and glass. Mies van de Rohe was the architect trailblazer that envisioned the first office building where the façade was completely made out of steel and glass, in the design for Berlin Skyscraper. There the façade wraps the building as a veil, it becomes an external hanging skin, like a curtain.

The architecture of skyscrapers continued to address the hanging envelopes made of glass in the following decades. The development of the curtain like glass – steel envelopes were accompanied by a major revolution in the field of glass production, the discovery of "Float glass" manufacturing technique that allowed for fast and high quality production of flat glass.

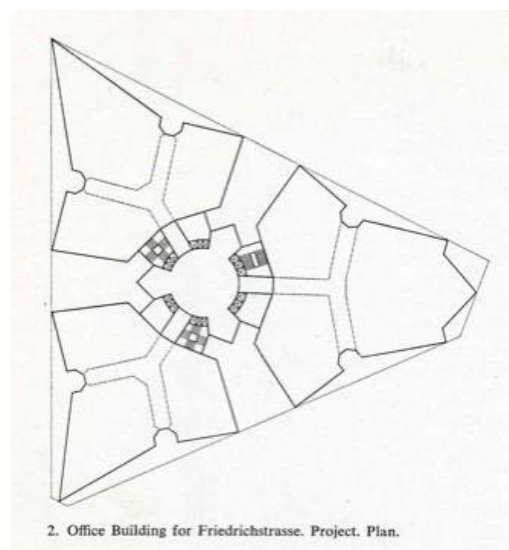
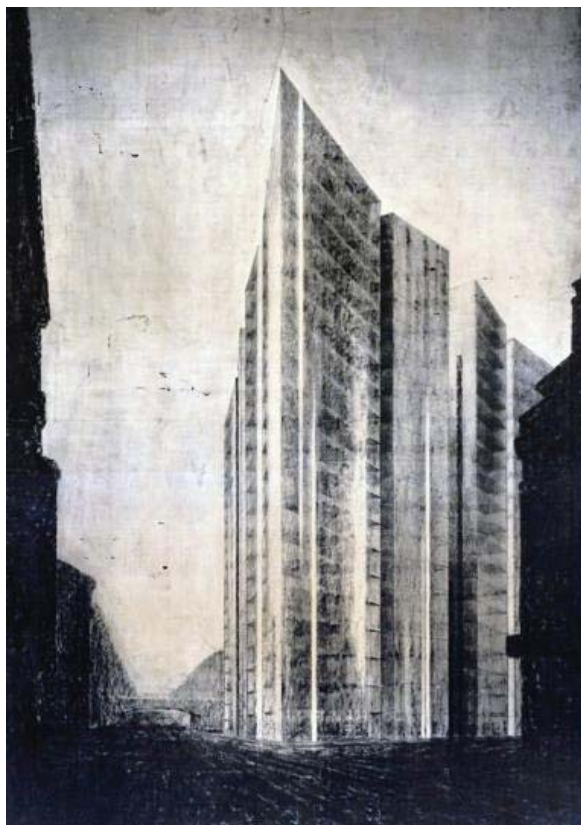


Fig.4_ Office building for Friedrichstraße, by Ludwig Mies van der Rohe - Drawing and floorplan - < www.studyblue.com >

Latest developments

In the late 80's a major breakthrough happened in the field of glass facades as the use of the material as structural component became true with the development of structural glazing. Glass after undergoing several treatments, based on the principle of Prince Rupert's drops¹, that increased its load bearing capacity, was able to form transparent structural components such columns, beams and slabs.

These developments brought architects and engineers in the recent decades to a constant strive and further research for the dissolution and maximum transparency in facades. It was inevitable that this would lead to attempts of erecting all – glass structures were no metal components to transfer the loads are present.

Despite the fact that glass as a material can be very strong, sometimes even compared to steel and concrete, it still remains a very brittle material with no – plastic behavior that cannot exhibit warning failure mechanisms. Additional to that, manufacturing limitations in sizes did not allow for the construction of components large enough to cover a wide range of designs. Until now these limitations and lack of knowledge for glass as a material with engineering potentials has restrained its broad use only in so – called "tertiary tasks" in terms of structural functions. This practically means that its use in a safe primary or secondary structure is still an issue as glass is characterized as "too fragile" and unpredictable as a primary or secondary loadbearing component. For that to be overcome we need to analyze in what ways glass with its unique structural behavior can be exploited as a safe structural component and offer the excellent space quality in designs that utilize each undeniable beauty.



¹ Prince Rupert's Drops (also known as Rupert's Balls or Dutch tears) are glass objects created by dripping molten glass into cold water. The glass cools into a tadpole-shaped droplet with a long, thin tail. The water rapidly cools the molten glass on the outside of the drop, while the inner portion of the drop remains significantly hotter. When the glass on the inside eventually cools, it contracts inside the already-solid outer part. This contraction sets up very large compressive stresses on the exterior, while the core of the drop is in a state of tensile stress. It can be said to be a kind of tempered glass

Fig.5_ Prince Rupert drops < www.cmog.org >



Research Definition

1.1 / Problem Definition

Background

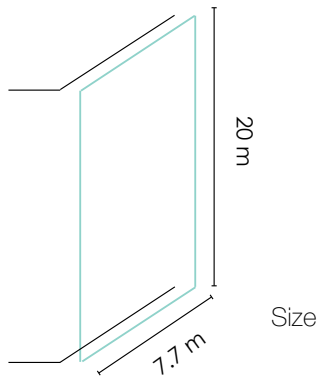
Architects worldwide have been striving in the last decades to develop all glass façade structures. This would allow them to provide their buildings with the maximum transparency possible by minimizing the obstructions of any skeleton made of steel or other opaque materials appearing in large surface or joints. This is extended further to an interdisciplinary study of glass facades that is undertaken in the fields of design, structural use of glass and combination of glass with other translucent or transparent polymers (such as polycarbonates or polyacrylates) as well as in the field of thermal comfort integration. The problems that they all have to face until now are focused on two main aspects:

01_ The first one is that glass as a material with many irregularities and special characteristics in its mechanical behavior cannot be trusted for loadbearing constructions on a large scale. The material's strength is a variable dependent on many aspects such as the loading time, the surface condition and area of loading. These aspects may define the probability of failure of a glass component only by means of statistical methods. Furthermore this results in a lack of systemized knowledge in the field of the structural use of glass, as it is based on knowledge from custom problems in case study applications. Finally from a structural point of view glass is a material with high compressive strength but is also very brittle and vulnerable to high stress peaks. These factors result in constructions of glass being reinforced with other materials, such as steel that can compensate for the low tensile strength of glass. The use of steel and other opaque materials at that point is not allowing architects to achieve a 100% degree of transparency. This becomes a design issue that is strongly connected to the structural application of glass.

02_ The second aspect is focusing on problems posed by the fabrication limitations in glass components. These constraints apply on the available sizes and the potentials of post-processing techniques in oversized components. Other issues that arise from that are the logistics and installation of oversized glass components. Finally the lack of an analytical database on the forming potential and manufacturing of glass products is holding back architects from a broader range of design solutions.

Given the aforementioned problems all glass façade constructions are generally limited in spans of one storey high floors.

OMA a leading architectural office worldwide and in the Netherlands has been involved several times in the field of research for innovations in glass technology. Their focus is to discover new ways to apply glass in the design of their buildings. This can be seen through several innovations as an outcome of their collaboration with experts in the field of glass structures, such as the sinus shaped glass façade applied first time in the Casa Da Musica facades in Porto. The new challenge formed by OMA in collaboration with leading experts in the field of glass facades and TU Delft is to take this to the next level and develop a new era of facades that will achieve maximum transparency.



1.1 / Problem definition

Commission project

This research is motivated by the OMA proposal and is focusing on the development of an all glass façade design & structure for one of the commission projects of the office regarding a new building of the **La Fayette Galleries** in Paris. The new façade has to fulfill several functional criteria which will form the brief for this design.

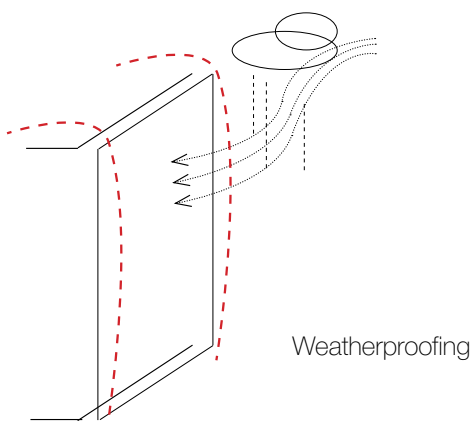
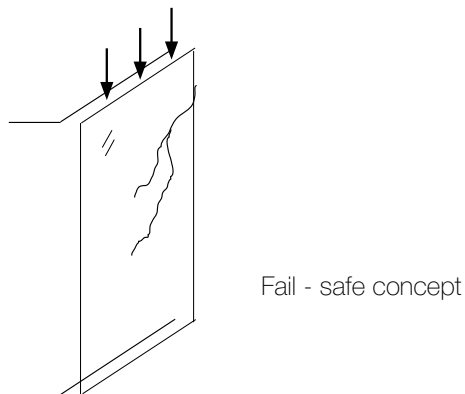
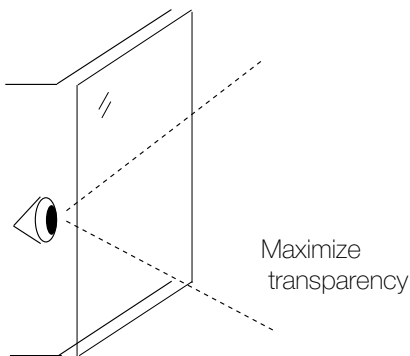
01_A new type of all glass façade should be dealing first of all with the problem of efficient structural use of glass in **constructions taller than one floor height**. In this case a façade should be developed large enough to explore this potential. Therefore the facade area that needs to be covered has been set to 30m (height) x15m (width).

02_As far as the **transparency** issue is concerned this design is meant to increase the levels to the **maximum degree possible (100%)**. Of course at this point one has to acknowledge that transparency is a **relative value** that needs to be defined more clearly as it can take many forms. It can be achieved in many ways and it can be also a metaphor in architectural expression.

03_Furthermore the challenge of this new façade is to combine an interesting design with a safe structure. This can be achieved only if the glass loadbearing components can obtain a **fail safe mechanism** that cannot be easily accomplished in 100% glass components.

04_As a typical envelope it should accommodate to a certain level other functionalities such as **insulation, weatherproofing, possibility of sun protection and serviceability**.

05_All these are the challenges that have to be taken into account and result in an **interesting design** that will utilize the state of the art technologies in glass structures.



1.1 / Problem Definition

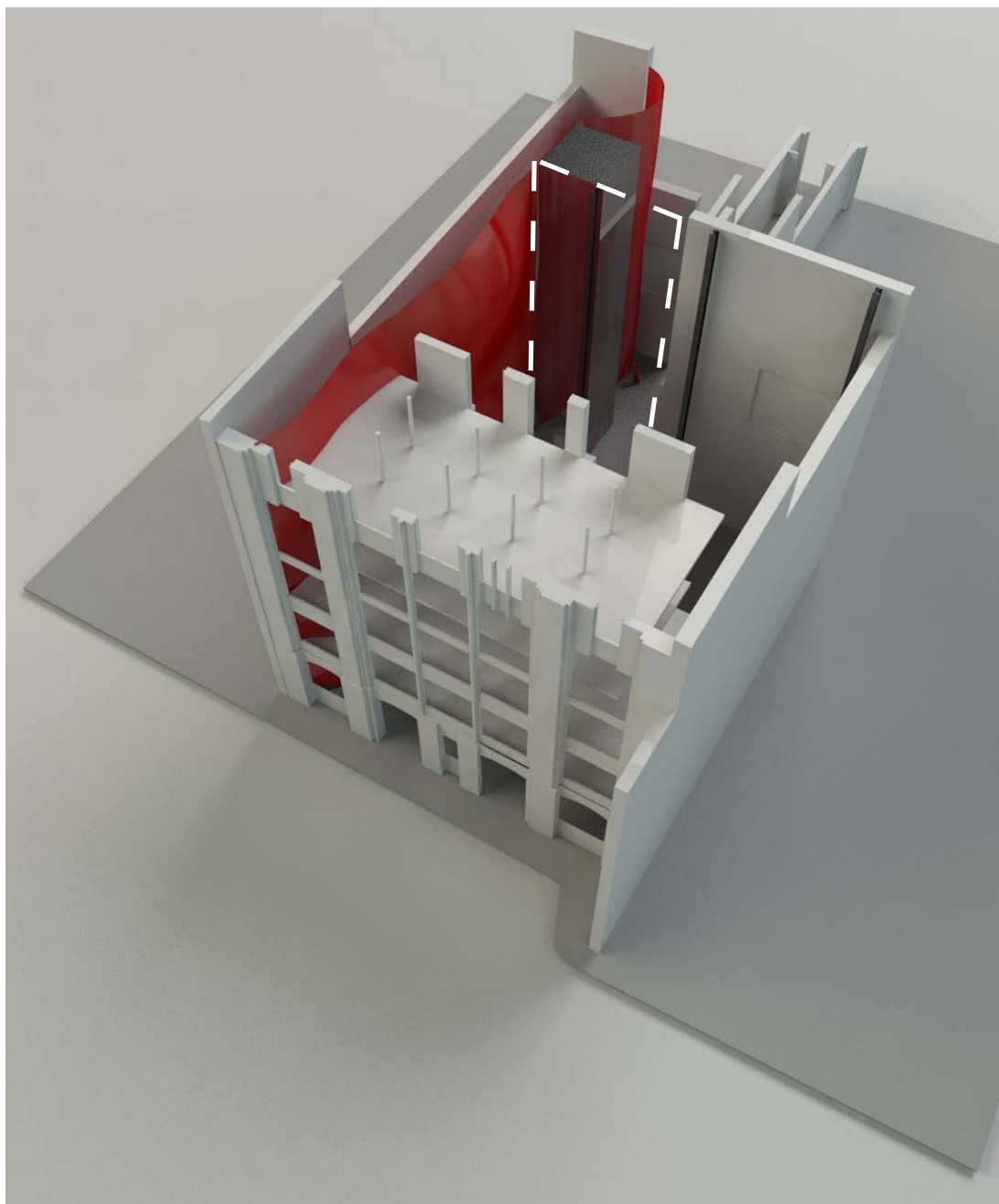


Fig.6_ 3D model of the case study, 'La Fayette Modern', in Paris - Design: OMA / 3D visualization: Katerina Doukari

1.2 / Goals

The above mentioned problems and attempts in constructing an all glass façade that would be able to accomplish maximum transparency in a façade 20 m high posed the question in what way this can be achieved.

The main goal of this research is to provide an analytical framework for the exploration of potentials in the structural applicability of glass in facades focusing in maximizing the effect of transparency and at the same time provide alternative design methods with the material. The framework occurs from the analytical qualitative and quantitative findings collected via literature study, descriptive analysis of existing case studies and finally calculations to evaluate the integrity of the systems. The goal is to understand the state of the art and develop new strategies to accommodate the structural design of an all – glass façade for the La Fayette Galleries so that can become the guide for future designs and create a reference for designers and engineers.

The research it will attempt to organize and systemize all the different aspects that one must consider when designing with glass and conclude with alternative proposals that integrate the programmatic functional requirements of a glass façade. **The concepts will be oriented towards the structural performance of the façade that can be mostly influenced by the geometries of glass components.** Alternatives for the design of the new façade of 20 m height and 7.7m width will be developed with focus on constructing an almost 100% glass façade where no secondary supports from metal frames are present. Finally the combination of glass with other transparent or non transparent materials will be explored in joining methods as well as in functional components that are introduced in the glass in order to enhance its tensile strength and built up a ductile behavior that is absent in normal glass.

1.3 /Research Question

The research question has been composed by the previous acknowledgements about the developments and requests in the field of glass structures and in particular from the request for a design of a new type of glass façade for the OMA project. In conclusion the research question is formed as follows:

What are the design strategies that one can employ in order to maximize transparency in glass facades and which strategy is the most appropriate to follow for the structural design for a transparent facade of the future that will be applied in La Fayette modern ? This question is further broken down in subquestions such as:

- 01_** What is the optimal geometry of glass components to be used for the construction of the facade?
- 02_** What are the criteria to evaluate an optimal structural design strategy for the glass facade?
- 03_** What are the parameters that can influence the performance of a glass component.
- 04_** How can manufacturing availability and processes influence the structural design with glass?
- 05_** What are the ways in which we can enhance the safety of the glass facade?
- 06_** How should a structural joint between glass components be designed in order to enhance transparency?

1.4 / Methodology

The methodology of this research is focusing on developing a broad database and a wide knowledge of the field of structural glass applications in facades. This background will form the basis for the generation of alternative concepts for the glass façade with the requirements mentioned in the brief. The concepts' integrity, efficiency and performance will be evaluated in a form of comparative assessment with between the developed strategies. The inventory and design proposals that this research will conclude in, must provide a design that will fulfill best the aspects of the brief and the functional requirements. The main research will be undertaken in four stages:

Stage 1 _ Analysis - Glass Technology

The first part is building up a catalogue of the state of the art of structural glass facades and structures by collecting data from **literature study** (books, publications, articles, conference proceedings, internet, site visits etc.) on already undertaken research as well as from analysis of case studies (a big part of it has been already conducted). The case studies will be either **built projects** or **experimental studies** on different systems. The choice of these precedents will be made with the **criteria of potential contribution in the solution of all glass components**. The analysis of the precedents will be oriented in the **form and fabrication potentials, structural principles, materialization, construction and joining methods**.

The editing of the information gained from the literature into a systemized database is the next step. The database will be organized in different sections depending on the focus (material, structural components, structural systems, loading cases, joining methods, manufacturing techniques, potential geometries etc.). This will help in understanding the state of the art and the design potentials. It will also help to gain a generic knowledge in order to reconsider new design methods.

In the second part of this step, a more detailed overview of certain categories related to precedent case studies will be given emphasizing on fabrication, structural principles and detailing.

Stage 2 _ Preliminary concepts generation

In this step the collected knowledge from the literature and systemization of the collected data will provide input for critical concept generation. Various strategies such as the self – supporting surfaces, curved glass, transparent adhesive bonding, creation of oversized components by methods of lamination with overlapping joints, hierarchical systems with all glass components etc. will hereby be investigated. The conceptual sketches generated will be focusing on all these different aspects (design, structure, joining methods and detailing).

In a further stage, design requirements will be given as an input from the architects and will define the aesthetic criteria to be taken into account for the final design strategy.

In the process the developed conceptual designs will be filtered through the façade' s technical requirements found in the brief:

- size – (20x7)
- aspect of transparency (defined by the intermediate joints)
- fail safe concept (assessed based on the composition of the elements & structural scheme)
- insulation integration (insulating panels)
- watertightness – airtightness (quality of the connections)
- sun protection integration (potential of sun protection)

Then the conceptual ideas will be listed according to their typologies.

Stage 3 _ 3 Design strategies

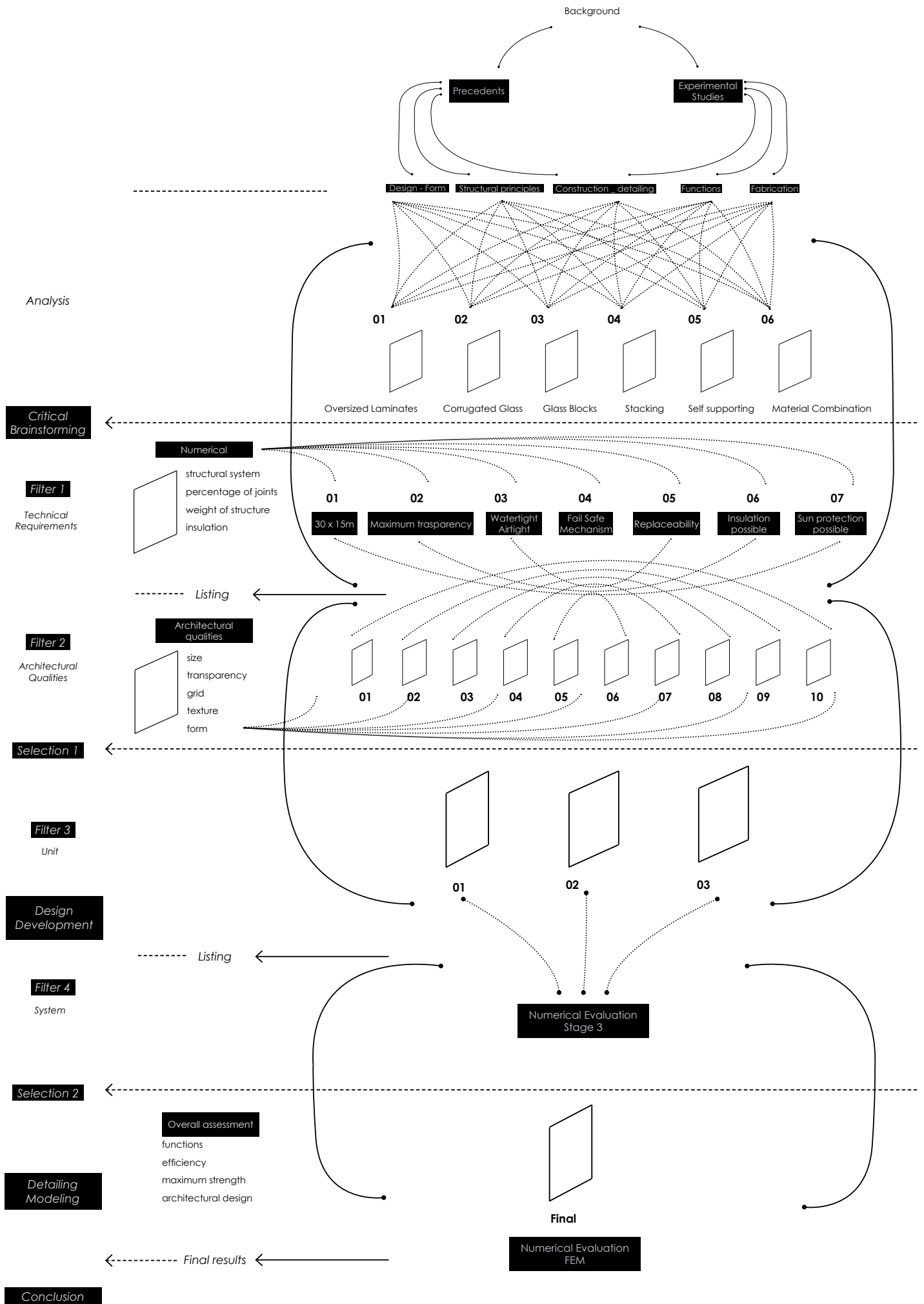
In this step there will be a first selection of the 3 most promising design typologies generated in the conceptual phase. For design typologies to pass through this filter they must obtain the criteria to provide a good structural design with a design versatility. The selected concepts will be developed further in design and construction principles. Drawings will be produced at scales 1-50 and 1-20 along with 3D illustrations in order to give an overview of the structural principles, the construction, as well as the aesthetics of the facades.

An extensive analysis of the typologies and design systems produced will help the final selection of design strategy for the facade. The criteria employed for the comparisons between them are mainly fabrication feasibility, form, structural performance and partly realization costs.

Stage 4 _ Final design development

In the final step a final selection of the 1 most suitable design strategy for the facade will be chosen. For that strategy there will be a shape optimization to select the facade with the best structural performance. The final stage will be focusing on the development and optimization of the detailing and construction of the design proposal with main goal to fulfill the requirements (maximum transparency, structure etc.). One of the purposes of this step is also the development of critical construction details at scale 1:5 and 1:2. The details will be drawn in CAD and computer modeled with maximum possible precision and special attention to the accuracy of dimensions.

The final design will be evaluated for its structural principles with finite element analysis software. The type of modelling will be dependent on the complexity of the design.



1.5 / Relevance

General scientific value

This façade will be designed for one of the projects currently conducted by OMA. The value of the research is directly related to a request of the market (architects ,leading experts in glass technology ABT -Rob Nijse, manufacturers - Scheldebouw) and the scientific community involved in the developments of glass facades (TU Delft).

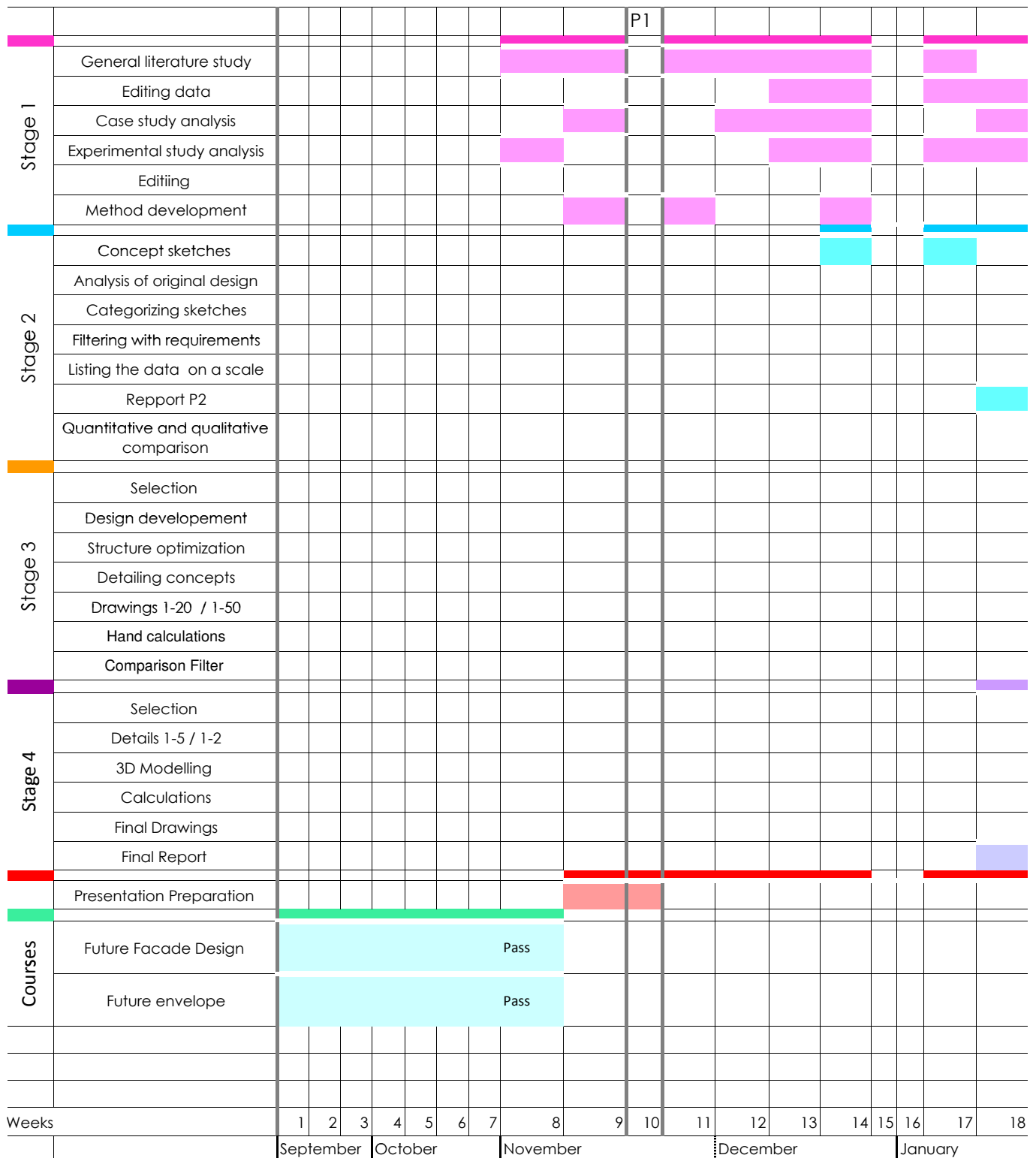
The contribution of this research is going to set the basis or inventory for the latest technologies in the structural glass field and the potential applicability in an architectural design for facades. These are accompanied by a systematic mapping of the method for designing new systems with structural glass. The methodology as well as the findings summed up in the final product can become a future reference for architects and engineers that are involved in the field.

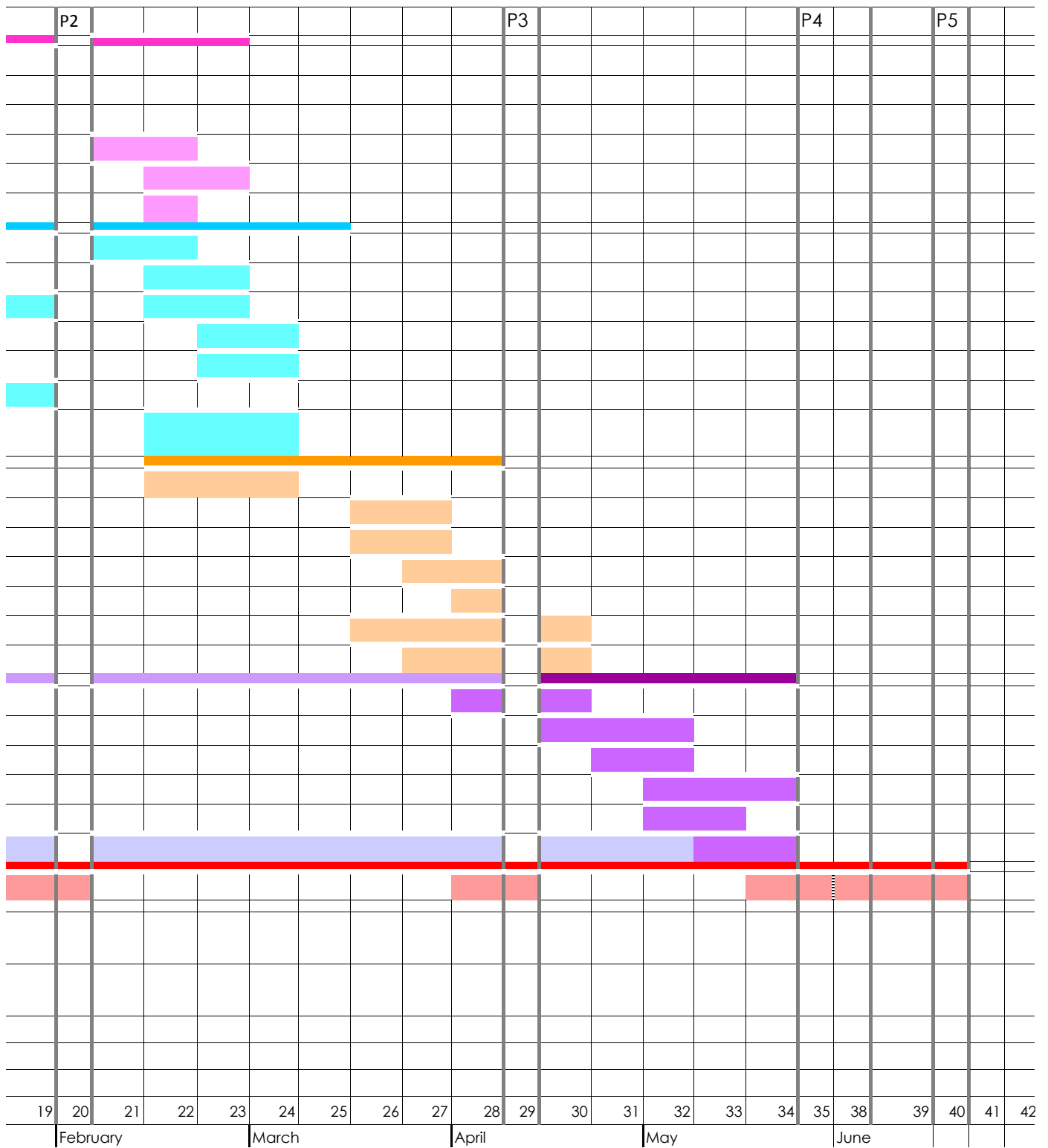
The realization of a 100% transparent façade is only the first step towards realizing completely transparent buildings. To develop the method of solving a less complex component such as a façade can become a basis or an example for broader applications. The findings of this process will also enable the architects to fulfil an "old dream" of a complete transparent envelope.

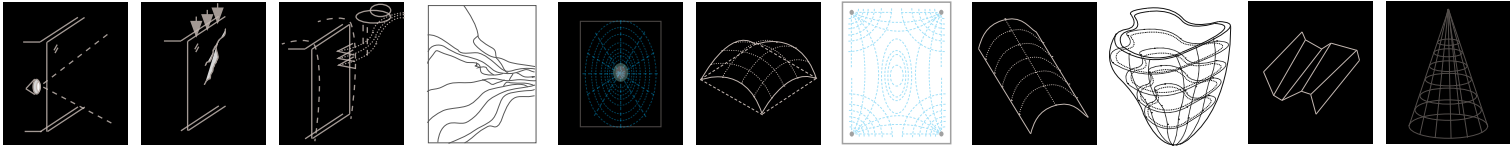
Personal value

Finally this process will enable me as, the student involved in this process, to broaden my knowledge in the field of structural glazing applications in facades and fulfil one of my personal goals of creating such a design that I have been slowly but steadily trying to achieve through several projects in the past.

Graduation Plan Design







Stage 1
Analysis-Glass
Technology

2.1/ Material Properties

Glass is produced by a mixture of silicon oxide, alkaline oxides and alkaline earth oxides that is heated up to temperatures exceeding 1100 °C.

There are general differences in the molecular structure of a material between its 3 different states, solid, liquid, gas. These changes can be observed in strength as well as density. When a material changes state from liquid to solid then a lattice structure is formed from the molecules that causes its volume to decrease. This phenomenon is the so - called crystallisation.

The odd characteristic of the molten mass is that it solidifies amorously without developing any crystal bonds . This happens because of the controlled cooling down process during the primary production of glass. It is due to that irregularity, that glass does not have a fixed melting point. Its structural state can be compared with that of liquids and molten materials, which like glass do not possess any properties dependent on direction. The transformation point from melt to solid or vice versa, lies around 600 °C. < **Glass in Building, 2009** >

The following significant properties of glass stemm from that basic atomic irregularity:

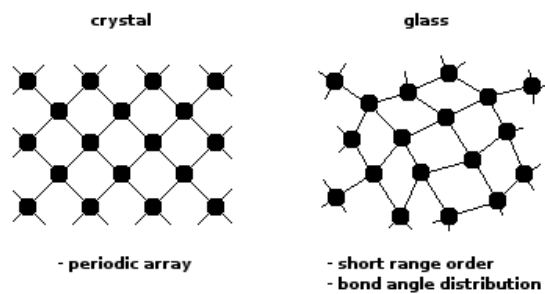


Fig 8. Difference in the molecular amorphous molecular structure of glass and that of a crystal

01 _ Transparency

This property is based on the atomic structure of the material and the non - crystallization as well as the special bonds developed within it.

Glass absorbs light of particular wavelengths, such as UV and infrared but the missing cross sections in the material do not allow the reflection of light that belongs to the visible optical spectrum. For that reason the atomic structure cannot absorb the visible light and therefore it can cross the material without any restrictions. However glass is impermeable for the ultraviolet radiation because the light energy is sufficient to put electrons in the glass in vibration.

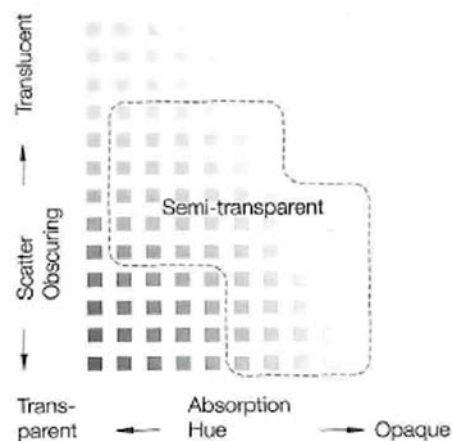


Fig.9. Diagram showing the transitions between transparency, translucency and opaque tones < **DETAIL Practice Glass in Building-Principles, Applications, Examples, 2009** >

2.1/ Material Properties

02 _ Fragility VS Strength

Glass is characterized as a typical brittle material. The maximum elongation is in the area of 0.1%. Even with the slightest extension out of these boundaries of elastic deformation glass is led to abrupt failure. This means that up to that point glass can behave as an ideal – elastic material under mechanical stress. There is no plastic behavior zone and therefore is not possible to anticipate its failure. The silicon rich composition is responsible for that kind of behavior but it is also the one to give glass its hardness and its high compressive strength. Its intact atomic bonding forces lead to a material with perfectly smooth surface and high mechanical strength. However a single damage to the microstructure within the body of glass and scratches can give rise to "Griffith Flaws"² with extremely high stress peaks when the element is subjected to mechanical actions.

Unlike other materials in glass no one can anticipate these stress peaks by presence of plastic deformations. Because the flaws are highly unlikely to be avoided we know beforehand that only a fraction of the material's strength can be utilized in the components, unless other measures are taken such as pre-stressing.

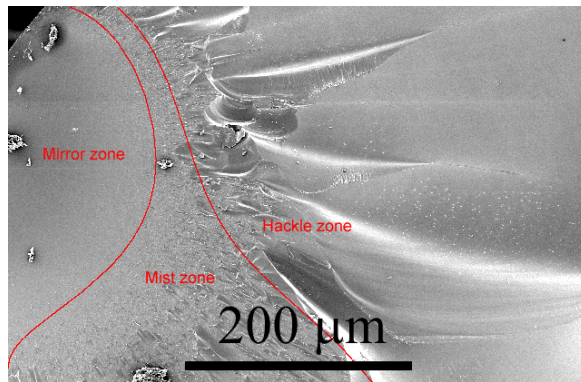


Fig.10



Fig.11

Fig.10_ SEM micrograph of glass fracture surface. Superficial inherent flaws in glass < doitpoms.ac.uk - University of Cambridge >

Fig.11_Zoomed view of fractured glass. < www.wikipedia.org >

² Griffith flaws on a glass surface. Fracture mechanics was developed during World War I by English aeronautical engineer, A. A. Griffith, to explain the failure of brittle materials.[1] Griffith's work was motivated by two contradictory facts:

- The stress needed to fracture bulk glass is around 100 MPa (15,000 psi).
- The theoretical stress needed for breaking atomic bonds is approximately 10,000 MPa (1,500,000 psi).

A theory was needed to reconcile these conflicting observations. Also, experiments on glass fibers that Griffith himself conducted suggested that the fracture stress increases as the fiber diameter decreases. Hence the uni-axial tensile strength, which had been used extensively to predict material failure before Griffith, could not be a specimen-independent material property. Griffith suggested that the low fracture strength observed in experiments, as well as the size-dependence of strength, was due to the presence of microscopic flaws in the bulk material.

To verify the flaw hypothesis, Griffith introduced an artificial flaw in his experimental specimens. The artificial flaw was in the form of a surface crack which was much larger than other flaws in a specimen. The experiments showed that the product of the square root of the flaw length (a) and the stress at fracture (σ_f) was nearly constant <<http://www.wikipedia.org>>

2.1 / Material Properties

03 _ Thermal Properties

"Glass has a very much lower thermal expansion coefficient $\alpha_t = 9 \times 10^{-6}$ (1/K) compared to that of steel $\alpha_t = 12 \times 10^{-6}$ (1/K)" <Glass Construction Manual, 1999, p.90>. This aspect can create issues when connecting the materials together in rigid supporting connections or in glued inflexible joints. Such detailing configurations can cause internal stresses developing in the two material due to the different rate and scale of thermal expansion. This can harm especially glass as it is a material highly vulnerable in local stress concentration.

The stresses occurring in the joined components can be caused by solar radiation concentration or the material being subjected to artificial heating or cooling. These temperature stresses can be calculated as follows:

$$\sigma = (\Delta \alpha \times T + \alpha \times \Delta T) E_1 / [1 + (E_1 A_1) / (E_2 A_2)]$$

or for large steel cross sections

$$\sigma = (\Delta \alpha \times T + \alpha \times \Delta T) E$$

where:

- σ = stress
- α = coefficient of thermal expansion
- T = temperature
- Δ = difference
- E_1, E_2 = modulus of elasticity of glass/ steel
- A_1, A_2 = cross sectional area of glass/ steel

Fig.12_ Origin of crack on the surface of glass pane due to thermal stress < readconsultingblog.blogspot.nl >

Fig.13_ Crack on glass surface caused by solar load and unsuitable detailing < www.johnsonwindowfilms.com >

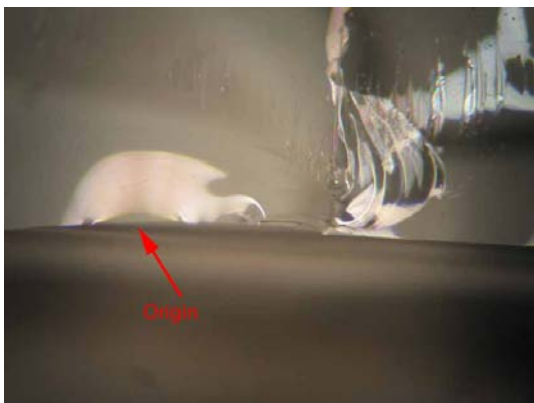


Fig.12



Fig.13

2.1.1 / Basic types of glass

	Density	Price	Young's Modulus	Hardness	Tensile Strength	Yield strength elongation 0%
Quartz glass	2170-2200	5140-8580	68-74	450-950	45-155	45-155
Soda lime glass	2440-2490	1160-1370	68-72	440-485	30-35	30-35
Borosilicate glass	2200-2300	3430-5150	61-64	84-92	22-32	22-32
Lead glass	3950-3990	3300-5100	53-55	472-525	23-24	23-24
Alumino silicate glass	2490-2300	1170-1370	85-89	68-75	40-44	40-44
	kg / m ³	EUR / kg	GPa	kg / mm ²	MPa	MPa

Table 14. - showing the properties of the different glass types <Glass Construction Manual, 2007>.

Compressive strength	Thermal expansion coefficient	Thermal conductivity	Poisson's ratio	Softening point	Strain point
1100-1600	0.55-0.75	1.4-1.5	0.15-0.19	1665	1070
360-420	9.1-9.5	0.7-1.3	0.21-0.22	726	510
264-348	3.2-4	1-1.3	0.19-0.21	820	510
232-244	8.82-9.18	0.82-0.86	0.23-0.24	631	
400-440	4.11-4.28	1-1.5	0.23-0.24		
MPa	$10^{-6} / K$	W / (m*K)		C°	C°

2.2 / Design considerations

Glass has been used only to tertiary components in façade structures for many decades. Since the glass technologies are becoming even more and more advanced, they have allowed for the use of the material as a loadbearing component too. However glass is a material with special and sometimes unpredictable mechanical behavior and therefore calls for detailed knowledge of its properties.

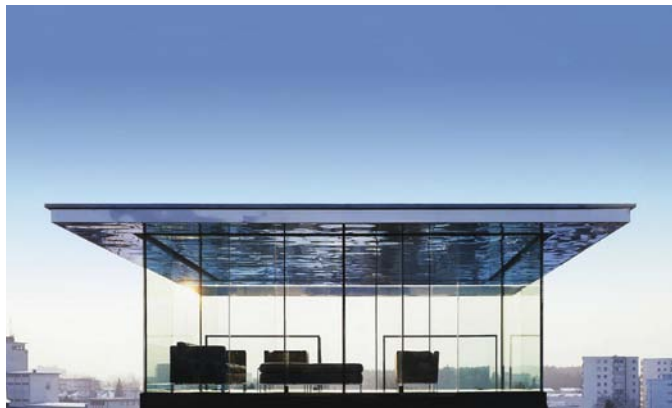


Fig.15_ All glass facade
< www.glasmarte.at/de >

In the material glass the theoretical strength is very much different from the practical strength. The material's theoretical strength according to Griffith is 10.000-30.000 MPa as it is dependent on its chemical structure and its strong atomic bonds.

But on the other hand its practical strength is around 100 MPa and the reason for that is that strength is a property of glass that is not pure, but is dependent from the material's surface state and the degree of damage. Therefore statistical methods have been developed to calculate in a design the probability of failure caused by the inherent surface damage distribution and the local stress by mechanical action. Therefore there are two key factors contributing to the glass strength

A | The size of the cracks~ distribution is a key aspect in this case.

B | The time of the use of glass components, which contributes in the accumulation of cracks of the surface as the components are wearing out from cumulative damages (scratches, corrosion, drilled holes etc.). This leads to rise of the probability for critical cracks to occur.

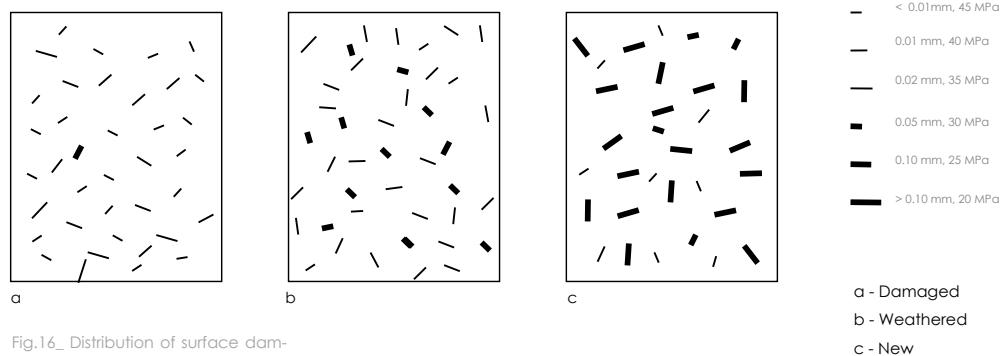


Fig.16_ Distribution of surface damage and margin of strength <Glass Construction Manual, 2007> re-edited

2.2.1 / Strength & Surface condition

The effective strength of glass components is not only dependent from the cracks size and distribution but also on the loading time. Therefore the glass pieces are allowed to higher stresses in the presence of a short term load. On the other hand the surface cracks are growing faster when they are subjected to long – term loading. This leads to the conclusion that the maximum stress that the glass can take over is decreasing.

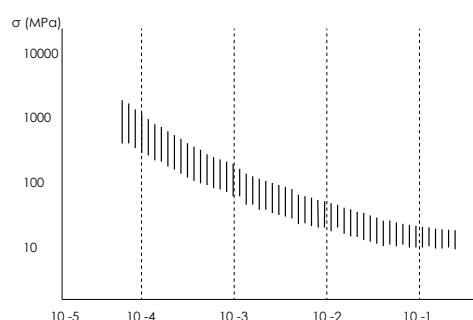


Fig.17_ Relationship between strength and crack depth
<Glass Construction Manual, 2007> re-edited

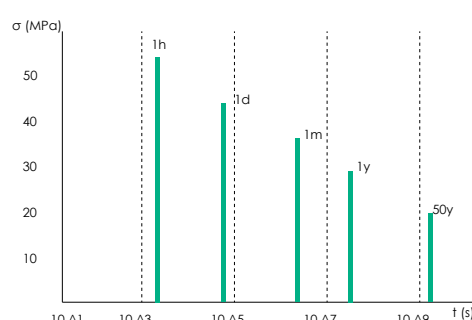


Fig.18_ Relationship between strength and loading time
<Glass Construction Manual, 2007> re-edited

2.2.3 / Strength & Area of loading

The same relationship applies for the area of the glass object and the maximum stress. Therefore the probability of failure increases in an analogous way with the size of the area where the stresses apply because of the distribution of flaws. This should be taken into account during experiments where the specimens tested are mostly relatively small.

2.2.4/ Strength & Enviromental Conditions

Low relative humidity can have a great impact on the effective strength of glass. In buildings is normally can fluctuate between 30 – 100%. However the impact on the bending strength of glass is great. The bending strength is also influenced by the temperature, but luckily the range of temperatures within the buildings is very low in relation to the minimum strength limit which is at 200 °C

2.2.5 / Failure behaviour

Glass as it was mentioned before is a brittle material that exhibits no plastic behavior like metal for example. This means that above the elastic zone the material presents sudden failure that cannot be anticipated by any deformations, thus making it dangerous for the use in structural components, unless measures are taken.

Therefore it is important to create a safe glass that is redundant and ductile ³. Ductility for the structure means that after slowly reaching the limits of load bearing capacity it will suddenly break (fail) and collapse. On the other hand a good structure must warn by deformation (cracking noises, signals of overloading).

_ **Steel** has the warning property in its material characteristics. It deforms under over loading (so-called yielding).

_ **Concrete** integrates steel rebars in the tensile stress zones and therefore it can achieve these properties as well, despite its brittle behavior as a material.

_ **Wood** squeaks and moans

_ **Glass** without reinforcement like concrete does not warn if load becomes too big.

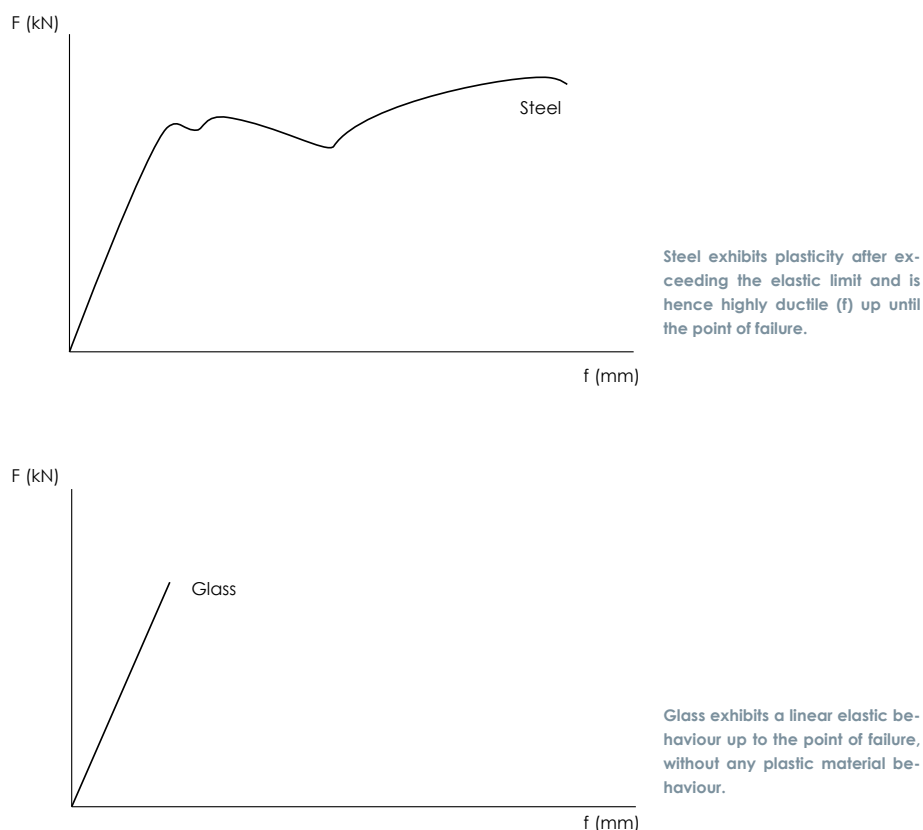


Fig.19_Comparison of the mechanical behaviour (failure) of steel and glass when subjected to stress (F). <Glass in Buildings, edition DETAIL Practice > re-edited

³ In materials science, ductility is a solid material's ability to deform under tensile stress; this is often characterized by the material's ability to be stretched into a wire. This mechanical property together with malleability, are aspects of and define the extent to which a solid material can be plastically deformed without fracture. <<http://www.wikipedia.org>>

2.2.5 / Failure behaviour

	Glass Soda lime silica	Concrete C25/30	Steel S 335	Stainless Steel 1.4301	Aluminium EN AW-6060
Modulus of elasticity (N/mm ²)	70.000	26.700	210.000	200.000	70.000
Poisson's ratio	0.2	0.2	0.3	0.3	0.3
Strength (N/mm ²)	Yield point	-	360	190	160
	Tensile strength	45	510	500-700	215
	Comp. strength	700	25		
Failure behavior	brittle	brittle	ductile	ductile	ductile
Density (kN/m ³)	25	25	78	78	27
Coefficient of expansion α (K ⁻¹)	0.9×10^{-5}	1.0×10^{-5}	1.2×10^{-5}	1.6×10^{-5}	23.5×10^{-6}

Table 20_Different material mechanical properties < Glass Construction Manual, 2nd edition, > re-edited



Fig.21



Fig.22



Fig.23

Fig.21,22,23_ Failure of aluminium, wooden boards and concrete beam respectively

2.3 / Structural design with glass

2.3.1 / Mechanical Quantities for glass

Before analyzing further the methods for calculating deformations and stresses in glass one has to built a background in terms and definitions of quantities that are very commonly used as a basis of the structural calculations.

The value of **density** for all materials and for glass as well is defined as the mass per unit volume:

$$\rho = m/V$$

The definition of **mechanical stress** σ is the force applied per unit area within an object:

$$\sigma = F/A_0$$

The definition of **strain** ϵ is the elastic deformation of a body when subjected to a force :

$$\epsilon = \Delta L / L$$

The **yield strength** (or point) σ_y can be defined as the the stress at which the material's strain changes from elastic deformation to plastic deformation, meaning that the deformation occurring is permanent.

Glass lacks of plastic behavior and therefore the yield strength for glass is the maximum strength at which the material fails.

Compressive strength σ_c is the normal stress at which the material, loaded under pressure, fails.

Tensile strength σ_t is the normal stress at which the material, loaded under tension (pulling), fails.

Hardness H_v can be defined as the value of resistance against permanent deformation. It is measured by a diamond point into the surface of the material. The most common unit scale used is the Vickers scale.

When a material is loaded with a force it will either fail or exhibit elastic deformation and return to each initial state after the force has been removed. For glass this is happening only under a certain temperature that the material can exhibit elastic behavior. This is called the **transformation temperature** T_g and the material above that temperature presents a plastic deformation too.

Force and elongation in the elastic zone can be related from the **Hooke's law**. In that area the **Young's Modulus** is defined as the slope of stress-strain curve and it is a value that defines the stiffness of the material.

$$\Delta L = (F / EA) L$$

$$E = \sigma / \epsilon$$

The **Poisson's ratio** ν , is defined as the negative ratio of the lateral strain, ϵ_2 , to the axial strain, ϵ_1 , when the object is subjected to axial loading:

$$\nu = \epsilon_2 / \epsilon_1$$

Relationship between the stress and surface condition. Griffith showed that because of material's inherent flaws the real strength is significantly smaller than the theoretical strength (10.000-30.000 N/mm²).

$$\sigma_c = \sqrt{((EG_c)/\pi a)}$$

The critical size of a flaw, c , is dependent on the material property E and the specific surface energy, G_c .
<Cecil Giezen, 2008>

2.3.2 / Calculating Deformations and stresses

Within the typical temperature range of buildings glass behaves ideally elastically. Although glass is basically a supercooled liquid it exhibits very high viscosity and allows no flows to take place. Therefore glass cannot exhibit a preferable degree of creep and no relaxation.

1st order theory

According to the first order theory the structural behavior of a material is assumed to be linear. This theory is often used to calculate the internal forces in a glass pane that is subjected to external mechanical actions. Based on this theory it is common to calculate simple structural patterns such as a rectangular pane supported on the two sides. For rectangular panes supported on 4 sides the tables of Bach can provide the maximum stresses. The stresses in the tables are also available for triangular and circular panes.

However with the first order theory the stresses calculated are usually higher for larger panes than those calculated according to the second order theory. Because the theory doesn't take into account geometric non-linearities, that generate membrane effects in the plane of the glass and are responsible for lower bending stresses, it results in thicker glass dimensions.

Second order theory & Finite Element Method (FEM)

Second order theory takes into account geometric non-linearities as well and therefore takes into account the membrane effects appearing in glass. The membrane effects are advantageous in glass design as they can compensate for tensile bending stresses.

Nowadays the complex design of stress transferring components in glass systems have made virtually impossible to calculate stress distributions manually. Therefore in our days stress transferring and deformation analysis in complete glass elements is being done using FEM (Finite Element Methods). But the use of such methods brings along several rules and considerations such as:

- 01_ Areas of stress concentrations must be carefully modelled.
- 02_ The simulated areas must be suitably and accurately modelled
- 03_ The modelling must include all resilient intervening layers (ex. setting blocks, EPDM intermediate layers, PVB foils etc.).

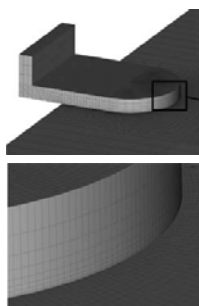


Fig.24

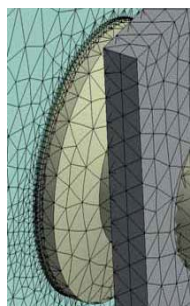


Fig.25

Fig.24, 25_ FEM models for calculation of stress transfer at joints with adhesives <www.glassfiles.com>

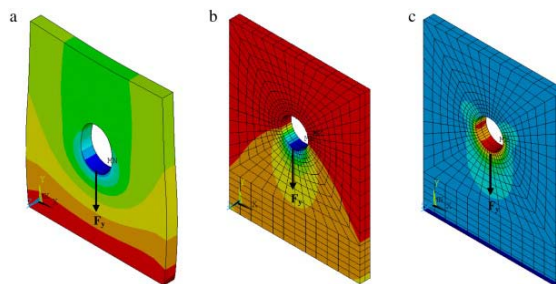


Fig. 26_ FEM models showing the deformation of a drilled hole in glass due to the stress concentration and the weight of the support. <www.glassfiles.com>

2.3 / Structural design with glass

2.3.3 / Design & Safety

Glass as an unpredictable material must be treated in a special way when designing with it. The result of a failure in a system or a glass component has an effect on the building as a whole. One of the ways to deal with that scenario is to increase the functional safety and therefore the dimensions of the components. But this is not always the preferred way to go, as it is against economical benefit and architectural expression. In a glass structural system the failure of a single component should never trigger the chain failure of multiple components because this can lead to the collapse of the entire structure. The following systems when designing can introduce the different strategies that can be followed in order to prevent that. When design a system too key aspects for safety must be taken into consideration.

01 _Aspect of residual load bearing capacity

After damage, the glass component should be able to possess sufficient load bearing capacity in order to remain at its position and bear the loads.

"The margin of safety against complete failure of a partially destroyed system is known as residual load bearing capacity" < **DETAIL Practice Glass in Building-Principles, Applications, Examples, 2009, p.39**>.

02 _Aspect of Redundancy

All glass structures should be designed with an inherent redundancy. By redundancy we mean that " upon failure of one load bearing element in a system the loads can be carried by other elements." < **DETAIL Practice Glass in Building-Principles, Applications, Examples, 2009, p.39**>

2.3.3 / Design & Safety

There are several design methods that one can define deriving from the special mechanical behavior of glass when subjected to stresses. The following table is presenting each method with its advantages and disadvantages.

Design method	Description	Advantages	Disadvantages
01 Permissible stress design	Permissible stress design is the design that is carried out on the basis of permissible stresses.	01 _Similarity to the existing methods . 02 _Simplicity	01 _The method does not do justice to the materials behaviour. 02 _The method leads to relatively high safety factors
02 Design according to probability of failure	This method is developed according to the theories of Kurt Blank that use fracture mechanics to describe the statistical nature of usable strength and the influences of load duration ,area under stress and ambient humidity.	01 _Far more accurate than permissible stress design. 02 _The approach takes into account the unfavourable influence of stresses acting on large areas over long periods of time.	It is unfortunately so far more complicated as a design method.
03 Limit state design	The limit state design is taking into account different statistical distributions on the material 's strength and the loading stresses (i.e wind, snow.) Considers different failure modes and limit states. It is based on the principles of fail - safe concept where the system is examined under different failure scenarios and it must possess a residual stability after the failure of individual components.	01 _Design compatible with the mechanical behavior of glass. 02 _Allows for the failure of individual components	Complicated method that requires an explicit examination of the failure behavior of individual components under different and multiple forms of failure scenarios in a structural system.

Table 27_Different design methods with glass < **Glass Construction Manual, 2nd edition, 2007**>

2.3.4 / Prestressing - Safe components

As mentioned before glass presents inherent flaws like chips, vents and cracks on its surface. These flaws are responsible for triggering crack propagation mechanisms when glass surface is subjected to tension. "Glass has no molecular mechanism to stop cracks and therefore a growing crack driven by tensile stress in the material grows in great speed until it meets a free edge" **<Glass Construction Manual, 2007>** .

In the case of tensile strength occurring in the glass the only way to take advantage of the effective strength of the material is to introduce an over-compressed zone at the surface. This compressive pre-stress of the surface is responsible for over-compressing these areas, so at the risk of a tensile stress the stress will be neutralized from the pre-stressed zone. This means that the glass increases its tensile strength by exactly the amount of pre-compression.

The pre-stressing can be achieved with different methods:

01 Mechanical Pre-stress

Is the glass that can be created by means of a dead load, or spring mechanisms. One example is the concentrically pre-stressed glass tube. The tube places the entire glass tubular cross section in compression, with the butt joints between the individual parts being realized purely via contact connections.

An axial tension load can be carried by neutralizing the in built compressive (pre) stress.

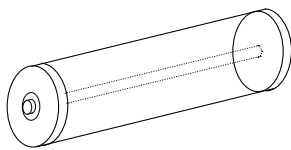


Fig.28

Fig.28_ Concentrically prestressed glass tube - sketch

Fig.29_ Concentrically prestressed glass tubes used in the glass facade of the London Tower, by Fosters. waagner-biro.com



Fig.29

2.3.4 / Prestressing - Safe components

02 Thermally treated glass

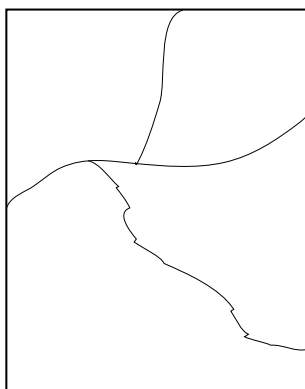
The annealed glass which is the basis product coming from the production of float glass is reheated and rapidly cooled down. This causes the outside "skin" to cool down quickly and become hard. The mass of the glass on the inside is still very hot and cools down slower. When a material cools down it shrinks. But because the outside has already hardened the shrinking inside firmly attached to the outer skin start to "pull" the hardened layer. As a result the outer layer is under compressive stress and the interior, subjected to balance laws, in tensile stress. Depending on the airflow rate for the cooling and the heating temperatures tempered or heat strengthened glass can be produced. The different way of treatment can introduce different levels of fluctuation in internal stress distribution.

02a Tempered glass

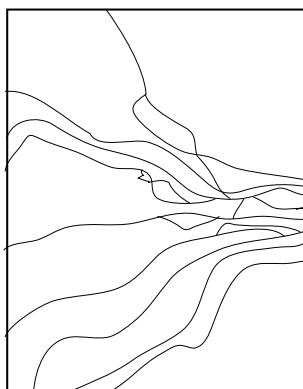
The toughening of glass is a physical process. A glass panel with all its holes drilled and polished edges is made of normal float glass. Then the element is heated up in a furnace at a temperature of 620 °C. After taking the panel out of the furnace the outside is ventilated with high airflow at room temperature. The maximum stress introduced with that technique is 90-120 N/mm². Toughened safety glass breaks into many fine pieces.

02b Heat strengthened glass

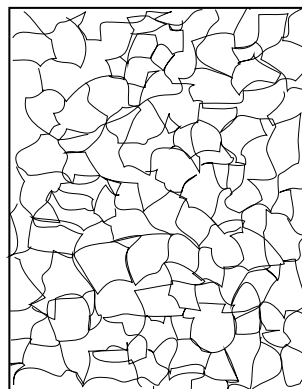
Heat strengthened glass is produced by heating the glass up to 1300 °C and then rapidly cooling it down with air. The same principle of cooling and hardening as in the thermal toughening applies here too. The maximum stress achieved with this method is 40 – 75 N/mm². Unlike toughened glass if the panel fractures the pattern of cracks is similar to the one of annealed glass but the pieces usually stick together instead of collapsing.



Annealed - large pieces with sharp edges (Tensile strength 45 MPa)



Heat strengthened - medium size pieces (Tensile strength 70 MPa)



Tempered - scattered small pieces without sharp edges (Tensile strength 120 MPa)

Fig.30_ Fracture pattern differences between annealed, heat strengthened and tempered glass < Glass Construction Manual, 2007 >, re-edited

2.3.4 / Prestressing - Safe components

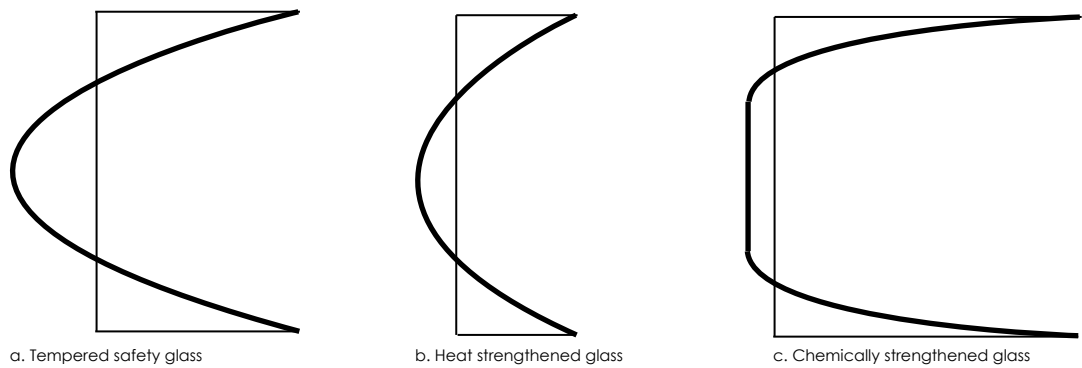


Fig.31

03 Chemically strengthened glass

Chemical strengthening in the glass can occur after treating the panes in a bath of molten potassium at 450 °C temperature. The sodium ions (Na) transfer in glass transfer in the salt and are being replaced by 30% bigger potassium ions (K). In comparison to tempered glass the compression layer is much thinner. The compressive zone introduced is up to 300 N/mm². Furthermore chemical strengthening is primarily applied in thin glass panels.

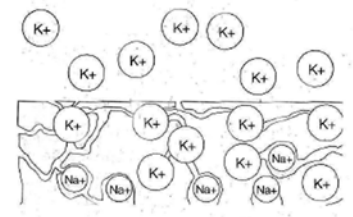


Fig.32

04 Laminating or layering of glass panels

Another way of making glass tougher is by gluing 3 panels together. One single panel can break inevitably by hitting it. If somewhere in the material the allowable tensile strength is exceeded then a crack will open and there is no mechanism to stop its growth. If however the broken panel is glued to another one then it will remain glued on the other one. Nothing will fall down given that the unbroken panel is able to carry the loads. In case of 3 layers then the intermediate is always protected. The outside are called therefore "sacrificial" < Rob Nijse, 2003 >.

There are several ways of joining methods in lamination:

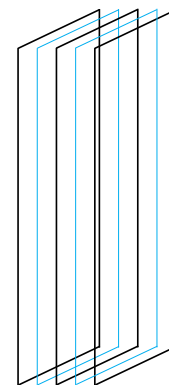


Fig.33

Fig.31_ Different stress distribution according to the toughening method. Near the surface glass is in compression and in the middle under tension.

Fig.32_ Chemical strengthening process

Fig.33_ Build up of glass laminates with interlayers - diagram

2.3.4 / Prestressing - Safe components

04a Laminating by transparent foil called PVB

The foil is placed on one layer and then the other panel is pressed against it mechanically, in a evenly distributed manner in a furnace heated up at 250 o C. The sizes of the furnace limit the sizes of the panels produced. Up to 2.5 x 4.5 m. Sometimes they can go up to 7 m with increased costs and time of delivery.

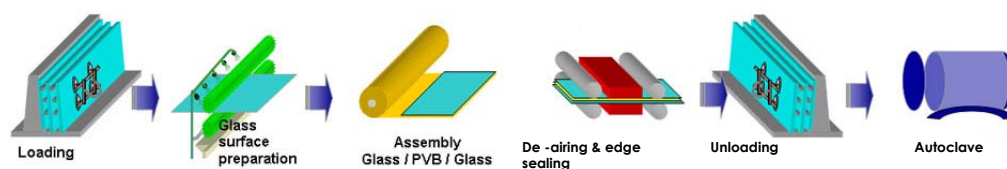


Fig.34

04b Laminating by stiff interlayer **Sentry Glas Plus**

The technology of SentryGlas interlayer, a special ionoplast polymer developed by Dupont, allows for extraordinary bonding characteristics and structural properties. The SG interlayer is used in lamination process to increase stiffness and loadbearing capacity of the glass structure. The laminate is produced by vacuum - bag lamination in temperature controlled auto-claves. "The mechanical properties achieved by this technique are almost equivalent to those of monolithic glass of the same size" **<Hanno Sastre, GPD 2012>**.

Manufacturer Seele Sedak has used for oversized glass elements in architecture, called **glascobond** (15 x 3.2 m).

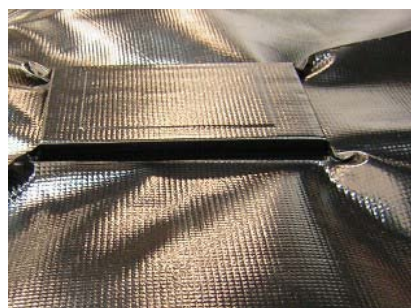


Fig.35

04c Laminating by resin

Glass laminates are usually produced by 2 pieces of glass sandwiched with a piece of interlayer film made of PVB, EVA or PU etc. However the interlayer adhesive foil could be also replaced by a liquid resin. During the lamination with liquid resin, the resin matrix is poured in a cavity between 2 pieces of glass resulting in seamless glass components. Resins create a rigid interlayer compared to PVBs. A good example of resin lamination is the laminated glass column.

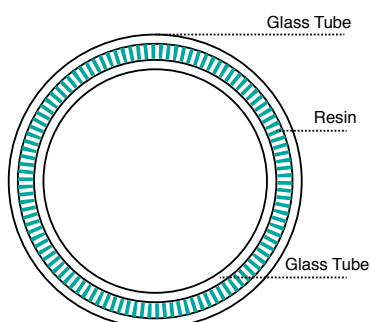


Fig.36

Fig.34_ The steps of PVB lamination process.

Fig.35_ Vacuum bag lamination of glass

Fig.36_ Diagram showing the layers of laminated glass column with resin.

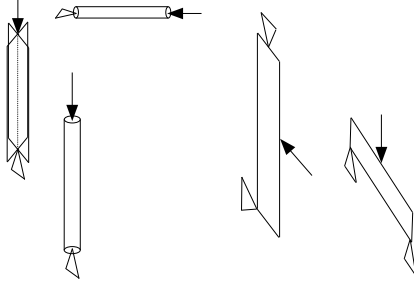
2.3.5 / Glass loadbearing components

The following table is a summary analysis of all the glass load-bearing component types, their composition and their loading conditions. The components are being categorized based on their geometry which is defined by their ratio between width and height dimensions.

Table.37_ Summary analysis of glass loadbearing components / Behaviour & Build-up

01

Linear 1D



Column

Rods & Bars

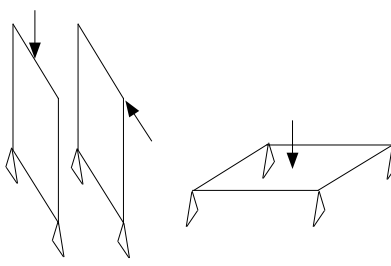
Mullion

Beam

Are components whose dimensions are small in 2 directions and large in a 3rd direction - lengthwise.

02

Surfaces 2D



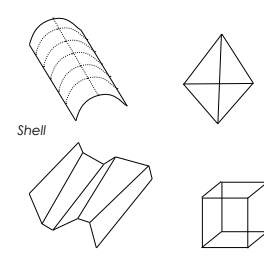
Plates

Slabs

Flat sheet geometry where the dimensions are large in the two directions and small in the third (thickness).

03

Shells 3D



Folded Plate

Cells - Unit

Shells are formations subjected to in-plane stresses and we distinguish them in two categories: the curved elements and the flat elements (faceted surfaces).

Columns & Bars

Generally subjected to **axial loads**.
In frames and girders ties and struts are respectively subjected to **tension** and **compression**.
In columns we can have depending on the joining method (articulated or fixed) respectively pure **vertical compressive axial load** or axial load **combined with bending stresses**.

Beams & Fins

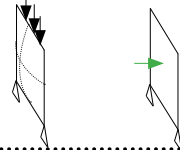
Generally correspond to the geometry of the linear elements but they are also subjected to bending and shear forces.
_transverse bending
_longitudinal bending
_shear stresses
_axial stresses
_Eccentric load can cause **torsion**

Plates

Are subjected to **axial forces** exclusively that act in the **plane** of the element itself. They can be prone to local buckling.
_Tension transferred by point fixings in friction.
_Compression transferred by point fixings in contact. In both cases laminated glass for residual stability reasons is employed.

Slabs

Subjected to forces acting perpendicular to their plane. Distinguished from the plates because of the different direction of the loading. They can be prone to local buckling.



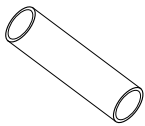
Shells

Shells are formations subjected to **in-plane stresses** and we distinguish them in two categories: the curved elements and the flat elements (faceted surfaces).



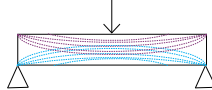
One - piece cross-section

Strips of float glass have maximum thick up to 25mm. The maximum slenderness ratio of 1/50 results in a maximum height of 1m for a compression member. Therefore glass tubes or solid cast glass struts are **more suitable as compression elements**.

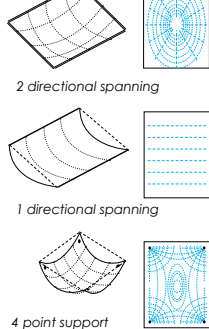


Plane Beams - Fins

Bending stresses around the major axis which places the **stress concentration around the edges**. Increasing depth can help reducing tensile bending forces. Lamination of 3 pieces toughened glass.
Carrying dead and wind loads. Outer edge subjected to compression



Single - ply slabs

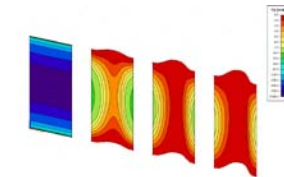


Single - ply slabs

Consist of a single pane of float glass, toughened or strengthened. The most common form in slabs. Carries the external wind loads and transfers them to the continuous supports at the edges (frame). Extremely slender.
Individual supports lead to thicker glass than linear supports.

Curved glass

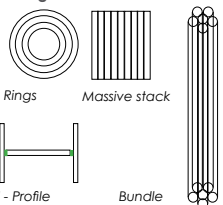
Cylindrical, conical, spherical, or any other curved forms, single pane or laminated toughened glass units. Reducing glass thicknesses because of the load bearing capacity of the shell.



Composite cross-section

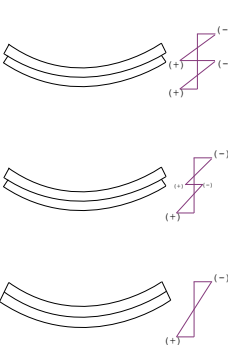
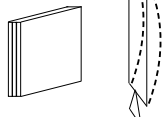
Compared to one - piece elements the combination of multiple cross sections joined together can create interesting and stronger compression elements.

_Glueing glass to glass
_Glueing glass strips to metal connecting sections
_Joining strips via individual fixings



Composite cross-section

Composing an extremely efficient cross section by composing individual monolithic elements. Creating shapes that can optimally handle the bending stresses. (ex. I - shape).
_higher torsional rigidity
_higher bending strength
_more stable
Contact or friction fixing points via elastic intermediate pad.



Multi - ply slabs

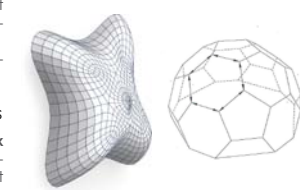
Consist of **multiple layers of single slabs** loosely stacked and bonded with adhesive. Shear stiff interlayer good for **bending stiffness**.
Non beneficial in safety if one of the plies brakes. In that case a more viscoelastic layer is preferred.
Residual stability after the failure of a single plane.

Multi - ply with edge seals

Creates a **short of hollow box** that is sensitive to deformations of the structure that cause twist.
The air cavity acts structurally. Benefit or disadvantage related to temperature and hence pressure conditions.

Faceted shells

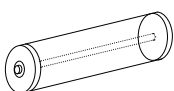
Faceted surfaces are consisted of elements with radius of curvature very large compared to their size. They are usually undergoing very high compressive stresses, which means that the stability has to be ensured.



Combination with materials

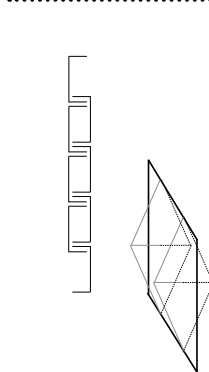
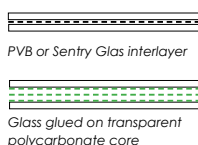
Limited use of glass in ties and struts because of the limited sizes of the product and sudden failure behaviour. Combining glass with other materials can allow overcoming these hindrance.
_plastic
_metal
_timber

Product of this method is the concentric prestressed monolithic glass tube



Material combination

Lending glass a **ductile behaviour** by combining it with a ductile material. Therefore now it can exhibit apart from high compressive strength an tensile strength in order to carry the safely the loads for a certain amount of time after it fails.



Slabs with ribs & stiffeners

Combination of slabs with ribs can allow for **larger spans** and more efficient structure. **Reducing stresses and deformations**.

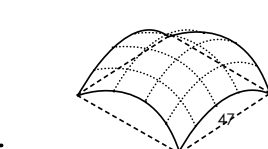
_Uninterrupted spans
_Additive assembly
_Multi-leaf insulating sections

Trussed slabs

The glass plane here carries the compressive loads and the truss in one or two axes the tensile loads. Truss connected via props or webs.

Membranes

Very interesting from engineering and architectural point of view. Elements are subjected exclusively to high tensile axial forces uni - directional or bi - directional. Transferring the forces to neighbouring elements is up to now feasible only by clamping or individual fixings. Causes local stress concentration.
Residual load bearing capacity is not yet adequate in tensile stresses.



2.3.6 / Structural systems

According to the significance of load bearing tasks assigned to the different components in a structural design with glass, we can distinguish different structural systems.

Hierarchical systems

These systems are based on a discretisation of complex structure in a hierarchy of substructures. The tasks within these systems are distinguished in load-carrying and load-applying. The different components are grouped into:

_ Primary structure is composed from the parts that carry all the loads and acting forces on the building and the dead loads. The failure of the primary structure is associated with the collapse of the entire building. (load bearing service core, columns, walls, floors, bracings that transfer vertical and horizontal loads to the foundations.

_ Secondary structures are integrated or attached to the primary structure. Failure of one of these systems can lead to a local or partial collapse only(built-in items, partitions, rooftop structures, annexes, façade elements)

_ Tertiary structures exist in large scale buildings and they are responsible of receiving weather loads and apply them and their self load to the secondary structures. (a window within a façade)

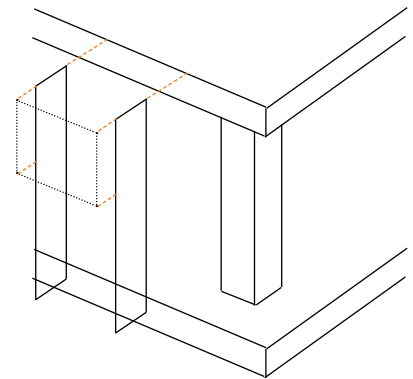


Fig.38_ Diagram showing the hierarchy of components in a hierarchical system.

Non - Hierarchical systems

"The non - hierarchical systems consist of an assemblage of identical elements that are interconnected" < **DETAIL Practice Glass in Building-Principles, Applications, Examples, 2009**>. These structural systems are designed in such a way that in the case of failure of one of the components the rest of the system can take over the loads based on the principles of redundancy. Unlike hierarchical systems here forces are not grouped but are spread like a net so that upon local failure they can flow around the damaged or weakened area.

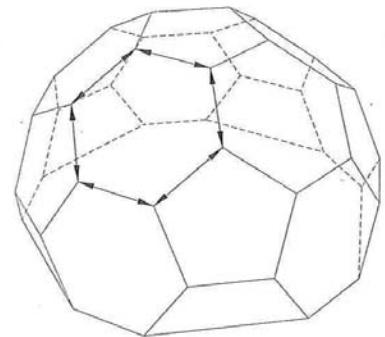


Fig.39_Principle of the flow of forces in a non-hierarchical load bearing system in the case of one component failure. Example of geodesic dome. < **Glass in Buildings, edition DETAIL Practice** >

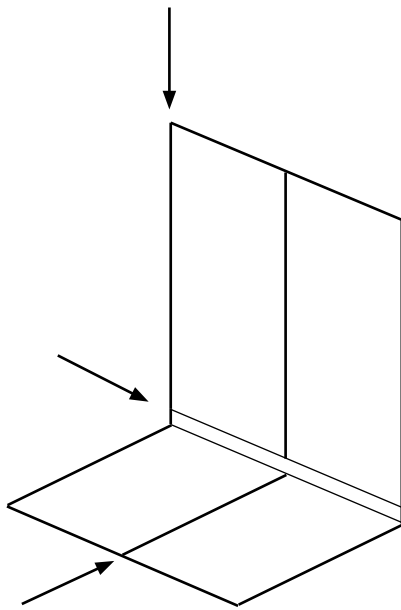


Fig.40_ Diagram showing the principle of stress transfer in the discrete work glass systems.

2.3.6 / Structural systems

03 Discrete-work systems

Systems designed in such a way where the different components, part of a structure, have a discrete role. For example a certain group of members is employed with certain loads, like the columns are mostly assigned with carrying the vertical loads and walls with horizontal loads. Such systems are very common in glass structures because load carrying functions are pre-defined for the different components participating and therefore restraint stresses are avoided.

Some defined residual load bearing capacity should be predicted for these components.

04 Redundant systems

Is a system where after the failure of one component the functions can be undertaken by other elements. Deliberate design of redundancy mechanisms is crucial in the design of glass structures.

2.3.7 / Loadbearing patterns in glass facades

The facade as a system has to bear several loads that are assigned to its function and can be distinguished in :

01_ **Self -weight**

02_ **Snow loads**

03_ **Wind loads**

04_ **Imposed loads**

05_ **Impact loads**

06_ **Loads due to restraint forces** (thermal loads, movements, explosions, earthquakes, etc.)

In practice there are 2 ways to design a facade system that carries the aforementioned loads:

01 Suspended

In the suspended scheme the facade construction is supported from the floor above each so as the self weight loads are tensile forces within the material. In this case the problems of stability can be eliminated. On the other hand stress concentration points can occur at the suspension areas.

02 Standing

In the standing facade scheme the construction is supported each time on the floor below and transfers the vertical loads (ex. self weight) to the primary structure by means of compressive forces. This kind of scheme is prone to stability issues and appropriate bracing systems need to be implemented.

2.3.8 / Established glass facade systems

By distinguishing the different ways of supporting the window panes on the secondary structure a series of already established facade systems can be named:

Post & rail facade

In this system the facade glass panes are supported on 4 sides on a grid structure system of posts and rails. The sizes of the post and rails differ in cross section but they must be all flush so that the panes are supported on all 4 sides. The edges of the glass are normally clamped. This is a pattern that creates a denser skeleton like image on the facade affecting the levels of transparency.

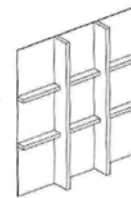


Fig.41_ Post & Rail facade

Posts only facade

This type of facade is supported on vertical elements (posts) normally clamped on 2 sides or held by point supports. The posts are taking over their self weight and the wind loads. This scheme allows for increasing the degree of transparency.

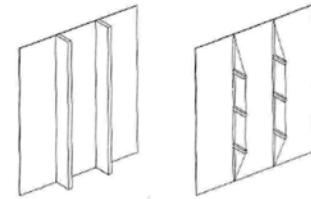


Fig.42_ Post facade. Beam & vertical truss.

Rails only facade

This type is supported on horizontal beams (rails) that resist the horizontal loads acting on the plane of the facade. The vertical loads are usually taken over by vertical ties that are attached to the rails and are suspended from the floor above.

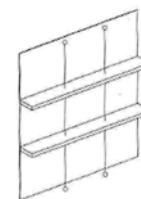


Fig.43_ Rails only facade system

Cable Facade

Such facades employ suspended constructions to carry the loads under tensile forces. These constructions enable a delicate grid of prestressed cables to form behind the facade. In cable stayed facades special bracing arrangements allow for carrying the horizontal loads. In this type of system the panes are usually supported at points.

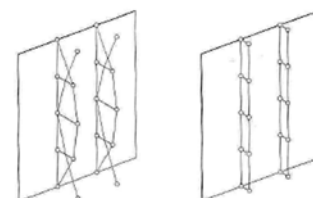


Fig.44_ Cable facade with stayed cable and parallel cables.

Structural Sealant Glazing (SSG)

This is a facade type where the panes are held in position by adhesive silicones instead of being clamped or screwed. In this type the adhesive is both sealing and carrying the loads of the elements. In this case the outer surface is flush with a smooth finish and a grid pattern that has the small size of the adhesive joint.

< Glass in Buildings, edition
DETAIL Practice >

2.3.8/ Established glass facade systems

All-glass facade

All - glass facades are mostly employing suspended constructions. The glass fins are usually assigned with the horizontal loads and provide stiffness to the facade. The panes are fixed on the fins by mechanical or adhesive joints. Usually all the individual components are assigned with vertical loads.

The panes of glass can be carrying their self weight, resist the wind loads acting on the facade, accomodate shear forces in the plane of the glass and support axial forces coming from the roof. In that case we are talking about combination of primary, secondary and tertiary tasks in one element.

Until now due to the risks mentioned about the unpredictable behavior of glass the use of such elements is only limited in one storey buildings and usually not public

2.4 / Constructing glass facades

The use of glass in construction must be treated with the utmost attention. It is due to wrong handling during the installation or not carefully designed details that the probability of failure from local stress peaks can be increased. Therefore the connections that are assigned to transfer the loads and to join the pieces must be very thoughtfully designed and realized.

2.4.1 / Design principles

There are several design principles that one must follow when designing with glass at a detailed level. These principles originate from the material's special characteristics and mechanical behavior.

- 01 _ No contact between glass and harder materials
- 02 _ Avoidance of restraint stresses due to unintentional loads
- 03 _ Choice of suitable geometry for the glass elements
- 04 _ Specification of a suitable method of connection
- 05 _ Ensuring a sufficient level of robustness of glass constructions
- 06 _ Guarantee of serviceability
- 07 _ Ensuring durability and weather resistance

2.4.2 / Stress transfer - Connection types

The following table is an analysis summary of the glass connections categorized based on the geometry aspects of the support they offer and the type of force transfer they accommodate. The analysis is focusing at the overview of the main categories of connections (drilled, clamped and material bonded) that we often meet in glass structures. The focus is on the main types of supports and last but not least schemes that explain the type of force transfer.

Table.45_ Summary analysis of basic connection types with glass and the force transfer types they accommodate.

01

Non - positive

In non - positive connections the joint is held together by applying a force that presses the individual elements together.

02

Positive

Positive connections are connecting individual components together based solely on interlocking of geometries

03

Material Bonding

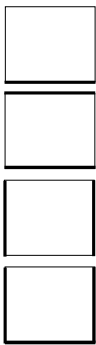
Forces can be transmitted through the adhesion connective forces developed in a molecular or atomic level.

Friction connection

In this type of connections the forces occurring in the glass element are transferred via friction to the joint. Here meaning the mechanical interlocking between the microscopic surface imperfections of the two material faces in contact. The forces are therefore transferred via axial/shear force from the glass to the joint.

Contact connection

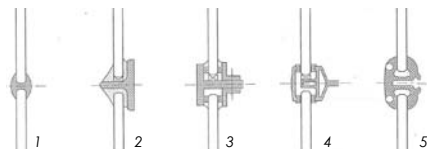
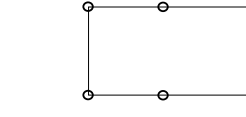
In contact connections the compressive force acting perpendicular to the contact faces provides the force-transfer mechanism.

Linear clamp fixing**01. Without safety****02. With safety**

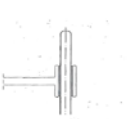
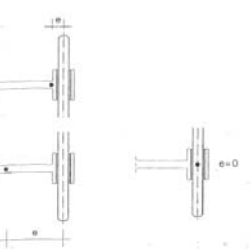
Linear supports offer resistance against wind pressure loads in facades.

**Point clamp fixing**

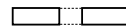
Resistance of facades against wind suction can be achieved by ways of individual clamping.

Combination clamp fixing

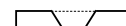
- 1 Lead light
- 2 Putty fillet
- 3 Rebate with glazing bead
- 4 Patent glazing with capping strip
- 5 Gasket glazing

Types of movability**01. Rigid fixing****02. Hinged fixing**

The disc point fixings are made of stainless steel and are in contact with two sides of the glass pane. Their diameter is according to the drilled hole and it should be at least 50mm.

Form of disc**Form of hole**

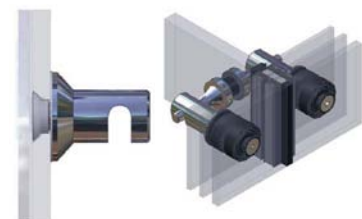
Cylindrical



Cylindrical - conical



Cylindrical - conical with undercut



Cylindrical - conical with undercut

**Glues**

Glueing is the most common way of adhesive bonding. Adhesive can be applied:

- _Whole surface
- _Linearly
- _Discrete points

**Silicones**

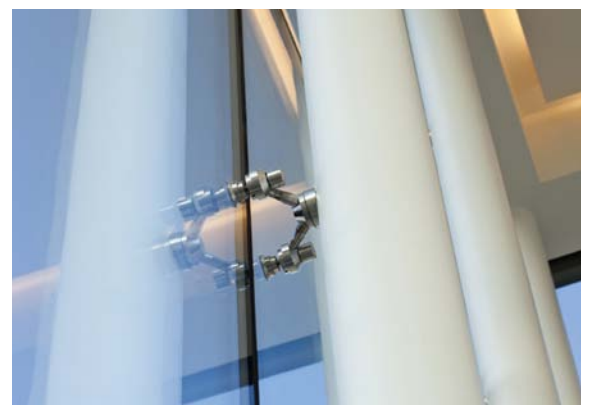
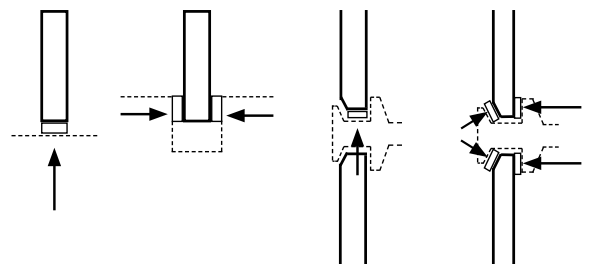
Is a type of facade construction in which the glass is permanently connected to an adapter frame via a loadbearing water-proof silicone joint

01. Black

Black silicon is made from polymer base plus chalk, silicic acid and soot fillers.

02. Transparent

Transparent silicones are possible, but require more expensive polymers such as resins. This is why they are not established in facades yet.

**Force transfer on supports**

2.5 / Fabrication of glass components

The fabrication of different types of glass components needs to be taken into account when design and re-thinking glass facades. The manufacturing processes available for the production of glass are one of the key aspects that define more or less the final design product. Due to the size limitations there must be a detailed knowledge of each process as well as of the characteristics it can give to a component.

Such features are:

- 01_ Optical quality**
- 02_ Size**
- 03_ Texture**
- 04_ Color**
- 05_ Geometry**
- 06_ Mechanical strength**
- 07_ Safety**

The processes can be divided according to the order they follow to primary production processes and secondary processes:

Primary processes	Secondary processes	
01_ Float Glass Floating / pouring still liquid glass on a bed of molten tin. This allowed the production of a glass panel with two perfectly flush surfaces. One is resulting from the perfectly flat surface of the molten tin and the other, upper one, from the gravity that flattens the surface of the molten glass. By cooling the slowly moving ribbon of the molten glass it can solidify and basically allow for a continuous process with the ribbon cut in different panels.	01_ Mechanical working Grinding edges Polishing edges Drilling Holes 02_ Forming Hot Bending Cold bending Fused Glass Glass blocks	04_ Strengthening - Safety Tempering Heat strengthening Chemical Strengthening Lamination
02_ Rolled glass It is sometimes also called cast glass. The name comes from an earlier manufacturing process. With that method the molten glass was poured onto a flat table and rolled flat. In the modern production method two water-cooled, contra-rotating rollers pass over a ribbon of molten glass that lies at temperatures around 1200 C°. The adjustable gap between the rollers can provide different thicknesses that fluctuate from 3 - 15 mm. After that step the glass is moving to the annealing lehr and is being cut to sizes. The optical quality of this process is inferior to that of the float glass.	03_ Surface treatment polishing & grinding Matt surfaces Thin coatings - metal oxides Heat insulation Sunscreen coating Optical coatings Thick coatings	
03_ Drawn glass This type of glass is not broadly used in the building industry because of its significantly lower optical qualities and productivity. In this method the glass ribbon is drawn vertically out of the melt. This glass due to its similarities in optical quality with the historical glasses is used often in restoration projects. < DETAIL Practice Glass in Building-Principles, Applications, Examples, 2009 >.		



Fig.46_ Glass with printed pattern (fritted)- Taken at BRS premises.

2.5 / Fabrication of glass components

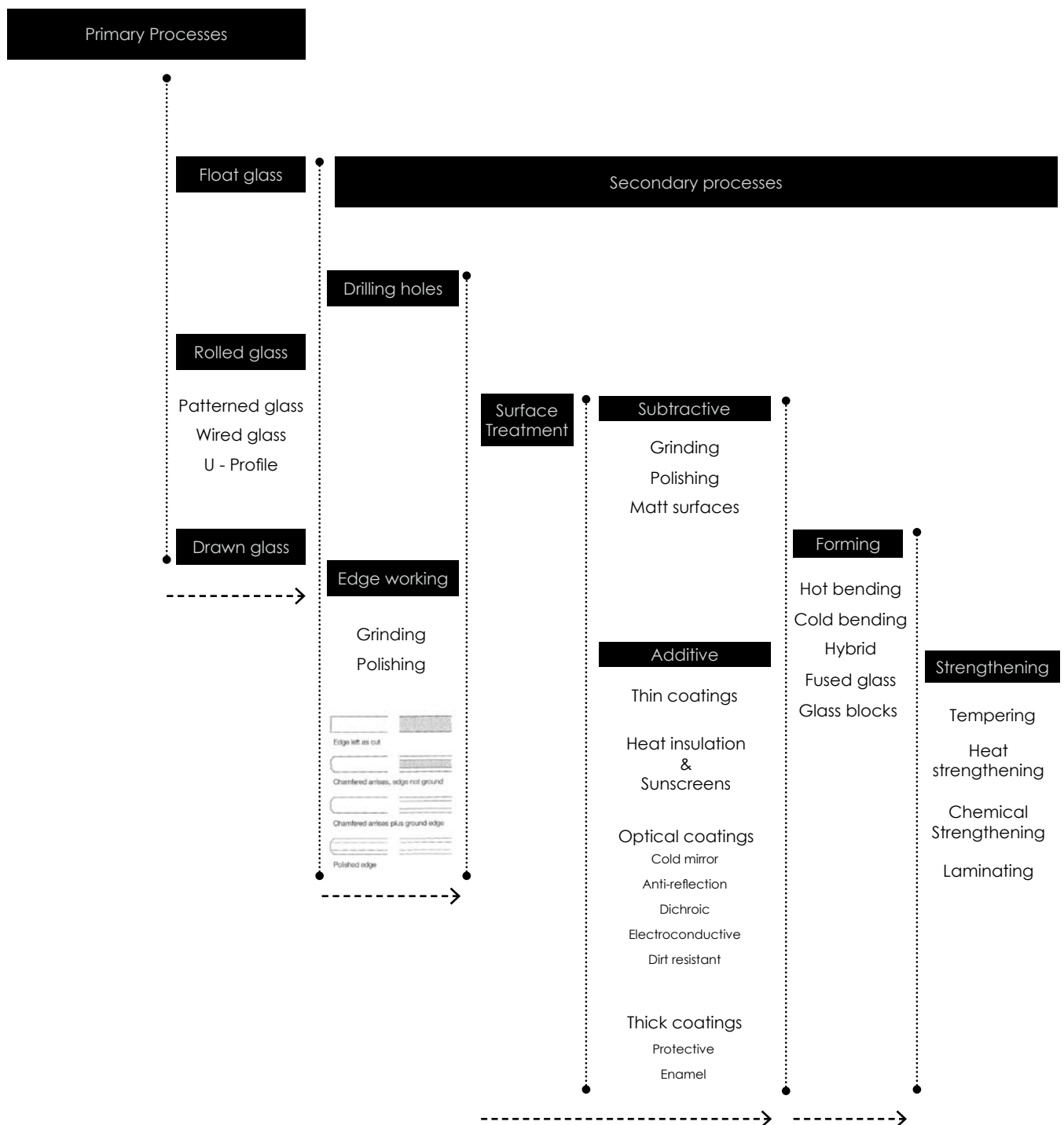


Fig.47_ Diagram describing the order of the processes in glass manufacturing.

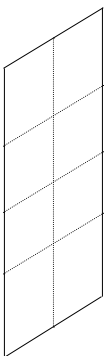
2.5.1 / Glass forms - Forming processes

Analysis summary of basic glass flat and curved forms of panelization and solid units formation and forming processes to assist their fabrication. They are categorized first according to geometry and then according to primary and secondary production.

Table.48_ Summary analysis of the primary geometry of glass components and the forming process possibilities.

01

Flat Glass

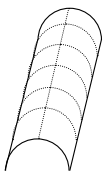


02

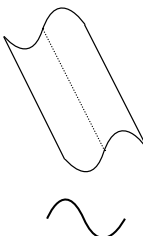
Curved

Single curved

Single panel



Corrugated



Double curved

A surface is doubly ruled if through every one of its points there are two distinct lines that lie on the surface. The hyperbolic paraboloid and the hyperboloid of one sheet are doubly ruled surfaces. The plane is the only surface which contains three distinct lines through each of its points.

Synclastic surfaces



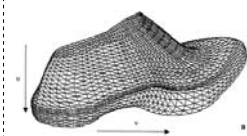
Anticlastic anticlastic



Freely developable surface



Approximation

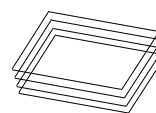


Smooth precise surface



03

Solid

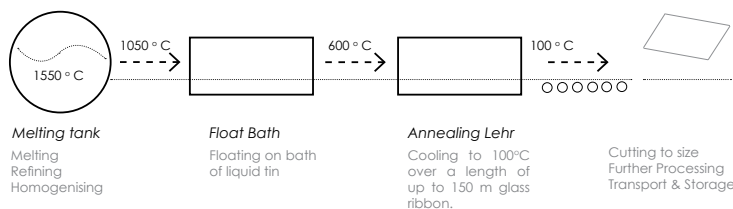


A solid or stereometric shape can be achieved by a mold that forms the glass into shape or by means of stacking flat surfaces until they achieve a 3D object.

Primary process - flat glass

Step 1 _ Production of flat glass

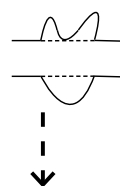
Floating / pouring still liquid glass on a bed of molten tin. This allowed the production of a glass panel with two perfectly flush surfaces. One is resulting from the perfectly flat surface of the molten tin and the other, upper one, from the gravity that flattens the surface of the molten glass. By cooling the slowly moving ribbon of the molten glass it can solidify and basically allow for a continuous process with the ribbon cut in different panels. Effects of the process



Cast glass

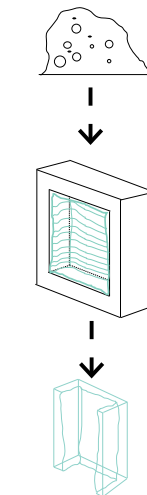
Glass casting is the process in which glass objects are cast by directing molten glass into a mold where it solidifies. Modern cast forming methods are. Sand casting and Kiln casting

Sand casting



Kiln casting

Pate de verre means glass paste. Crushed glass mixed with binders. The paste is applied in the inner surface of a negative mould as a coating. After the coating is fired at the appropriate temperature the glass is fused and creates a hollow unit that can have thick or thin walls.

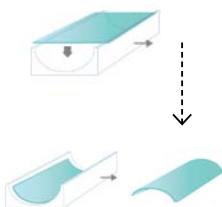


Curved forming

Step 2 _ Production of curved glass

Hot - Bending

Curved annealed glass is manufactured by slowly heating flat glass up to the softening temperature. When the flat panel starts slumping by gravity, it is taking its curved shape on the customized mold. Once the geometry is achieved a slow cooling process follows known as "annealing". Curved glass can be also produced tempered and heat strengthened.



Cold - Bending

During the cold-bending process, several sheets of tempered glass are combined to make a laminated safety glass sandwich and then shaped as a glass/film laminate in an autoclave to become a single unit. Two processes:

Cold-bending with shape-enhancing lamination

By using shear-compliant film (PVB film) sheets of glass are mechanically anchored to a shape-fixing substructure, in order to lend permanence to their shape.

Cold-bending with shape-fixing lamination

By using shear-resistant film (SG film by DuPont) shapes are maintained solely on the strength of the film's shear resistance.

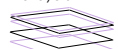
Once laminated in the autoclave, the composite glass sheet permanently retains its geometric curvature without being dependent on a shape-fixing substructure.



Lamination frame



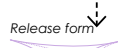
Glass and interlayers



Lamination

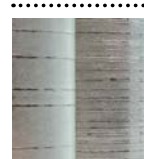
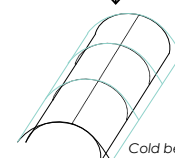
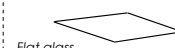


Release form



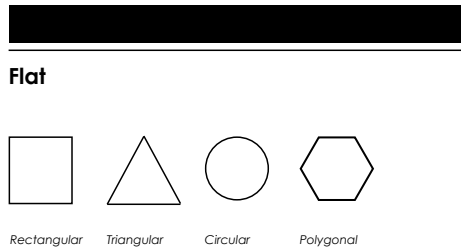
Hybrid forming

The skin could be created using single-curvature hot-bent glass according to a limited number of families but is preferred to use "ad hoc" panels produced using variable mould machines. The glasses are, then, successively cold-bent, before lamination or on-site, in order to adapt its curvature to the all different non - circular supporting lines.

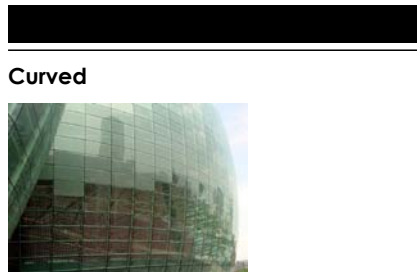


2.5.2 / Geometry generation

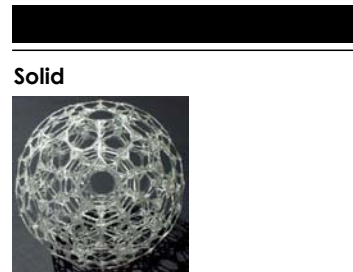
Analysis summary of the component geometry generation from generic geometric forms. The aim of this table is to understand the possibilities of geometry generation in components and furthermore to search for the suitable fabrication methods.



Flat



Curved



Solid

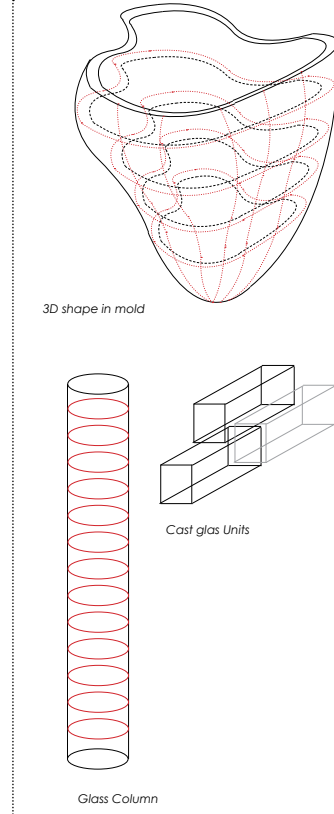
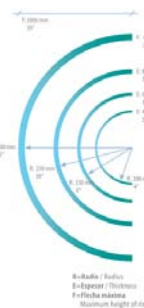
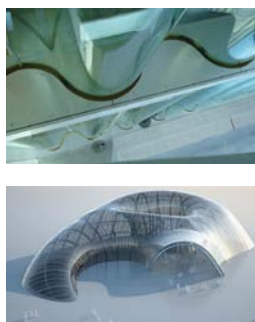
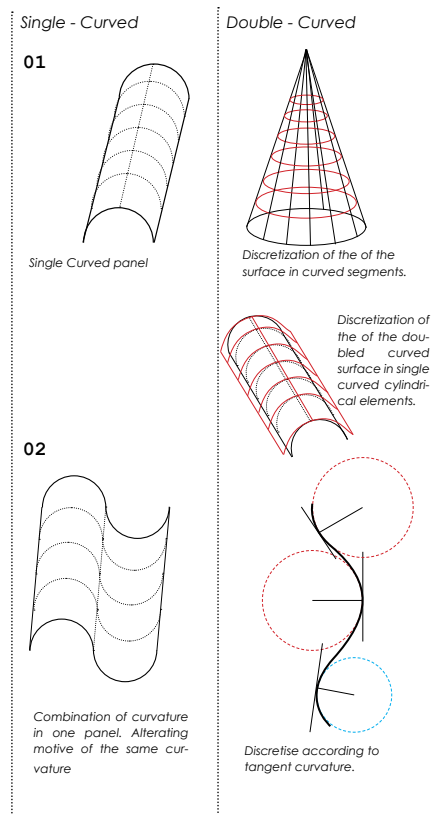
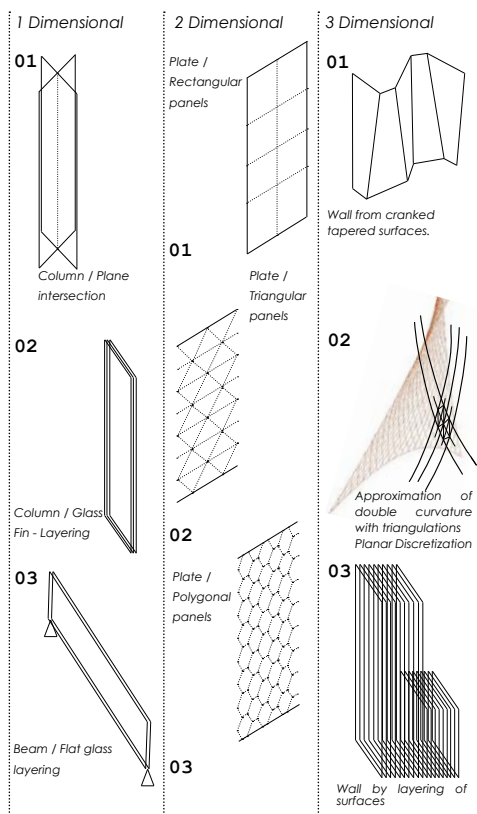


Table.49_ Summary analysis of the primary geometry and geometry generation from primary glass shapes.

2.6 / Case studies

The case studies have been chosen from a broad field of already undertaken research in the field of all glass facades and other structures. Therefore they are ranging from built examples to experimental cases of objects, structures, components, joining methods etc. The focus is to analyse and understand the technologies already applied or tested that can be possibly utilized in the new facade. The selection of the examples has been in all these cases focused on the effect of transparency attempts that have been done in order to maximize it. The second criterion is emphasis on creating efficient and structurally innovative glass loadbearing components.

Some of the case studies have been already categorized according to their general significant features that can be either morphological (ex. corrugated glass facades) or a special type of fabrication (ex. oversized laminates) or a type of transparent joining method (transparent adhesives, glass welding).

2.6.1 / Oversized Laminates

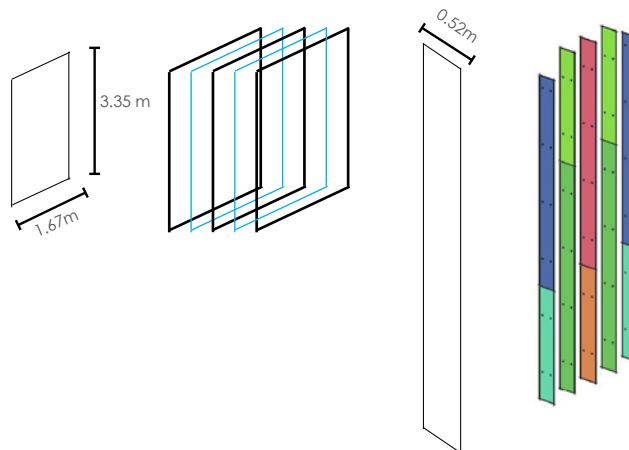
Apple Inc retail store

New York , 5th Avenue / Glass Cube 1.0 & 2.0

James O' Callaghan

Fabrication

1 Glass panel height	3.35 m
2 Glass panel & glass fin width	1.67m & 0.52m
3 Glass build up of facade panel	3x10mm HT glass with 1.52mm PVB interlayer
4 Glass build up of glass fin	5x12mm HT glass with 1.52mm PVB interlayer
5 Support of facade panel	Top & Bottom linear support



In the category of oversized glass laminates the cases of the glass cubes for the Apple retail stores in New York and Shanghai are being analysed. In the Apple glass cube number one, one of the noted advancements is the use of splice lamination technique for the production of oversized fins of 10m height. The glass slices are build up by overlapping the joints between 5 layers of glass sheets. The facade of the glass cube is supported by the stiff glass fins laminated with Sentry Glas Plus (a special ionoplast stiff interlayer used for lamination, adding stiffness to the components)

Special Considerations

_The high strength laminates are designed and engineered using **finite element method**.

_Need to take into account the **different load durations**

_The **temperature under which the load occurs**, because of possible creeping arising due to the interlayer. < Hanno Sasstre, GPD2012 >

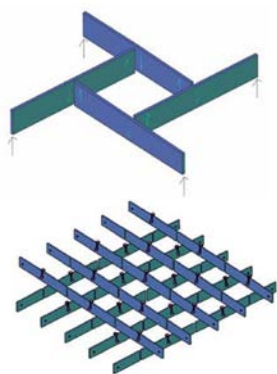


Fig.50_ View of the sky through the roof structure of the Apple cube 1.0

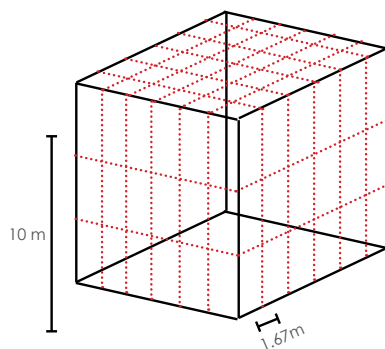
2.6.1 / Oversized laminates

Apple Inc retail store New York , 5th Avenue / Glass Cube 1.0 & 2.0 James O' Callaghan

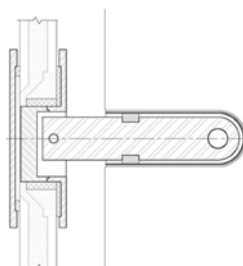
Structure



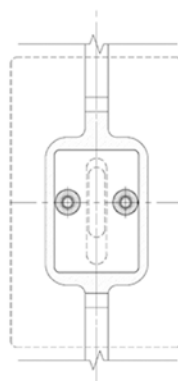
Roof Lattice - Lamellar principle



Connections

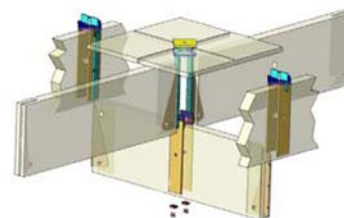


Front



Side

Facade plane to fin connection



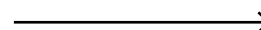
Roof connection



Fig.51_ Roof connection of the lamellar glass beam structure in the Apple glass cube. The connection is developed especially as a moment connection.
< glassfiles.com >

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The facade of the glass cube is supported by the stiff glass fins laminated with Sentry Glas Plus (a special ionoplast stiff interlayer used for lamination, adding stiffness to the components). Furthermore the facade panels act as bracing and the whole structure is prevented from twisting by the special lamellar roof structure and the roof panes.



2.6.1 / Oversized Laminates

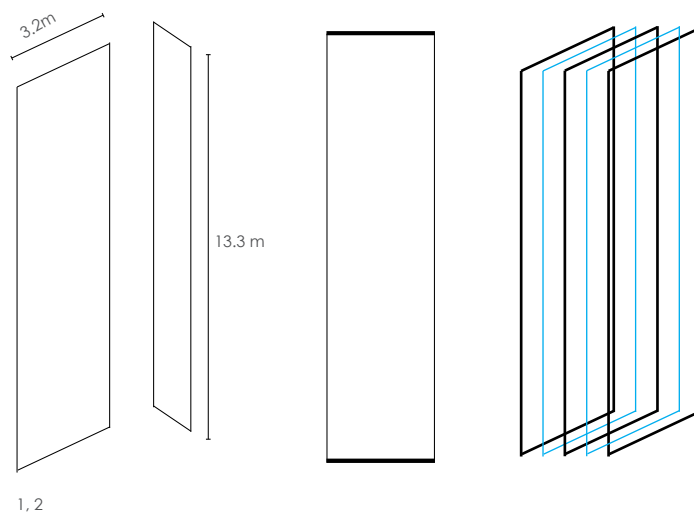
Apple Inc retail store

New York , 5th Avenue / Glass Cube 1.0 & 2.0

James O' Callaghan

Fabrication

1 Glass panel & glass fin height	13.3 m
2 Glass panel width	3.2m
3 Glass build up of facade panel	3x10mm HT glass with 1.52mm PVB interlayer
4 Glass build up of glass fin	5x12mm HT glass with 1.52mm PVB interlayer
5 Support of facade panell	Top & Bottom linear support



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In the Apple Glass Cube 2 the advancements of fabrication translate into improvements on the transparency levels. We can acknowledge at this point how strong is the connection between these two aspects. Here for the first time elements of 10.30 meters high are introduced fully laminated with the highest quality. This translated automatically to less joints per facade, hence more transparency.

For this project the manufacturer Seele Sedak has used a special product developed for oversized glass elements in architecture, called **glascobond** (15 x 3.2 m). Glascobond the trademarked laminated glass product from Seele Sedak is made using Dupont' s Sentry Glas films coupled with proprietary lamination process quality.

The technology of SentryGlas interlayer, a special ionoplast polymer developed by Dupont, allows for extraordinary bonding characteristics and structural properties. The SG interlayer is used in lamination process to increase stiffness and loadbearing capacity of the glass structure. The laminate is produced by vacuum - bag laminating in temperature controlled autoclaves. The mechanical properties achieved by this technique are almost equivalent to those of monolithic glass of the same size. < Hanno Sasstre, GPD 2012 >

2.6.1 / Oversized laminates



Fig.52



Fig.52, 53_ Exterior views of the Apple glass cube 2.0 during the day and night time.

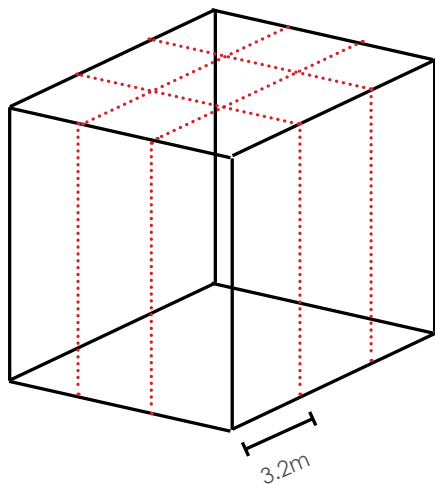
2.6.1 / Oversized Laminates

Apple Inc retail store

New York , 5th Avenue / Glass Cube 1.0 & 2.0

James O' Callaghan

Structure



_Stability maintained from the stiffness of the side walls.

_Roof 2 single spanning beams & not structural gril-lages as in the 1st version.

_ Roof panels cold bended in a subtle 2 dimensional curve for the drainage of water.

< O' Callaghan, Challenging Glass 3, 2012 >

Connections

_Fewer facade elements result to **fewer connections**.

_ **Embedded fittings** in the glass resulting in a smooth surface.

_ Rotating metal tab into the insert aligned with the vertical joint. Cover silicone joint.

< O' Callaghan, Challenging Glass 3, 2012 >

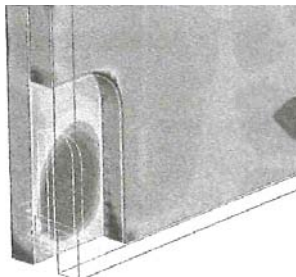
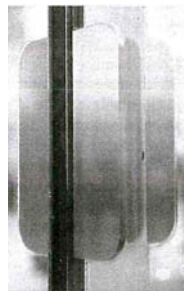


Fig.54__ Embedded fittings for the Apple cube 2.0
< Challenging Glass 3, Proceedings, 2012 >

2.6.1 / Oversized laminates

Apple Inc retail store
New York , 5th Avenue / Glass Cube 1.0 & 2.0
James O' Callaghan

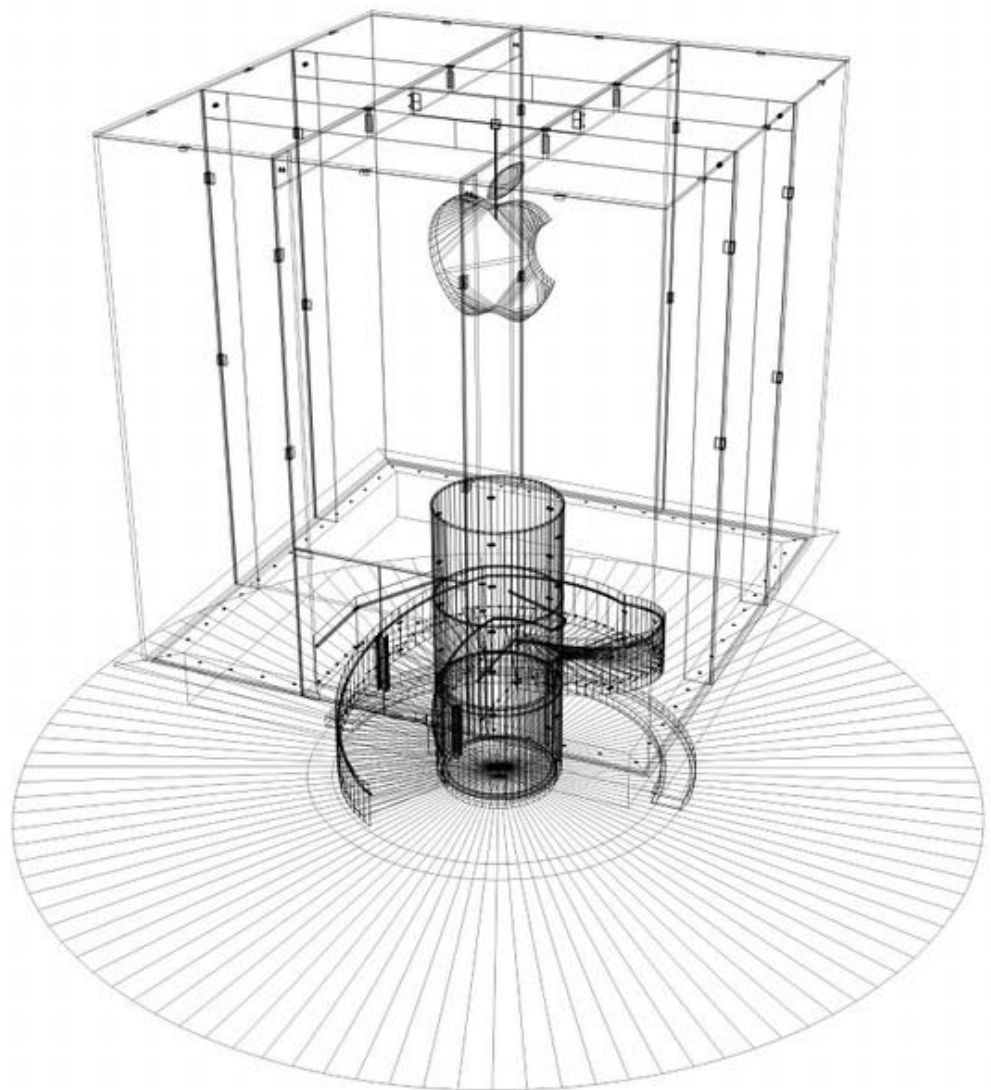


Fig.55_ Sketch up model showing the structure of the Apple cube 2.0

2.6.1 / Oversized Laminates

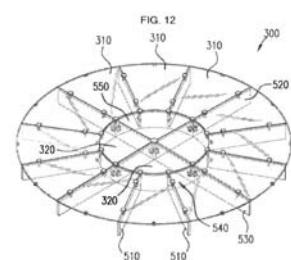
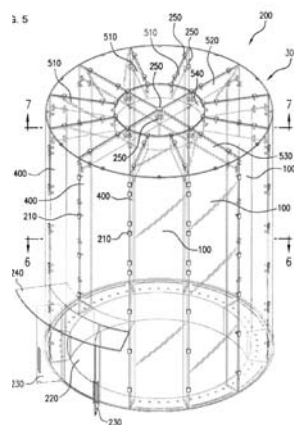
Apple Inc retail store Shanghai James O' Callaghan



Fabrication

- | | |
|----------------------------------|--|
| 1 Glass panel & glass fin height |13.3 m |
| 2 Glass panel width |3.2m |
| 3 Glass build up of facade panel |3x10mm HT glass with
1.52mm PVB interlayer |
| 4 Glass build up of glass fin |5x12mm HT glass with
1.52mm PVB interlayer |
| 5 Support of facade panell |Top & Bottom linear support |

Structure



Connections

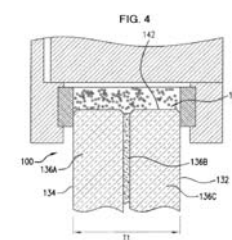


Fig.58_Fin to panel connection
< www.patentlyapple.com >

_Shear connection of the laminated wall plane.

_Adhesive bond - Lamination of components with transparent SentryGlas interlayer.

Fig.56,57_Perspectives of the Apple Inc. store in Shanghai

2.6.2 / Corrugated glass facades

Casa Da Musica, Porto

OMA

ABT, Rob Nijssen

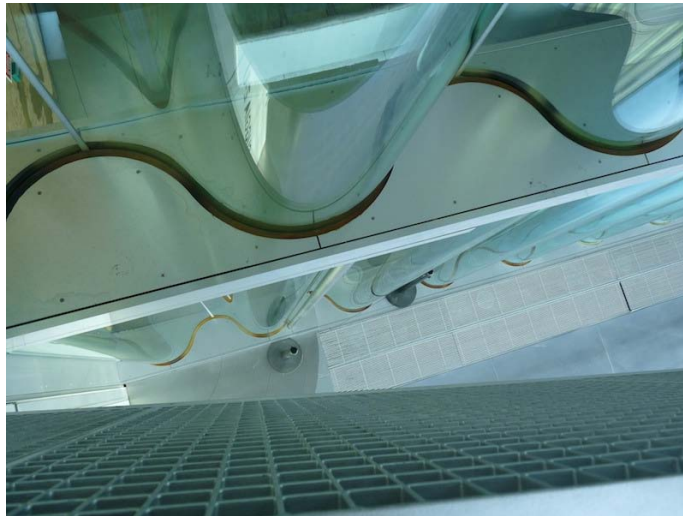


Fig.59_ Close up of the support point at the corrugated glass facade in Porto, Casa da Musica, OMA



Fig.60_ Exterior view of the corrugated glass facade in Porto, Casa da Musica, OMA

The structural principle behind the corrugated facade is the combination between a flat glass sheet and a structural glass fin. The glass panels perform better against wind loads compared to a flat glass of the same thickness. This is based on the properties of the bended glass that can reduce deflection of the panels.

2.6.2 / Corrugated glass facades

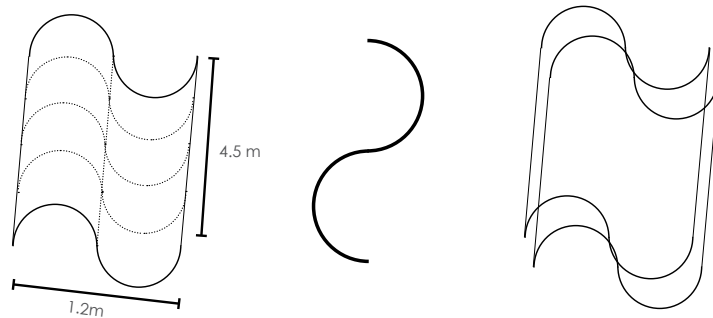
Casa Da Musica, Porto

OMA

ABT, Rob Nijse

Fabrication

- 1 Glass panel height 4.5 m
- 2 Glass panel width 1.2m
- 3 Glass build up of inner panel 2x 6mm
- 4 Glass build up of outer panel 2x10mm
- 5 Support of facade panell Top & Bottom linear support



The corrugated glass facade consists of panels that are bended respectively with an alternating arch motive of a certain radius. The panels were produced at the special size of 4.5m by the spanish firm CRI-CURSA. The shape accuracy of the panels was tested, for high quality, so it can fit the appropriate tolerances. A sinus shaped cut-out on a metal plate was used as a guide for the glass, where the requirement was that all the panels had to go through in order to be used for the facade. This process brought the tolerances for such large elements up to the minimum of (+-) 2 mm.

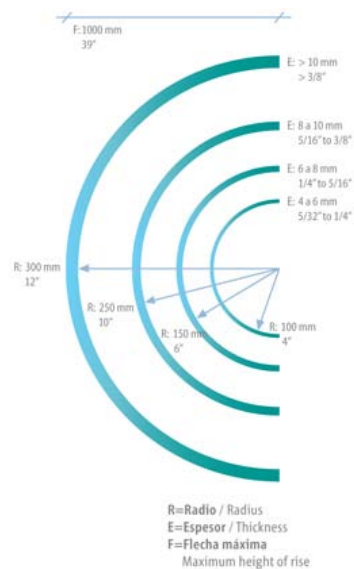


Fig.61_ Maximum radius sizes produced with hot bending process < www.cricursa.com >

2.6.2 / Corrugated glass facades

Casa Da Musica, Porto

OMA

ABT, Rob Nijse

Structure

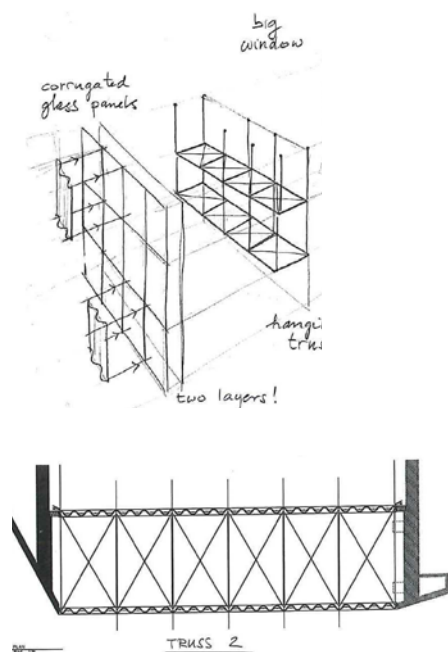


Fig.62_ Sketches and floorplan of the facade structure with the horizontal trusses per floor. < Glass in structures, 2003 >

This is one more realized example (other than the Apple Cubes) where the manufacturing is determining the appearance of the facade (transparency) as well as the structural design.

Due to the maximum allowable size the facade was split in 3 horizontal zones.

The dead load of the facade is received in tension as rods are carrying the load of each storey to the roof.

The glass panels are combined with horizontal trusses that provide stability against the wind loads < Rob Nijse, 2003 >

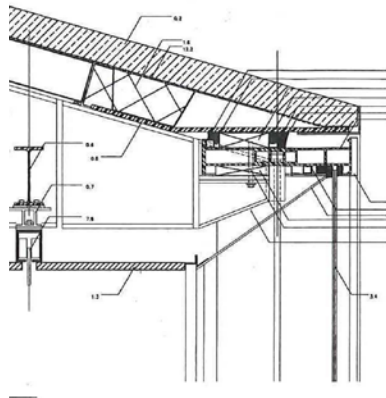


Fig63,64_ Perspective of the horizontal trusses at the Casa da Musica, Porto, by OMA

2.6.2 / Corrugated glass facades

Casa Da Musica, Porto
OMA
ABT, Rob Nijse

Connections



The support of the glass panels is a linear clamp that follows the shape of the panels and it is fixed on a steel beam of a custom cross section. The clamp allows a certain degree of rotation (movement) and also buffers the deviations from the manufacturing with an intermediate soft material (e.g. silicon, neoprene etc.).

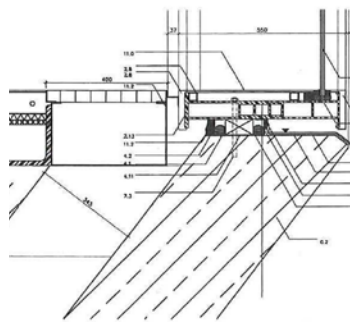
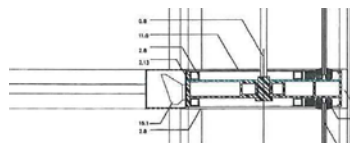
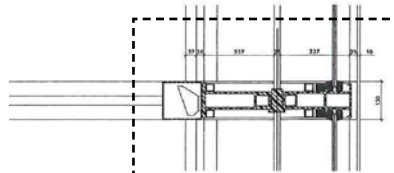
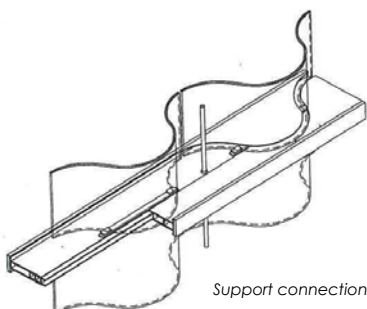


Fig. 65_Vertical section detail and axonometric detail of the horizontal support. < Glass in structures, 2003 >



Support connection

Facade Section detail

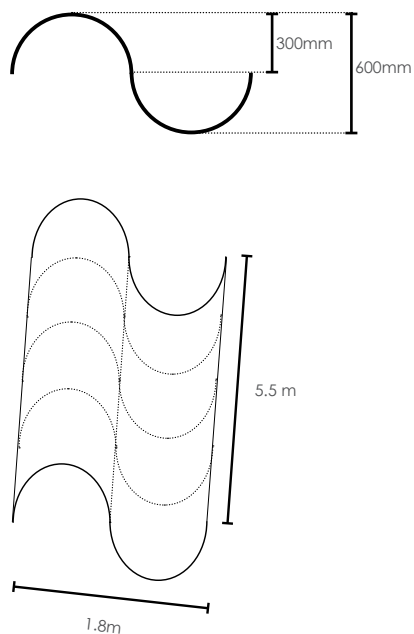
2.6.2 / Corrugated glass facades

MAS an de Strom, Antwerp

Neutelings & Riedijk
ABT, Rob Nijse

Fabrication

- | | |
|---------------------------------|-----------------------------------|
| 1 Glass panel height | 5.5 m |
| 2 Glass panel width | 1.8m |
| 3 Glass build up of inner panel | 12mm |
| 4 Support of facade panel | Top & Bottom linear support |



In this facade the panels are manufactured by the company SunGlass in Italy. Their technologies and machinery allowed for larger panels that reach this time the length of 5.5 m.



Fig.66_ Perspective of the corrugated glass facade at the Mas Museum, in Antwerp

2.6.2 / Corrugated glass facades

MAS an de Strom, Antwerp
Neutelings & Riedijk
ABT, Rob Nijse



Fig.67_ View of structural silicon joint between the corrugated glass panels

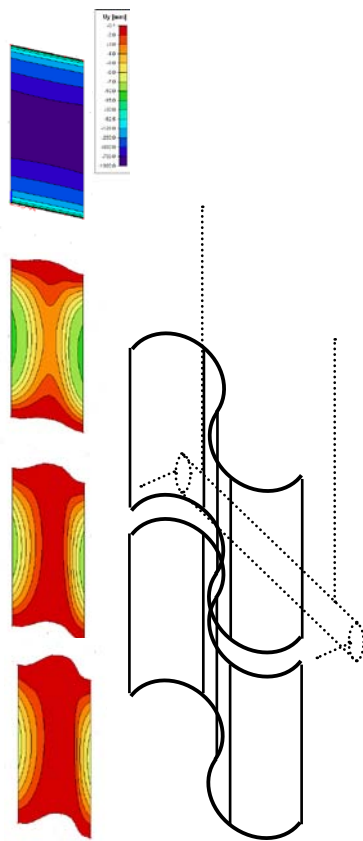


Fig.68_ View of the top detail and hidden sunscreen on the ceiling.

2.6.2 / Corrugated glass facades

MAS an de Strom, Antwerp
Neutelings & Riedijk
ABT, Rob Nijse

Structure



This is an evolution of the previous system. Here the stacking of 2 times 5.5m high panels allows for an 11m facade. There is still a support half way that is as slender as possible of a steel tube connected to the adjacent concrete blocks. The horizontal beam has to be stiff enough to carry the loads of the top element. < Rob Nijse, GPD 2011 >

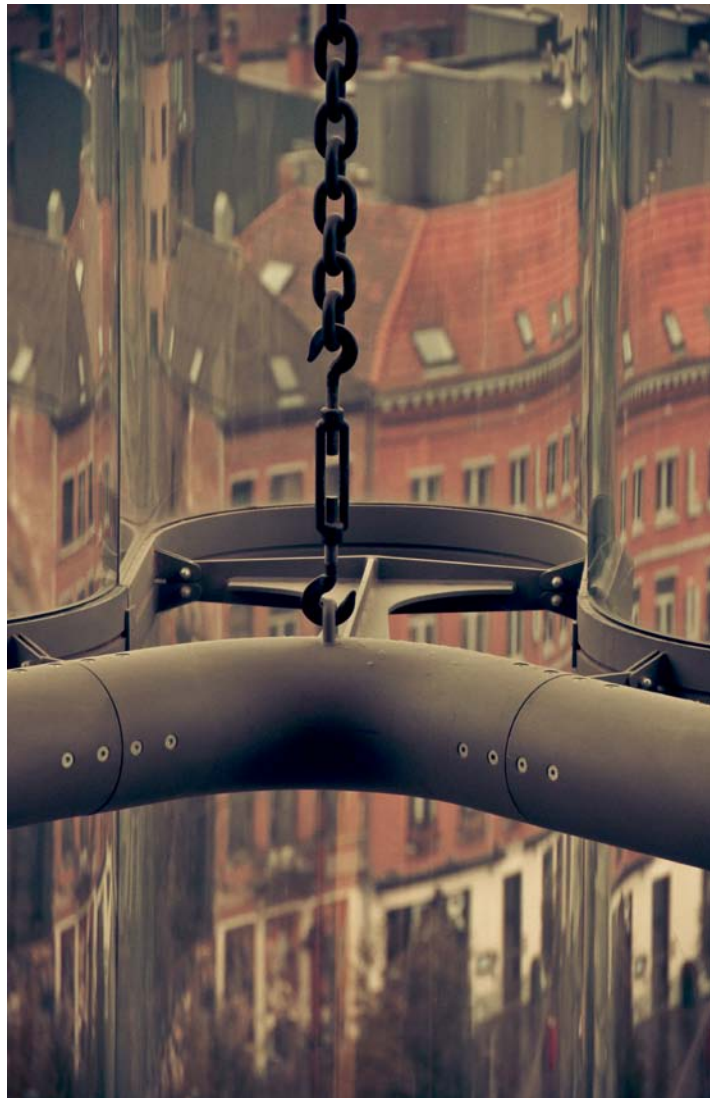


Fig.69_ View of the hanging beam connection at the corner of the facade.

2.6.2 / Corrugated glass facades

MAS an de Strom, Antwerp
Neutelings & Riedijk
ABT, Rob Nijse

Connections



Fig.70_ View of the corner detail of the facade

Fig.71_ View of the intermediate horizontal clamp linear support.



This project is a proof that a-symmetric profiles in a-symmetric cross sections mean extra stresses for the material glass.

The corrugated panels consist of a convex and a concave part. Under pressure loading conditions the convex part will deflect more and will flatten out. On the other hand the concave part will retain its initial shape." This can cause the whole profile to rotate " < Rob Nijse, GPD 2011 >

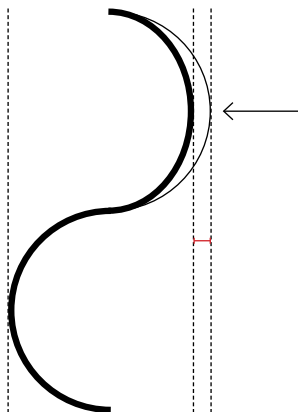


Fig.72_Diagram showing the uneven deflection between concave and the convex part.

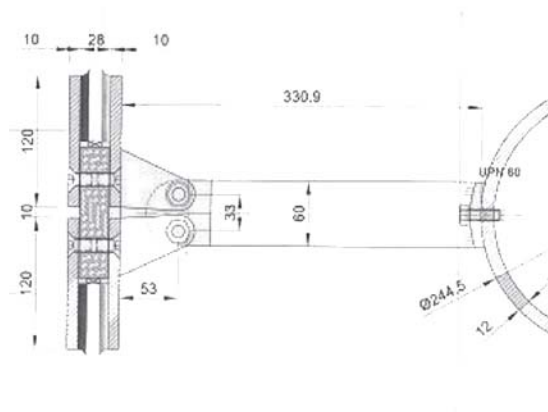


Fig.73_Detail of the horizontal support & joint. < Rob Nijse, GPD 2011 >

2.6.3 / Cold bended glass structures

TGV train station, Strasbourg RFR Niccolo Baldassini

Structure



Fig.74

The prestressed structure is constructed of steel and seamless decomposed into elements sought to maximize the views axially therethrough. South orientation of the canopy has posed important energy issues.
< Niccolo Baldassini, 2012 >



The free - form surfaces are depending their structural performance on the properties of bended glass and the strengthening of the glass components through the process of cold bending.

But all of them are based as well on a steel or aluminium frame loadbearing sub - structure. Unlike the corrugated or flat structural glazing facades that don't use cables or frames for the support of the panels on the surface plane.

Fig.74,75_ Views of the smooth curvature of the glass facade at the Strasbourg station.< www.rfr-group.com >

2.6.3 / Cold bended glass structures

**TGV train station,
Strasbourg**
RFR Niccolo Baldassini

Fabrication

1 Panel sizes	4500mm / x 1500mm
2 Radii	12m - 36m
3 Glass build ups	2 x tempered glass, PVB laminated
4 Support of facade panel	4 sided linear support with vertical clamping

During the cold-bending process, several sheets of glass are combined to make a laminated safety glass sandwich and then shaped as a glass/film laminate in an autoclave to become a single unit. We generally distinguish between two processes:

Cold-bending with shape-enhancing lamination

By using shear-compliant film (PVB film) sheets of glass are mechanically anchored to a shape-fixing substructure, in order to lend permanence to their shape.

Cold-bending with shape-fixing lamination

By using shear-resistant film (SG film by DuPont) shapes are maintained solely on the strength of the film's shear resistance.

Once laminated in the autoclave, the composite glass sheet permanently retains its geometric curvature without being dependent on a shape-fixing substructure.

< SEELE SedaK GmbH , 2012 >



Fig.76_ Cold bending lamination process. Courtesy of Seele Sedak

2.6.3 / Cold bended glass structures

Fondation Luis Vuitton pour la creation

Frank Gehry
RFR Niccolo Baldassini

Fabrication

The freely developable surfaces made out of glass are nowadays feasible through the discretization of the free form geometry. Discretization is defined as the process of partitioning a continuous surface into discrete counterparts that make the surface suitable for numerical evaluation.

The skin could be created using single-curvature hot-bent glass according to a limited number of families but is preferred to use "ad hoc" panels produced using variable mould machines. The glasses are, then, successively cold-bent, before lamination or on-site, in order to adapt its curvature to the all different non - circular supporting lines.

Structure

The twelve windows are very large structures combining wood and steel and supported by poles lengths and inclinations variables. They are coated with glass screen printed white hot bent curvatures following variables.

< T/E/S/S atelieur d'ingenieur >



Fig.77

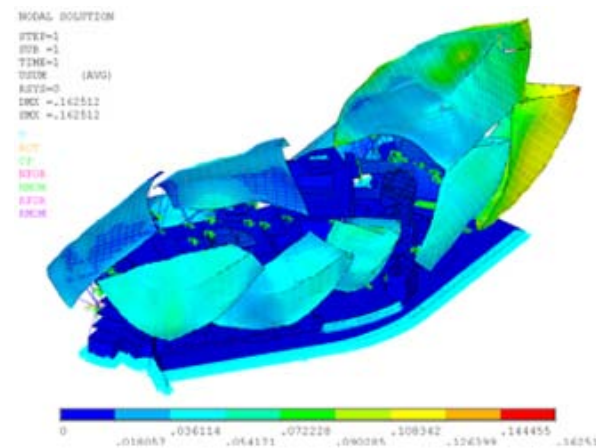


Fig.79



Fig.77,78, 79_ Model views of the facade from hybrid bended glass pieces of the Fondation Louis Vuitton pour la Creation, by Frank Gehry / Structural analysis model < www.tess.fr >

2.6.4 / Stacking

Laminata House

Van der Erven / Kruunenberg



Fig.80_Interior view of the wall of the Laminata House
< Glass in structures, 2003 >

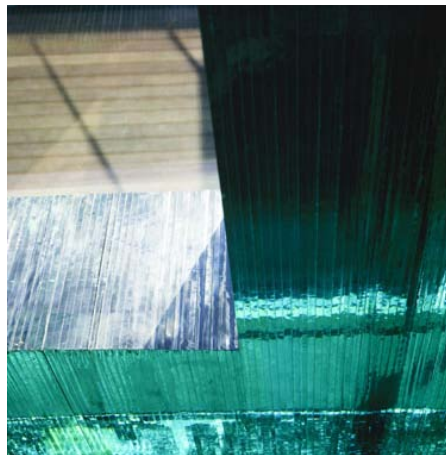


Fig.81_Close-up to the detail of the wall with the opening
< Glass in structures, 2003 >

Construction

Two component silicone oil is used as an adhesive for the joining of the glass layers. About 10.000 plates of glass are employed for this construction. This type of adhesive is proofing the house against moisture that would lead to algae growth between the joints. < Rob Nijse, 2003 >

Structure

Glass massive walls laid on a concrete base. The glass walls carry a wooden roof

Glass billet-

by Axis Facades



Fig.82_Glass billets by Axis Facades.

Sculpture "Borealis"-

by Danny Lane studio

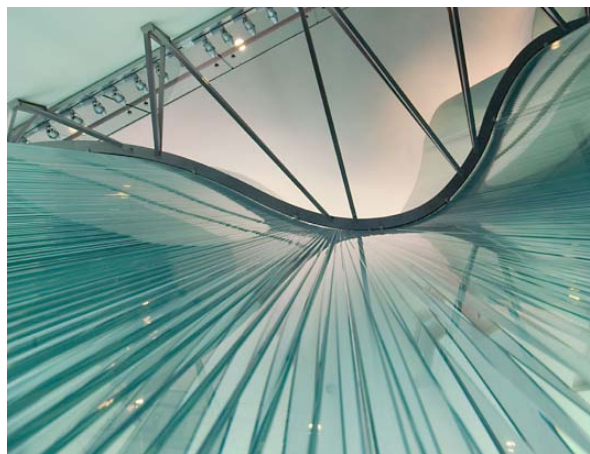


Fig.83_Sculpture 'Borealis', by Danny Lane studio.

2.6.5 / Glass units

Optical glass house, Japan by Hiroshi Nakamura



Fig.84

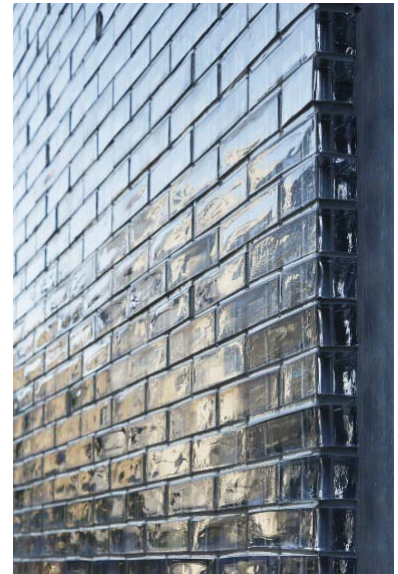


Fig.85

Hiroshi Nakamura & NAP designed an amazing house with optical glass facade and an indoor courtyard. Surrounded with tall buildings this box-shaped abode features a facade made of 6,000 borosilicate glass blocks. The glass blocks were created specifically for the structure assembled together with help of steel bolts and beams. Thanks to micro asperities in the glass the creators called the facade a waterfall as they create a certain optical illusion.

The facade is 8.6 x 8.6 high and animates the street with its unique ability to display both transparency and translucency depending on the light conditions. Their high degree of transparency was achieved by using borosilicate, the material used to make optical glass. The difficult casting process required slow cooling to remove residual internal stress and achieve precise dimensions. Yet the glass still retains micro-scale surface irregularities that generate and project unexpected visual effects around the interior spaces.



Fig.86

Fig.84_ View of the facade's peculiar light variations that give life to the enclosed garden. < www.dezeen.com >

Fig.85_ View of the irregularities that the glass bricks present from the outside of the facade. < www.dezeen.com >

Fig.86_ A unit of optical cast glass brick especially fabricated for the facade of the house in Hiroshima. < www.dezeen.com >

2.6.5 / Glass units



Fig.87 The casting process. The blocks were produced in moulds with high accuracy and controlled cooling process to avoid residual stresses.

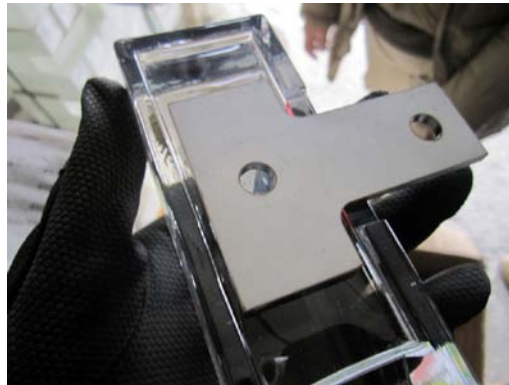


Fig.88 Flat steel bars inserted in the glass brick shape.

The glass blocks are strung together by stainless-steel bolts suspended from a beam above. They are also stabilised by stainless-steel flat bars at 10mm intervals. The mass of the supporting beam below is laterally minimised by employing a pre-tensioned steel beam encased in reinforced concrete. Despite the facade's massive weight, it appears to be transparent from both the garden and street. Seen from inside, the glass garden brings the entire house to life.

Monumento 11M by FAM Arquitectura y Urbanismo



Fig.89



Fig.90

Fig.89,90_ Views of the exterior and interior of the Monumento 11M for the victims of terrorist attacks in Madrid Spain.

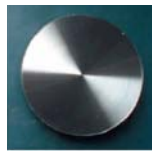
2.6.6 / Adhesives

Analysis summary of adhesives. Types of adhesives, properties of structural silicones and transparent adhesives mechanical properties are analysed in this table.

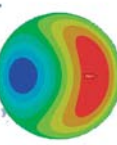
Table.91_ Summary analysis of structural adhesives and the properties of common silicon as well as other adhesive families.

Advantages	Disadvantages
01 Loadcarrying ability both in tension and compression.	Absence of trust in durability. Lack of experience.
02 The bonding can be performed without the presence of clamps or other mechanical supports.	The strength compared to some mechanical support is relatively small.
03 The size of the support construction becomes smaller and therefore enhances less visual obstruction. This leads to a reduction of the eccentricity in glass and decreases the local stress values.	Many parameters influence the strength of bonded constructions (e.g. weather conditions, surface treatment , loading levels etc.).
04 The smaller size of the support leads to a reduction of the eccentricity in glass and decreases the local stress values.	Curing time plays an important role, because no loading can take place before the adhesive is completely cured.
05 It can realize bonded point fixings that don't require any drilled holes, which can cause higher stress concentration.	The application and handling of adhesives is complicated and requires special skills and craftsmanship.
06 Compensation of tolerances and movements from deformations due to temperatures is easy to achieve.	The application and handling of adhesives is complicated and requires special skills and craftsmanship.
07 Constant loading can help avoiding stress concentration zones.	The replacement of a broken window plane is much more complicated.

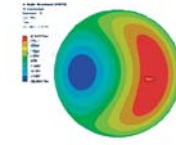
Transparent Structural Silicone Adhesive (TSSA)



A-Bolt Maximum Capacity

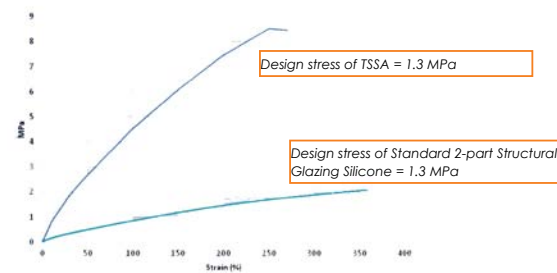


Stresses at whitening



Stresses at failure

One new product is a thermoset structural silicone that is transparent and exhibits relatively high strength and stiffness.



UV - Light Curable Bonds

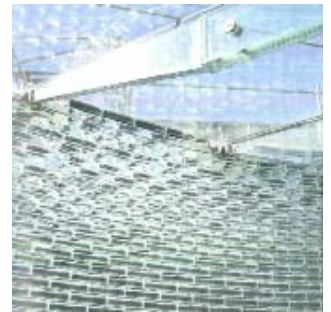
Due to its transparency, glass constructions bonded with light and UV-curing acrylates, possess enormous visual appeal, especially in an architectural context.

Parameters affecting the stress distribution of the bonded joint

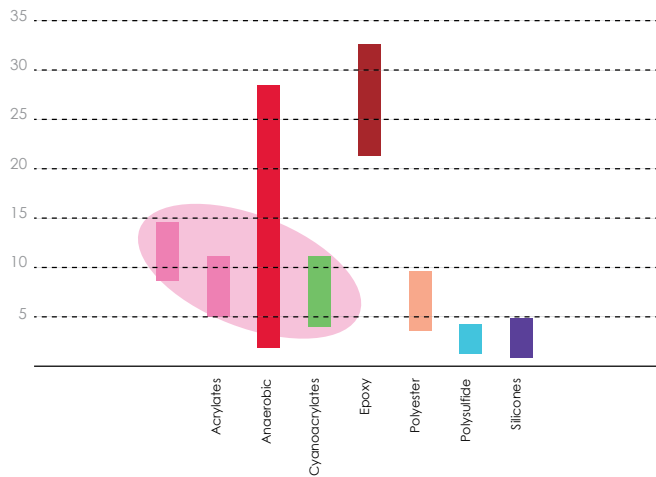
The thickness of the glass pane, as well as the metal supports-brackets have an effect on the internal stress distribution of the glued joint.

_PP4468 adhesive used
_monolithic tempered glass

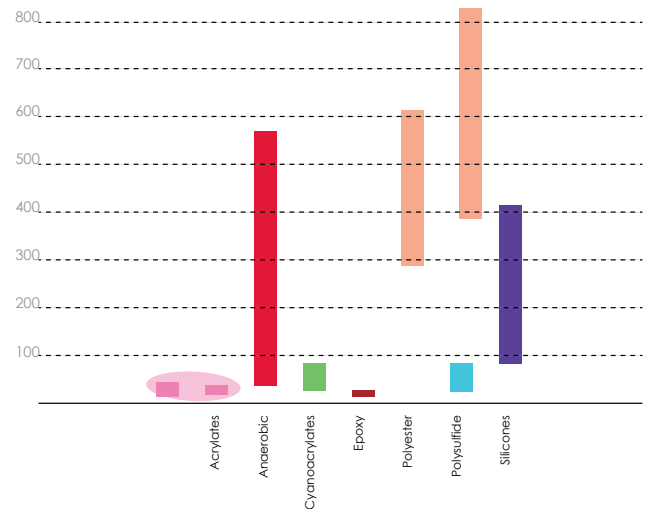
The geometry, the adhesive and, even more importantly, the placement of the support mechanism all have an effect on the stress distribution which must not be neglected but, rather, fully considered in the design and dimensioning of bonded joints that utilize light-curing acrylates.



Tensile Strength (MPa)



Elongation - strain (%)



Name of adhesive	Typical uses
Acrylic	structural, reinforcement, automotive
Anaerobic	mechanical, medical, automotive
Cyanoacrylates	precision industry
Epoxy	structural, aerospace, buildings, transportation
Polyester	structural
Polysulfide	sealant for wood, concrete, metal, glass
Silicones	sealant in buildings, automotive industry, aerospace

Name of adhesive	Type of joint		Materials to be bonded							Joint geometry					Recommended loading					Function		Characteristics	
	Flexible	Rigid	metals	polymers	glasses	composites	ceramics	natural	dissimilar	Butt	Scarf	Sleeve	Lap	Tee	compression	shear	bending	torion	peeling	waterflight/airlight	dismountable	Discrete	Continuous
Acrylic																							
Anaerobic																							
Cyanoacrylates																							
Epoxy																							
Polyester																							
Polysulfide																							
Silicones																							

2.6.7 / Glass Welding

During experiments that were conducted at a summer workshop hosted by the ILEK (Institute of Lightweight Structures and Conceptual Design) it was attempted by students to create glass-only joints.

Commonly in order to join glass elements together more than one materials are being utilized. In these series of experiments in order to achieve only glass joints welding was used to combine glass rods or glass panes. To reduce thermally introduced stresses in the glass, borosilicate glass was utilized. In the process of welding the individual glass elements were first preheated and subsequently heated locally to the welding temperature and joined. Glass objects with transparent joints were the result. < Kerstin Puller, GPD 2011 >



Fig.92



Fig.92,93_ Linear glass welding and glass-glass joint connecting glass rods < www.glassfiles.com >

2.6.8 / Glass columns

Laminated glass column



Fig.94_ Borosilicate Glass tubes. < www.tykchina.com >

Within the frame of ZAPPI research a special technique for laminating glass tubes in a column component was developed by Fred Veer and Pastunink.

A transparent column composed out of 2 concentric glass tubes was laminated with two parts epoxy resin. After intensive testing of the lamination process it was feasible to create totally transparent components that fit the scale of the building.

"Compression tests showed safe, gradual and controlled failure behaviour compatible with the ZAPPI safety philosophy." < **E.J. van Nieuwenhuijzen**, **GPD 2005** >

Safe failure is presented when a component under gradually increasing loading exhibits visible damage without failing abruptly. Usually a durable deformation comes first until the component fails completely.

In the laminated glass column both of the glass tubes can carry the load, the resin will slow down and arrest cracks while keeping the fragments of broken glass together after failure in such a way that they can still carry some compressive forces. < **E.J. van Nieuwenhuijzen**, **GPD 2005** >

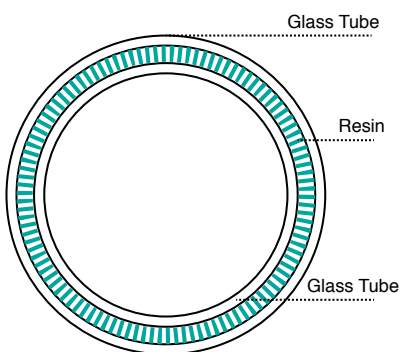


Fig.95_ Layers of glass column laminate build up.

2.6.8 / Glass Columns

Bundle column

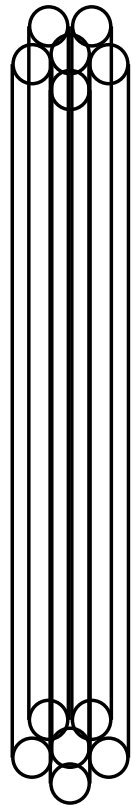


Fig.96



Fig.96,97_ Bundle of glass columns used for a table support. <Glass in Structures, 2003 >

Increasing the compressive strength of a glass column by combining in a cross section several massive glass bars and join them by transparent adhesives together.



2.6.9 / New Design possibilities



Fig.98_ Deformed glass plane (Linear supports). < www.glassfiles.com >

During the series experiments that were conducted at a summer workshop hosted by the ILEK (Institute of Lightweight Structures and Conceptual Design)

In this project planar glass elements were supported either on a planar or a linear grid and subjected to temperatures of about 650-750 °C. At these temperatures the glass lost most of its stiffness and started to sag between the supports. With higher temperatures and longer exposure durations more sagging occurred. A variation of geometries was obtained varying the heating parameters and the location of the supports. Since the inherent stiffness of the glass was largely reduced during the thermal exposure, shapes were formed which mainly carry the self-weight through tensile stresses and thus recall the design vocabulary of lightweight structures. < **Kerstin Puller, GPD 2011** >



Fig.99_ Deformed glass plane (Point supports).< www.glassfiles.com >

The out of plane deformation of the sagged glass portions increases the geometric stiffness of the overall glass pane for lateral loads. As a consequence, thoughtfully three dimensionally deformed glass panes may need smaller glass thicknesses than planar ones – leading to an enhancement of the visual and the structural performance simultaneously.

2.6.9 / New Design Possibilities

Two different approaches were followed with the goal to achieve a flexible glass element.

01_ One of them applied a lamination technique using PVB foil. Utilizing the flexibility of PVB at room temperature, the foil was used to create a flexible laminate. Glass elements were cut in regular sizes and applied to both sides of the continuous foil. This composition was placed in a vacuum bag and laminated together in a kiln. After cooling the flexible hybrid was removed from the bag and could be positioned in manifold configurations.

02_ Another project also followed the idea of connecting smaller glass elements but used threads instead of a laminate foil. To ensure a connection between the glass and the threads, the latter were placed in between two glass elements; the arrangement was positioned in a kiln and subjected to temperatures around 800 °C. This temperature allowed the glass to melt, enclosing the threads.

< Kerstin Puller, GPD 2011 >

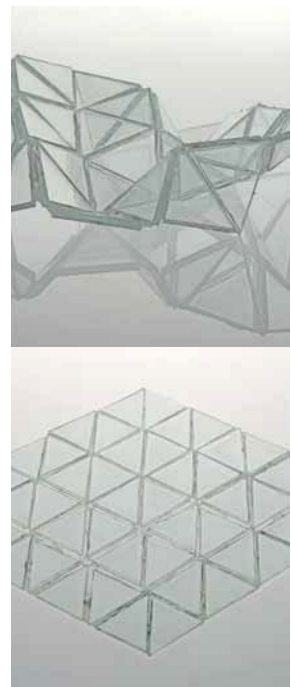


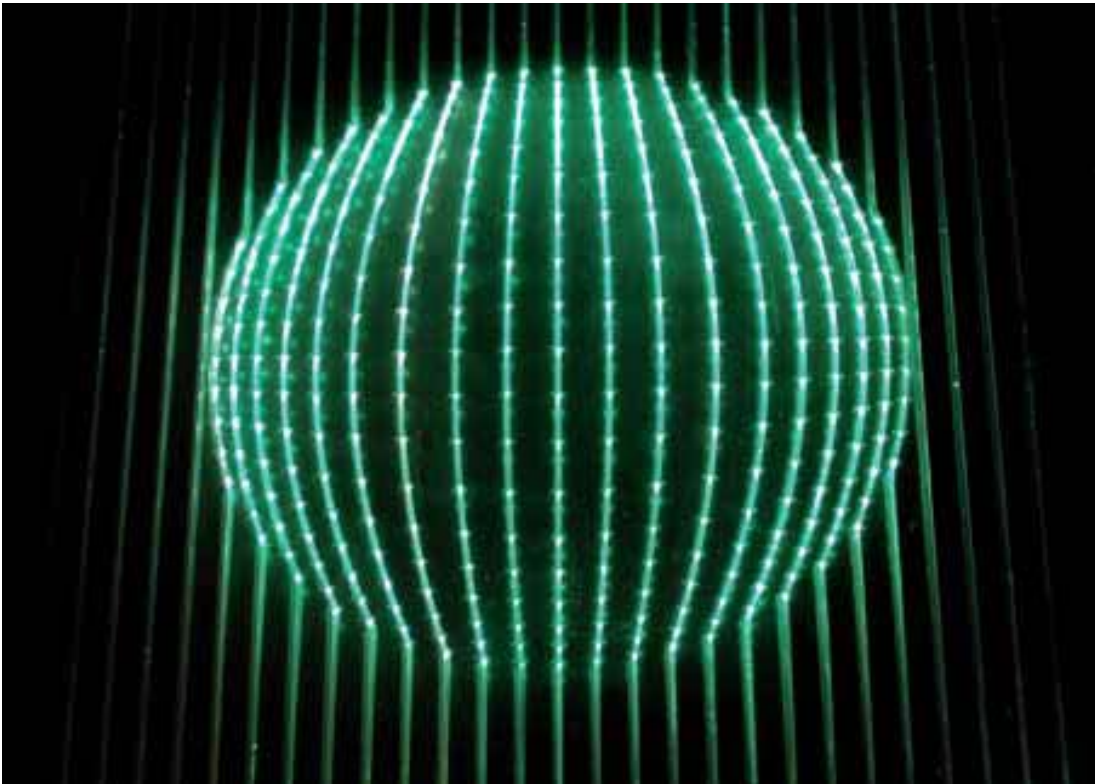
Fig.100

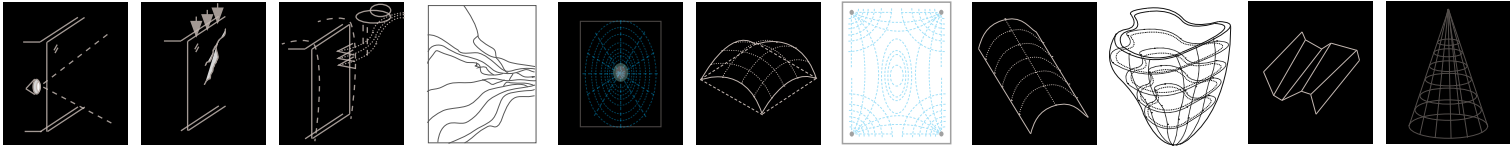


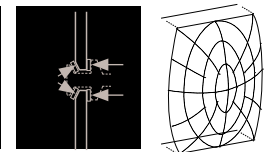
Fig.101

Fig.100_ Flexible glass surface using lamination foil.

Fig.101_ Flexible glass with embedded threads.







Stage 2
Preliminary
Concept
Generation

3.1 / Oversized flat laminates

The first design concept for the facade of 30 meters high and 15m wide (initially required size of the facade) is the structural glass components that are oversized and they follow principles of the lamination with oversized components of 10 or even 15 m high that are reinforced by stiff interlayers like the Sentry glass Plus at the Apple glass cube.

The second option for generating such large components in the lamination with overlapping joints that ends up creating a monolithic element with the same properties as a piece of glass of that size.

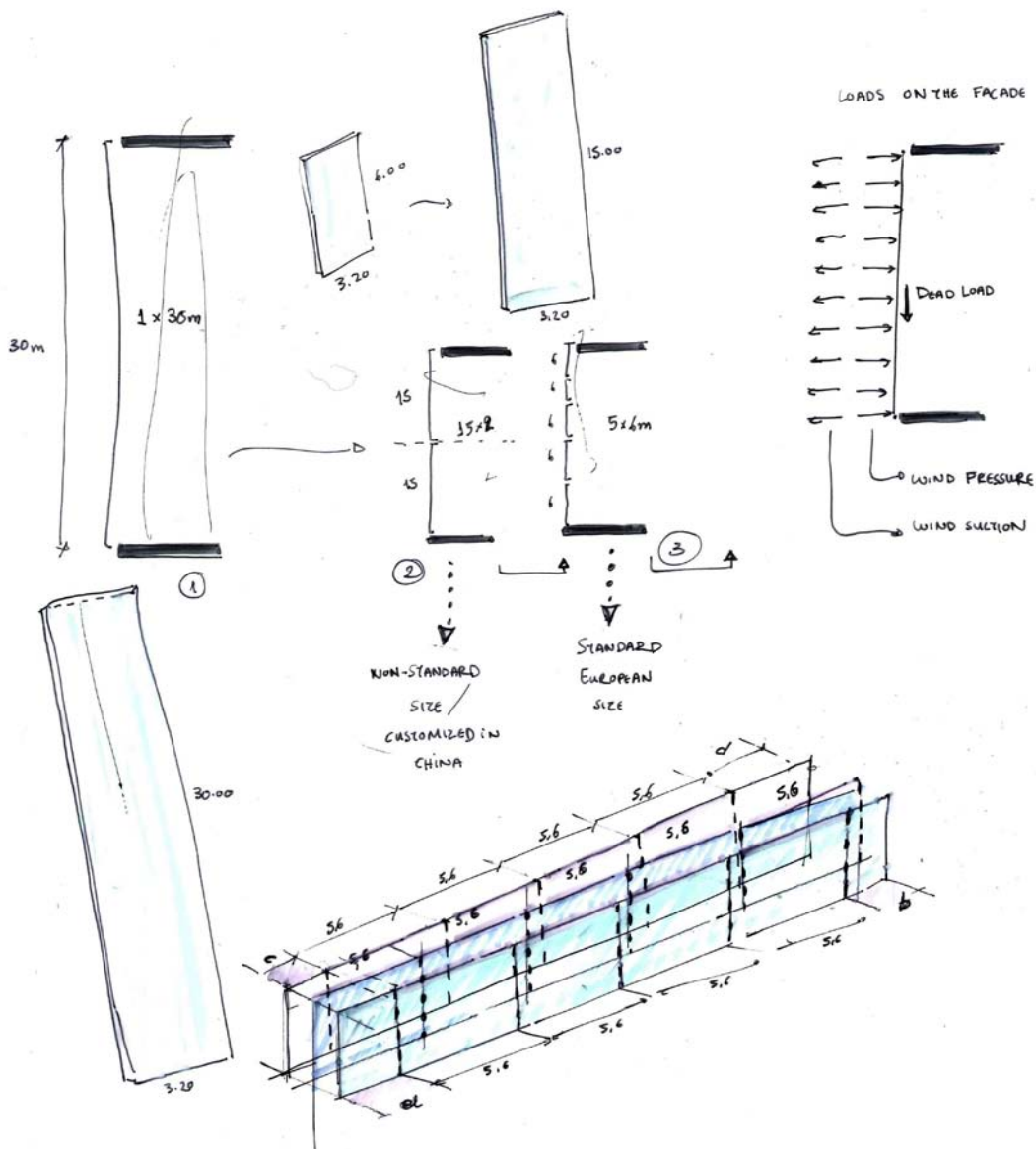
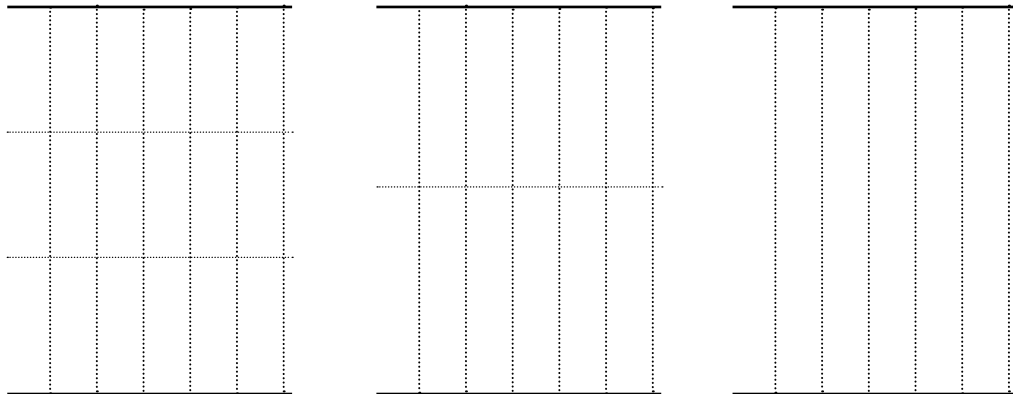


Fig.102_ Sketches of the overlapping elements concept. Oversized units.

3.1 / Oversized flat laminates



There are 3 ways to span the opening of 30m height

01_

3 Standing elements on top of each other of 10m size and laminated with stiff interlayer. The wind loads are carried by vertical fins that are constructed as continuous elements following the techniques of spliced beams. The technique describes the construction of an oversized glass component by using smaller elements that can be produced by laminating in slices that overlap. This is also called overlapping joint technique like in the case of the apple cube store Nr. 1 described in Stage 1.

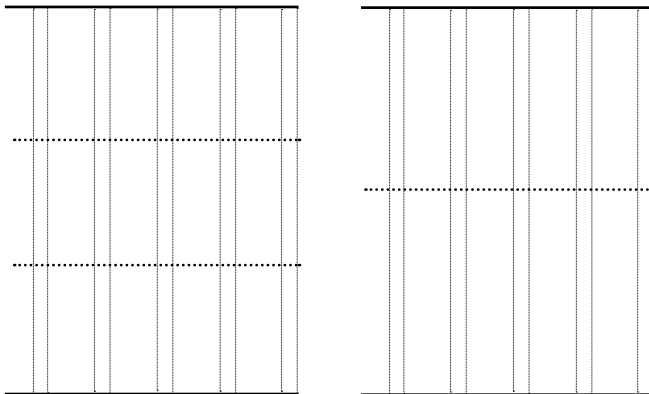
02_

2 Standing elements on top of each other of 15m size and laminated with stiff interlayer. The wind loads are carried by vertical fins behind the facade constructed in the same principles. The challenge faced in this design proposal is the transportation and installation difficulties posed by the size of the components. There is only one similar reference for realizing this size of glass structure in the Apple retail pavilion in Shanghai.

03_

Extreme case of 1 standing loadbearing piece of glass laminate 20m size and laminated with stiff interlayer and generated by overlapping joint laminate. The wind loads are carried by vertical fins behind the facade constructed in the same way. The benefit of a continuous oversized element in this case would be of course to avoid all the problems that are posed by the connection points in the glass that create weak areas for the material. Glass performs better as a structural member under tensile stresses when constructed as a monolithic component and not when interrupted from divisions. This would be an ideal case from one point of view but on the other hand the manufacturing limitations and logistic issues emerging from this concept make it not the most feasible, economical or logical solution to follow.

3.2 / Corrugated glass - curved elements



The second design strategy to employ for constructing the facade of 20 meters high and 7.7m (adjusted size concept) wide is the corrugated glass elements or curved that can allow for the facade to combine the plate action with the fin in one element and therefore become more efficient in the use of glass.

01_

The first idea was a hybrid between the flat glass components and the Combining bended glass pieces and flat to construct an alternative of the corrugated effect. Here the bended part towards the inside is constructed by 3 different hot bended glass pieces and represents a sort of fin that develops in one surface with the hole facade.

The part that is protruding is created from flat laminated pieces with main aim to increase the part of the grid between the vertical elements and leave the surface undistorted from corrugations.

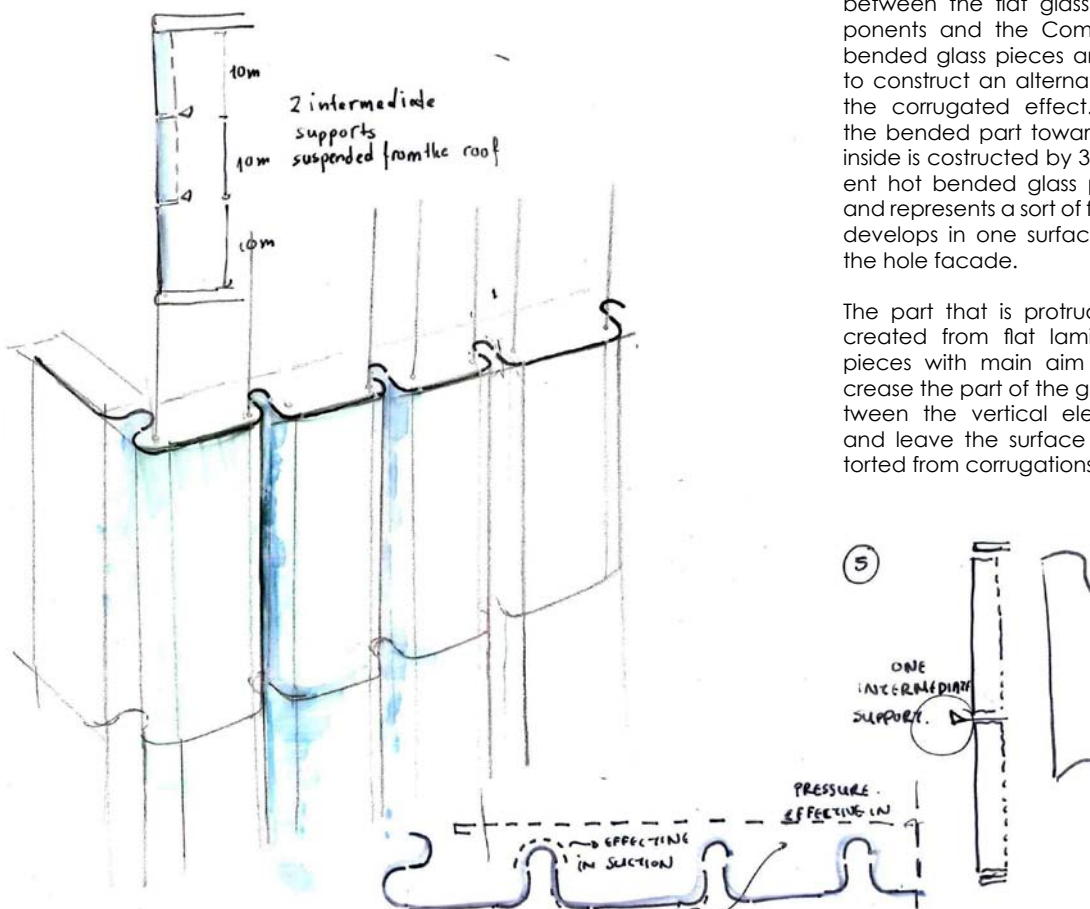


Fig.103_ Sketches of the concept where bended parts are combined with flat to create one surface.

3.2 / Corrugated glass - curved elements

02_

In this concept an alternative geometry to the sinus shaped elements is presented. This design of an element attempts to combine a pressure and a suction resistant surface combined in the same surface and developed along the diagonal.

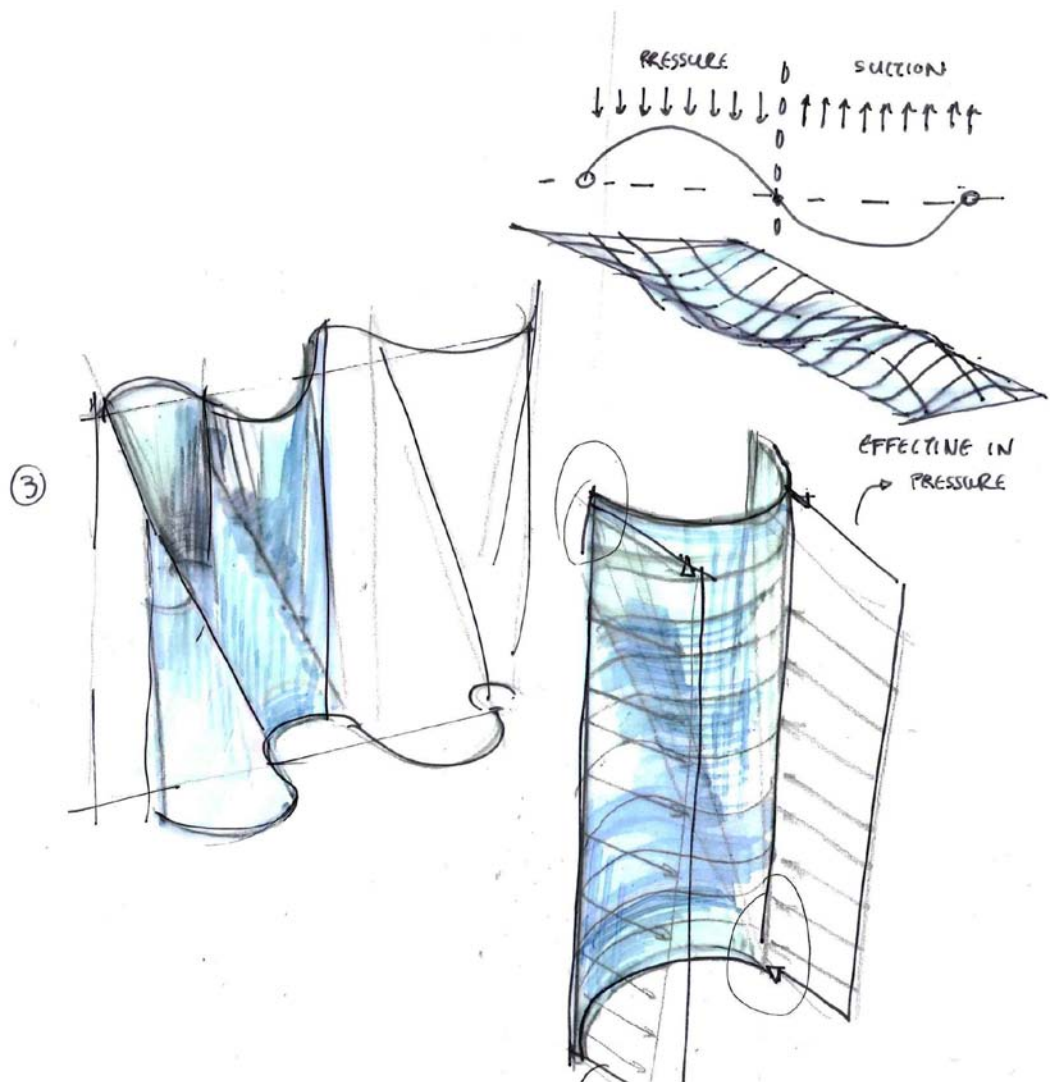


Fig.104_ Sketches for an alternative corrugating pattern of a glass panel.

3.3 / Stacking

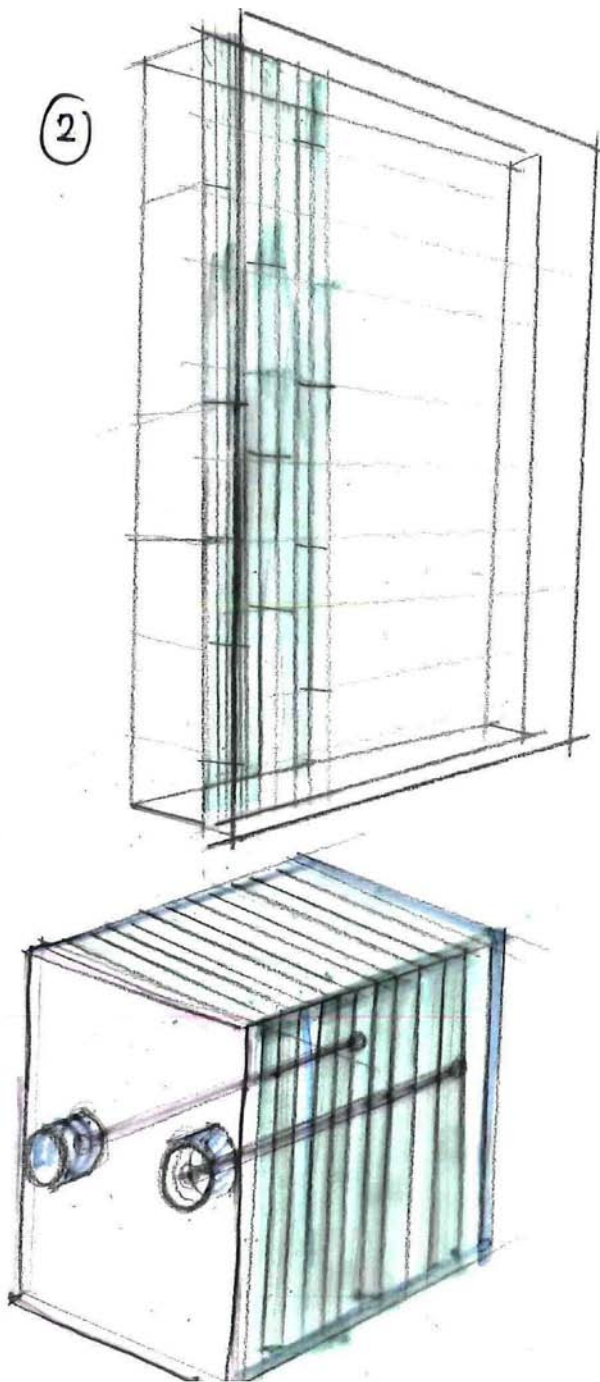


Fig.105_ Sketches of massive wall.
Stacking concept 1.

Fig.106_ Sketch of massive wall pre-
stressed unit. Stacking concept 2.

01_

In this concept a facade is developed using the principles of stacking but in a vertical sense like the massive glass walls of the Laminata house.

This design can create an interesting play with light coming through the facade. Although it is not achieving maximum transparency it creates a kind of translucency that is architecturally appealing. This is achieved by constructing a wall that is consisted of layers that don't depend on any frames and carry their own weight. The stability here should be secured from the thickness of the wall. Maybe there is a potential of treating it as an inclined wall from one side in order to create a more efficient shape for the bending stresses acting on the plane of the façade .

Here the wall must act as one monolithic element and depends a lot on the quality of the adhesive used to keep the layers together. This type of design can also very easily integrate embedded connections in the laminated layer scheme.

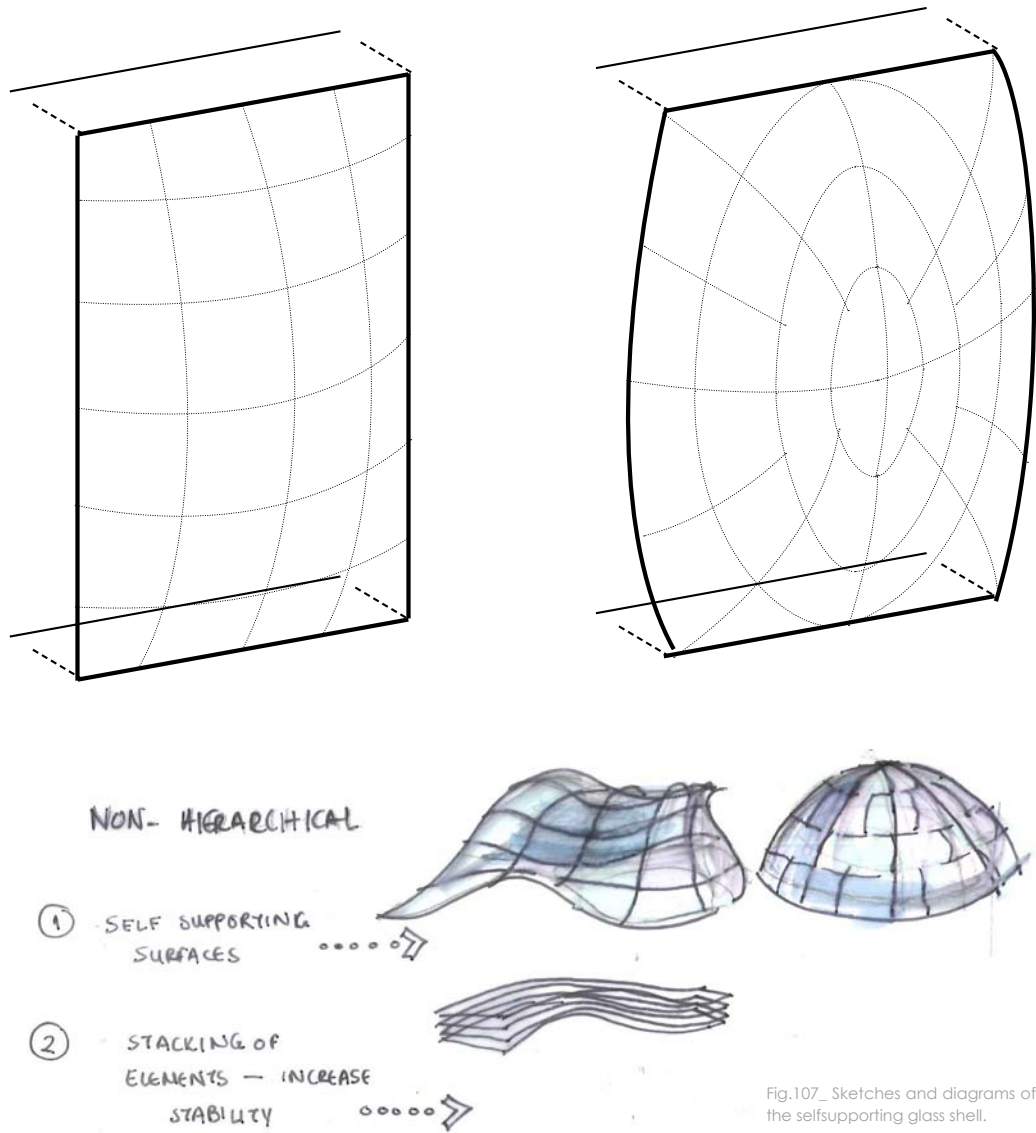
In this possibility the interlayers of glass can be interrupted by polycarbonates or sandblasted and translucent pieces that will create an even more versatile image and increase the potential of this design. Of course this scheme is quite expensive in terms of the use of glass and demands a great deal of labouring skills for the assembly process.

The potential of prefabricating larger components to reduce the amount of work on site could be examined.

02_

Another concept coming from the idea of units with stacked glass panes is the cube that is being compressed by a metal rod like in the concentrically pre-stressed tubes . The problem here is that maybe only a glue or resin more efficient for these components.

3.4 / Self supporting surfaces

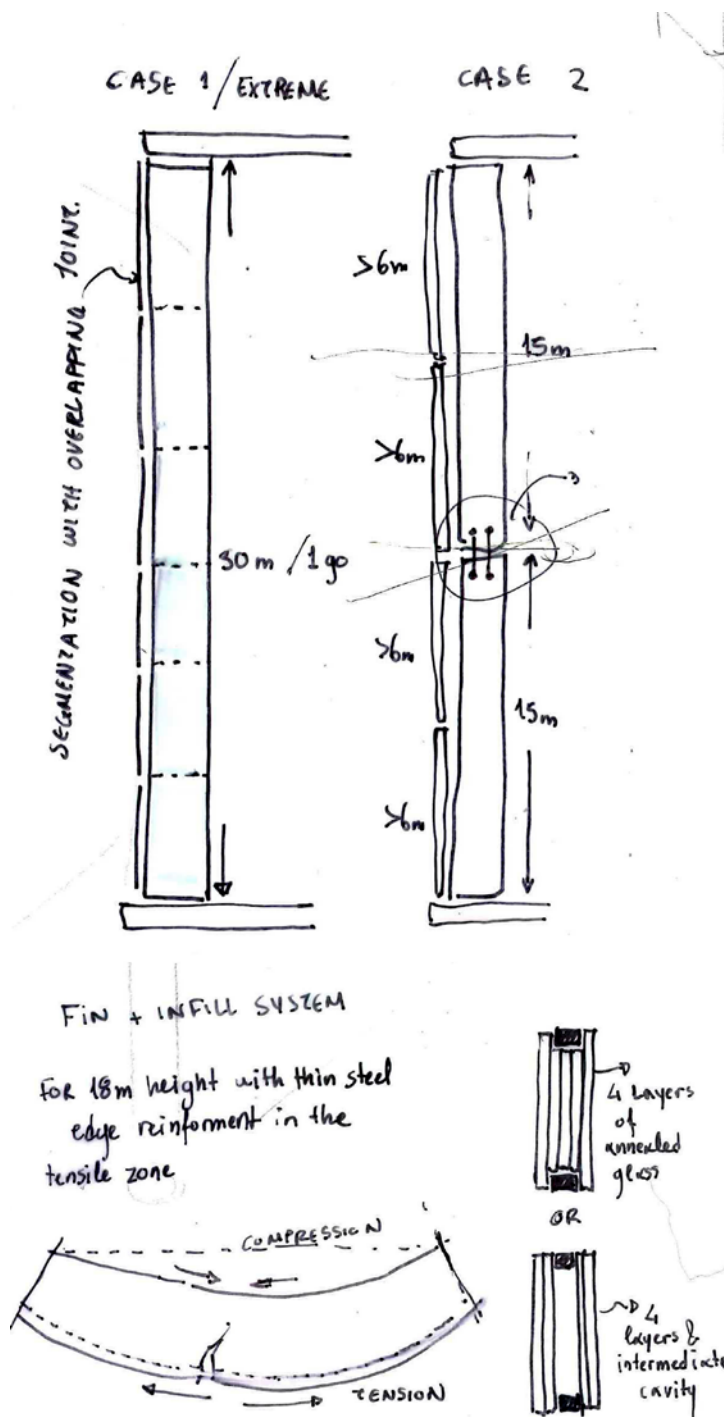


Here the facade is constructed as a shell or self supporting geometry like the synclastic dome of the ILEK and then it is placed on a ring beam that is attaching it to the floors.

The surface bonds are formed by adhesives and the geometry can be optimized using parametric design software. The software can optimize the surface in terms of shape thickness position of the joints so as to achieve an optimal self supporting system according to the loads that it has to carry with the minimum amount of joints.

One could say that this way of approach is very similar to the corrugated or bended facades. But here the surface is acting more as a single shape whereas in the corrugated schemes we have the pattern of a repeating module.

3.5 / Combination



Here the combination of glass and embedded reinforcement steel bars can allow the component to behave better under tensile bending stresses that the glass alone cannot compensate. The thought here is to implement a steel rebar at the tensile zones of the glass fins to accommodate bending stresses.

Fig.108_ Sketches of ideas for the combination of glass with other materials as reinforcement

4 / Selection process

In this stage of the research a decision for a more focused approach on the design was made. This was because the tremendous amount of opportunities found in the state of the art technologies and the limited amount of time to conduct this research wont allow for proper evaluation in such a range of schemes. Another reason for limiting the strategies looked into, is the very different approaches that have to be followed between them during the more detailed design process. It has been decided to look at a more detailed level the following, based on the primary geometries, strategies. The aim is to provide alternative designs for a façade that is:

- 1_ Composed from flat glass elements
- 2_ Composed from corrugated or bended glass panels
- 3_ Utilizing the different shapes of glass columns

At this stage the concepts produced earlier, are organized in these 3 categories and new ones are added according to the new strategies (glass columns). Furthermore at this point combinations are still examined.

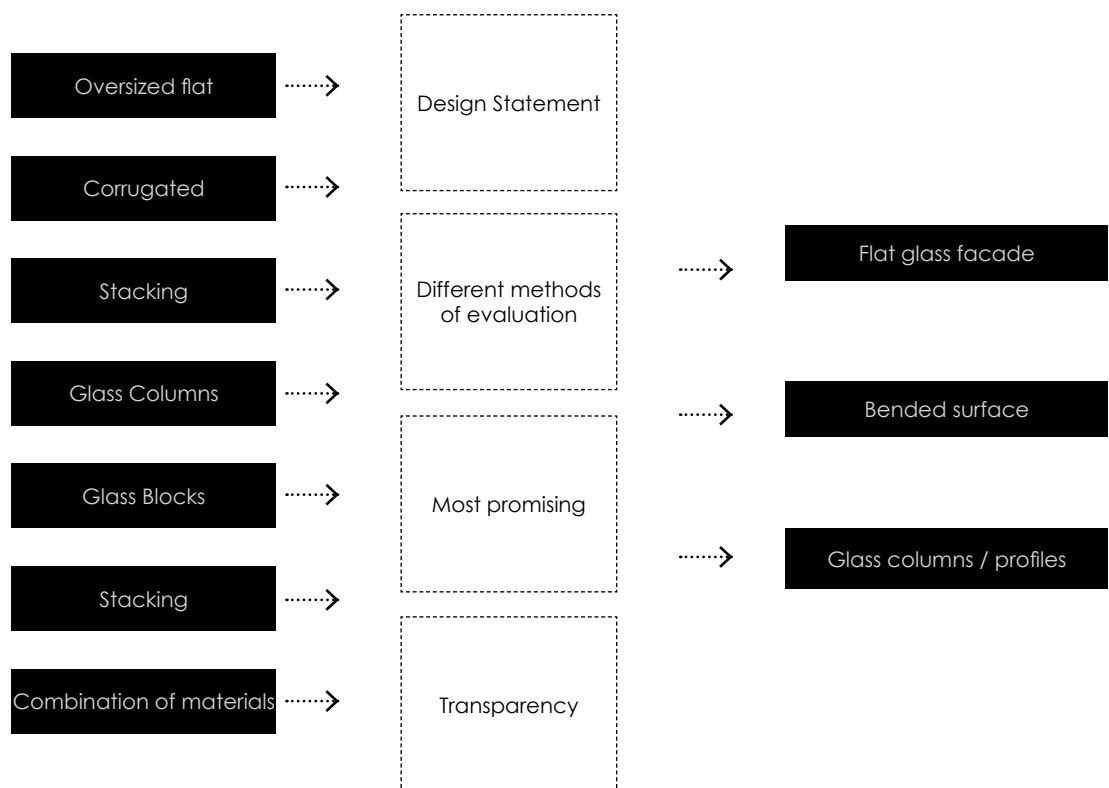
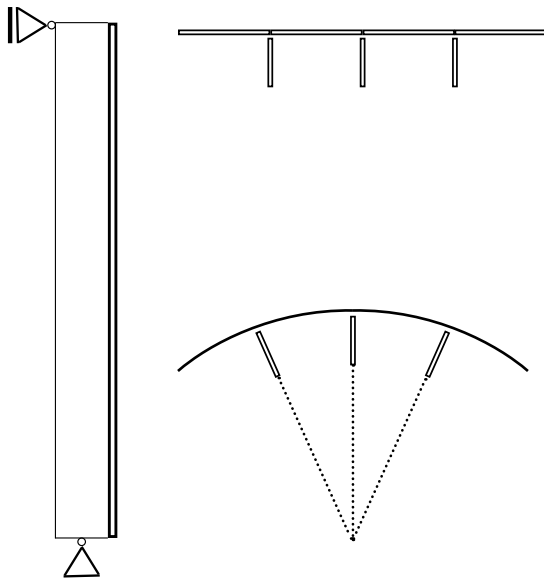


Fig.109_ Diagram for selection criteria (filter) for designs.

01 Strategy flat components - *Optical Illusion*



The first is the concept that utilizes the principles of the flat elements that can be oversized and build up in strong laminates. Here an attempt of generating a façade that creates an optical illusion was made. The structural glass fins supporting the envelope are oriented in such a way, so as their extension lines are coming to one focal point. This could achieve one position in front of the façade that ensures maximum transparency. In order for this to happen the whole surface of the façade has to be bended in a mild curvature that resembles a focal lens.

Structural principle:

Glass plates attached to glass fins. The fins take up the bending stresses from the wind load and secure stability.

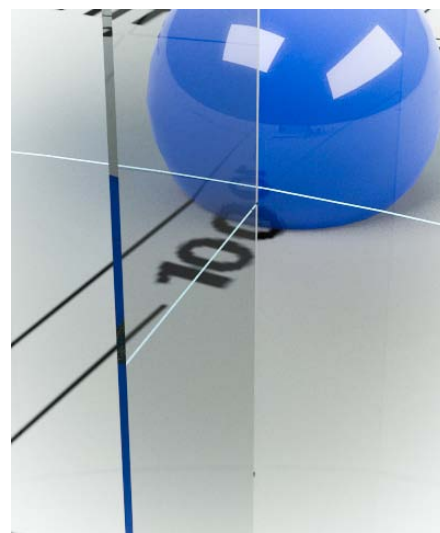
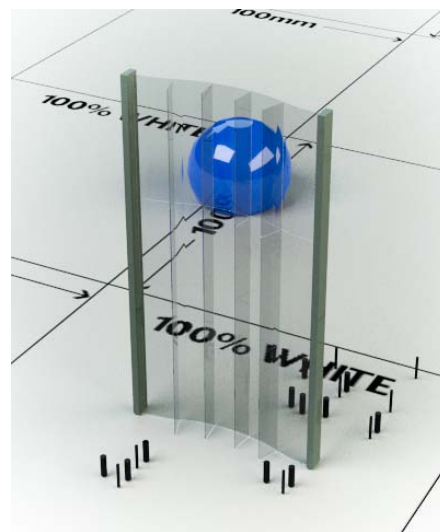
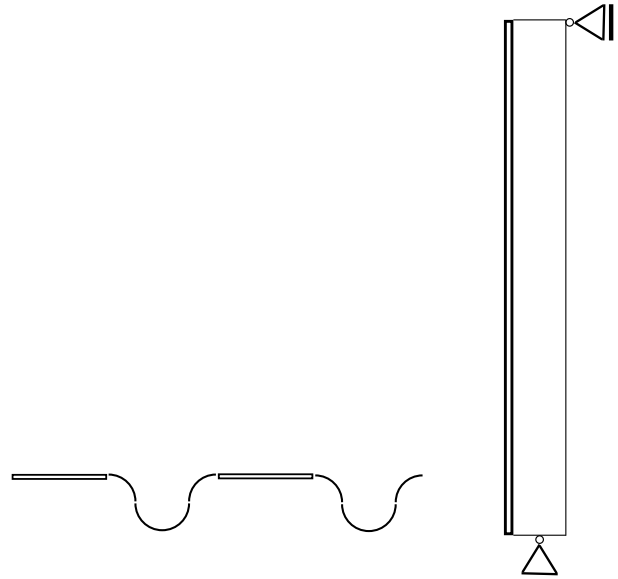
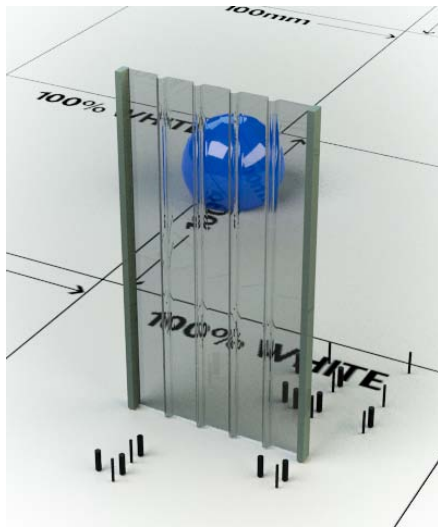


Fig.110_ Rendered views of the first concept. Complete image of the facade and close up.

4.1 / Concepts

01a Combination strategies - Alterating pattern / Flat & bended



The second revised concept is the one with the combination between the bended glass and the flat panels. In this approach it is attempted to eliminate the harsh lines of structure appearing on the surface of the façade from fin-like elements and create a smooth continuous surface. This is also an attempt to create a more open grid without many distortions like in the case of a fully corrugated façade.

Structural principle:

Flat glass plates acting as structural envelope and bended sheets are assembled in a continuous surface. The bended part is replacing the function of the structural glass fins but more locally.

Fig.111_ Rendered views of the concept of a hybrid surface, composed by bended and flat elements.

02a Strategy bended / corrugated components - Glass curtain 1

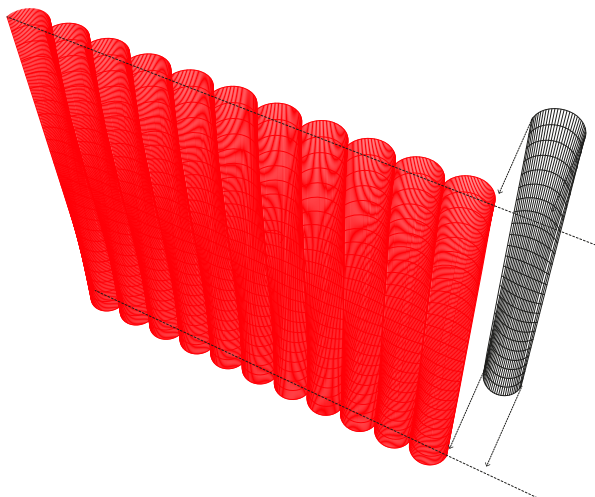
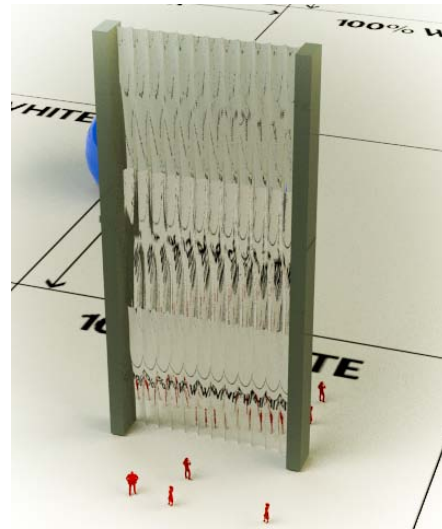
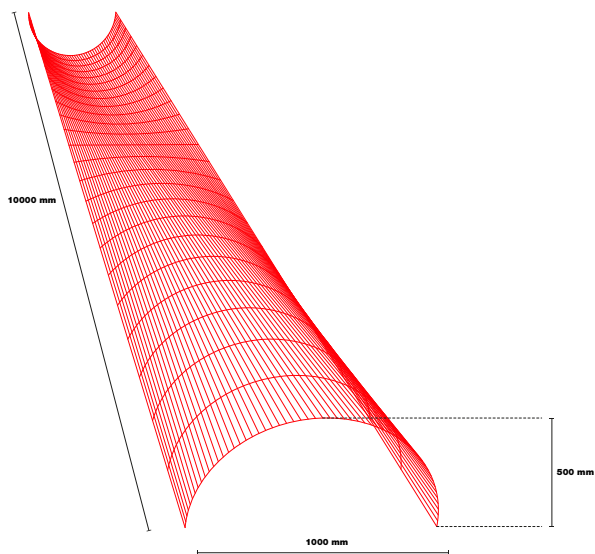


Fig.112_Panel size and shape / Horizontal assembly of 1 row.

Fig.113_Concept of the glass curtain 1.

The third concept has two variations. Here the aim is to create the image of a distorted glass surface that resembles a flowing curtain.

Structural principle:

The first alternative is to develop a surface that can achieve both actions Resistance in wind pressure and in wind suction. Since the façade is an element that is very prone to the wind actions, it has to be reinforced to resist the bending stresses caused by them. In this case the panel itself bended is allowing for stiffer glass geometry.

Here an alternative of the corrugated glass façade is presented, where the semi-cylinder geometry is shifted along the height of the element creating two effective zones, one in pressure and one in suction.

4.1 / Concepts

02b Strategy bended / corrugated components - Glass curtain 2

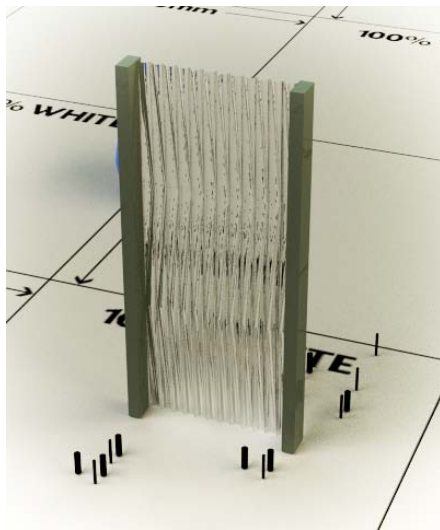


Fig.114_ Concept of the glass curtain 2.

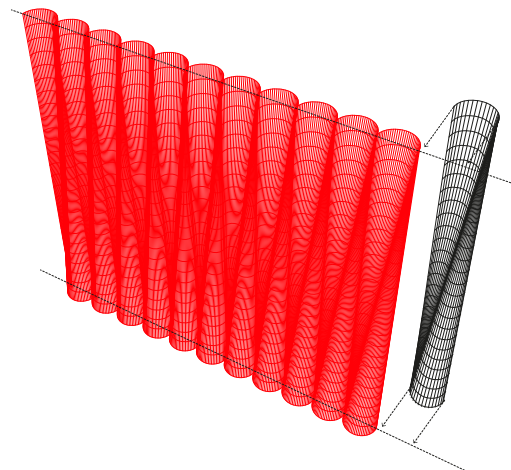
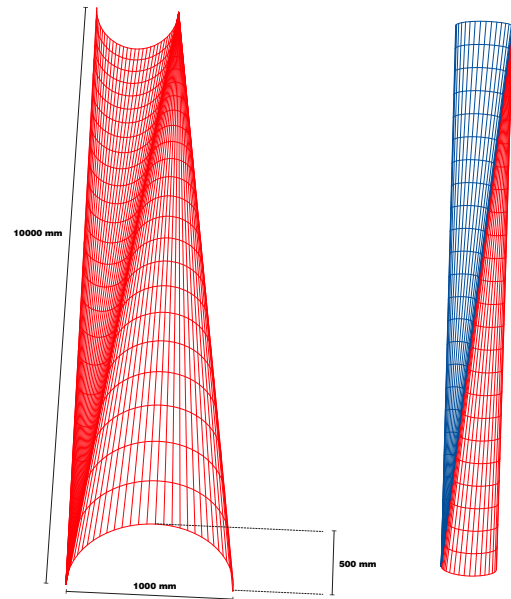


Fig.115_Panel size and shape / Horizontal assembly of 1 row.

Structural principle:

The second variation is based again on the effectiveness of the corrugated geometry in resisting against wind load actions. This time though the panel is a variation of the sinus - shaped panel. The difference is that here the corrugation is developed along the diagonal and not along the middle vertical axis of the panel.

03a Glass Columns - Ribbed plate _ I -profile

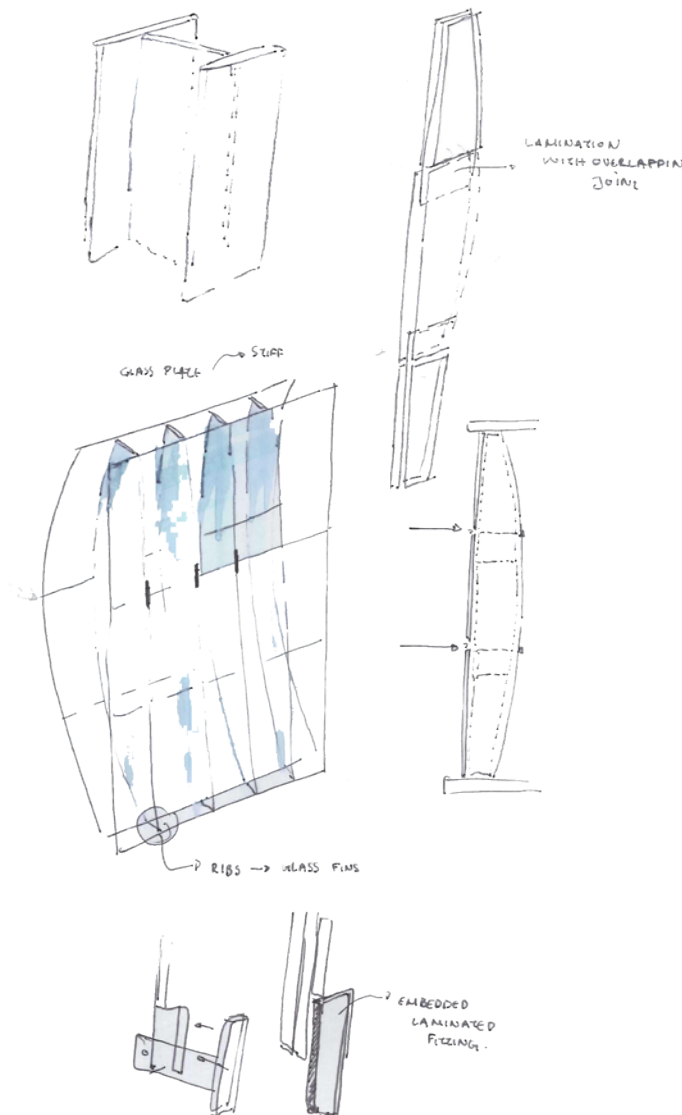


Fig.116_ Concept sketches of the glass-rib reinforced facade (I-profiles).

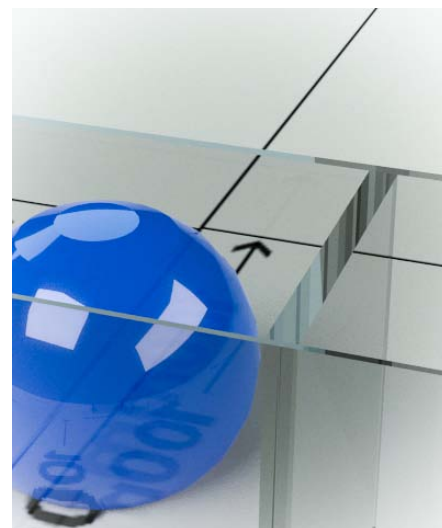
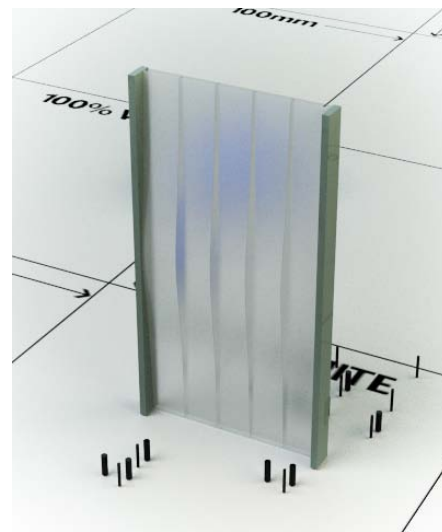


Fig.117_ Concept illustrations of the glass-rib reinforced facade (I-profiles).

The third category of concepts developed, belongs to the family of glass columns. Here the façade schemes developed are utilizing the structural benefits of the different cross sections like tubes and I-profiles to create the envelope. The individual columns assembled in series become the façade itself. In the first variation a façade based on the principle of the I-profile is created. The assembly of many I-profiles in a row translates into a scheme of ribbed plate which was introduced as method of stiffening plates in an earlier chapter.

Structural principle:

The glass I-profile is an effective geometry in compression, bending and buckling as it behaves in a similar way to the steel I-beams. Of course when assembled in a façade scheme it has to be explored further in terms of proportions of the panel. The individual column elements can take up better the bending stresses and can also transfer the dead load of the façade when assembled in stacking scheme.

4.1 / Concepts

02b Strategy bended / corrugated components - Glass curtain 2

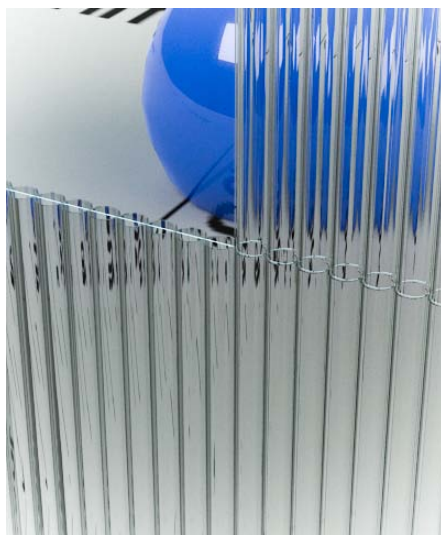
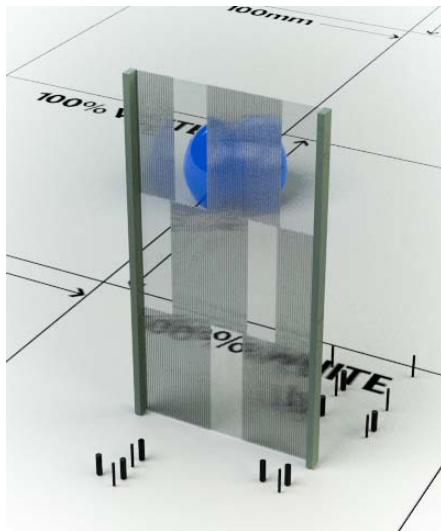


Fig.118_ Visualization of the glass column facade. Glass tubes are being stacked on top of each other.

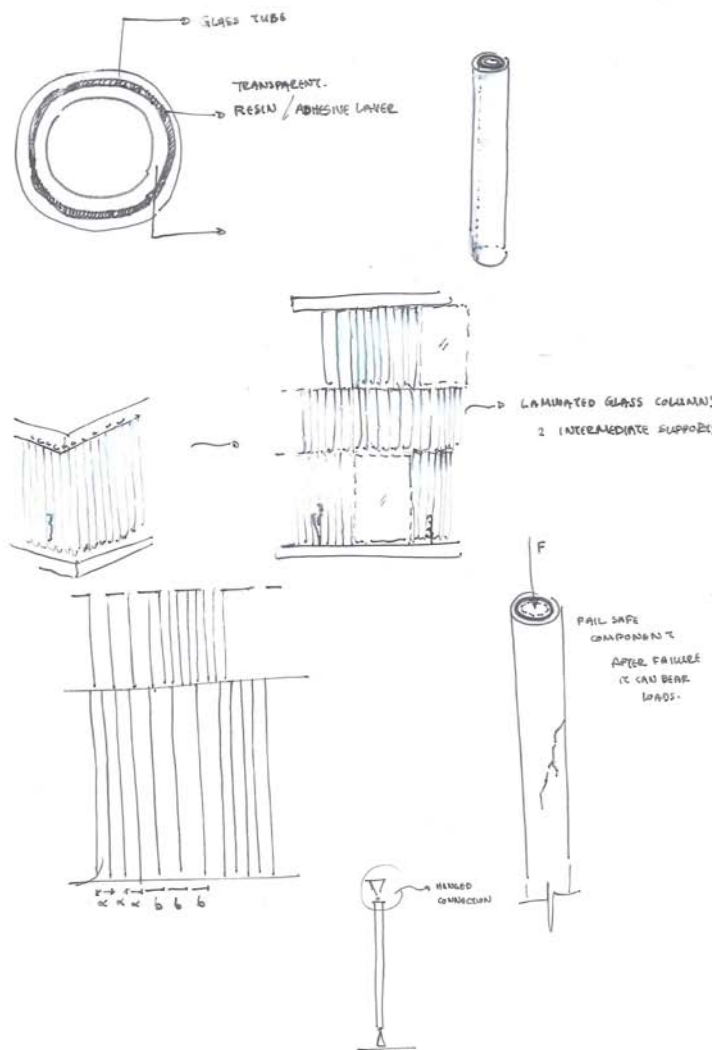


Fig.119_ Concept sketches of the glass column facade. Principles / Division / Connections / Impression.

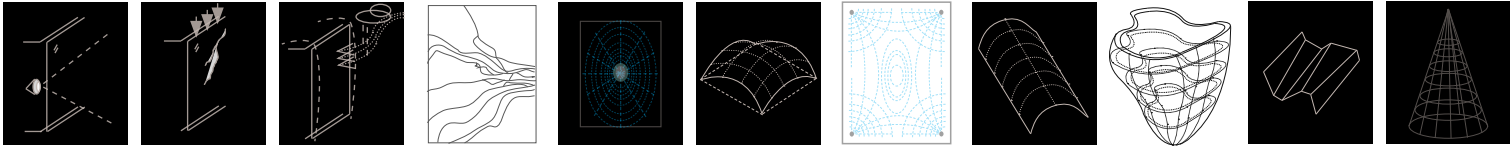
Structural principle:

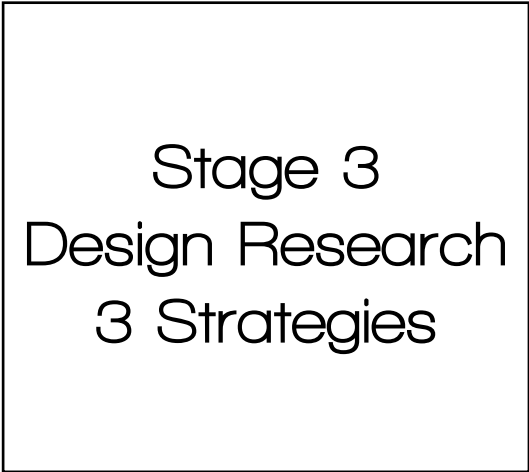
The glass tube is an effective geometry in compression, bending, buckling and torsion. Here the structural benefits of this shape are presented in a scheme where the façade assembled from glass tubes stacked on top of each other.

4.2 / Conclusions

In this part the brainstorming and visualization of several concepts made it even more obvious that there is a tremendous amount of choices and that the variations themselves can be developed into many more of the same families. Each one of them can be expressed in different sizes, different grid divisions, and different geometry shapes. Furthermore there can be sometimes a confusing perception between the primary component and geometry of the component used and the final image and geometry of the façade.

This can be very problematic especially in the case of the flat screen geometry and the I-profile cross section. In this case there is not a clear strategy followed for the structural and architectural design since the flat screen can be achieved from the individual flat components, but it can be also achieved from the I-profile. On the other hand I-profiles belong to the strategy of glass columns. There is a profound difficulty in categorizing the design according to the strategy because the strategies at this point were defined based on both, elements and appearance.



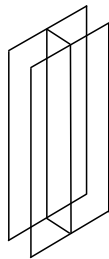


5 / 3 Design strategies

According to the aforementioned conclusions, the criteria for selecting strategies don't lead to clearly defined approach and this is because the criterion of appearance is sometimes intersecting with the criterion of primary component used for the system.

From the experience gained during this process it has been decided to base the design strategies primarily on the component with different primary geometries. In this case the 3 most promising were chosen to form the 3 strategies for developing the designs and structural systems. The strategies are:

1| A façade system with flat oversized glass laminates that employ the principles of the **I - profile glass column**.



2| A system that is based on the combination of **round laminated glass columns and the bundle of columns**.



3| Last but not least the system based on the benefits of **bend-ed glass sheets** (single - corrugated or double curved) .

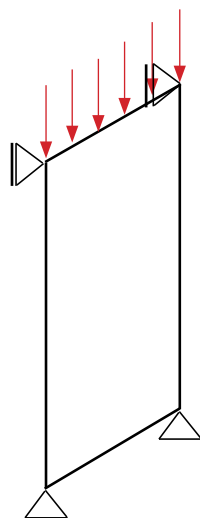


01 Structural design

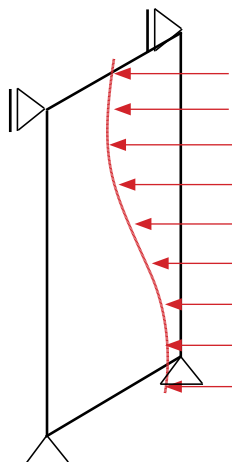
To justify the choices for the cross sections we have to first go through the loading actions on the façade. If we assume the façade as a flat glass plate the actions taking place on it are:

- 01_Dead load (in plane action) _Self weight (in plane action)
- 02_Wind load pressure and suction (out of plane action translated into in plane in the component)
- 03_Horizontal axial loads (in plane action)
- 04_Impact loads (out of plane translated into in plane)

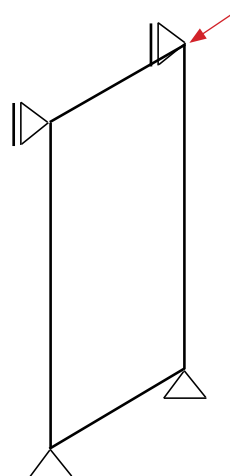
According to these actions there are several methods to follow for stiffening the plate geometry so as to be able to receive these loads. The important aspect is to always make sure that we reduce the impact of the tensile stresses introduced on the surface or the edges of the glass plane.



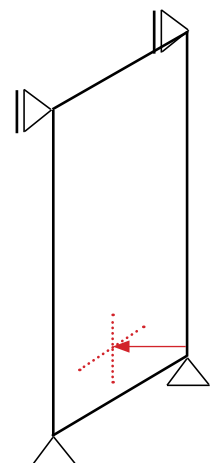
01
Dead load, self weight
Static - Long term load



02
Wind load, pressure or suction
Dynamic - short term load



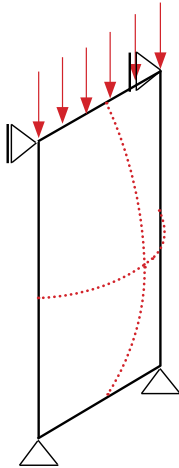
03
Horizontal in - plane load
Short term or long term load



04
Impact load
Short term load

5.1 / Common Features

Loading condition and effect

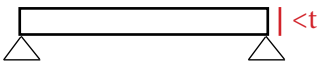


01 In the first case the dead load is posing an axial load evenly distributed on the edge of the plate causing it to local bending or buckling around the middle.



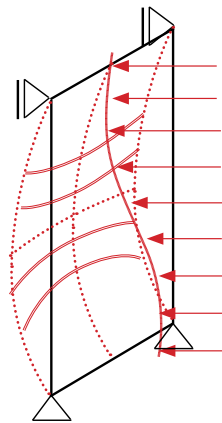
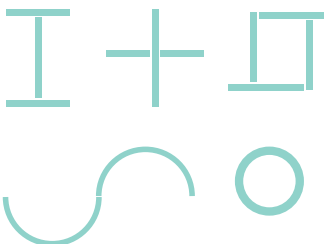
01

One solution in this case is to improve the thickness of plate and fix the ratio of span and thickness to avoid buckling.



02

The other solution is to use a different cross section like one with transverse elements or I - profile, tube, curved, cross etc.



02 In the second case the loading action of the wind is causing bending stresses that have a maximum in the middle when the support is linear at the top and the bottom of the element. The local stresses have a peak in the middle of the element and the edges (support).



01

The first solution in this case is to fix the ratio of the span and thickness of the plate but this leads to very inefficient use of glass.

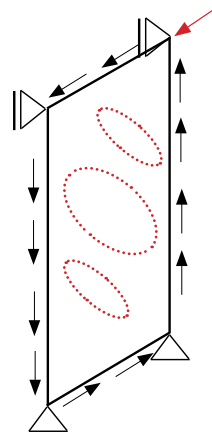
02

Select a stiffening method by adding transverse fin that acts as bracing and transforming the shape of the cross section into a more efficient scheme.



03

Here we can apply the principles of the I-profile known from the steel cross sections and the ribbed plate as an alternative that fits the proportion of a plate.

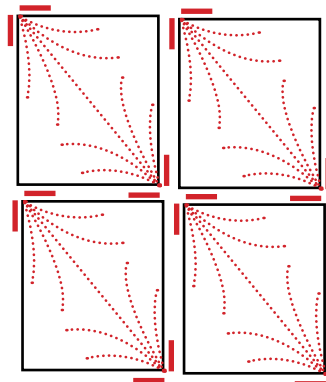


03 In the third case the horizontal axial load posed on a plate element locally when it is fixed linearly on all four sides it can cause shear buckling.



01

One solution is to transfer the load as bracing by the design of the connection. Elastic pads can be placed as setting blocks on the two opposite corners along the diagonal. These will transfer the load via contact by posing a compressive load on the edge of the component.



Solution / Stiffening method

The most important of the loading actions on the façade causing the unwanted tensile stresses in the glass is the wind. Therefore the scheme of the cross section if we want to activate the glass as structural element is the most important. The key aspect of this principle is also the aspect of symmetry.

To explain the choices of form and the use of I-profile principles we have to go through several strategies used from the theory on how to improve the flat glass components performance under loading that we face in the situation of a façade.

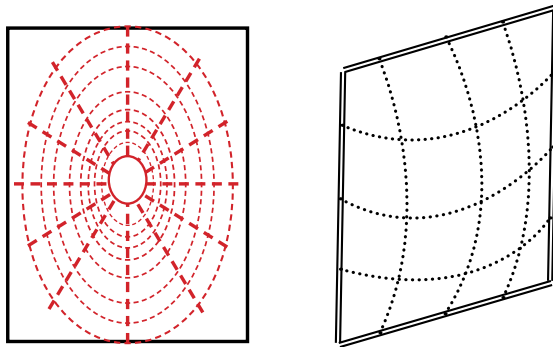


Fig.120_ Stress distribution & deformation on the surface of a glass panel linearly supported on 4 edges.

5.1 / Common features

In this phase of the research I proceed with these 3 systems as they are able to possess all three the following very important characteristics

01 Self-supporting skin

The first is the potential to create self-supporting glass units that are able to perform both as structural elements as well as envelope. This can be done with all three components as they are integrating both functions in their shape.

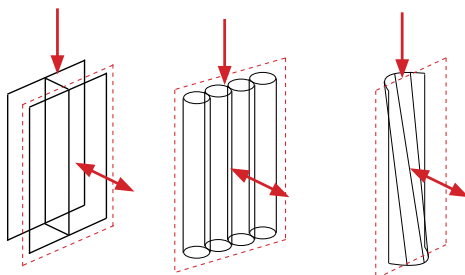
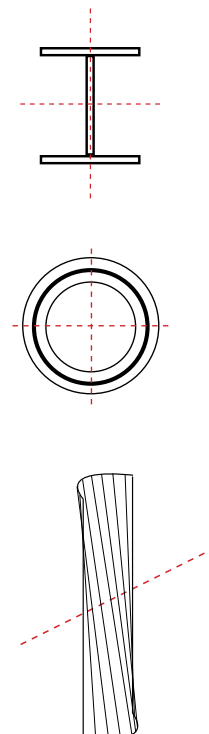


Fig.121_ Units being both structure and envelope.

02 Symmetry

The second very important feature is that all these three components have a symmetrical cross section and along at least one axis and therefore the load actions can be distributed evenly along the cross sectional area. This is compatible with the mechanical behaviour of the material as glass can perform better in even distribution of loads than on highly concentrated load actions.



5.1 / Common Features

03 Quality of joints

All three components offer the potential of creating seamless appearance and transparency for the connections, as the majority can be glued with the use of transparent adhesives. This increases the potential of achieving a frameless façade. Furthermore this can guarantee a faster installation time (less pieces to assemble etc.) and potentially better performance of the glass structure, since the quality will increase if components can be prefabricated in a scheme that integrates structure and skin instead of assembling the load bearing structure and the infill glass panels separately on site. Furthermore, since the integration of the skin and the loadbearing function the components created shouldn't include many on-site connections and should be manufactured as a rigid body in the factory under controlled quality conditions.

04 Homogeneous appearance

The symmetry is what brings also a homogeneous appearance for the façade, as it is able to deliver the same image from both sides. These characteristics can be found in all three strategies and it is the combination of these features that makes this research unique.



Fig.122_ Glass I-profile < Glass in Buildings, edition DETAIL practice >

05 Design versatility

The design versatility is another common characteristic of all three, as the variations in shape of the components can create multiple interesting and flexible design alternatives

06 Assembly in modules

The last but not least is that, since the design is based on a single component it can be developed in modules that will provide the final façade scheme. This allows greater degree of flexibility for the construction, as well as faster assembly times. On the other hand these units should be connected in a way so as to allow an overall cohesive performance of the plane of the façade.

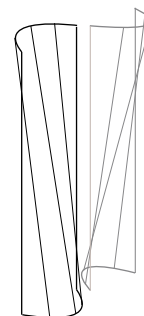
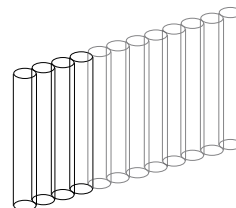
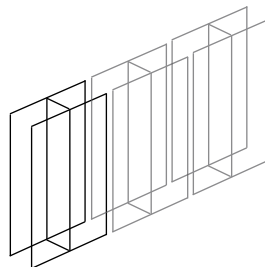


Fig.123_ Assembly in modules.

6 / Analysis of the 3 strategies

At this stage the three strategies are being analysed in detail focusing on the following aspects

- 01_ Primary geometry and form
- 02_ Structural benefits of single component and system
- 03_ Safety and post breaking behaviour
- 04_ Manufacturing and processing

These aspects for each strategy will be examined at both levels, that of the unit and that of the overall façade system. Then the proposed designs will be compared through the following filter of criteria that will determine in the next level which one of the three strategies can provide the most efficient structural design for the

- 01_ Feasibility of structure/ Structural performance
- 02_ Form & Design potential
- 03_ Type of connections
- 04_ Degree of transparency
- 05_ Manufacturing
- 06_ Insulation integration

This filter of criteria will determine in the end which of the 3 strategies is providing the most efficient structural design solution for the case study of the "La Fayette Modern".

6.1 / Analysis of the unit

To first check into the properties of each unit the most important aspect is the manufacturing process with the available sizes of the geometry of the components and at a next level the transportation. These two aspects are very much defining the size feasibility and also the overall costs for the facade design.

6.1.1 / I- profile units

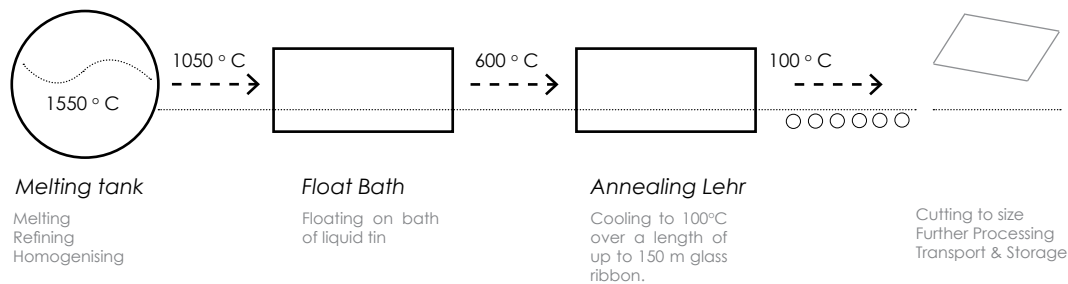
First the unit created out of I-profiles is consisted out of flat components assembled in a cross section. The units are principally a normal I – profile cross – section or a scheme of ribbed plate with different variations.

Primary production

The primary production followed is the one for creating float glass. The process invented by Sir Alastair Pilkington in 1952 is the most common for the production of flat glass.

The molten glass at a temperature of 1000 °C is poured while being still liquid on a bed of molten tin. The difference in density of the two materials creates a clear separation of the molecules of the glass from those of the tin in the interface between them. This leads to the production of a glass panel with two perfectly flush surfaces. One is resulting from the perfectly flat surface of the molten tin and the other, upper one, from the gravity that flattens the surface of the molten glass. Thickness is controlled by the speed at which solidifying glass ribbon is drawn off from the bath. By cooling the slowly moving ribbon of the molten glass it can solidify and basically allow for a continuous process with the ribbon cut in different panels.

6.1.1 / I- profile units



Production of oversized elements - Limitations

The standard manufacturing size of raw flat glass is 6m x 3.21m but nowadays we see more often customized production for oversized panels that exceed this size.

01 Limitations during raw production

Usually what limits the glasses length is not the production process, but the post processing machinery sizes as well as the overhead cranes that are used for stacking the glass from the cutting table to the storage. For larger panel sizes that can vary from 8-12 meters length the production is customized on demand and therefore the manufacturing costs are increasing. On the other hand the increasing demands from the architects for larger glass sizes has brought the manufacturing technologies closer to production of elements that can sometimes reach dimensions 4.2 x 25 m, that was produced in China.

02 Limitations in post processing - Tempering

Limitations can be posed also from the post-processing. The largest tempering oven size in Europe can temper glass sheets up to 8 m whereas in China the size can be a little bit bigger, up to 14m. The width is normally limited up to 2.7m but sometimes it can reach up to 3 m. Furthermore laminating autoclaves in glass facilities are also limited in size. The largest existing can laminate up 15x3 m and it belongs to company Seele Sedak < O' Callaghan, 2009 >.



Fig.124_ Oversized glass units. Photo courtesy of Seele Sedak GmbH.

6.1.1 / I- profile units

03 Limitations in post processing - Lamination

The company Seele Sedak is nowadays one of the pioneering in post –processing oversized components. Especially lamination process for custom oversized elements is one of the company's signature services. The glass sheets are being laminated in the gas-tight, sealable, pressurized autoclaves and the company claims to be able to laminate sizes up to 17m length < SEELE Sedak >.



Fig.125_ The largest lamination autoclaves. Photo courtesy of Seele Sedak GmbH.



Fig.126_ Vacuum Bag lamination in large autoclaves. Photo courtesy of Seele Sedak GmbH.

Splice lamination

Another way of creating oversized flat glass components, is by slice – lamination. The technique was developed and examined further in the project of the Apple cube 1.0. In this project the concept of creating glass fins that exceed the standard 6m raw size led to the development of slice –lamination. This meant constructing 10m high fins with slices of 6m long, by offsetting each panel from its adjacent laminate, similar in effect to the way plywood is made < O'Callaghan, 2009>. The segmentation scheme can be either symmetric, with coinciding beams, or asymmetric, with staggered seams < Louter, 2011>.

One of the main challenges with this technique occurs in the size of the lamination autoclaves. The process must be done in an autoclave that has the total size of the final length of the assembled slices. According to precedents there is no autoclave that can provide lamination for such elements, like the ones necessary for the Apple cube (10m) or for the case of the La Fayette modern (20m), in the glass industry. However it has been realized with autoclaves from the aircraft industry < O'Callaghan, 2009>. The size of these autoclaves is available from 10m minimum length. Furthermore the largest so far glass element produced with this technique is a glass beam of 21m long that was produced by Glass Trösch in Switzerland and was exhibited at the Glasstec 2010 fair in Düsseldorf.

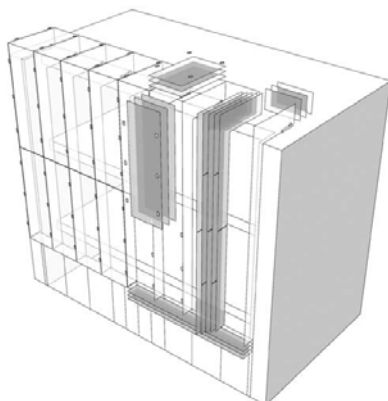


Fig.127_ Slice laminated glass fins, for the facade of the Apple store in Sydney. < O' Callaghan, 2009 >

³ Plywood is a manufactured wood panel made from thin sheets of wood veneer. Plywood layers (called veneers) are glued together, with adjacent plies having their wood grain at right angles to each other, to form a composite material.

6.11 / I- profile units

Technical information SEELE Sedak on lamination
Autoclave 1: max. 4,500 x 17,000mm; 14'-9" x 55'-9" Autoclave 2: max. 3,285 x 15,000mm; 10'-9" x 49'-2" Autoclave 3: max. 2,800 x 12,500mm; 9'-2" x 41'-0" Autoclave 4: max. 600 x 1,500mm; 1'-11" x 4'-11"
Lamination interlayers: SG®/PVB/TPU/EVA
Intermediate materials used: Sefar fabrics, Southwall XIR-interlayer and more
Special laminations: Lamination of metal parts, wood, screens and other materials within glass units.



Fig.128,129,130_ Lamination with Sentry Glas. Laying the interlayers and aligning the holes. Photo courtesy of Seele Sedak GmbH.

6.1.2 / Curved units

The second strategy is based on the façade produced out of curved components. The curved components are supposed to be developed in approximately 4 double curved units vertically that all together complete the scheme of one unit.

Primary production

The second strategy is based on the façade produced out of curved components. The curved components are supposed to be developed in approximately 4 double curved units vertically that all together complete the scheme of one unit.

The primary production of the curved units is that of simple float glass at first. Then the flat sheet has to be formed into shape to obtain the desired curvature. The method of forming to be followed is depending on the shape and of the component and the degree of the curvature. It also depends on the type of geometry we want to achieve, meaning single or double curved.

Forming processes & challenges

There are two main processes followed to produce bended glass sheets and the choice is more or less defining the properties of the element:

01a Hot Bending process / Size limitations

Curved annealed glass is manufactured by slowly heating flat glass up to the softening temperature (**720 °C** for SLSG, IABSE). When the flat panel starts slumping by gravity, it is taking its curved shape on the customized mould. Once the geometry is achieved a slow cooling process follows known as "annealing". Curved glass can be also produced tempered and heat strengthened. The shape can vary from single curves to compound curves (sphere, corrugated, twisting shapes etc.). Finally the maximum height and of the panels produced with hot bending process can reach approximately 6 m height due to manufacturing and transportation limitation < R. Nijse 2009 >. Most of the examples that have shown the limitations in production come from the corrugated glass facades. Until now the maximum panel size used is 5.6m high for the facades of the University of Doha in Qatar (project under construction) < R. Nijse 2009 >.



Fig.131

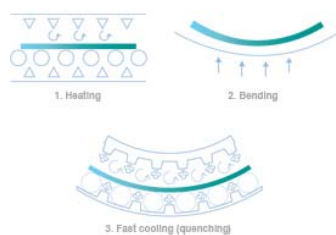


Fig.131,132_ Hot bending process / Hot bending and tempering simultaneously < www.cricursa.com >

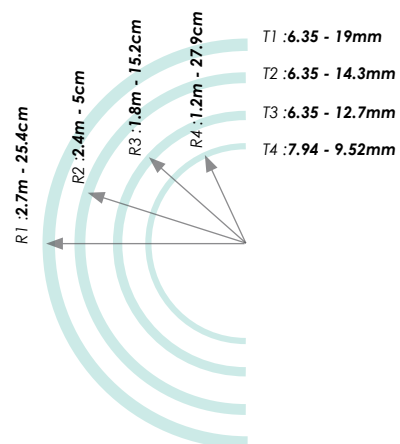


Fig.133_ Maximum & Minimum Radii in the hot bending process. < Courtesy of Seele Sedak >

6.1.2 / Curved units

01b Hot Bending process / Shape & cost limitations

The architectural necessities for more complicated freely formed glass shapes have brought up the issue of manufacturing difficulties as well as the increasing price due to the variation and the small series to be produced.

The current production technique of such panes necessitates the making of ceramic or steel mould, by milling or by forging into shape (hammering, pressing) with much manual labour <Karel Volders GPD 2007>. Despite the fact that the current technique offers especially by milling, high geometrical accuracy, the manufacturing, transportation and storage of such moulds are costly because of the constant risk of breakage.

A solution to reduce the costs is to utilize the new developed technologies for reusable and adjustable moulds to match each time the uniqueness of the shape.

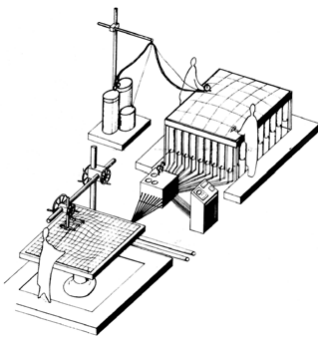


Fig.134_ Mould for producing shell structures, connected to matrix, by Renzo Piano, 1966 < Karel Volders, GPD 2007 >

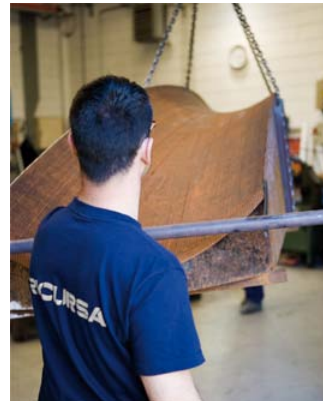


Fig.135_ Custom made steel mould for hot bending < www.cricursa.com >

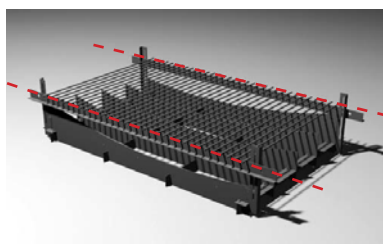
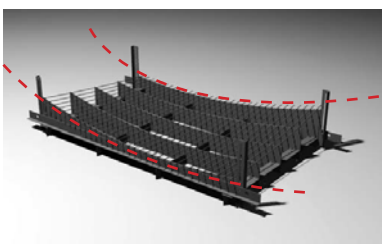


Fig.136,137_ Adjustable mould No.1 with rods < Karel Volders, GPD 2007 >

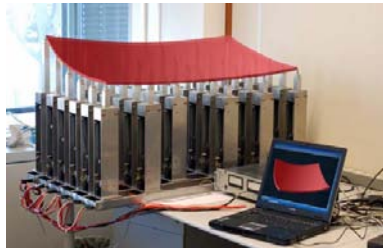
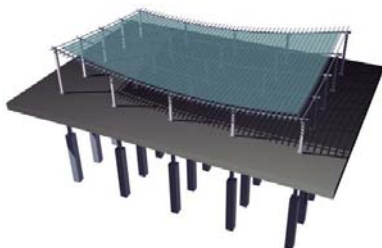


Fig.138,139_ Adjustable mould No.2 /Computer steered working mould with freely curved working surface < Karel Volders, GPD 2007 >

6.1.2 / Curved units

02a Cold Bending process

The cold bending process is a more recent development than the hot bending process for producing curved façade elements. In this process the flat sheet of glass is bent into a curtain curvature at ambient temperature (the process is being analyzed in Stage 1).

02b Cold bending / Costs and limitations

This alternative process appears to be cheaper to the warm bending process, where the glass piece has to be heated up beyond its softening point in order to obtain the new shape in the mould.

The difference is that here the interlayer used during the lamination is responsible for keeping the element into shape or the connections used to fix the element into shape in-situ on a subframe. Therefore the method can be considered also cheaper. "Sometimes we see like in the case of the Strasbourg TGV station that the elements are bent before lamination to achieve tighter radii to match the architectural geometry" < [Nicollo Baldassini, GPD 2009](#) >. This statement implies the limitations in shaping and curvature of the chosen technique. Also the method is still under development and studies concerning the true strength and allowable curvature of the panels as well as the dependence on the properties of the adhesive layer < [Zhaohong Lu, Mauro Overend](#) >.

Choice for

"The decision to opt for cold-bending or hot-bending really depends on the specifications of the individual project. If the glass is not intended for overhead walk-on areas or if soft coatings are not essential, then it is possible not only to create larger radii for facade structures using hot-bent glass – more or less regardless of thickness – but also any shapes whatsoever, including totally amorphous ones." < [SEELE SEDAK, 2012](#) >.

The choice is also made according to mechanical properties of the component after processing which will be analyzed in later stage.

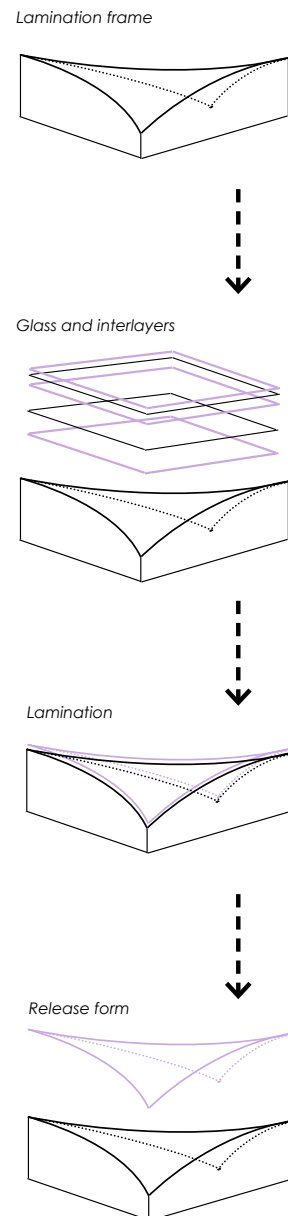


Fig.140_ Process of shape enhancing lamination with cold bending.

6.13 / Tube units

The final unit to be analyzed is the one assembled from tube components. The glass tube is an element that has been used in many other applications but very far from the scale of structural elements in pharmaceutical industry, in chemical industry for laboratory tests, in optical fibers, in lighting etc. The closest application so far close to the architectural scale application is that for interior decoration. The most common glass type used for the production of tubing is high quality Borosilicate glass which is also more expensive than simple Soda Lime glass.

In the case of the glass facade design the tubes are functioning in units of single row of tubes or bundles of three layers.

Primary production

There are two primary production processes for tubing:

01 Danner Process

The most common production method for tubing is the Danner process that was invented by an American engineer named Edward Danner in 1912. In this process the molten glass falls onto a rotating, slightly downward pointing mandrel. Air is blown down a shaft through the middle of the mandrel by a tractor mechanism. The diameter and thickness of the glass tubes can be modified by regulating the strength of the air flow through the mandrel and the speed of the drawing machine. The maximum allowable wall thicknesses by this process are only up to 10mm < Structural use of glass, IABSE 2008 >.

02 Centrifuging process

The latest developed process for the production of tubing allows for larger cross sections but is more expensive. During the centrifuging process the molten glass is poured into a steel mould that rotates at a certain speed. "At high speeds the glass can achieve almost cylindrical shapes and after has cooled down sufficiently the rotation stops and the glass is being removed from the mould" < Structural use of glass, IABSE 2008 >.

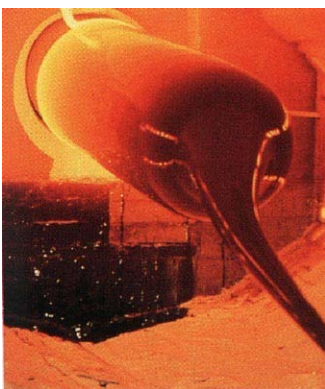


Fig.141_ Danner process for glass tubing production.



Fig.142_ Borosilicate tubes produced with the centrifuging process

6.1.3 / Tube units

Production of tubes as structural elements

The company Schott was the first one to provide tubing for architectural and structural use that was first applied in the experimental case of the laminated glass columns, developed by F.Veer and Pastunink. "The columns in the experimental case were developed by 2 concentric tubes laminated together with two part UV curing epoxy resin" < F.A. Veer, GPD 2005 >. The process for the production of the laminated glass column was improved up to a level where the adhesive wouldn't create problems of shrinking or bubbles during the curing process. The quality of the lamination process was regulated by controlling the speed that the adhesive is poured in the cavity between the tubes.

The result is an element that is able to perform as structural glass column with a safe failure behavior as the adhesive used can slow down the crack growth.

Production limitations & costs

The limitations coming from the production of the tube components is the standard size that at the moment is available at 1500mm length produced by company Schott. The company Schott claims that in the Duran Tubing series there is a possibility however to produce special lengths between 1000 – 10.000 mm on request. This of course is something that can increase the costs enormously. As already mentioned the available wall thickness and diameter of the tube is also limited reaching only up to 420mm diameter and 10mm wall thickness. Another problem occurring is that these dimensions for diameter can bring tolerances up to +5 mm, which is a fact already mentioned in the difficulties of the manufacturing method used, that only approximates the cylindrical shape. So, the larger the diameter, the higher the tolerances. < Schott GmbH, Duran Series >

Until now there are a few examples of application especially for interior wall use. The one is a building designed by Spanish architects Arquía - Caja in Bilbao and the other from Foster + Partners in London. In both cases the application is focused on the interior and the height of the tube construction does not exceed the 2 storeys height.



Fig.143, 144, 145_ The Walbrook project by Foster + Partners in London UK. Interior views of the wall division made out of glass tubes.

6.13 / Tube units

Tubing Sizes for the Schott Duran series

Outside Diameter		Wall Thickness		Weight per Tube Length approx. 1500mm		Carton Contents		Pallet Load	
 mm		 mm		 g		 Number of Tubes Weight approx. kg		 Number of cartons Weight approx. kg	
190	±2.10	5.0	±0.50	9 716		1	9.7	20	194.0
		7.0	±0.80	13 455		1	13.5	20	270.0
200	±2.40	5.0	±0.80	10 241		1	10.2	20	204.0
		7.0	±1.00	14 190		1	14.2	20	284.0
		9.0	±1.20	18 055		1	18.1	20	362.0
215	±2.50	7.0	±1.10	15 293		1	15.3	9	137.7
		9.0	±1.20	19 473		1	19.5	9	175.5
225	±2.70	7.0	±1.10	16 028		1	16.0	9	144.0
		9.0	±1.30	20 418		1	20.4	9	183.6
240	±2.90	9.0	±1.30	21 836		1	21.8	9	196.2
250	±3.00	5.0	±0.80	12 867		1	12.9	9	116.1
		7.0	±1.10	17 866		1	17.9	9	161.1
		9.0	±1.30	22 782		1	22.8	9	205.2
270	±3.00	5.0	±0.80	13 917		1	13.9	9	125.1
		7.0	±1.10	19 337		1	19.3	9	173.7
		9.0	±1.30	24 672		1	24.7	9	222.3
300	±3.80	5.0	±0.80	15 492		1	15.5	9	139.5
		7.0	±1.20	21 542		1	21.5	9	193.5
		9.0	±1.40	27 508		1	27.5	9	247.5
315	±3.90	7.0	±1.20	22 645		1	22.6	9	203.4
		9.0	±1.40	28 926		1	28.9	9	260.1
325	±4.00	9.0	±1.40	29 871		1	29.9	4	119.6
		10.0	±1.40	33 085		1	33.0	9	297.0
350	±4.00	5.0	±0.80	18 118		1	18.1	4	72.4
365	±4.50	7.0	±1.40	26 321		1	26.3	4	105.2
400	±5.00	6.0	±1.50	24 829		1	24.8	4	99.2
415	±5.00	7.0	±1.50	29 997		1	30.0	4	120.0
420	±5.00	10.0	±2.00	43 063		1	43.1	4	172.4

Table.146_ Dimensions for tubing from the series Duran borosilicate tubes. < Schott Duran >

6.1.4/ Transportation & Installation

Logistics for oversized glass units

Logistics could be another limitation or challenge for all the oversized components that will compose the facade. In the present state for the flat the components the company Seele is the only pioneering in this field since it possesses the knowledge and experience from the manufacturing and transportation of such components for the Apple Inc. retail stores that take advantage of the oversized glass elements.

It is a fact that the logistics might be even more challenging than the production itself. The fragile components should reach safely and in perfect condition their destination. The logistics are organized by the company that uses special suction lifters produced in-house, as well as rigid protective frames that secure the sheets during the transportation and also prevent them from flexing. The company is also responsible for planning the transportation routes whether these are overland, by sea or in the air.

Of course the logistics that are custom organized for such projects can be always an aspect of increasing the costs. On the other hand one should look at the available sizes of standard shipping containers in the market. So far it appears that the largest size available can have length up to 45'/ 13.716 m.

This means that in the case of the design strategy with the oversized flat elements the largest piece cannot exceed the dimension of 13m. The width limitation is predefined from the manufacturing process and as such it fits in the standard size container.

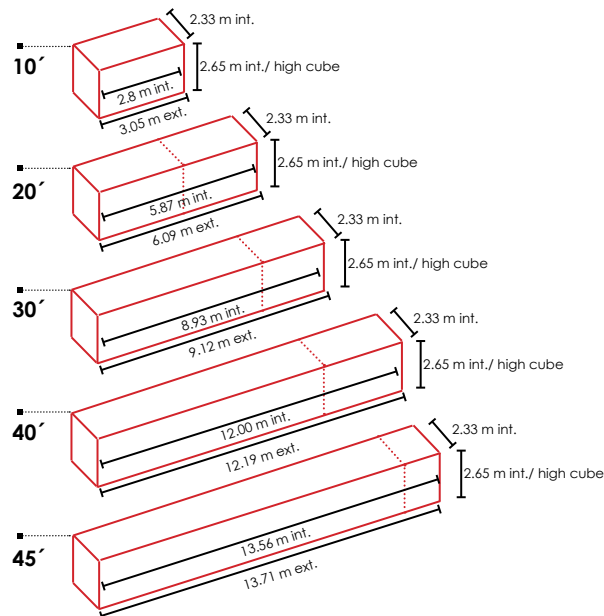


Fig.147_ Standard sizes of shipping containers.

Fig.148,149,150_ Photos of Seele containers and transportation process of oversized elements. < Courtesy of Seele Sedak >



Fig.148



Fig.149

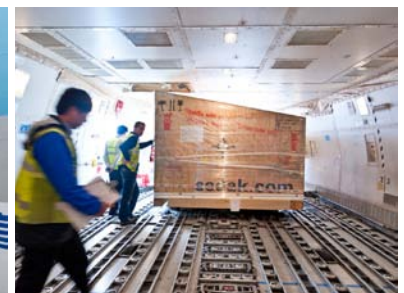
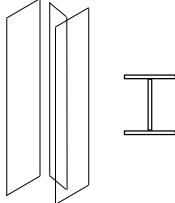
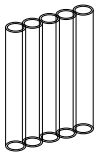
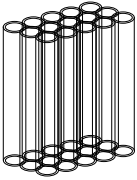
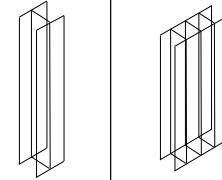


Fig.150

6.1.5/ Summary table of unit evaluation

Geometry					
Primary shape	 Hollow tubes		 Bended surface		 Flat sheet
Unit scheme	 Single row	 Bundle	 Single curved	 Double curved	 I-profile Ribbed plate
Manufacturing					
Process	Danner process	Centrifuging process	Hot Bending	Cold Bending	Float glass
Max. Raw size	--	standard 1500mm SCHOTT -10000mm	6000mm length	size of flat panel depending on radius	approx. 25000mm
Max. Processing size			6000mm length		8000mm in Europe 15000mm in China
Min. Radius /Diameter	10mm	10mm	++	+	
Max. lamination size	--	+	every size produced	every size produced	15000mm in glass industry 23500mm in aircraft autoclave
Max. Realized size		unknown	5600m length		14000m
Tolerances		-- (+5)	- (+2mm)(depends on the complexity and size)	+	++ (for oversized (+1mm/m))
Costs	+	--	-- custom mould + adjustable mould	+	++ (for oversized)
Logistics					
Feasibility	+	+	+	+	++ (depending on producer)
Costs	+	+	--	- (for pre-bent)	++ (for oversized)
Safety					
Lamination		+	+	++	++
Tempering or Heat strengthening		+(size limitation)	++	++	++

++	Very feasible/ Very high
+	feasible/ high
-	less feasible/ not so high
--	Limited

Table.151_ Overview of the unit properties in terms of feasibility.

6.1.6 / Conclusions

As a result on this research on the units we can see was it is feasible and suitable for the geometries in terms or manufacturing. We can generally see that most of the units are feasible to construct with the available manufacturing methods and the sizes available in the market allow for relatively oversized components. Certainly the flat units used for the strategy 1 with I – profiles are presenting the greatest flexibility maximizing the potential for transparency. The curved units are next in terms of size and the hot bending method seems to be the method for allowing greater flexibility in shape and curves if the component does not apply for overhead glazing. Hot bending offers the widest range in curvature intensity but the costs can be relatively high due to the degree of customization and labour compared to the cold bending method. Finally the tubes appear to be the least developed in manufacturing potential shape of all. The standard size is very limited but there are a few examples that show potential of higher range of length but with a relatively high price. Ultimately all three units possess a good degree of feasibility that can be utilized further for the design of the façade system.

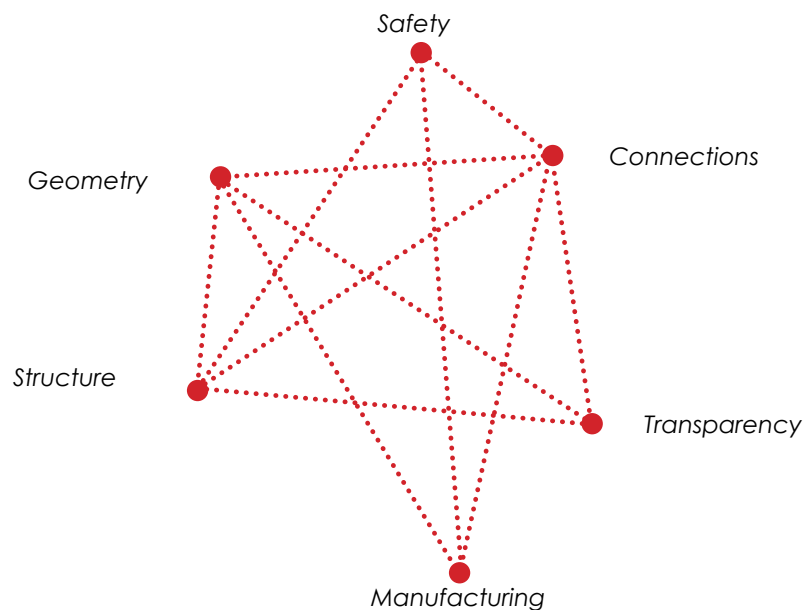


Fig.152_ Diagram showing the relations scheme between the different design parameters of the façade.

However when one wants to evaluate the complete façade systems, designed with the three types of units, the evaluation process can be much more complicated, and the selection becomes even more difficult. From the literature study and the study on precedents there are several observations done, concerning the relationship between the different parameters that affect the structural design with glass.

Fig.153_ Analytical Diagram showing the relations between the different design parameters of the façade.

6.2/ Analysis of facade design systems

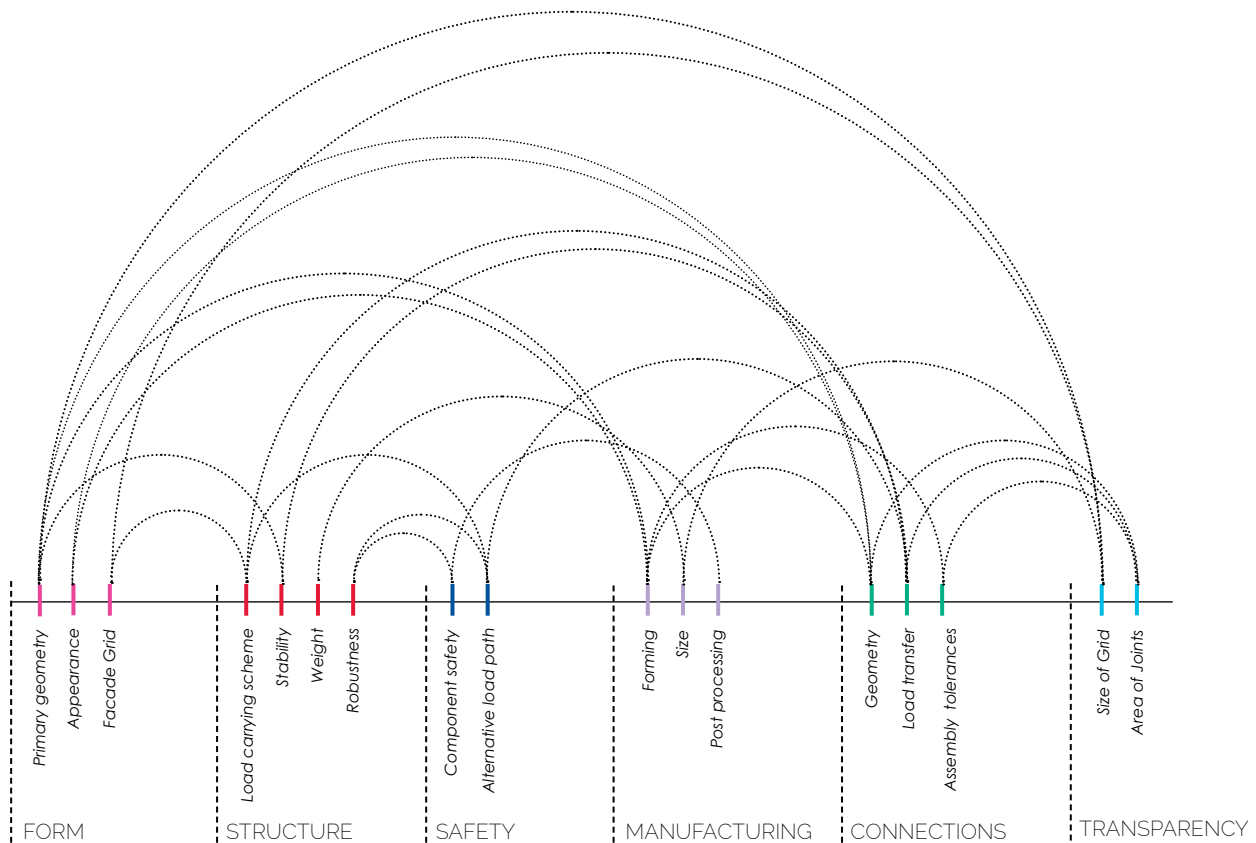


Fig.153

STRUCTURE

The first parameter which is the **structure** (meaning the structural feasibility) depends on the geometry of the scheme, the type and quality of joints, that influence the transfer of forces, the assembly process and finally influences the overall safety scheme and overall stability of the façade.

CONNECTIONS

The **connections** depend on the geometry of the component the load transfer they have to accommodate, the safety scheme with the alternative load paths, the maintenance plan and the assembly plan, the manufacturing processes and can influence the appearance and the general performance of the façade – as structure and as envelope.

FORM

The parameter of **design form** depends on the geometry chosen for the unit which can influence the degree of variation in the design, it depends also on the available manufacturing sizes that allow for dense or wide grid, the assembly pattern, the joint type.

MANUFACTURING

The **manufacturing processes** available can influence almost the 90% percent of the other design parameters like the overall quality and properties of the structure, the geometry feasibility, the joints, and the appearance with the optical quality of the different components.

TRANSPARENCY

The degree of **transparency** depends on the type of joints (larger or smaller), the geometry chosen that allows for larger or smaller grid and higher or lower distortion, the structural scheme overall that suggests the number of supports, the size of the components and the façade division.

SAFETY

Finally the **safety** of the structure depends on the chosen structural scheme and above all the type of glass provided by a certain process(annealed, heat strengthened or fully tempered and laminated) as well as the design of the joints that provide the alternative load paths to ensure a post breaking stability of the façade.

6.2 / Analysis of facade design systems

We can tell from the figure below that there are so many interrelations between the design parameters that lead to a very complicated design process. At this point in order to select appropriate systems to develop in each design strategy a more simplified method of cascading selection is chosen. This means that at this step the feedback for each step is skipped and the selection is moving forward to end up with a final system. The choice starts from the form finding and the geometry and next the façade division options follow. Finally the structure and safety scheme is chosen with the appropriate joints to complete the system. Sometimes more than one options can occur in each strategy.

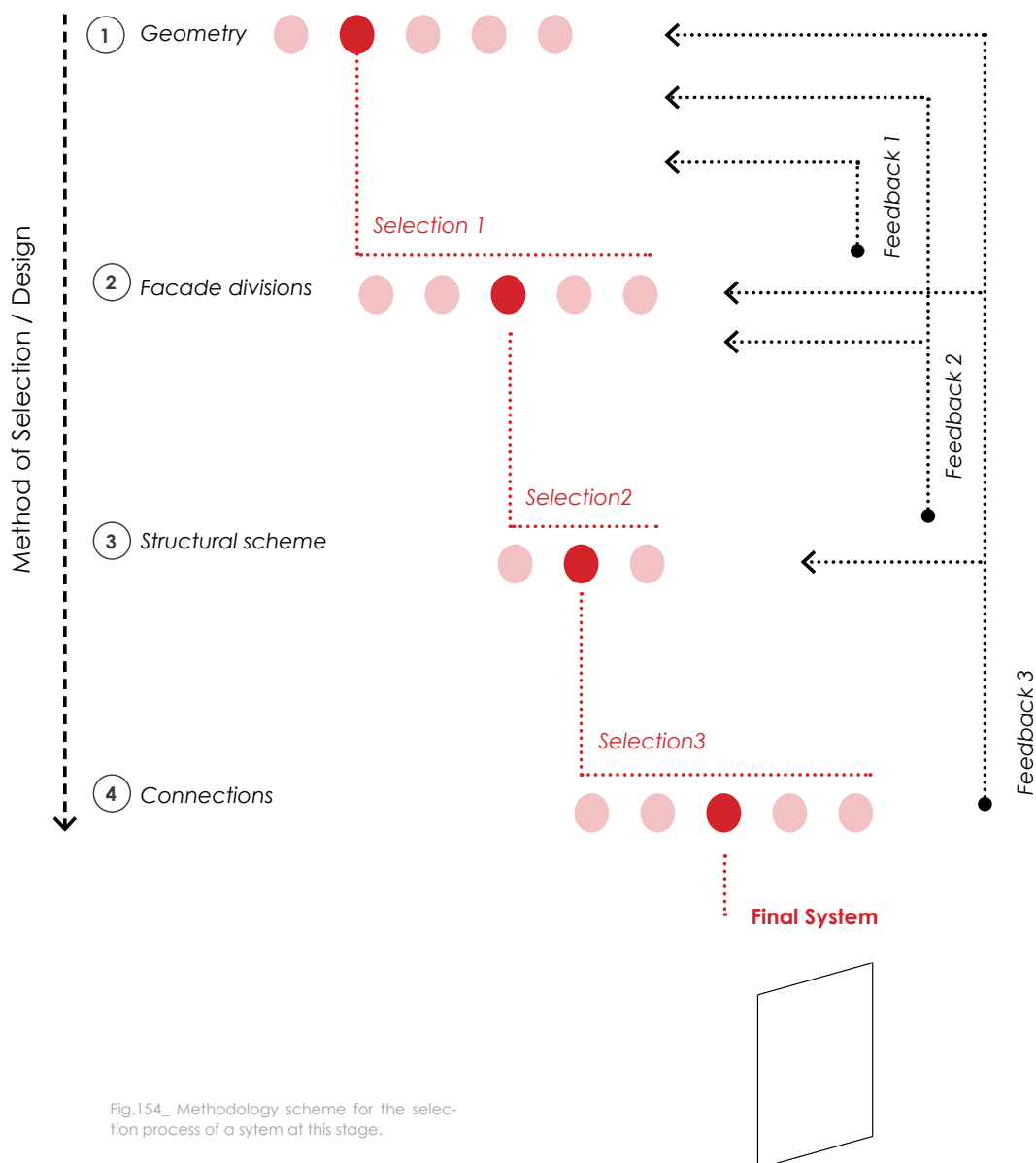


Fig.154_ Methodology scheme for the selection process of a system at this stage.

6.2.1 / Design Strategy 1 - Flat screen (I-Profile)

In the first strategy there is an attempt to bring the image of a transparent flat screen to the façade. As it is already mentioned from studies undertaken in TU Delft on I – profile glass columns it has been proven that they can act in a similar way as in a steel cross section. Therefore they can become an element that performs very well under compressive axial load preventing from buckling and torsion or under wind load preventing from bending deformation.

01 Form finding

The next step is to optimize the cross section so as to achieve interesting design and structural performance. A series of potential unit form studies can explain the differences on the different variants of this cross section for the façade.

01

A first standard approach is to create a larger thickness for the glass by building it up in layers using a stiff intermediate ionoplast layer like SGP.

03

Next option is the one of the I-profile. In this case we have more even distribution of the material along the cross sectional area. It is symmetrical and minimizes the deflection caused by the wind loads following the principles of the transverse element.

05

The evolution of the previous scheme and a cross section that is closer to the standards of the plate unit is the two plates with two ribs in between. In this case we have better distribution of the loads.

02

The second is to increase the thickness locally by attaching a transverse glass fin that acts as bracing which is the standard form of cross section used until now. T-shape

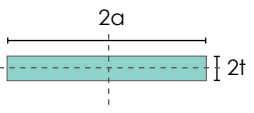
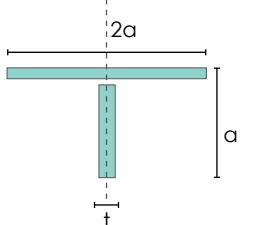
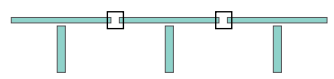
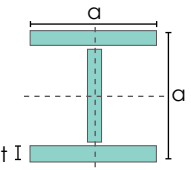
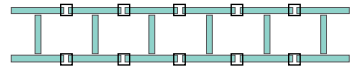
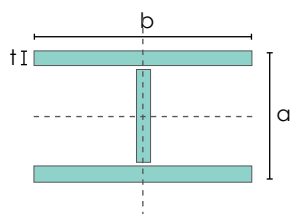
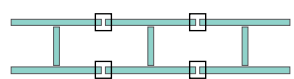
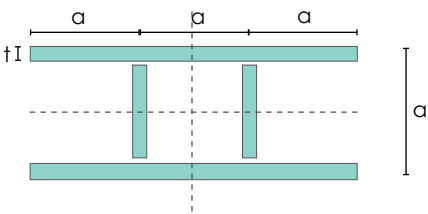
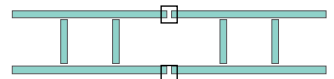
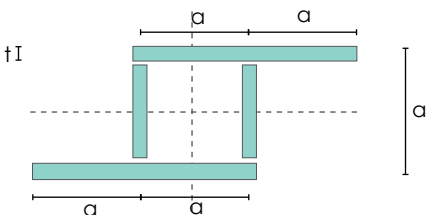
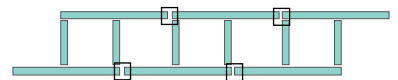
04

The next cross section is an I-profile with The two flanges protruding more from each side so as to help creating a stiff plate scheme. Here though we face the problem of large cantilevering parts from the two sides of the cross section that will cause high stress concentration in the zone close to the transverse element.

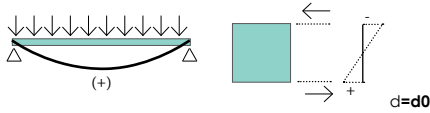
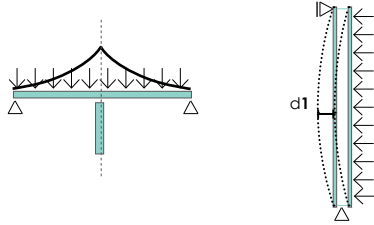
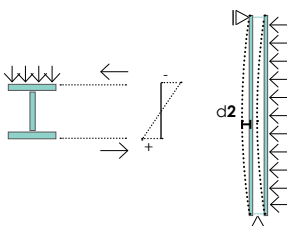
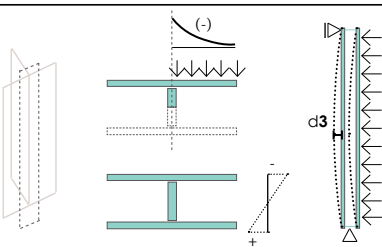
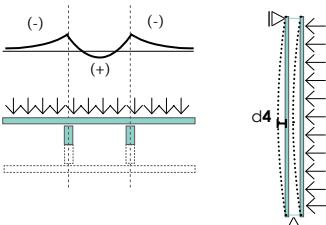
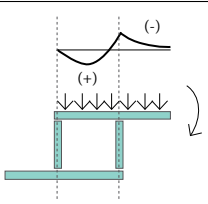
06

The last case is repeating the last scheme but here we have two open ends so as to help to differentiate the scheme of the assembly.

6.2.1 / Design Strategy 1 - Flat screen (I-Profile)

	Form / shape	Symmetrical	Assembly mode
Thick plate		YES	
T - shape		NO (one axis)	
I - profile		YES	
Wide I - profile		YES	
Ribbed plate		YES	
Ribbed plate 2 open edges		NO (assymetry in both axes)	

6.2.1 / Design Strategy 1 - Flat screen (I-Profile)

Load Distribution	Advantage	Disadvantage
 (+) $d=d_0$	Transverse elements not present and therefore transparency levels can be higher.	Non feasible for stability Inefficient use of material
 d_1	Fins act as bracing. Scheme for efficient use of material.	Asymmetrical cross section Standard solution
 d_2	Even distribution of the loads. Efficient distribution of material. Symmetrical appearance.	Small cross section in width is going to bring to many joints on the facade.
 d_3	Larger parallel flanges - Wider grid without many joints Symmetry	Large cantilever part - High bending stresses around the transverse element.
 d_4	Better performance in bending More even distribution of load less deflection - ribbed scheme Wider grid	The width and the thickness has to be optimized to achieve efficient use of material. More transparent joints might appear from the transverse elements.
 (+)	More interesting scheme for assembly Joints don't align in the same level	Prone to torsion Uneven load distribution because of the asymmetry
$d_0 > d_1 > d_2 = d_3 > d_4$ Deflection comparison		

6.2.1 / Design Strategy 1 - Flat screen (I-Profile)

After analyzing the different patterns of unit the choice is to continue with the pattern that is based on the ribbed plate. The reason is as it was already analyzed on the table that it is a cross section that could work on the level of a façade scheme because of the proportions. The ribbed plate is also a unit scheme that combines a wider surface so as to open the façade grid more than we could do if using the literal scheme of the I-profile. Deriving from this we can assume that the opaque joints on the façade will be less allowing for higher transparency.

02 Façade divisions

Based on the manufacturing potential of the flat elements provided by the glass industry and other transportation limitations we can end up with the conclusion that the façade assembled from flat pieces can be almost constructed out of units of the 20m high. But due to logistics and assembly limitations we can go for also more flexible grid. The possibilities for grid division here would be almost endless. The only limitation we can assume is the width that is limited to the size of approximately 2.7m. The façade overall dimension is 7.7x 20m and on that are based the divisions presented in table at opposite page.

After presenting the potential façade divisions we can see that the divisions get influenced from the aspects of manufacturing limitations, logistics and assembly limitations and the choice of one will influence the appearance of the façade the transparency levels, because of the different joints appearing on the surface and the costs due to the size selected.

As it is presented in the table we can clearly see the advantages and disadvantages of each one and we can acknowledge the fact that the possibilities are endless and only a few are presented in this research. The choice is to move further with the most challenging but at the same time feasible option which is the second façade division in the category of even grid. This solution is the only from the feasible that can provide the highest transparency level, given the amount of joints and at the same time a feasible unit size that can be repeated with the same size every time. The assembly can still be a challenge but it will be analyzed in further chapter.

6.2.1 / Design Strategy 1 - Flat screen (I-Profile)

Even Grid				
	01	02	03	04
	01 _ Extreme solution. _ Manufacturing limits _ Difficult logistics Non _ Feasible	02 _ 2 Pieces _ High transparency _ Feasible assembly /logistics Feasible	03 _ Medium transparency _ Feasible assembly /logistics _ Non economical size Feasible	04 _ Low transparency _ Feasible assembly /logistics _ Economical panel size Feasible
Uneven Grid				
	01	02	03	04
	01 _ Entrance indication _ Extreme solution. Non _ Feasible	02 _ Uneven grid _ Assembly / logistics challenge Feasible	03 _ Random grid _ Many custom pieces _ Uneconomical solution Feasible	04 _ Random grid _ Many custom pieces _ Lower transparency levels Feasible

6.2.1 / Design Strategy 1 - Flat screen (I-Profile)

03 Structural Design / Failure mode

The structural concept scheme chosen for this strategy is to carry the dead load of the top elements in stacking by the bottom element activating, in this way the benefits of the ribbed plate cross section and the compressive strength of the material. Another advantage coming from the self-supporting geometry is the fact that we can avoid vertical substructure like cables that carry the elements in tension from the top. Also the adequate depth of the cross section shows that the action of the vertical joints between the panels is also reduced allowing us for minimizing their size and use a more flexible material like structural silicon.

The bending action due to the wind load on the surface of the façade will be counteracted by the cross section. The factors that can contribute to the performance of the cross section against the wind loads is the axis of centroid*, the thickness of the glass flanges and the depth of the ribs. The risk here is the stresses developed to create problems at the middle horizontal joint forcing it to act as a hinge. This joint has to act as firm connection that is completely rigid and doesn't allow for translation or rotation in the x, y or z axis.

Last but not least the robustness in failure of one of the bottom panels will be ensured first by the build up of the panel. This at the level of the unit will make sure that the interlayer of the laminated component will slow down the cracks and will keep the shards together so as to have a certain residual load bearing capacity. The horizontal joint and the cross joint should make sure that the loads of the top element will be redirected to the neighboring glass units at the bottom until the element is replaced.

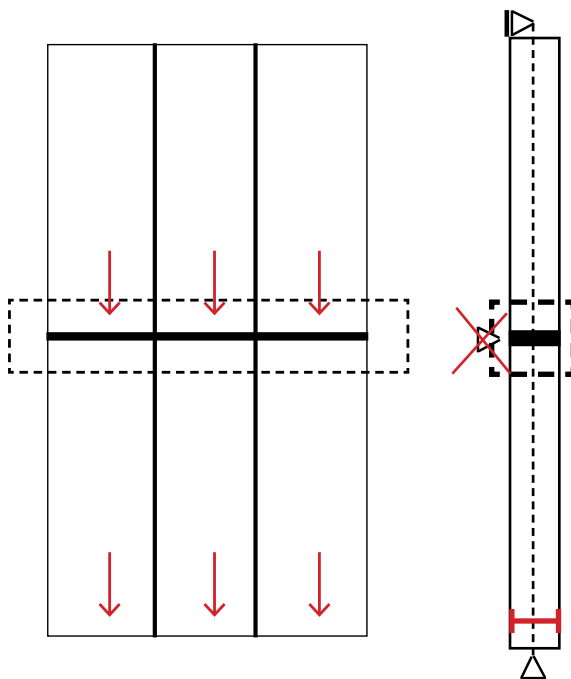


Fig.155_ Load bearing scheme.

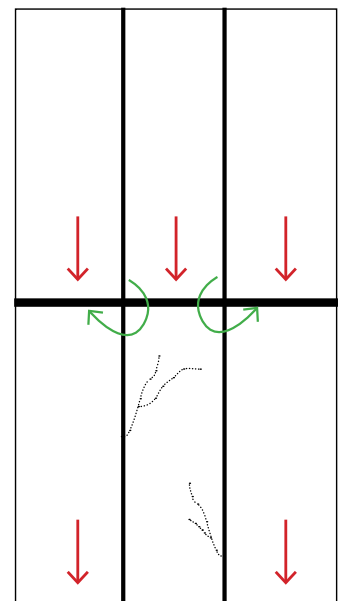


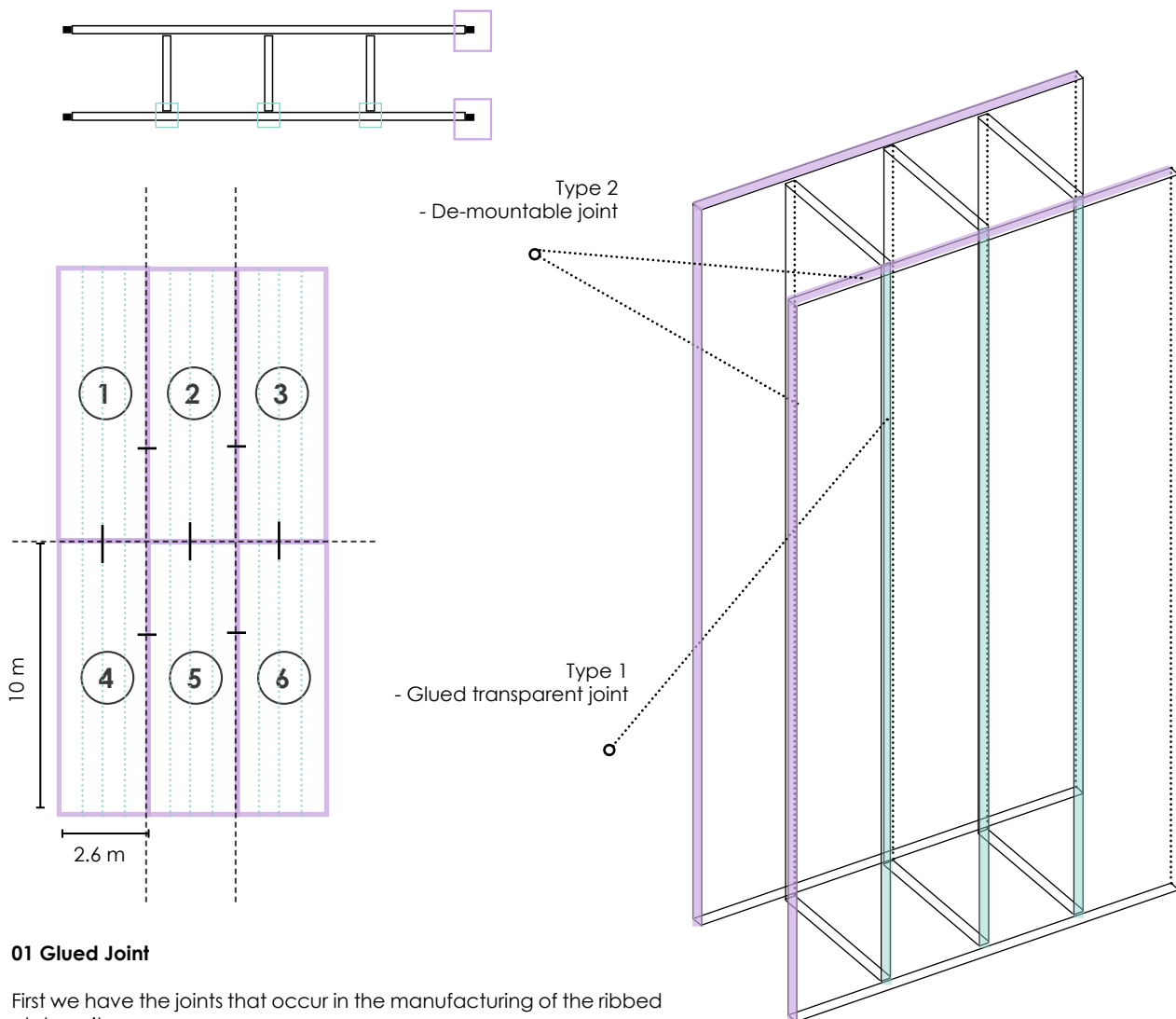
Fig.156_ Robustness. Upon failure of one panel.

6.2.1 / Design Strategy 1 - Flat screen (I-Profile)

03 Joints

The type of joint is a very important aspect that influences many aspects of the façade design and especially the structural behavior, as well as the transparency that we are mostly here try to improve.

The connections in the façade are divided in two types:



01 Glued Joint

First we have the joints that occur in the manufacturing of the ribbed plate unit

The scheme of the ribbed plate that is used for both structure and envelope gives the opportunity of prefabrication. Therefore the joints between the two plates and the transverse glass ribs can be high quality glued connections. Here very high quality transparent adhesives or the latest technology of structural glazing tapes can be employed for the construction of this joint. The advantage of prefabrication is to avoid the dry connections between structural elements and limit them to the minimum number as they can traumatize the glass during assembly and potentially create superficial flaws from the working on site. On the other hand the quality of the glued joint can be secured if produced in laboratory conditions.

Fig.157_ Two different types of joint occurring on the unit.

6.2.1 / Design Strategy 1 - Flat screen (I-Profile)

Optical properties of these joints:

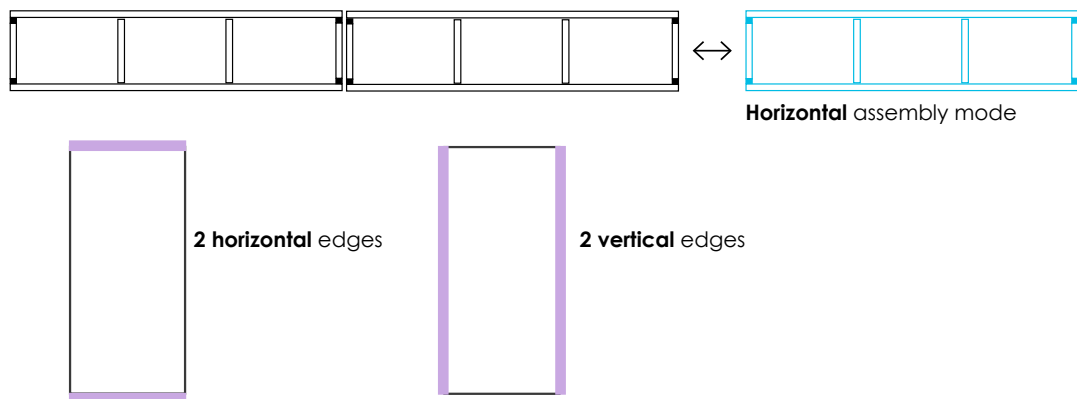
- _ Transparent
- _ Show a solid glass edge
- _ The joints have to be perfectly aligned with the glass rib's edge during assembly at the factory
- _ The joint has to be bubble free

Furthermore these joints have to transfer the forces from the plate element to the vertical ribs. It is a rigid joint and the degree of movement is defined from the properties of the adhesive. The rigidity of the connection allows for better structural integrity as it allows for the unit to create one rigid body. All these aspects and others mentioned above are only dependent on the chosen adhesive and the success of application and the curing process.

02 On - site connection

The second category of joints is the de-mountable connections between the panels.

The demountable joints developed have to connect the panels to each other. Each unit has 2 types the vertical and the horizontal.

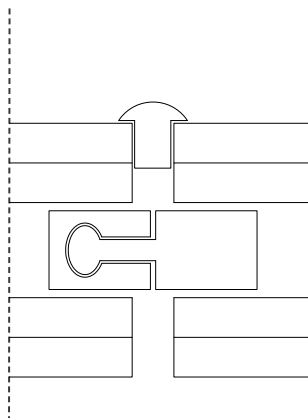
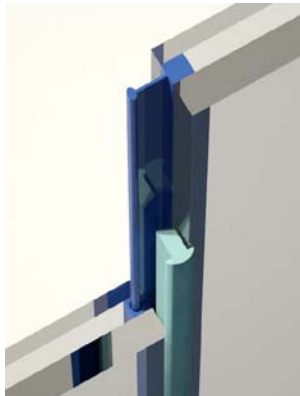


Furthermore there are some important requirements that these connections need to meet:

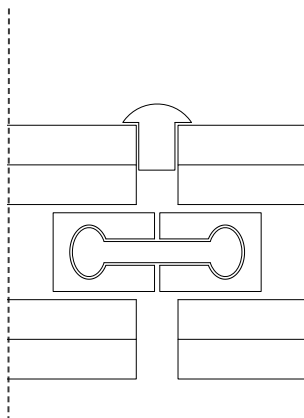
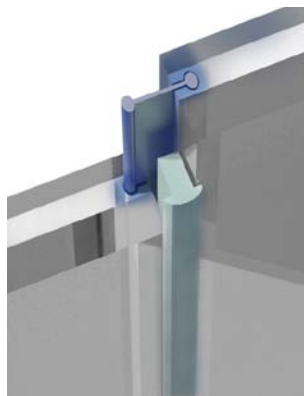
- _ It has to be a connection that allows assembly between the panels on site.
- _ The joints have to allow for maximum transparency and therefore they need to have visible thickness equal or smaller than 20mm-
- _ They need to transfer the stresses between the panels and allow them all together to move as one rigid surface (dead load, shear, tensile stresses, prevent rotation and take thermal expansion movements)
- _ They need to provide water-tightness and air-tightness since the façade is the boundary between exterior and interior space.

Several concepts have been developed in principle for this category of joints.

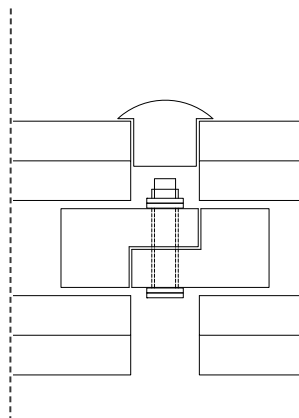
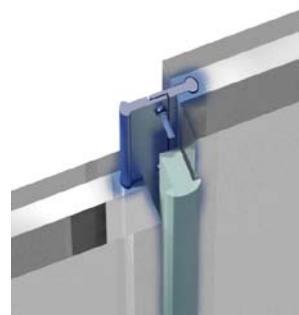
6.2.1 / Design Strategy 1 - Flat screen (I-Profile)



- _ Asymmetrical cross section.
- _ Asymmetrical loading
- _ Potential local stress peaks
- _ Difficulties in installation - minimum tolerances



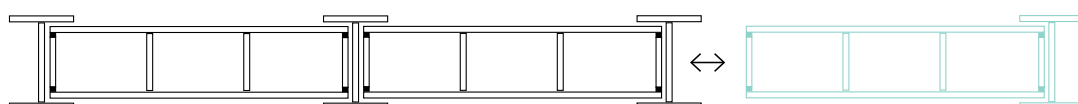
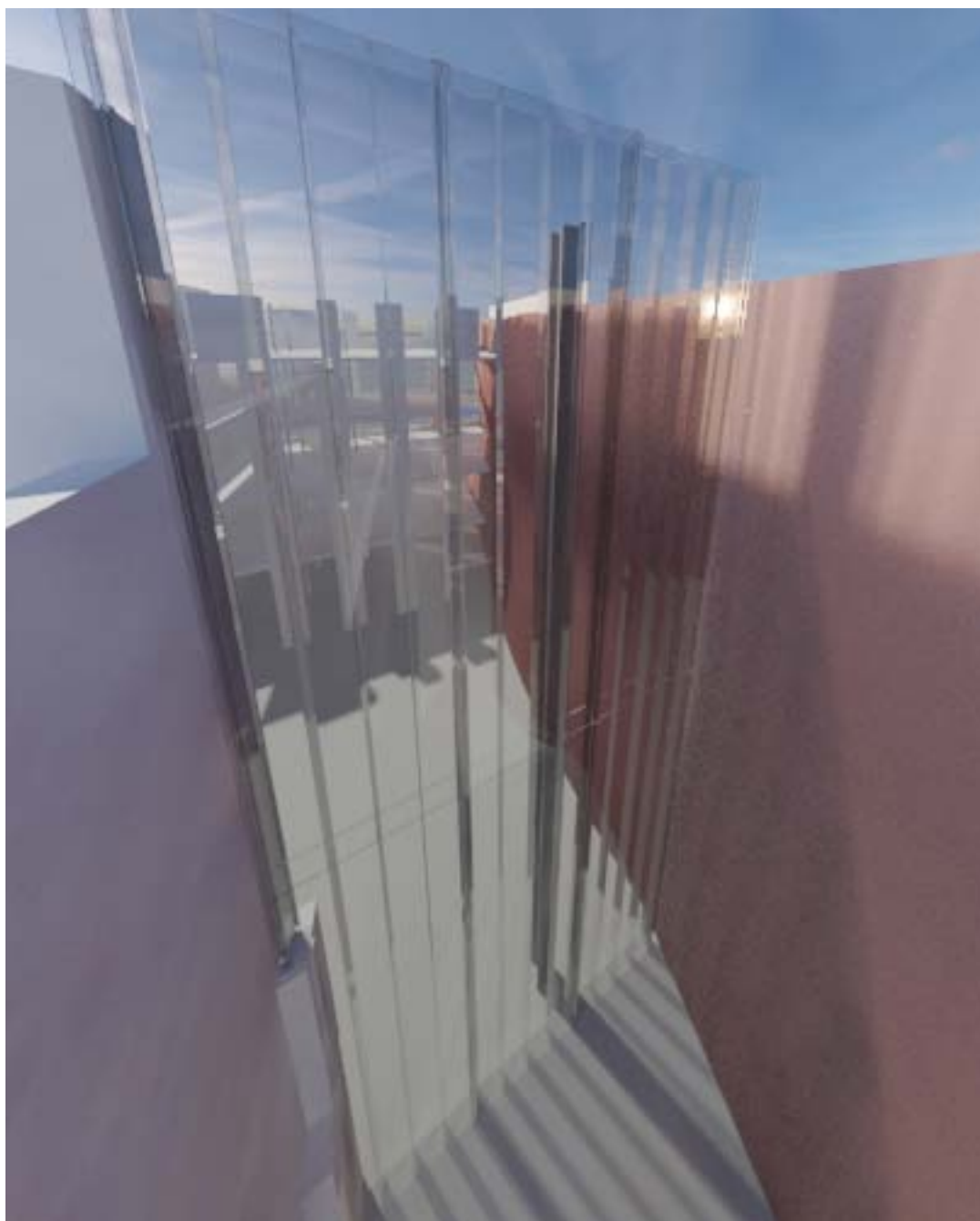
- _ Symmetrical cross section
- _ More even distribution
- _ Easier to assemble - Challenging in tolerances



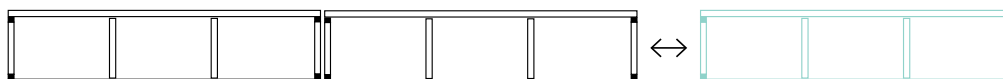
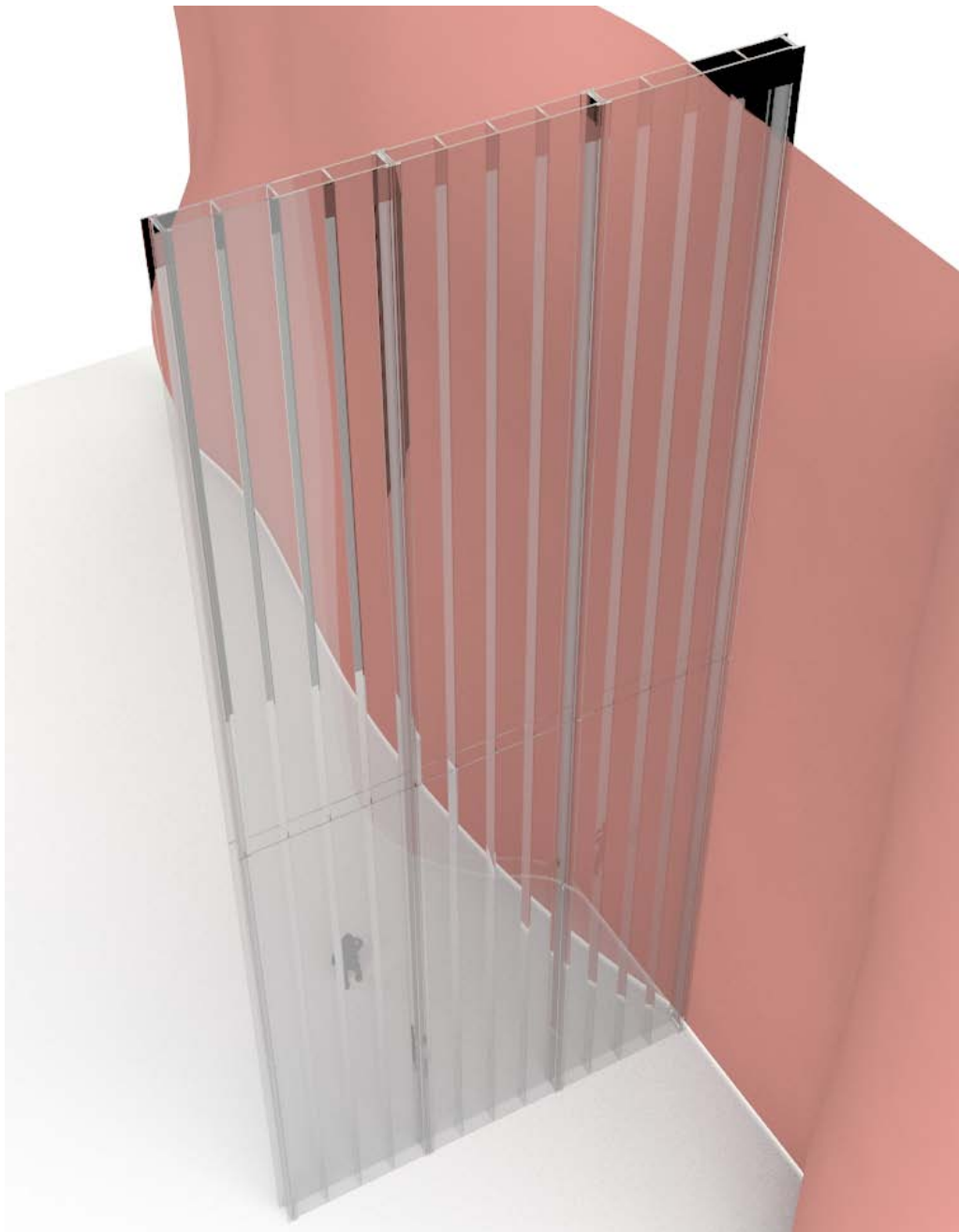
- _ Symmetrical cross section
- _ More even distribution
- _ More flexibility during assembly

6.2.1 / Design Strategy 1 - Flat screen (I-Profile)

SCENARIO 1 - I - profile + ribbed plate



6.2.1 / Design Strategy 1 - Flat screen (I-Profile)



6.2.2 / Design Strategy 2 - Glass Curtain (Curved Shell)

The design strategy 2 is the strategy where the benefits of the corrugated geometry are explored. The aim is to create the appearance of a 3dimensional glass surface that brings transparency to the maximum. The design should look almost like a glass curtain that is free standing in space. The structural principle behind is the element of the bended surface that allows for higher stiffness against the wind load action on the façade.

This strategy is inspired by the corrugated glass facades developed by Rob Nijse and where used in the facades of 'Casa da Musica', in Porto and the 'MAS an de Strom' museum building that have been analyzed in stage 1.

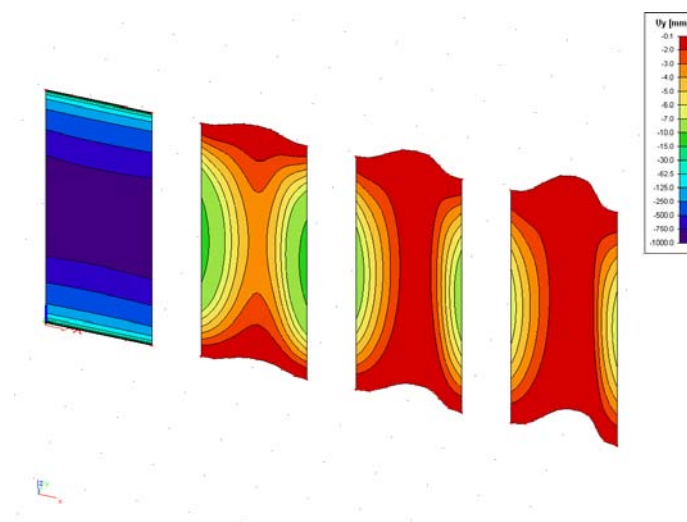
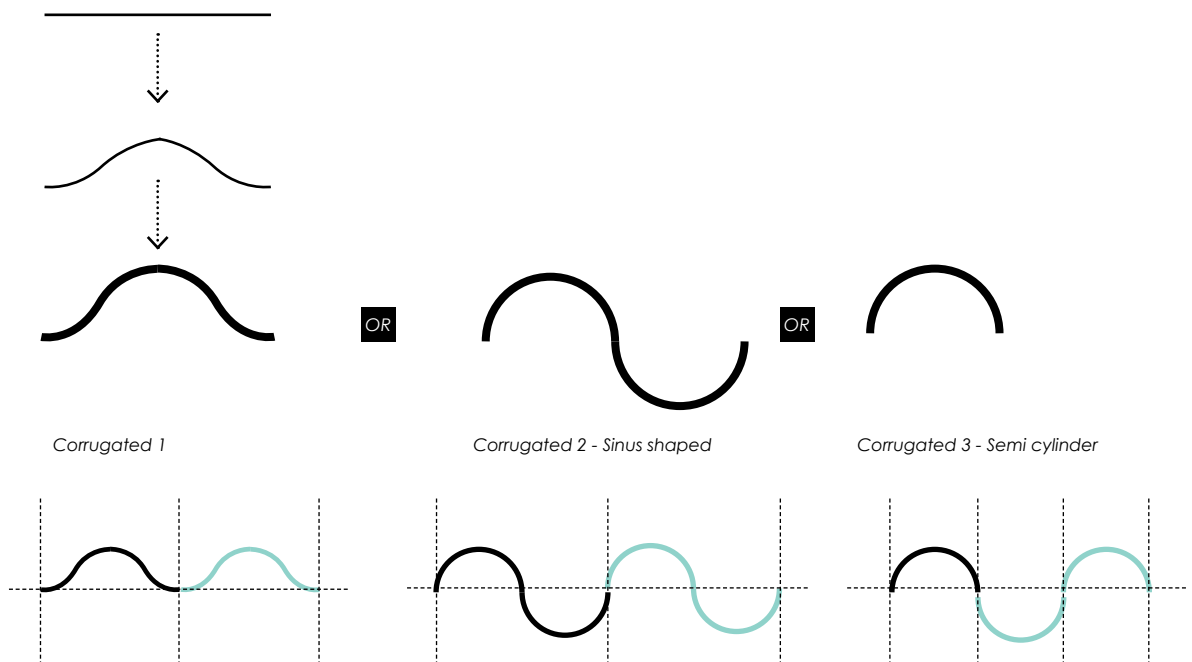


Fig.158_ Principle of the corrugated panel. Stress distribution.



6.2.2 / Design Strategy 2 - Glass Curtain (Curved Shell)

01 Form Finding

Based on the analysis on the corrugated facades a research is conducted on developing a new form for the panel that will combine a resistance action against the wind pressure and suction. The component panel will be later assembled in an effective scheme on the façade that will benefit from the geometry and also present an interesting image. According to these requirements several form finding concepts were developed.

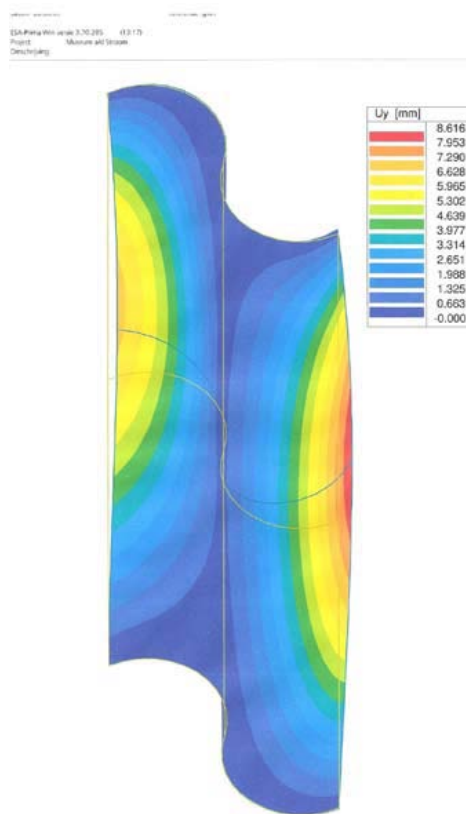


Fig.159_ Deformation of a single sinus shaped glass panel. <
R.Nijssen, GPD 2009 >

01

The first concept is that of twisted curvature along the central horizontal axis. This leads to a shape that is concave at the top and convex at the bottom as it shifts along the vertical axis. The purpose is to accommodate both positive and negative pressure. The element is developed at the whole height of the façade. The horizontal assembly is done by alternating the geometry of the panel each time so it can act as a surface with a 3d truss action. The only weak point is the central horizontal axis where the radius curvature is almost zero. This is a weak point for local stresses to occur.

02

The second case is that almost similar to the corrugated panel developed for Casa da Musica but here the edges are approaching zero curvature and again the shape is twisting from top to bottom. This geometry that is flattening close to the edges where the connection with the next panel is can cause weak areas where the stresses developed will affect the panel. Again the geometry is alternating in horizontal assembly and the horizontal axis is again another weak point.

03

The third scenario is attempting to avoid the weak horizontal axis at the center by shifting the twisting axis at the 2/3 of the total height. The aim is by alternating the geometry never to have a zero curvature point aligning with the central axis. This however is causing a different curvature of the top and the bottom part as well as other problem of complicated assembly between the panels horizontally. The joints created have asymmetry issues that will bring uneven distribution of loads and create weak points for the glass.

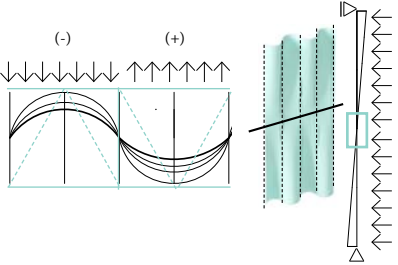
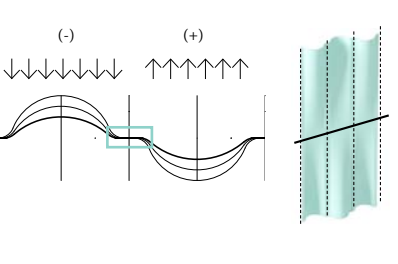
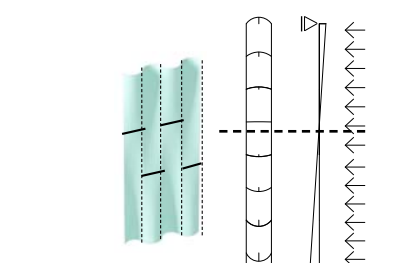
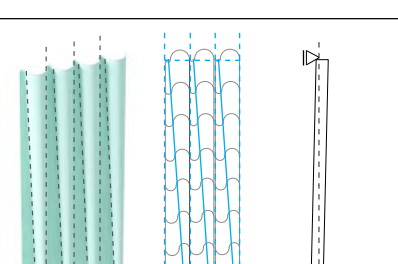
04

The last proposal of form for the component of the glass curtain is a corrugated geometry that develops along a random diagonal of the rectangle starting approximately from the 3/4 of the top edge to end up at the 1/4 of the bottom edge approximately. The reason for not taking the diagonal starting from the corners is to avoid the extremely intense curvature and small radius that cannot be achieved in manufacturing process of any kind. This geometry apart from potentially being very effective for a self supporting glass façade is also the one closest to resembling a glass curtain.

6.2.2 / Design Strategy 2 - Glass Curtain (Curved Shell)

	Form / shape	Geometry type	Assembly mode / Horizontal
01 Twisted curve 1		DOUBLE CURVED	
02 Alternative 2		DOUBLE CURVED	
03 Twisted curve 2		DOUBLE CURVED	
04 Glass curtain		DOUBLE CURVED	

6.2.2 / Design Strategy 2 - Glass Curtain (Curved Shell)

Vertical	Load Distribution	Advantage	Disadvantage
		_Appearance _Self supporting _Material efficiency	_Difficult geometry _Weak middle axis
		_Wider grid _Interesting shape	_Difficult geometry _Weak middle axis _Weak points around the vertical joint
		_No weak middle axis _Better stability	_Very complicated assembly _Vertical edges don't match
		_Very interesting appearance _Geometry acting as a truss in 2 planes	_Complicated curved shape _High manufacturing costs _Difficult logistics

6.2.2 / Design Strategy 2 - Glass Curtain (Curved Shell)

From the summary analysis table of the design proposals based on the bended geometry there have been observations of the designs that lead to the choice of two most interesting and appropriate. Overall the bended geometries are challenge in manufacturing and detailing for the façade. The first design choice is the one for the twisted curve 1 because the geometry can be analyzed in segments of conical geometry. The challenge with these segments is the connection at the middle panel, where the weak horizontal axis occurs.

The second selected geometry is the glass curtain because of the feasibility of the shape, the benefits of the surface as a structural self supporting shell and the interesting architectural shape.

02 Façade divisions

The manufacturing limitations of the bended elements depend on the chosen form processing methods and they are usually more restraining than in the case of the flat element.

Chosen forming process

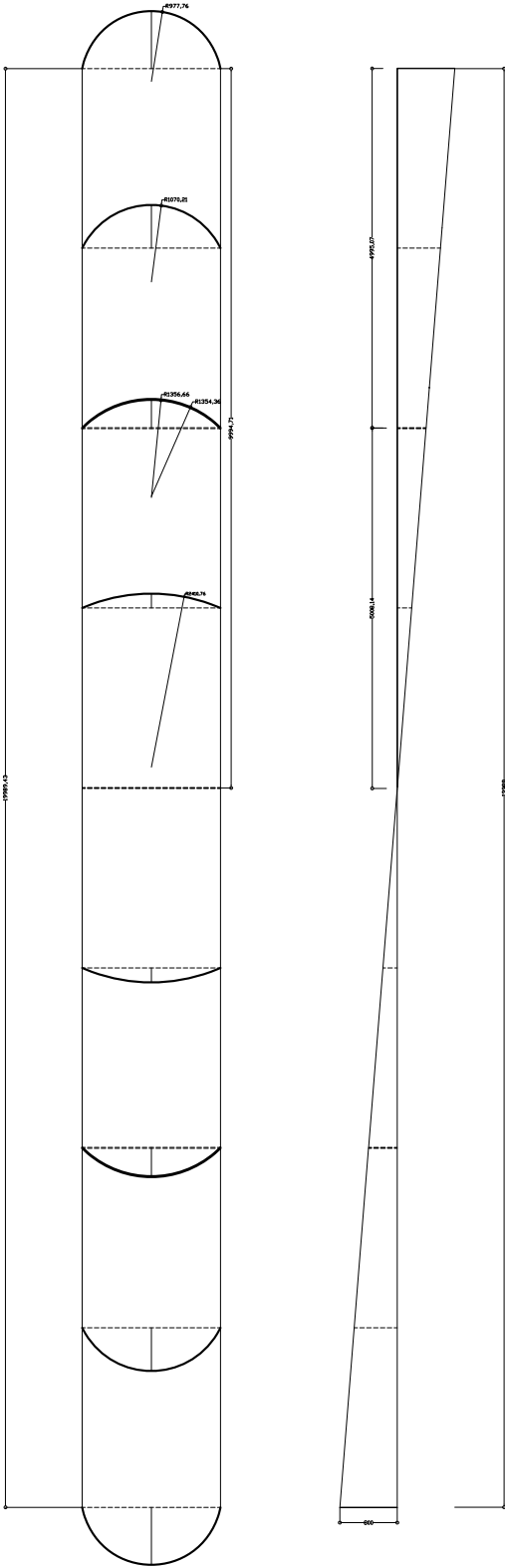
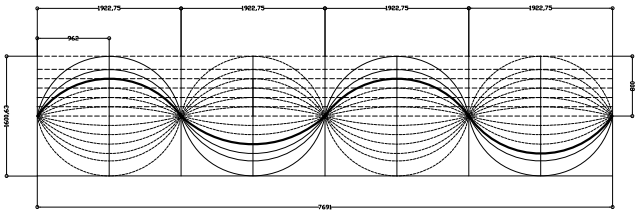
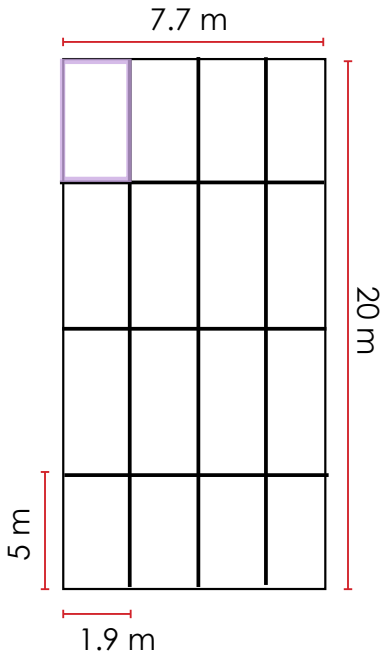
At this point we have to define the chosen forming process for the panels. As we already know from previous chapter the intensity of the curvature and the use of the glass is what defines the choice. In this case in order to approximate the depth of the curved element we need to use a size that is approximately $L/10$ of the span of the 20m. The chosen depth will be at approximately 1600mm and the depth for each unit is 800mm. The minimum radius that occurs from the design is about 998mm. Another aspect is the residual stresses in the bended panel. The choice for cold bending as a forming process has as a downside the residual stresses in the panel and therefore is not the optimum solution. This aspect paired with the complicated double curved geometry leads to the choice of hot bending. This choice will affect the cost that can increase dramatically due to customized mould unless we use the adjustable mould for the production of the pieces.

With the chosen method the maximum height of the panel can reach up to 6m. According to the previous division for the flat panel façade this cannot be done in 3 segments along height but 4 and each will measure 5 m. On the other hand the width is predefined from the length of the arc that it is possible to produce and in this process is about 2.5m. Again from the façade divisions of the flat screen we can see that the minimum amount of segments can be 4 horizontally.

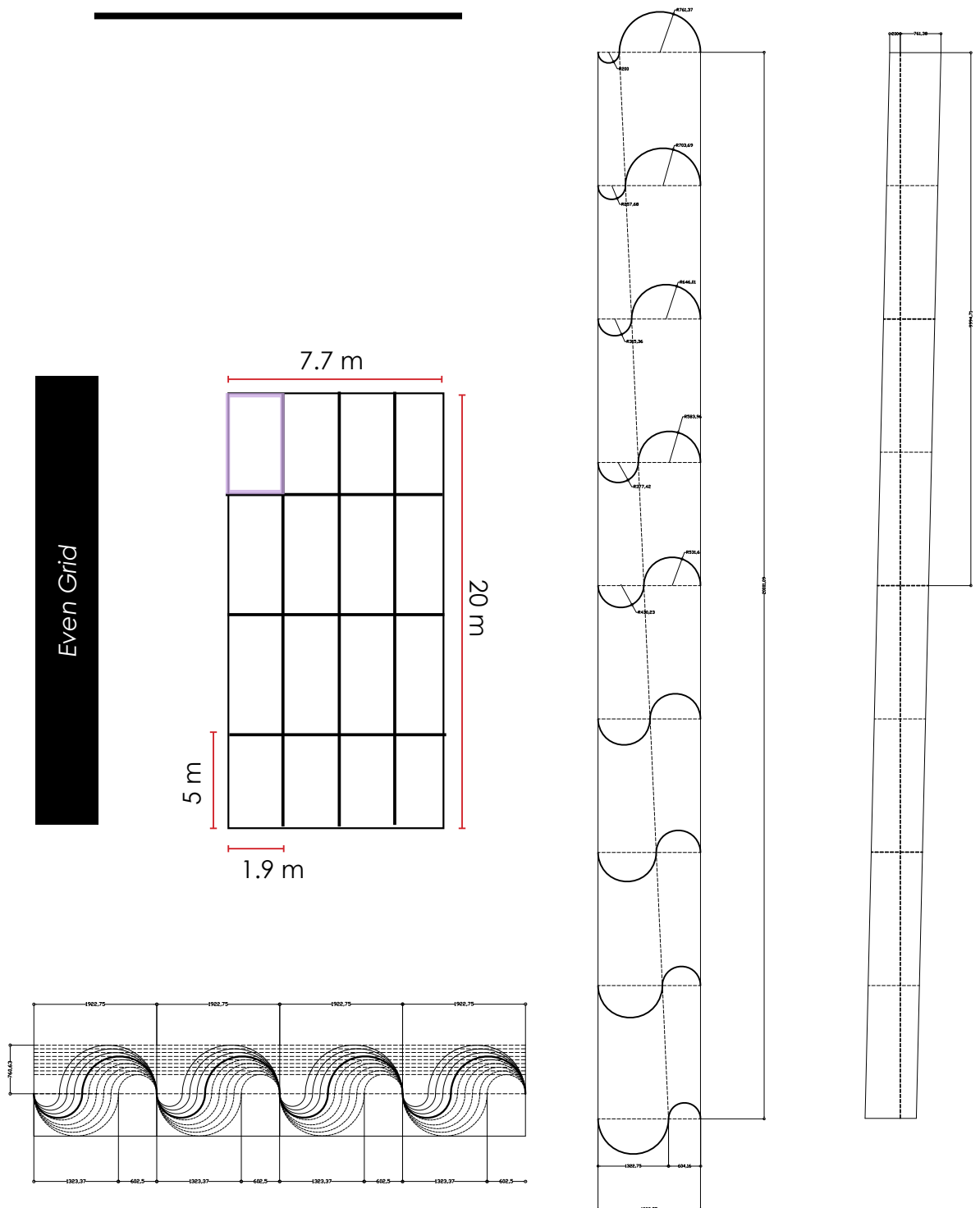
Grid

The grid of the façade according to the previously analyzed aspects can only be 4 segments horizontally by 4 segments vertically of elements 5m high. The façade grid is chosen to be even because of the already complicated geometry. The shape of the façade will be also clearer if the grid is not exaggerated as well. Given all these factors that contribute to these decisions the outcome of the division is explained in the drawings for the following unit choices:

Even Grid



02 Glass Curtain



6.2.2 / Design Strategy 2 - Glass Curtain (Curved Shell)

03 Structural design

The structural concept scheme chosen for this strategy based very much on each beneficial bended geometry and the ability of these elements to withstand windloads, is again to carry the dead load of the top elements in stacking by the bottom element keeping also the whole section under compression. Another advantage coming from the self-supporting geometry is the fact that we can avoid vertical substructure like cables that carry the elements in tension from the top that has been seen in previous examples of façades with corrugated elements. Previous examples, like in the case of the Mas an De Strom show that the action of the vertical joints between the panels is also reduced in the bended geometry as they are not directly exposed to the wind forces.

The bending action due to the wind load on the surface of the façade will be counteracted by the stiffness of the curved cross section. The factors that can contribute to the performance of the cross section against the wind loads is the height of the wave, the thickness of the glass. "With several calculations we learned that from a ratio of 1 to 20 of the wave-height to span the structural effect of the corrugate-ness is evident" < Rob Nijse, GPD 2009 >.

The risk here is the stresses developed to have a bad effect on the horizontal joints. Therefore they have to act as firm connection which secures also the continuity of the bended panel. Another requirement with this type of geometry is to manipulate the different behavior between the concave and the convex part under wind loading. It has been noticed that the convex part tends to deflect more and therefore can cause the whole profile to rotate in the direction of the convex part < Rob Nijse, GPD 2009 >.

Last but not least the robustness in failure of one of the bottom panels will be taken care of the joints and the type of glass used as in the latter case (Strategy 1).

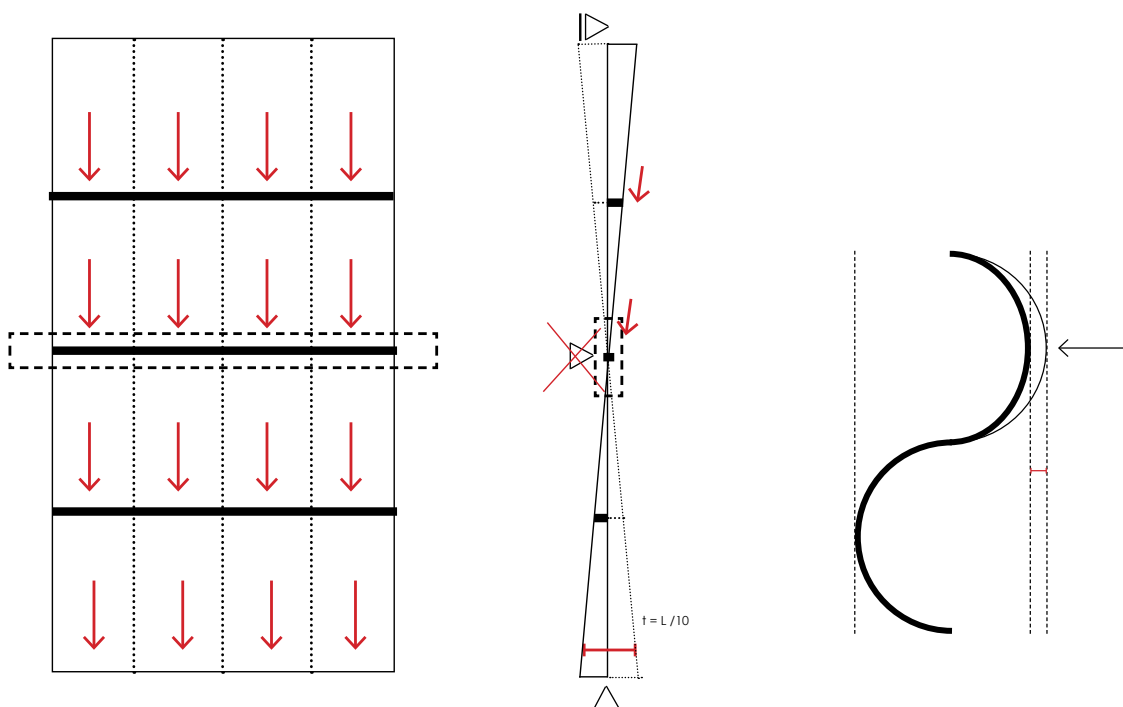


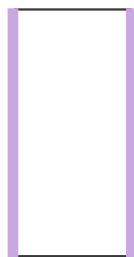
Fig.160_ Load bearing scheme in stacking due to the effective geometry

6.2.2 / Design Strategy 2 - Glass Curtain (Curved Shell)

04 Connections

From the structural scheme we know that the panels carry the dead load in stacking, since the geometry allows for high compressive load. On the other hand the surface has to act as a cohesive 3dimensional body. Then and only then it will be feasible to act effectively against the wind load.

The connections of the curved panel play a very important role if we want to obtain this property in the façade. Because of the geometry it is also very challenging to maintain the transparency levels high. First in order to understand the detail principles we need to follow for the façade, we need to analyze the panels and the type of joint. We are going to distinguish them according to their position. In the curved panel façade we meet two types of joints:



2 vertical edges



2 horizontal edges

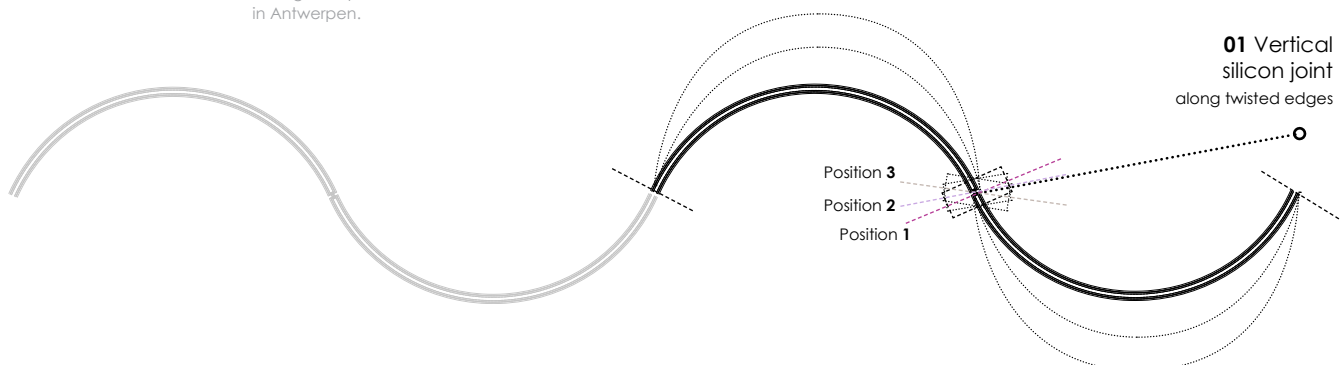


Fig.161_ Vertical silicon joint between corrugated panels in the Mas Museum in Antwerpen.

Vertical Joints

In the bended panels as we have seen from previous examples of the corrugated glass facades the vertical joint is always not the most important one. It can be in most cases a flexible silicon joint that allows the movement between the panels as they are subjected to bending stresses. These stresses cause the maximum deformation around the middle vertical edge. The joint has to be flexible enough to transfer shear stresses coming from this action. The structural silicon is strong and flexible enough to accommodate that.

Because of the complicated geometry we expect also certain inaccuracies and tolerances around $\pm 2\text{mm}$ along the edge if not more. This size has to be taken into account for the size of the joint.



6.2.2 / Design Strategy 2 - Glass Curtain (Curved Shell)

Horizontal Joints

The horizontal joints are in this case and all the previous cases of the corrugated glass facades the most important type of joint. They have to serve continuity of the surface from the top to the bottom. This is because they must prevent the tensile stresses occurring from the wind on the glass to open the joint and lose continuity of the surface. Until now for that reason a linear clamping steel profile was chosen for the solution of this problem. Another reason to choose for that is the assembly feasibility and the preference of clamp instead drilled connections as it is logical for not creating stress concentrations in this geometry.

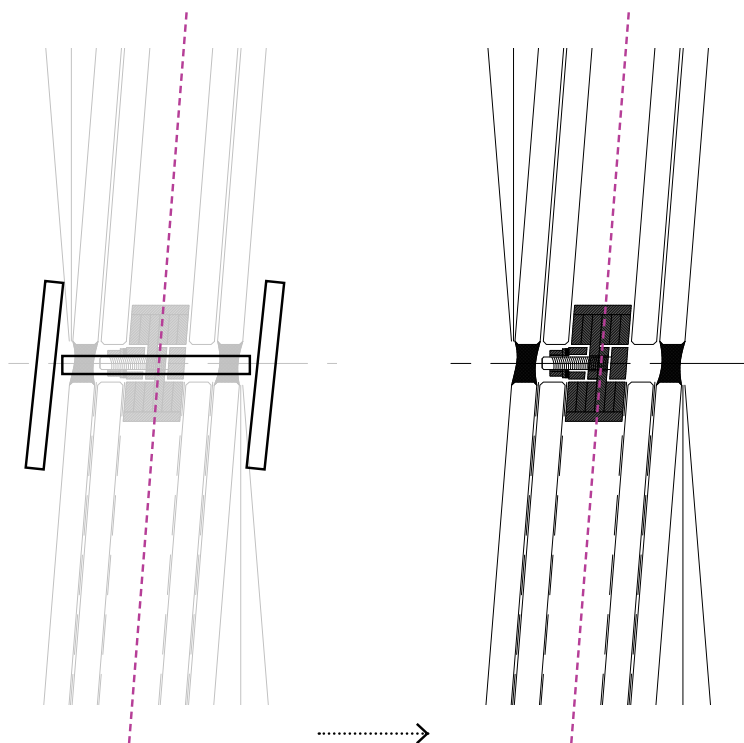
Furthermore robustness and post failure behavior is determined mostly from the horizontal joints. If a panel breaks at the bottom of the façade then the linear joint has to be continuous and able to transfer the dead load of the top panel to the panel at the sides. This is called creating an alternative load path until the panel that broke is replaced.

Taking all these into account the big challenge in this design is to maximize the transparency of the curved façade by minimizing the size of the linear joint and still keeping it effective for the structural scheme.

As it was already mentioned the technologies of embedded connections in the laminate of the glass have been tested with success in real life for the very recent projects of the Apple Inc. retail stores. The glass sheets though used in these projects necessitate no insulating properties and are commonly flat.



Fig.162_ Facade installation process at the Mas An de Strom. Horizontal clamping joint.



Principles - Goal

The goal in this case is to attempt to apply the benefits of the embedded connections in a laminate on a double curved façade with such a geometry. This could help minimizing the surface of the visible joint on the façade. Previous studies at the TU Delft have shown that this type of connections can be achieved for the flat geometry at same time integrating the scheme spacer of an insulating unit. It is a new challenge to achieve this level of integration and maximize transparency for a double curved self supporting glass façade for the La Fayette modern. The two main problems that we have to overcome for that are the manufacturing inaccuracies and the difficulty of the geometry.

6.2.2 / Design Strategy 2 - Glass Curtain (Curved Shell)

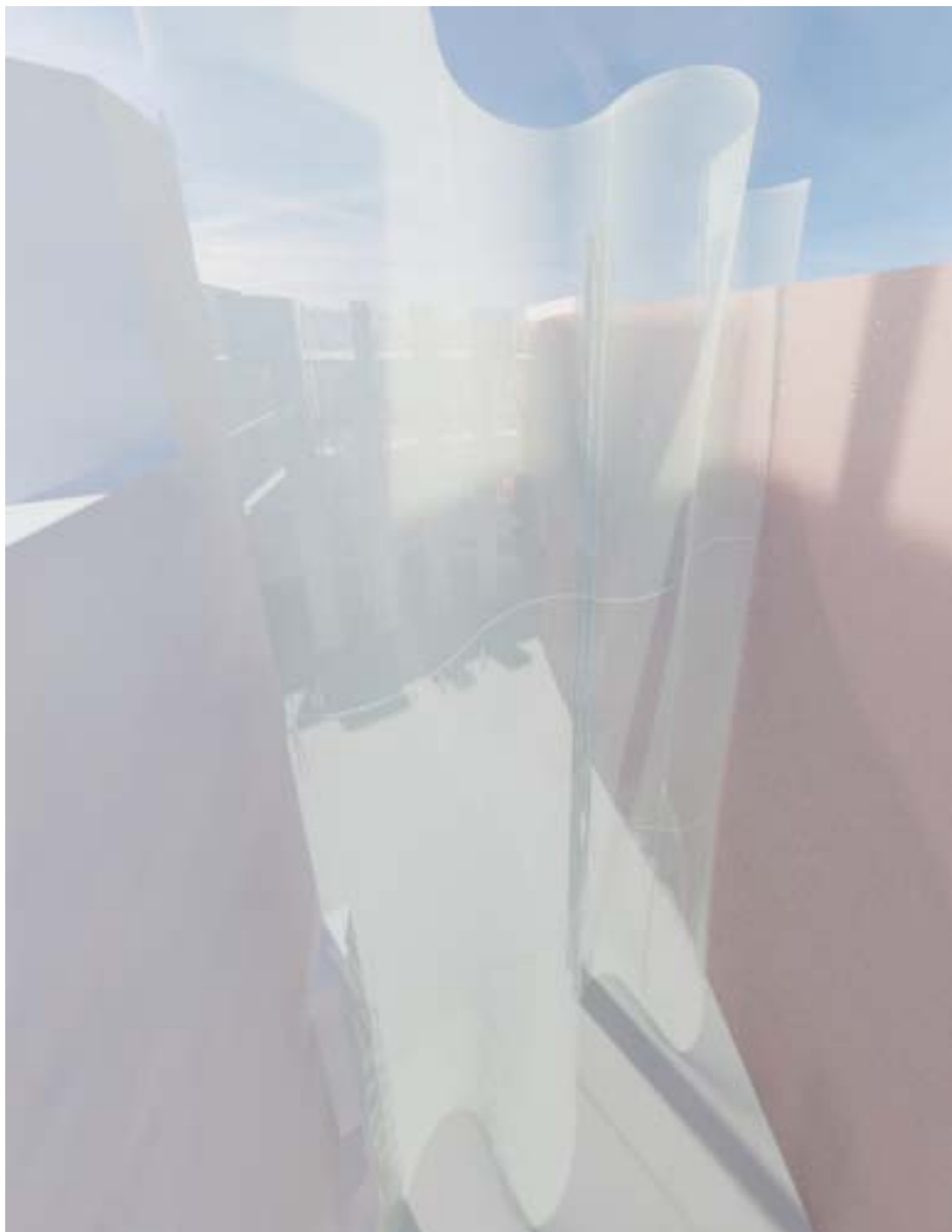


Fig.163_ Rendered view / From the top

6.2.2 / Design Strategy 2 - Glass Curtain (Curved Shell)



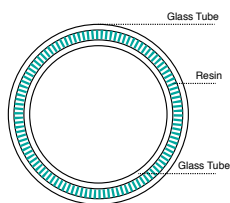
Fig.164_ Rendered view / From the bottom

6.2.3 / Design Strategy 3 - Bubble wall (Glass Tubes)

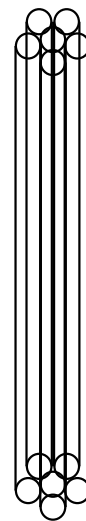
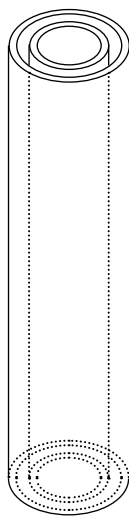
The third design strategy is based on the element of glass tubes and massive glass cylinders. Due to manufacturing size limitations and material costs emphasis is given to the tube cross sections (instead of massive bars).

From studies conducted on the tubular glass column it is already known that the elements can possess a great ability to carry extreme compressive loads than other type of cross sections. Therefore it is considered to be a suitable component to be used in the construction of a self supporting all – glass façade for the La-Fayette Modern. Other reasons for the use of the tube are the effectiveness in buckling and torsion as well as the commercial availability <Fred.A.Veer, GPD 2005>.

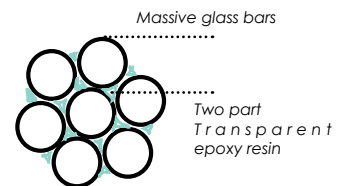
The first geometry is the hollow tube and the second is the massive rod where the shape can have the same effects under loading. An addition here is the possibility of assembling it in bundles. The bundles of glass bars where designed for column elements that can carry very high compressive loads <Rob Nijse, 2003>. Here the properties of the one cylindrical cross section are combined in a bundle of 7 load carrying bars that are glued together with a rigid transparent adhesive. This scheme can ensure more even distribution of the compressive load over the area of 7 glass rods. This can have a big impact on the effectiveness of the cross section in axial compressive load as well as in bending as we increase in that way the effective thickness.



Laminated glass tubes



Bundle of glass bars



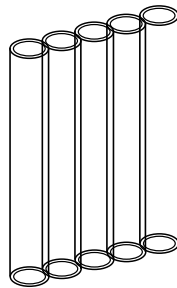
6.2.3 / Design Strategy 3 - Bubble wall (Glass Tubes)

01 Form finding

From the previous principles a form finding research led to these possible schemes for the façade.

01

The first approach is the use of tube glass unit assembled in one row and stacked on top of each other to span the whole height of the façade.



02

The second approach is that of combination of the single tubular cross section with the properties of the bundle. Here we can have a façade with a thickness of 3 layers of tubes instead of one. This can achieve better performance against bending from the wind loads on the façade. This form can actually take insurmountable variations as the composition of the bundle can change depending on the size of the tubes and the layering pattern. It is also a very interesting architectural solution because of the different sizes and shapes as well as the possibility of integrating elements of light in the tube. Unfortunately the distortion levels in the tube facades don't allow for transparency but an interesting distortion.

03

Another variation coming from the previous principle of the bundle is to create the layers by alternating massive rods in the core and hollow tubes in the external layers.

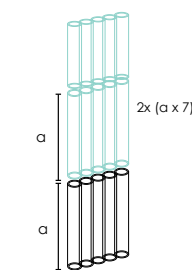
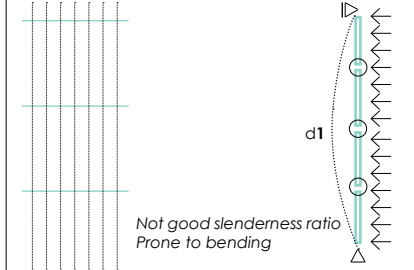
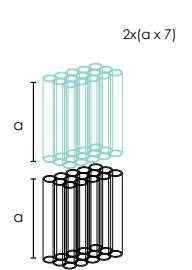
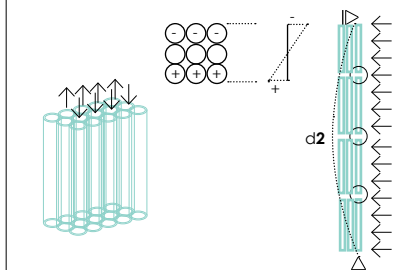
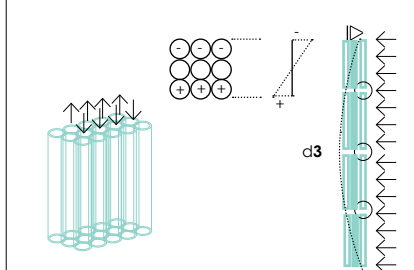
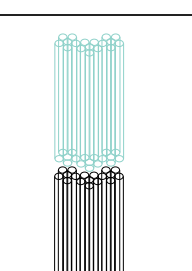
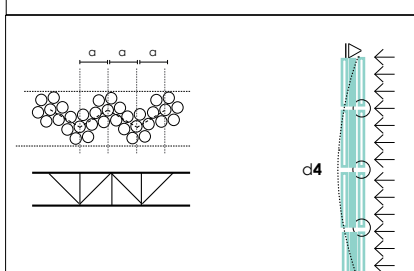
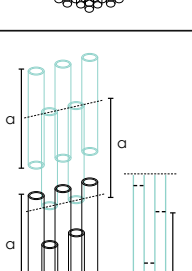
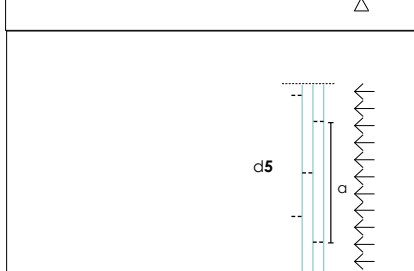
04

Another interesting solution is to use the bundle scheme of 7 bars to assemble the façade in a way so as the row is acting as a truss in the direction of the wind.

05

All the variations mentioned above can be assembled so we can have overlapping joints horizontally from one unit to another since this would help here in our case not to have continuous weak joint that could act as a hinge. The horizontal joints here as we saw in previous design strategy are also a weak area against bending stresses from the wind.

	Primary element	Form of unit	Assembly mode / Horizontal
01 Twisted curve 1			
02 Alternative 2	 Principle 		
03 Twisted curve 2	 + Principle 		
04 Glass curtain	 Principle 		
	 + Principle Overlapping joint		

Vertical	Load Distribution	Advantage	Disadvantage
 2x (a x 7)	 Not good slenderness ratio Prone to bending	_Appearance _Small distortion	_Not good stability _Difficult joining
 2x (a x 7)	 d2	_Better stability _Design variety	_Expensive _High distortion _Difficult joining
	 d3	_Better stability _Design variety	_Absence of transparency _Ineffective use of material
	 d4	_Effect of truss _Design variety	_Not cost effective _High level of distortion
	 d5	_More effective assembly for stress distribution _Extreme design variety	_Complicated assembly
d1 > d2 > d3 > d5 > d4			

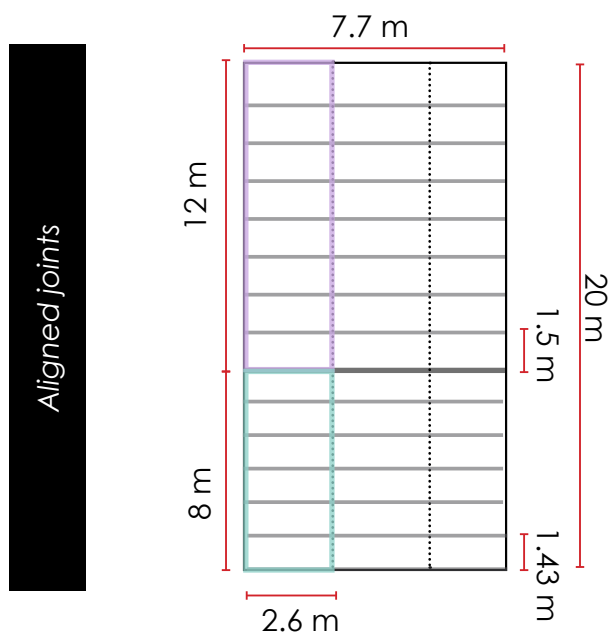
6.2.3 / Design Strategy 3 - Bubble wall (Glass Tubes)

The summary analysis of the different potential presented on the last table is helping us make the choice for the optimum solutions regarding appearance, structure feasibility and cost effective use of the material. Since we already know that the tube components are probably the most expensive of the three design components benefit is to make a choice that doesn't go for extreme use of material. For that reason we opt for the hollow sections. In that area there is the potential to go for a façade system with one row of tubes but also with multiple. From structural point of view the 3 rows of tubes provide better stability and performance against bending stresses. But it is a choice that could be very cost inefficient. For further design development it is chosen to go for both solutions. There is also under examination the design of the tube units with overlapping joint.

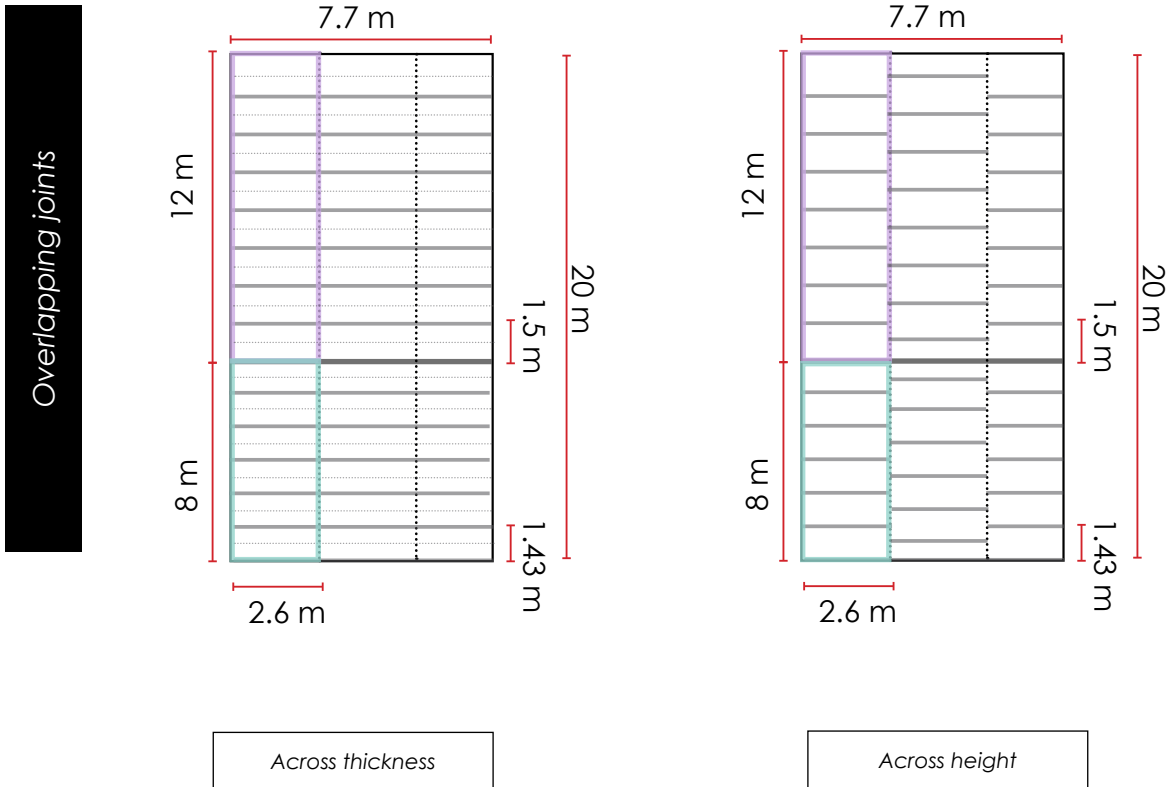
02 Facade divisions

The manufacturing limitations for the tubes are very restraining for the division of the façade. The maximum standard height of the tubes is reaching only 1.5m and therefore the solution of the joints later has to be smart enough so as to allow for transparency. The significantly small length of the tubes is introducing approximately 14 horizontal joints across the whole façade. On the other hand it would be easy if we already build the panels up to a certain length and then transfer them. The maximum transportable length would be 13 m and therefore according to the dimensions of the façade and the maximum height of the tube this could be done with 8 pieces of 1.5 m height that will enable the 12m length panel to be prefabricated and transported. On the other hand the maximum transportable width will stand at around 2.6 and therefore we have a division of 3 segments horizontally for the façade.

This pattern could be alternated a bit if we choose for the overlapping joint along the thickness of the panel. There the potentials for dividing the overlapping segments are too many to be able to map them all within the scope of this research.



6.2.3 / Design Strategy 3 - Bubble wall (Glass Tubes)



6.2.3 / Design Strategy 3 - Bubble wall (Glass Tubes)

03 Structural design

The structural design concept for the tubes facade follows the principles of structural design of the previous two strategies, for same reasons. It is said that actually the tube is one of the most effective geometries to receive compressive loads and therefore the stacking scheme can be ideal. However the proportions of the elements are one more time defined from the manufacturing sizes and there is a necessity for reinforcement, or a type of cross section with multiple row of tubes to withstand the loads.

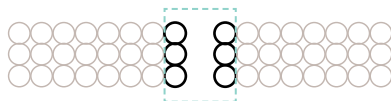
04 Joints

Again the façade joints will be divided according to their properties and stresses they accommodate in vertical joints and horizontal joints.

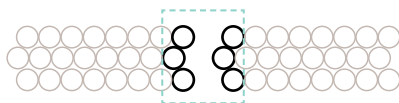
Vertical joints

The vertical joints as it was already analyzed in the previous chapter can be consisting in this kind of self supporting units out of silicon. In the case that we have a high bending stiffness of the element, especially in the case of the bundle we can assume that a simple silicon joint will do. Since the geometry is already very complicated at the edges of such elements we need to really think of the simplicity of the joint as well as the water-tightness and air-tightness of the façade.

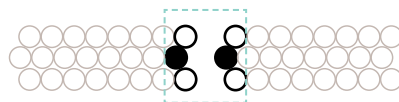
In the schemes below a few assembly modes of the vertical joints are presented as options for the bundle unit, since it seems to be more feasible to achieve a watertight connection here than in the simple one row of tubes.



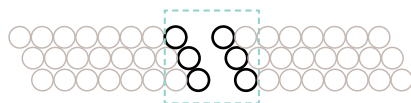
Option 01
Parallel edges - Not good contact scheme / potential hinge



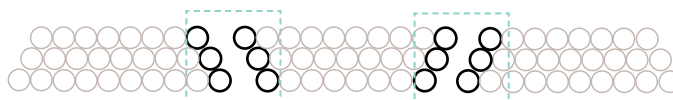
Option 02
Male female - Good contact scheme / Uneven stress distribution



Option 03
Internal connection (other material) - Good contact scheme / Difficult assembly



Option 04
Diagonal - Good contact scheme / Uneven load distribution



Option 05
Counteracting diagonal - Good contact scheme

6.2.3 / Design Strategy 3 - Bubble wall (Glass Tubes)

Horizontal joints

For the horizontal joints as we can see from the façade division scheme we can distinguish two types. The rigid or fixed joints that will be created between the tubes so as to extend them to the maximum transportable size and the one mounted on site joint that will be placed somewhere around the 1/3 of the height of the façade.

The rigid joints that appear on the surface of the façade are too many and therefore they have to be transparent otherwise the whole transparency essence is going to be lost. There have been experiments during the past for combination of the tubular glass column with a PMMA connection at the top and the base. There are certain observations about this type of connection after the compression tests that were conducted for columns 1.5 m high.

The PMMA joints are bonded adhesively to the glass columns or they are let with the glass edges loose. The PMMA as a material has significantly lower hardness and Young modulus from glass and therefore it can easily deform and function as a hinge.



Fig.165_ Rendered view / Concept for a transparent sleeve joint.

Requirements for the joint

01

No local contact because it will cause local stresses

02

Carefully design the supports

03

Use of material at the supports (Depending on hardness & transparency)

04

Watch out for differences in height of the concentric tubes – Uneven distribution

6.2.3 / Design Strategy 3 - Bubble wall (Glass Tubes)

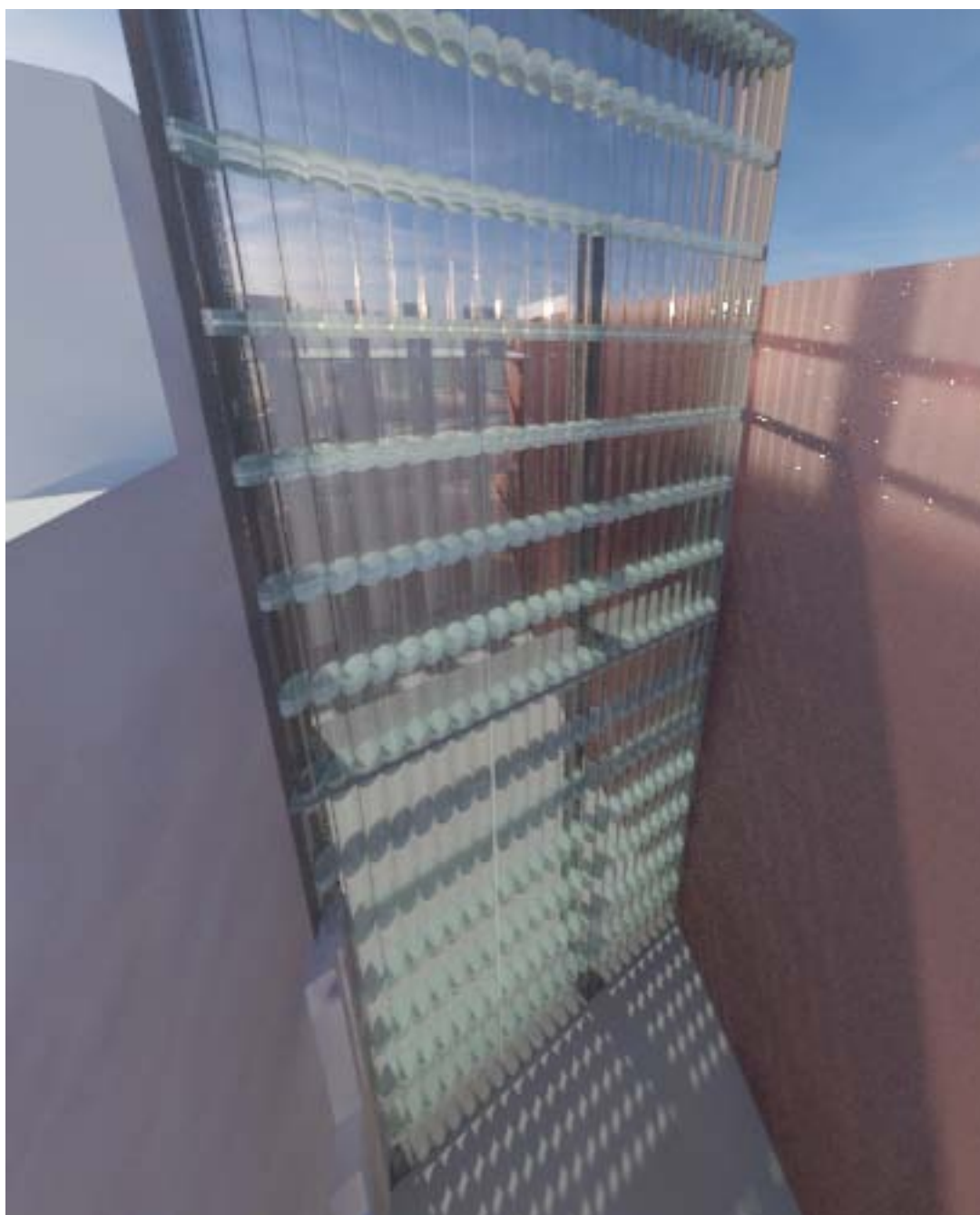


Fig.166_ Rendered view of the facade with a single row of tubes. Oversized units are created by assembling tubes vertically with intermediate transparent joints.

6.2.3 / Design Strategy 3 - Bubble wall (Glass Tubes)

Concept 1 / Single row

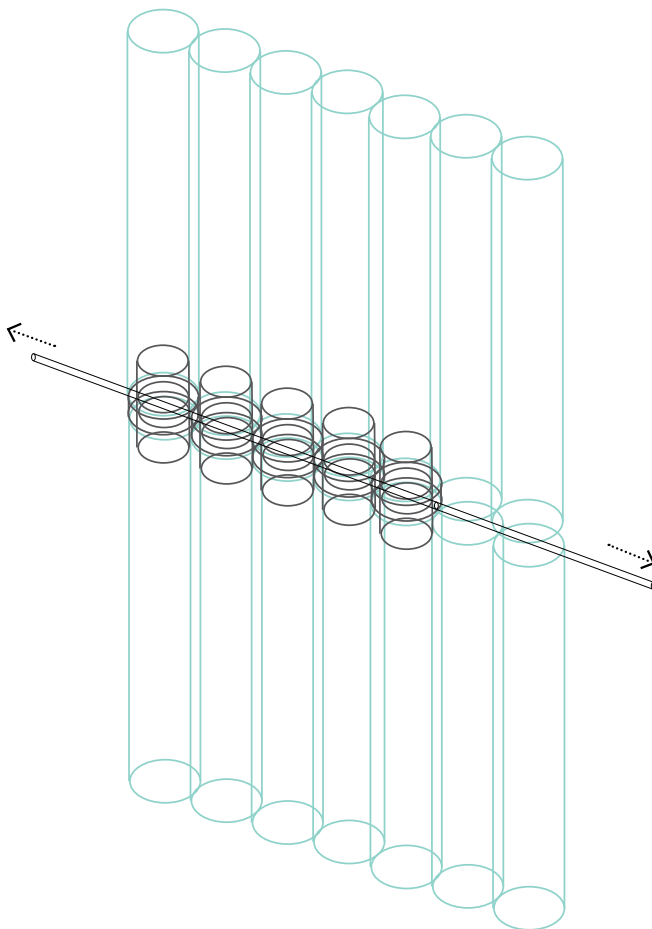


Fig.167_ Diagram 3D showing the concept of the single row unit of tubes. The stability is enhanced by horizontal post tensioned cables that go through the transparent sleeves.

Concept 2 / Multiple rows

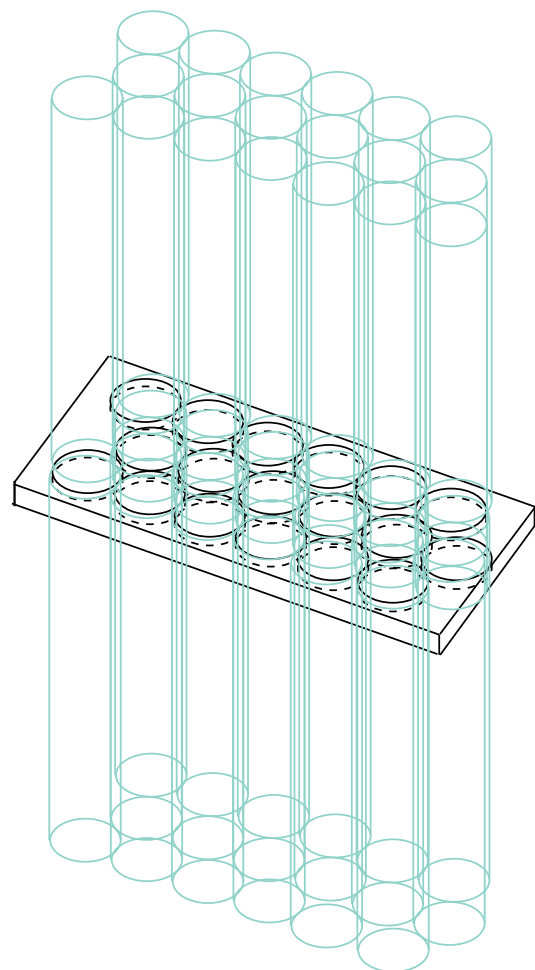


Fig.168_ Diagram 3D showing the concept of the multiple tube unit. The diagram shows the dish shaped connection between the oversized units. The tubes can be fixed by pouring resin that will stabilize their position over a layer of padding that can be used for setting of the tubes.

6.3 / Conclusions

	Units			System				Overall Feasibility
	Size	Costs	Form potential	Structure Feasibility	Form / Appearance	Joints	Transparency	
Strategy 1 / I-profile	++	+	-	++	-	+	++	++
Strategy 2 / Curved	+	+	++	+	++	-	+	+
Strategy 3 / Tubes	--	--	+	-	++	--	-	+

++	Very feasible
+	feasible
-	less feasible
--	Limited

Table.169_ Overall feasibility of the 3 strategies

In the Table 169 we can see a general evaluation of the 3 design strategies that is summing up the information gathered from the design and literature research in the previous chapters. The assessment is qualitative and focuses on the aspect of feasibility in both the level of the unit / component and that of the system. The latter are being summed up in the evaluation of the overall feasibility.

From the data gathered we can end up with the following conclusions:

The **flat components** used on the first strategy present trivial limitations in size and cost (assuming that the techniques are more developed for this geometry) and the only downside comes to their appearance and the limited design versatility. In a system with the benefits of the I-profile we can achieve high levels of structural feasibility and high flexibility in the design and realization of the joints. The overall transparency can be highly promising since it is the most developed system in terms of size and precedents that show how we can minimize the obstructions by integrating the joints in the glass laminates.

A **curved geometry** comes along with adequate feasibility in the size of the components, since we can produce and process elements up to 6m high. The costs can be moderated by the type of forming process and especially if we choose for production with an adjustable mould in hot bending process. Since the geometry chosen in this strategy presents intense radii we can only use this method. This choice allows also for great design flexibility. On the level of the system the curved geometry exhibits excellent structural performance compared to the flat, since the shape is more effective against bending. The overall transparency can be highly improved since the vertical secondary support is reduced but the joints can be a challenge with this kind of complicated geometry.

Last but not least the third strategy is the one that comes with the most limitations. The geometry of the **hollow tube** is the smallest in available size and also the most expensive in terms of manufacturing costs. Of course the design variations that can be achieved with this component are without a doubt many. On the level of structural feasibility the tube as an individual component is very effective in structural performance, but on the level of the system it is a weak geometry because the limited size won't allow for the time being large spans. The joints in terms of feasibility can be challenging as they have to take up large tolerances (- + 5mm). Ultimately the transparency can be highly affected first because of the tube that produces a distorted transparency but also because of the number of joints that occur. From the design analysis it has been mentioned that the development of intermediate transparent joints could help towards that direction.

6.4 / Selection of Design strategy

The result of the analysis and the observations that one can make from the conclusions lead to the fact that more or less all design strategies can provide a final feasible design that achieves the goals set in the brief for the façade. Each and every strategy though presents a different set of demands on the more detailed level of design. Since it is part of the early decisions to proceed with one design typology at this point the choice can be made.

The chosen design strategy from which the final design will occur and be developed further is that of the curved shell. This strategy has been chosen for a set of reasons that are presented here:

01 Transparency

It offers a high degree of transparency and almost equal degree of distortion with a flat surface.

02 Structure

It performs better against bending stresses since the bended geometry is principally stiffer than the flat

03 Size

The curved element can be produced oversized up to a good level that allows for a large grid in the façade.

04 Processing

The curved elements can be also strengthened and laminated to provide better performance and a degree of safety

05 Design Versatility

The processes available for the forming of the curved elements and especially the hot bending can offer an extremely high degree of design flexibility

06 Information availability

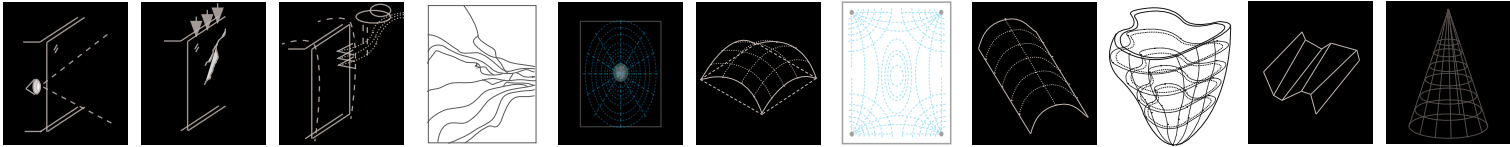
There is some information on this type of facades that can be extracted from precedents (ex. Casa Da Musica, Mas an de Strom, Library of Doha). The available information is not so much as in the case of flat elements but there is certainly more than in the case of tubes, where almost no precedents are available.

07 Architects Feedback

It was an initial preference of the architects (OMA) to achieve an image that is close to a glass curtain. This shape can only be achieved with the segments of curved glass sheets.

Finally the bended shell strategy allows the façade to achieve the highest level of integration between form and structural function. The unique benefit of the bended geometry to be somewhat self-supporting blends in perfectly with the function of the envelope. This is probably the most promising attribute of this type of facade that can possibly allow for complete freedom from any secondary frames that prevent complete transparency in modern glass facades.

In the end it is of a high interest to produce test ideas that take advantage of the geometry in that scale and also to provide new alternatives for joining methods of the panels, an issue that is already challenging enough with the complicated geometry of the double curved panels.





7 / Final steps

The result of the analysis and the observations that one can make from the conclusions lead to the fact that more or less all design strategies can provide a final feasible design that achieves the goals set in the brief for the façade. Each and every strategy though presents a different set of demands on the more detailed level of design. Since it is part of the early decisions to proceed with one design typology at this point the choice can be made.

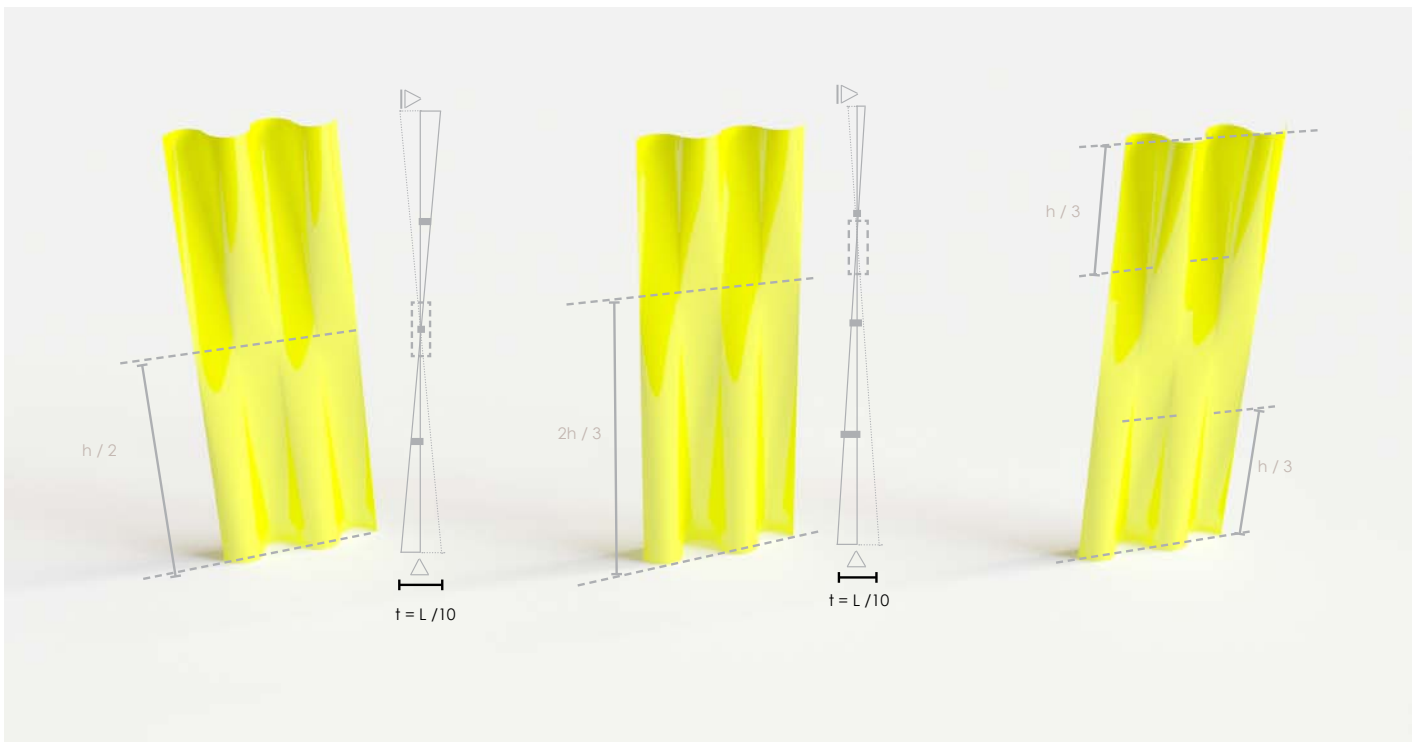
The façade system that was chosen at this stage to be developed is taking into account the advantage of the bended geometry to create a stiff surface that will ensure stability of the façade against the wind-loads without being assisted from secondary support frames.

The form of the surface at this point is not finalized. Up until now the façade options developed in the design strategy 2 were mostly design driven options that can be manufactured that can be manufactured from oversized curved components. The next step is to choose the optimal surface from the point of view of structural performance. In the previous stage there was a form finding analysis that presented the structural flaws and benefits from a set of surfaces.

In this short study it was also understood that, almost all, the designs developed had to face a common problem of the weak axis developed in the middle of the façade. This problem was initially generated from the design concept of the twisted panel geometry, where at almost every option a weak axis where the geometry presents a flattened part occurs. If this axis is presented especially in the middle of the surface then it coincides with the region of the façade where the highest bending stresses occur due to wind action.

Fig.170 (opposite)_ Set of surfaces for optimization. Visualization of the problem of the weak axis

7.1 / Form optimization



01

- _Common symmetry axis
- _Middle weak point

02

- _Common symmetry axis
- _Elevating the twist axis higher ($2h/3$)
- _Avoid weak central connection

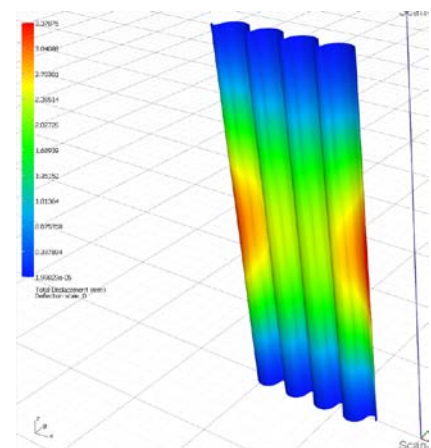
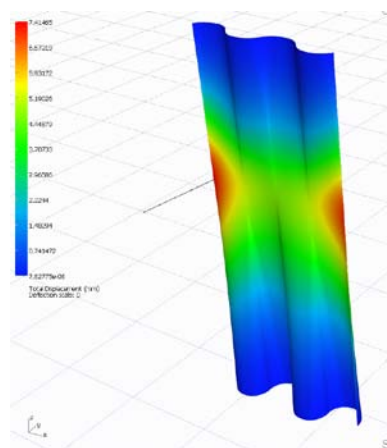
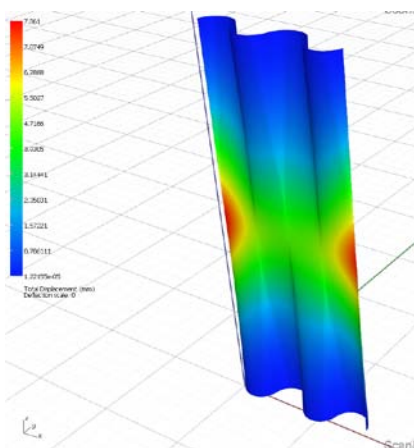
03

- _ Not common symmetry axis
- _ Alternating for each panel
- _ Avoid weak central connection
- _ Complicated surface
- _ Uneven load distribution

In order to come up with the final optimal surface a set of surface options was tested with FEA (Finite Element Analysis) software tool 'Scan & Solve' for Rhino (3D modeling software). The tool allows for quick evaluation of the stresses and the displacement of the surface after application of the main loading scenario that the façade will undergo. Unfortunately the tool is not highly developed so as to allow for accurate simulation but it is considered to be a suitable method to predict the displacement and the general performance of the element.

The results are presented in the following set of figures. We can also distinguish the variations between the different surfaces.

7.1 / Form optimization

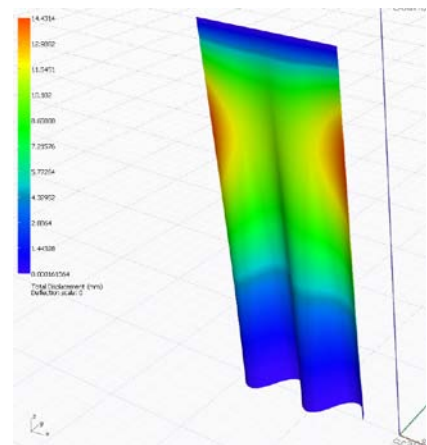
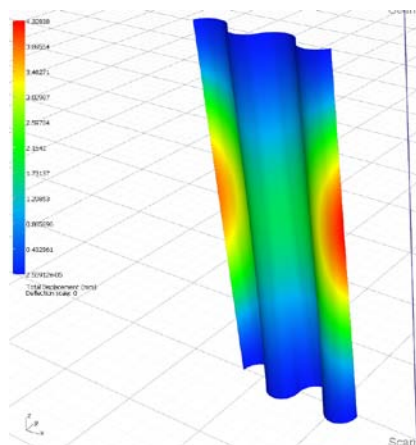
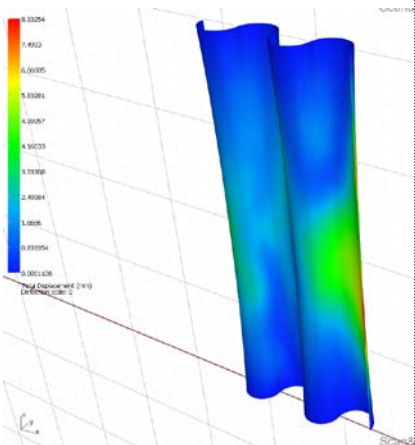


01 The first design appears to have as expected a big displacement towards the middle axis that intensifies closer to the edges. Furthermore something that is not evident from the approximate evaluation is the fact that the weak flattened middle part could also contribute to local buckling from the dead load of the top element.

02 In the second solution the geometry occurs from the same rules but this time the axis of twist is transferred higher. This is to avoid the buckling problem and the weak zone of the middle with the high bending stresses. The displacement though seems to not be improved.

03 In the third geometry, an attempt to increase the thickness of the geometrical cross section is being done (waveheight). At the same time an asymmetrical sinus shape cross section appears, as the corrugation has a shifting axis along the diagonal. However as it seems from the quick evaluation this doesn't decrease the displacement much.

7.1 / Form optimization



04 This option is an attempt to create a shape closer to the original corrugated façade. The difference is that in the side view the wave height is increased but it is reducing towards the middle. This shape is performing quite well regarding the bending due to wind load and the deflection seems to be lower than the previous shapes but it appears to introduce asymmetrical deformation.

Maximum displacement: 8.33mm

05 The fifth surface is an alteration of the previous concept. This time the reduction of the waveheight is happening towards the top edge and this is an attempt to lower the center of gravity and increase the resistance against bending.

Maximum displacement: 4.32mm

06 Finally an evolution of the latter is a surface that starts as a corrugated at the bottom edge and reaches the top as one flat surface locally at the top support. This is an idea driven from the previous concept but here it is more intensified. The aim is again to lower the center of gravity and enhance the stability. The final shape if seen from a side view resembles that of a pyramid/tapered fin from both sides.

Maximum displacement: 14.12mm

7.1.1 / Simulation inaccuracies

After the simulation with the Scan and Solve tool there were several points realized. These are summed up mainly in the one conclusion; that the simulation is failing to provide accurate results, that can be valuable for the selection process of the right surface. These is caused by several reasons explained here:

1st Geometry & Material

The model that was evaluated in the software was each time a continuous surface representing the surface of the facade with the respective geometry. To that geometry the thickness is given as monolithic element thickness. This problem occurs from the fact that the model in this software can be only a solid element out of one material. Subsequently it excludes the option of modelling a laminated glass, or even the build up of 2 layers of glass.

2nd Boundary conditions

The boundary conditions that are presumed in this design have been already once presented in strategy number 2.

A better description of the situation is that the surface of the facade, based on precedent examples of corrugated facades is chosen to be linearly supported at the top and at the bottom. The sides of the facade in the structural scheme are free to move. The bottom edge is, as it is in 90% of the cases, a clamped connection that is approached as a hinge in the structural models. The top connection has to accommodate movement of the adjacent structure of the building (ex. concrete slab or steel beams). In this case it has to be a roller support that is allowing movement in the z-axis.

In the case of Scan and Solve, due to limited experience with the software, these boundary conditions could not be modelled correctly. Therefore the only solution was to model the supports as fixed (transferring forces and moments).

3rd Safety factor

In this step of the selection process the safety factor that is applied in all structures in order to provide the reliability of the structural design, under limit state conditions, was not applied. This makes the simulations even less trustworthy.

4th Maximum stresses

The tool does not provide the option to change the coordinate system from global to local, so as to check the in-plane stresses. These are the stresses, that we are interested in comparing with the maximum allowable for glass. Since this is not feasible here the only comparison could be done only based on the displacements. This indication was not enough especially when all the above points are leading to major inaccuracies.

7.1.2 /Conclusions Scan & Solve

Due to the inaccuracies experienced in the simulations with the first tool it was made clear that the geometry has to be modelled carefully and with a different software that allows for stepped calculations. What is more, the detailing, glass build-up and safety factors should be decided before the calculation.

The previous points make clear that this could not be done for all 5 geometries due to time constraints. Therefore the choice at this point is to follow rules of thumb as well as architectural criteria for the selection of a final surface. The choice is to go for the 6th surface. The reasons for the choice is a combination of:

Fig.171 (opposite)_ Set of 6 surfaces. Evaluation of the volume for the overall material use in each design.

7.1.2 /Conclusions Scan & Solve

01 **Design value**

It is probably the most interesting of the designs as it resembles the shape of a glass curtain hanging from the ceiling.

02 **Structural shape**

The shape is a double curved sinus shaped shell that is reduced at the top into a flat straight edge. The benefits of this shape are, that it combines the stiffness of the bended geometry with pyramidoid shape (in a side view) that can provide greater stability to the facade.

03 **Transparency connections**

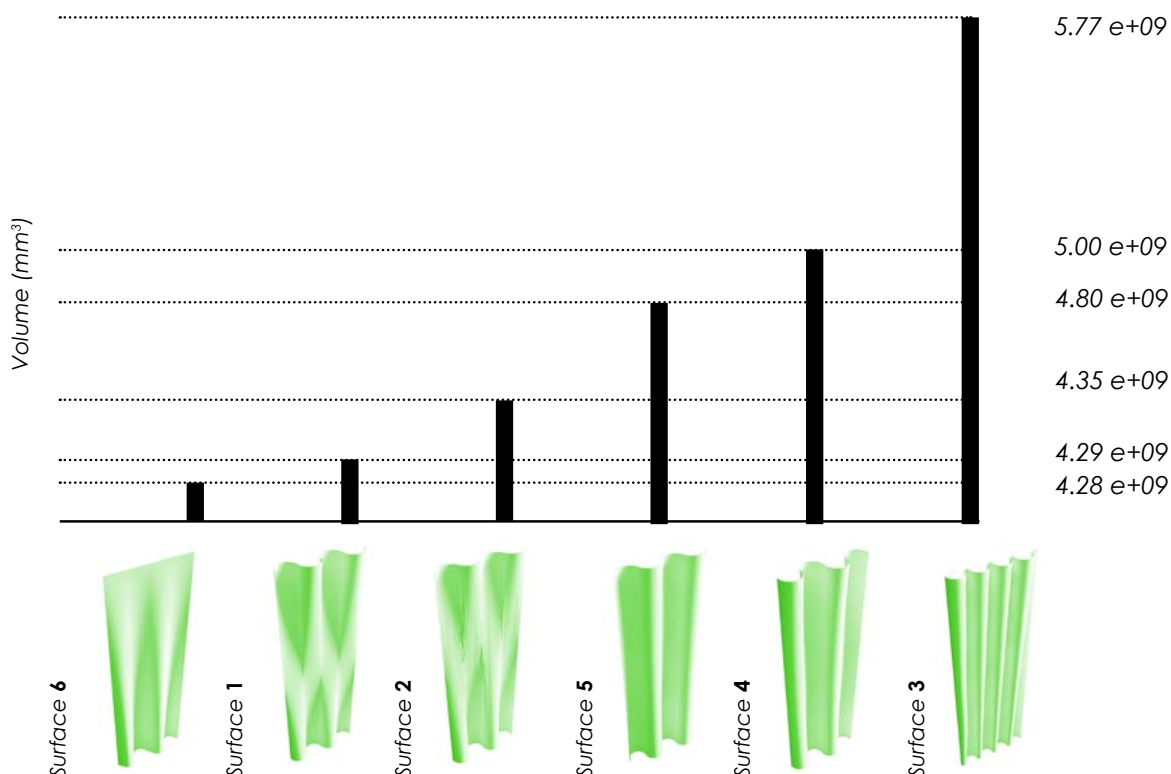
The transparency aspect in the case of this facade is more likely to be improved as the thickness is maintained almost throughout the whole span. Therefore the displacement occurring in the middle of the facade is smaller than in other cases and is not coinciding with a joint. The result is that there is no need for additional support behind the surface of the facade that would have been necessary in other cases; the case of the twisted panel across the middle.

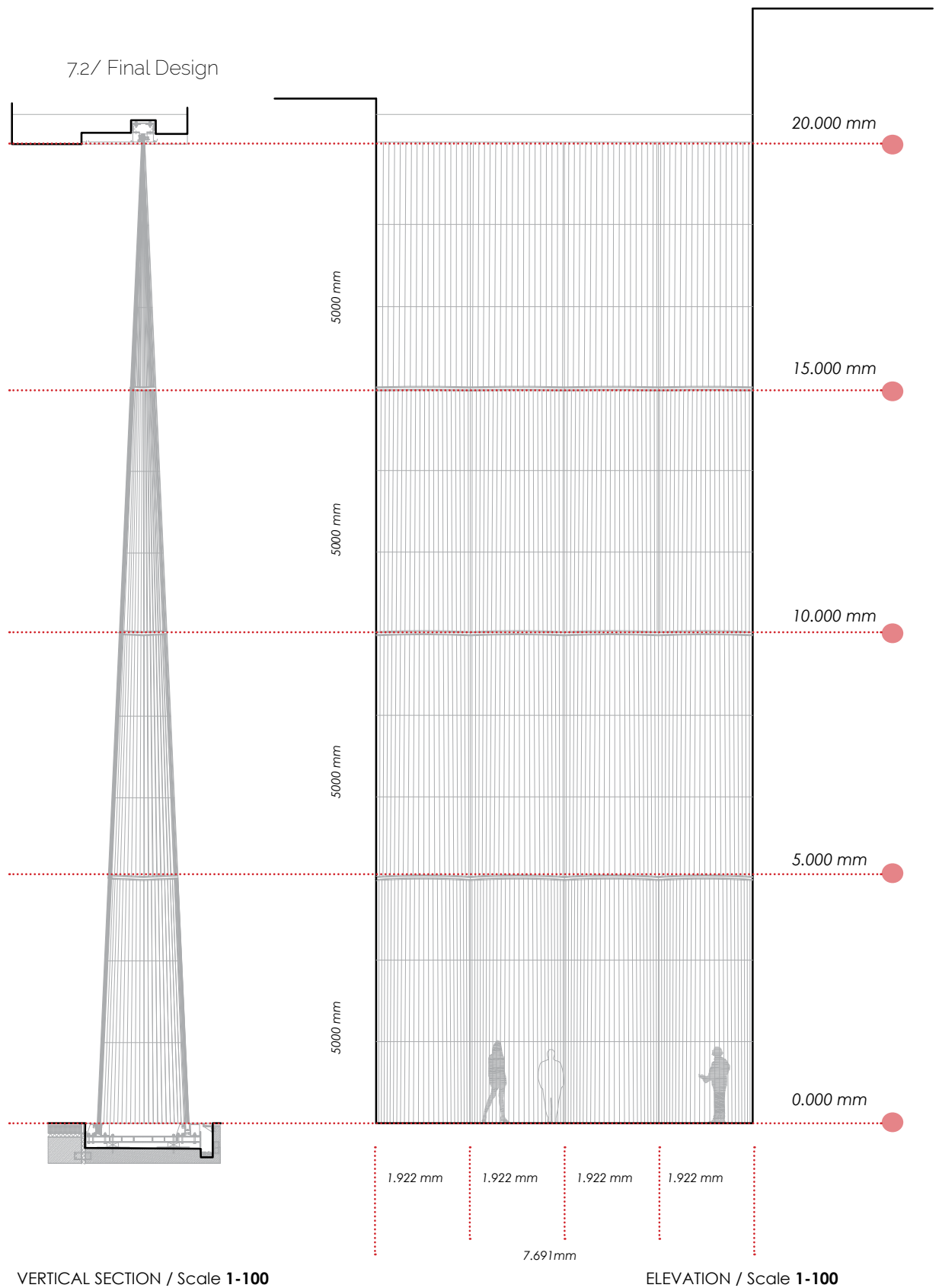
04 **Manufacturing**

As almost all the other shapes it can be manufactured divided into oversized bended components with method of the hot bending. Especially because the curvature is reduced towards the top edge, the overall complexity and intensity of radii is less than in the other facade shapes.

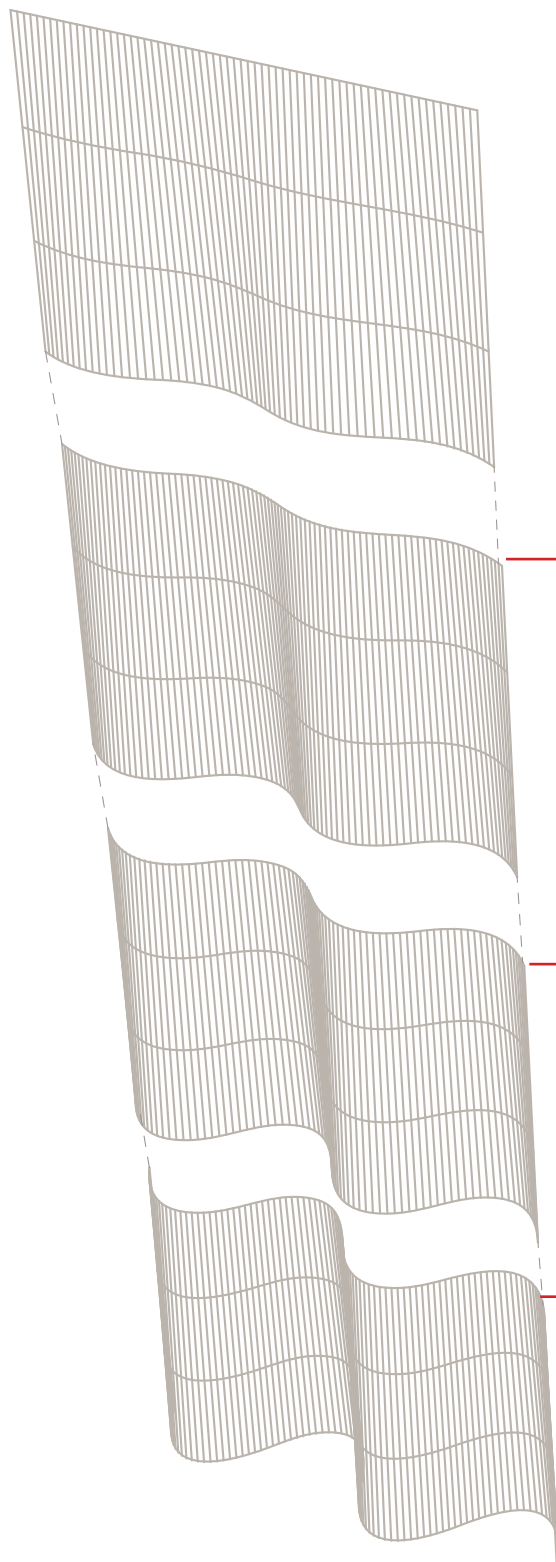
05 **Cost**

Probably it can be also considered the most cost effective shape as the use of material is less in this case. This can be also seen also from the table.

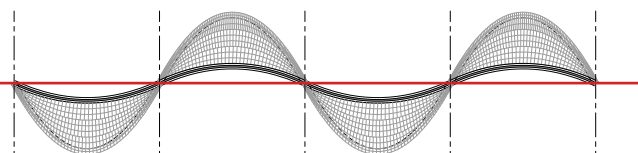




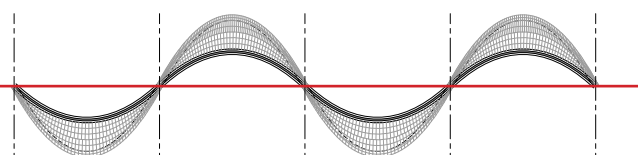
7.2 / Final Design



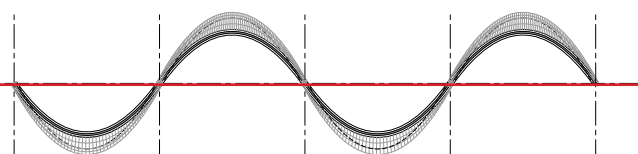
Horizontal Section 04



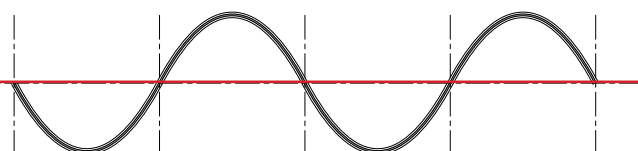
Horizontal Section 03



Horizontal Section 02



Horizontal Section 01



AXONOMETRIC PROJECTION

7.2.1 / Structural Design

Before we analyze the choices made for the structural design we have to mention first the prerequisites that will be taken into account. Already from the brief, one parameter that has been underlined, was the aspect of a fail safe concept for the facade. This is more important here than in other types of structure since we have to deal with an unpredictable material when it comes to failure of the facade.

7.2.1.1 / Safety - Reducing risk of failure

As it has been mentioned already in previous chapters the risk of glass structural components to fail abruptly due to the materials mechanical behavior is high. Since we don't want the structure to impose such risks there are several measures that can be applied in order to reduce the vulnerability of the structure and the

Measures for reducing risk:

Increasing the redundancy (post failure behavior) and avoiding complete failure. Increasing the redundancy and decreasing the damage sensitivity are the key objectives with which the structural glass safety should be optimized and of course this could also lead to a lower safety factor. Both of these aspects can be altered via a wide range of measures. We can distinguish between 3 levels of scale at which the structural safety can be influenced.

01 **Material level(micro)**

Altering the chemical composition and/or microstructure of a material to make it meet specific performance requirements.

02 **Element level (meso)**

Adjusting the element design, e.g. geometry, material selection, etc.

03 **Structure level (macro)**

Changing the overall structural composition, side constraints and/or external influences < Bos, 2009 >

In order to reduce damage sensitivity and enhance redundancy:

01 *On material level*

Thermal prestressing

The most common and widely applied method to decrease damage sensitivity and to enhance the redundancy levels on the material scale is the thermal pre-stressing which has been extensively described in stage 1 (pre-stressing glass components) of this research. The two most known methods are fully tempering and heat strengthening. The choice of the strengthening method for the façade elements is dependent on the benefits and drawbacks of the two methods.

Tempered glass is considered to be stronger against a number of failure causes:

- soft body impact
- thermal stress
- long term loading
- general loading

On the other hand it is more sensitive to some others :

- hardbody impact
- deep scratches
- chipping
- nickel sulfide inclusion*

Heat strengthened glass is generally considered to possess the lowest degree of damage sensitivity from both fully tempered and annealed glass, for it combines much of the advantages of the FTG (thermal stress resistance, long term stress resistance (dead load)) with those of annealed glass (impact / scratch resistance) < Bos, 2009 >.

7.2.1.1 / Safety - Reducing risk of failure

Assume compressive stress equal to the tensile stress

It is proved by laboratory tests that glass breaks in compression in much lower values than the named one <Veer, 2006>. The reason behind, is that the flaws inherent to glass lead to uniaxial forces that cause tensile stresses. Indeed, for example in the case of annealed glass, the value of 20Mpa, equal to its tensile strength, agrees well with the minimum values of all the data sets of experiments held by Veer in TU Delft for more than 7 years <Veer, 2006>. Therefore, this value consists the lower boundary for the structural calculations and should be regarded as the maximum value for both tensile and compressive stress. In the case of heat-strengthened glass this value is 40 MPa.

Minimize the stresses due to superficial flaws

Glass failure is governed by stress concentration around the superficial defects. These defects make the strength of an individual glass component, hard to predict. Minimizing the defects is probably aiming to constrain or avoid the cause of the defect. These are mostly coming from the machining processes (cutting, grinding and polishing glass edges), or primary processing like the annealing. An improper annealing can cause glass to crack on the cutting table due to residual stresses <Veer, 2006>. This suggests that one should use the right settings for the machines for cutting and grinding as well as maintain them properly.

02 On element level

Lamination

The most widely applied safety enhancing technique for glass, in construction, is laminating. Lamination as a method of enhancing the stiffness of a component is also analytically mentioned in stage 1. With regard to damage sensitivity, lamination provides a highly effective protection for the inner/non-impacted layer(s) < Bos, 2009 >

Of course it has been proven with multiple test and investigations that the technique of lamination provides a crack growth barrier. This barrier allows the level of damage to vary between different degrees and to ultimately enhance the redundancy of the element.

Additionally the effects of lamination in the post breaking behavior of the element are dependent on the choice of interlayer as well as the type of glass (annealed, heat strengthened, fully tempered). From the method we know that lamination of a transparent plastic film between two or more flat(or bended) glass planes enables after breakage the fragments to adhere to the film so that a certain degree of structural capacity is achieved as fragments 'arch' or lock in place. < IABSE, 2010 > Of course this indicates that the post breaking behavior is influenced by the type of fragmentation. The structural capacity is therefore increasing as the fragment size increases. This is the opposite to the tensile strength for each type of glass.

From the point of view of the interlayer the most widely used material is Polyvinyl Butyral (PVB). Normally 2 or more PVB foils of nominal thickness 0.38mm form a PVB interlayer. Usually for heat treated glass or curved as in the case of the façade design the components must be laminated with more than four, sometimes 6 foils in order to compensate for the unevenness of the glass panels due to tempering < IABSE, 2010 >. In the most recent years alternative interlayers like SG (Sentry Glas) are being used and they can provide higher stiffness and temperature resistance, tearing resistance and tensile strength compared to PVB. Other materials like cold poured resins are being used as interlayer of 1 - 4 mm thickness.

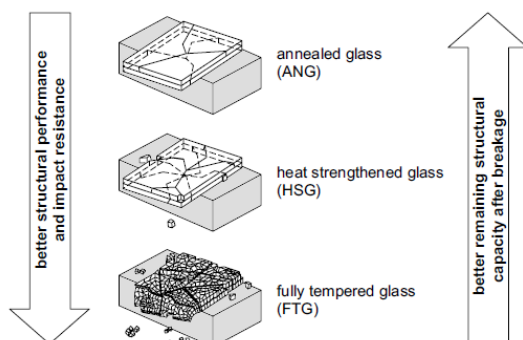


Fig.172_ Post breakage behavior of laminated glass made of different glass types < Mathias Haidmann, 2010 >

7.2.1.1 / Safety - Reducing risk of failure

Recession of the inner ply

Another measure that can be taken to reduce the damage sensitivity of the glass component is to protect the laminate ply that is contributing to the structural capacity, by receding it. The inner layer of the ply can be thus protected from stress corrosion.

Stainless steel edge reinforcement

Furthermore an alternative measure is the edge stainless steel profiles that are applied in glass beams and they were proven to act as a form of metal protective covering that prevents the damage to reach the inner layer.

Protection of the edges

Last but not least a protective covering protects the edge against moisture induced stress corrosion although no quantitative studies have proven that yet < Bos, 2009 >.

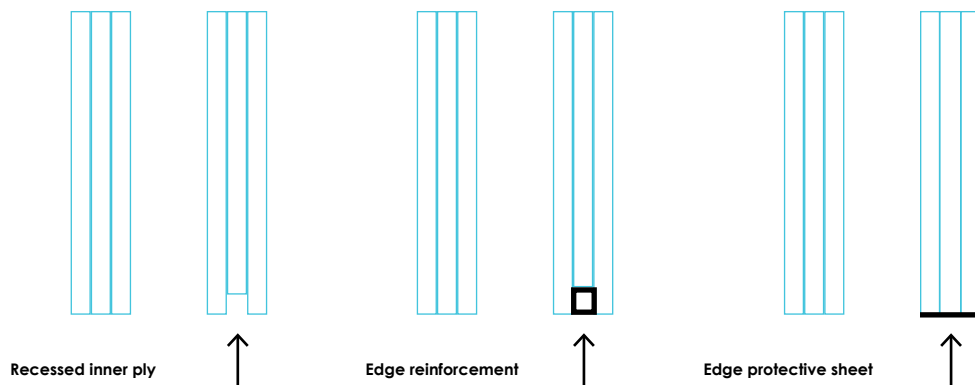


Fig.173_3 Measures for reducing damage sensitivity on element level

03 On structure level

On structure level the two most common methods followed to achieve mainly safe failure behavior is :

Provide alternative load paths:

Introducing alternative load paths in a structural scheme allows for lowering the damage sensitivity levels. However this is a method that enhances more the redundancy of the structure and/or individual elements. This can be achieved, for example, by having components span more than one field or through the interconnection of multiple components <Bos, 2009>. A scheme explaining the principles in glass facades is shown in fig. xxx. For this method to be effective the adjacent elements need to be sufficiently strong to bear the loads of the failed element and to avoid progressive failure of the structure until the element is replaced < Bos, 2009 >.

In the case of the façade of the La Fayette this could be achieved by the continuity of the horizontal joint in the cross joints, that should be able to redistribute the loads to the neighboring panels.

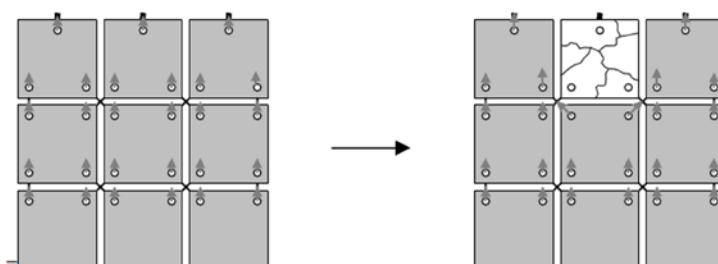


Fig.174_ Alternative load paths secured in a hanging facade scheme.

7.2.1.1 / Safety - Reducing risk of failure

Compartmentalization

Compartmentalization is usually applied in horizontally oriented structures like bridges and aims at restraining the effects of failure in local field of the structure (compartments) and allowing only those to collapse while the rest is left intact.

Hyper-static structure

Another way is to opt for a hyper-static structure where it is ensured that the failure of individual components or limited amount of components won't affect the global stability of the structure.

Scheme that keeps the structure under compression and not under tension

Finally follow a structural scheme that allows the glass to be loaded in compression and not in tension. Since glass is weak in tension creating this scheme that is introducing compressive forces on it could compensate for the tensile stresses that will occur from imposed actions and increase the overall strength. This scheme is preferably a scheme where the dead load of the elements is carried in stacking and it avoids hanging components. Subsequently the gravity is keeping the plates in place.

Minimizing the stresses introduced from connections

The localized stresses introduced by certain types of connections, like drilled or bolted connections, can be eliminated by using adhesively bonded connections or dry connections between the glass components. This way we avoid the stress peaks introduced locally around the drilled holes in glass.

7.2.1.2 / Structural design of the facade

Based on all the previous fundamental rules for enhancing the safety of a glass structure we can establish the structural design for the facade of the La Fayette Modern. The choices are made in a similar structure with the three levels of measures. The micro, the meso and the macro.

Micro / Material level

In the first level that of the material the choice is to opt for a the heat strengthened glass that has a maximum tensile strength of 70 Mpa. The choice for this type of glass, is because the process of heat strengthening is happening with a lower cooling rate than fully tempered glass. Subsequently the material is left with lower residual stresses.

The second aspect of this choice is that heat strengthened glass has a larger type of fragmentation that is closer to annealed glass and therefore it is better for securing higher load bearing capacity after breakage.

Meso / Element level

In the level of the component the different oversized panels are subjected to a very strong principle that applies both in the meso and the macro level (that of the structure). This principle is the bended geometry that is responsible for creating a component that is stiffer than a flat. In this case the geometry itself is creating an archlike cross-section that counteracts the bending forces that have a stronger effect in the middle of the panel.

7.2.1.2 / Structural design of the facade

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01 Micro / Material level

Thermal pre-stress

In the first level that of the material the choice is to opt for a the heat strengthened glass that has a maximum tensile strength of 70 Mpa. The choice for this type of glass, is because the process of heat strengthening is happening with a lower cooling rate than fully tempered glass. Subsequently the material is left with lower residual stresses.

Since the function of the building is a multiple use public art space with a café and restaurant, the façade needs to obtain a high degree of impact resistance so as to protect the visitors (soft body impact). Furthermore the choice of this type of glass will increase the structural capacity of the elements as we need strong glass to compensate for the tensile stresses caused from bending action (on the surface of the façade)

The second aspect of this choice is that heat strengthened glass has a larger type of fragmentation that is closer to annealed glass and therefore it is better for securing higher load bearing capacity after breakage.

02 Meso / Element level

Geometry

In the level of the component the different oversized panels are subjected to a very strong principle that applies both in the meso and the macro level; that of the structure. This principle is the bended geometry that is responsible for creating a component that is stiffer than a flat. In this case the geometry itself is creating an archlike cross-section that counteracts the bending forces that have a stronger effect in the middle of the panel.

Laminated facade panels

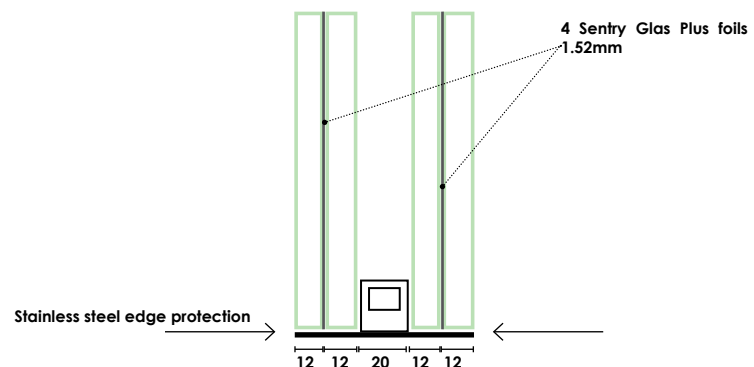
Lamination is chosen as a method of decreasing the levels of damage sensitivity. The build up of the panels is following the scheme of an insulated glass unit. In this scheme the inner and outer leaf are laminates of heat strengthened glass with an interlayer in between. The choice of interlayer hasn't been done at this point is something that is out of the scope of this research since it is going deep into the material science field. According to information gathered from the literature and precedents the PVB is the most common interlayer used in the lamination process. On the other hand the most recent alternative with remarkable performance and extraordinary properties is the Sentry Glass (ionoplast) interlayer that has been used in the cases of apple stores. SG might be adding to the general structural capacity of the laminate since it is stiffer and also proven to be more temperature resistant and 5 times more tear resistant than PVB. However due to this inherent stiffness the interlayer is making the lamination process way more difficult and also if we want to apply this in a double curved laminate it could be even more challenging. According to Dr Karel Volers (specialist in manufacturing of free from glass elements) this could be probably feasible with current techniques, but it hasn't been tested yet. Another question at this point would be if the stiffness of the interlayer would introduce residual stresses in a curved glass unit, as it is forced into a curved shape. The interlayer chosen finally is Sentry Glas 1.52 mm that is meant to compensate for the unevenness between the two bended glass sheets.

7.2.1.2 / Structural design of the facade

Structural spacer / Edge protection

Last but not least the curved shell units of the facade should be insulating units. This brings the typology of the cross section to double glazing with an intermediate spacer element, where both glass leaves are laminated. The spacer being a stainless steel structural spacer can enhance the stiffness of the facade panels. However it doesn't have the same benefits as in the flat panels, as the stiffness is already given by the geometry. Ultimately the edge of the facade bended plates are protected with a flat metal edge that is running along the peripheral of each element. This structural principle is often met in the cladding of aircrafts, where the vulnerable edges of the sandwich composite panels are protected by a steel edge.

Fig.175_ Diagram showing the composition of the build-up and the measures applied for reducing damage sensitivity of the element.



Thickness of plies

The thickness of the plies is a parameter influenced by the structural capacity needed for the components but most importantly the exact number is defined by the thicknesses available from glass manufacturers and post processing.

As already mentioned in one of the measures of increasing the safety of the structure is to design a hyper-static structure so as the components involved after failure of one should be able to take over the loads.

The plies that compose the panels of the facade should have a manageable thickness in order to be subjected to warm bending process and to achieve a lamination process without high tolerances. The maximum bendable size found in the market is 19mm. However it is not recommended to use such a thickness as we would have to deal with very large weight added to the structure and high tolerances. Ultimately the plies are chosen with a thickness of 12 mm and the panels' total build up consists of 2 times **12 / 1.52 / 12** and a spacer of **20 / 20 / 2**.

03 Macro / Structure level

Geometry

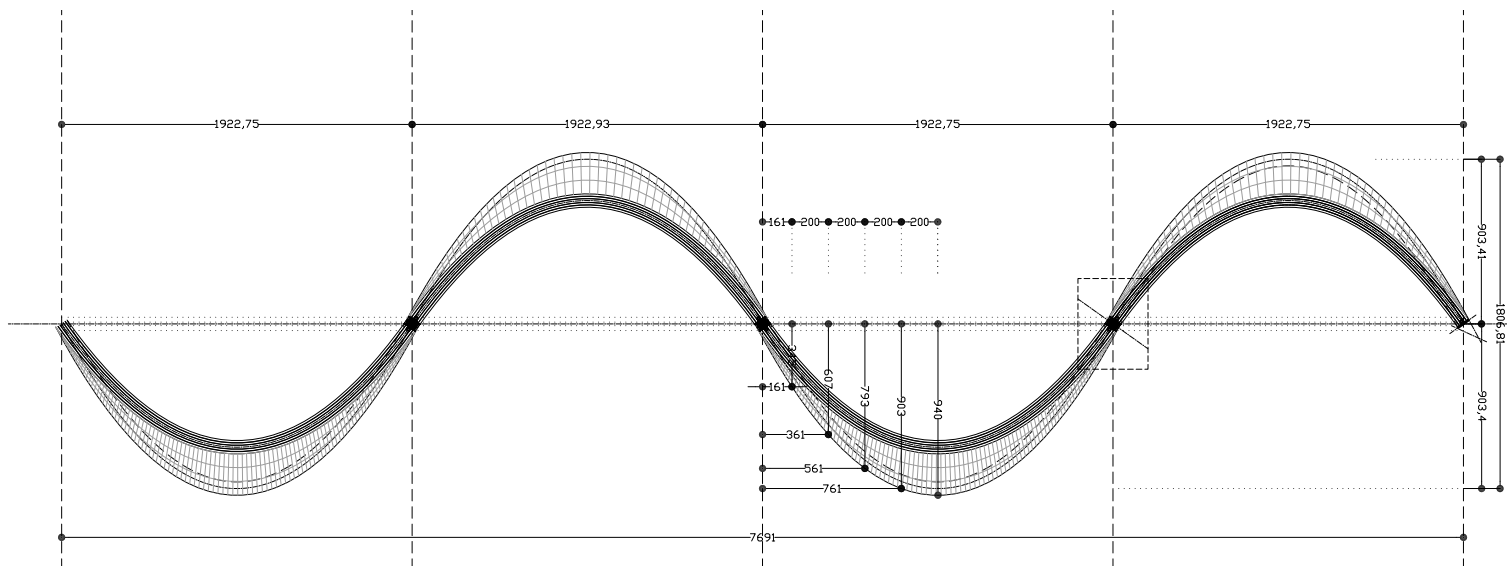
In the level of the structure the principle behind the design is that of the load bearing structural skin. The structural scheme of the facade follows a repetitive mode of alternating bended elements so as to counteract both negative and positive lateral forces acting on the surface of the facade. On the other hand the whole facade geometry is a wide sinus shaped curve at the bottom that develops into a double ruled surface reducing towards the top into a flat edge.

The alternating reducing curved parts of the shell have the action of tapered flat fins that support the surface of the facade from both sides. Furthermore the wider base transfers the center of gravity lower, thus enhancing the stability and the buckling resistance due to the dead load.

7.2.1.2 / Structural design of the facade

Dimensions

From studies and tests conducted on the realized corrugated glass facades designed by Rob Nijse it has been proven that the geometry should be effective against the wind – load if the waveheight to span ratio is 1/20. This doesn't apply completely in the new geometry as the surface follows different rules. The sinus wave is designed so as to start with a height of 1800mm at the bottom and reduce itself in the middle at a wave height of approximately 1000mm. Then the dimensions of the waveheight in the zone of the middle where the critical area is, will be subjected to the rule of the 1/20 of ratio (waveheight / span) since the span is 20.000 mm.



PLAN SECTION / Scale 1-20

Load carrying scheme

As mentioned in a previous chapter the façade is aiming to perform as stiff 3-dimensional surface that is able to act as structural skin without any additional.

Since the bended panels cannot be fabricated in length larger than 5.6 m the surface as indicated before has to be divided into 4 pieces vertically and 4 horizontally. This causes problems in the performance of the geometry as it is interrupted due to manufacturing constraints.

However this indicates that for this 3D surface to work as a mechanical whole the joints that occur between the panels have to be firm connections. These connections are contributing by transferring moments and forces as if the surface was an intact body securing continuity of the geometry.

The dead load of the upper panels is carried in theory ideally in stacking due to the stiffness of the bended geometry and the compressive strength of glass. Since the waveheight is also wider at the bottom the geometry is able to carry the weight load without facing the problems of buckling. All in all this act keeps the panels under compression scheme where the glass behaves better as a material.

Under lateral loads caused by the wind the facade ,given the required continuity, secured by the joints , should act as a plate linearly supported at the bottom and the top edge. Since it is not recommended for glass itself to transfer moments in a fixed connection scheme the bottom edge is usually a hinge that is translated into a clamp fixing. On the other hand the top edge has to move independent from the buildings adjacent structure (beam and slab). Therefore the top connection is a roller that allows for movement in the z-axis and restraints the translation in the y-axis (direction of the wind load) and x-axis .

7.2.1.2 / Structural design of the facade

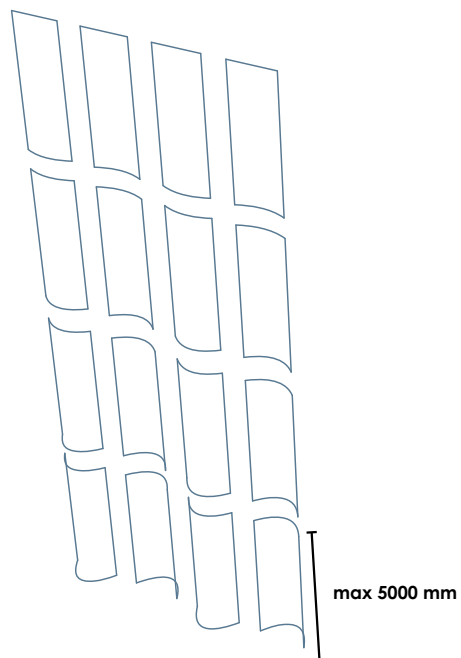


Fig.176_ Segmentation of the surface in manufacturable panel sizes.

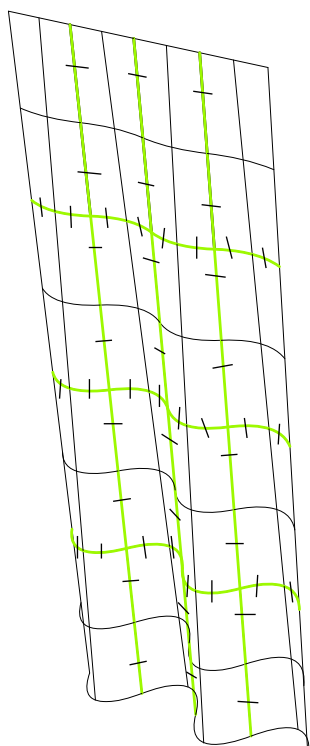


Fig.177_ Firm joints between the panels so as to transfer forces and moments. Create an intact surface.

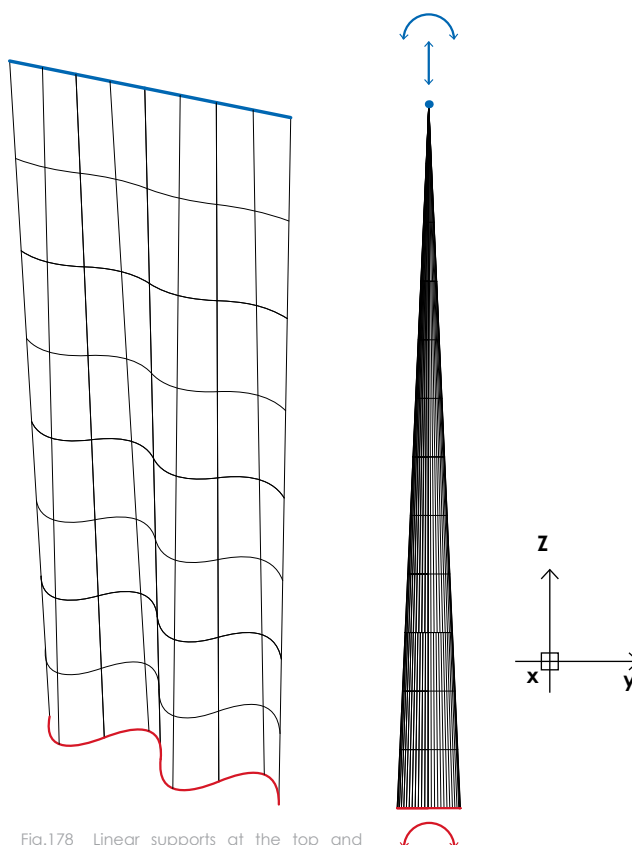


Fig.178_ Linear supports at the top and bottom. Top roller & bottom hinge performance.

7.2.1.2 / Structural design of the facade

Connections / Detailing

As it was already mentioned a great deal of the success of the structural scheme is dependent on the connections between the panels that have to be able to transfer the forces and the moments caused on this interface.

01 Requirements

These connections have to be able to achieve three main conditions. The first has to do with their structural performance and their ability to be **strong enough to transfer the loads** and keep the panels firmly connected so as to serve the **continuity** of the 3dimensional surface. Within this frame we can include their ability to provide **alternative load paths** especially through the cross joints between four panels in order to provide a degree of redundancy for the structure.

The second and very important aspect, that was already a prerequisite from the beginning of this thesis, is that they have to **increase the levels of transparency by being as small as possible**. At this point it should be mentioned that the smallest current intermediate structural joints provided in bended glass facades are those of MAS an De Strom with a face of 150mm.

The last and also very important is to take into account tolerances for facilitating the assembly process. Since we already have to deal with oversized components and complicated geometry tolerances is a very important factor especially when we try to create such a small connection. An aspect that is increasing the degree of complexity in these joints is that of geometry, where the deviations from manufacturing processes of bended elements are expected to be higher than in simpler straight and flat geometry.

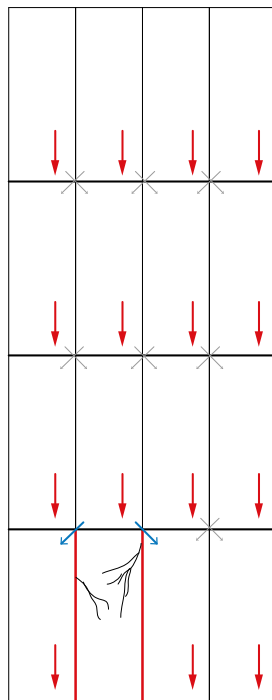


Fig.179_ Principle of alternative load paths provided by the cross joints between 4 panels. Loads have to be re-distributed.

02 Principles

One of the main principles when designing connections between glass and other materials is to avoid direct contact between glass and harder materials (e.g. steel, aluminium, concrete etc.) by employing intermediate softer materials (e.g. plastics, resins, neoprene, injection mortars, fibrous gaskets etc.). These intermediate materials have often smaller or same stiffness to glass but they should be durable and corrosion resistant.

The most recent advancements in adhesives and glued connections have indicated new type of joints that accommodate more even distribution of loads, prevent stress concentration that occurs in bolted or drilled connections and provide transparent glues that are durable enough and tolerant to 'yellowing'. In the latter family belong the **SGP** (Sentry Glas Plus) ionomer interlayer and **GB 350** acrylate, both tested in structural bonds between metal and glass in the cases of the All Transparent Pavillion, experimental study of TU Delft, and the reinforced glass beams. The SGP is also known in the latest advancements for the achievement of embedded connections in the glass laminate. These connections were applied in multiple cases of glass stairs for the Apple Stores and the Apple glass Cube No. 2, by Eckersley / O' Callaghan.

The principle of the proposed connection between the curved glass units is to use the structural spacer and the protective edge as the interface that will transfer the forces and connect the 2 panels together; horizontally & vertically. This is a principle very commonly applied in the detailing of aircrafts' composite skin. The panels have usually a steel protective edge that creates the interface for the connection.

As the spacer is adhesively bonded to the glass the force is transferred in contact by introducing compression in the surface of the glass that is in contact with the spacer. The bond can be achieved with a strong adhesive interlayer such as SG.

7.2.1.2 / Structural design of the facade

As it has been analyzed in previous chapters describing the general recommendations for the joints in the corrugated glass facades, the most critical joints are the horizontal ones, whereas the vertical joints are less prone to stresses, as they are benefited by the geometry. However the non perfectly symmetrical cross section of the facade, that is reducing in depth towards the top, is allowing for almost flattened parts to occur at the top. In these parts the vertical joints might have the almost the same conditions to face as in the horizontal parts.

Therefore it has been decided to follow the same principles in both joints.

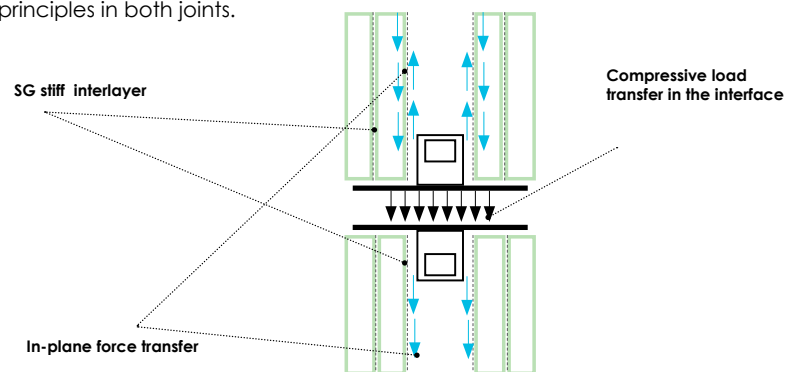


Fig.180_ Principle of compressive load transfer via the spacer and the edge interface between 2 panels.

03 Joint geometry

The geometry of the interface between the panels is a typical lap joint. Furthermore the connection follows the path of an extrusion that runs along the edge. The stainless steel edges and the lap interface are forming one solid piece. This piece with the reversed bottom connection are interlocking so as to create a solid 'setting block' that covers almost the full cross sectional width. The two edges are fastened together with a 6 mm diameter bolt. In the process a second type of joint geometry was developed. In the second case the force transfer is done via conical protrusions at the underside of the spacer. These interlock respectively with 2 separate stainless steel setting blocks.

One of the conditions that must be ensured in order to achieve the better force distribution from the top to the bottom panel is the symmetry and the perpendicularity to the generating surface ; surface of the facade.

The condition of the perpendicularity is a key aspect that is also contributing to the complexity of the joint in manufacturing terms. Ultimately the horizontal joint has to be bended and twisted with 3 degrees of twist to the initial position at the edge and the vertical follows a straight path , but still has to twist in order to meet the neighboring edge perpendicular.

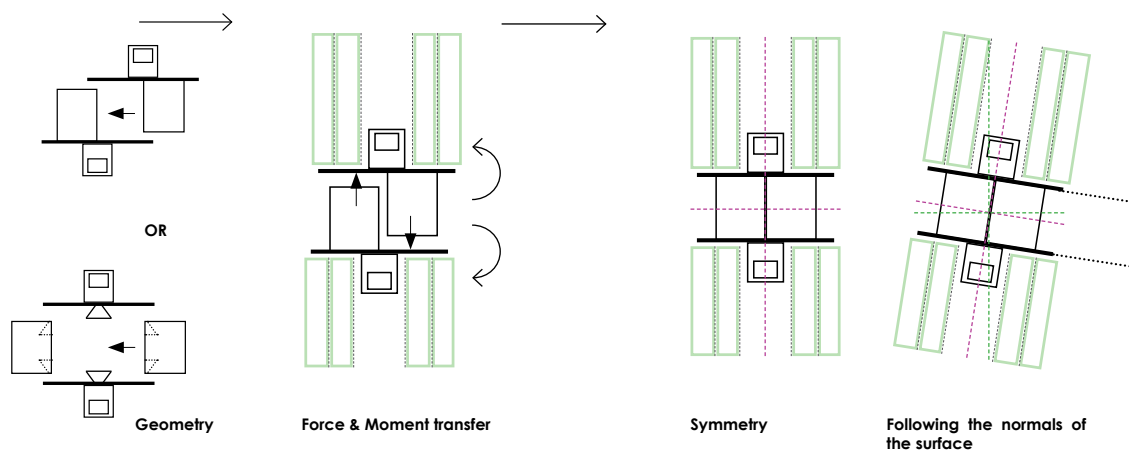


Fig.181_ Joint geometry and condition of force transfer.

7.2.1.2 / Structural design of the facade

04 Assembly

The detail has been worked out in such a way, so as it allows for tolerances that will facilitate the installation process. At this stage the process is valid in principle but there are yet parts to be solved and obstacles to be overcome. Several alternatives have been developed but all of them are based on the same basis. Two main alternatives have been developed in drawings.

Horizontal Joint 1

The stainless steel (or titanium) interfaces created between the top and the bottom, as well as the spacer can be produced as stainless steel (or titanium) extrusions. This is a very special process done by company Plymouth commonly for aerospace industry. The constraint is that the shape of the cross sections should fit into a circle of 150mm diameter (for titanium) and 140mm diameter (for stainless steel). Since the facade cross section of the profiles can fit this dimension the extrusion and the deformation is feasible. However the tolerances from such process can be close to ± 2 mm, given that the length of the cross section is the length of the arc at various positions.

After the extrusion the profiles can be bended and twisted. Furthermore the glass sheets are being bended with hot bending process using the adjustable mold in order to achieve accuracy. The plies can be bended spontaneously using a separating powder between the sheets in order to achieve matching curvatures. After they are bended the edges have to be water jet cut in order to achieve the desired perpendicularity for the joints. Ultimately the last stage of the glass plies processing is the tempering of the sheets. Last but not least all the glass layers and the stainless steel cross section can be laminated in the autoclave.

Taking the tolerances of the extrusion process into account a gap is intended in the middle 4mm in order to avoid overlapping, as well as 2 mm for the contact faces between the top and the bottom. For the above mentioned reasons the installation is being completed in 2 phases. First is the setting of the profiles. Next in line is the adjustment of the 2 by introducing a padding for aligning the screw holes. After that the bolts can be tightened. Last the top horizontal 2 mm gap has to be filled with a material that allows force transfer without performing as a hinge. One of the solutions that were examined is the an additional bushing that will close off the space or liquid resin that will harden later and create the interface. The initial concept was based on having the same bushing to close off the gap but afterwards to inject resin through the bolt, that will fill up all the cross section. A third option would have been to use an expansion anchor bolt that would grip the cross section after the setting of the profiles. The last option hasn't been detailed out yet. Finally the finishing and weatherproofing of the joint can be done on both sides by silicone or by a push-in gasket. This solution is also a final touch secure a more homogeneous appearance for all joints.

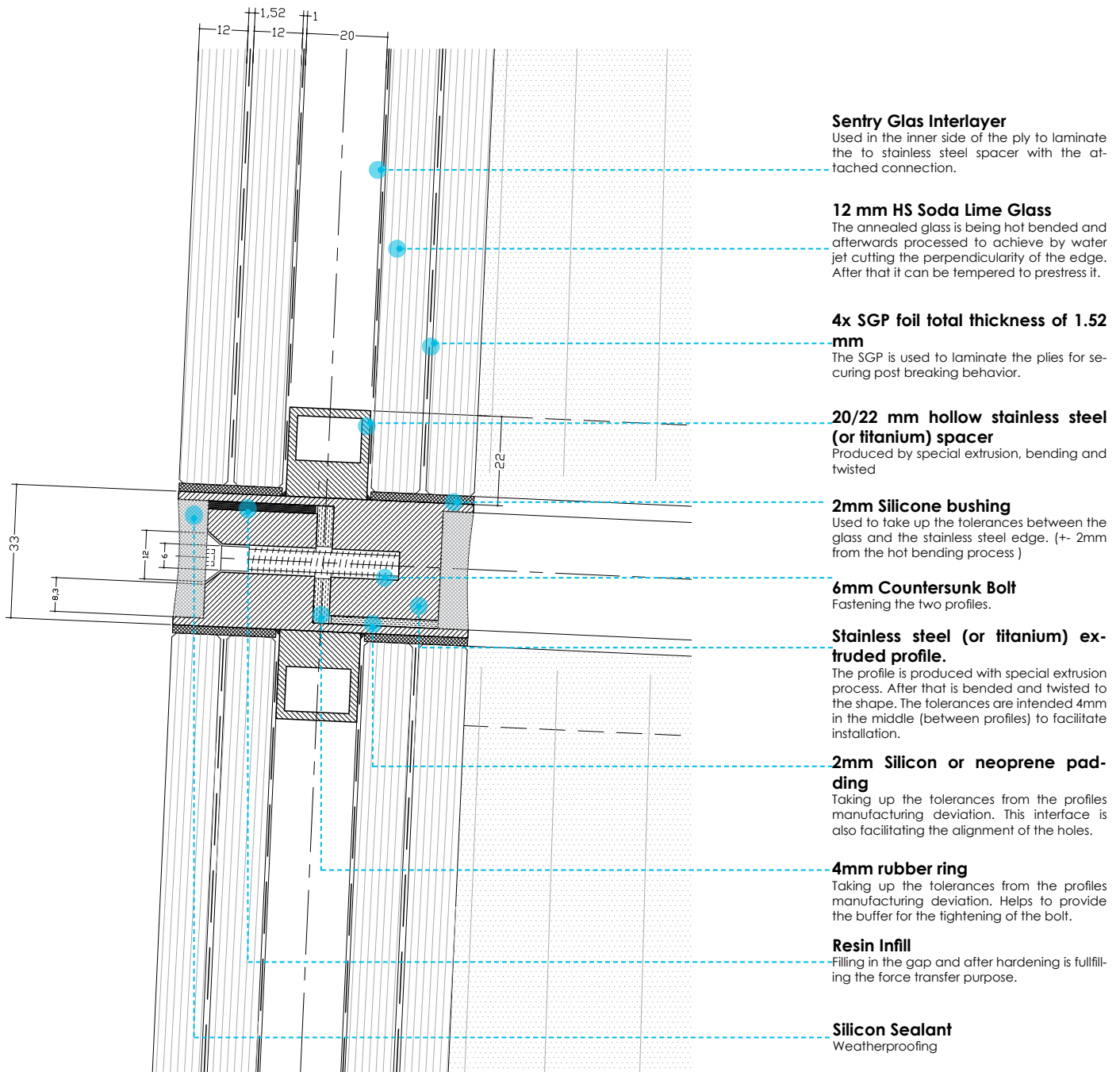
Horizontal Joint 2

In the second alternative the geometry and therefore the force transfer is changing. In the first joint ultimately the performance and the compressive force in particular are dependent on the properties of the resin infill that will secure the vertical force transfer as well as the rotation limitation.

However if the geometry is slightly adjusted, a more flexible joint and less prone to tolerances can be produced. So for this second concept the vertical force transfer is done by conical protrusions that are attached at the top and bottom spacer. The interlocking interface between them is achieved by 2 setting blocks carrying the negative undercut of the protruding parts. As they slide towards the middle they can be set at various positions and therefore allow the top panel to rest on them. This is done mainly because the conical part is set and transfers the forces adequately. However even in this solution there is still an issue with the tolerances in the conical interlocking point.

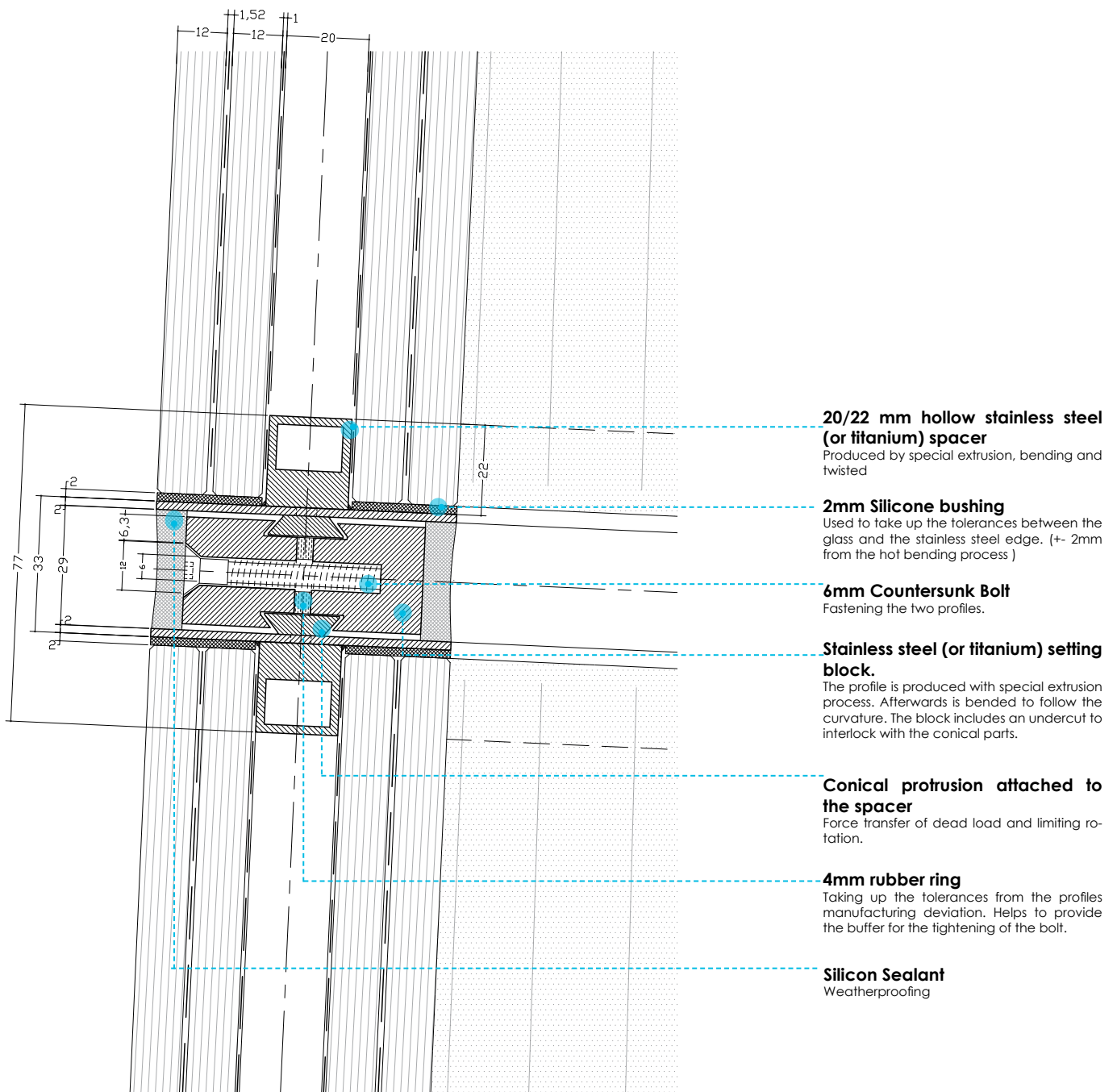
To sum up the final size of the joint width on the facade will be at every horizontal position **33mm**; extremely small compared to the scale of the facade and the purpose it is serving.

7.2.1.2 / Structural design of the facade



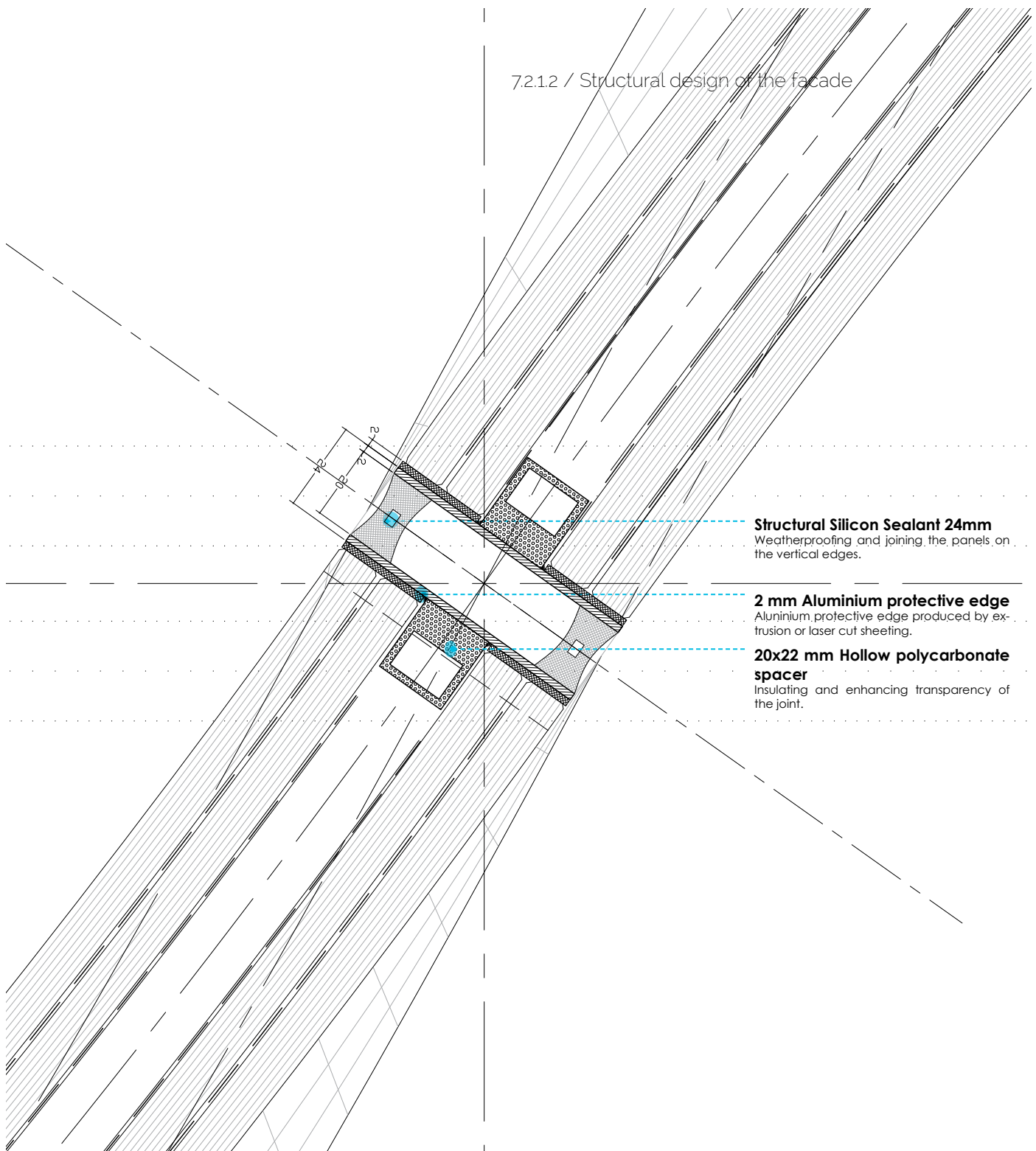
HORIZONTAL JOINT 1 DETAIL / Scale 1-1

7.2.1.2 / Structural design of the facade



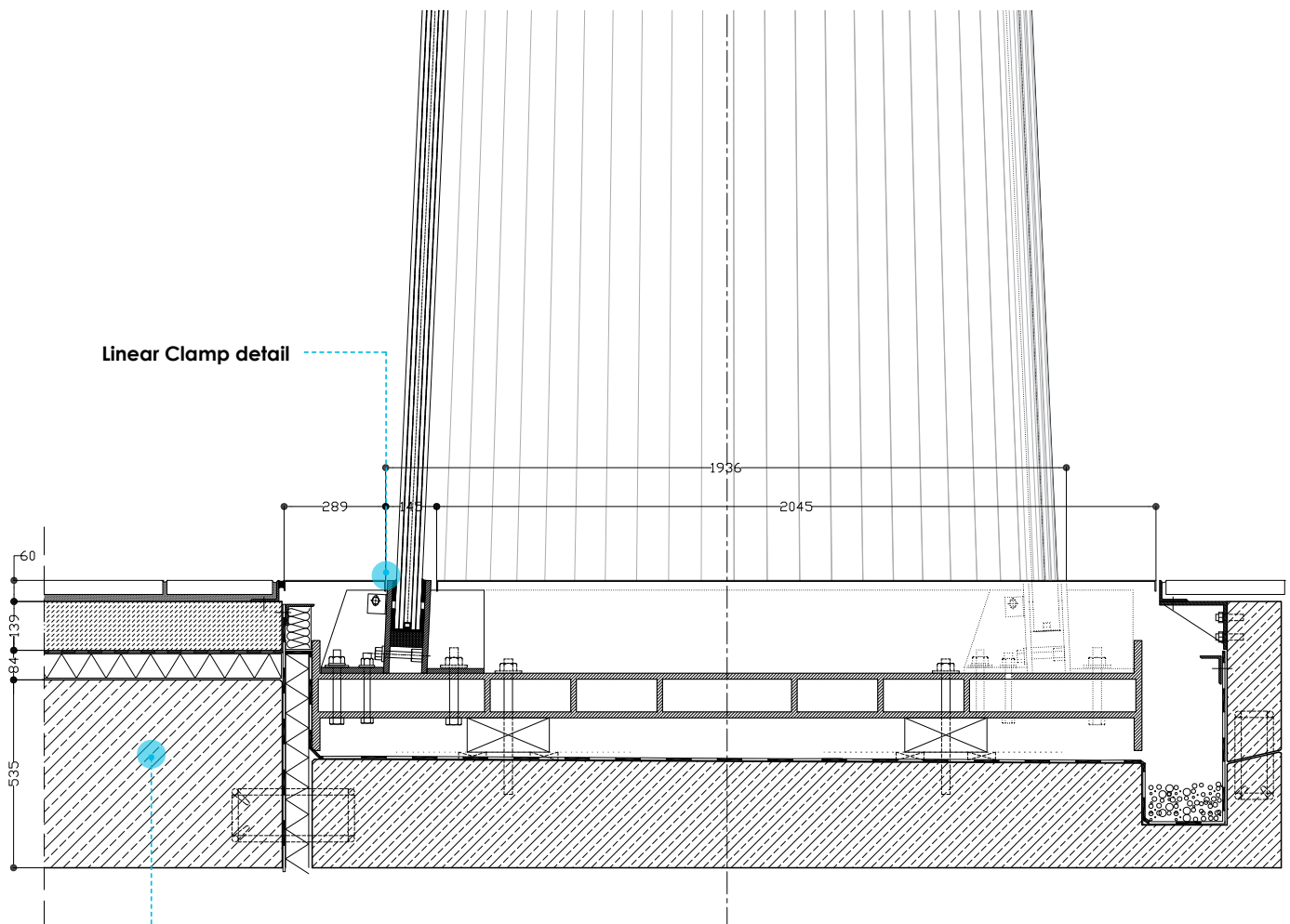
HORIZONTAL JOINT 2 DETAIL / Scale 1-1

7.2.1.2 / Structural design of the facade



VERTICAL JOINT DETAIL / Scale 1-1

7.2.1.2 / Structural design of the facade



Floor Build up

Stone tiles 30mm
Mortar 20mm
Cement screed 140mm
Polyethylene membrane
Insulation
Concrete 530mm

05 Supports

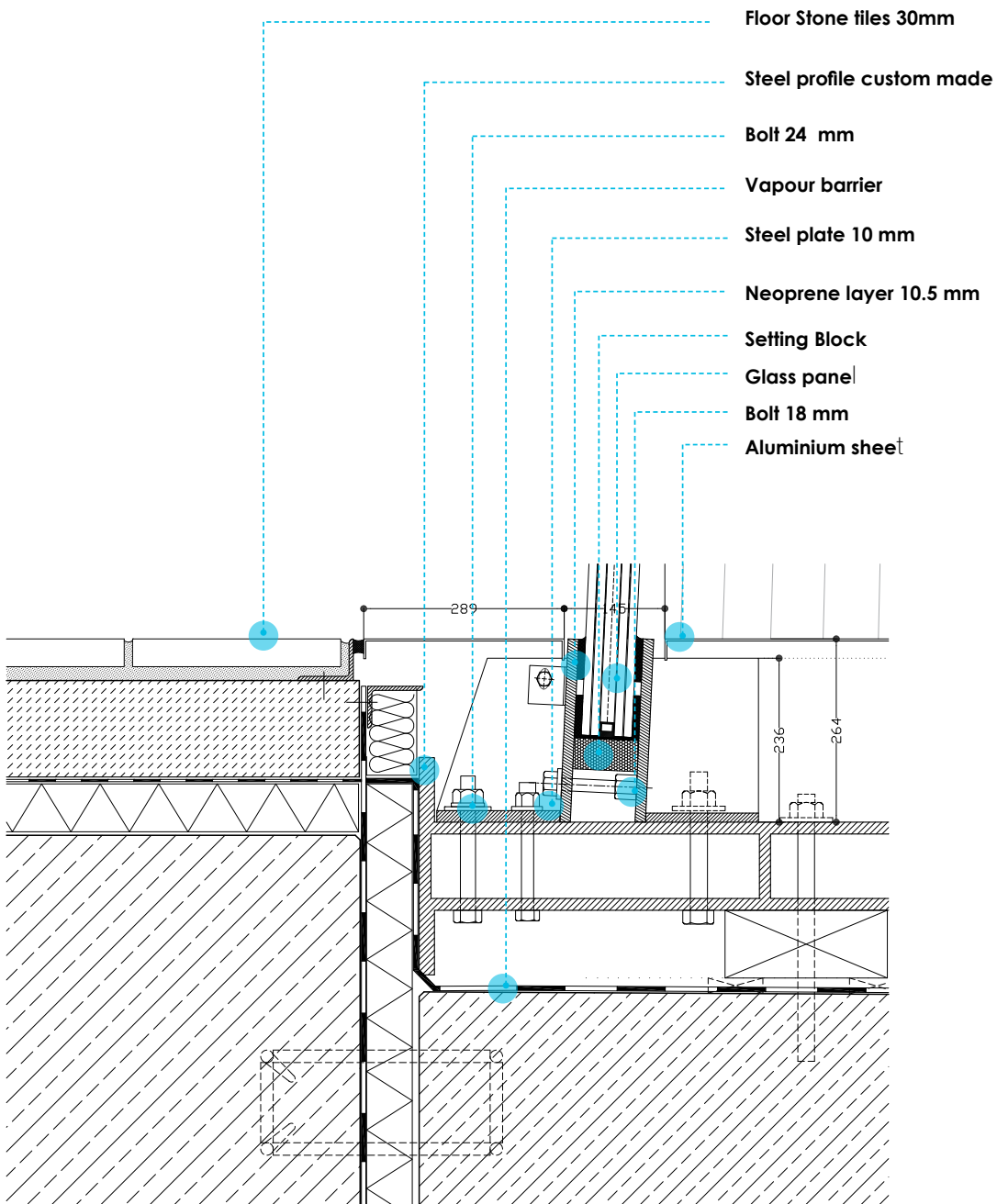
For the linear supports as it has been mentioned before the bottom is going to perform as a hinge and the top as a roller allowing movement in the z-axis.

The hinge is achieved by clamping the glass component between to steel faces. The material is not directly connected to the steel profile, but in between them there is a 10mm layer of EPDM.

Regarding the roller support, this is being achieved by holding the profile between 2 flexible gaskets that allow the top flattened edge to slide up and down, while keeping it from moving in and out or sideways. The edge is not restricted from the top as the distance from the top element is adequate to allow this movement.

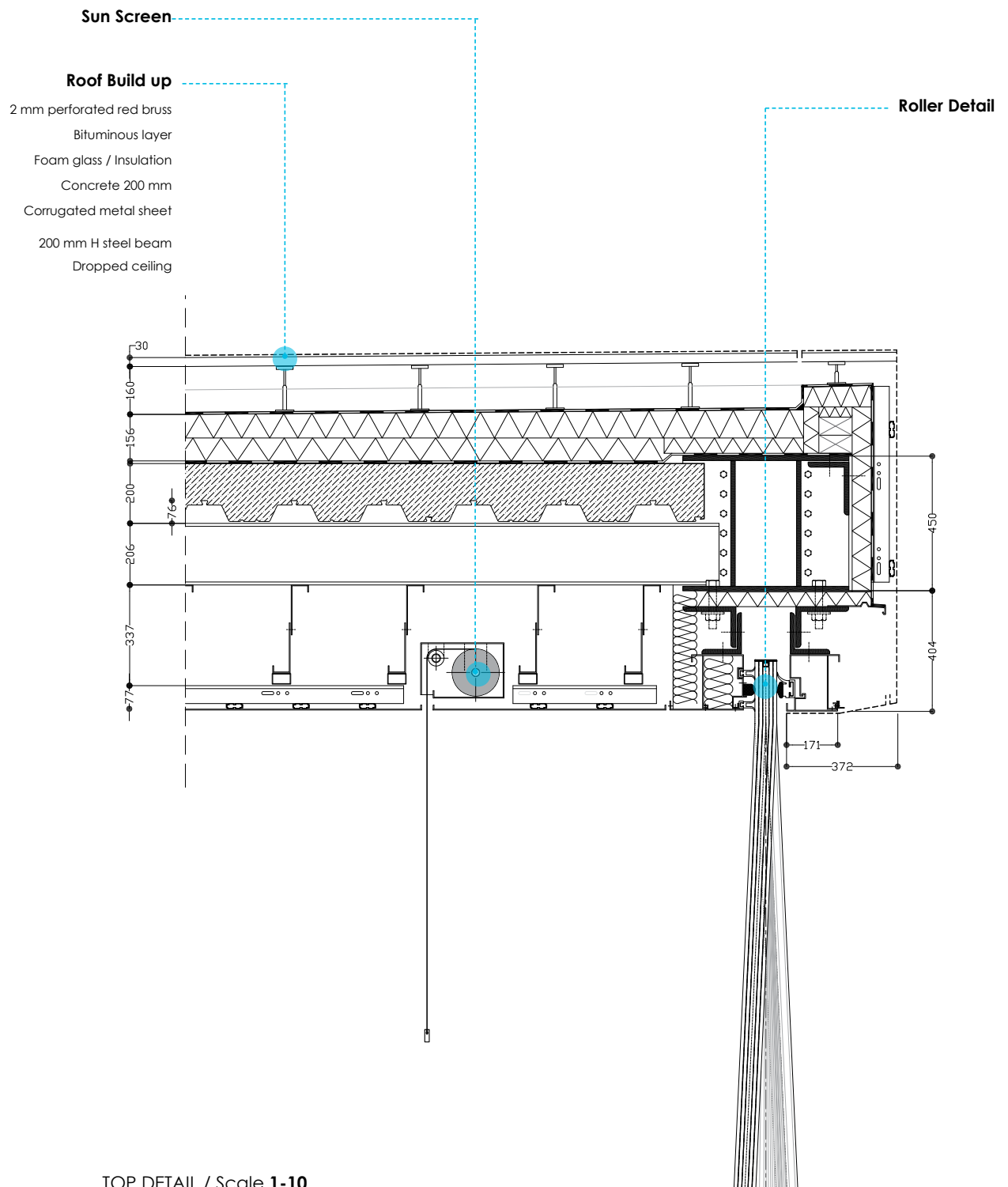
BOTTOM DETAIL / Scale 1-10

7.2.1.2 / Structural design of the facade

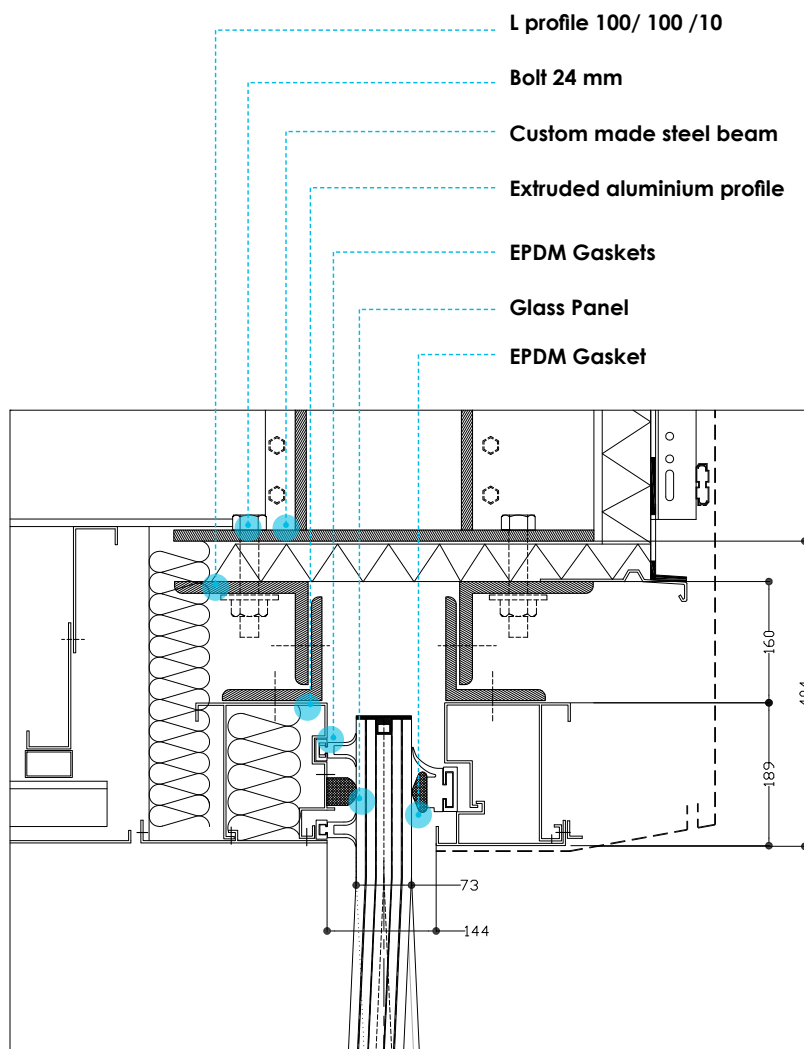


BOTTOM DETAIL / Scale 1-5

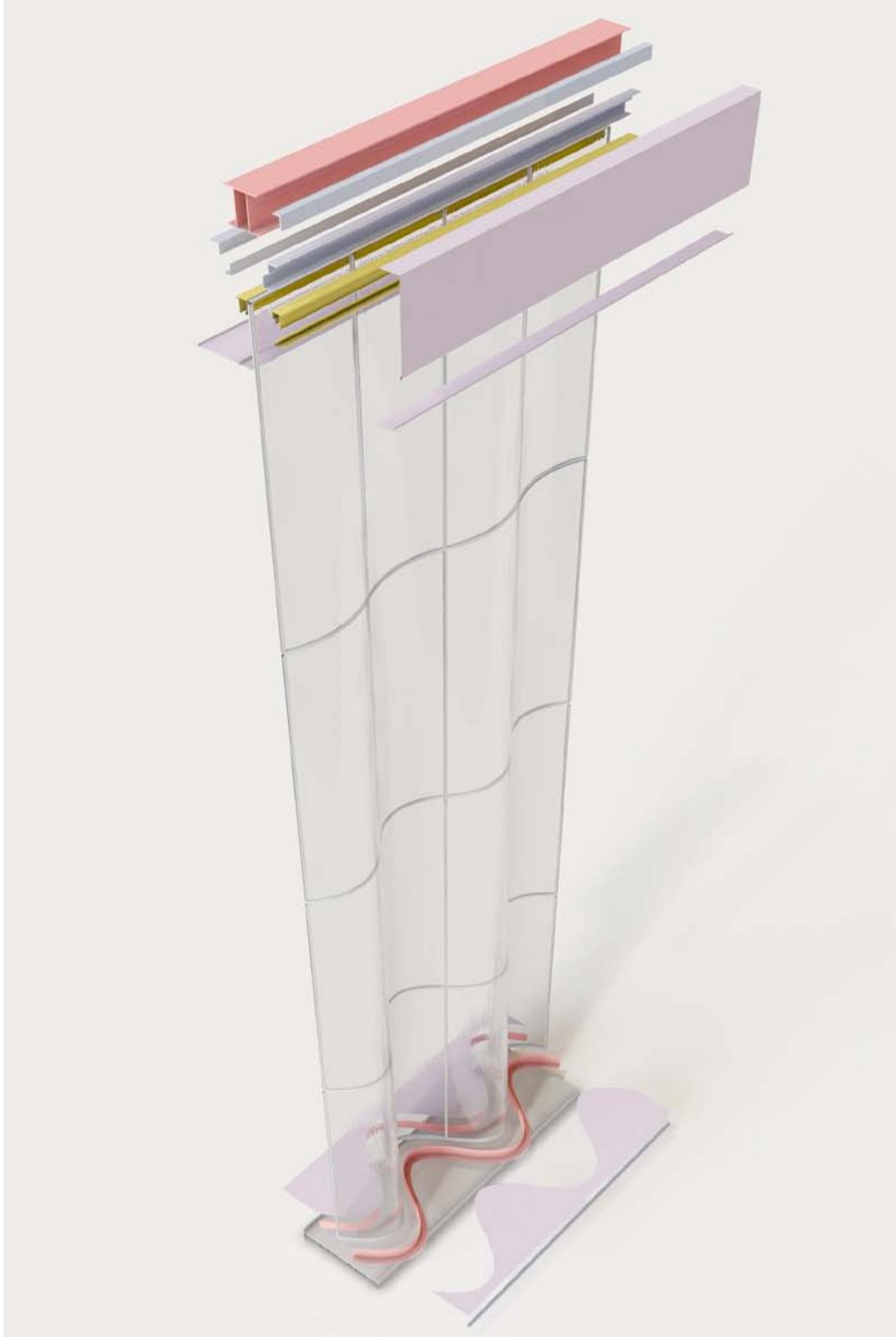
7.2.1.2 / Structural design of the facade



7.2.1.2 / Structural design of the facade

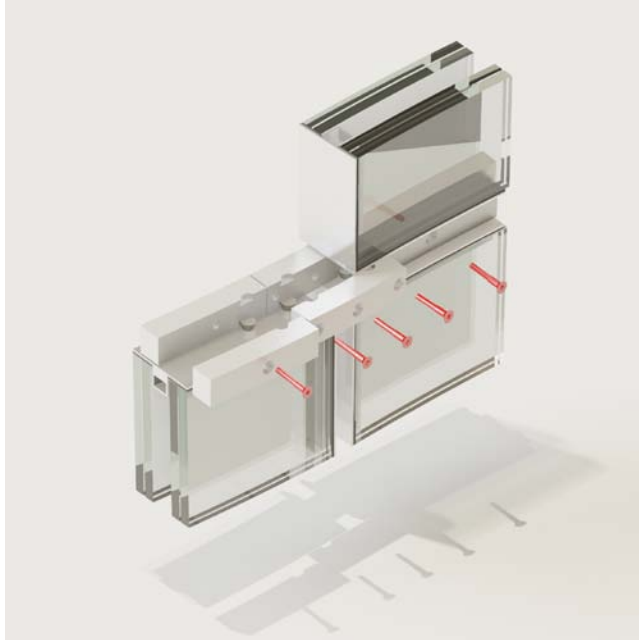


TOP DETAIL / Scale 1-5



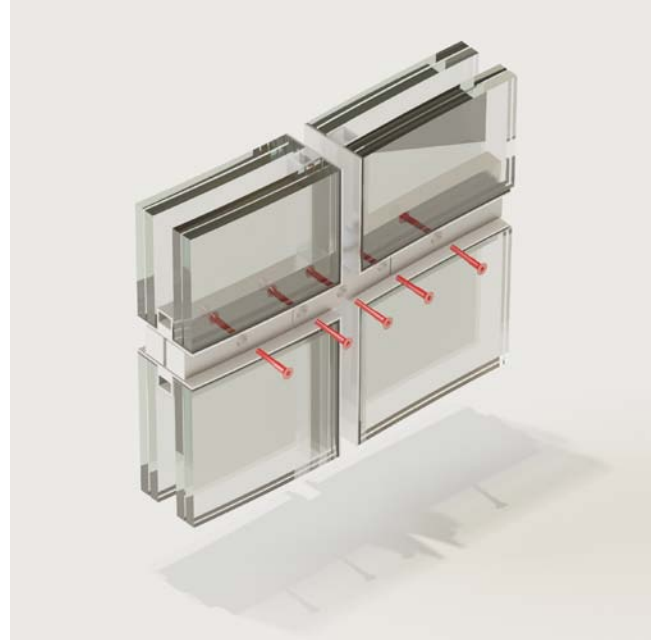
Render diagram showing an exploded perspective view of the facade and demonstrating the different pieces that compose it.

Assembly step 1



Rendered view of cross joint (concept 2) _ Step 1/ The setting blocks are interlocking with the conical parts of the spacer and edge profile.

Assembly step 2



Rendered view of cross joint (concept 2) _ Step 2 / The setting blocks are fastened with series of 6mm countersunk bolts. This secures the connection from movement. The load path is kept by a element that grips on all 4 panels.

Assembly step 3



Rendered view of cross joint (concept 2) _ Step 3/ The final step is to seal off the joint with a structural silicon sealant. Both vertical and horizontal joint.

7.2.3 / Safety factor of the facade

Risks in designing with glass

The increasing use of glass as a material in structures demands a detailed knowledge of its mechanical properties and behavior. These 2 aspects will very much determine the way we dimension the glass elements.

As it has been already mentioned, glass is a material that has equal Young's modulus with aluminium (70Mpa) and compressive strength almost higher of that in concrete, yet is not considered as reliable as these conventional materials in structures.

This is determined also by the fact that glass fails unpredictably over the elastic limit. While in materials the stress at which failure occurs is the failure stress, in metals there is also a stress at which a plastic deformation starts to occur the yield stress. The ability of metals to deform before complete failure is not met in glass, where failure is abrupt without any pre-existing deformation.

In order to dimension a structure out of glass we need first to determine the strength of the material < F.A. Veer, 2007>. Although glass is considered to have a very high theoretical tensile strength (10.000 N/mm²), due to its intact atomic bonds, the material's surface has many irregularities which act as weaknesses when glass is subjected to tensile stress <prEN 13474-3, 2009>. These superficial imperfections can lead to high local stress peaks that lead to crack propagation that glass as a material has no mechanism to stop.

The presence of these irregularities can be caused by attack from moisture or by contact with a hard material and they are continuously modified by moisture present in the air around the element <prEN 13474-3, 2009>. Subsequently the brittle failure of glass is not only stress dependent but also flaw dependent.

One of the parameters that influence the inherent superficial weaknesses of glass is the processing. There are several parameters that stem from the processing of glass and can influence significantly its inherent strength, such as:

- 1) **Residual stresses occurring in the glass from an improper annealing process**
- 2) **Finishing processes reduce the strength of glass**
- 3) **Damage caused by the setting and maintenance of machines (for grinding and polishing) < F.A. Veer, 2007>.**

Definition of the safety factor

Due to the fact, that we cannot predict the quality of the glass component coming from the production lines the allowable design strength is reduced much lower than the theoretical compressive strength of 200Mpa.

The strength reduction can be determined in the calculation and sizing process by the factor of safety. The factor of safety (FoS), also known as safety factor (SF), is a term describing the load bearing capacity of a system beyond the expected loads or actual loads.

$$SF = \text{Total structural capability (strength)} / \text{Required structural capability (strength)}$$

It is a measure of structural reliability as it provides a design margin over the theoretical design capacity so as to allow for uncertainty in the design process; introduced by inaccuracy in calculations, practical material strength and manufacturing quality and is applied in order to reduce the probability of failure in a structure.

7.2.3 / Safety factor of the facade

Essentially, it indicates how much stronger the system is than it usually needs to be for an intended normal load condition. The higher the safety factor, the lower the probability of structural failure and the more stress cycles* the structure can take. On the other hand high safety factors can lead to heavier components and therefore increase of the construction cost something that needs to be dealt under a compromising. There can be several parameters that determine or influence the factor of safety, such as:

- 01 _ Accurate prediction of the imposed loads that should come from a detailed risk analysis.
- 02 _ The type of the load (static or dynamic)
- 03 _ The scale of the load
- 04 _ The failure mode (progressive or sudden) or other different failure modes chosen
- 05 _ Non homogeneous material properties
- 06 _ Variations in the quality of workmanship (manufacturing/ installations errors)
- 07 _ An analytical risk analysis describing the consequences of failure (cost of human safety and financial cost)
- 08 _ Estimation of deteriorating factors, such as poor maintenance, corrosion (lifetime of the material).
- 09 _ Importance of several components contributing to the structural integrity of the façade, such as key connections.
- 10 _ Local conditions (strong climatic phenomena, storm, snowstorm, strong winds, earthquake actions etc.)

All the aforementioned aspects influence the safety factor. From that we can realize that, the deeper the knowledge and the higher the control of the designer over these aspects, can lead to reduction of the safety factor. This control can be obtained via deep knowledge of the material's mechanical properties, found in accurate calculations followed by laboratory tests simulating the extreme conditions under which the structure will be subjected. Finally very strict quality controls of the material determining even the amount of the inherent damage (scratches), as well as in the post construction phase detailed instructions for maintenance and cleaning and ultimately instructions during the installation of the pieces that could reduce possible damage. It has been proven from several tests and studies that the first cleaning of the glass construction (after the installation) is the most fatal one in terms of flaw generation on the surface of the elements.

A live example of a low safety factor being determined by a high quality and control over the properties of the materials can be found in aerospace industry. In order to achieve a demand for a low structural weight the safety factors should be around (1.2 – 1.5). These factors are compensated by high precision and detailed control of the materials used.

Usually the minimum safety factors for materials according to their application can be found in design specifications or building codes and national standards written by the industry, states, federal agencies and provide levels of safety with reasonable costs.

Such standards and design specification can be found for all building materials such as steel, concrete, timber etc. However there is no determined safety factor for glass in a load bearing structure because of its unpredictable failure and the limited use of it as a load-bearing material.

7.2.3 / Safety factor of the facade

In glass instead of safety factor, design stresses are given at a probability of rupture that is low enough to be considered acceptable.

The American glass producer Libbey Owens Ford has recommended a design modulus of rupture under a 'non factored load' (NFL) of 2.8 ksi for annealed glass, which assumes a probability of breakage of 8 per 1000, or 0.008, which is accepted in most applicable codes as the standard value of probability of breakage for design purposes.

The non factored load corresponds to a load duration of 60 seconds, which is appropriate to use directly for wind loadings. In other words, for a piece of annealed glass subject to a wind load, the maximum bending moment divided by the section modulus must not exceed 2.8 ksi. For a longer duration load, a reduction factor is applied; for fully tempered and heat strengthened glass, an increase factor is applied. < David Kuffermann, 2008 >

By this approach an engineer can determine the type of thickness of flat glass elements for a given application. For most typical glass uses in buildings, the guideline for design is found in ASTM E 1300, Standard Practice for Determining Load Resistance of Glass in Buildings. This is limited to uniformly loaded rectangular panels having continuous support on all four edges. Finite element analysis may be required for non-rectangular panels and for other more complicated support conditions < David Kuffermann, 2008 >.

Table for safety factors of material according to their application
< <http://www.roytech.co.uk> >

1.25-1.5	Material properties known in detail. Operating conditions known in detail. Loads and resultant stresses and strains known with high degree of certainty. Material test certificates, proof loading, regular inspection and maintenance. Low weight is important to design.
1.5-2	Known materials with certification under reasonably constant environmental conditions, subjected to loads and stresses that can be determined using qualified design procedures. Proof tests, regular inspection and maintenance required
2-2.5	Materials obtained from reputable suppliers to relevant standards operated in normal environments and subjected to loads and stresses that can be determined using checked calculations.
2.5-3	For less tried materials or for brittle materials under average conditions of environment, load and stress,
3-4	For untried materials used under average conditions of environment, load and stress,
3-4	Should also be used with better known materials that are to be used in uncertain environments or subject to uncertain stresses.

7.2.3 / Safety factor of the facade

In brittle materials like glass the ultimate strength should be used as the theoretical maximum and the factors above should be approximately doubled. Subsequently the safety factors for glass structures should be ranging from 5 to 8.

The definition of risk in a structure can be given as the probability that an event will occur and the consequences of that event and it can be described as $\text{risk} = \text{probability} * \text{consequence}$. From the last expression we can observe that if the consequence of an event is small, a high probability of that event is likely to be accepted; if, on the other hand, the effect is large, a low probability will be required. Thus, it also seems clear there are two principal ways to minimize risk: diminish consequence or reduce probability (or both). <Freek Bos, 2009>

The measures for reducing this risk were introduced earlier in the chapter for the enhancing the safety of a structure in the three levels (micro, meso, macro).

Additional measures to these can be :

01 Accuracy of performance simulations

The level of precision of the structural simulations can determine also the value of the safety factors used. So the more accurate, the lower this value can be. For accurate simulations one should take into account:

_The type of the loading action . Almost all actions are time dependent and therefore the simulations should be dynamic and not static, since glasses' strength is also time dependent. A glass element can sustain a short term load that is sometimes more than double a long term load without causing failure < David Kufferman, 2008 >.

_The strength of the lamination interlayers. We should also taken into account the temperature in the glass because the strength of the interlayers is not only time but also temperature dependent.

_ All the materials should be modeled accurately and with the exact dimensions and properties.

_ The right type of mesh for the geometrical family as well as a high density should be chosen to have a greater accuracy in the results.

02 Laboratory tests

Laboratory tests on smaller scale specimens to demonstrate and test the principle of the larger components could be conducted. This can be a method to evaluate localized performance (e.g. connections).

Chosen safety factor

The safety factor of the facade is chosen according to the latest updated standards on glass construction design found in the DIN 18008 and TRLV. The regulation describes the required analysis for the ultimate limit state and the serviceability limit state of glass components. In the DIN the characteristic bending tensile strengths for the different types of glass are :

- _Annealed glass **45 N/mm²**
- _Heat Strengthened glass **70 N/mm²**
- _Fully Tempered glass **120 N/mm²**

The facade belongs in the category of heat strengthened glass and therefore the glass would normally have a maximum allowable strength that of HSG. However the regulations are referred to flat glass and because in the case of the corrugated there is no clear standard we are going to choose a lower value. That of the annealed glass for the calculations. Therefore the material's partial safety factor is going to be :

$$Y_{M,A} = 1.8$$

7.2.4 / Performance Simulations

The simulation of the structural performance of the facade was undertaken with **iDIANA FEM** structural simulation software.

7.2.4.1 / The model

Taking into account the geometrical complexity of the structure and considering the time limitations a simplified 3 dimensional model approximating the situation was used for the calculations. For the simulation model only a vertical continuous segment of the facade was utilized. The model is representing the goal that we are trying to achieve by having firm connections between the panels. In an ideal situation this will work only if the joints are completely firm. Here we want to test how the glass will be stressed with the given principle.

The fact that not the whole surface but only one half a wave is used, is due to efficiency in the calculation process. Since the element will behave in a similar way in every position we just need to test one element in two reversed loading situations.

In i DIANA the model is imported as surface model that was created with Rhino 3D modelling program. This is because in iDIANA or other similar types of software it is almost impossible to model such complex surfaces with double curvature.

Geometry & Material attributes

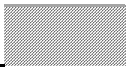
The chosen mesh division for the elements is 40 and the mesh type is shell for (noumero) because it is a double curved shell element. The surface was given material properties that of 'soda lime glass' and the physical properties of 'plate' with a thickness of 24mm(that of 2 sheets of glass).

Boundary conditions

Regarding the boundary conditions, a hinge was modeled at the bottom edge by allowing rotation in all three axes X, Y and Z. The top roller condition was modeled by allowing translation in the Z axis and rotation in all three axes.

Load cases

The facade was loaded by wind load under 150 kg/m and the gravity. As we have to distinguish between negative and positive pressure load, there were two load cases created to represent these two actions combined each time with the dead load. Finally the wind load was modelled simplified as a static load with a factor of **1.6** .

Parabolic panel total	Load Case 1	Load Case 2
Nr. of Surfaces <u>1</u>	Gravity <u>Gravity</u>	Gravity <u></u>
Nr. of Lines <u>4</u>	Wind pressure <u>0.002354 N/mm2</u>	Wind suction <u>(-)0.002354 N/mm2</u>
Nr. of Points <u>4</u>		
Mesh type surface <u>qu8 cq40s</u>		
Mesh type midlines 		
Material surface <u>Glass</u>		
Material midlines 		

7.2.4.1 / The model

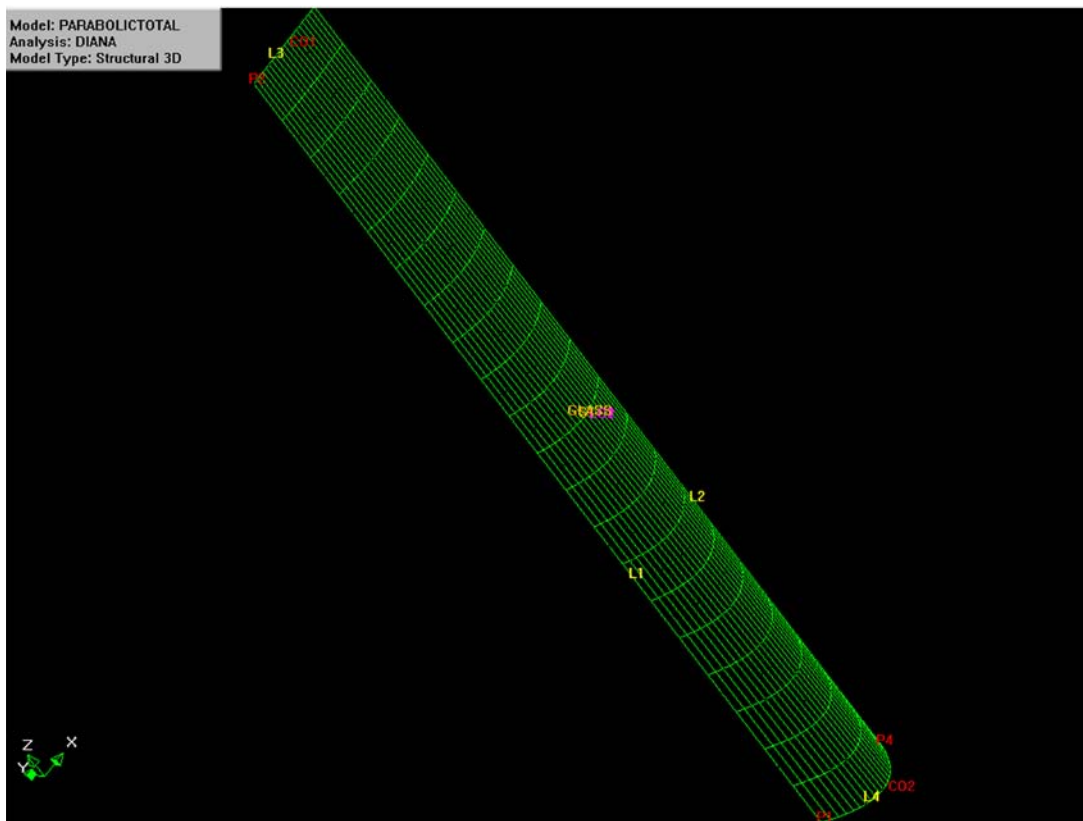


Fig.182_Model of the panel in iDIANA

7.2.4.2 / Ultimate limit state

Taking into account the maximum allowable tensile strength that we estimated in the previous chapter, for the safety factor, the design load stress will have to be equal or lower to that. If we apply the partial safety factor $\gamma_{M,A} = 1.8$ to the maximum tensile strength for annealed glass **45 N/mm²** we get an allowable stress of 26 Mpa, and the maximum stress occurring in the plane of glass should be under that limit.

After we apply the two load cases we can see that the design stress is equal to the allowable stress. The maximum principle stresses occurring in plane of the facade in the first loading scenario (combination of positive wind pressure and gravity) indicate a stress level of **52 MPa** that appears very close to the side edges of the top almost flattened part. Because we have laminated glass this stress is divided in two panes of glass and therefore it is under the maximum allowable. Another aspect that we have to take into account is the surface that we take into account in the results. Meaning within the cross section of glass if the stress is at bottom, the middle or the top plane. In this case the stress level is taken from the bottom plane/surface.

However on the case of the reversed loading scenario (combination of negative wind pressure and gravity) the stresses that occur in the plane of the facade are just above the allowable 56.7 MPa this could be depending again on the plane that we choose to calculate. In this case because it is the reversed situation we choose the opposite of the previous condition, therefore the top plane/surface. The whole situation here indicates that we probably increase the thickness of the glass or generally make more accurate modelling because in this situation and the previous we are ignoring the complete build up of the facade which is **2 times 12mm glass/ 20 mm stainless steel spacer / 2 times 12 mm glass**. Instead of that we only take 2 times 12mm as one monolithic shell of 24mm thickness.

7.2.4.2 / Ultimate limit state

Load Case 1	Max	Min
EL. S1. S1/ Principle stress 1 (algebraic largest) (N/mm2)		
Bottom surface	52	-5.71E-03
Top surface	113	-5.88E-03
EL. S1. S2/ Principle stress 2 (N/mm2)		
Bottom surface	2.41	-6.55E+00
Top surface	5.86	-1.27E+01
EL. S1. S3/ Principle stress 3 (algebraic smallest) (N/mm2)		
Bottom surface	3.69E-02	-6.10E+01
Top surface	3.97E-02	-5.81E+01

Load Case 2	Max	Min
EL. S1. S1/ Principle stress 1 (algebraic largest) (N/mm2)		
Bottom surface	60.2	-3.62E-02
Top surface	56.7	-3.91E-02
EL. S1. S2/ Principle stress 2 (N/mm2)		
Bottom surface	6.41	-2.41E+00
Top surface	12.6	-5.79E+00
EL. S1. S3/ Principle stress 3 (algebraic smallest) (N/mm2)		
Bottom surface	5.50E+01	-5.14E+01
Top surface	5.81E-03	-1.12E+02

Fig.183_ Results for principle stresses in LC 1 and LC 2

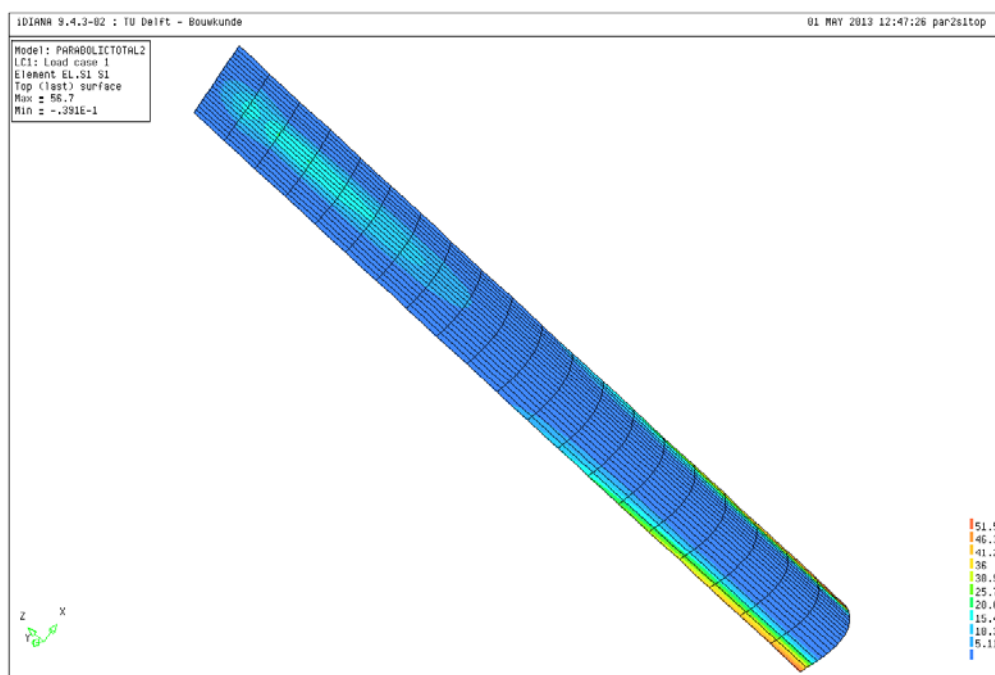


Fig.184_ Loadcase 2 - First principle stresses diagram

7.2.4.2 / Ultimate limit state

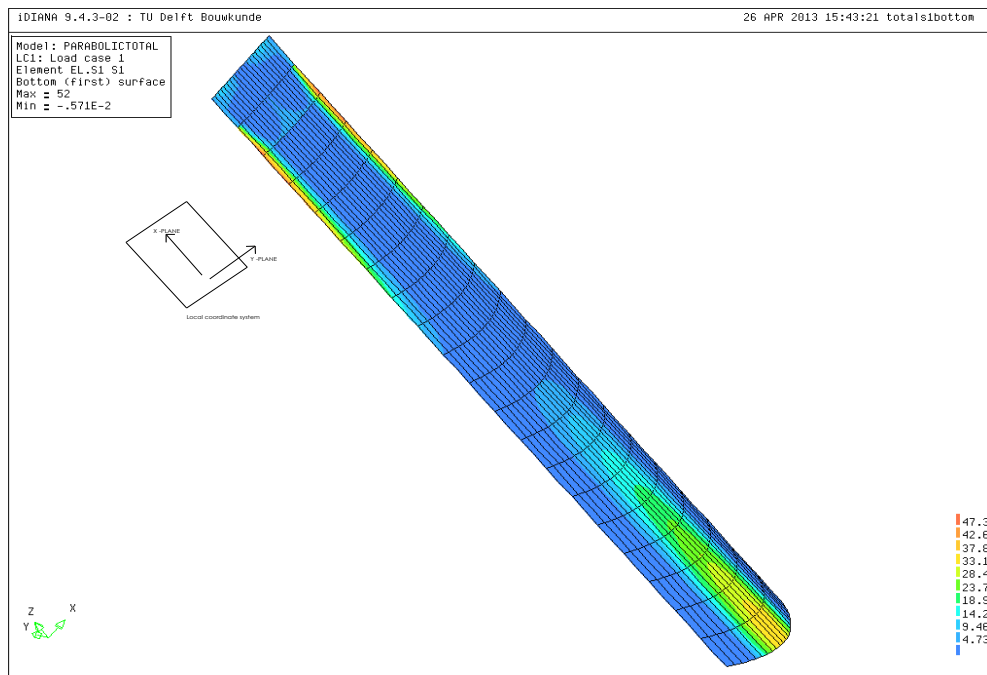


Fig.185_ Loadcase 1 - First principle stresses diagram

7.2.4.3 / Serviceability Limit state

For the allowable deflection there is no specific requirement to limit the deflection of the glass under loading. However consideration should be given to ensure that the glass is not excessively flexible when is subjected to loads, as this can cause alarm to the building users.

According to the **prEN 13474-3 (2009)** european norm, upon the absence of standards for the allowable deflection requirements, the deflections at the middle of the panel should be limited to the $1/65$ of the span or 50mm, whichever value is the lowest.

The maximum deflections of the panels do not exceed the value for the **1/65** but they are above the 50mm. However the maximum deflection occurs towards the top and not in the middle. Regarding this situation we cannot conclude about the appropriateness of this deflection. Since the norms are only referring to flat panels and also make a very broad generalization it is not simple at this point to assume that the displacement of the facade would be considered alarming. It is an issue that is left to be clarified within the scope of new norms that are relating probably the deflections to the geometry and also the scale of a facade. Finally based on the scale aspect of a facade it doesn't seem objective to set the same 50mm boundary for a facade with 20m span and a facade with 5 meters span.

7.2.4.3 / Serviceability limit state

Load Case 1	Max	Min	Load Case 2	Max	Min
FBX...G RESFBX / support reaction	1.37E+05	5.20E+03	FBX...G RESFBX / support reaction	1.33E+05	5.12E+03
DTX...G RESDTX / total displacement	106	0	DTX...G RESDTX / total displacement	105	0

Fig.186_Reaction forces and global displacement

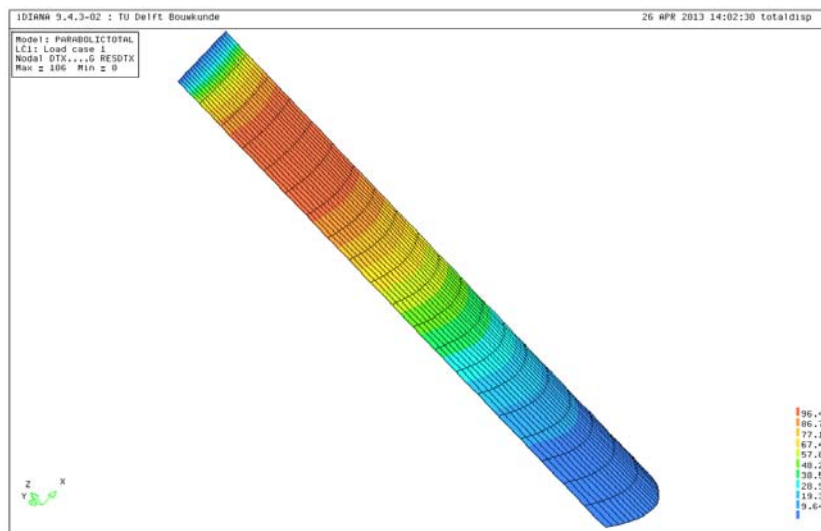


Fig.187_loadcase 1 - maximum displacement diagram

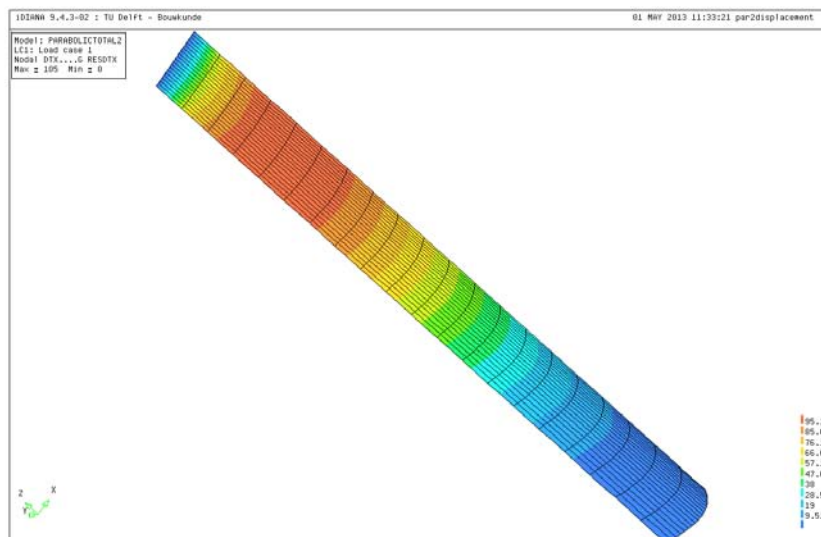


Fig.189_loadcase 2 - maximum displacement diagram

7.2.4.4 / Simulation Conclusions

The simulation of the structural performance of the facade showed that the solution might be feasible with certain alterations. The maximum stress in the second loading condition could be adjusted by adding thickness to the glass or by using fully tempered glass. On the other hand the deflections could be reduced depending on the types of supports at the top and the bottom.

Maybe a different modelling approach with more information and greater accuracy would have brought more accurate results. Subsequently the simulations show that the principle of the facade could be adopted with certain alterations or more accurate simulation that will prove its reliability.

Finally in order to test further if this was the right choice for a surface two more typologies of panels were simulated with a model of the same nature and under the same loading conditions. The results are presented in the Appendix and they show that there is one typology that performs better but in the end the choice of the surface was also driven by other criteria, like the design in the terms of shape and the efficiency in the use of the material.

72.5 / Final Design Visualization



Fig.190_ view from exterior

7.2.5 / Final Design Visualization



Fig.191_ view from interior

8 / Final conclusions & recommendations

Through the research presented in the previous chapters it was made clear that there are three design strategies with which we can achieve to maximize transparency in the facade of the La Fayette modern with a size of 20m high and 7.7 meters wide. These strategies that can be utilized for the structural design of the facade are employing the structural benefits of self supporting geometries like **the tube, the bended shell and the I-profile or rib-reinforced glass plate**. Furthermore the elements can be utilized for the construction not only of the La Fayette facade, but also any other facade with similar scale, given the right adjustments in the dimensions.

During the study it was found that in order to maximize the transparency a very strong obstacle that we have to **eliminate is the secondary supporting frames** of any kind, including the systems that are based on cables. In order to do that the main aspect was to find the glass geometries that are stiff enough to do that. From the geometries examined and based on the architectural criterion and the criterion of creating an integrated solution the bended 3 dimensional surface was utilized to create a structural design for the La Fayette that combines a very innovative design that has never been tried before with the material glass. The bended shell was design so as to be self-supporting structural skin and to function as a rigid surface against the windloads. In this solution the level of integration between structure and envelope is extremely high and it is most certainly for that reason a very promising design principle that can be adjusted and used in many architectural applications.

One of the drawbacks that had to be faced in this design strategy was the size of the elements as the manufacturing limitations pose a great deal of influence on the overall performance of the structural design. The maximum size of 5.6 meters for bended geometry and the overall limitations in curvature brought the problem of the structural continuity and of course a certain amount of connection and joints between the panels that needed to be as transparent as possible, or with the smallest surface possible.

The solution was to design the connections between the panels so as they can be firm and create an intact surface scheme. For the transfer of forces between the panels, the structural spacer and the interface created between the stainless steel edge covers was used. The detail created had to deal with the irregularities of the deformed glass surfaces and the deviations coming from the manufacturing techniques for the production of bending components. **A connection was designed so as to allow for the installation in 2 phases in order to facilitate accurate assembly of the curved oversized panels and to create afterwards very strong and firm connections.** The surface of the horizontal joint (largest) on the facade was made to be 33 mm of joint surface and additionally another 44mm of spacer surface appearing behind the glass. The already existing solutions for intermediate connections between curved glass panels are achieving a minimum area of joint of 150 mm. In that sense **the new design scores higher in the aspect of transparency by minimizing the area of this joint.**

Because of the limited timeframe the insulating properties of the facade were not in the scope of this research. Another important issue that could be dealt in the future is the estimation of the insulating value of the facade as well as the possibility of creating the structural spacer out of transparent material like polycarbonate. There the materials' strength in combination with the properties of a transparent structural adhesive should be tested for bearing the loads of such a facade and transfer forces. Additionally ideas for integrated sunshading could be examined. One of the problems of the hot - bended panels is that they cannot take up Low-E coating treatments. Therefore the application of such a coating or other coatings in this kind of panels could be studied further. An idea towards that direction is to test the possibility of integrating the coating on a pvb mesh or a polymer mesh in the laminate.

Due to the un-developed yet production techniques the tolerances in the hot bended glass components as well as the steel sections is remaining one of the biggest problems. A future improvement would be a way to control the processes so as to reduce the deviations and to make the tolerances of profiles as tight as possible. One proposal for that and especially for bended and twisted components would be to look into customized production, using rapid prototyping techniques to construct moulds or to 3D printing with metal foam.

The second step to that is the future study in materials that can be used as fillings or injection materials for small and tight structural connections. Finally the possibility of replacing the steel parts with composite cross sections that can be custom made and easier to follow such shapes.

8 / Final conclusions & recommendations

Ultimately, since the structural design involves a lot of interrelated parameters and especially values that can vary according to manufacturing processes, material properties and geometry properties, for the design of such facades that involve a complicated ruled geometry an advanced parametric tool could be designed that can at least control all these various aspects simultaneously. This would give the chance for better optimization regarding material properties, geometrical properties as well as provide a direct output for fabrication of complex components. One simple example is that the stiffness of the geometry is dependent on the intensity of the curvature against the span, to that condition are added various alternatives of supporting cases. These two aspects alone could be influencing the final shape that will be restrained from another parameter that of fabrication.

Although several aspects need to be looked into more detail for the final evaluation and also laboratory test to be conducted for testing the structural performance of such a complicated shape, the proposed design for a glass self - supporting facade of 20m high, with interesting shape and almost invisible connections can be achieved.

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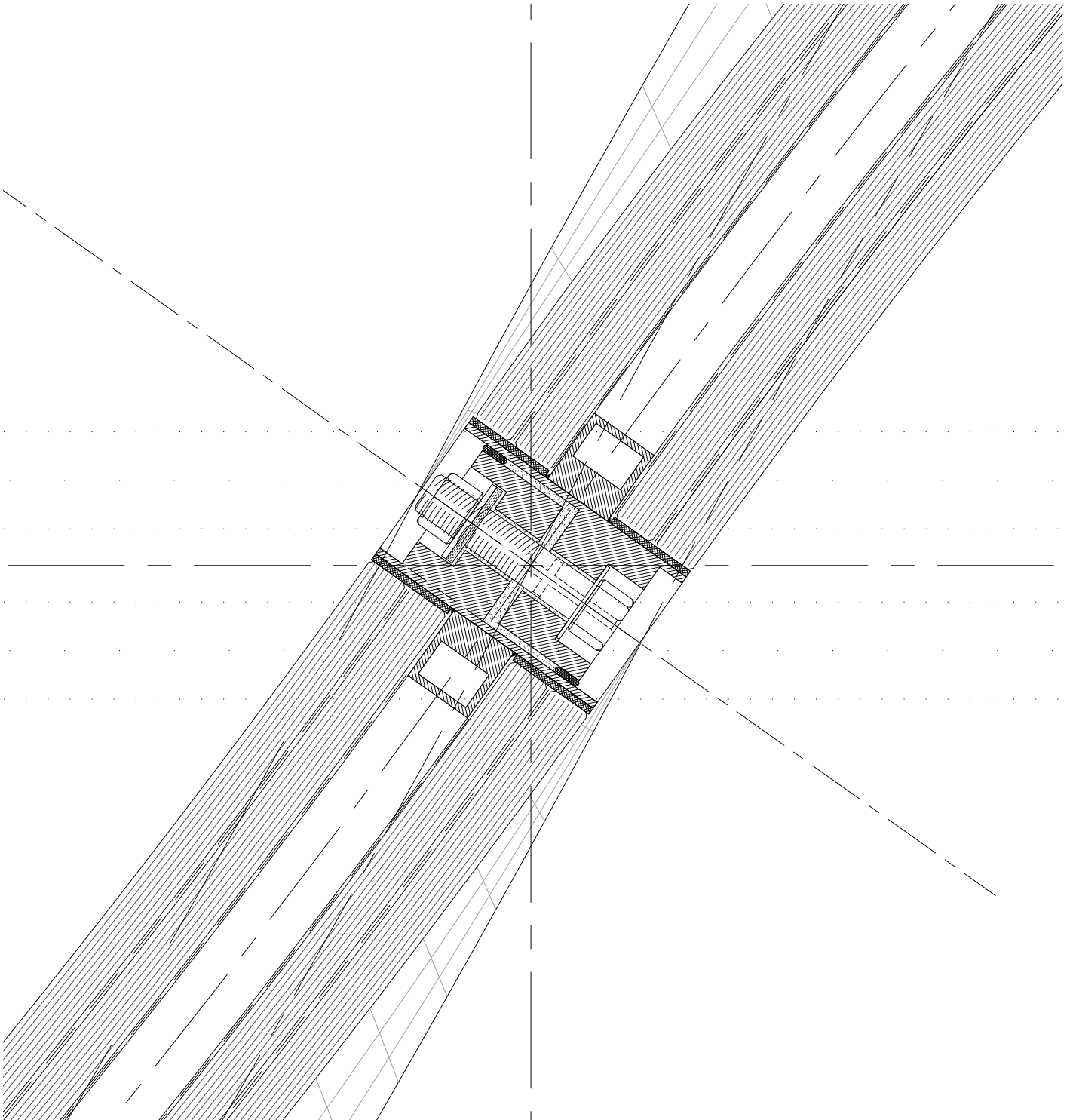
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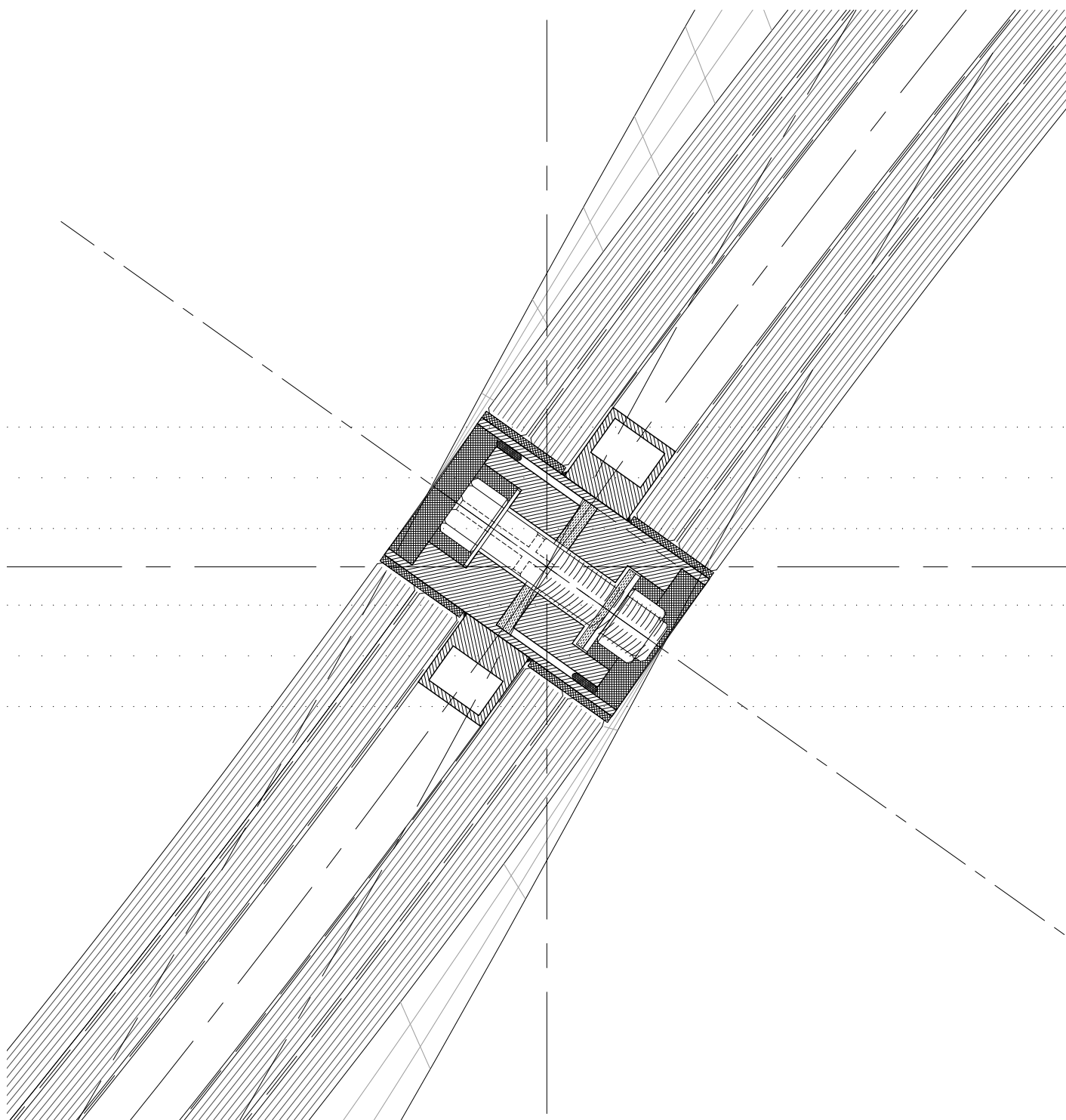
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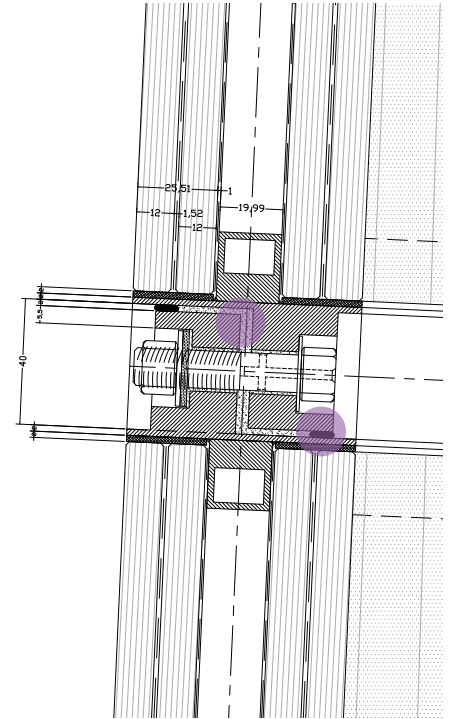
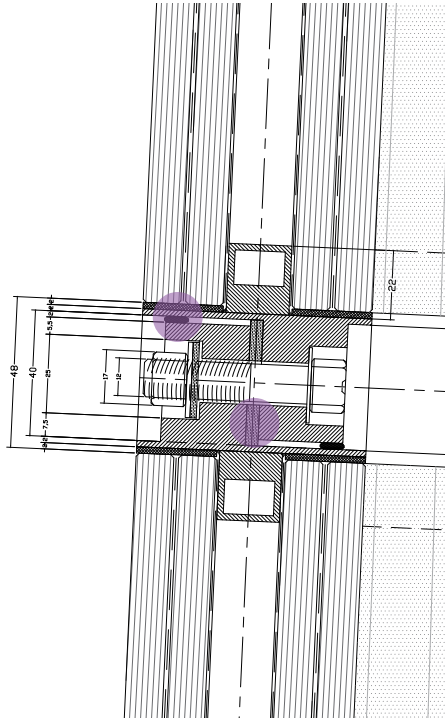
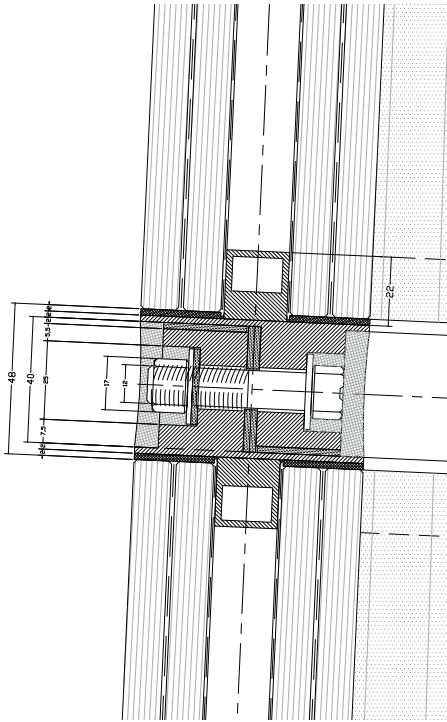
Appendices



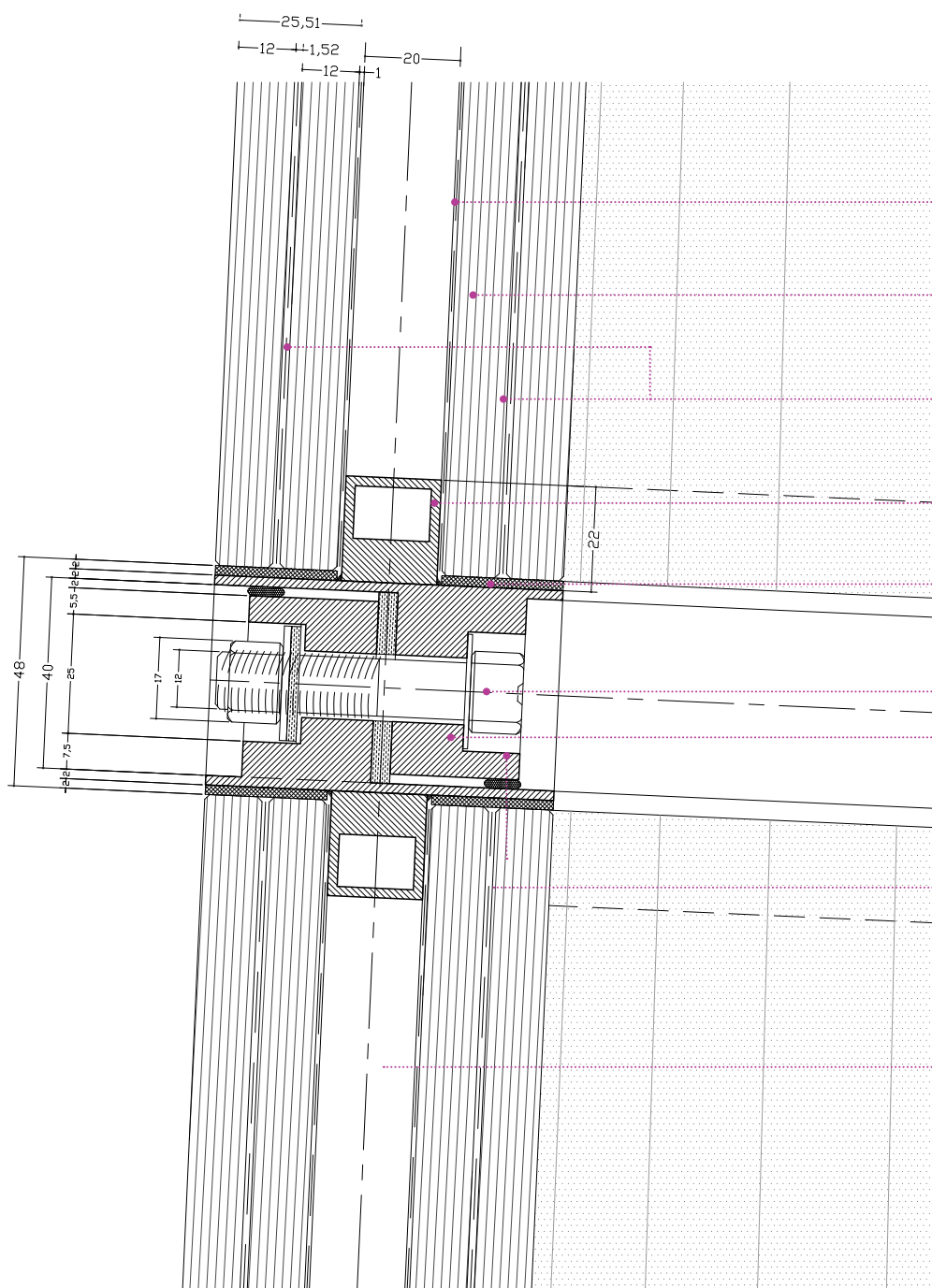
VERTICAL JOINT DETAIL / Scale 1-1 (**Alternative 1**)



VERTICAL JOINT DETAIL / Scale 1-1 (Alternative 2)



Horizontal JOINT DETAIL / (Alternative 1,2,3)



Sentry Glas Interlayer

Used in the inner side of the ply to laminate the to stainless steel spacer with the attached connection.

12 mm HS Soda Lime Glass

The annealed glass is being hot bended and afterwards processed to achieve by water jet cutting the perpendicularity of the edge. After that it can be tempered to prestress it.

4x PVB foil total thickness of 1.52 mm

The PVB is used to laminate the plies for securing post breaking behavior.

20/22 mm hollow stainless steel spacer

Produced by special extrusion, bending and twisted

2mm Silicone bushing

Used to take up the tolerances between the glass and the stainless steel edge. (+/- 2mm from the hot bending process)

12mm Bolt

Fastening the two profiles.

Stainless steel extruded profile.

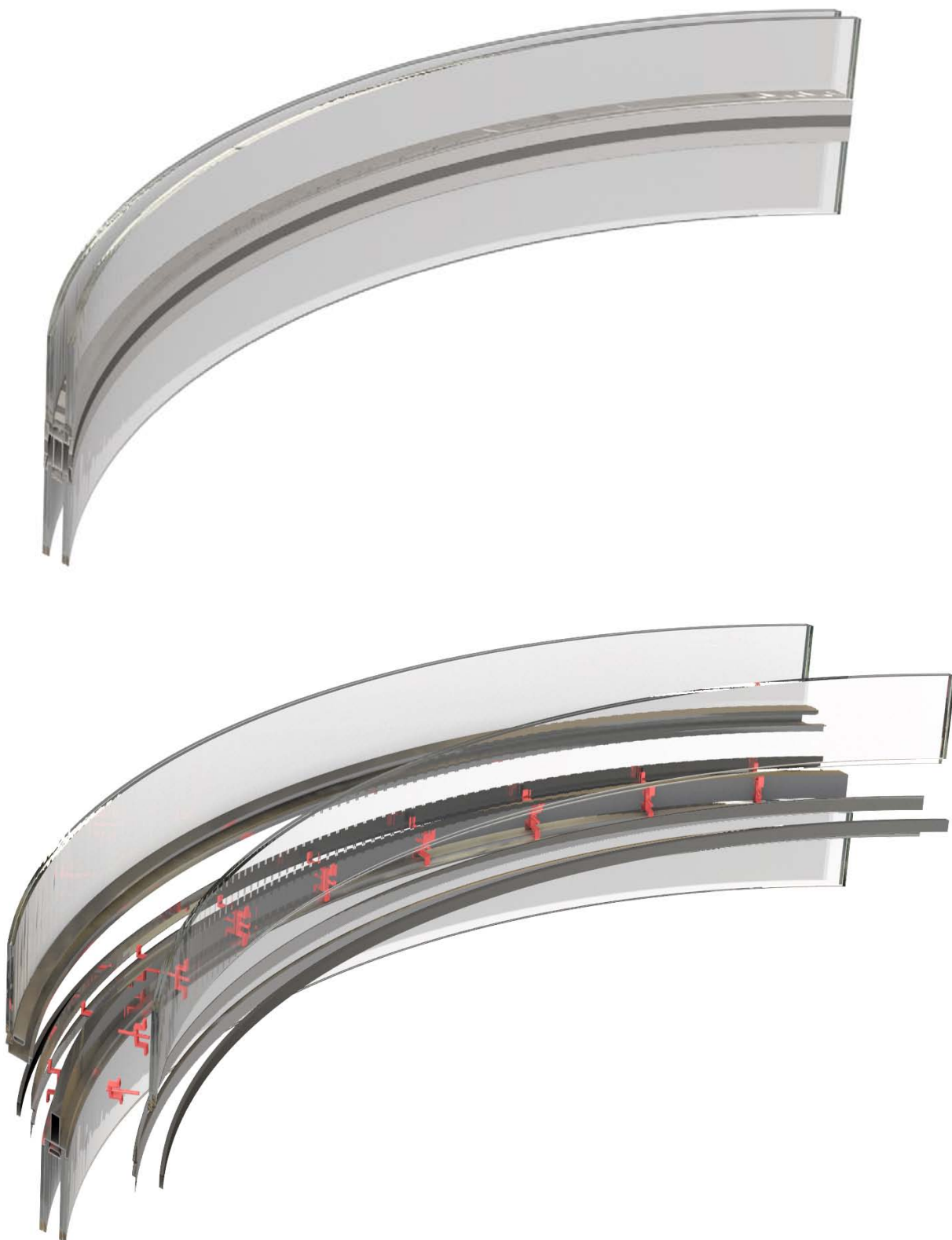
The profile is produced with special extrusion process. After that is bended and twisted to the shape. The tolerances are intended 4mm in the middle (between profiles) to facilitate installation.

2mm Silicon or neoprene bushing

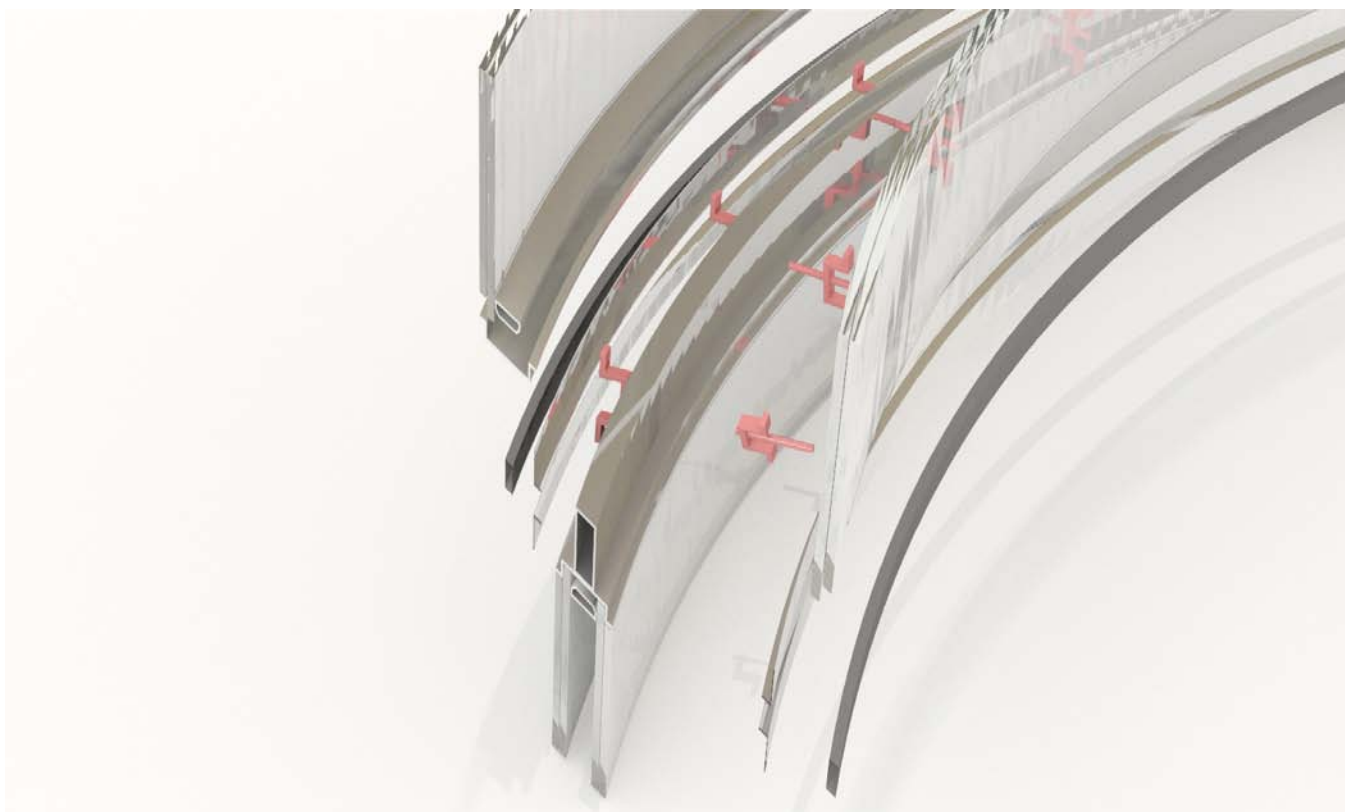
Taking up the tolerances from the profiles manufacturing deviation. This interface has not been completed in design.

4mm rubber ring

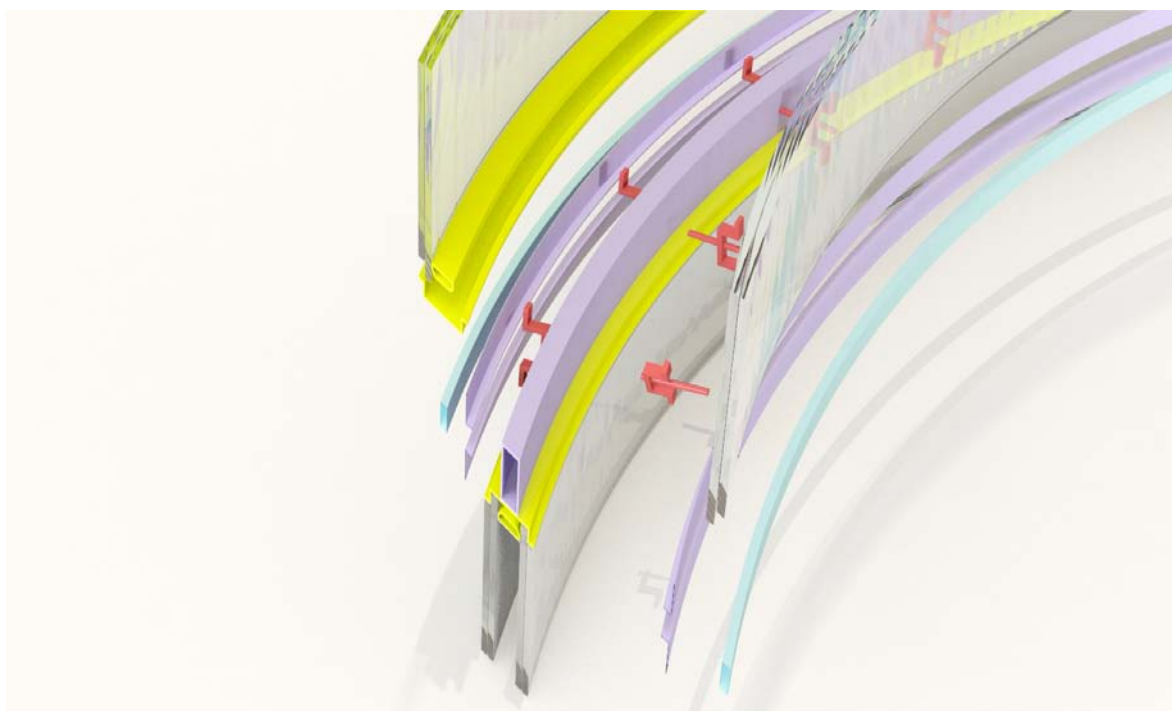
Taking up the tolerances from the profiles manufacturing deviation. Helps to provide the buffer for the tightening of the bolt.



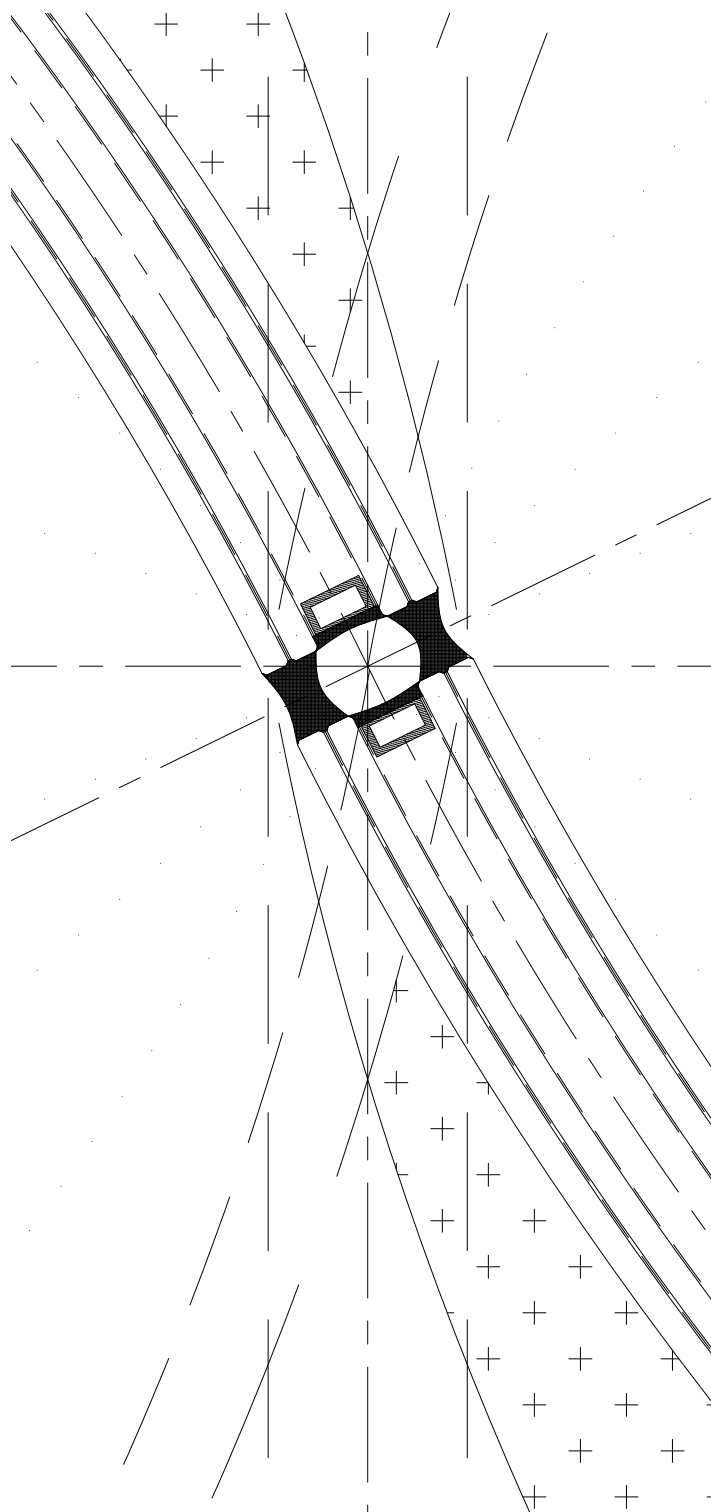
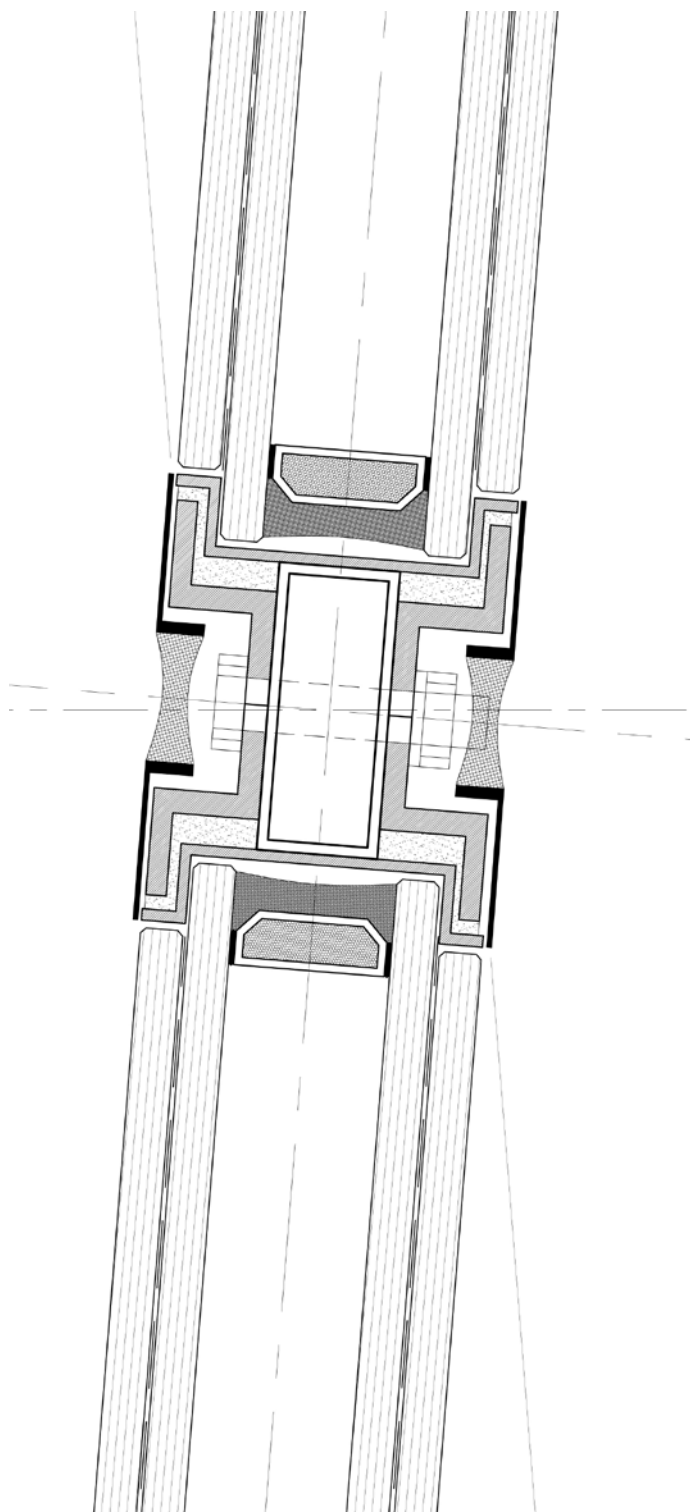
Initial concept for Horizontal joint (embedded clamp) _ Rendered views



Initial concept for Horizontal joint (embedded clamp) _ Rendered views

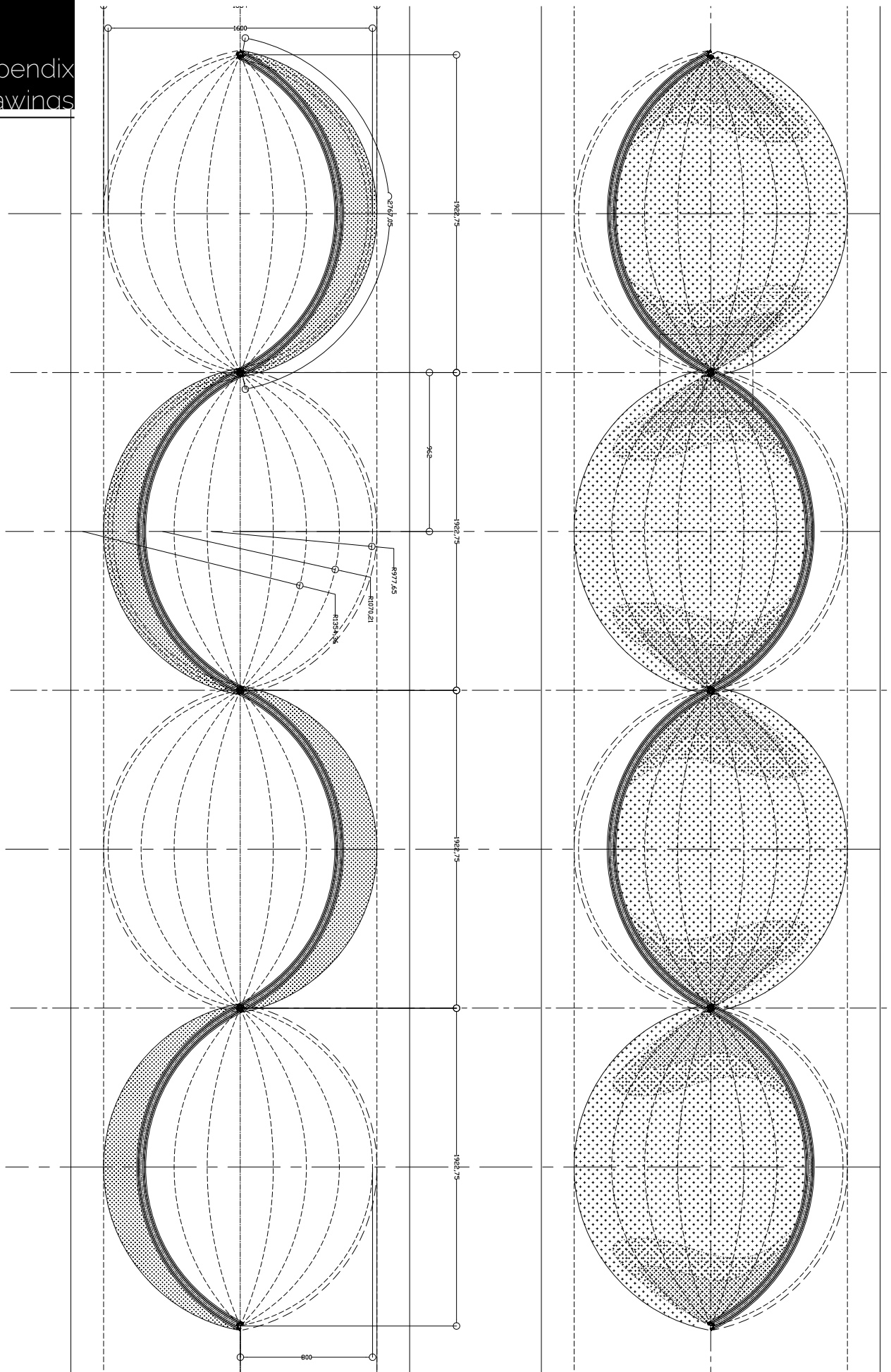


Initial concept for Horizontal joint (embedded clamp) _ Rendered views indicating materials

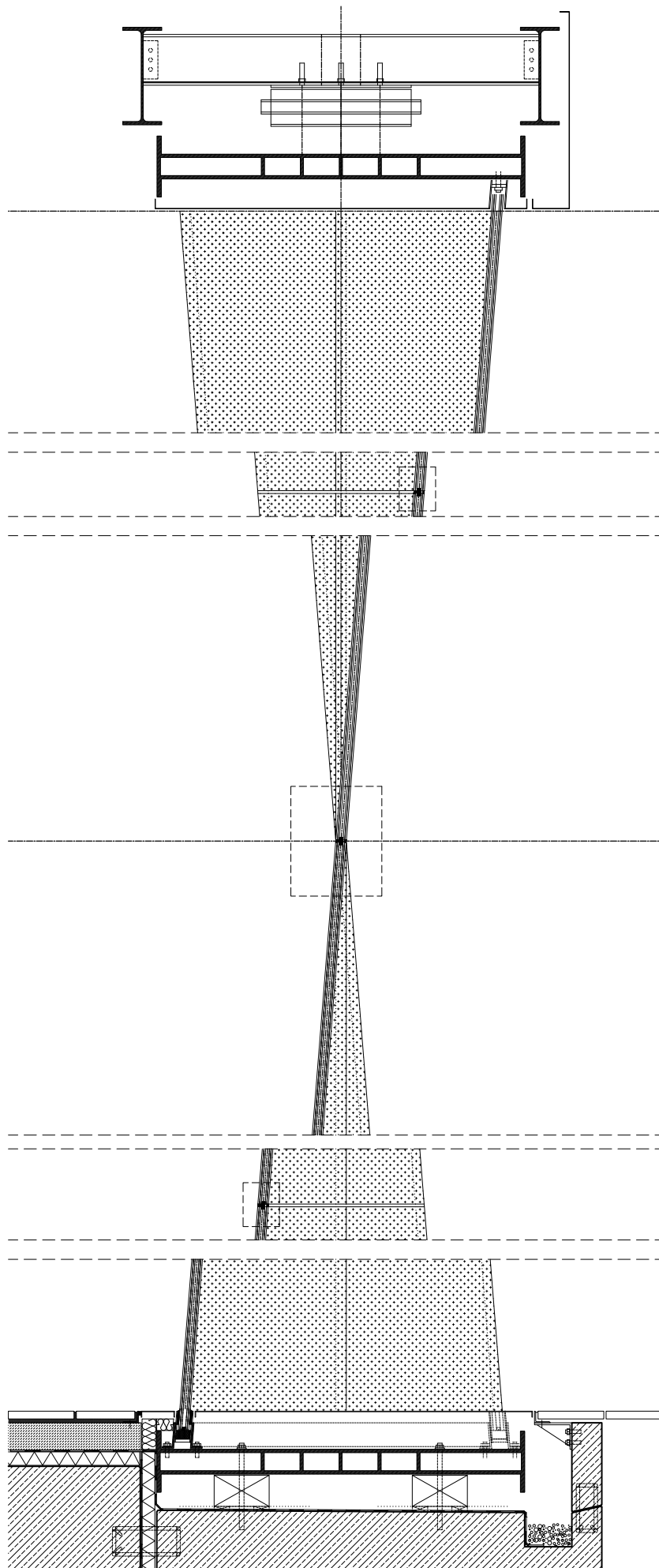


Initial concept for Horizontal joint (embedded clamp) _ drawing 1-1

Initial concept for vertical joint _ drawing 1-1



Floorplans 1-20 / Previous design concept (Twisted panel)



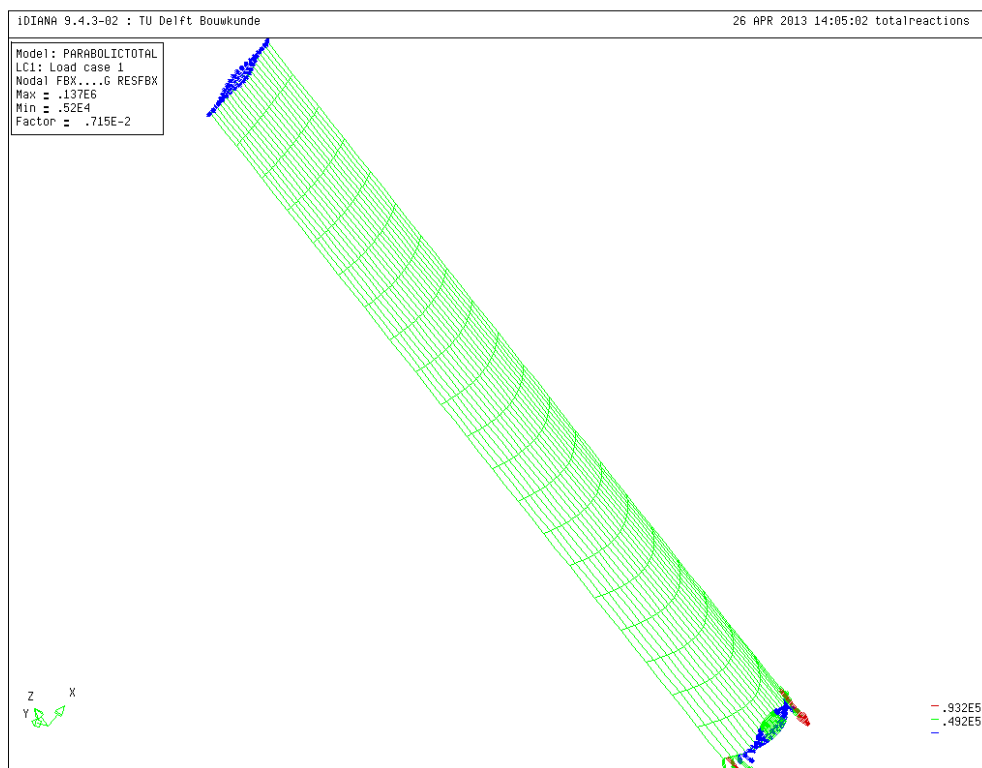
Section 1-20 / Previous design concept (Twisted panel)

Appendix Calculations

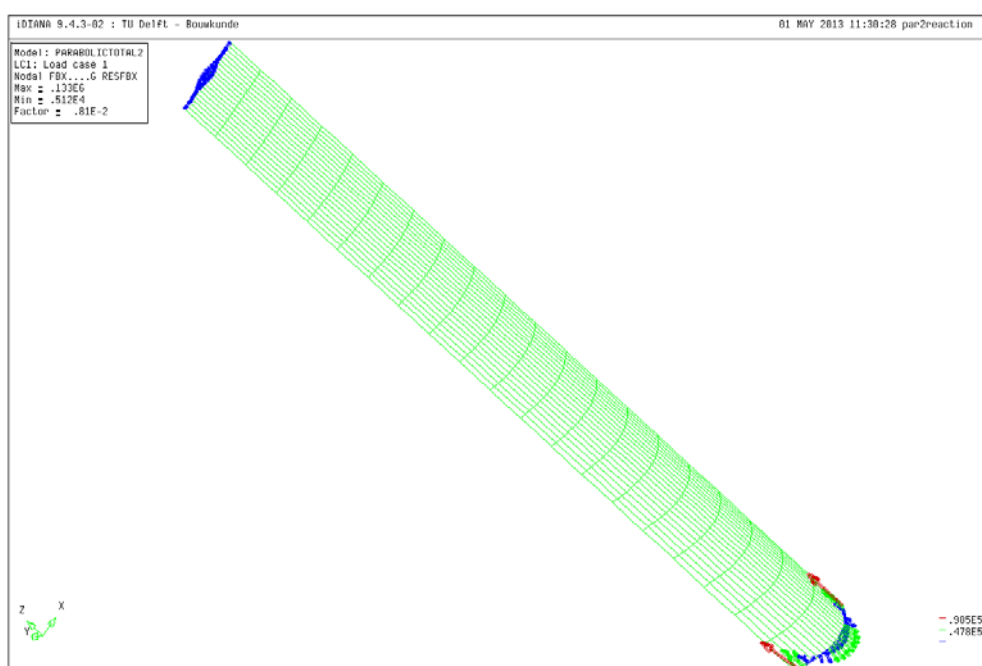
Load Case 1	Max	Min
FBX...G RESFBX / support reaction	1.37E+05	5.20E+03
DTX...G RESDTX / total displacement	106	0
EL. MXX.L MXX/ Bending moment on x-plane	4.76E+03	-304
EL. MXX.L MY/ Bending moment on y-plane	547	-1.11E+03
EL. MXX.L MXY/ Torsional moment	1.25E+03	1.25E+03
EL. NXX.L QXZ/ Shear Forces x-plane	27.2	-60.1
EL. NXX.L QYZ/ Shear Forces y-plane	7.00E+01	-70
EL. SXX.L SXX/ Normal stresses x-plane (N/mm2)		
Bottom surface	51.8	-61
Top surface	113	-57.8
EL. SXX.L SY/ Normal stresses y-plane (N/mm2)		
Bottom surface	6.00E+00	-6.86
Top surface	5.94E+00	-19.2
EL. SXX.L SXY/ Shear stress x/y plane (N/mm2)		
Bottom surface	23.2	-23.2
Top surface	6.53	-6.52

Load Case 2	Max	Min
FBX...G RESFBX / support reaction	1.33E+05	5.12E+03
DTX...G RESDTX / total displacement	105	0
EL. MXX.L MXX/ Bending moment on x-plane	3.05E+02	-4.69E+03
EL. MXX.L MY/ Bending moment on y-plane	1.10E+03	-5.39E+02
EL. MXX.L MXY/ Torsional moment	1.24E+03	-1.24E+03
EL. NXX.L QXZ/ Shear Forces x-plane	59.4	-26.9
EL. NXX.L QYZ/ Shear Forces y-plane	6.91E+01	-69.1
EL. SXX.L SXX/ Normal stresses x-plane (N/mm2)		
Bottom surface	60.2	-51.2
Top surface	56.4	-112
EL. SXX.L SY/ Normal stresses y-plane (N/mm2)		
Bottom surface	6.75E+00	-5.96
Top surface	1.90E+01	-5.86
EL. SXX.L SXY/ Shear stress x/y plane (N/mm2)		
Bottom surface	22.9	-22.9
Top surface	6.44	-6.45

Analytical Calculation results (parabolic panel)



Analytical Calculation results (support reaction) Load case 1



Analytical Calculation results (support reaction) Load case 2

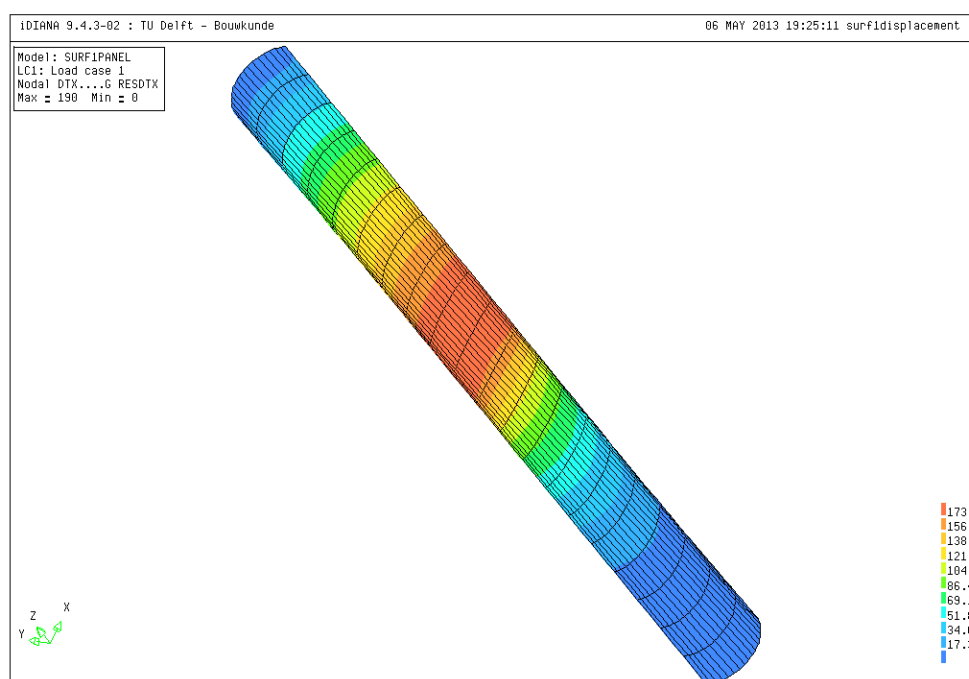
Appendix Calculations

Panel 1 / Twisted along middle

Nr. of Surfaces	1
Nr. of Lines	4
Nr. of Points	4
Mesh type surface	qu8 cq40s
Mesh type midlines	
Material surface	Glass
Material midlines	
Load Case 1	
Gravity	
	0.002354
Wind pressure	N/mm2

Load Case 1	Max	Min
FBX...G RESFBX / support reaction	1.14E+05	1.20E+02
DTX...G RESDTX / total displacement (mm)	190	0
EL. S1. S1/ Principle stress 1 (algebraic largest) (N/mm2)		
Bottom surface	49.7	-2.47E-01
Top surface	38.5	-3.15E-02
EL. S1. S2/ Principle stress 2 (N/mm2)		
Bottom surface	13.2	-5.11E+00
Top surface	10.6	-1.06E+01
EL. S1. S3/ Principle stress 3 (algebraic smallest) (N/mm2)		
Bottom surface	3.01E-02	-8.99E+01
Top surface	2.82E-02	-1.14E+02

Analytical Calculation results (alternative panel 1)
Load case 1



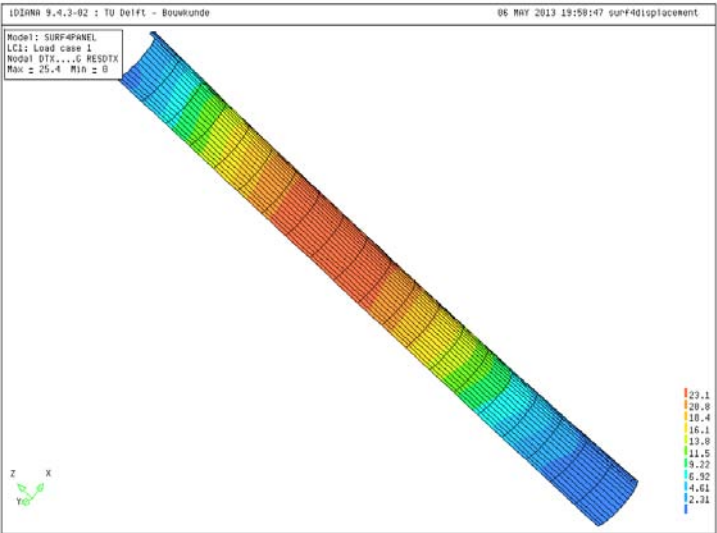
Analytical Calculation results (displacement) Load
case 1

Panel 2 / Corrugated (reduced in the middle)

Nr. of Surfaces	1
Nr. of Lines	4
Nr. of Points	4
Mesh type surface	qu8 cq40s
Mesh type midlines	
Material surface	Glass
Material midlines	
Load Case 1	
Gravity	
	0.002354
Wind pressure	N/mm2

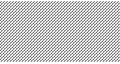
Load Case 1	Max	Min
FBX...G RESFBX / support reaction	7.25E+04	4.48E+02
DTX...G RESDTX / total displacement (mm)	25.4	0
EL. S1. S1/ Principle stress 1 (algebraic largest) (N/mm2)		
Bottom surface	26.8	-1.97E-02
Top surface	27.8	-2.09E-02

Analytical Calculation results (alternative panel 2) Load case 1



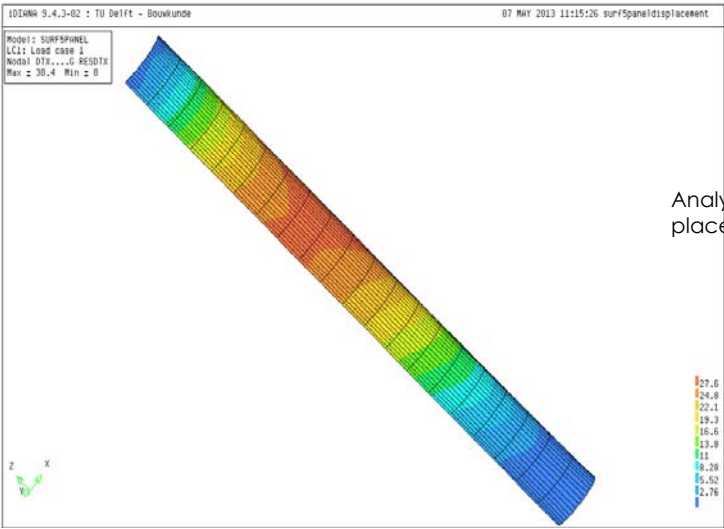
Analytical Calculation results (displacement) Load case 1

Panel 1 / Corrugated (reduced towards the top)

Nr. of Surfaces	1
Nr. of Lines	4
Nr. of Points	4
Mesh type surface	qu8 cq40s
Mesh type midlines	
Material surface	Glass
Material midlines	
Load Case 1	
Gravity	
Wind pressure	0.002354 N/mm2

Load Case 1	Max	Min
FBX...G RESFBX / support reaction	7.86E+04	8.68E+01
DTX...G RESDTX / total displacement (mm)	30.4	0
EL. S1. S1/ Principle stress 1 (algebraic largest) (N/mm2)		
Bottom surface	29.4	-2.15E-02
Top surface	28.3	-2.00E-02

Analytical Calculation results (alternative panel 3) Load case 1



Analytical Calculation results (displacement) Load case 1

