P5 Presentation

The transparent facade of the future
Design strategies for maximizing transparency with self-supporting glass facade systems

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RESEARCH DEFINITION

STAGE 1 → Analysis of Glass Technology

STAGE 2 → Preliminary Concepts

STAGE 3 → Design Research 3 Design Strategies

STAGE 4 → Final Design Development

CONCLUSION
/// RESEARCH DEFINITION ///
THE CASE STUDY

OMA  ABT  TU Delft  SCHELDEBOUW

Size 20 m 7.7 m

Maximize transparency

Interesting design + Structural feasibility

Fail-safe concept

Weatherproofing
“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’?”

1 | What is the optimal geometry of glass components to be used for the construction of the facade?

2 | What are the criteria to evaluate an optimal structural design strategy for the glass facade?

3 | Which parameters can influence the performance of a glass component?

4 | How can manufacturing availability and processes influence the structural design with glass?

5 | What are the ways, in which we can enhance the safety of the glass facade?

6 | How should a structural joint between glass components be designed in order to increase transparency?
/// STAGE 1_ ANALYSIS OF GLASS TECHNOLOGY ///
/// STAGE 2_PRELIMINARY CONCEPTS GENERATION ///
NEW Design methodology based on Glass Component type

- Glass I - profiles
- Glass curved sheets
- Glass tubes

Feasibility of structure
Joints
Degree of transparency
Form - architectural quality
Construction feasibility
Assembly
Manufacturing & Construction costs
/// STAGE 3_DESIGN RESEARCH - 3 STRATEGIES ///
Dead load, self weight

Wind load, pressure or suction

Horizontal in-plane load

Impact loads

Load Actions

Resulting Condition

Stiffening Methods

01 Use effective cross sections

Use effective cross sections

Transfer the load as bracing

Ratio thickness - span

01 Ratio thickness - span

02 Use effective cross sections

Transfer the load as bracing

Ratio thickness - span
01 **Self supporting skin /**
   No secondary support

02 **Symmetry /**
   at least along one axis

03 **Homogeneous appearance /**
   Same from exterior and interior

04 **Transparent or frameless joints /**

05 **Design versatility /**
   Many form potential

06 **Modules /**
   Possibility of assembly in units
Geometry of component

Manufacturing process

Quality of structure
Available size
Maximum process size
Tolerances
Costs

Logistics

Transportation feasibility
Installation feasibility
Costs

Unit feasibility
Overall costs
<table>
<thead>
<tr>
<th>Geometry</th>
<th>Unit scheme</th>
<th>Manufacturing</th>
<th>Logistics</th>
<th>Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Primary shape</strong></td>
<td><strong>Unit scheme</strong></td>
<td><strong>Process</strong></td>
<td><strong>Max. Raw size</strong></td>
<td><strong>Min. Radius (Diameter)</strong></td>
</tr>
<tr>
<td>Flat sheet</td>
<td>Flat sheet</td>
<td>Float glass</td>
<td>approx. 25000 mm</td>
<td>8000mm in Europe</td>
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<tr>
<td>I-profile</td>
<td>I-profile</td>
<td>Cold Bending</td>
<td>size of flat panel depending on radius</td>
<td>-</td>
</tr>
<tr>
<td>Double curved</td>
<td>Double curved</td>
<td>Hot Bending</td>
<td>6000mm length</td>
<td>++</td>
</tr>
<tr>
<td>Single curved</td>
<td>Single curved</td>
<td>Centrifuging process</td>
<td>standard 1500mm SCHOT -10000 mm</td>
<td>420mm</td>
</tr>
<tr>
<td>Bundle</td>
<td>Bundle</td>
<td>Daner process</td>
<td>- -</td>
<td>- -</td>
</tr>
</tbody>
</table>

**Costs**
- Custom mould
- Adjustable mould

**Tolerances**
- (-+2mm)
- (-+5 mm)
- (+-1 mm/m)
- (+-2mm)

**Feasibility**
- For oversized
- For oversized (depending on producer)

**Lamination**
- For oversized
- For oversized (depending on producer)
SYSTEM PARAMETERS

- Appearance
- Facade Grid
- Stability
- Weight
- Robustness
- Component safety
- Alternative load path
- Forming
- Size
- Post processing
- Geometry
- Load transfer
- Assembly tolerances
- Size of Grid
- Area of Joints

FORM

STRUCTURE

SAFETY

MANUFACTURING

CONNECTIONS

TRANSPARENCY
STRATEGY 2
GLASS CURTAIN

01 Twisted curve 1

02 Alternative 2

03 Twisted curve 2

04 Glass curtain

01 Standing

02 Half hanging - Half standing

03 All hanging

Even Grid 4 x 4

20 m

7.7 m

5 m

1.9 m
**STRATEGY 3**

**TUBE WALL**

01 Single row hollow tubes

02 Multiple rows hollow tubes

03 Hollow out massive core

04 Massive bundles

01 Standing

02 Half hanging - Half standing

03 All hanging

01 Intermediate transparent sleeve
CONCEPT 1
Single row units

01. Single row hollow tubes with intermediate transparent sleeve joint. Stabilized by post tensioned rods.

CONCEPT 2
Multiple row units

02. Multiple row of tubes. Intermediate support. Tubes fixed in a special dish profile with resin added at the bottom.
<table>
<thead>
<tr>
<th>Strategy</th>
<th>Units</th>
<th>System</th>
<th>Overall Feasibility</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Size</td>
<td>Costs</td>
<td>Form potential</td>
</tr>
<tr>
<td>Strategy 1 / I-profile</td>
<td>++</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Strategy 2 / Curved</td>
<td>+</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Strategy 3 / Tubes</td>
<td>- -</td>
<td>- -</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>Units</td>
<td>System</td>
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<td>+</td>
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</tr>
<tr>
<td>Strategy 3 / Tubes</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
</tbody>
</table>

1 | Transparency
2 | Structural performance
3 | Size
4 | Design Versatility
5 | Processing
6 | Information availability
7 | Architects’ preference

**SELECTION OF STRATEGY**

26
/// STAGE 4_FINAL DESIGN DEVELOPMENT ///
Common symmetry axis
Middle weak point

Common symmetry axis
Elevating the twist axis higher (2h/3)
Avoid weak central connection

Not common symmetry axis
Alternating for each panel
Avoid weak central connection
Complicated surface
Uneven load distribution
Maximum displacement
7.86mm

Maximum displacement
7.41mm

Maximum displacement
3.33mm

Maximum displacement
8.33mm

Maximum displacement
4.32mm

Maximum displacement
14.12mm
01 Geometry & Material

The calculation can be done only for monolithic solid element. Not an option to model separate materials. The surface has to be only out of one material.

02 Boundary conditions

Non accurately modeled. They are presented as fixed, instead of hinge at the bottom and roller at the top.

03 Safety factor

The partial factor of safety to enhance reliability of the structure is not applied.

04 Maximum stresses

Not an option to evaluate the stresses in plane of the facade. We can only check for displacements and global stresses.
Design Value

The most interesting of the designs. Resembles a glass curtain hanging from the ceiling.

Structural shape

Stiff double-curved sinus shaped shell reducing towards the top to a flat edge. The pyramidoid scheme provides greater stability by lowering the center of gravity.

Transparency

The deflections are transferred at the top part of the element. No need for additional supports behind the surface like in the twisted panel.

Manufacturing

Because the curvature is reduced towards the top edge, the overall complexity and intensity of radii is less than in the other facade shapes.

Cost

The most effective shape as the use of material is less. Calculated volume $4.28e+09$ mm$^3$. 

\begin{figure}
\centering
\includegraphics[width=\textwidth]{diagram.png}
\caption{Selection of surface}
\end{figure}
MEASURES FOR SAFE STRUCTURE

**Material Level (micro)**
- Tempering
  - Chemical
  - Thermal
- Minimize surface flaws
  - Control of processing
  - Etching (acid) after polishing

**Element Level (meso)**
- Lamination
  - Sentry Glass Plus (ionomer)
  - PVB
  - EVA
  - Cold poured resins
- Type of glass build up
- Protection of edges
  - Recession of ply
  - Edge reinforcement
  - Edge cover

**Structure Level (macro)**
- Structure’s resistance
  - Scheme under compression
  - Geometry
  - Geometry
  - Design hyperstatic
- Robustness
  - Alternative load paths
  - Compartementalization
  - Avoid localized stresses
  - Symmetrical cross sections
  - Avoid drilled or bolted connections

**Reduce damage sensitivity**
**Increase redundancy**
**Material Level (Micro)**

- **Annealed glass**
  - Lower damage sensitivity
  - Long term stress resistance
  - Thermal stress resistant
  - Impact resistant
  - Scratch resistant

- **Heat strengthened glass**
  - Soft body impact resistant
  - Thermal stress resistant
  - Long term load resistant
  - Prone to hardbody impact
  - Prone to deep scratches
  - Chipping
  - Nickel sulfide inclusions

- **Fully tempered glass**
  - Cutting or drilling remains possible
  - Thin layer of compression
  - Prone to self-fatigue
  - For complicated geometries
  - Expensive process
  - Rare in structural application

- **Chemically strengthened**
  - Prone to hardbody impact
  - Prone to deep scratches
  - Chipping
  - Nickel sulfide inclusions

**Maximum Tensile strength**

- **Annealed glass**: 45 N/mm²
- **Heat strengthened glass**: 70 N/mm²
- **Fully tempered glass**: 120 N/mm²
- **Chemically strengthened**
### Material Level (Micro)

#### Materiel

- **Annealed glass**
  - 45 N/mm²

- **Heat strengthened glass**
  - 70 N/mm²

- **Fully tempered glass**
  - 120 N/mm²

- **Chemically strengthened**
  - 120 N/mm²

#### Material Properties

- **Steel**
  - F (kN)
  - f (mm)

- **Glass**
  - F (kN)
  - f (mm)
LAMINATION OF FACADE PANELS

Polyvinyl Butyral (PVB)
- Tensile strength $\leq 20$ Mpa
- High elasticity
- Affected by temperature
- Load duration dependent
- Prone to creep
- Average tear strength

SentryGlas Plus (SGP) (DuPont™)
- Tensile strength 300 MPa
- 100 times more rigid structure
- Less affected by temperature
- Load duration dependent
- 5 times higher tear strength
- Difficult in lamination
- Thinner laminates
EDGE PROTECTION

Edge protection
Soft metal (aluminium)

SGP foils
Stainless steel spacer

12 12 20 12 12
Dead load is carried in stacking

- Keeps the glass under compression
- Avoid vertical substructure
- Increase transparency in vertical joints

Wind load is counteracted by stiff geometry

- Waveheight to 1/20 of the span
- Bottom wave 1800 mm
- Middle wave 1000 mm
- Symmetrical
- Pyramidoid scheme that enhances stability
- Low gravity center

Edge supports

- Bottom linear (hinge)
- Top linear (roller) z-axis
- Sides are free to move
Segmentation of the facade
- 4 segments vertically
- 4 segments horizontally
- Maximum manufacturable sizes

Intermediate connections
- Secure continuity of surface
- Transfer forces and moments (Firm)
- Should not perform as hinge

Intermediate joint should not act as a hinge.
CONNECTIONS / REQUIREMENTS

01 Strength
The connections to bear the loads imposed on the facade:
- Dead load
- Lateral loads

02 Geometry
Their geometry should ensure continuity of the surfaces. Take into account the complexity of the surface.

03 Robustness
Provide alternative load paths in case of failure of one panel or more.

04 Size
Increase the level of transparency by being as small as possible. Smallest existing size now 150mm.

05 Installation
Take into account the assembly process with the appropriate tolerances.
01 Avoid contact of glass with hard materials

02 Structural spacer and edge used as an interface to transfer the forces between the glass.

03 The geometry of the joint should follow the perpendicularity of the curved surface.

04 According to the fabrication deviations +/- 2mm tolerances are introduced as intended to avoid overlapping profiles.

Interlocking geometry following the normals of the surface

Compressive load transfer in the interface

In-plane force transfer

SG stiff interlayer

STRUCTURE
LEVEL (MACRO)
**CONNECTIONS / DETAILING**

- **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 pre-stress it.

- **Sentry Glas Plus Interlayer**: The SGP 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 Neoprene sheet (hardness 90-100)**: 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.
CONNECTIONS / DETAILING

- Sentry Glas Plus Interlayer
- 20/22 mm hollow stainless steel spacer
- 12 mm HS Soda Lime Glass
- Stainless steel extruded profile
- 12mm Bolt
- 4mm rubber ring
- Silicon Sealant
- 2mm Neoprene sheet (hardness 90-100)
- 2mm Silicone bushing
**CONNECTIONS / FABRICATION STEPS**

**Annealing and bending**

Adjustable mould - ‘Flex-rod’ system. Actuators adjusted according to computer model output.

**Water jet cutting**

Water jet cutting the edges of glass so as to achieve the perpendicularity across the edges.

**Strengthening**

Heat strengthening glass after the bending process. Chemical strengthening could be a second option because of the geometry.

**Stainless Steel extrusion & forming**

Using special machines for the aircraft industry stainless steel extrusions that fit the diameter of 140 mm are possible. Used for producing the spacers. After that the shapes can be bent and twisted.

**Aluminium extrusion & forming**

Aluminium extruded parts are used for producing the connector and edge piece later on they are bending and twisted together to form the final profile shape.

**Lamination of the components into one element / panel**
CONNECTIONS / DETAILING

Sun Screen

Roof Build up
2 mm perforated red bruss
Bituminous layer
Foam glass / Insulation
Concrete 200 mm
Corrugated metal sheet
200 mm H steel beam
Dropped ceiling

Roller Detail

STRUCTURE
LEVEL (MACRO)

L profile 100/100/10
Bolt 24 mm
Custom made steel beam
Extruded aluminium profile
EPDM Gaskets
Glass Panel
EPDM Gasket
CONNECTIONS / DETAILING

Floor Stone tiles 30mm
Steel profile custom made
Bolt 24 mm
Steel plate
Steel plate 10 mm
Neoprene layer 10.5 mm
Setting Block
Glass panel
Bolt 18 mm
Aluminium sheet

Linear Clamp detail

Floor Build up
Stone tiles 30mm
Mortar 20mm
Cement screed 140mm
Polyethylene membrane
Insulation
Concrete 530mm
MODEL DESCRIPTION

Simplified model

- 24 mm monolithic glass
- One surface top to bottom
- No separations between the panels
- Model of one segment
- One material (Soda Lime Glass)
- No joints modelled
- Restraint at the top and bottom
- 2 Loading scenarios
- Mesh type curved shell QU8 CQ40S

Load Case 1

Gravity

Wind pressure 0.002354 N/mm²

Load Case 2

Gravity

Wind suction (-)0.002354 N/mm²

Physical
Simplified
ULTIMATE LIMIT STATE

Load Case 1

<table>
<thead>
<tr>
<th>EL. S1. S1/ Principle stress 1 (algebraic largest) (N/mm2)</th>
<th>Max</th>
<th>Min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom surface</td>
<td>52</td>
<td>-5.71E-03</td>
</tr>
<tr>
<td>Top surface</td>
<td>113</td>
<td>-5.88E-03</td>
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</table>

Load case 1

Maximum tensile stress (bottom) = 52MPa
For 2 laminated panes equals the maximum

Load Case 2

<table>
<thead>
<tr>
<th>EL. S1. S1/ Principle stress 1 (algebraic largest) (N/mm2)</th>
<th>Max</th>
<th>Min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom surface</td>
<td>60.2</td>
<td>-3.62E-02</td>
</tr>
<tr>
<td>Top surface</td>
<td>56.7</td>
<td>-3.91E-02</td>
</tr>
</tbody>
</table>

Load case 2

Maximum tensile stress (top) = 56.7MPa
For 2 laminated panes is just above the maximum

Maximum allowable tensile strength 45MPa (annealed)

Material Factor $\gamma_M = 1.8$

Load factor (wind load) $\gamma_C = 1.6$

Design load $\leq 26$Mpa
PERFORMANCE
SIMULATIONS

Load Case 1
Max
Min
FBX...G RESFBX / support reaction
1.37E+05

DTX...G RESDTX / total displacement
106

Load Case 2
Max
Min
FBX...G RESFBX / support reaction
1.33E+05

DTX...G RESDTX / total displacement
105

Load case 1
Maximum displacement 106 mm < 307 mm

Load case 2
Maximum displacement 105 mm < 307 mm

Maximum allowable deflection
1/65 of span
OR
50 mm

Span
20000 mm

Allowable deflection
307 mm
CONCLUSIONS / MEASURES

**Ultimate Limit State**
1 | Increase accuracy in the modelling of the surface
2 | Conduct additional laboratory test on specimens
3 | Increase the thickness of the glass
4 | Use Fully Tempered glass

**Serviceability Limit State**
1 | We cannot take into account the lower limit of 50mm deflection since it is not given for the certain geometry
2 | Increase the accuracy of the calculations / The spacer stiffness could have spring action.
3 | The connection of the facade to the wall should allow for deflections of 100mm
The maximum transparency can be achieved for a glass facade of large scale by utilizing a self-supporting geometry like the one proposed.

We can improve the structural performance through the stiffness of the curved geometry and provide a safe structure.

We can maximize transparency in the curved geometry by using the special type of joint that is embedded in the laminate and can transfer forces via the spacer and an interlocking geometry.

The size of connection achieved can be 33 mm.
Thank you
APPENDIX / ALTERNATIVES SURFACES SIMULATION

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
Wind pressure 0.002354 N/mm²

Table:

<table>
<thead>
<tr>
<th>Load Case 1</th>
<th>Max</th>
<th>Min</th>
</tr>
</thead>
<tbody>
<tr>
<td>FBX...G RESFBX / support reaction</td>
<td>1.14E+01</td>
<td>1.30E+02</td>
</tr>
<tr>
<td>Wind pressure</td>
<td>0.002354</td>
<td>N/mm²</td>
</tr>
<tr>
<td></td>
<td>190</td>
<td>0</td>
</tr>
</tbody>
</table>

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
Wind pressure 0.002354 N/mm²

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</tr>
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<tbody>
<tr>
<td>FBX...G RESFBX / support reaction</td>
<td>7.86E+04</td>
<td>8.68E+01</td>
</tr>
<tr>
<td>Wind pressure</td>
<td>0.002354</td>
<td>N/mm²</td>
</tr>
<tr>
<td></td>
<td>30.4</td>
<td>0</td>
</tr>
</tbody>
</table>

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
Wind pressure 0.002354 N/mm²

Table:

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<tbody>
<tr>
<td>FBX...G RESFBX / support reaction</td>
<td>7.25E+04</td>
<td>4.48E+02</td>
</tr>
<tr>
<td>Wind pressure</td>
<td>0.002354</td>
<td>N/mm²</td>
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<tr>
<td></td>
<td>25.4</td>
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</table>

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
Wind pressure 0.002354 N/mm²

Table:

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<thead>
<tr>
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</tr>
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<tbody>
<tr>
<td>FBX...G RESFBX / support reaction</td>
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<td>8.8E+01</td>
</tr>
<tr>
<td>Wind pressure</td>
<td>0.002354</td>
<td>N/mm²</td>
</tr>
<tr>
<td></td>
<td>30.4</td>
<td>0</td>
</tr>
</tbody>
</table>

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

Table:

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<td>Wind pressure</td>
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<td>N/mm²</td>
</tr>
<tr>
<td></td>
<td>30.4</td>
<td>0</td>
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