Kinetic Thin Glass Façade

A study on the feasibility of a water- and airtight kinetic façade with a bending-active thin glass element
Context

- Transparency in buildings is an increasing trend

Hiroshi Senju Museum, Karuizawa, Japan

Chanel Amsterdam, Amsterdam, Netherlands

Apple Fifth Avenue, New York City, USA
• Transparency in buildings is an increasing trend
• Rapid development of research and production techniques

"Initially, it was not the architects who took architecture into the modern age, but rather engineers and planners from so called non-artistic disciplines"

Mirko Baum
Transparency in buildings is an increasing trend

Rapid development of research and production techniques

→ alternative product: chemically strengthened (ultra) thin glass*

* Thin glass → t < 2 mm
Ultra thin glass → t < 0.1 mm
Possible design
bending-active, kinetic thin glass element
**Possible design**
bending-active, kinetic thin glass element
Possible design
bending-active, kinetic thin glass element
Possible design
bending-active, kinetic thin glass element
“How can a kinetic façade element featuring a bendable thin glass panel be designed to be water- and airtight in closed condition?”
Option 1: Magnetic Force
- thin glass laminate
- metal strip
- fixed magnetic gasket frame

Option 2: Tensile Force
- thin glass laminate pressed onto gasket through tension
- frame equipped with rubber gasket
- shafts pulled tightly to frame to create tension in glass

Option 3: Elastic Fabric
- thin glass laminate
- elastic fabric stretched between frame and glazing
- openings for ventilation between shaft and frame
Approach and Methodology

design proposals
Approach and Methodology

**design proposals**
- determination of glass laminate configuration via FE methods
- ranking of most suitable laminate configurations
- demands not satisfied: pick next preferred configuration from ranking
- stability (ULS, SLS) under wind load via FE methods
- demands satisfied
- test three options

**elaboration of selected proposal**
- technical detailing
- product choice
- mock-up design

- conceptual detail design and initial product research
- evaluation of each proposal via critical assessment of simplicity, functionality and material capacity
- 1:5 scale mock-up of most promising proposal
- demands satisfied
Structural Suitability

Glass Laminate Configuration
Structural Suitability

Glass Laminate Configuration

- Safety Regulations
- Adding stiffness etc.

![Glass Laminate Diagram](image)
Structural Suitability

Glass Laminate Configuration

- smallest radius that can be achieved by controlled bending (lowest stress)
- highest stability of the glass laminate against external loads (e.g. wind)
- minimum required force to achieve the radius

**Variations E₁ to E₅**

- $E = 74,000 \text{ MPa}$
- $v = 0.23$
- $E = 0 \ldots 2030 \text{ MPa}$
- $G = 0 \ldots 700 \text{ MPa}$
- $5$ variations $E₁$ to $E₅$
- $E = 74,000 \text{ MPa}$
- $v = 0.23$

<table>
<thead>
<tr>
<th>$t₁$</th>
<th>$t₂$</th>
<th>$t₃$</th>
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</thead>
<tbody>
<tr>
<td>0.55</td>
<td>0.38</td>
<td>0.85</td>
</tr>
<tr>
<td>0.85</td>
<td>0.76</td>
<td>1.1</td>
</tr>
<tr>
<td>1.1</td>
<td>1.52</td>
<td></td>
</tr>
</tbody>
</table>

$P₁ = E₁, E₂, E₃$
**Glass Laminate Configuration**

- **smallest radius** that can be achieved by controlled bending (lowest stress)
- highest **stability** of the glass laminate against external loads (e.g. wind)
- **minimum** required **force** to achieve the radius

**90 possible configurations!**

<table>
<thead>
<tr>
<th>reference config.</th>
<th>varying glass thickness</th>
<th>varying interlayer thickness</th>
<th>assymetric configuration</th>
<th>varying interlayer stiffness</th>
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<tbody>
<tr>
<td><img src="image1" alt="reference config." /></td>
<td><img src="image2" alt="varying glass thickness" /></td>
<td><img src="image3" alt="varying interlayer thickness" /></td>
<td><img src="image4" alt="assymmetric configuration" /></td>
<td><img src="image5" alt="varying interlayer stiffness" /></td>
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</table>

- variable thickness
- fixed thickness

<table>
<thead>
<tr>
<th>E1 = 2030 MPa</th>
<th>E3 = 1450 MPa</th>
<th>E3 = 343 MPa (ref)</th>
<th>E4 = 435 MPa</th>
<th>E5 = 100 MPa</th>
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</thead>
</table>

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**Evaluation of Results: Glass Thickness Effect**

The thicker the glass, the higher the max. principal stresses.

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**Glass-Thickness-Dependent Maximum Principal Stress at Edge of Outer Surface as Function of Bending Radius**

- **Glass Thickness 2x0.85mm [reference]**
- **Glass Thickness 2x0.55mm**
- **Glass Thickness 2x1.1mm**

- Mechanical strength after safety factor
- Radius range
Structural Suitability

Interlayer Thickness

Interlayer Stiffness

PVB-Thickness-Dependent Maximum Principal Stress at Edge of Outer Surface as Function of Bending Radius

PVB-Type-Dependent Maximum Principal Stress as Function of Bending Radius

E1 = 2030 MPa
E2 = 1450 MPa
E3 = 943 MPa (ref)
E4 = 435 MPa
E5 = 100 MPa

with $v = 0.45$
### Evaluation of Results: Ranking

<table>
<thead>
<tr>
<th>Choice No.</th>
<th>1st glass thickness $t_1$ [mm]</th>
<th>PVB thickness $t_2$ [mm]</th>
<th>2nd glass thickness $t_3$ [mm]</th>
<th>PVB Type $p_2$</th>
<th>final value [%]</th>
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<tr>
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<td>E5</td>
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<td>0.55</td>
<td>E4</td>
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<td>13</td>
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<td>E3</td>
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<tr>
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<td>E2</td>
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<td>0.55</td>
<td>E4</td>
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<tr>
<td>18</td>
<td>0.55</td>
<td>0.76</td>
<td>0.55</td>
<td>E3</td>
<td>-24.2</td>
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<tr>
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<td>0.55</td>
<td>0.76</td>
<td>0.55</td>
<td>E2</td>
<td>-24.15</td>
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<tr>
<td>20</td>
<td>0.55</td>
<td>0.76</td>
<td>0.55</td>
<td>E1</td>
<td>-24.13</td>
</tr>
</tbody>
</table>

Preferred choice: 1 (0.55 mm PVB, 0.38 mm 1st glass, 0.55 mm 2nd glass)

Softest interlayer: 0.55 mm PVB
3 Options under Wind Load

Option 1: Magnetic Force

Option 2: Tensile Force

Option 3: Elastic Fabric

Option 2 + 3: Tensile Force / Elastic Fabric

wind load

support reactions
Option 1: Magnetic Force
Method: Wind suction on glass surface supported by magnetic force
Decisive properties:
• Max. deformation under wind load

Flat glass

→ max. deformation = 19.5 mm
**Option 1: Magnetic Force**

Method: Wind suction on glass surface supported by magnetic force

Decisive properties:

- Max. deformation under wind load

Curved glass

→ max. deformation < 1 mm (!)
3 Options under Wind Load

Option 1: Magnetic Force

Option 2 + 3: Tensile Force / Elastic Fabric

wind load
support reactions
Option 2+3

Method: Wind suction on curved glass supported by two shafts

Decisive properties:

• Max. deformation under wind load

→ tensile force of 2550 N required to keep stable!
3 Options under Wind Load

Option 1: Magnetic Force

Option 2 + 3: Tensile Force / Elastic Fabric

wind load
support reactions
Approach and Methodology

- Conceptual detail design and initial product research
- Evaluation of each proposal via critical assessment of simplicity, functionality, and material capacity
- 1:5 scale mock-up of most promising proposal
- Elaboration of selected proposal:
  - Technical detailing
  - Product choice
  - Mock-up design

- Determine glass laminate configuration via FE methods
- Ranking of most suitable laminate configurations
- Stability (ULS, SLS) under wind load via FE methods
- Demands satisfied: pick next preferred configuration from ranking
- Test three options

DESIGN

Structural suitability

Practical feasibility

design proposals
Option 1: Magnet
Option 1: Magnet

Water-airtightness possibly achievable with elaboration of conceptual details
Option 2: Tension
Option 2: Tension

- gaps in corner joints
  → would require similar solution as magnet
Practical Feasibility

**Option 2: Tension**

- gaps in corner joints
  → would require similar solution as magnet
Option 2: Tension

- gaps in corner joints
  → would require similar solution as magnet
Option 2: Tension

- gaps in corner joints
  → would require similar solution as magnet
Option 2: Tension

- gaps in corner joints → would require similar solution as magnet

Further concerns:

- Large force required against wind load
- Pressure not likely to be equally distributed
Practical Feasibility

Option 3: Elastic Fabric
Option 3: Elastic Fabric

- Leakage at corner joint
Practical Feasibility

Option 3: Elastic Fabric

- Leakage at corner joint
Practical Feasibility

Option 3: Elastic Fabric

- Leakage at corner joint
- Ventilation gap limited
**Option 3: Elastic Fabric**

- Leakage at corner joint
- Ventilation gap limited

Further concerns:
- High elasticity required + unequal stretching
- Obstruction of view
<table>
<thead>
<tr>
<th>practical feasibility</th>
<th>Option 1</th>
<th>Option 2</th>
<th>Option 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>o magnet can provide enough pulling force for water- airtightness</td>
<td>o additional horizontal frames required</td>
<td>o simple gasket detail possible</td>
<td>o bent edges permanently sealed</td>
</tr>
<tr>
<td>o magnet pulling force adjustable</td>
<td>o abrupt opening movement due to magnetic holding force (only if permanent magnet)</td>
<td>o unequally distributed pressure</td>
<td>o limited ventilation gap</td>
</tr>
<tr>
<td>structural suitability</td>
<td>o large force required to keep glazing shut</td>
<td>o applied force may result in bending of shafts</td>
<td>o large force required to keep glazing shut</td>
</tr>
<tr>
<td>o magnetic pulling force can also be used against wind suction</td>
<td>o applied force may result in bending of shafts</td>
<td>o fabric may pull back edges of glazing with tendency to return to original length</td>
<td>o possible abrasion of fabric due to over-stretching</td>
</tr>
</tbody>
</table>

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Design Choice

Option 1: Magnetic Force

Option 2: Tensile Force

Option 3: Elastic Fabric

---

Thin glass laminate pressed onto gasket through tension

Frame equipped with rubber gasket

Shafts pulled tightly to frame to create tension in glass

---

Thin glass laminate

Elastic fabric stretched between frame and glazing

Openings for ventilation between shaft and frame

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Expected Performance of the Proposed Design

<table>
<thead>
<tr>
<th>Requirements / Qualities</th>
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</thead>
<tbody>
<tr>
<td>watertightness</td>
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<tr>
<td>airtightness</td>
</tr>
<tr>
<td>thermal insulation</td>
</tr>
<tr>
<td>acoustic insulation</td>
</tr>
<tr>
<td>safety</td>
</tr>
<tr>
<td>stiffness under high wind load</td>
</tr>
<tr>
<td>natural ventilation</td>
</tr>
<tr>
<td>transparency / optical quality</td>
</tr>
<tr>
<td>cost-effectiveness</td>
</tr>
</tbody>
</table>
Possible Applications

Greenhouse/Botanical Garden

Possible Applications

- Single Skin Facade
- Double Skin Facade
- Interior Glazing

Requirements / Qualities

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Status</th>
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</thead>
<tbody>
<tr>
<td>thermal insulation</td>
<td>X</td>
</tr>
<tr>
<td>(only if heated and unheated spaces are divided)</td>
<td></td>
</tr>
<tr>
<td>acoustic insulation</td>
<td>X</td>
</tr>
<tr>
<td>safety</td>
<td>✔</td>
</tr>
<tr>
<td>transparency / optical quality</td>
<td>✔</td>
</tr>
<tr>
<td>showcasing the innovation</td>
<td>X</td>
</tr>
</tbody>
</table>
AGC Technovation Center, Gosselies, Belgium

- Outer skin of open double-skin façade
- No thermal and acoustic insulation
- Functions solely as sun-protective layer and for power generation
- “Show room” for company’s innovative product range

→ Alternative design: closed cavity façade
Approach and Methodology

**Design Proposals**
- Determination of glass laminate configuration via FE methods
- Ranking of most suitable laminate configurations
- Stability (ULS, SLS) under wind load via FE methods
- Test three options

**Design Suitability**
- Demands not satisfied: pick next preferred configuration from ranking

**Practical Feasibility**
- Conceptual detail design and initial product research
- Evaluation of each proposal via critical assessment of simplicity, functionality and material capacity
- 1:5 scale mock-up of most promising proposal
- Demands satisfied

**Elaboration of Selected Proposal**
- Technical detailing
- Product choice
- Mock-up design
Elaboration of Selected Design

Focuses:

• Magnet-gasket design
• Mode of operation (kinetics)
• Facade profile design
• Manufacturing, assembly
Gasket with Embedded Switchable Magnet

- Electro-permanent magnet placed inside gasket
- Dampening chamber and dart unaffected by wires
- Wires leading from coils to aluminium profile through locally cut slit into EPDM gasket
Mode of Operation

- Linear movement
- Rotational movement
- Rail incl. steel plate facilitating linear movement
- Steel bearing facilitating rotational movement
- Shaft supporting laminated thin glass
Elaboration of Selected Design

Façade Profile Design

- Unitised system

Schüco USC 65 unitised system
Elaboration of Selected Design

**Façade Profile Design**

- Unitised system
- Adjustments made to fit design

Schüco USC 65 unitised system

- Profile widened (to house rail, magnetic gasket etc.)
- Outer gasket eliminated (now single sided)
- Insulating layer eliminated (double-skin facade)
Façade Profile Design

- main structural frame
- additional aluminium profile
- curved aluminium extrusion

Curved aluminium profile with transom helps to fixed aluminium folded aluminium plate with curved edges bolted onto main structural frame in the factory

(source: www.nonferrous.com)

(source: www.aluminiumdesign.net)
Façade Profile Design

- Gap between main frame and additional transom
Elaboration of Selected Design

Façade Profile Design

- Gap between main frame and additional transom

→ covered with aluminium plate, edges made airtight with silicone
Final Design
Final Design
Final Design

Horizontal Detail Centre 1:20

- Unibond system
- Main structural frame
- Folded aluminium profile bolted onto structural frame
- EPDM gasket with inserted electroperament magnet
- Curved extruded profile with rainscreen welded to folded profile
- Thin glass laminated with acoustic interlayer 0.55-0.38-0.55 mm

Horizontal Detail Bottom 1:20

- Aluminium clip-on rainscreen cap
- Stainless steel rail screwed on structural frame
- Bearing facilitating rotation of shaft
- Stainless steel cylindrical shaft placed into bearing, supporting glazing

- Extruded aluminium
- Structural frame
- Folded aluminium profile
- Thin glass laminate
- EPDM gasket with embedded electroperament magnet
- Curved extrusion
- Aluminium profile
Final Design
Conclusion

Answer to Main Research Question:

“How can a kinetic façade element featuring a bendable thin glass panel be designed to be water- and airtight in closed condition? ”

Design involves:

• Glazing consisting of two thin glass elements (0.55 mm) laminated with acoustic interlayer (0.38 mm) with metallic strip attached

• Switchable electro-permanent magnets placed inside the gasket

• Principle of active bending (1D-linear movement to 2D-deformation)

• Bespoke facade profiles designed to accommodate requirements
Discussion

• Research does not present optimal or only possibility to achieve the goal

• Meant to offer new insights into the field and form a basis for further research

• Many choices made during the process are subjective, although supported by numerical data and arguments from previous literature

→ main objectives fulfilled within theoretical framework:

1) Addition of a second layer of glazing to comply with safety regulations

2) Investigation of possibilities to combine the bending of thin glass with water- and airtightness properties
Possibilities & Limitations

- **Sustainability** (reduced use of raw materials, lightweight loadbearing structures)
  → increased use of aluminium for stiffness

- **Cost reduction** (reduced use of raw materials, lightweight loadbearing structures)
  → chemical strengthening process, necessity of bespoke elements

- **New architectural impressions**
  → large variety of new possibilities, new architectural era?

Recommendations for further research

- Investigation of **other possible uses** for thin glass in architecture
  → for bending: sun shading, solar power generation, structural (load reduction)
  → building parts/types: glass roof, greenhouse, interior glazing, single skin

- Possibility to make **insulating glass unit** (double glazing)
Thank you for your attention!