THE GLASS DOME

Design technology for a dry assembled and cast glass dome

P5 Presentation, 31-01-2018, TU Delft
THE GLASS DOME

Mentors:

- Faidra Oikonomopoulou
- Regina Bokel
- Telesilla Bristogianni
Motivation: For centuries....

(source: www.tumblr.com).

(source: www.florenceforyou.com).

(Middle Earth Home, 2017).

(Smith, 2006).
Motivation: The industrial revolution led to...
Motivation: Dome designs aim for....

VISUAL FUNCTION

LARGE SPAN

Future??
Motivation: Evolution of the glass dome...
Motivation: What about the future.....

An all-glass dome out of cast glass components

(source: www.brickowl.com)
Motivation: Function.....
Motivation: Current aviaries.....
Motivation: South-east of France....

'Villars Les Dombes'

Moderate climate
Motivation: ‘Parc des Oiseaux’

Bird park: ‘Parc des Oiseaux’
Aviary for Lori parrots
Main question

“How can a solely glass dome be developed and assembled from structural cast glass components while providing thermal comfort and being minimum invasive for the local environment?“.

Sub questions

▪ What is the optimal shape of the cast glass components?
▪ What techniques can be used to minimize the number of different molds?
▪ What techniques can be used to connect the components and create a demountable structure?
▪ What strategies can optimize the dome transparency?
▪ What strategies can be used to create thermal comfort while being minimum invasive for the local environment?
The idea...
1. Literature results
**Domes:** Compressive force system...

![Diagram of dome structure showing stress distribution](source: http://shells.princeton.edu/Balz.html)
Domes: *Compressive force system*...

\[ 0^\circ \leq \Phi \leq 51.82^\circ \]

**STRESS RESULTANTS**

- **Domes**
  - Thermal performance
  - Glass
  - Interlocking systems
Domes: Shallow Glass Dome...

SHALLOW DOME

Φ = 45°

For who?
Thermal performance: Shallow dome for...

COMFORT

[Diagram of a shallow dome withComfort]
Thermal performance: Thermal environment...

\[ T_{\text{comf}} = 0.31T_o + 17.8 \quad (\text{ASHREA55}) \]
**Thermal performance:** Comfort temperature...

<table>
<thead>
<tr>
<th>Time</th>
<th>Indoor Temperature</th>
<th>Outdoor Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>09:00-19:00</td>
<td>30 °C +/- 5</td>
<td>19 °C +/- 5</td>
</tr>
<tr>
<td>19:00-09:00</td>
<td>30 °C +/- 5</td>
<td>18 °C +/- 5</td>
</tr>
</tbody>
</table>

**PASSIVE SYSTEMS**
Thermal performance: focus on...
Thermal performance: Thermal mass...

![Diagram showing thermal mass effects in a dome structure]

-Thermal Mass: 35944.8

-Literature Results:
  - Domes
  - Glass
  - Interlocking Systems
Thermal performance: *Natural ventilation*...
Thermal performance: White wash paint...

**SUMMER**: 8\textsuperscript{th} Apr. – 30\textsuperscript{th} Sep.

**FALL**: 1\textsuperscript{st} Oct. – 12\textsuperscript{th} Nov.
Shallow (Aviary) Dome

Glass Type?
Glass: Production technique.....

CAST GLASS

+ HIGH FORM FLEXIBILITY

(source: ifitshipitshere.com).

+ MONOLITHIC STRUCTURE

(Literature results: Domes | Thermal performance | Glass | Interlocking systems)
Glass: Production technique.....

ANNEALING PHASE

a. Dependent factors
- Temperature difference
- Thermal expansion
- Thickness
- Type of glass

b. Parameters
- Shape
- Mass distribution
- Sides exposed to cooling
- Thermal mass & features kiln
SODA-LIME GLASS

€/KG

KG/m³

Interlocking systems
Glass: Existing cast glass structures.....

‘OPTICAL HOUSE’

‘CRYSTAL HOUSE’

Demountable

Transparent

(Fujii, nacasa & partners, 2013).

(Nijisse, 2015).

Literature results: Domes | Thermal performance | Glass | Interlocking systems
Interlocking systems: Demountable & transparent.....
Interlocking systems: Examples...

(source: www.fantv.nl).

(source: Archiweb, 2014).

(Macleod, 2014).

(Roblin, 2010).

(source: Archiweb, 2014).

(source: www.fantv.nl).
Interlocking systems: *Interlock + interlayer*

**INTERLOCKING SYSTEM**

**INTERLAYER**

(a) peak stresses

(b) interlayer

**INTERLOCK**

RING

ARCH

R1

R2

R3

R1
Interlocking systems: Ring & Arch interlock....


Literature results: Domes | Thermal performance | Glass | Interlocking systems
2. General design
General design: Floor plan...
General design: Cross section A–A′...
General design: *Oculus*...

- 2 panels laminated of safety glass
- Aluminium window frame
- Bird-net
- Steel compression ring
General design: *Oculus detail A* ...
3. Component design

Design principles | Previous attempts | Final component | Interlayer | Feasibility
Design principles: *Existing cast glass interlocking systems*...
**Design principles:** General principles...

1. **Mass <10kg**
   - **Reduce annealing time**

2. **One component**
   - **Minimize different steel molds**

3. **Round edges**
   - **Prevent peak stresses**

4. **Homogeneous mass distribution**
   - **Ensure homogeneous shrinkage**
**Design principles:** *Dome principle...*

<table>
<thead>
<tr>
<th>Design Component</th>
<th>Previous Attempts</th>
<th>Final Component</th>
<th>Interlayer</th>
<th>Feasibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Mass &lt;10kg</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. One component</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Round edges</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Homogeneous mass distribution</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Spherical configuration</td>
<td></td>
<td>Design omnidirectional</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Small elements</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**DOUBLE CURVED**
SPHERE BASED DESIGN
Previous attempts

A. One component

B. Two components
Final component: Fully omnidirectional...

<table>
<thead>
<tr>
<th>Sphere</th>
<th>Radius (mm)</th>
<th>Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>45,025</td>
<td>92,05</td>
</tr>
<tr>
<td>B</td>
<td>46,192</td>
<td>92,19</td>
</tr>
<tr>
<td>C</td>
<td>33,460</td>
<td>66,92</td>
</tr>
</tbody>
</table>
Final component: *Amount of components...*

<table>
<thead>
<tr>
<th>#Rings</th>
<th>#Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>197</td>
<td></td>
</tr>
<tr>
<td></td>
<td>128</td>
</tr>
<tr>
<td></td>
<td>733</td>
</tr>
<tr>
<td></td>
<td>1225</td>
</tr>
</tbody>
</table>

**Total:** 139132
Final component: Final shape & inspiration

2.5 kg < 10 kg

(a) Anterior view showing regions of the vertebral column

(Tortora and Derrickson, 2009)
Final component: *First mold design*...
Final component: First mold design....
**Final component**: Final mold design.

**STEEL PRECISION MOLD + VENTS**

- **glass**
- **air**
- **air**
Final component: Post-processing....
Final component: Transparency....

Positive lens

Negative

Positive lens
Final component: *Transparency*...
Final component: *Transparency*...
Interlayer: Ring & arch direction...
Interlayer: Ring layers....
Interlayer: Optimization...

0 < x < 5 mm
Feasibility: Reference, Armadillo Vault....
Feasibility: Constructing the Glass Dome...
Feasibility: Pre-stress & maintenance...
4. Validation

Structural performance | Thermal performance
Structural validation: *Focus on...*

1. Support-wall thickness
   - Compressive force system
   - Interlayer selection

2. Symmetrical load-case
   - Asymmetrical load-case

3. Arch interlock
**Structural validation**: Stress resultants symmetrical load-case.....

(source: http://shells.princeton.edu/Balz.html)
Structural validation: *Wall thickness of the support structure*...
MATERIAL SELECTION

1. Structural requirements:

\[ \sigma_{\text{contact}} \leq 20 \text{ MPa} \]

\[ \sigma = E^* \varepsilon = E^*(\Delta L/L) \]

\[ \sigma_{\text{contact}} = E_{\text{int}} \frac{2\Delta}{t_{\text{int}}} \]

\[ E_{\text{int}} / t_{\text{int}} \leq 20/(2 \times 0.25) \leq 40 \text{ N/mm}^3 \]

2. General requirements:

- Optical quality/transparent
- Durable
- Service temp: > 50°C

3. Manufacturing requirements:

- Thickness: 2–12mm
- Solid complex 3D
Structural validation: TPU...

**TPU & Compression molding**

- Amount interlayers glass dome
Structural validation: TPU....
Structural validation: Diana...

Compressive force system

LC1: Self-weight

LC2: Self-weight + Wind
Structural validation: *Output Diana*...

**Resultants** \[ \text{arch} \] (Nxx)

**LC1: Self-weight**

**LC2: Self-weight + Wind**
**Structural validation**: Output Diana.

Resultants \textbf{ring} \((N_{yy})\)

\textbf{LC1: Self-weight}

\textbf{LC2: Self-weight + Wind}
### Structural validation: Comparison of the results...

#### LC1 (symmetrical)

<table>
<thead>
<tr>
<th>direction</th>
<th>Diana</th>
<th>Hand</th>
</tr>
</thead>
<tbody>
<tr>
<td>LC 1 (Sym)</td>
<td>LC 1 (Sym)</td>
<td></td>
</tr>
<tr>
<td>Ring</td>
<td></td>
<td></td>
</tr>
<tr>
<td>top</td>
<td>-6.41</td>
<td>-6.86</td>
</tr>
<tr>
<td>base</td>
<td>-1.68</td>
<td>-1.67</td>
</tr>
<tr>
<td>Arch</td>
<td></td>
<td></td>
</tr>
<tr>
<td>top</td>
<td>-6.41</td>
<td>-6.86</td>
</tr>
<tr>
<td>base</td>
<td>-7.99</td>
<td>-8.04</td>
</tr>
</tbody>
</table>

#### LC2 (asymmetrical)

<table>
<thead>
<tr>
<th>Diana</th>
<th>LC2 (Asym)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-7.12</td>
</tr>
<tr>
<td></td>
<td>-1.72</td>
</tr>
<tr>
<td></td>
<td>-7.12</td>
</tr>
<tr>
<td></td>
<td>-8.92</td>
</tr>
</tbody>
</table>
Structural validation: *Comparison of the results...*

<table>
<thead>
<tr>
<th>direction</th>
<th>Diana</th>
<th>Hand</th>
<th>Diana</th>
<th>LC2 (Asym)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring</td>
<td>LC1 (Sym)</td>
<td>LC1 (Sym)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Diana</td>
<td></td>
</tr>
<tr>
<td>top</td>
<td>−6,41</td>
<td>−6,86</td>
<td></td>
<td>−7,12</td>
</tr>
<tr>
<td>base</td>
<td>−1,68</td>
<td>−1,67</td>
<td></td>
<td>−1,72</td>
</tr>
<tr>
<td>Arch</td>
<td>LC1 (Sym)</td>
<td>LC2 (Asym)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Diana</td>
<td></td>
</tr>
<tr>
<td>top</td>
<td>−6,41</td>
<td>−6,86</td>
<td></td>
<td>−7,12</td>
</tr>
<tr>
<td>base</td>
<td>−7,99</td>
<td>−8,04</td>
<td></td>
<td>−8,92</td>
</tr>
</tbody>
</table>
Structural validation: *Output Diana*...

Maximum *principle stress* (S3)

**LC1: Self-weight**

**LC2: Self-weight + Wind**
### Structural validation: Comparison of the results...

<table>
<thead>
<tr>
<th>Principle stresses at base (N/m²)</th>
<th>LC 1 (Sym)</th>
<th>LC 2 (Asym)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S2 (min)</td>
<td>-8,86E+04</td>
<td>-7,98E+04</td>
</tr>
<tr>
<td>S3 (max)</td>
<td>-4,76E+05</td>
<td>-6,44E+05</td>
</tr>
</tbody>
</table>

\[ 6.44 \times 10^5 \text{(SYSTEM)} \, \text{N/m}^2 \leq 6.16 \times 10^6 \text{(TPU)} \, \text{N/m}^2 \]
Structural validation: *Physical arch test*...
Structural validation: Physical arch test....

Start

REDUNDANT

End
Thermal performance: *Focus on...*

1. **Ventilation rate**

2. **Comfort**
   - a
   - b
   - c
Thermal performance: Natural ventilation rate...

**Summer**
- $T_{in} = 36^\circ C$
- $T_{out} = 40^\circ C$
- $T_{in} = 31^\circ C$
- $T = 35^\circ C$
- $(T - 4)$

**Fall**
- $T_{in} = 8^\circ C$
- $T_{out} = 19^\circ C$
- $T_{in} = -3^\circ C$
- $T = -5^\circ C$
- $(T + 2)$
VENTILATION RATE:

\[ n = \frac{Q}{V} = 100 \times 35 \text{ (m}^3/\text{h}) / V = 0.6 \text{ h}^{-1} \]

\[ v < 0.5 \text{ m/s} \]

slight breeze

\[ v = 0.5 \text{ m/s} \]

\[ n = 2 \text{ h}^{-1} \]

OPENINGS

\[ A = \frac{n \times V}{C_d \times 3600} \times \sqrt{\frac{p}{2 \Delta p}} = m^2 \]

\[ A = 9.3 \text{ m}^2 \]

\[ \Delta P = gh \times (P/R) \times (1/Tout - 1/Tin) = -0.21 \text{ Pa} \]

\[ \Delta T = 0.6 \]
Thermal performance: Input Design Builder...

1

2

3

a

b

c

Structural validation | Thermal performance
Thermal performance: *Consequence of the passive strategies...*
Thermal performance: Consequence of the passive strategies...
Thermal performance: Daily simulation...

6th of July

![Graph showing thermal performance data for 6th of July]

- Air Temperature (°C): [Data values]
- Radiant Temperature (°C): [Data values]
- Operative Temperature (°C): [Data values]
- Outside Dry-Bulb Temperature (°C): [Data values]
**Thermal performance:** Conclusion passive strategies....

<table>
<thead>
<tr>
<th>Time/Date</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Air Temperature (°C)</strong></td>
<td>11.73</td>
<td>24.95</td>
<td>32.98</td>
<td>31.13</td>
<td>30.63</td>
<td>30.58</td>
<td>17.48</td>
</tr>
<tr>
<td><strong>Radiant Temperature (°C)</strong></td>
<td>12.65</td>
<td>25.93</td>
<td>36.00</td>
<td>36.65</td>
<td>33.68</td>
<td>34.33</td>
<td>20.15</td>
</tr>
<tr>
<td><strong>Operative Temperature (°C)</strong></td>
<td>12.10</td>
<td>25.14</td>
<td>31.10</td>
<td>32.80</td>
<td>32.16</td>
<td>32.16</td>
<td>18.91</td>
</tr>
<tr>
<td><strong>Inside Temperature (°C)</strong></td>
<td>9.94</td>
<td>22.88</td>
<td>29.00</td>
<td>24.17</td>
<td>25.83</td>
<td>26.84</td>
<td>13.45</td>
</tr>
</tbody>
</table>

19/18°C > T > 30°C
Thermal performance: Air to water heat pump & Fan Coils

- **Summer**: Evaporator connected to the condenser via a blue line.
- **Fall**: Condenser connected to the evaporator via a red line.

**Fan coils**
Thermal performance: Final result....

**SUMMER**

**FALL**

passive systems (61%) & active system (39%)
Evaluation: *Main research question...*

"How can a solely glass dome be developed and assembled from **structural cast glass** components while providing **thermal comfort** and being **minimum invasive** for the local environment?".
1ST: OMNIDIRECTIONAL CAST GLASS COMPONENTS
2\textsuperscript{nd}: PASSIVE STRATEGIES
2nd: PASSIVE STRATEGIES
SHARP EDGES
**Evaluation:** Stiffness of the entire system...

- Changing thickness

\[ E(T) \]

\[ E(t) \]
Evaluation: *Local heating units*...
“Architecture is measured against the past, you build in the present, and try to imagine the future”

(Richard Rogers)
THANK YOU