FLOATING STRUCTURES

Floating Centre for the Performing Arts in the Harbour of Scheveningen

Engineering Calculations P5

Architectural Engineering Graduation Studio

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LAB07 - Architectural Engineering

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Ir. F. Heinzelmann (Florian) Revolt House (during P1)

Argumentation of choice of the studio
The architectural engineering studio is for me the best choice, because there is a strong relation between architecture and engineering (technology). Coming from a technical background, this specialisation is the most related to me and I thought this was the most interesting and fun specialization to do.

Title
Title Floating Structures:
Subtitle Research into the possibilities for a Floating Centre for the Performing Arts in the Harbour of Scheveningen
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**APPROACH**

*The relationship between floating body and the structure on top*

The most important feature of my approach is the relation between the building and the floating body. There needs to be a balance between them, to keep the structure floating and stable. In my opinion the floating body should be designed for the building, so the shape should be giving the stability instead of a ballast system. I see the floating body as a reflection of the building.

**Principle of design: Form Follows Force**

With a uniform load, the body can be a simple slab, or a slab, with an extension on the end, to get it more stable. But in general it’s a (simple) uniform body.

![Uniform load results in a uniform body](image)

With a non-uniform load, the body has to be adapted or be balanced with ballast. I choose to design the body and let the body respond on the structure (load) that is on the floating body.

![Non-uniform load results in a non-uniform body](image)
HYDROSTATICS

Floating theatre

Architectural design

Architectural design (after integration of engineering)

Calculation method

The design is made in Rhinoceros, a 3D modelling program, for this program several plugins are used for this design.

Plugins used:

- T-splines, for bended shell surface (architectural);
- Orca3D, calculation of floating structure, immersion, heel and trim (engineering);
- Grasshopper, creation of algorithms and calculation centre of gravity (engineering).

To calculate the weight and to optimize everything for the calculation I simplified the model into surfaces, for this surface I added the weight per square meter (density x thickness). In this way the calculation takes less time and also changes in the design are easier to change in the calculation.

Note:

During the calculations I found out that Orca3D, was not able to calculate the centre of gravity of the bended shell surface. Therefore I did this calculation with grasshopper and used the calculated centre of gravity as input data for Orca3d.
**Floating calculations - Process**

**STEP 1: Analysing the model and prepare for calculation**

Floating body (green), main steel structure (grey) and secondary structure (red)

Added floor slab (cyan)
Added air-bridge (red)

Added acoustic ceiling (yellow)
Added vertical walls (magenta)

Added shell structure (blue)
STEP 2: Creating Grasshopper scheme

Before making this grasshopper scheme I made a calculation with Orca3D, which gave me the result that the calculated centre of gravity by Orca3D was in the wrong position.

I solved this problem with recalculating the centre of gravity with grasshopper.
Output data of grasshopper, different centres of gravity (blue dots)

Input data for Orca3D, centres of gravity

1. bridge
2. ac.ceil.
3. shell
4. wall
5. structure
6. floor
**STEP 3: Assigning weight and loads**

To calculate the weight and to optimize everything for the calculation I simplified the model into surfaces. I calculated the centres of gravity and the areas with Grasshopper.

The weights are calculated per square meter, the weight of the building is quite low, but this is because it is just a shell, made from composite with some insulation. Also the interior is made from composite.

The floating body is calculated with Orca3D, this is because it is being optimized in shape and therefore the weight is changing. The floating body is a lot heavier than the building, this is because it is made from concrete and has thick walls because of the water pressure. This is also good for the stability, because it lowers the centre of gravity (principle of weight stability)

### Deadweight (PB)

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Name</th>
<th>Area (m²)</th>
<th>Thickness (mm)</th>
<th>Density (kg/m³)</th>
<th>Weight per sq. m (kg)</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Air-bridge</td>
<td>102</td>
<td></td>
<td>150</td>
<td></td>
<td>15330</td>
</tr>
<tr>
<td>2</td>
<td>Acoustic ceiling</td>
<td>803</td>
<td></td>
<td>50</td>
<td></td>
<td>40171</td>
</tr>
<tr>
<td>3</td>
<td>Shell</td>
<td>2869,481</td>
<td></td>
<td>50</td>
<td></td>
<td>143474</td>
</tr>
<tr>
<td>4</td>
<td>Wall</td>
<td>1035,997</td>
<td></td>
<td>50</td>
<td></td>
<td>51800</td>
</tr>
<tr>
<td>5</td>
<td>Steel structure</td>
<td>2755,577</td>
<td>6</td>
<td>7800</td>
<td>50 (46.8)</td>
<td>137779</td>
</tr>
<tr>
<td>6</td>
<td>Floor slab (prefab)</td>
<td>675</td>
<td>60</td>
<td>2400</td>
<td>150 (144)</td>
<td>101107</td>
</tr>
<tr>
<td></td>
<td><strong>Total building</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>489661</strong></td>
</tr>
<tr>
<td></td>
<td>Floating body, weight varies because of shape change, approximately weight =</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>800000</td>
</tr>
<tr>
<td></td>
<td><strong>Total structure estimated</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>1289661</strong></td>
</tr>
</tbody>
</table>
Live loads (VB) People

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Name</th>
<th>Area (m²)</th>
<th>Weight per sq. m (kg)</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>People sitting centre</td>
<td>322,2316</td>
<td>250</td>
<td>80558</td>
</tr>
<tr>
<td>2</td>
<td>People sitting side left</td>
<td>21,83312</td>
<td>250</td>
<td>5458</td>
</tr>
<tr>
<td>3</td>
<td>People sitting side left</td>
<td>21,83312</td>
<td>250</td>
<td>5458</td>
</tr>
<tr>
<td>4</td>
<td>People walking</td>
<td>224,0712</td>
<td>450</td>
<td>100832</td>
</tr>
<tr>
<td>5</td>
<td>People real-life (75kg)</td>
<td>582</td>
<td>92</td>
<td>53925</td>
</tr>
</tbody>
</table>

Live loads (VB) Wind

Calculation of wind pressure

\[
P_w = 1.24 \text{ kN/m²} \quad \text{(area 2, non-build environment, 30 meter)}
\]

\[
C_{\text{index}} = 0.8 \quad \text{(façade, perpendicular)}
\]

\[
C_{\text{dim}} = 0.9 \quad \text{(h = 30, b = 40)}
\]

\[
\text{Prep} = P_w \times C_{\text{index}} \times C_{\text{dim}}
\]

\[
= 0.89 \text{ kN/m²}
\]

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Name</th>
<th>Area (m²)</th>
<th>Weight per sq. m (kg)</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wind front</td>
<td>715</td>
<td>89</td>
<td>63635</td>
</tr>
<tr>
<td>2</td>
<td>Wind side</td>
<td>539</td>
<td>89</td>
<td>47971</td>
</tr>
</tbody>
</table>

*horizontal wind is important for stability*
STEP 4: CALCULATION DEAD WEIGHT (PB) AND OPTIMIZING SHAPE

Note: The trim result is shown, but not important for the permanent load, because the building is symmetrical over the related axis. The minor angle that is show is due to imperfections in the modelling software. For the side wind, the trim result is relative.

A. Basic shape

Basic shape, with representing waterline

Results:

<table>
<thead>
<tr>
<th>Weight (kgf)</th>
<th>Sinkage (mm)</th>
<th>Heel (deg)</th>
<th>Trim (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1659614</td>
<td>1978</td>
<td>4,2</td>
<td>0,016</td>
</tr>
</tbody>
</table>

Building is heeling to much
B. Basic shape, with hollow centre

Basic shape, with hole (U-shape)

Basic shape, with hole (U-shape) with representing waterline

Results:

<table>
<thead>
<tr>
<th>Weight (kgf)</th>
<th>Sinkage (mm)</th>
<th>Heel (deg)</th>
<th>Trim (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1454302</td>
<td>2482</td>
<td>4,987</td>
<td>0,016</td>
</tr>
</tbody>
</table>

Heeling and sinkage (immersion) have increased because of lower volume
C. Optimizing shape for dead weight (PB)

First I mirrored the water line and cut the floating body. Then I recalculated the structure a few times until I got the optimized shape.
Results:

<table>
<thead>
<tr>
<th>Weight (kgf)</th>
<th>Sinkage (mm)</th>
<th>Heel (deg)</th>
<th>Trim (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1320057</td>
<td>3694</td>
<td>0.116</td>
<td>0.016</td>
</tr>
</tbody>
</table>

The building is now stable for the deadweight
STEP 5: CALCULATION LIVE LOADS

There are two kind of live loads, on is the live load due to people, the other is due to the wind.

For the live load due to people, there are two scenario’s, the first one is people walking and the second one is people sitting. Sitting is represented by a load of 2,5 kN/m² and walking by 4,0 kN/m², this is according to regular building regulations.

I also made a calculation with the maximum amount of people in the theatre, with an average weight of 75 kg per person, this is done to reference how it in real-life would be. According to the Dutch Building Regulation, there is a new code called the NTA 8111:2011, according to this code the live load due to people should be calculated due to 75 kg per person. This code is the first Dutch code on floating buildings.

Floor plan with different live loads due to people
A. People walking

People walking, with representing waterline

Results:

<table>
<thead>
<tr>
<th>Weight (kgf)</th>
<th>Sinkage (mm)</th>
<th>Heel (deg)</th>
<th>Trim (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1420889</td>
<td>3500</td>
<td>2.309</td>
<td>0.016</td>
</tr>
</tbody>
</table>

Building is heeling within margins (4 degree)
B. People sitting

People sitting, with representing waterline

Results:

<table>
<thead>
<tr>
<th>Weight (kgf)</th>
<th>Sinkage (mm)</th>
<th>Heel (deg)</th>
<th>Trim (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1411531</td>
<td>3364</td>
<td>3,045</td>
<td>0,016</td>
</tr>
</tbody>
</table>

Building is heeling within margins (4 degree)
C. People Real-life

Results:

<table>
<thead>
<tr>
<th>Weight (kgf)</th>
<th>Sinkage (mm)</th>
<th>Heel (deg)</th>
<th>Trim (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1373982</td>
<td>3537</td>
<td>1,618</td>
<td>0,016</td>
</tr>
</tbody>
</table>

Building is heeling within margins (4 degree) and this is more realistic then the building regulation for traditional buildings.

There will be a balance system in the floating body, with ballast tanks. In this way the theatre can be balanced out due to the effect of the people. So when the theatre is not full or has a non-even distributed load (people) the theatre will always be levelled.

Also due to this balance system, the heel effect of the people and the heel effect of the wind don’t have to be combined (summated). Because the building is in a levelled position after balancing.
D. Wind load on side

Wind load on side, with representing waterline

Results:

<table>
<thead>
<tr>
<th>Weight (kgf)</th>
<th>Sinkage (mm)</th>
<th>Heel (deg)</th>
<th>Trim (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1383582</td>
<td>3608</td>
<td>1,276</td>
<td>0,936</td>
</tr>
</tbody>
</table>

The building is heeling and trimming within margins (4 degree)

The effect of the side wind is not so large
E. Wind load on front SUMMER

Wind load on front, with representing waterline

Results:

<table>
<thead>
<tr>
<th>Weight (kgf)</th>
<th>Sinkage (mm)</th>
<th>Heel (deg)</th>
<th>Trim (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1383692</td>
<td>3426</td>
<td>2,391</td>
<td>0,016</td>
</tr>
</tbody>
</table>

Building is heeling and trimming within margins (4 degree)

The effect of the front wind is slightly larger than the wind from the side, this is because the width of the floating body

Note:

The effect of the wind might look large, but this calculation shows a scenario of storm in summer, which is not really realistic.

In the winter period, when there is a lot more wind, there is an extension to the building, which creates more stability.
F. Wind load on front WINTER

Wind load on front winter, with extension, with representing waterline

Results:

<table>
<thead>
<tr>
<th>Weight (kgf)</th>
<th>Sinkage (mm)</th>
<th>Heel (deg)</th>
<th>Trim (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2579208</td>
<td>3658</td>
<td>0.998</td>
<td>0.007</td>
</tr>
</tbody>
</table>

Building is heeling and trimming within margins (4 degree)

FINAL CONCLUSIONS:

The building is stable for hydro stability calculations, and the calculations proof that in an engineering point of view the theatre can work properly.
Floating pontoon

For the floating pontoon I designed a simple hollow U-shape structure, that is made from concrete. Due to this the pontoon has a high stability, the centre of gravity is very low.

For this system there should be a balance system, with concrete or steel blocks that can be placed in the hollow U-shape, to balance the structure. Because the permanent load is always changing on these pontoons, I made the decision to have this system. If I wanted to change the shape of the floating body to the above structure, you should build a new pontoon every time, which is a total waste of material.

Calculation

For this calculation I only used the permanent load of the pontoon (dead weight) and the live load of 9 actors.

Results:

<table>
<thead>
<tr>
<th>Weight (kgf)</th>
<th>Sinkage (mm)</th>
<th>Heel (deg)</th>
<th>Trim (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>217500</td>
<td>1829</td>
<td>0.216</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Building is heeling and trimming within margins (4 degree)

The effect of the actors is neglectable, only 0.216 degree. We can see there is almost no effect due to the actors.
ROTATION MECHANISM

The flexibility creates potentials for the functions and architecture, but is giving problems (that can be solved) for engineering.

The following aspects are important for the flexibility of the theatre: rotation around z-axis, movement on z-axis, skewing and heeling (rotation around x and y-axis) and also fixing the building on this rotation point.

There can be simple solutions for all these aspects

For example, the rotation can be done with an ordinary engine which makes the building rotate. But now several questions arise, like how do you stop the building from rotation? And is this the most elegant and smart way to do?

My main goal is to fix all the solutions for the aspects into one single system.

Fixing the building: Foundation pole (green)
Vertical movement (z-axis): Telescopic cylinder (cyan)

Rotation (z-axis): Axis (grey) with slewing ring (purple) and hydraulic engine
Rotation (z-axis): Axis (grey) with slewing ring (purple) and hydraulic engine

Rotation in x-y-axis and translation for rotation in z-axis: Constant-velocity (CV) joint
Fixing the rotation structure to the floating and above structure: Steel ring and extra beams

Details of Constant-velocity (CV) joint:
The structure that is on top of the floating platform can be divided into three parts.

The main structure, red colour, the secondary structure, grey colour, and the façade structure (third structure), green colour.

The main and secondary structure are carrying most of the load and are also the elements that provide the stability.

**CALCULATION - SECTION**

*Load cases*

Span = 5 meters

1. Permanent load - shell = 1,5 kN/m2 = 7,5 kN/m1
2. Permanent load - floor = 2,94 kN/m2 = 14,7 kN/m1
3. Variable load - wind = 1 kN/m2 = 5 kN/m1
4. Variable load - people = 4 kN/m2 = 20 kN/m1

Combinations 1 + 2 and 1 + 2 + 3 and 1 + 2 + 4

Results are the maximums of the different combinations
Permanent load

Variable load - wind
Variable load - people
Analysis - Moment (My)

Analysis - Tension
Analysis - Shear force (Vz)

Analysis - Displacement (Uz)
## Results and check data

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length beam</td>
<td>54,742 m</td>
</tr>
<tr>
<td>cantilever, length x 2</td>
<td>109484 mm</td>
</tr>
<tr>
<td>sheared distance (toog) (f) z-axis</td>
<td>6,54 m</td>
</tr>
</tbody>
</table>

### shear force (Vz)

*output scia engineer 2009*

| Vz                                      | 819,21 kN     |

### moment

*output scia engineer 2009*

| Md                                      | 2639,53 kNm   |

### beam tension

*output scia engineer 2009*

| σ                                       | 336,50 N/mm²  |

### displacement (z)

*output scia engineer 2009*

| uz                                      | 475,80 mm     |

### strength check

*output scia engineer 2009*

| σ = 336,50 N/mm²                         | toelaatbaar σ_max = 355 N/mm² |
| σ < σ_max = 336,50 < 355,00 N/mm²       | CORRECT       |

### bending check

*output scia engineer 2009*

| u_z = u_occuring = 475,80 mm             | 6977,936 mm   |
| u_allowed = l / 250 = 218,97 = 437,936 + shear 6977,936 | |
| u < u_allowed = 475,80 < 6977,94 mm     | CORRECT       |

Horizontal displacement is about 50 mm, and is therefore negligible.
STRUCTURAL CALCULATIONS - FIXED BUILDING

Structural elements

The main element is the truss, colour red, that is the shape of the building.

The structure in between are the floor beams and the columns, colour grey, which are also part of the main structure, this structure is supporting the shape of the red truss.

These main elements are arrayed around the floating building and are connected with horizontal beams and also the floors are creating a slab, which ensures the horizontal stability in one direction.
To ensure the stability of the building in the other horizontal direction, two stability walls are added, colour green and purple diagonal. These walls provide stability and stiffness in the building.

Whole structure with floors, on the red structure is also a shell that connects all the elements, this also increases the stability of the structure.
CALCULATION - SECTION

Load cases

Span = varies between 10 and 3 meters

1. Permanent load roof = 2,3 kN/m² = 6,9 - 23 kN/m
2. Permanent load floor = 7,7 kN/m² = 23,1 - 77 kN/m
3. Variable load (Wind) = 1 kN/m² = 3 - 10 kN/m
4. Variable load (People, floor) = 4 kN/m² = 12 - 40 kN/m

Combinations 1 + 2 and 1 + 2 + 3 and 1 + 2 + 4

Results are the maximums of the different combinations

Permanent load
Variable load - wind
Variable load - people
Analysis - Moment (My)
Analysis - Tension
Analysis - Displacement (Uz)
Results and check

data
Length beam 39,274 m = 39274 mm
sheared distance (toog) (f 1 z-axis 6,764 m = 6764 mm

shear force (Vz)
output scia engineer 2009
Vz = = 954,84 kN

moment
output scia engineer 2009
Md = = 3974,26 kNm

beam tension
output scia engineer 2009
σ = = 239,80 N/mm²

displacement (z)
output scia engineer 2009
uz = = 51,10 mm

strength check ugt
output scia engineer 2009
σ = 239,80 N/mm² toelaatbaar σmax = 355 N/mm²
σ < σmax = 239,80 < 355,00 N/mm² CORRECT

bending check bgt
output scia engineer 2009
uz = uoccurring = 51,10 mm
uzallowed = l / 250 = 157,10 + shear 6921,10
uz < uzallowed = 51,10 < 6921,10 mm CORRECT

horizontal displacement is about 50 mm, and is therefore negligible.

BOTH STRUCTURES ARE ABLE TO WITHSTAND THE FORCES