Parametric Design and Structural Analysis of a Viewing Tower

Bachelor End Project Report

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INTRODUCTION

The impact of the built environment on our planet has become a major concern in recent years. The built environment is responsible for 37% of annual global CO_2 emissions in 2021 (UN Environment Programme, 2022). To address this, architects and engineers have been exploring new approaches to design and construction that are more sustainable and environmentally friendly. One promising alternative is the use of parametric design. It is a design method that involves the use of algorithms and computational tools to generate and analyse complex geometric forms. In combination with structural analysis, parametric design can lead to innovative and material-efficient structures that can be rapidly iterated and optimized (Holzer et al., 2007).

The iterative design approach enables the semi-automated creation, study, and optimization of multiple design variations. This can be applied on different levels of analysis from individual elements to the whole structure. This design approach is guided by a selection of input and output parameters. The input parameters are variables that can shape the geometry, function, dimensions, and other factors. The output parameters or key performance indicators (KPIs) are selected and computed values that describe the fitness of the structure or elements. They represent the design goals of the project and what the structure is optimized for.

This study represents the application of parametric design and the structural analysis of a viewing tower. The program of a viewing tower allows users to enjoy long-distance views of the scenery and a unique experience of the environment. The site location is next to Palm Beach in Roermond, The Netherlands.

The focus of this study and its research goal is the creation of such a tower that has a low environmental impact through the efficient use of material, is technically and structurally sound, can easily be prefabricated, constructed, and demounted, as well as being architecturally attractive.

This report describes the design process, outcome, and structural analysis of such a parametric viewing tower.

A. DESIGN DEVELOPMENT

A01. Design Brief

The goal of this project is the development of a viewing tower located next to Palm Beach in Roermond, NL. Table 1 shows the list of requirements given by the design brief that need to be fulfilled. We can see from this that the town needs to have a shape where the top platform is offset from the button to achieve the 35% maximum projected overlap. This can be done for example by tilting the tower or rotating it. To reach the top of the tower a relatively long ramp needs to be integrated into the tower as a tower height of 50 m and a slope of 6° results in an approximate length of 479 m.

Table 1 List of Requirements

Requirement	*Value*
Height	50 m
Area, top platform	45 m^2
Railing length, top platform	min. 35 m
Project overlap top area to ground area	max. 35%
Program	viewing tower incl. weathertight multifunctional room plus two extra smaller platforms
Slope, walking paths	max. 6°
Design considerations	Spatial aspects Functional aspects Technical aspects Structural safety Buildability Demountable and reusable Fully prefabricated Short construction period on site Efficiency of material use Safety regulations (fire, evacuation, etc.)

A02. Input and Output Parameters

This design approach is guided by a selection of input and output parameters. The input parameters are variables that inform the geometry, function, dimensions, and other factors. They can be adjusted, and the geometry is computed rather than manually drawn. The output parameters or key performance indicators (KPIs) are chosen and computed values that describe the fitness of the structure or elements. They represent the design goals of the project and what the structure is optimized for.

A02.1. Input Parameters

Two types of input parameters have been developed: (a) parameters that define the shape and formation of the structure and (b) parameters for the dimensions of elements. Parameters of the first type are illustrated in Figure 1. The input parameters define the solution space or in other words the possible structures that can be created with them. How the input parameters achieve the geometry is further explained in A03. The aim was to enable the creation of simple to complex structures giving an architect or developer maximum freedom to create the desired shape and expression. This was done so that the parametric design stays relevant and can be applied to different projects and locations with different budgets, requirements, and goals.

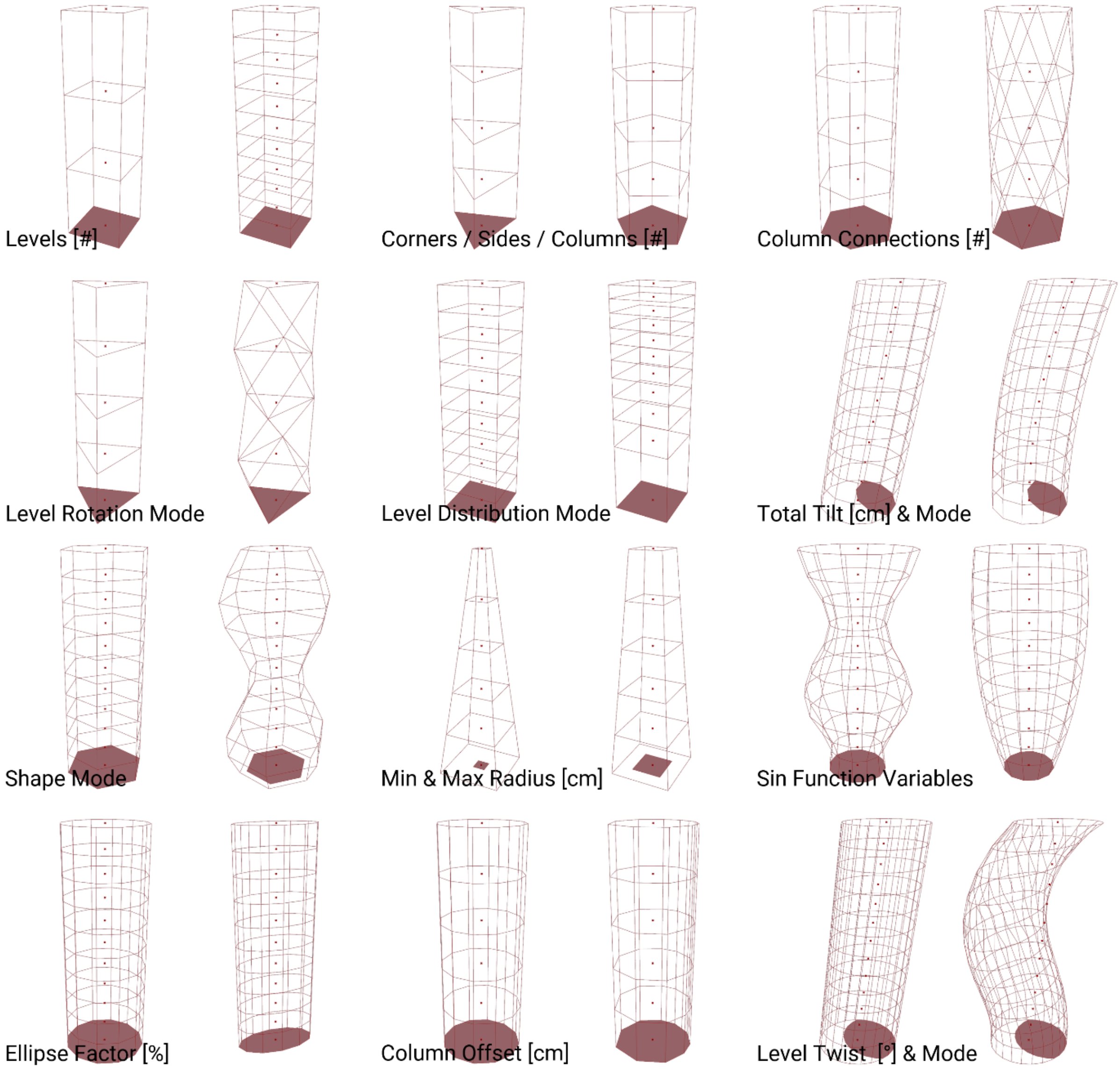


Figure 1 Input Parameters and Geometric Solution Space

The second type of parameter that define the size and dimension of elements allows for their rapid iteration and optimization. Each type of element is defined separately. Most elements have one open variable for example height and depth are computed with a ratio function. The columns are further broken down into sections along the height of the tower. A reduction factor defines the sliming of elements from one section to the next. This is further elaborated under A04.2. and the final dimensions are illustrated in B04.

A02.2. Output Parameters

Two types of output parameters can be distinguished: (a) checks for the fulfilment of design requirements as listed in the design brief and (b) key performance indicators (KPIs) representing the goals of the project and optimization targets for the structure and elements. The type (b) output parameters are not listed here again. They are identical to the values listed in Table 1. Calculating them helps to make sure the design structure fulfils the design requirements. KPIs are approximated with multiple variables. Table 2 lists them and shows the connections.

Table 2 Output Parameters

Key Performance Indicators	*Output Variables*
Structural Integrity	Maximum global deflection [cm]
	Total beam strain energy density [MJ/m^3]
	Avg. column length [cm]
	Avg. column angle [°]
Buildability & Complexity	No. of connections [#]
	No. of elements [#]
Material Intensity	Material volume [m^3]
	Material mass [t]

Structural integrity is assessed with the maximum global deflection of the tower. This value should be minimized and represents one of the final unity checks. The total strain energy density in beam elements presents the stresses in the structure and how hard the elements need to work under load. It should also be minimized. Longer columns and ones that are more leaning rather than being perfectly vertical are more likely to buckle and are more receptive to higher stresses. The number of connections and elements indicates the buildability and complexity of the structure. A higher number of connections is more difficult to assemble and more expensive to fabricate. The column length also predicts how easily elements can be handled on-site. Material volume and mass represent the material impact of the structure. A lower amount is desirable to achieve a more sustainable design.

It becomes clear that not all parameters work in the same direction so a trade-off is required. More and bigger elements can mean a stronger structure but also drives up material impact and construction costs. This means a balance between structural integrity to buildability and material intensity needs to be found. This is the goal of the variance study optimization described under A04.1.

A03. Parametric Design Script

The parametric design script is the technical implementation of the approach in the software application Rhino 3D specifically its Grasshopper functionality. Grasshopper is a visual programming interface that allows for the algorithmic and parametric design of the tower. The script is structured into multiple sections. Figure 2 illustrates the flow of data and how the script is built up and works. Imported processes like the creation of the main tower structure are further broken down into steps. The steps for the main tower correspond to the input parameters and related solution space described in Figure 1.

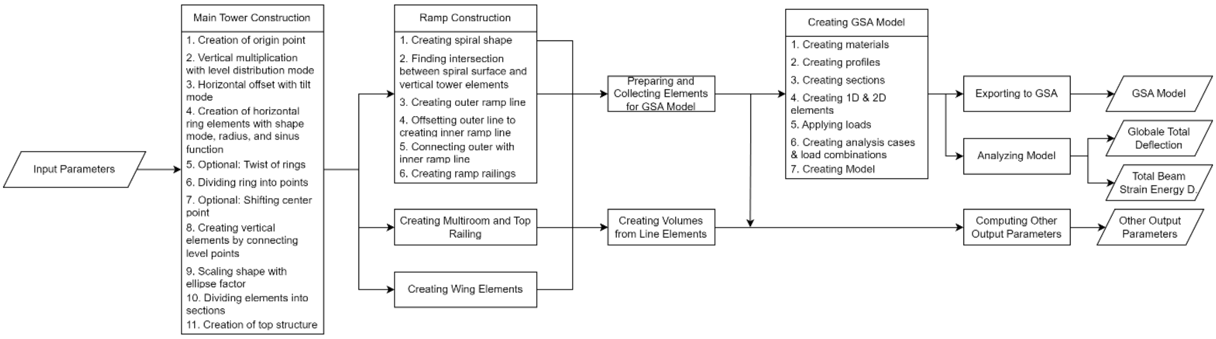


Figure 2 Parametric Design Script Flow Chart

The script utilized mathematical formulas to create the geometry. The curved shape of the tower can be created with the help of a sinus function depicted in Equation 1. The y variable stands for the dynamic radius of the tower rings and the x for the vertical position. The horizontal offset of the tower (tilt) as well as the level distribution has different modes programmed in that can be selected from. One is linear another exponential among others.

$$y = a \times \sin(b \times x + c) + d$$

Equation 1

Oasys Software's GSA application was deployed for the structural analysis of the tower. Some of its analysis functionalities are directly integrated via a plugin into Grasshopper. This enables the partial calculation of the structure directly and live in the script. This was used to compute the output parameters, total global defection as well as beam strain energy density. This direct feedback in the script on the structural integrity of the design allowed it to be integrated into the optimization algorithm (see A04.).

Having the GSA model setup in the Grasshopper script also enabled an iterative design process where it was easy to go back and forth between the two software when a more thorough structural analysis was required. That is because only a few manual steps were needed for the exported model from Grasshopper to be analysed in GSA. This is important as it maintains the parametric and iterative nature of the workflow and did not create a gateway or waterfall process where going back would have been time-consuming or resulted in double work.

A04. Optimizations

To achieve the design goals and create a tower structure that is structurally sound, architecturally attractive, economical, and material-efficient optimization algorithms were used within the Grasshopper script. The Galapagos functionality was utilized for this. The optimization was done in two stages and on two levels of analysis: the whole geometry and for dimensioning of elements. Galapagos uses a fitness function where it assigns each design option a finesse value. The fitness function is based on the output parameters. Each design option represents different permutations of the input parameters. The optimization employs an evolutionary process. For each round random input values are selected. The process gradually narrows down to an optimal solution by selecting the permutations with the best fitness score from each generation to the next.

The process has no inherent intelligence and is entirely guided by the fitness function. As such it is important to define a function that results in a desirable outcome. No resulting geometry was simply taken as is but analysed and manually adjusted. The main output of this process is not the geometry itself but rather insights into the relationship between input and output parameters and how to achieve a good balance between different output parameters as described in A02.2.

A04.1. Variances Study

The variance study focuses on finding an optimal geometry for the tower. This represents a diverging phase in the design process to create design options to choose from. It incorporates manual design with computational generative design. This process also ensures that only relatively optimized structures are compared to each other. The fitness function used here is shown in Equation 2. The total global defection is weighted by a factor of 10 to make sure the optimization algorithm only produces structures that do not deflect too much. The high factor on the requirements checks ensures that only viable options that meet them are chosen. The variables are also normalized to eliminate differences in magnitudes in values. For this study, only the geometry input parameters were used. The dimensions of elements were calculated based on the number of columns and levels.

$$Fitness\ Value = Deflection * 10 + Joins + Elements + Mass + Requirement\ checks * 1000$$

Equation 2 Variance Study Fitness Function

An additional target was to create three different structures with unique structural mechanisms. The optimization process was each time slightly adjusted by limiting and setting certain input parameters to achieve this target.

The visual representation of the results is depicted in Figure 3. Variants 01 and 02 are generated design options. Variant 01 has a straight column beam design, the tilt is mathematically described with a root function and the levels have a slight horizontal twist. Variant 02 is constructed with large, long columns that balance each other. The required projected overlap of the top to the ground area is achieved with a rotation in the platform. Variant 03 is predominantly handmade. It is made up of a grid shell structure comprised of elements that form triangles that distribute the loads.

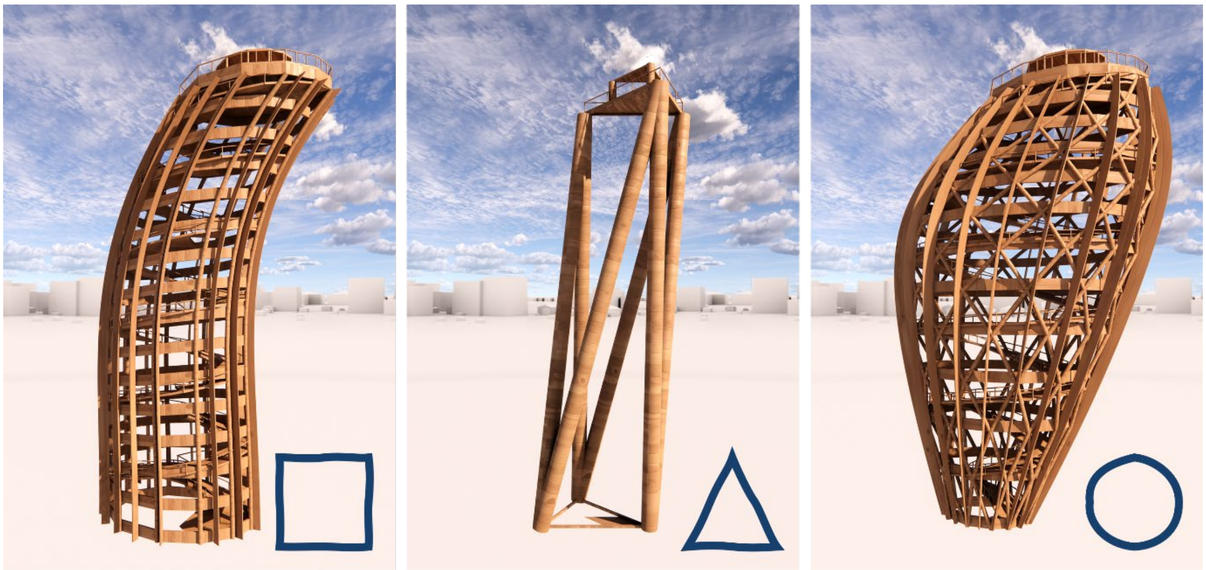


Figure 3 Render of Variances

Table 3 Variance Study Fitness Values

	Max. Deflection [mm]*	*No. of Connections [#]*	*No. of Elements [#]*	*Mass [t]*	***Fitness Value***
Variant 01	9.72	176	341	163.3	**1.5955**
Variant 02	7.12	6	12	40.6	**1.6875**
Variant 03	8.35	156	444	222.7	**1.5592**

**Deflection under simplified not final structural analysis loading*

Variance 03 was chosen for further development. It was chosen because it has the best fitness value, is architecturally appealing, and has a good balance of connections, elements, mass, and defection. It also represents an interesting target for further shape and element optimization (see A04.3), as well as structural analysis.

A04.2. Dimensioning of Elements

For the second round of optimizations, the level of analysis is on the elements, not the geometry. As such only dimensioning input parameters were used. The geometry parameters remanded fixed. The fitness function was adjusted to also include beam strain energy to consider the stresses in the elements (see Equation 3). The design requirement checks were dropped because the geometry didn't change anymore, and the checks were already fulfilled. The weighted factor for deflection was removed because a deflection unity check was introduced. That means only options that fulfilled the unity check were considered. The results produced by the algorithms were nevertheless further improved by manual adjustments.

$$\begin{aligned} Fitness\ Value = {} & Deflection + Strain\ Energy + Joins + Elements + Mass \\ & + Deflection\ Unity\ Check * 1000 \end{aligned}$$

Equation 3 Dimensioning of Elements Fitness Function

A04.3. Other Optimizations

In addition to the generative and automated optimization with Galapagos, the structure was also manually adjusted in Grasshopper and in a second step in GSA. The adjustments in Grasshopper happened chronologically after a variance was chosen and before the dimensioning of elements. The GSA adjustments were conducted as a final step after the Grasshopper work was finished. The cumulation of changes can be seen in the final design.

The chosen variant achieved the design requirements, but it was much larger than needed. This meant more material was used than is required to meet the targets. As such the size of the tower was reduced resulting in a new top area of to a new of 93m^2 from an original 195m^2.

Wind load particularly from the south direction was identified as the leading load case for the structure, therefore it was important to optimize the structure to withstand it. For this, the elliptical ratio (how slim or round a horizontal section of the tower is) was increased from 0.66 to 0.8.

Multiple profile sections for the ring and vertical elements were introduced so that they become gradually lighter and smaller along the height of the tower. The sections are part of the input parameters through a reduction factor. The sections are illustrated in Figure 4.

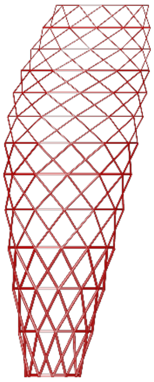


Figure 4 Dimension Sections

Improvements were also made to the ramp and roof structure of the tower. Bar elements were added to support the ramp. The results for the top structure can be seen in Figure 5. The aim was to design a structure where the elements and forces do not meet at a single point. Instead, they are distributed with a central ring and the resistance is increased by adding a connected second layer that forms tringles around the rings.

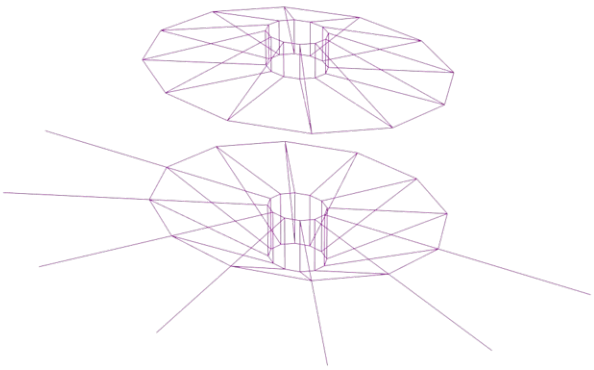


Figure 5 Top Structure

After an initial round of structural calculations in GSA adjustments were also made to the geometry and profiles in GSA directly. They are highlighted in Figure 6. At the top of the structure, the railing density was increased. The profile of the main beams connecting the outer and inner rings was increasing in size as the shear stresses were too high in the elements. Additional members were also added underneath the half cantilevering multipurpose room to support it so that loads can be transferred also to the large wing column on the side of the tower where the ramp emerges. On the bottom of the structure extra columns were added to support the ramp as well as increase the size of the members in the lower part of the ramp. After a more detailed analysis of the structure and elements reinforcements were also added to the lower columns (steel roots) and selected ramp members (steel plates). They are illustrated in the detail drawing that can be found in C04.

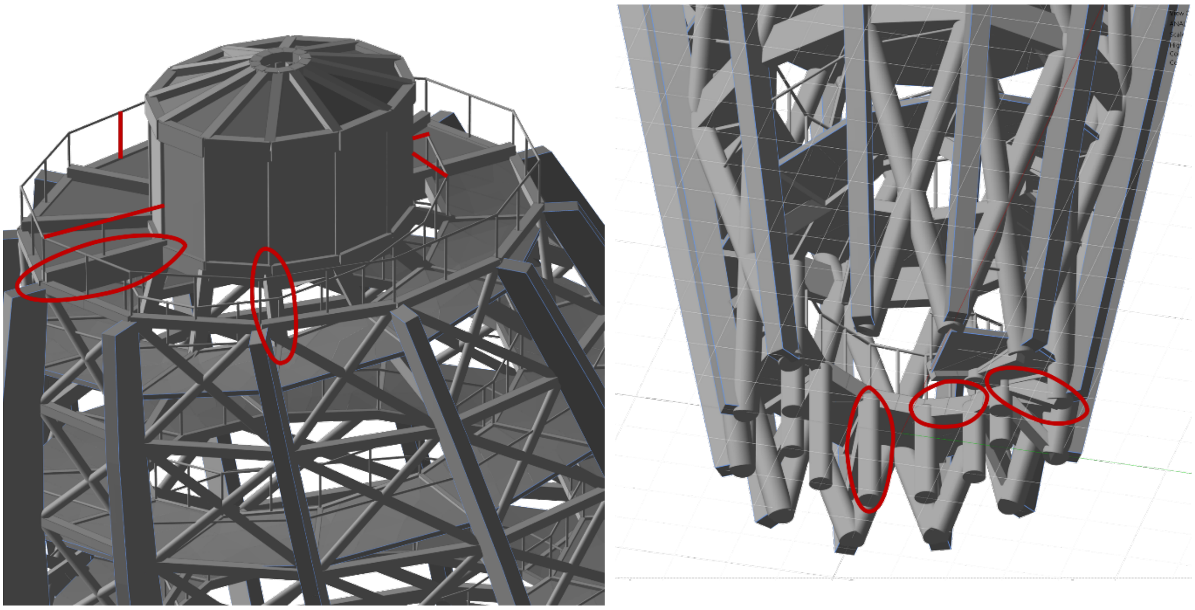


Figure 6 Improvements in GSA

B. FINAL DESIGN

This chapter of the report elaborates on the different aspects of the final design.

B01. Final Input and Output Parameters

Table 4 shows the inputs used to inform the model as well as the output parameters. All output parameters fulfil the design brief requirements and the KPIs show desirable outputs.

Table 4 Final Input and Output Parameters

Input Parameters	*Value*	*Output Parameters*	*Value*
Levels [#]	12	*Area Top Level [m^2]*	93.6
Corners [#]	12	*Area Button Level [m^2]*	31.9
Bar Connections [#]	2	*Projected Overlap Top on Button Area [%]*	33.7
Level Rotation	Off	*Railing Length [m]*	35
Level Distribution Mode	graph mapper	*Slop of Ramp [°]*	6
Total Tilt [cm]	672	*Avg. Column Length [cm]*	565
Tilt Mode	graph mapper	*Avg. Column Angle [°]*	91
Max Radius [cm]	912	*No. of Connections [#]*	777
Min. Radius [cm]	364	*No. of Elements [#]*	1891
Sinus Function Var. a	3	*Volume [m^3]*	327
Sinus Function Var. b	0.187	*Mass [t]*	147
Sinus Function Var. c	0.249	*Maximum global deflection [cm]*	4.86
Sinus Function Var. d	-0.534	*Total beam strain energy density [MJ/m^3]*	0.108
Ellipse Factor [*]	0.8		
Column Offset [cm]	0		
Level Twist [°]	0		
Reduction Factor [*]	0.67		

B02. Drawings

The final design of the structure is shown in Figure 7 below.

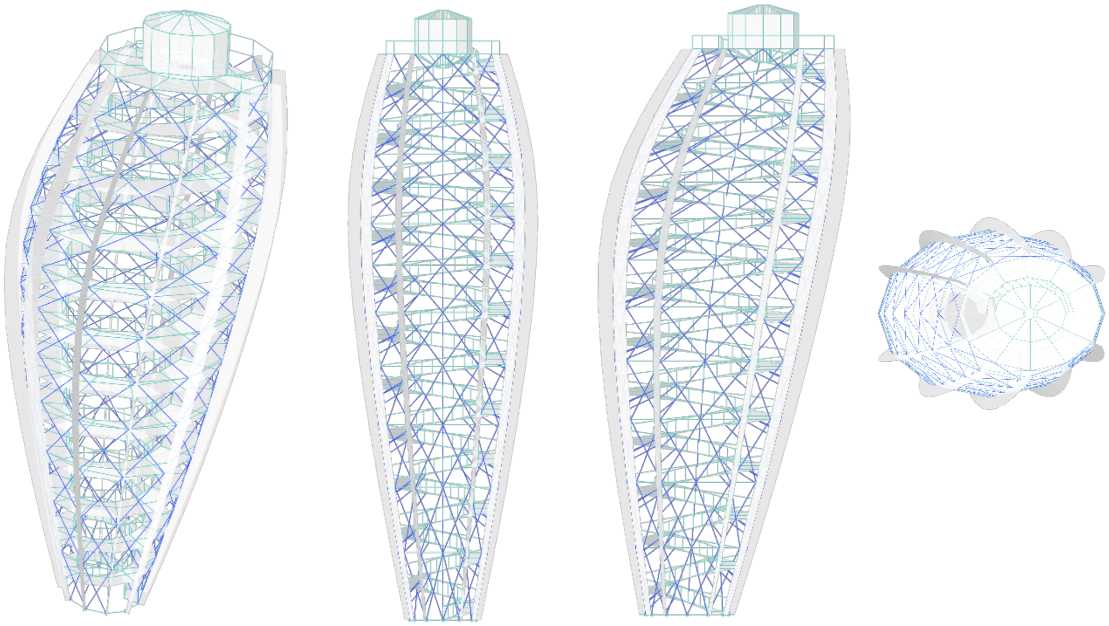


Figure 7 Drawing of Final Design (Perspective, Front, Side, Top)

B03. Renders

Based on the final design, several renders were made. They are shown in Figure 8 below and demonstrate the flexibility of the design in different locations.

Figure 8 Renders Final Design

B04. Profiles and Materials

In Table 5, different materials used in the design are listed, along with their profile illustrations. Except for the railing all other 1D elements are designed from Glulam. The 2D elements are made from CLT. The Glulam and CLT were chosen because of their sustainability credentials. They have a low embodied energy and can easily be prefabricated and quickly and efficiently assembled on-site. The different profile sections along the height of the tower can also be seen in the table below.

Table 5 Profiles and Materials

Name	*Material*	*Profile*	*Height / Diameter [cm]*	*Width / Thickness [cm]*	*No. of Elements*
Bar Section 1	Glulam (GL24h)	●	48		22
Bar Section 2	Glulam (GL24h)	●	42		57
Bar Section 3	Glulam (GL24h)	●	36		72
Bar Section 4	Glulam (GL24h)	●	30		72
Bar Section 5	Glulam (GL24h)	●	24		72
Ring Beam Section 1	Glulam (GL24h)	▤	72	24	36
Ring Beam Section 2	Glulam (GL24h)	▤	48	24	36
Ring Beam Section 3	Glulam (GL24h)	▤	36	24	36
Ring Beam Section 4	Glulam (GL24h)	▤	24	24	48
Stair Section 1	Glulam (GL24h)	▤	24	12	495
Stair Section 2	Glulam (GL24h)	▤	36	18	62
Top Structure Section 1	Glulam (GL24h)	▤	48	24	142
Top Structure Section 2	Glulam (GL24h)	▤	72	24	11
Top Column Section	Glulam (GL24h)	●	12		14
Railing Section	Aluminium 6061	○	6	0.5	740
Ramp 2D Section	CLT (CL24h)	▤		12	
Wing-Shaped Column Section	Glulam (GL24h)	▤		36	
Platform Section	CLT (CL24h)	▤		12	

B05. 3D Printed Model

A presentation model was 3D printed. Figure 9 shows the printing process of the model. A PLA filament was used that is partly made of wood dust to resemble the Glulam used in the tower.

Figure 9 3D Printed Model

C. STRUCTURAL ANALYSIS

This chapter of the report elaborates on the structural analysis of the parametric tower.

C01. Structural Behaviour and Flow of Forces

The tower is comprised of a grid shell structure. It utilizes a network of interconnected linear members to create the curved shape of the tower. As a whole, they form a stable structure. It is designed to efficiently distribute the loads while being lightweight, material-efficient, and visually appealing. The crossing vertical elements are modelled as bars while the horizontal rings are beam elements. Extra strengths and stability are provided by the wing-shaped columns on the outside of the structure.

The structure transfers the loads through the nodes to adjacent members and eventually to the supports. Loads are distributed among multiple members resulting in reduced stress concentrations. The grid shell structure is loaded in a combination of tension and compression. The concave sides are predominantly under tension while the convex sides are under compression. The combination creates a balanced and stable structure that can resist loading.

The design of the nodes is an important element in a grid shell structure. This is further elaborated in the details under C05.2.

C02. Load Cases & Combinations

There are seven load cases applied to the structure. These cases are self-weight, dead load, live load, snow load, and wind loads south, west, and east. In Figure 10 below the load case are illustrated.

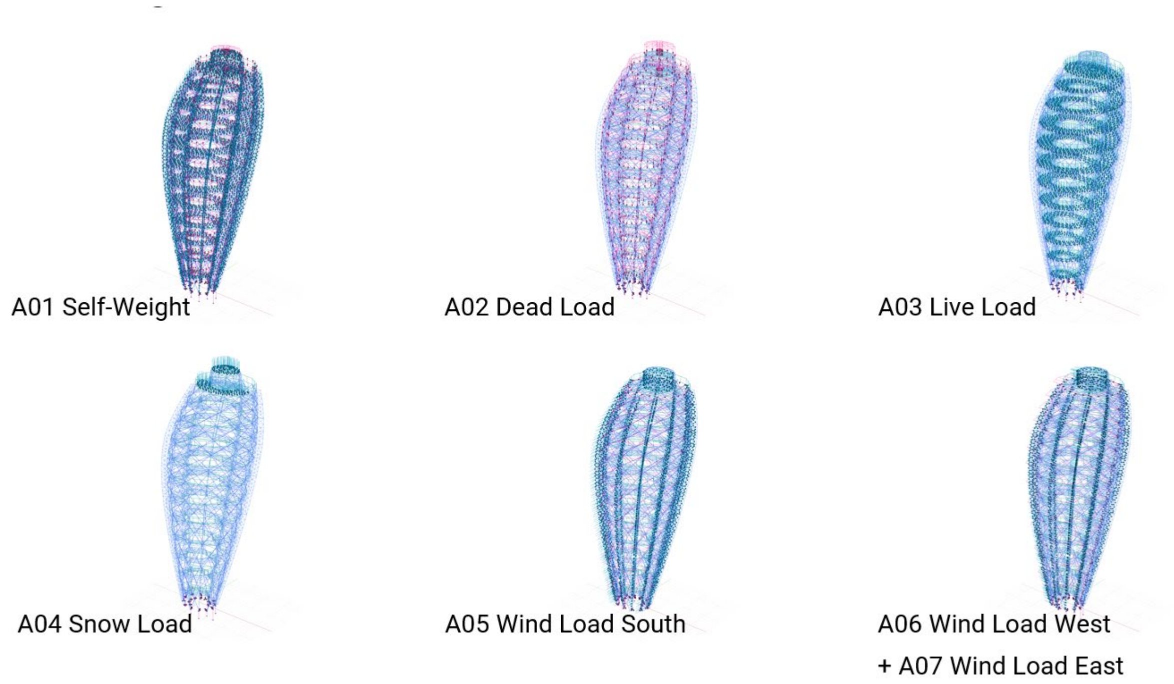


Figure 10 Load Cases

Table 6 describes the load combinations. Six ultimate limit states (ULS) and six serviceability limit state (SLS) combinations are analysed. In addition, two envelope combinations are created with the ULS and SLS cases respectively. The envelope cases represent the maxima of the comprising load combinations. They are predominantly used for the structural analysis and unity checks both in Grasshopper as well as GSA.

Table 6 Load Combination

Case	*Name*	*Description*
C1	**ULS Permanent Loads**	1.35A1 + 1.35A2 + 0.6A3 + 0A4 + 0A5 + 0A6 + 0A7
C2	**ULS Live Load**	1.2A1 + 1.2A2 + 1.5A3 + 0A4 + 0A5 + 0A6 + 0A7
C3	**ULS Snow Load**	1.2A1 + 1.2A2 + 0.6A3 + 1.5A4 + 0A5 + 0A6 + 0A7
C4	**ULS Wind Load South**	1.2A1 + 1.2A2 + 0.6A3 + 0A4 + 1.5A5 + 0A6 + 0A7
C5	**ULS Wind Load West**	1.2A1 + 1.2A2 + 0.6A3 + 0A4 + 0A5 + 1.5A6 + 0A7
C6	**ULS Wind Load East**	1.2A1 + 1.2A2 + 0.6A3 + 0A4 + 0A5 + 0A6 + 1.5A7
C7	**ULS Envelope**	C1 to C6
C8	**SLS Permanent Loads**	1A1 + 1A2 + 0.4A3 + 0A4 + 0A5 + 0A6 + 0A7
C9	**SLS Live Load**	1A1 + 1A2 + 1A3 + 0A4 + 0A5 + 0A6 + 0A7
C10	**SLS Snow Load**	1A1 + 1A2 + 0.4A3 + 1A4 + 0A5 + 0A6 + 0A7
C11	**SLS Wind Load South**	1A1 + 1A2 + 0.4A3 + 0A4 + 1A5 + 0A6 + 0A7
C12	**SLS Wind Load West**	1A1 + 1A2 + 0.4A3 + 0A4 + 0A5 + 1A6 + 0A7
C13	**SLS Wind Load East**	1A1 + 1A2 + 0.4A3 + 0A4 + 0A5 + 0A6 + 1A7
C14	**SLS Envelope**	C8 to C13

C03. Design Strengths

Table 7 below shows the material attributes and the wood classifications needed for the structural analysis of timber structures and members.

Table 7 Material Attributes & Wood Classifications

Material	Glulam			
Strength class	GL24h			
Strength, bending, characteristic	$f_{m,k}$	24	$[N/mm^2]$	ETA-12/0281
Strength, shear, characteristic	$f_{t,0,k}$	19.2	$[N/mm^2]$	
Strength, compression, parallel, char.	$f_{c,0,k}$	24	$[N/mm^2]$	
Moment of elasticity, mean	$f_{v,k}$	3.5	$[N/mm^2]$	
Moment of elasticity	$E_{m,0,mean}$	11500	$[N/mm^2]$	
Density, characteristic	ρ_{mean}	420	$[kg/m^3]$	
Climate class		3		Outdoors
Material factor	y_M	1.25		Glulam
Modification factor	k_{mod}	0.65		Load duration: medium-long, climate class 3, Glulam, EN 14080
Modification factor, creep	k_{def}	2.00		Climate class 3, Glulam, EN 14080
Modification factor, height	k_h	1.00		Volume effects for Glulam
Variable load factors	$\Psi_{0, A}$	0.60		Table NB.2 A1.1 Load Type Category C (meeting place)
	$\Psi_{0, H}$	0.40		Table NB.2 A1.1 Load Type Category H (roof)
	$\Psi_{1, A}$	0.70		Table NB.2 A1.1 Load Type Category C (meeting place)
	$\Psi_{2, A}$	0.60		Table NB.2 A1.1 Load Type Category C (meeting place)

Following timber-specific formulas the design strength values are calculated. These calculations are shown in Table 8 below.

Table 8 Design Strength Calculations

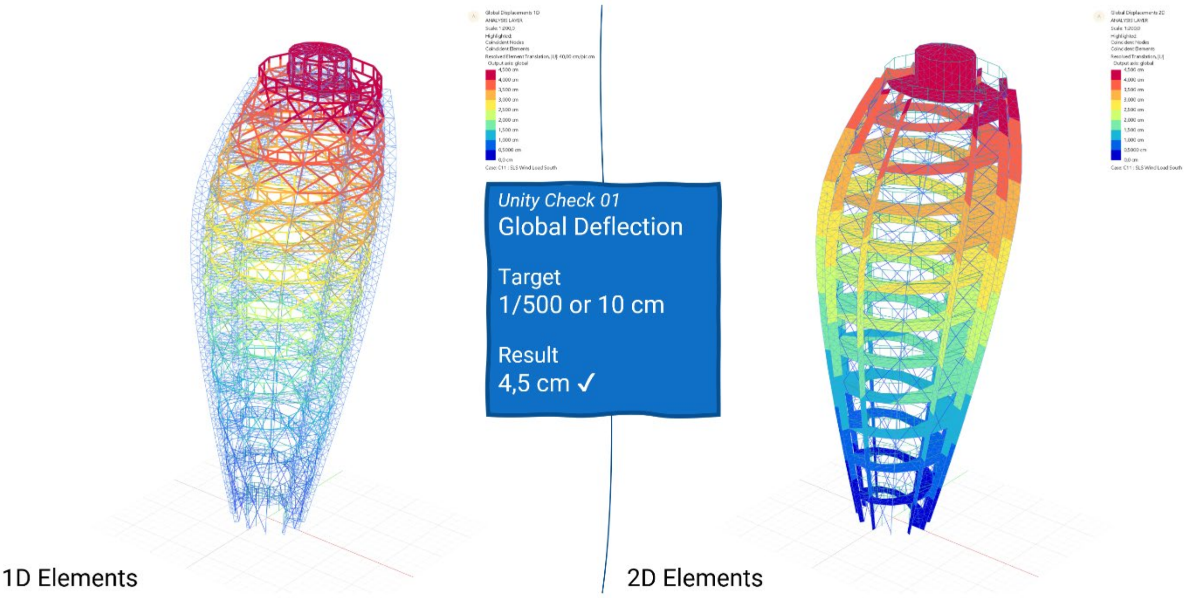
Strength, bending, design value	$f_{m,d}$	12.48	[MPa]	$= (f_{m,k} / y_M) \cdot k_{mod} \cdot k_h$
Strength, shear, design value	$f_{v,d}$	1.82	[MPa]	$= (f_{v,k} / y_M) \cdot k_{mod}$
Strength, compression, design value	$f_{c,0,d}$	12.48	[MPa]	$= (f_{c,0,k} / y_M) \cdot k_{mod} \cdot k_h$

C04. Verification of Profiles and Structural Integrity

For the verification of the profiles, materials, and structural integrity of the structure four levels of unity checks are performed.

C04.1. Total Global Deflection

The total global deflection of the tower should be below 1/500 of the height of the tower. The deflection of 4,5 cm even falls below 1/1000. Figure 11 illustrates the deflection in the structure for the 1D and 2D elements respectively.



Unity Check 01
Global Deflection

Target
1/500 or 10 cm

Result
4,5 cm ✓

Figure 11 Total Global Deflection

C04.2. Element Relative Displacements

The relative displacements of the different structural elements are shown in Table 9. Only the elements with the worst unity checks results are shown here. All results are positive.

Table 9 Element Relative Displacements

Element	*|U| [cm]*	*Length [cm]*	*Max U [cm]*	*Unity Checks*
1328	0.06596	67.22	0.13444	0.490628
1329	0.06077	75.11	0.15022	0.40454
1314	0.04393	54.8	0.1096	0.400821
1326	0.0426	59.99	0.11998	0.355059
1312	0.03726	53.79	0.10758	0.346347
…				

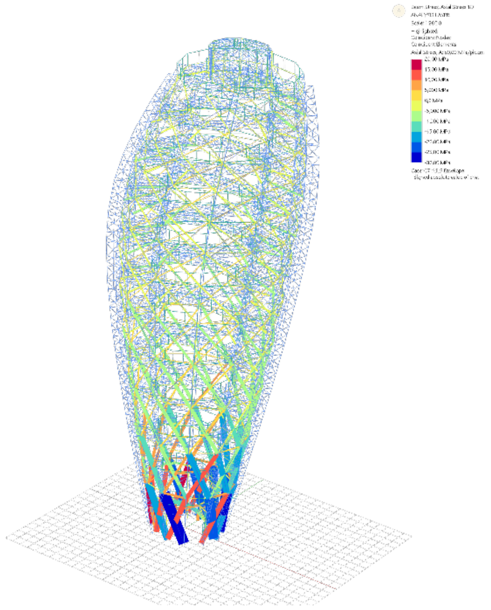
Unity Check 02
Relative Disp.

Target
1/500 of L

Result
All ✓

C04.3. Element Buckling

Buckling is checked for the vertical elements with the highest axial stresses. The axial stresses are shown in Figure 12. As is expected the highest stresses can be found in the ground members. The bar with the highest load is analysed.



Unity Check 03
Element Buckling

Target
$F_d < F_b$

Result ✓

Figure 12 Axial Stresses

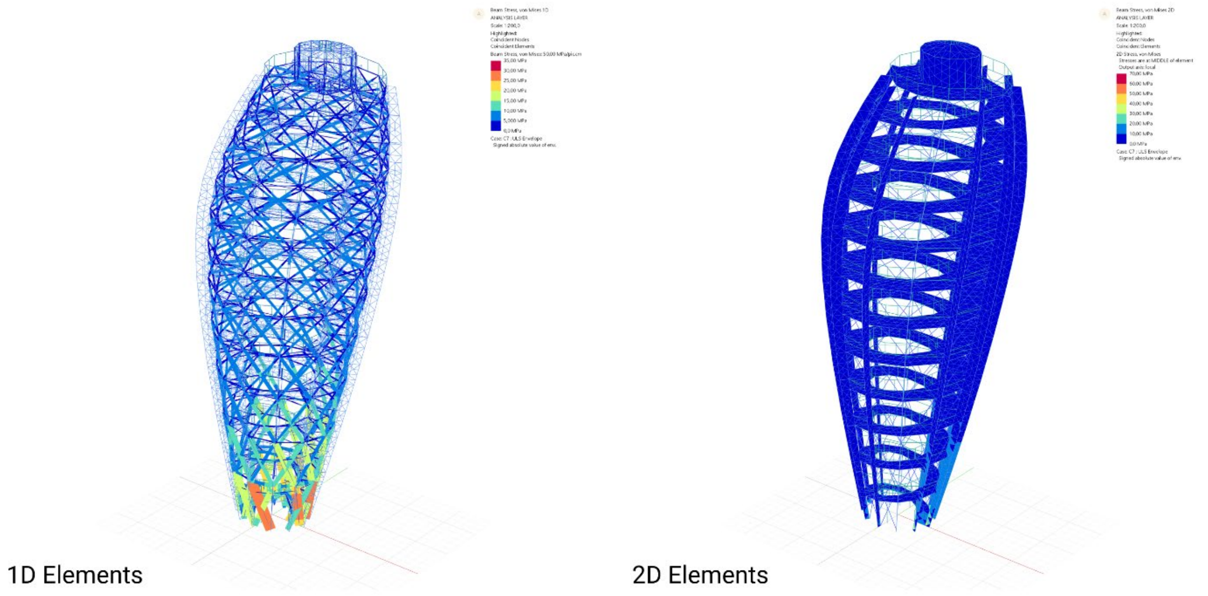
The calculations of the buckling load for this member are shown in Table 10 below. The unity check is positive.

Table 10 Calculating Buckling Load

Load on column	F_d	3006.00	[kN]	
Buckling load	F_b	7323.21	[kN]	$= (\pi^2 \cdot E \cdot I) / L^2)$
Unity check, buckling		0.41		$F_d / F_b < 1$
Safety margin		59%		

C04.4. Element Stresses

As an approximation for the stresses in the members, the von Mises stresses are shown for the 1D and 2D elements respectively. For this, the ULS envelope case is used. The highest value is 35 MPa. This exceeds the design strength of the elements. A closer look is needed.


1D Elements

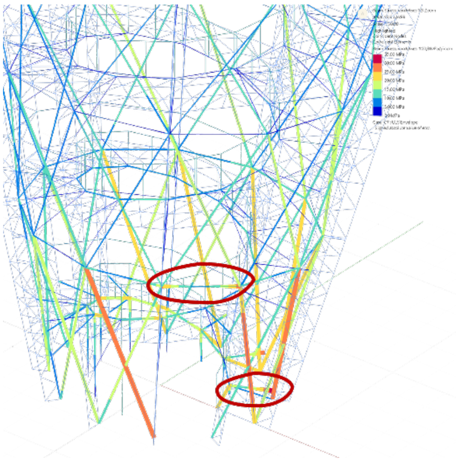
2D Elements

Figure 13 Element Stresses, von Mises

To verify if the stresses are too high bending and shear unity checks are performed for all 1D members. Three elements fail the unity checks. Figure 14 shows where they are located. Above the entrance where one pair of bars is removed and in the lowest ramp beams where forces accumulate. The issue of the failed members will be solved with extra reinforcement. This is illustrated in a detail drawing below (C05.3.).

Table 11 Elements Bending and Shear Unity Checks

Element	*Bending Stress [MPa]*	*Unity Check*	*Shear Stress [MPa]*	*Unity Check*
876	25,5	**2,043269231**	1,864	**1,0241758**
839	18,91	**1,515224359**	1,76	0,967033
23	16,81	**1,346955128**	2,076	**1,1406593**
818	11,75	0,94150641	1,114	0,6120879
615	10,24	0,820512821	0,902	0,4956044
607	10,24	0,820512821	1,275	0,7005495
469	10,13	0,811698718	1,088	0,5978022
624	9,894	0,792788462	0,8967	0,4926923
643	9,557	0,765785256	0,07406	0,0406923
612	9,307	0,745753205	0,8536	0,469011
…				



Unity Check 04
Element Stresses

Target
$\sigma_d < f_b$

Result all ok exept for 3 elements

Figure 14 Highlight of Failed Elements

C05. Details and Connections

The section of the report shows the detail drawing of the tower. They address critical points as well as the constructability of the structure.

C05.1. Foundation

The supports are loaded both in tension and in compression (see Figure 15) as such a common compression foundation is not adequate.

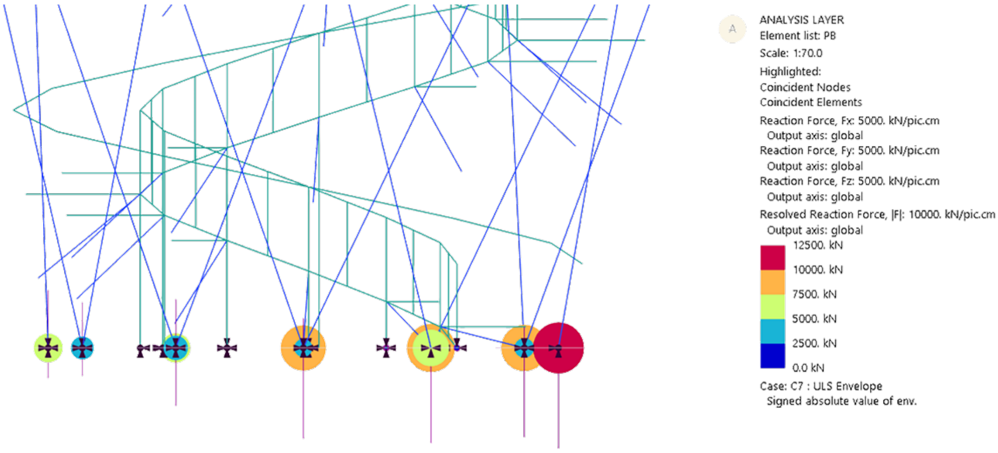


Figure 15 Foundation Reaction Forces

To solve this issue a tension pile foundation is utilized. The piles are driven deep into the ground. They can take tension loading because friction forces between the piles and the soil keep them in the ground. Figure 16 illustrates the foundation connection. Here the support meets the vertical bar elements as well as the wing-shaped columns. The piles are prefabricated. A pile cap is cast in place on top of the pile and below the steel connections. This detail also shows the steel root reinforcement used on the lower two levels of the tower. It strengthens the bar elements that experience the highest stresses.

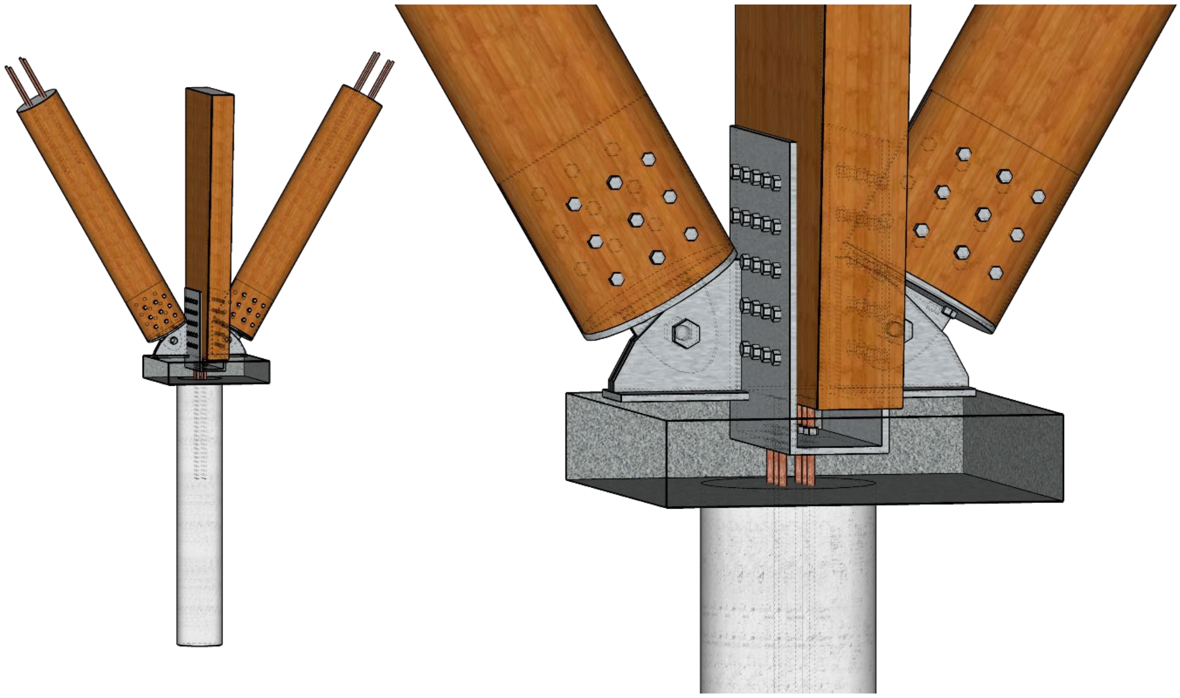


Figure 16 Foundation Detail

C05.2. 8-Point Connection

For the grid shell structure to function it is important that the connections are formed properly. At the nodes, 8 members come together. This connection is illustrated in Figure 17 below. The Glulam elements as well as the steel connections are prefabricated for a quick assembly on-site.

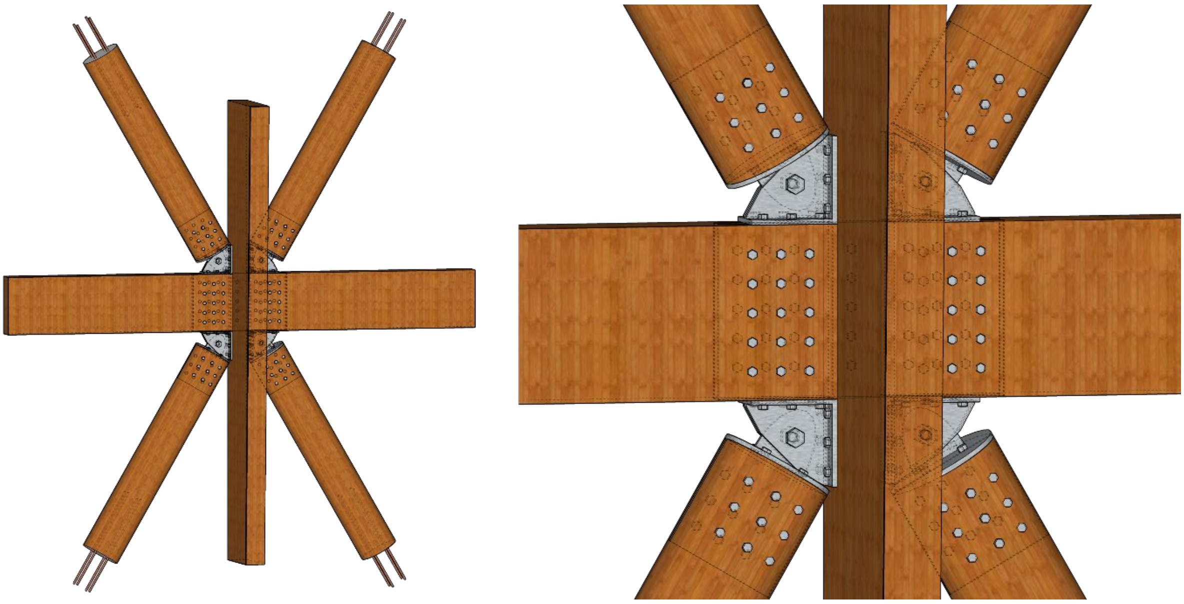


Figure 17 8-Point Connection Detail

C05.3. Beam Reinforcement

The three members that failed the bending and shear unity checks require extra reinforcement. Steel plates can be attached to the site of the element with steel bolts. The plates are attached on the sides instead of the bottom because the elements fail both in bending and in shear. See Figure 18 below for the detail drawing of the reinforcement.

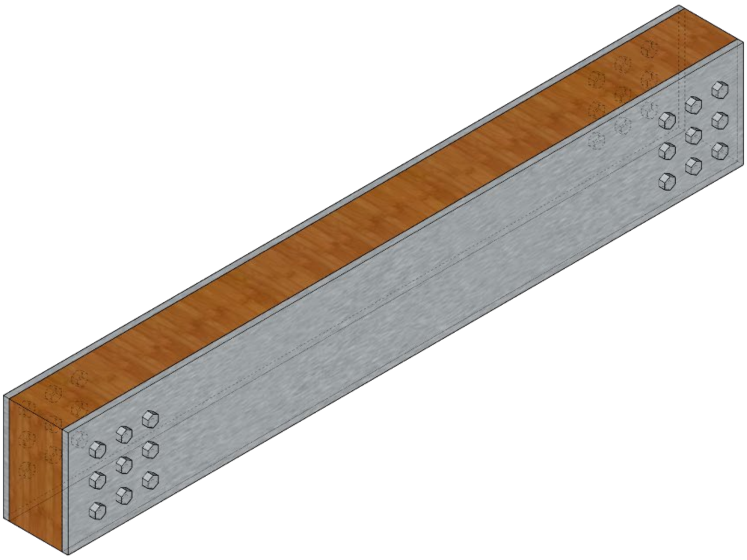


Figure 18 Beam Reinforcement Detail

D. CONCLUSION

The urgent need for sustainable building practices leads architects and engineers to explore innovative new design and construction methods. Parametric design has the potential to create material-efficient structures that can be rapidly optimized and iterated. If this is coupled with the use of sustainable building materials such as timber, it will lead to structures with minimized environmental impact.

This study has set out to create a viewing tower that has a low environmental impact through the efficient use of material, is technically and structurally sound, can easily be prefabricated, constructed, and demounted, as well as being architecturally attractive.

In the creation of the tower, this study has demonstrated the application of parametric design in combination with using input and output parameters, generative design, optimization algorithms, an iterative design process, engineered timber, and a grid shell structure.

By utilizing these elements, the research goals, design brief requirements, and key performance indicators set out for this viewing tower were successfully achieved. The structural analysis and design development have demonstrated that the final tower design is structurally sound, can be prefabricated and quickly constructed. The use of optimizations has resulted in a material-efficient structure that has a minimal environmental impact.

In conclusion, this report has elaborated on the design process, results, and structural analysis of such a parametric viewing tower.

REFLECTION

This project has been an exciting journey. I learned how to use parametric design and work with Grasshopper. I gained a deeper understanding of structural engineering and how to work with GSA. The setup and usage of multiple load combinations and envelope cases was a very useful learning. Wind loading was also a bigger focus than in previous projects.

The project allowed for a lot of freedom to explore different aspects. Examples of this include the creation of a unique geometry that is described mathematically, choosing the right input and output parameters, experimenting with optimization algorithms and generative design.

Especially insightful, was the integration of the structural analysis in the design process. It provided a direct feedback loop on each design iteration. This was only practically possible by the integration of GSA functionality directly in Grasshopper. One thing I have learned for the next project is that I would either fully integrate all unity checks in Grasshopper or switch back and forth between GSA and Grasshopper much earlier in the process. This needs to be set up so that the model can be exported and imported with minimal manual work. The alternative is to ensure that the unity checks are calculated correctly in the script.

The script developed for this project relied too heavily on deflection checks. This resulted in a structure that was optimized for minimal deflection but not stresses. At least in the early to middle part of the project. An integration of stresses checks could have resulted in a different variance study.

Other performance indicators could also be integrated like a construction cost or a CO_2 equivalent impact estimator.

An interesting structural system that is related to the grid shell structure that could have been explored in the variance study is a hyperbolic tower. Such a structure can be created with the current script, but it is not optimized for it.

Overall, this project has been very insightful on many different levels.

REFERENCES

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APPENDIX

TU/e EINDHOVEN
UNIVERSITY OF
TECHNOLOGY

Declaration concerning the TU/e Code of Scientific Conduct for the Bachelor's final project

I have read the TU/e Code of Scientific Conduct[i].

I hereby declare that my Bachelor's final project has been carried out in accordance with the rules of the TU/e Code of Scientific Conduct

Date

08-07-2023

Name

Jonas Merlin Aron Chenderasa

ID-number

1562126

Signature

Jonas Ch

Submit the signed declaration to the student administration of your department.

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[i] See:https://www.tue.nl/en/our-university/about-the-university/organization/integrity/scientific-integrity/
The Netherlands Code of Conduct for Scientific Integrity, endorsed by 6 umbrella organizations, including the VSNU, can be found here also. More information about scientific integrity is published on the websites of TU/e and VSNU

February 21, 2020