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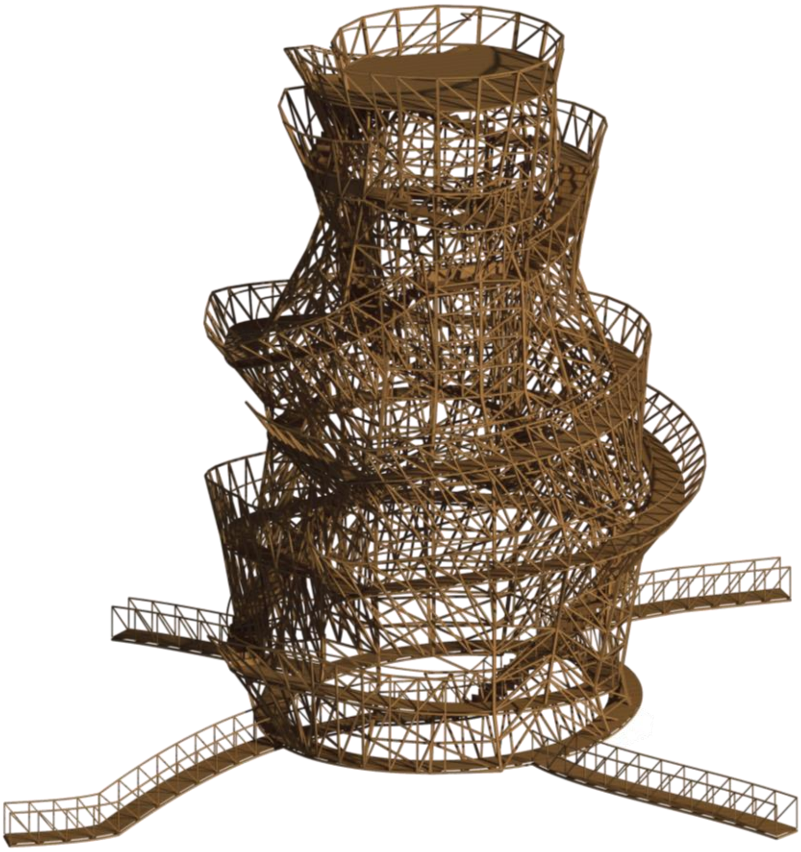

View of Wood

Structural Concepts for an Observation Tower Displaying the Potential of Timber

Master's Thesis in the Master's Programme Structural Engineering and Building Technology

KARIN CAJMATZ

Department of Architecture and Civil Engineering
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Master's Thesis BOMX02-17-6
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Cover:
Axonometric drawing of the proposed wooden obeservation tower. Author's own copyright.

Department of Architecture and Civil Engineering. Göteborg, Sweden, 2017

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ABSTRACT

In modern times, timber building has been limited, to the benefit of steel and concrete. This thesis aims at creating a new interest for, and to draw attention to, timber building. Though timber is on the rise again, many new timber structures do not utilize the material to the best of its potential and part of the problem is a lack of skilled carpenters. From this came the idea to create this timber observation tower that is meant to be built as part of an educational process to teach carpentry and which will, when completed, allow visitors to experience the forest landscape, i.e. the source of the timber, in a new way.

This thesis first looks at reference projects to visualize what has been built already and what structural systems may be beneficial for such a tower. It then goes into conceptual design of the tower structure to finally end up in a first proposal of a wooden observation tower. The conceptual design handles the overall structure of the tower and the load bearing system. The design proposal goes more into detail and proposes two alternative solutions for the assembly of the tower, which have different influences on how the load bearing system would work. These examples of the joinery that would enable the tower to be built by inexperienced workers concludes the thesis and suggests the next iteration of the design.

Along with a parallel thesis in architecture, this thesis is a part of this tower project. Throughout the whole process, a combination of physical and digital models has been used and the alternations between them has been important to always find the most effective way to investigate matters. At the beginning the work was focused on references, but early on the collaboration with architecture became very important. An example is the idea of two separate walk paths that led to the development of the initial concepts for the structural system. The finished design proposal is very much a product of the two theses and this close collaboration.

Key words: Timber observation tower, Observation tower, Timber engineering, Conceptual design, Structural concept

View of Wood
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Examensarbete inom masterprogrammet Structural Engineering and Building Technology

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SAMMANFATTNING

I modern tid har trä som byggnadsmaterial fått stå tillbaka till förmån för stål och betong. Det här examensarbetet syftar till att väcka intresse för och dra uppmärksamhet till träbyggande. Trä som konstruktionsmaterial blir allt populärare idag, men trots detta nyttjas inte alltid materialet till sin fulla potential. En del i problemet är bristen på duktiga snickare. Ur detta kom idén att skapa ett utsiktstorn av trä som kan byggas som en del i en träbyggnadsutbildning och som, när det är färdigställt, kommer att ge besökare möjlighet att uppleva skogslandskapet, dvs källan till byggnadsmaterialet trä, på ett nytt sätt.

Examensarbetet inleds med en presentation av en rad referensprojekt för att visa vad som byggts och vilka bärande konstruktioner som kan användas för den här typen av torn. Arbetet fortsätter därefter med konceptuell design av tornets bärande konstruktion för att slutligen leda till ett första förslag till en design av utsiktstornet. Den konceptuella designen syftar främst till att diskutera den övergripande strukturen och hur den hanterar laster. I designförslaget hanteras mer detaljerade frågor och två förslag på knutpunkter presenteras, vilka får olika konsekvenser för hur tornet byggs och hur det hanterar laster. Dessa förslag på knutpunkter som möjliggör att tornet kan byggas som del i en utbildning av oerfaren arbetskraft avslutar examensarbetet, samtidigt som de uppmuntrar till en nästa iteration av projektet.

Arbetet har utförts som en del i detta tornprojekt, parallellt med ett examensarbete inom arkitektur. Genom hela processen har en kombination av fysiska och digitala modeller använts och växlandet mellan de två har varit viktigt för att hela tiden använda den mest effektiva metoden för en viss undersökning. Från början låg fokus på referensprojekt, men tidigt i processen blev samarbetet med arkitektur viktigt. Ett exempel på detta samarbete är idén om två separata gångbanor som ledde till utvecklandet av de första strukturella koncepten. Det slutliga designförslaget är i allra högsta grad ett resultat av det nära samarbetet mellan de två examensarbetena.

Nyckelord: Utsiktstorn av trä, Utsiktstorn, Träbyggande, Konceptuell design, Strukturellt koncept

Contents

Preface

This thesis work has been carried out from January 2016 to April 2017. The work is part of a project that aims to increase the use of timber in construction in Dalsland, Sweden, but also to increase the local knowledge and skills in carpentry. Aside from this thesis I have been working on my master's thesis in architecture "View of Wood - Experiences and Perspectives of Forest and Timber in an Observation Tower" at the Chalmers School of Architecture in parallel within this project.

Throughout this work, the discussions I've had with and the feedback I've received from my tutors Jonas Carlson and Kengo Skorick and my examiner Morten Lund at the Chalmers school of Architecture have been invaluable. Professor Roberto Crocetti at the Department of Structural Engineering, Lund University, has also contributed with discussions, feedback and pointing me in the direction of interesting reference projects. My examiner for this thesis, Karl-Gunnar Olsson, has helped me a great deal too, especially in summing everything up and helping me add those final touches to better explain my work.

Finally, I would like to thank all other teachers and staff at the Chalmers School of Architecture for their support and guidance throughout this work and in the unconventional process of doing two master's theses in parallel. I would also like to thank the other students of the Matter Space Structure studio, where I've been sitting during the whole time I've been working on my theses, for an inspiring and enjoyable working environment.

Göteborg, May 2017

Karin Cajmatz

Notations

Roman upper case letters

A	Area (of the projection of the structure on its windward side)
$\mathrm{A_{ref}}$	Reference area for wind load
$A_{ref90°}$	Reference area for wind load hitting at 90°
$A_{ref45°}$	Reference area for wind load hitting at 45°
C_e	Exposure coefficient
C_t	Thermal coefficient
F_w	Resultant wind force

Roman lower case letters

c_d	Dynamic factor
c_f	Force coefficient
$c_{f,0}$	Force coefficient of structures or structural elements without free-end flow
c_s	Size factor
g_k	Characteristic value of a permanent action
k_{cr}	Reduction factor due to cracks for shear capacity
$q_{k,1}$	Characteristic value of the leading variable action 1
q_d	Design value of a load combination
$q_{k,j}$	Characteristic value of the (accompanying) variable action j
q_p	Peak velocity pressure
s	Snow load on the structure
s_k	Characteristic value of snow on the ground at the relevant site
v_b	Basic wind velocity
z	Height above ground
z_0	Roughness length
z_e	Reference height for external wind action
z_{min}	Minimum height

Greek lower case letters

γ_d	Coefficient for safety class
γ_M	Partial factor for material properties
μ_i	Snow load shape coefficient
ψ_0	Factor for combination value of a variable action
$\psi_{0,j}$	Factor for combination value of a variable action j
ψ_λ	Reduction factor of force coefficient for structural elements with end-effects

1 Introduction

Throughout history, timber has been a common construction material in Sweden. The country has always had, and still have, a lot of forest and hence the material has always been available. Looking back, the knowledge of how to build was common knowledge, compared to today. A survey done in 1910 by Nordiska museet (the Nordic museum, Stockholm) showed that every second man in Sweden knew how to build a log house (Sveriges Arkitekter, 2016). Today, knowledge of the material and carpentry is on the verge of dying. Very few architects and engineers have knowledge of the timber material today. Those who still possess the practical and traditional knowledge of how to see and smell the material to know what to use it for are to a large extent older men, so this knowledge is at the risk of dying with them. This also, by extension, has negative consequences for the quality of the Swedish timber as the lack of knowledge and interest influences the strategies used in forestry. Before, forests consisted of mixes of species and age of trees, but in the modern forestry, once and area has been cleared, only one species is planted. The consequence of this lack of diversity is a lowered resistance towards disease and a lower amount of heartwood (Svensson, 2016).

When it comes to timber building, Sweden is falling behind. But there are examples to take after and to learn from. The interest for and knowledge of timber as a material in architecture is much bigger in for example Switzerland, Austria and Germany. In these countries, the traditional ways of working have been kept alive and modern wooden architecture and structural engineering has been developed on a sound foundation of traditional techniques and extensive knowledge of how the material functions. Therefore, they today have skilled carpenters and companies that are working towards the same goal; to create a future where modern techniques are based on traditional knowledge (Svensson, 2016).

A Google image search for “modern timber construction” shows some interesting and technically advanced projects, things that would not have been possible to build without traditional knowledge of the material and the carpentry in combination with modern engineered timber products and digital fabrication. Translating the search phrase into Swedish changes the results drastically. Of course, it narrows the search from worldwide to mainly Sweden, but the most interesting thing is that all images now show boxes. Building after building shows up and they’re all boxes. There is no telling if they are wooden or built from steel or concrete.

Traditionally timber structures were built by hand by workers and private citizens who in many cases didn't have any formal education. Today there is a lot of knowledge of the properties of timber and there are engineered timber products such as glued laminated timber (glulam) and cross laminated timber (CLT). However, there is a tendency towards using for example CLT in a similar way as prefabricated concrete elements are used. To use the modern timber products and fabrication methods that are available today in a way where timber is used to its full potential it is necessary to obtain knowledge and skilled carpenters once again. That way timber can be a part in ensuring a sustainable future construction industry.

This thesis addresses our lack of knowledge of the timber construction material through a case study that aims to develop a concept for how to build an observation tower as an educational project to teach the trade. The background of the case study is in short a desire to use more of the locally available timber in construction in Dalsland, particularly in the municipality of Bengtsfors. To do so a raised interest for timber building is required, and to achieve that interest requires attention. To draw this attention, the idea was to build something public to show how the local high quality timber could be used and from there came the idea to build an observation tower in the forest landscape. That way not only the quality material could be experienced, but the forest, that is the source of the material, as well. Furthermore, there is a desire to acquire skills and knowledge about carpentry locally and to build this tower within the scope of carpentry courses in local education. That way, in the future, local buildings can be built by local workers using local material. With this project, the municipality is hoping to draw attention both to the built object, but also to the project and the design and construction process.

1.1 Aim and objectives

The aim of this thesis is to show the potential of timber as a construction material for the future by showing how it can be used in a way that utilizes modern technique without making it too complicated. The result is meant to be a proposal for the structure of an observation tower, which will showcase the possibilities of timber as a structural material and which will be simple enough to be built by inexperienced students within the scope of courses to teach carpentry. The thesis aims to investigate how modern timber structures can be built utilizing both regular structural timber and engineered timber products in combination with modern fabrication techniques such as CNC milling. Moreover, focus will be on the simplicity of the erection in order to realize the vision to build the tower within education. Therefore, the major part of the members of the structure should not be bigger than that they can be handled by the workers themselves using only simple lifting equipment, i.e. cranes and such heavy machinery should not be required, or at least the need for them be very limited.

The thesis aims to investigate several concepts for load bearing tower structures and to show pros and cons with them in order to eliminate those with less potential and move forward with the more promising alternatives. The aim is that finally one concept, which is suitable for the case study, will be developed to a level where solutions for the main connection details are presented.

Another objective is to show the possibilities that arise when the two disciplines of architecture and structural engineering collaborate. To achieve that, this master thesis will be carried out in parallel with a master thesis in architecture that is approaching the wooden observation tower from a different perspective, but which has the same tower in Bengtsfors as a case study. The two theses will give input to each other along the way to achieve a design process where both disciplines are involved on equal terms from the very beginning.

This thesis is carried out in steps. Within each step are some questions to consider. The idea is that by going through these steps and answering these questions, the thesis will eventually answer the main thesis questions that have been set up.

1.1.1 Inspiration and references

- *What types of timber towers have been built before? What do they look like?*
- *What types of structures have been used for timber towers? How do they carry load?*
- *What other inspirational projects are there?*

1.1.2 Conceptual design

- *What is the relationship between the spaces where the visitors are (stairs, viewing platforms etc.) and the load bearing structure?*
- *What criteria should be fulfilled for the tower to have the desired function?*

1.1.3 Final design

- *Can the structure be built from only members small enough to handle by one or a few workers?*
- *How can the details be solved in such a manner that they are easy to assemble for a construction crew of students?*

1.1.4 Problem

Finally, the actual thesis questions will be answered by going through the process of answering all the above.

- *How can a timber observation tower be designed so that it both exhibits the qualities of modern timber construction and can be built by student as part of an education?*
- *What connection details are suitable for such a load bearing structure?*

1.2 Limitations

The design phase of this thesis will be limited to observation towers made of timber without elevators, lighting or other installations. Not including an elevator simplifies the load cases and limits these to only live loads (people, wind and snow) and permanent load. Not including any installations simplifies the construction process and helps to enable implementation of the idea of utilizing inexperienced labor. Furthermore, in the calculations that are made, no attention is put to either dynamic behavior or fire resistance.

The thesis intends to investigate many possible solutions. To make this possible, initially the concepts will only be investigated through sketches. In the next step the structures will be investigated through physical models and preliminary calculations. For the final chosen concept, connection details and the assembly processes will also be considered.

The case study of the thesis will aim at showing possibilities for a wooden observation tower in Bengtsfors built from the local timber. Therefore, the intention is to use wood species and timber products available in Sweden as well as the possible fabrication methods that are commonly available.

To provide a 360° view, the tower must get the visitors to above the tree tops. To do so at the site for the case study, the tower should be ~25 m tall.

The thesis is intended to produce a concept that is clear enough to be used for architectural drawings, but which still requires some analysis of a structural engineer before drawings for the actual construction can be prepared.

1.3 Method

This thesis will start by researching existing structures, primarily focusing on timber towers, but also considering other tower structures and other timber structures in the cases where they are deemed inspirational. The next step will be to come up with and evaluate several concepts for load bearing structures for wooden observation towers. Those concepts that are determined to be the best ones will be developed further and evaluated once again. After the second evaluation only one or a couple of concepts will remain, for which more detailed studies into the structural system as well as some joints will be performed.

This thesis work will be carried out in parallel with a master's thesis in architecture by the same student. Both theses will have the observation tower in Bengtsfors as a case study, but approaching it from different angles. While this thesis is addressing the concept for the load bearing structure, the thesis in architecture will address the visitor's experience of the forest landscape, the view and the site.

1.3.1 Investigations of existing structures

The first step of this thesis will be to investigate existing structures, with a main focus on wooden observation towers of different kinds. The towers will be investigated in terms of their load bearing structure and how they function. Relevant to consider is of course the size of the tower, especially the height, as well as when it was built, i.e. what technology was available and used at the time of construction and how long the structure has been in use. Based on these investigations, a discussion will be made comparing different solutions and their pros and cons as well as their potential for the case study of this thesis.

In addition to investigating towers, a brief look at other inspiring structures will be done. Perhaps there are other techniques that may be of interest for this project, besides those found in existing towers.

1.3.2 Program and functions

What the tower as a structure is supposed to perform and enable has to be stated. Some aspects are given by the site, such as height and possible footprint area. Aside from the obvious function to provide a view for the visitor, other functions may develop in the architecture thesis and become input into this thesis along the way.

1.3.3 Tools to create and analyze concepts

The development of the structural concepts and the analysis of those will be carried out in different ways. As a first step through simple evaluations, discussions and small physical models. As the number of concepts decrease and the evaluations become more detailed, analysis using computer software will be performed. Throughout the process, a combination of physical and digital models will be used to investigate the structure.

1.3.4 Concepts of different kind

Based on the research and the prerequisites, several concepts will be sketched. The initial aim will be several very different concepts. From these initial ideas, 5-10 concepts will be developed. These concepts will be developed to a level where qualified reasoning can be made. Based on such discussions an evaluation will be performed.

1.3.5 Further work in developing the concepts

After the first evaluation, approximately half of the original concepts should remain. These concepts will then be developed further. The systems will need to be refined and more in depth analysis performed. Thereafter a new evaluation will be done to select the concepts that is found to be the most promising.

1.3.6 Development of the most promising concept

For the final concept, the main structural details will be investigated and suggestions for the design of these details will be made. This concept will be investigated both by utilizing computer tools for structural analysis and through physical model. The physical model will aim at visualizing and increasing the level of understanding of how the system looks and functions and to identify and understand the important details to be solved within the project.

1.3.7 Evaluation of the work and ways to move forward

It will be important to continuously question and evaluate the work; both the method and the results. To evaluate the concepts, it will be necessary to develop criteria to base the evaluation on. These will be based on various aspects set up as criteria and prerequisites based on the research as well as the case study. To be able to create useful evaluation criteria it will be necessary that the terms according to which the evaluation is to be performed are clear.

Some interesting criteria may be number of unique elements, difficulties in construction, possibility to prefabricate, size of components, structural efficiency etc. What is considered beneficial or not may vary, depending on for example fabrication method. Say all elements are to be produced by hand, then it may be a lot better if there are just a few unique elements, but if they are to be produced by CNC-milling, then it doesn't matter if they are all different. Number of principles for assembly details is however desirable to keep at a minimum regardless of fabrication method, since the mounting involves people and therefore the more complicated the system is made, the greater the risk of something going wrong is.

In the first evaluation, the concepts will not be developed very far and hence the criteria on which they’re evaluated cannot be too detailed. For example, connection details will most likely not be possible to even discuss at this point. In the next evaluation however, when the concepts have been developed further, more detailed criteria can be applied.

When the project is finished, an overall evaluation of all work done will be made. This will result in a discussion of the method used as well as the results obtained in the thesis. The conclusion of this should consist of two parts; what has been done so far and what is left to do. The latter of these parts shall take up areas that were intended to be covered in the thesis, but that for some reason weren't, as well as new questions that have arisen and other subjects that are important for the result of the case study to be able to result in a real built project.

1.4 Outline of thesis

This thesis consists of an investigation into built structures followed by a design part. The first part provides insight into what has been done before in terms of wooden towers as well as what other structures there are to draw inspiration from. The design part goes through several conceptual ideas, developed with a basis in the investigation of built structures, to find the most suitable structure for the case study of this thesis.

After considering the background of the case study, the next step will be the investigation of reference projects. The built examples will be categorized based on load bearing systems and discussed according to questions raised in Section 1.1.1 and parameters mentioned in Section 1.3.1.

The design phase that follows starts from a brief description of several possible concepts for load bearing structures in timber towers and then proceeds to evaluate and eliminate concepts based on criteria set up within this thesis as well as criteria developed in the parallel master's thesis in architecture. Eventually, as the concepts are being developed, evaluated and eliminated, only one concept remains, which is being investigated and described even further.

The thesis ends with a discussion about the work carried out within this thesis and the collaboration with the parallel master thesis in architecture as well as what the next step could be within both the case study and the process of regaining knowledge and skill in timber construction to the Swedish work force.

1.5 My background and interest in the subject

I got my bachelor degree from Architecture and Engineering at Chalmers in 2012. Since then I have studied structural engineering for one semester at EPFL in Lausanne, Switzerland, interned at a structural engineering office and thereafter studied two master programs; in structural engineering and architecture, at Chalmers. Over time my interest in timber structures has developed and it was clear to me that I wanted to work with the material for my master's theses in both structural engineering and architecture. Another wish I had going into the process of finding a subject for my theses was that I wanted both theses to be connected in some way.

The case study I have chosen is very strongly related to both the field of architecture and the field of structural engineering. I do believe that this thesis will benefit from the fact that I have a background in architecture as well and that it will be an asset that I am doing my master's thesis in architecture on the same case study and in parallel. My intention is to enable the theses to give input to each other. That way I hope to be able to benefit from the two disciplines working closely together and understanding the issues handled within the other field at once.

1.6 The case study and initiation of the project

As a case study this thesis will investigate how to build a load bearing structure for an observation tower in the municipality of Bengtsfors, utilizing local resources in the form of material, knowledge and manpower. This thesis is part of a larger project raising the question of how to utilize the resource that is the forest in Dalsland, Sweden, particularly in the municipality of Bengtsfors. This larger project involves a wide range of participants, including the adult education in Bengtsfors, Stenebyskolan, DaCapo (Gothenburg University), the municipality of Bengtsfors, the region of Västra Götaland, Chalmers (where this thesis and the parallel thesis in architecture are included) among others. In this project, the idea is that the people that represent this long line of stakeholders will contribute in their own ways, both economically and more hands on. Among the involved people are some that are being educated in carpentry, others are immigrants with various educations from their home countries and who can partake in the project and at the same time take a step closer to integration into the Swedish society and labor market. There are also people with a background in architecture, planning and structural engineering as well as representatives from tourism. There are many people who have worked with timber in different ways without any formal education, there are also those who have various educations within the field.

One goal of the project is of course to build an observation tower in Bengtsfors, on top of the hill Majberget, right next to the town's railway station. Another, and equally important goal, is to create a process where the modern timber and forest industries and the modern fabrication methods meet all the above mentioned collaborators within the project and utilizes the best of their competences to create something new. The intended way of doing this is by bringing the participants together in workshops where collaborations and investigations will be carried out with the aim of developing innovative solutions for timber structures. Input from these workshops will then be used in various ways by different participants, e.g. in courses at the adult education and by me as input to both my structural engineering and my architecture master’s theses. The aim is to refine the ideas from the workshops and in the end to use them to build the observation tower.

For this thesis, what is maybe most important to keep in mind are two things; that the municipality would like this project to bring attention to them and that the tower is meant to be built within the scope of the education. What this means is that the tower should have some sort of an eye opening effect. It should be something out of the ordinary to create this sought after attention, not just for the project as such within the educational community or construction related professions, but as a tourist attraction too. The fact that it is part of an education means that it should be easy to build and not require a lot of heavy machinery and such, so that the actual construction can be done by the students.

Worth mentioning is also the fact that Stenbyskolan has a relatively advanced CNC machine, which could be utilized for production.

1.6.1 The site

The site is a plateau on the site of the local history museum (Swedish: hembygdsgård) Gammelgården. Most parts of it is visible rock and some parts are covered in low vegetation (Figure 1.1). The site has no clearly defined boundaries, but an area of approximately 20x30 m can be used for the tower. It goes for the whole site that foundation must be made through anchoring into the rock.

Figure 1.1 The site for the tower. Author's own copyright.

The local history association (Bengtsforstraktens Hembygdsförening) who owns the property has said that they will provide the necessary ground space for the tower with very few conditions. The conditions they do have are that the tower shall draw attention and attract visitors and that it shall be accessible, not necessarily that there should be a wheelchair adapted ramp to the top, but it should be possible to make the site accessible so that everyone who visits the museum can get to the site and get something out of the tower. They point out that in terms of accessibility, it is not just physical disabilities, but also impaired vision and hearing that needs to be taken into account, especially since many of those visiting the area today are elderly. Regarding the choice of foundation, the land owner doesn't state any clear rules in terms of drilling into the rock and such, but they do express that they would appreciate an approach aiming at minimized interventions.

1.6.2 Climate aspects

Climate change and global warming is a real issue today. Steel and concrete, the two main construction materials of modern times, both have a big negative impact on the environment due to their large carbon dioxide emissions. Timber on the other hand can be said to have the opposite effect. There is an ongoing shift in the construction industry where more and more and taller and taller structures are being built using timber as the main structural material. However, these are buildings that are being built in a similar fashion as steel and concrete structures have been built for a long period of time, using prefabricated elements such as walls, modules, columns and beams that are assembled on site and usually covered up in gypsum or such.

Aside from the carbon dioxide emissions related to production of the material, there is also the issue of carbon dioxide emissions due to transportation. It is easy to argue that the less something has to be transported, the smaller are the carbon dioxide emissions related to the same transportation. Furthermore, timber is significantly lighter than steel and concrete, which influences the transportation. So, in other words, it makes sense to use local materials. Sweden has a lot of forest, and the specific region for the case study of this thesis is no exception. Hence, it makes sense to build in timber.

Timber has many advantages. Among those are the fact that it is a renewable resource that never has to be placed in landfills, but can be reused and as a final stage be used as an energy source through burning. Other advantages are its local availability that implies short transportation and the lightness that means it can be used to build upon existing structures (Svenskt trä, n.d.a). In order for us to be able to use timber to its full potential in the future we should be careful to conserve the traditional skills before it’s too late. Perhaps we would want to build in a different way than what the traditional techniques imply, but nevertheless it is knowledge to build upon and to develop. To do so we need to not just build more with timber in the today increasingly common industrial way, but we also need to increase the use of real carpentry skills.

2 Reference Projects

Before going into the design of a new tower, a lot can be gained from studying previously built structures. It is also worth considering what actually defines an observation tower. First one may think that it is a tall structure with some sort of platform at the top and that whether it is a tower or not has to do with the relation between height and width. However, there exist a wide range of observation towers spanning from towers that fit the preconceived to those that more resemble a vertical playground, as well as those that are about as wide as they are tall.

Observation towers, built for the sole purpose of providing an enjoyable view for the visitor, became common around the end of the 18th century. Later, the function of an observation tower has often been combined with a water tower or a radio mast, giving the high towers, of up to 200 m, a greater purpose. Aside from observation towers, there are also watchtowers. These towers are meant for keeping guard, e.g. to look out for forest fires, and can be combined with the function of an observation tower or be used as observation towers during times when the risk of forest fires is insignificant. Many of the earliest observation towers, from before World War I, were built in stone, even though timber and iron structures occurred as well (Wikipedia, n.d.a).

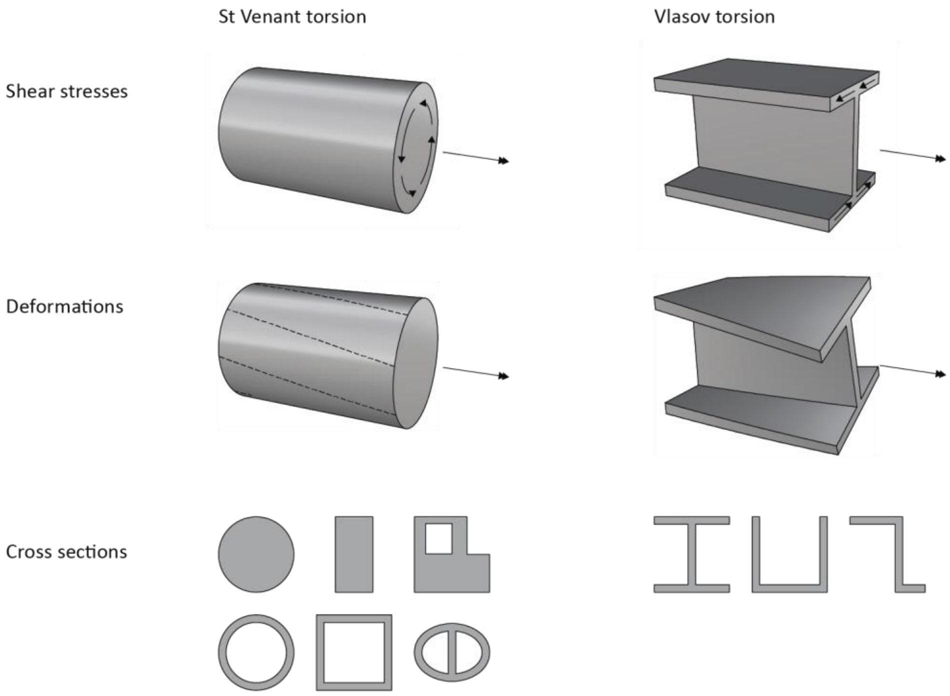


Figure 2.1 St Venant and Vlasov torsion. Author's own copyright.

In this chapter, an overview of some tower structures will be given. The main focus will be on observation towers from the past two decades, but some other towers, both of other types, other materials and older towers will be presented. All towers have been sorted into categories depending on their load bearing structure and are presented, within each category, in the order they were built. Some other reference projects, that aren't towers, will also be mentioned.

Some examples will be highlighted and the concepts for how their load bearing structures function will be explained. It will first of all be considered how the structures transfer vertical load down to the foundation. How the structure behaves under horizontal load will be described too. Another important aspect to consider is how the structure is able to withstand torsion. In all such analysis, it is important to note that what is presented is just an interpretation of the structure and that it may or may not coincide with how the structure was originally designed and how it actually functions.

Regarding torsion, there are two types of torsion; St Venant and Vlasov (Figure 2.1). St Venant torsion is characterized by shear stresses that create closed stress trajectories. It is caused by a twisting moment and occurs in closed, or massive, cross sections. Vlasov torsion on the other hand occurs in open thin walled cross sections, where closed trajectories can’t appear. In a circular cross section, only St Venant torsion appears, but in an arbitrary cross section, the total torsional moment is the sum of the torsional moments related to both St Venant and Vlasov torsion (Dahlbom & Olsson, 2015).

In addition to vertical, horizontal and torsional load carrying behavior, some other things may be of interest. For example, a slender structure or member may be subject to buckling. In what way is the buckling withstood? The joinery is another important thing. Can the elements rotate freely in relation to each other? Or are the joints moment resisting?

2.1 Lattice towers

Among lattice structures are a wide variety of structures, not the least in terms of shape. Lattice structures include ordinary trusses, but also gridshells, hyperbolic structures, plane frames and space frames.

2.1.1 Truss towers

In its simplest form, the truss tower could be square or triangular in plan, with a uniform width from bottom to top, a staircase in the middle and a viewing platform at the top. Looking at the built truss towers however, they are way more interesting. There is the pre World War II radio masts that in silhouette resemble the Eiffel tower and the Sky Walk, which can be seen as three towers that carry walkways and a long slide. All of these towers are presented below. Though very different in terms of overall shape and expression, they all have structural systems that are based on trusses.

Radio masts from before World War II can be found in Germany and Poland. The transmitter mast in Ismaning, Germany, was built in 1932 (Figure 2.2). At that time it was 115 m tall, but later an addition was made which rendered the mast

165 meters in height. The base of the tower was 20 m wide. The wooden truss system consisted of members with sections measuring 140 x 240 mm or smaller, with joints constructed using Kübler dowels and bronze joints. After surviving the second world war, the tower was torn down in 1983 due to its bad conditions and the far too high costs associated with refurbishing it to the building regulations of that time (Natterer & Winter, 2004).

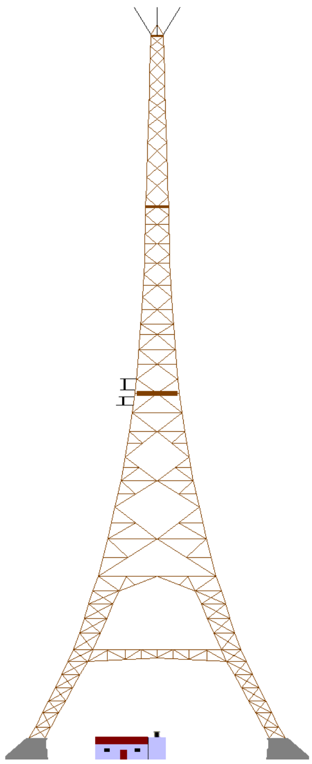


Figure 2.2 Drawing of the transmitter mast in Ismaning (Vakarel, 2006). CC BY-SA 3.0.

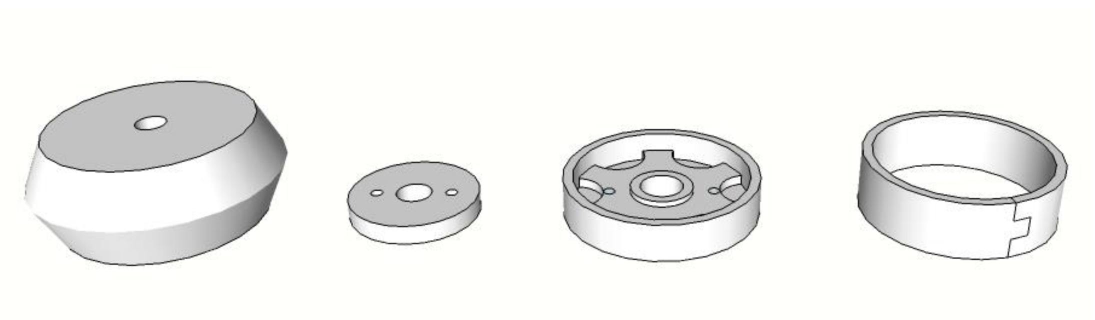


Figure 2.3 From left to right; Kübler dowel, two types of shear plates and split ring. Author's own copyright.

Kübler dowels, that were used in the Ismaning mast, can be considered an early type of shear plate or split ring (Figure 2.3). The Kübler dowel is double-tapered and each half is to be embedded in each of the two pieces of wood to be connected and all three parts are then held together by a bolt. This renders a connection that can transfer large loads without exhibiting the same slip as an ordinary screwed or bolted connection, but which is not able to transfer shear. The Kübler dowel was most likely the inspiration for shear plates and split rings (Stalnaker & Harris, 1997). Shear plates and split rings can be used to connect both to pieces of wood and one piece of wood to a piece of metal. The load in these connections is transferred from one element to the other via shear. These types of connectors are today most commonly used in heavy timber structures to connect either ordinary timber members or glulam members (Canadian Wood Council, n.d.). As these connectors are embedded in the timber, they could be interesting to use in an observation tower as most of the steel, aside from the ends of the bolt, would be protected from weather by the timber.

Figure 2.4 Gliwice radio tower (Górny, 2012). CC BY-SA 3.0.

The Gliwice radio tower from 1935 (Figure 2.4), is lower than the mast in Ismaning with its 111 m. At the time of construction, it was located in Germany, but the town of Gliwice is today a part of Poland. The tower was built from larch wood and with all connectors made of brass. This mast enabled broadcastings that were possible to hear from all over Europe as well as parts of Asia and North America. Today the radio tower no longer functions as a radio tower, but it is however still in use, but for various other types of antennas. The tower, even though it is more than 80 years old, is supposedly the highest wooden structure in Europe today (Muzeum W Gliwicach, n.d.). Just like the transmitter mast in Ismaning, the structure of this tower is a truss system.

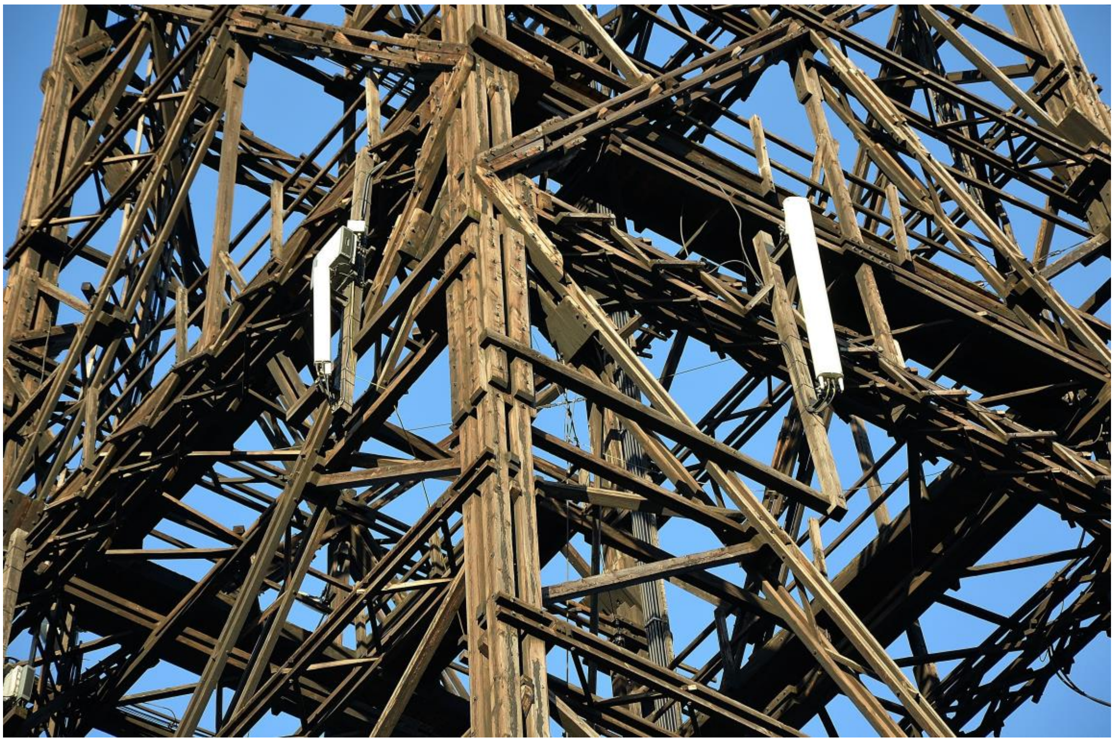


Figure 2.5 The truss structure of the Gliwice radio tower up close (Grycuk, 2012). CC BY-SA 3.0 PL.

Both of the above radio masts have very similar structures. In both cases the vertical loads are due to the dead load of the structure along with the radio equipment. How those loads are carried, via compression, down the ground is easily understood. However, for such structures wind load becomes important. Wind, or horizontal load, makes the mast function as a cantilever from the ground and causes tension along one side of the mast and compression along the other. As the wind can blow from any direction, all sides of the mast must be designed to withstand both the vertical load and the effect of the wind from any direction. The structural elements in themselves therefore must be sized for both the worst compressive and tensile forces, but perhaps more importantly, the connections between the elements has to withstand both forces. The solution to this problem can be read in the double members and overlapping joints (Figure 2.5). When it comes to the overall shape of the structure, it is interesting to note that it is not of equal width from bottom to top, nor does the width decrease linearly. The shape of the structure is related to the load it is subjected to. An equal width of the structure from bottom to top or one that decreases causes different dead loads and axial stress in the members (Figure 2.6). The structures response to horizontal load gives an explanation to why the towers are shapes as they are. Wind load, which is the primary horizontal load, creates a moment that is increasing at the bottom of the tower. By giving the structure a silhouette that resembles this moment diagram, it becomes better suited to withstand this load. Regarding torsion, the four trusses that make up the sides of the towers together creates a closed cross section. Hence, torsion will be effectively resisted according to St Venant theory as the stresses can find paths to travel around the structure and spiral down to the foundation.

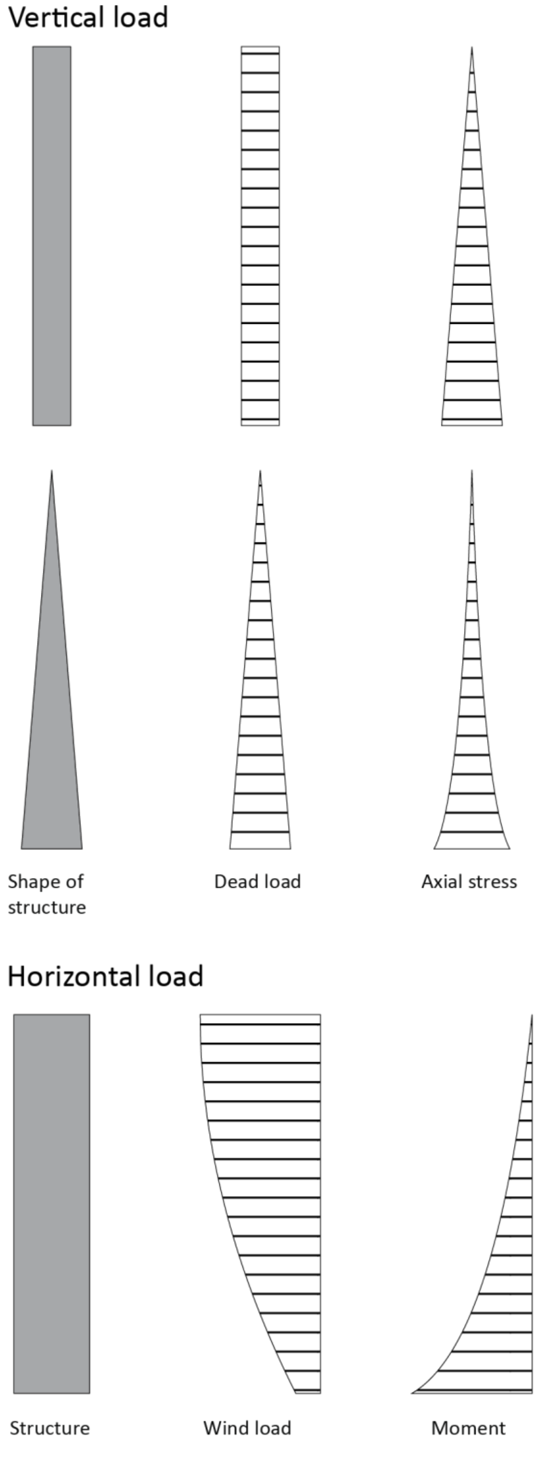


Figure 2.6 Behavior of structures under vertical and horizontal load to explain the design of the truss radio masts. Author's own copyright.

Figure 2.7 Observation tower at Ermitage Saint-Antoine by Christian Côté (Ermitage Saint-Antoine, n.d.) Printed with permission.

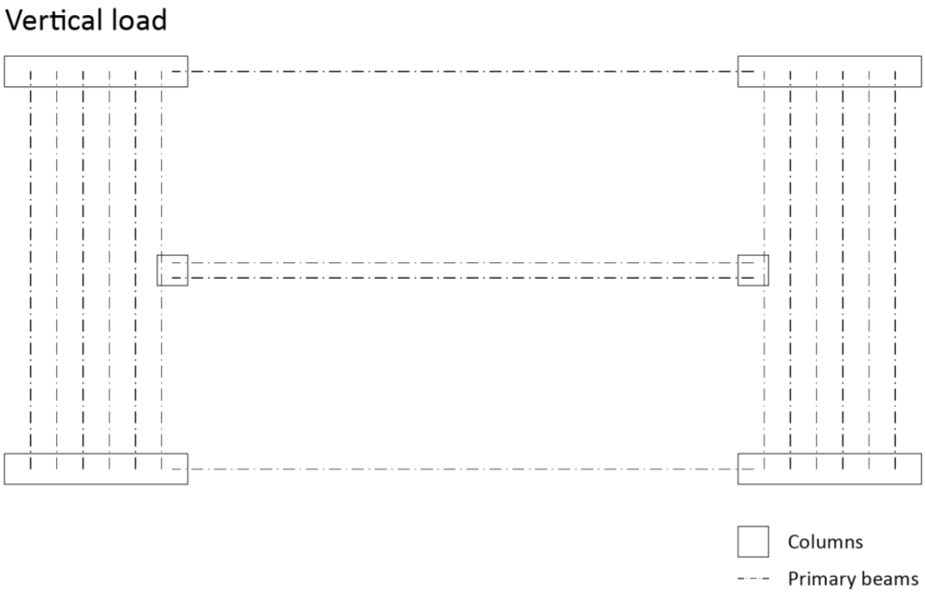


Figure 2.8 Plan view of the structure that transfers vertical loads. Author's own copyright.

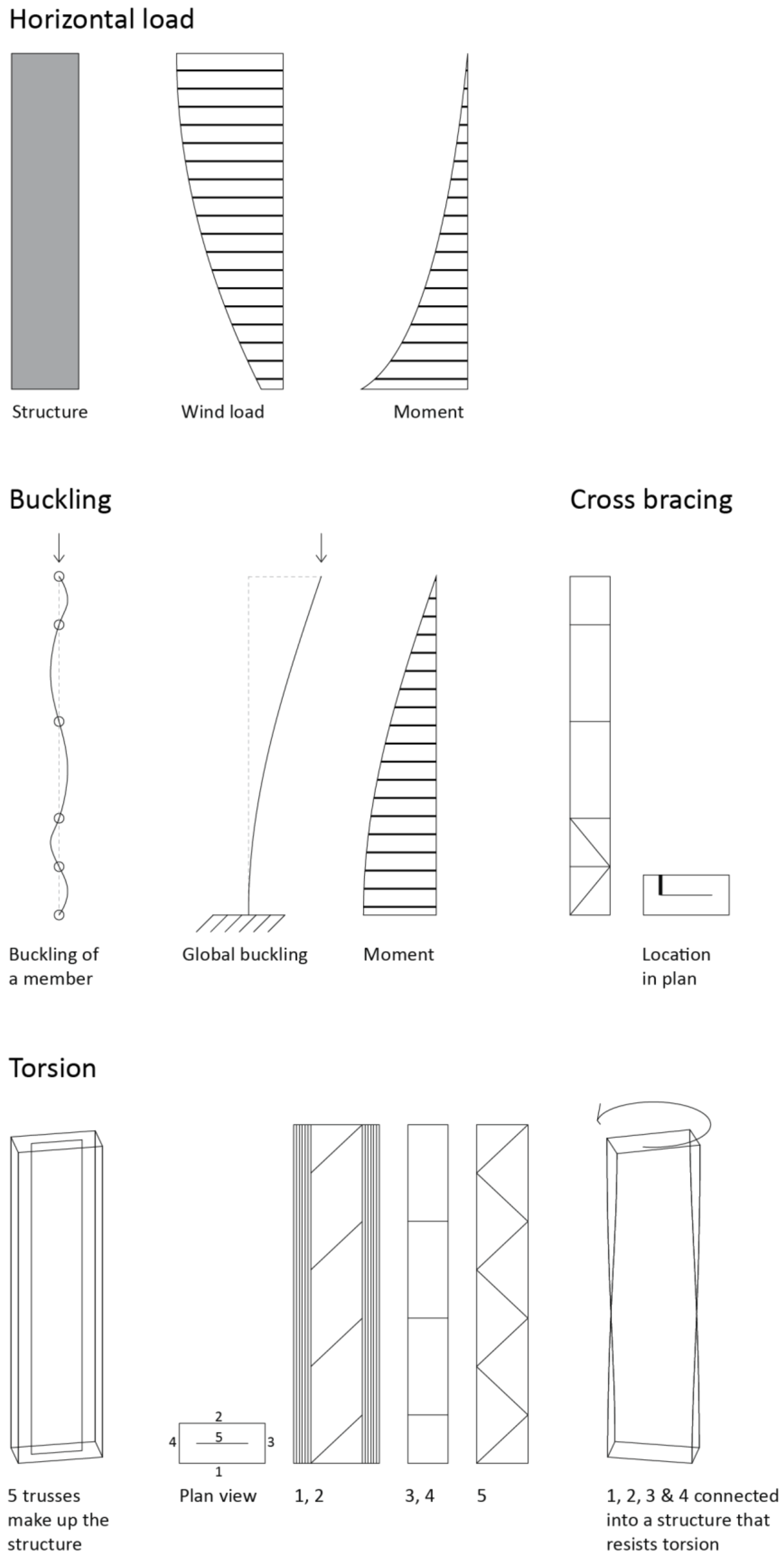


Figure 2.9 Horizontal loads, buckling and torsion. Author's own copyright.

Another example of a truss tower, which differs greatly from the radio masts, is the observation tower at Ermitage Saint-Antoine in Québec, Canada from 2009 by architect Christian Côté (Figure 2.7). This tower is 23.7 m high. Its main load bearing structure is the four columns in each corner, each of which consists of 7 glulam elements (Nordic Structures, n.d.).

The vertical load is transferred via the beams in the flights of stairs and the landings down into the columns in the corners and between the flights of stairs (Figure 2.8). To resist horizontal load all four sides of the tower functions as Vierendeel trusses, which is like a truss but where all joints are rigid and transfer moments in (Figure 2.9). If the wind is hitting the wider side of the tower, it is resisted by the gable side trusses and the other way around. Between the flights of stairs, the two columns along with the railings make up an ordinary truss beam, which also contributed to horizontal stability. The Vierendeel trusses are all connected into a rectangular structure that functions as a closed cross section resisting torsion according to the principle of St Venant.

When subjected to excessive vertical load, individual members as well as the structure as a whole may buckle. This behavior renders horizontal forces that are similar to horizontal load, and which is hence resisted in the same way. This structure has a uniform width, though the moments due to buckling load as well as horizontal loads creates greater moments at the bottom of the tower. It can be seen in photos from the tower that to better resist these moments, cross bracing has been added at the bottom of the tower (Figure 2.9) (Groleau, n.d.).

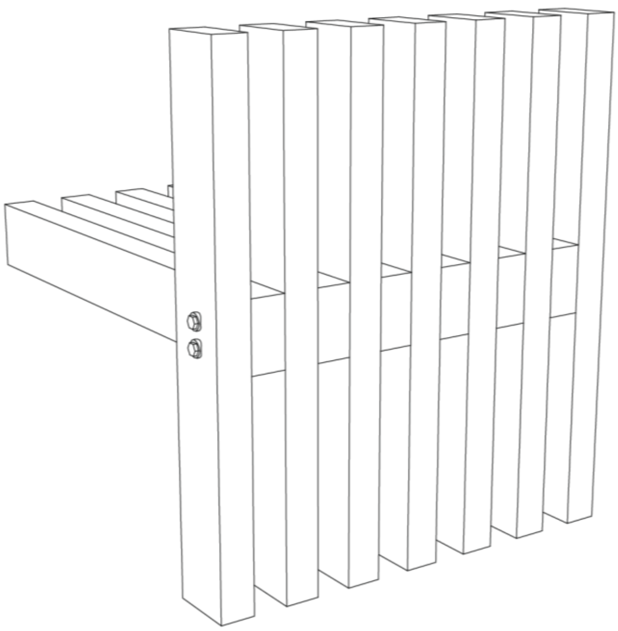


Figure 2.10 Two bolts ensures moment transferring joints. Author's own copyright.

The Vierendeel truss requires moment transferring joints. These joints are obtained by the utilization of two bolts to connect the elements that are the web members in the Vierendeel truss as well as the beams that carry landings/stairs with the columns that are the flanges of the truss (Figure 2.10) (Groleau, n.d.).

A more recent example which exhibits another type of timber truss structure is the Sky Walk in the Czech Republic by Fránek Architects, which opened in 2015 (Figure 2.11). This structure consists of six triangular timber steel hybrid trusses. Three of the trusses function as columns and are connected with the other three that function as beams. Onto this frame, the walkway is built. The walkway consists of a triangular steel truss, on top of which the wooden walkway is attached. The inclination is such that it enables wheelchairs to go up. To handle wind loads, the structure is anchored to the ground with concrete foundations. Cross bracing and thin cables increases the rigidity of the structure as well (Howarth, 2015).

Figure 2.11 The Sky Walk observation tower by Fránek Architects (BoysPlayNice, 2015). Reprinted with permission.

This tower has the vertical trusses that have exactly the shape which was described as the simplest one, i.e. a triangular cross section of uniform size. However, these trusses are just parts of the structural system. Globally, the structure functions like three vertical columns connected by three diagonal beams that together make up a frame structure where each of the six included elements locally functions as trusses. This frame structure then functions as a supporting structure that allows for the winding and irregular walk path to exist.

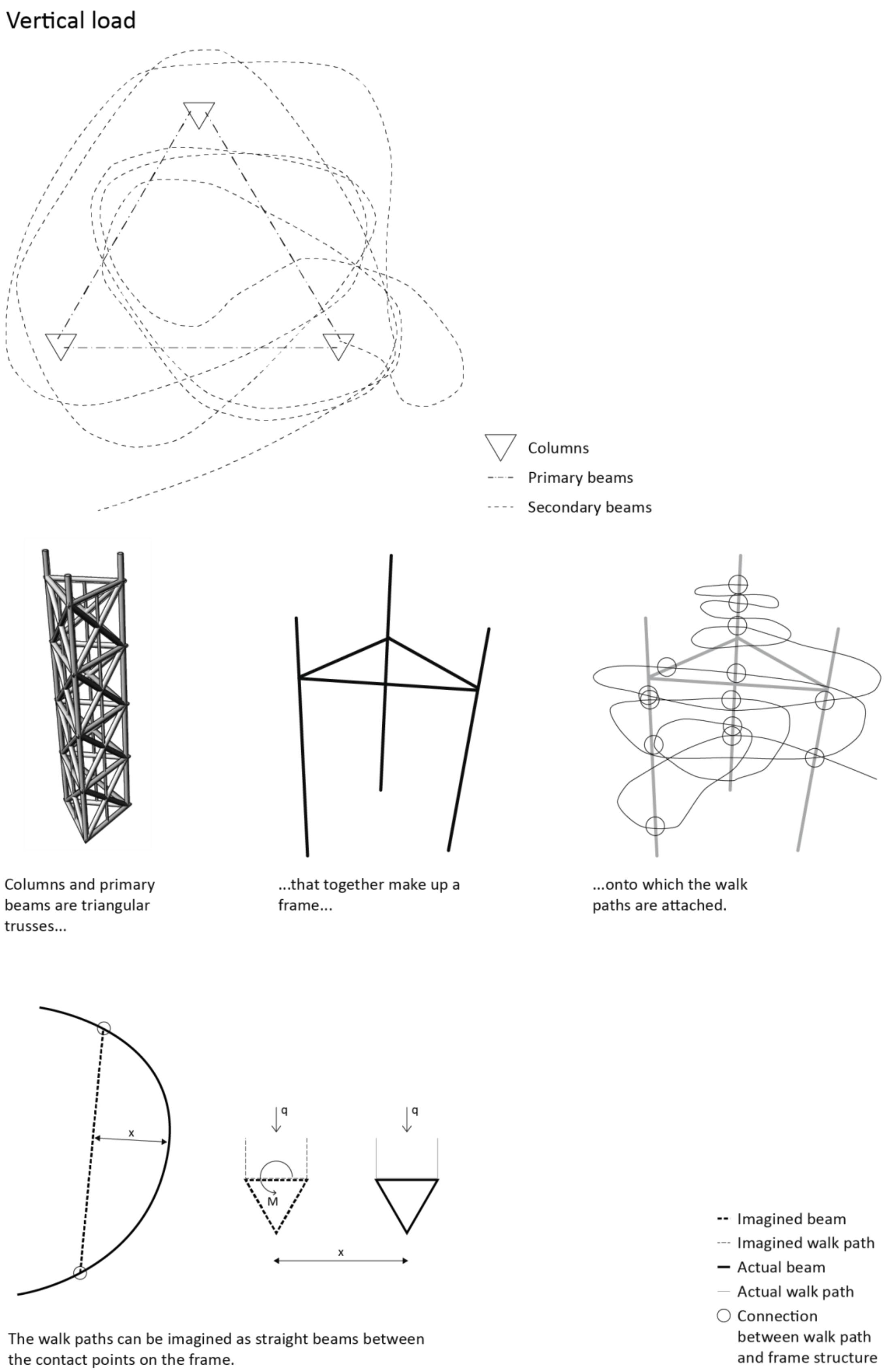


Figure 2.12 Concept for how vertical load is carried. Author's own copyright.

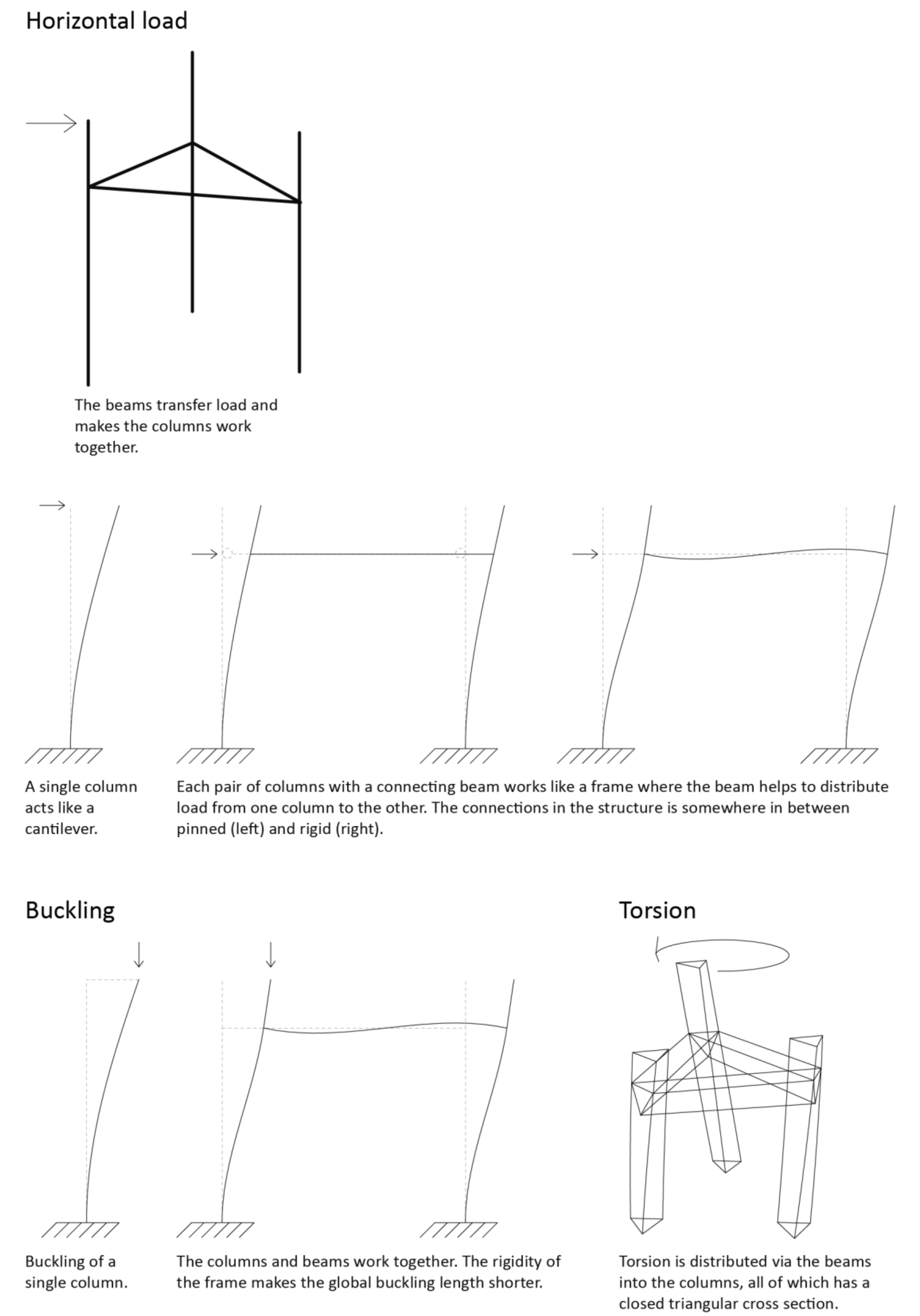


Figure 2.13 Horizontal loads, buckling and torsion. Author's own copyright.

When vertical load is applied onto the walk paths, it is transferred either directly, or via bending in the beams, into the columns and down (Figure 2.12). The truss under the walkway carries load from one connection point with the frame structure to the next. It could be imagined as a straight element between these connection points, onto which a vertical load, equal to that applied to the actual path, is applied. In addition to this vertical load, the imagined straight path is also subjected to a moment, equal to the vertical load times the distance between imagined and actual path. The triangular truss structure under the walkway then functions as a closed cross section, transferring the torsion due to the moment according to the St Venant principle.

To resist horizontal load and torsion, the six elements within the frame work together (Figure 2.13). The beams help to distribute load between the columns. The connections between the columns and beams has some rigidity and hence a certain ability to resist moment, which help to shorten the global buckling length of the system.

2.1.2 Double curvature towers

Gridshells are a way of creating structures that gain stability not just from bending and the shape of an arch, but from double curvature. A gridshell can be compared to other shell structures, such as domes, which can carry load due to the stiffness provided by the three-dimensional form of the structure. The gridshell is basically a shell where unnecessary material has been removed and the stresses have been concentrated to the remaining strips that make up the lattice of the gridshell. Apart from these structural properties, gridshells are interesting because of the way they are constructed. A gridshell is assembled flat on the ground and is then pushed and pulled to deform this lattice into the final structure without adding any additional structural members (Paoli, 2007).

The Korkeasaari Lookout Tower at the Helsinki Zoo in Helsinki, Finland (Figure 2.14), is an observation tower with a load bearing gridshell structure. The tower was designed by architect Ville Hara and the HUT Wood Studio at the Helsinki University of Technology and built by a group of 8 architecture students from the university in 2002. It is 10 m high and consists of 60x60 mm wooden battens, pre-bent in seven different ways and further adjusted on site to create this structure. The 72 long battens are connected through more than 600 bolted joints (arcspace.com, 2004).

Gridshell towers are uncommon. Gridshells are perhaps most common as single story structures. However, the Finnish tower above is an exception. That tower is only 10 m tall. Building higher in a similar fashion is possible. Since the structure is open, the wind will blow straight through leaving essentially only vertical loads to be carried by the structure. However, as the building is made taller it would resemble less and less a gridshell, both in its shape and the way of construction, since laying it out flat on the ground probably wouldn't be an adequate method. Instead of being a shell, it would be more of a tube with a truss structure.

The shell carries all vertical loads. This may explain why the curvature is small in the two bottom sections, below the platforms, and much larger in the top part. The two lower sections carry most of the vertical load and as an initial curvature causes a bigger curvature when axial loading is applied, making these segments almost straight increases their capacity and makes the slender elements possible. At the top however, the vertical loading is just the dead load of the shell, and hence a larger curvature is possible. At the top of the tower, the structure can also function as arches, which isn't really the case for the lower parts of the structure. Furthermore, the two platforms functions like tensile rings that pulls the shell together, when vertical load causes the members to bend out.

Figure 2.14 Observation tower at the Helsinki Zoo by HUT Wood Studio/Ville Hara (TTKK, 2011). CC BY-SA 3.0.

Regarding horizontal load, it is transferred down to the foundation via the grid, where some members will be compressed and some tensioned, much like in the following examples of hyperbolic structures. Torsion is resisted according to the St Venant principle, where the grid makes the whole structure function like a tube, i.e. a closed cross section.

Another example of double curvature structures is the hyperbolic structure (Figure 2.15). Vladimir Shukov (1853-1939), a Russian engineer, is considered the first one to work with such structures. A clear benefit of the lattice hyperbolic structure compared to other curved structures is that the elements of the lattice are straight (Calvert, 2007). The towers created by Shukov became very popular for several reasons. They were highly efficient light weight steel structures and in addition to this, they were also easy to build. This type of tower structures was significantly cheaper to build than others. They were also aesthetically pleasing and could be built either as one hyperboloid or as a number of hyperboloids stacked on top of each other. (Beckh, 2015).

The hyperbolic structure is created by rotating an inclined line around a vertical axis. The hyperbolic structure that Shukov created consists of a lattice of two sets of these lines, tilted and running in opposite directions. Though Shukov worked with steel, the geometry and mathematics behind the system is independent of material and hence are the same for timber. In fact, when he applied for a patent for this type of structure in 1896 he wrote "A lattice-form tower characterized in that its load-bearing structure consists of straight wooden beams, iron tubes or angle profiles which cross over one another and lie on the directrix of a solid of revolution and that takes the form of a tower" (Beckh, 2015).

Figure 2.15 37 m high hyperbolic structure by Vladimir Shukhov (Karelin, 1896).

Figure 2.16 The tower in Holmers-Halkenbroek, The Netherlands by Tentech (Vries, 2004a). Printed with permission.

An example of a hyperboloid timber observation tower is the 15 m high tower by Tentech (Figure 2.16). It is located in the nature reserve Holmers-Halkenbroek in the province Drenthe, The Netherlands (Vries & Gard, 2006). This tower was built in 2004, as a result of a research project on the strength of round wood and focusing on small diameter Larch and connections for such elements (TU Delft, n.d.). The load bearing structure in the tower consists of two parts. There is a system of columns connected to the floors of the platforms, which only carries vertical load. The other system is the hyperboloid shaped structure on the outside of the tower, which carries all horizontal loads, its own dead load as well as some of the vertical load from the top platform. The diameters of the beams could, with this structural system, be kept small; 140 mm at the bottom section and 120 mm in the rest of the tower (Vries & Gard, 2006).

The meetings of the slanted elements that make up a hyperboloid means that there will be a certain eccentricity in the nodes. Aside from two members leaning in opposite directions there is also the ring and, in this case, sometimes a vertical member too meeting in the node. This means that three or four elements that in a perfect theoretical model meet in one point are placed as layers outside of each other. This eccentricity of course has to be taken into account in the structural analysis of the structure, but it also has to be considered and solved practically in the joinery.

Figure 2.17 Node in the Holmers-Halkenbroek tower (Vires, 2004b). Printed with permission.

In this case, the members are not continuous over the nodes. Instead, they consist of shorter elements that are joined together in the nodes (Figure 2.17). A threaded steel rod was inserted into each end of the round wood members. The rod was anchored in a steel block that goes straight through the cross section of the member. That is the steel rectangle that can be seen in each member a couple of decimeters away from the actual joint. The ends of the members are covered by a steel plate that is used to lock the rod after a certain prestress has been applied to it. That way the rod inside the wood is prestressed and the rod continues out through the plate and is inserted into a hole in what the designers call a chaining block and locked on the inside of it with special locking disks. The chaining blocks are 120 mm long pieces of SHS 120x120x10 profiles where holes and incisions have been made so that the rods can be attached. The members of one layer of the construction, e.g. the slanted members in one direction, are attached to one chaining block and the chaining blocks of each layer is attached to that of the next layer. This makes up a patented jointing technique where each member can always be taken out and replaced if necessary. It is also a system that is suitable for joints where loading shifts between tension and compression and can hence be used for trusses among other structures (Vries & Gard, 2006).

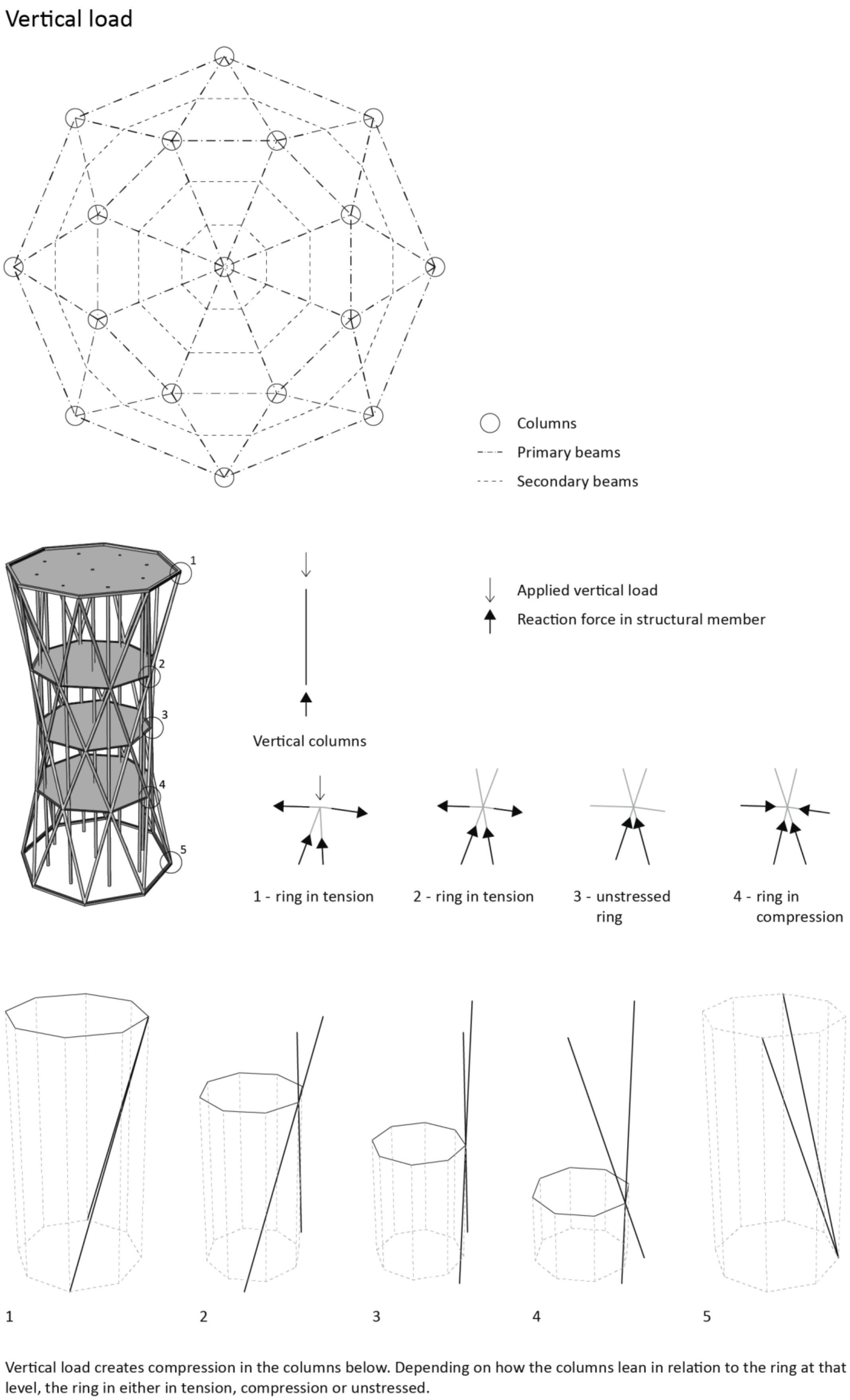


Figure 2.18 Concept for how vertical load is carried. Author's own copyright.

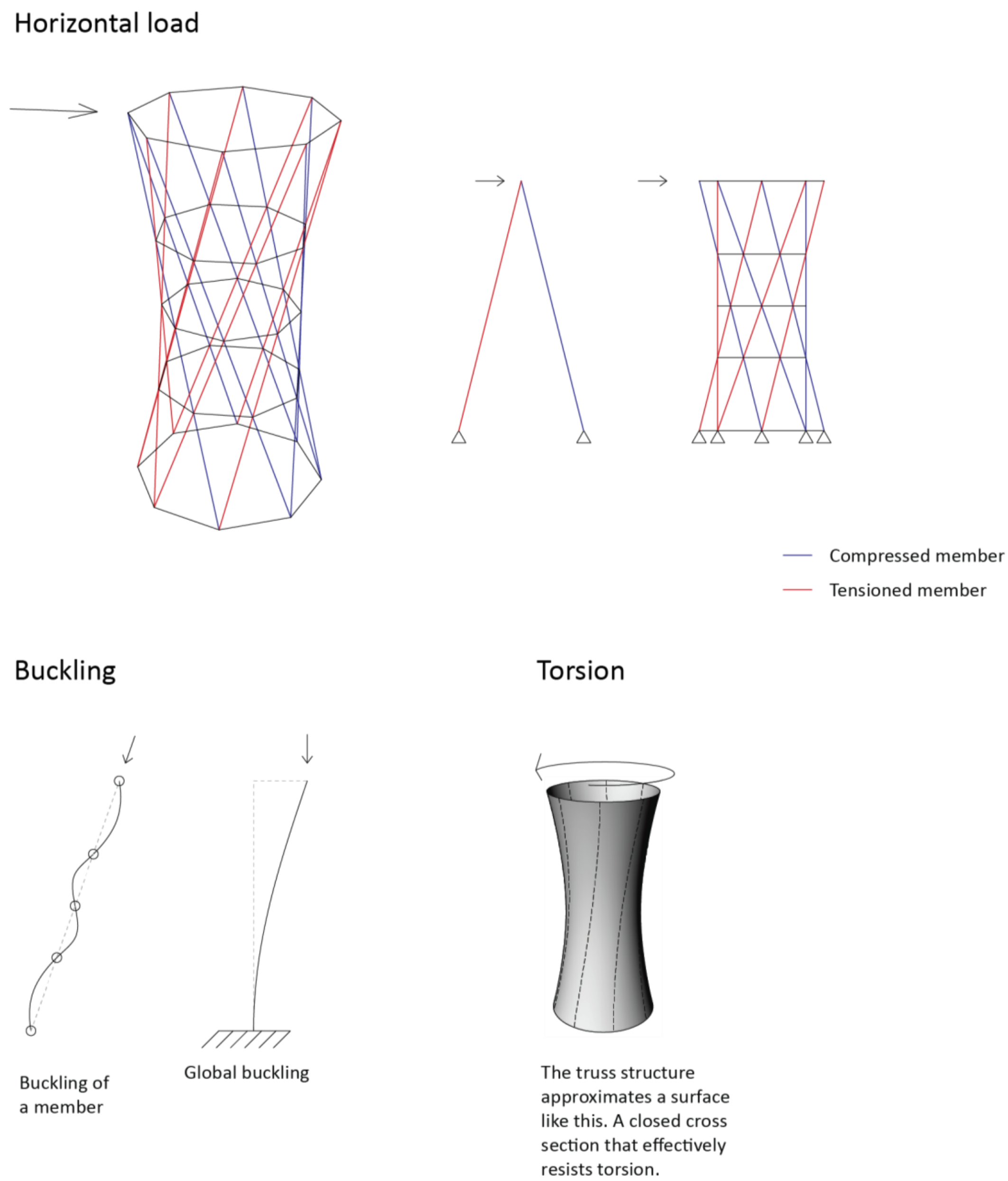


Figure 2.19 Horizontal load, buckling and torsion. Author's own copyright.

As previously mentioned, vertical load is carried by the vertical columns as well as the slanted columns. When vertical load is applied at a platform in the tower, the load is transferred via bending of secondary beams into the primary beams and further into the columns (Figure 2.18). Load in the vertical columns simply goes straight down. In the slanted columns, the load also causes stresses in the ring at the level where the load is applied. For example, the slanted members are leaning out in relation to the ring at the top level, which causes tension in that ring. This happens to all rings above the waist of a hyperbolic structure. At the waist level, the slanted columns aren't leaning at all in relation to the ring, leaving the ring unstressed. Below the waist, slanted members lean in towards the ring, making it compressed. At the bottom of a hyperbolic structure, there are no longer any members below the structure, and hence the ring at this level cannot be subjected to any stresses due to vertical load at this level. A vertical load at any level only causes stresses in the ring at that level and not in any of the rings below, unless the load causes individual members to buckle.

Horizontal load, buckling and torsion are resisted by the hyperbolic structure, without any help from the vertical columns (Figure 2.19). When subjected to a horizontal load, the slanted members work in pairs, where the member leaning towards the load becomes compressed and the one leaning in the direction of the load becomes tensioned. Just like with vertical load, horizontal loads affect the members below the level at which it is applied. The platforms at each level are triangulated by the primary beams. This makes the platforms function as plates to distribute the horizontal load between the couples of slanted members.

If the vertical load is large enough to cause an individual member to buckle, this will cause deformations that give raise to horizontal forces, which in turn will be resisted at the levels where they occur. Similarly, if a vertical force causes buckling of the global system, it can be compared to applying a horizontal load at the top of the structure. When subjected to torsion, the truss system of the structure functions as a closed cross section, resisting torsion according to the principle of St Venant.

Figure 2.20 Jüburg Hemer landmark by Birk Heilmeyer und Frenzel Architekten and Knippers Helbig Advanced Engineering (Asio otus, 2010). CC BY-SA 3.0.

Another example of a hyperbolic timber structure is the Jüburg Hemer Landmark in Germany by Birk Heilmeyer und Frenzel Architekten and Knippers Helbig Advanced Engineering (Figure 2.20). Built in 2010, this tower measures 23.5 m in height. It consists of 240 straight glulam members of Siberian larch with an 80 x 80 mm cross section. The lattice consists of two layers of timber members where only the outer layer is load bearing. There are no steel columns or central mast or any other additional vertical load bearing members in the structure. The tower is anchored 6 m deep into the bedrock in order to resist wind loads. The structure is also stiffest at the bottom and less and less stiff further up in the tower, in accordance with what is required to handle the loads the structure is subjected to. The decreasing stiffness is obtained by going from units of six timber members at the bottom to only two at the top. In addition to this decreasing number of timber members, the diameter of the tower is also increasing from 6 m at the bottom to 9 m at the top, making the possibilities for views out from the tower better and better further up in the tower (ArchDaily, 2010).

Figure 2.21 The Strand East Tower by ARC-ML architects and eHRW engineers (Wood Beton, 2012a). Reprinted with permission.

Yet another example of a hyperbolic timber structure is the Strand East Tower in London, UK, designed by ARC-ML architects and eHRW engineers, which was built in 2012 (Figure 2.21). This self-supporting structure is 40 m high, of which the first 3.5 m are made of steel and the rest is wood. The lattice is 16 cm thick and consists of larch glulam. The two layers of the lattice are rotating in different directions, with a total twist of 80°. Along the height of the tower are 16 horizontal galvanized steel rings, which stabilize the wooden laths along their length and makes sure that the laths are twisted in the appropriate way. The self-supporting shape along with the fact that the tower only functions as a sculpture has made it possible to leave the inside empty so that the structure is transparent (Figure 2.22). The tower was prefabricated in four sections; one of steel and three of timber. The idea is that the tower should be possible to disassemble and re-erect in a different place, but also possible to disassemble into its structural components to be used for something else (Lorusso, 2012).

Figure 2.22 The inside of the Strand East Tower from below (Wood Beton, 2012b). Reprinted with permission.

The hyperbolic structure may be better suited for towers than gridshells are. A strong argument for this is the fact that Shukov originally developed this structural system to build towers and that it became very popular for its material efficiency, among other things. Gridshells on the other hand are meant to carry load in the arches of the dome like double curved surfaces, which requires a certain width to function. The examples of timber hyperbolic towers above show that the structural system is still viable today and that it exhibits ample architectural qualities.

The gridshells and hyperboloids are both structures that are dependent on their geometry to be stable. When shaped in the correct way, they are both geometrically stable. The geometry of these are both double curved. A big difference between the two is that the arches of the gridshell usually start and end on ground level, while the hyperboloid on the other hand can be seen as arches that start and end with a connecting ring and allows for the structure to be placed vertically. Furthermore, the elements of the hyperboloid are straight, which isn't possible in a gridshell.

2.1.3 Plane frame and space frame towers

Among the lattice structures are also the plane frames. These, as well as their three-dimensional equivalent, the continuous space frames, makes it possible to create truss like structures of relatively free form.

The Bird Observation Tower on Graswarder, Germany by von Gerkan, Marg and Partners (gmp) was built in 2005 (Figure 2.23). The tower is 15 m high and created to enable ornithologists as well as other tourists to be able to observe birds in the area without disturbing them. The architects describe the structure as 'a sculpture made of beams and ledgers with diagonal bracing'. It is supposed to resemble a sitting bird and is made of Siberian larch that blend well into the surroundings (gmp, n.d.).

Figure 2.23 Bird Observation Tower on Graswarder by gmp (Leiska, n.d.a). Reprinted with permission.

The structure could be said to consist of two plane frames, connected by stairs, viewing platforms and bracing members into a three dimensional space frame structure. The members of the plane frames are continuous and connected by a single bolt in each node (Figure 2.24), creating a lattice in a similar way as in a gridshell. The way load is carried differs from the gridshell. In this structure, the load carrying system is more resembling an ordinary truss. Vertical loads are primarily carried by the vertical elements of the structure, while horizontal load renders some elements in compression and others in tension. The tower utilizes the possibilities rendered by the structural system to create a structure that cantilevers out in two directions, just like the tail and body on a sitting bird.

Figure 2.24 The members of the lattice are all continuous (Leiska, n.d.b). Reprinted with permission.

2.2 Post and beam towers

These structural systems consist primarily of vertical posts and horizontal beams. As fully rigid joints are very difficult to obtain, especially in timber structures, the common way of accounting for lateral loadings such as wind is by complementing the beam and post structures with some diagonal bracing members.

The tower Vidablick (Swedish, means *wide view*) in Rättvik, Sweden, opened in the summer of 1898 (Figure 2.25). The 28 m tall tower was designed by Olof Klockors. It is a timber structure with an internal spiral staircase. At the top are three viewing platforms above each other. Another viewing platform, which is weather protected, is found at the middle of the tower (Wikipedia, n.d.b). Looking at the tower it can be seen that it is stabilized by wires stretching from the top of the tower to the ground some meters away from the base. It can be assumed that these wires are a later addition to ensure safety in and around the tower.

Figure 2.25 The Vidablick observation tower in Rättvik by Olof Klockors (Ellgaard, 2015). CC BY-SA 4.0.

Another Swedish observation tower is the Mejdåsen tower from the 1940's (Figure 2.26). This tower is 22 meters tall and located in Björbo (Enmalm, n.d.). Just like in the case of the Vidablick tower, there are wires to stabilize the tower. The same assumption can be made here, i.e. that they have been added later for safety purposes.

Looking at these examples of older towers, from the 19th century and the first half of the 20th century, they are both built in a way that reminds a lot of traditional platform frame structures used for ordinary houses with story high vertical studs, battens and diagonal bracing members (Figure 2.27). These towers are both over 20 m tall and, considering when they were built, it is fair to assume that they were built primarily by hand, without the aid of cranes and such at the construction site. However, the stabilizing wires should also be noted. Though the towers were probably built without them, they are necessary today. This necessity could have two underlying reasons; either they are necessary for the tower to remain standing or they are necessary for the tower to be considered safe enough for visitors according to the rules and regulations of today.

Figure 2.26 The Mejdåsen observation tower (Ellgaard, 2014a). CC BY-SA 4.0.

Figure 2.27 Interior of the Mejdåsen observation tower (Ellgaard, 2014b). CC BY-SA 4.0.

Both of these old Swedish observations towers can be compared to regular platform houses, just in more stories than regular houses. The structures of the towers carry vertical load much like the structure of the Saint-Antoine tower (Figure 2.8), i.e. it is transferred via bending in beams into the posts. Horizontal loads are resisted with the aid of the diagonal members. How torsion is resisted depends on the connections between the different sides of the towers, they may not function as a closed cross section and hence Vlasov torsion may be prominent. The cables that can be seen around both towers are most likely modern additions to ensure the safety of the visitors today, hence they are not included in the original idea of the structural concept, but they help keep the vertical members in compression even when the structures are subjected to horizontal loads.

A significantly newer example of a post and beam structure is the Seljord watch tower in Seljord, Telemark, Norway by Rintala Eggertsson Architects (Figure 2.28). This tower is 12 m tall and was built in 2011 (McGuickin, 2014). The tower is built using glulam. It is only about half as high as the old Swedish towers presented above. Looking at the inside of that tower (Figure 2.29), it is seen how diagonal glulam members are bracing this structure. The tower has a sparse cladding. At night, when the lights are on inside, this makes the tower look like a lantern and the internal structure becomes visible from outside (Figure 2.30). Aside from being built from glulam, the structure is not much different from the old Swedish observation towers.

Figure 2.28 Seljord observation tower by Rintala Eggertsson Architects (gunnsteinlye, 2012). CC BY-NC-SA 2.0.

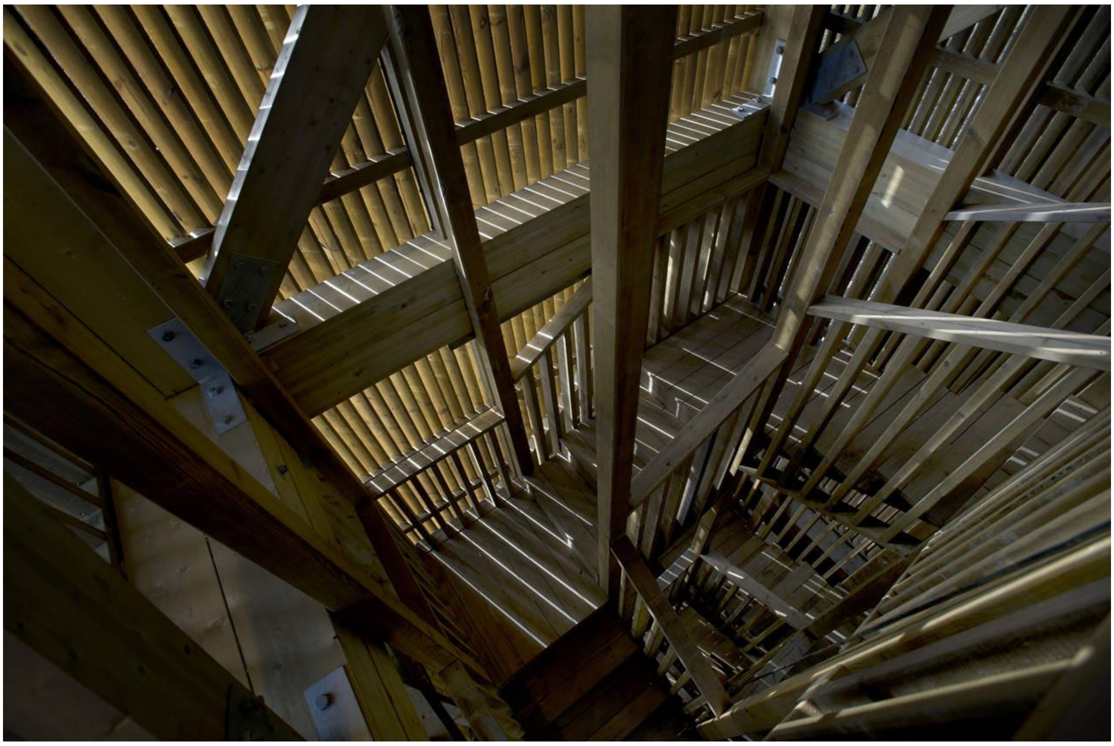


Figure 2.29 The interior of the Seljord observation tower (Jenssen, 2012a). Reprinted with permission.

Figure 2.30 The Seljord observation tower by night (Jenssen, 2012b). Reprinted with permission.

Another post and beam tower is the Pyramidenkogel tower in Austria from 2013 (Figure 2.31), which is built as a lighthouse project for the timber industry. It was designed by the architects Klaura, Kaden + Partners along with the structural engineers Lackner + Raml. The structure consists of 16 curved glulam columns connected by 10 steel ellipses, rotated in relation to each other and braced with 80 steel struts (Rubner Holzbau, n.d.). The tower is 100 m tall and is the world's tallest timber observation tower, including space for technical installations and an antenna for radio and other communication at the top (Wikipedia, n.d.c). The tower is anchored 20 m deep down in the bedrock below (Giraldeau, 2013).

Figure 2.31 Pyramidenkogel tower by Klaura, Kaden + Partners and Lackner + Raml. Author's own copyright.

In this tower, which is significantly higher than the other post and beam towers presented above, only the vertical columns are made of wood while the horizontal and diagonal members are made of steel. This leaves this tower looking wooden from a distance, but internally, the steel, which in addition to parts of the load bearing structure, is used for stairs, landings and a long slide, takes over in terms of visual impression (Figure 2.32). Architecturally, only letting the columns be made of wood makes their shape very defined and from the outside the vertical direction of the tower becomes prominent. However, when on the inside of the tower, the structure is not experienced primarily as a timber structure, making it feel a little hypocritical to call it a lighthouse project for the timber industry. Structurally, how the loads are carried is equivalent to the other towers presented in this section, though it is likely in this case that the structure functions like a closed cross section, i.e. that St Venant torsion is predominant.

Figure 2.32 Interior of the Pyramidenkogel tower. Author's own copyright.

2.3 Plate and slab towers

This category contains, among other types, plate structures. These structures are made up of plates that carry load in their plane and that are connected through continuous shear connections along their edges. Here are also stacked structures, consisting of logs or planks that are piled on top of each other, including ordinary log constructions (Swedish: timrade konstruktioner). Stave structures (Swedish: stavverk), consisting of logs that are standing side by side, is also a type of slab structure. So is post-and-plank (Swedish: skiftesverk). Regarding these last two types, no examples of towers have been found.

2.3.1 Stacked towers

Perhaps the most common stacked timber structure is the log house. Like the towers presented below in this section, they consist of massive elements that are stacked on top of each other to create walls. Log houses are commonly assembled for example by notching each member in such a way that it fits together with the members placed perpendicular to it. However, the definition of stacked only speaks about how the members are placed on top of each other. As can be seen in the examples below, the way of connecting them to each other may vary.

An example of a stacked tower is the Sauvabelin tower from 2003 in Lausanne, Switzerland by architects B. Bolli and R. Mohr, the City of Lausanne and structural engineers Natterer Bois Consult (Figure 2.33). It consists of 200 x 400 mm Douglas fir beams stacked as a double helix with a metal rod like a spine through the center of the beams to keep them together and with 24 supporting columns around. At the top of the tower is a viewing platform at over 30 m above ground. The total height of the tower is 36 m. The size of the tower differs from 12 meter in diameter at the ground level to 6 m at the level of the top platform (Natterer & Winter, 2004).

Figure 2.33 The Sauvabelin tower by architects Bolli and Mohr and structural enginner Natterer Bois Consult in Lausanne, Switzerland (Gzzz, 2013). CC BY-SA 3.0.

The only thing that really reminds of the ordinary log construction when it comes to this tower is the size and massiveness of the slabs used to create the double helix staircase. This structure functions as a pile of logs that cantilever out from a central point, over which all elements meet, and which is stable partly because each element cantilever equally much in both directions from this middle point, but primarily because the logs are connected by a metal rod through this central point and stabilized by the surrounding vertical posts. The way the loads are carried can perhaps be compared to a truss, where the double helix functions as bracing members between the vertical members around it.

Scholzberg Tower (Figure 2.34), in Lučany nad Nisou, Czech Republic is another example. It was built by a group of students in 2006. Martin Rajniš and Jan Mach at e-MRAK, the architects behind the tower, describes it as "vertical storage of the wood in the form of a tower", which quite well describes the structure. It consists of planks stacked on top of each other. There is an outer 3 x 3 m structure of stacked straight elements. In the middle is a double helix stair also consisting of stacked straight elements that are placed in between the outer ones so that the double helix sticks out through the square at the sides, but runs free of the corners. The structure is essentially assembled using just timber (Figure 2.35). However, the timber structure isn't stable in itself as the members aren't actually joined together and is therefore tied down with steel wires that are anchored in the ground about 7 meters away from the tower (e-MRAK, 2014).

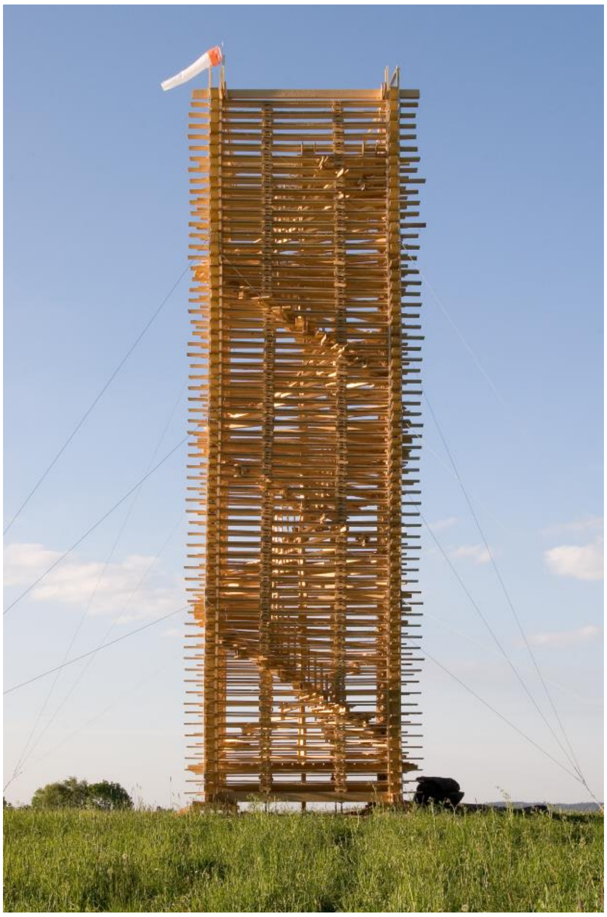


Figure 2.34 Scholzberg tower by e-MRAK architects (Ciglerova, 2006a). Reprinted with permission.

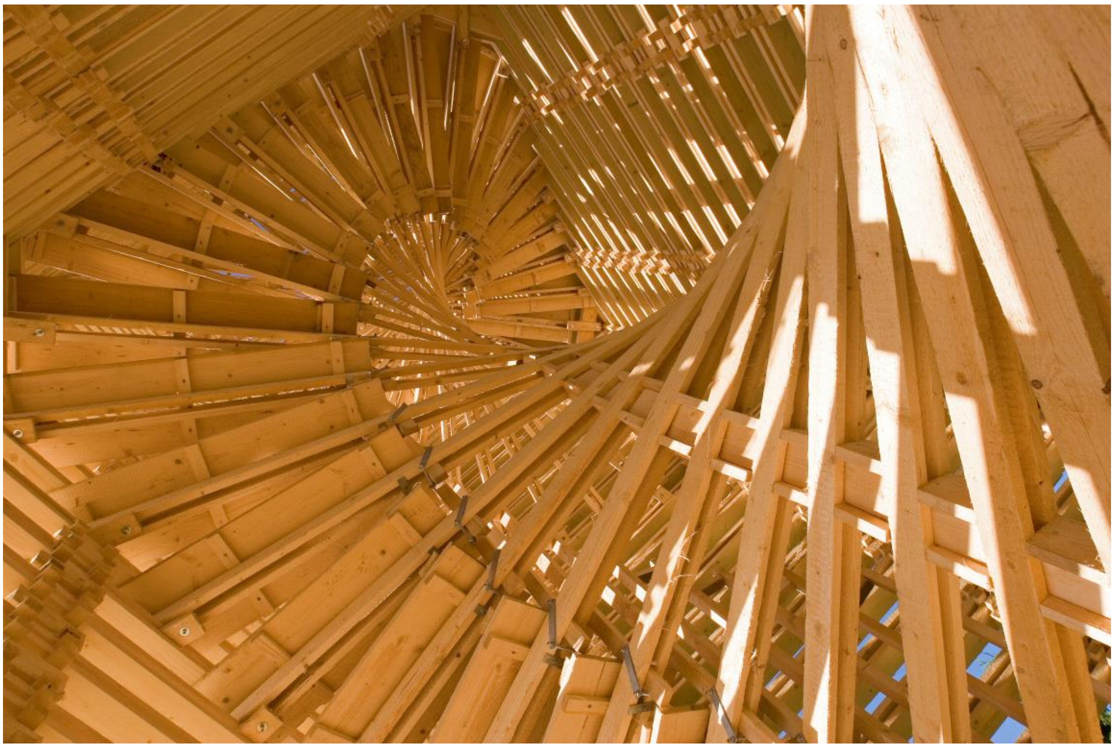


Figure 2.35 Inside view from the tower where it can be seen how the elements of the double helix are placed between the elements of the square structure (Ciglerova, 2006b). Reprinted with permission.

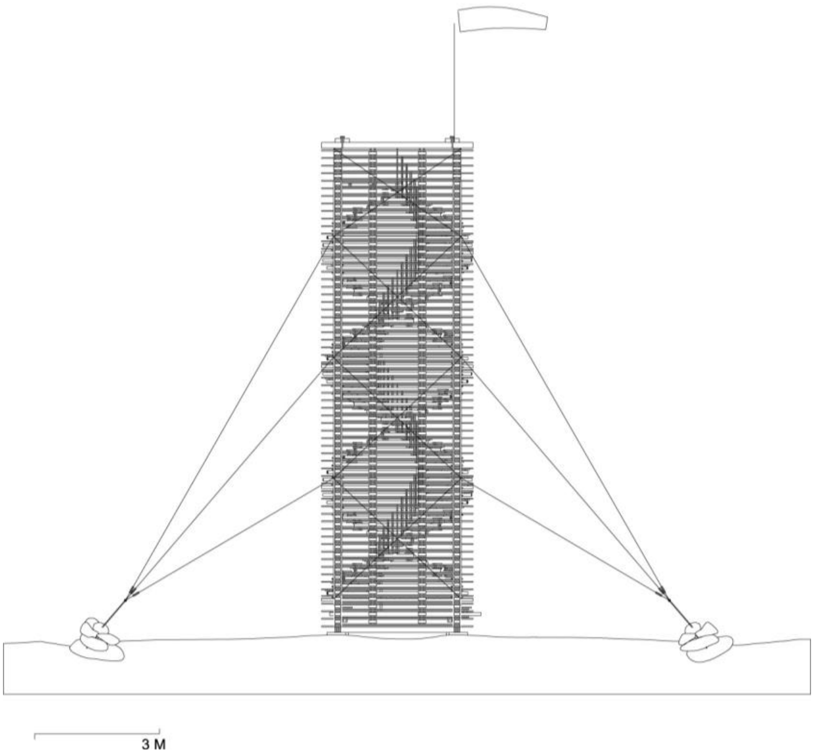


Figure 2.36 The Scholzberg tower is made stable with the help of cables, tying it down to the ground (e-MRAK, 2006). Reprinted with permission.

The Scholzberg tower is in some ways more a reminder of the log construction as it consists of planks that are stacked on top of each other in a system where every other plank is placed in a direction perpendicular to the ones before and after in a square shape. However, the apparent resemblance ends here, because this structure is not a pile of logs that are actually connected to each other through notching, but that are kept in place by vertical elements that prevents individual elements from slipping out of the pile as well as bracing wires that pulls the structure down towards the ground and hence keeps it together and stable.

Structurally, stacking beams on top of each other is a viable solution to transfer vertical load down, but as soon as loads start to act in other directions it requires the members to be anchored to each other in some way. According to the architects at e-MRAK who designed and built this tower, the construction method is very simple. All structural members are simply stacked on top of each other. That means that for the structure to withstand wind loads and loads from visitors that creates asymmetric loadings, the whole tower structure is instead kept in compression with the help of cables (Figure 2.36).

2.3.2 Plate towers

Plates are able to transfer in plane forces effectively. The elements are joined along the edges, preferably with connections that can transfer shear. In timber construction, the modern industrialized CLT element buildings are a clear example.

Plate structures are not common among timber towers, but there are some examples. TimberTower is a company that started its business in 2008 (TimberTower, n.d.a). Their product, the TimberTower, is a plate structure (Figure 2.37). It is not a specific tower, but a concept for a windmill which could be built anywhere. They produce towers that are 100 m high, not including the rotor blades, and with a diameter of 7 m at the bottom and 2.9 m at the top. They are also developing 140 m high towers with a base diameter of 11.3 meters (TimberTower, n.d.b). The towers consist of a prefabricated falsework, which contains stairs and installations, around which cross laminated timber (CLT) panels are placed. The CLT panels are placed in a corkscrew pattern, so that the top and bottom edge of adjacent panels don't align, and connected to each other using steel mesh plates (TimberTower, n.d.c).

Vertical load is transferred straight down in the plates. Horizontal loads, which occur both due to wind and due to the movement of the rotor blades, makes the whole structure function like a cantilever. It is therefore beneficial that the structure is wider at the base, where the moment becomes largest. Regarding torsion, the structure is a closed cross section. The corkscrew pattern in the placement of the plates further ensures that the tower doesn’t function as shorter tubes placed on top of each other, but a continuous closed cross section where St Venant torsion is predominant.

Figure 2.37 TimberTower (TimberTower GmbH, n.d.). Reprinted with permission.

Another example of a plate structure tower is the bell tower in Gastonia, North Carolina, USA, by MDS10 Architects, which was completed in 2010 (Figure 2.38) (WoodWorks, 2010a). CLT was first introduced in the United States in 2009 and the almost 24 m high bell tower was the first non-residential structure of CLT in the country. At that time, the material wasn't manufactured in the US, instead it was imported from Europe. It is the comparison with concrete that is emphasized regarding this structure. The CLT tower was quick to assemble, low weight and environmentally friendly. Despite its low weight, it is also stable and can withstand high wind loads. (WoodWorks, 2010b).

Vertical loads in the tower are carried in bending in the slabs out to the walls, where it is transferred down in compression. Horizontal load is resisted by shear forces between the slabs and the walls placed in the direction of the wind. Regarding torsion, depending on how the wall elements are connected to each other the structure may not function as a closed cross section. If these connections aren’t strong enough, Vlasov torsion will occur, in which case two parallel walls can be compared to the flanges of an I-beam (Figure 2.1).

When it comes to plate structures made of timber, multistory buildings consisting of larger CLT elements that are both assembled and carrying loads in a similar fashion as prefabricated concrete elements are becoming increasingly popular to build. The two examples of towers are not very different from this, i.e. vertical loads are carried mainly in the plane of the CLT element and sometimes, where there are floor slabs, through bending out to the vertical elements.

Figure 2.38 Bell tower in Gastonia, NC by MDS10 Architects (Coastal Clock & Chime Co, 2010). Reprinted with permission.

2.4 Arch towers

Arches is not the first type of structure that comes to mind when thinking of towers, but there is in fact some observation towers with arches as their load bearing structure. One example is the Vårdkasen start and observation tower on Vårdkasberget, Härnösand, Sweden by TM-Konsult, which opened in 2008 (Figure 2.39). The tower is accessible via an elevator that takes the visitor to all three stories of the tower (Härnösands kommun, n.d). The total height of the tower is 16 m (Svenskt trä, n.d.b).

Figure 2.39 Start and observation tower on Vårdkasberget by TM-Konsult (TM-Konsult, n.d.). Reprinted with permission.

In this tower, vertical load is carried by the arches and the elevator core. Horizontal force is resisted by the arches, similarly to how the pairs of members in the hyperbolic structure resists horizontal load (Figure 2.19). The slabs function as bracing against both buckling of the arches and to distribute horizontal load. The central core, which has a closed cross section, resists torsion according to the principle of St Venant. The stair leading up to the first floor may also contribute to rotational stiffness, by making the structure up to that floor stable, so that the core only has to brace the upper three quarters of the structure.

Another example is the tower in the Bavarian Forest National Park in Neuschoenau, Germany by Architekt Josef Stöger, which opened in September 2009 (Figure 2.40). It is 44 m tall, with a 550 meters long ramp with an inclination of up to 6% leading from the ground and up (Architekt Josef Stöger, n.d.). The ramp leads up to 40 m height, enabling both wheelchairs and strollers to come up here. The absolute top, at 44 m height, is reached by climbing stairs for the last 4 meters (Baumwipfelpfad Bayerischer Wald, n.d). The egg shaped tower is built around three big fir trees, so that as you go along the ramp up the tower you get to experience these trees and the life that goes on in them from angles and heights that are not normally accessible to humans (Twisted Sifter, 2012).

Figure 2.40 Observation tower in the Bavarian Forest National Park by Architekt Josef Stöger (High Contrast, 2010). CC BY 3.0 DE.

In this tower, the compression forces from the arches are resisted by a steel compression ring at the top. This allows for the creation of a viewing platform at the very top of the structure. In terms of lateral stabilization another approach has been chosen compared to the Swedish tower. The tower is braced by X-bracing and with horizontal members at the bottom and the spiraling walkways further up, all in steel, to resist wind load. The bracing members also prevent buckling of the arches and makes the structure function as a closed tube like cross section, similar to the trusses in the Sky Walk (Figure 2.12 and Figure 2.13), to resist torsion.

Though arches aren't common in tower structures, the two examples above show that it is possible to use them for towers both higher and lower than the case study project for this thesis. The arches in these towers are connected at the top either directly to each other in a central meeting point or by a compression ring. The outwards forces from the arches at their base also need to be anchored, either by connecting these ends of the arches by a tensile ring or, which is more likely to be the case here, by anchoring each arch to a concrete or rock foundation.

2.5 Other references

Besides towers, there are a few other projects that have been inspirational for this thesis. One of these is the Ribbon chapel in Japan by Hiroshi Nakamura & NAP Architects, which consists of two winding paths around a central wedding chapel (Figure 2.41). Its architecture is based on the idea of having two paths, one for the bride and one for the groom, that intertwine on the way to the top where the couple is joined, just like their lives are being intertwined. Structurally, the two spirals support each other due to the way they meet and can be physically connected along the way. By being connected to each other they are much more efficient in resisting horizontal loads and vertical vibration than if there had been just one spiral (ArchDaily, 2015). In the middle of the spirals is the actual chapel, which perimeter has a load bearing structure consisting of steel posts. The inner spiral is connected to these posts that carry the vertical loads, while the outer spiral is only connected to the inner one, through which its vertical loads are transferred (Cosma, n.d).

Another inspirational project is the METLA Forest Research Centre in Finland by SARC Architects. In the design of this building, a goal was to use the local timber products in innovative ways and wood is the primary construction material used in the project (ArchDaily, 2009). It is the columns in the vestibule that are interesting as a reference for this thesis. These columns are placed in groups of four, connected at the bottom and leaning out (Figure 2.42). Each column tilts outwards and connects at the top to a column from the neighboring group. The columns are made up of four parts that are bent in such a way that the column becomes thicker at the middle. The four parts are connected with steel plates. This method makes the middle part of the column less prone to buckle, while the spacing between the four parts of the column reduces the visual heaviness that a thicker column could otherwise provide, leaving the overall impression of a carefully detailed and slender structure.

These columns are a way to transfer load around the most logical load path (Figure 2.43). The most effective and logic way to transfer a vertical load is straight down in a column. Say that for some reason the straight column can’t be placed there, but a curved one can be used instead. When that column is subjected to a vertical load, it wants to bend out even further. In this example, the connections between this column member and the one opposite will then be subjected to a tensile force, which is resisted by the opposite member. This opposite member can then be compared to an arch subjected to three point loads.

Figure 2.41 The Ribbon Chapel by Hiroshi Nakamura & NAP Architects (Koji Fujii / Nacasa and Partners Inc., 2015). Reprinted with permission.

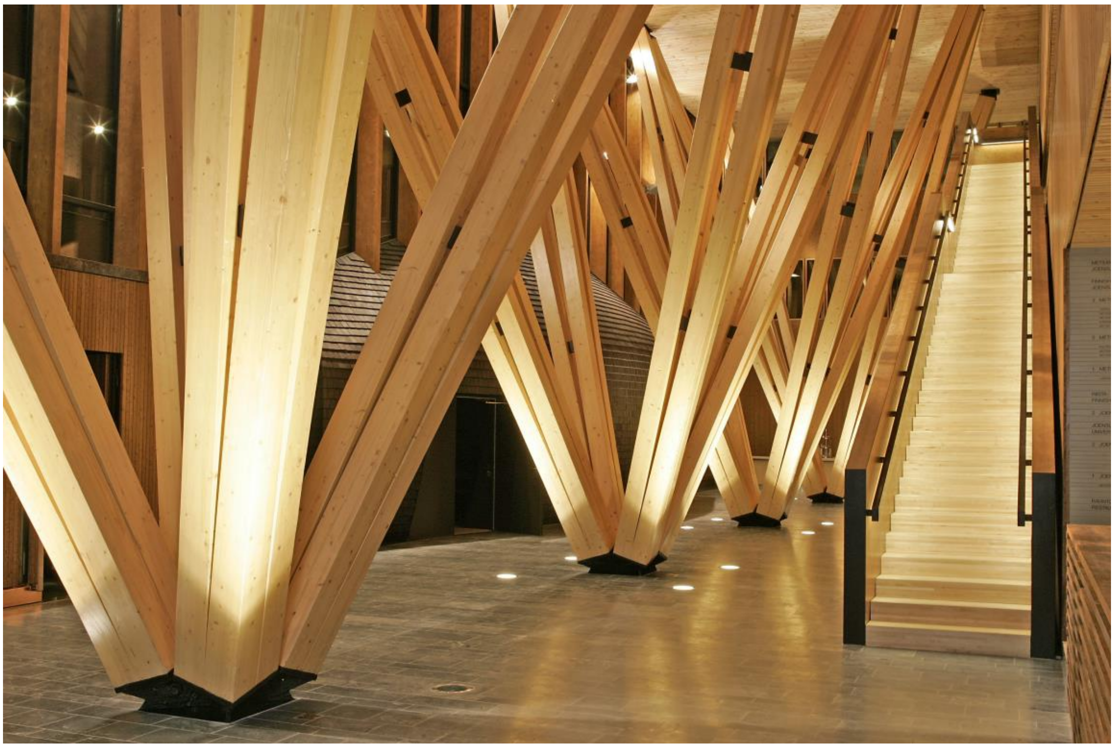


Figure 2.42 Glulam columns in the METLA Forest Research Centre by SARC Architects (Erkki Oksanen/Luke, n.d.). Reprinted with permission.

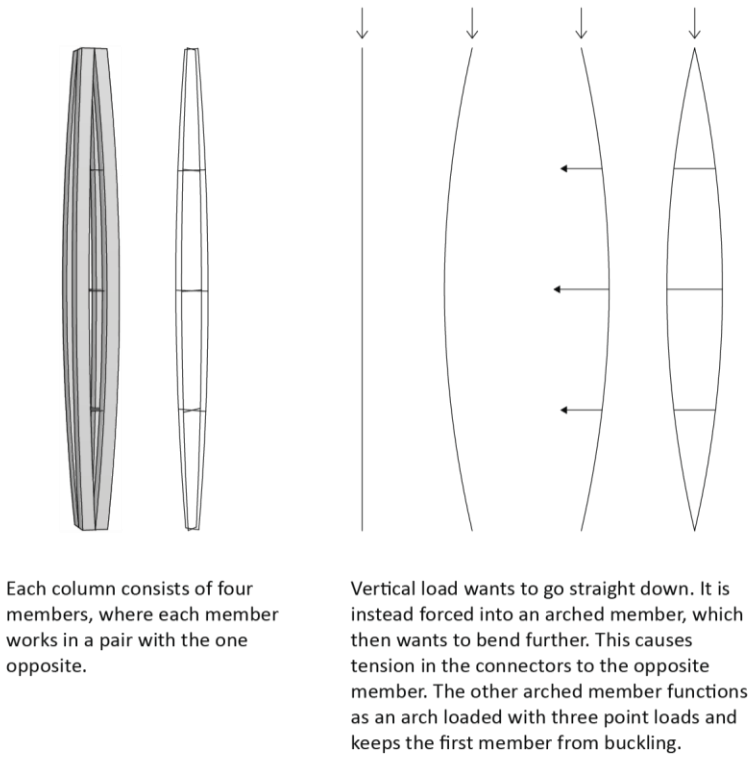


Figure 2.43 Alternative load paths in a column. Author's own copyright.

Figure 2.44 Cantilever bridge in Bhutan (Fynn, 2007). CC BY-SA 3.0.

A cantilever bridge in Bhutan is another source of inspiration (Figure 2.44). The bridge, which is symmetrical around its center point, can be seen as two cantilevers that meet at the middle. Each of these cantilevers consists of four cantilever beams on top of each other and that work together (Figure 2.45). One beam of this height could not carry the required length, but each beam can carry one part of the span. The idea is that one beam carries from where the beam below ends and out to the end of the beam itself. By connecting the beams, they are able to transfer the vertical load, i.e. the shear force, to the beam below. This means that there isn't any shear force in a beam when there is a beam below and that the moment remains constant for the part of the beam that is above the beam below. Essentially, looking from the bottom up, there is a short cantilever beam that can carry a certain length. Above that is a new beam, that can carry another length and so on until the structure reaches the middle of the bridge and meets the cantilever from the other side.

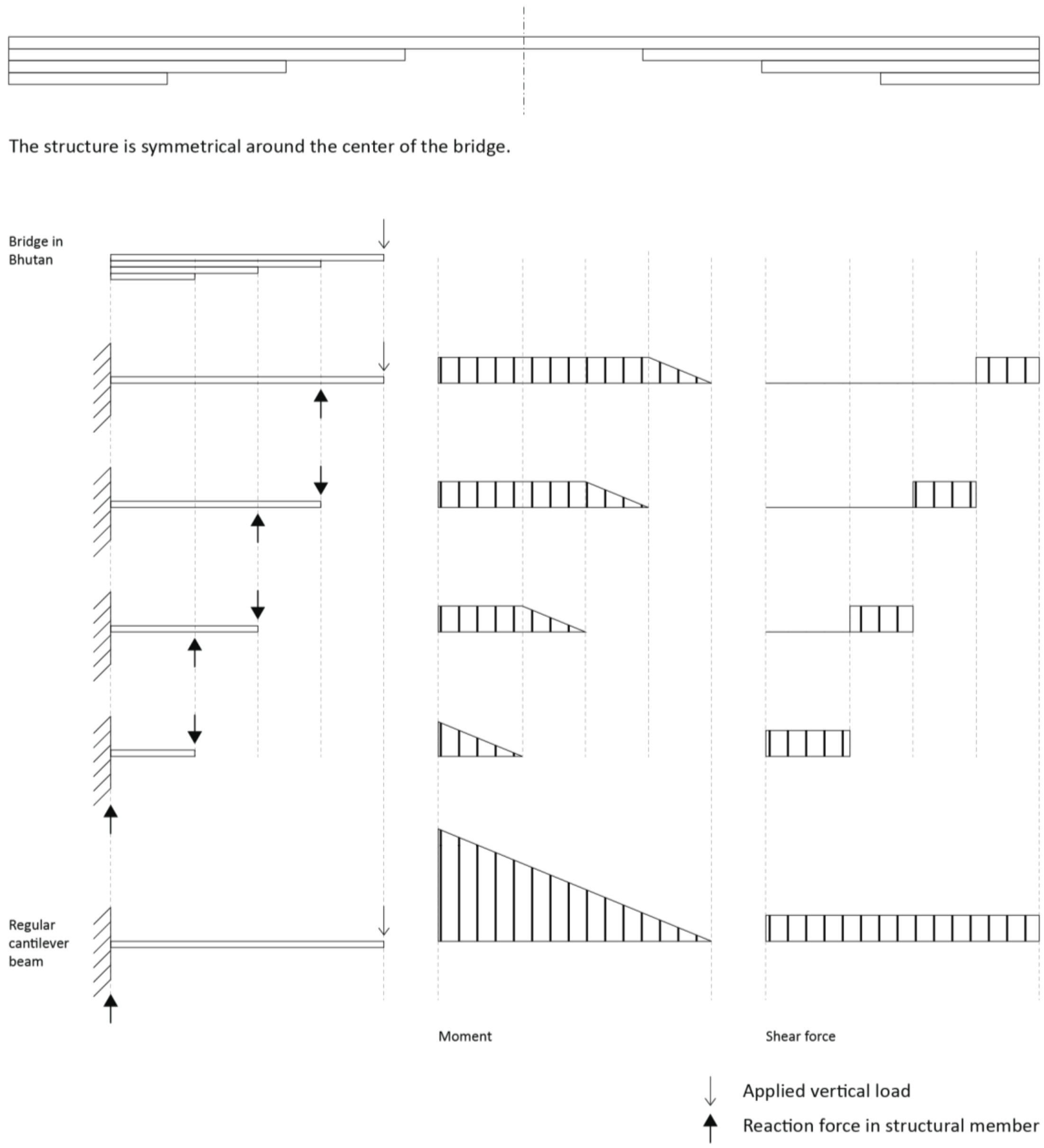


Figure 2.45 Concept of cantilever beams that support each other. Author's own copyright.

2.6 Discussion - structure, material, method and function

Among the examples mentioned above, 15 out of 20 towers were built during the 21st century. The other towers are the two pre world war radio masts, Shukov's hyperbolic tower and the two old Swedish observation towers. However, the above examples only represent a small portion of all wooden towers, be they observation towers or other types, so no real conclusions about the use of timber in towers throughout history or such can be drawn from that.

Something that is perhaps more interesting to discuss is whether there are particular solutions that are used for observation towers and others that are used for more practical uses. The above reference projects are in no way to be seen as a complete overview of all timber towers that have been built throughout history. The aim in the search for reference projects has been on observation towers. Therefore, it says more if there is a type of structure where there is no observation tower represented than if there is no tower with another function. In the case of the plate structures, the only towers represented is a windmill and a bell tower, i.e. no observation tower. If speculating, a reason for this could be the relative young age of engineered timber materials such as CLT panels as a structural material for high structures. It is also a fact that CLT panels are great to create walls, while in an observation tower as much openings as possible is often desired and hence columns are more desirable than solid panels.

The truss radio masts really stick out from the other structures within the same category. They were built much earlier, without glulam and are significantly taller. The radio mast structures resemble the Eiffel tower greatly, so one could argue that there is nothing stopping the construction of such a truss tower as an observation tower. However, it is important to remember that it is just that, a resemblance. The Eiffel tower is a steel structure, while the radio masts presented in this thesis are made of timber and may be sensitive to for example wind load in the sense that they can become too swaying to be suitable as observation towers.

Looking at the time of construction, all types of load bearing structures are represented among the 21st century structures. Looking at the five older towers, the radio masts are built as trusses, Shukov's tower is a hyperbolic structure just like what is used in other reference towers and the Swedish observation towers are essentially platform frame houses of significant height. Many of the 21st century structures are built using materials and methods that were not available a century before. Glulam is one such product, along with CLT. The methods for fabrication and construction are also modern. Many of the newer towers have likely been created as prefabricated elements of large sizes and heavy weight, which has required heavy machinery on the construction site to put these pieces into place. The design processes however are not ones that will necessarily have been dependent on modern technique. Though probably all newer towers have been designed, in part or in total, using computers and potentially also parametric design software, all of them could have been designed with hand drawings and all of them have structural systems that can be understood and explained without computers.

The stacked towers stick out from the rest of the structures in the way that load is transferred in the material. Structurally, stacking beams make little sense. The most material efficient way to carry loads can be said to be either in tension or compression and to use dimensions that are just as big as what is needed for the load in consideration, which would imply a truss structure or similar. In the case of the stacked elements, the load is primarily carried in compression within the timber members, but the forces are usually a lot smaller than the capacity of the members and the timber is also subjected to compression perpendicular to the grain, which is far less efficient than parallel to the grain.

2.7 Discussion - Appearances

Structural efficiency and what system is chosen for what purpose are obvious considerations for the structural engineer, but for the visitors of the observation tower and all those residing within its visual range, what they see and experience is of greater importance. It has been discussed how gridshells and plane frames have similarities and how a truss can be a frame, all of which is interesting in order to make sense of how different structural systems function and to categorize them, but not to predict how they will be perceived and whether or not they will be appreciated.

2.7.1 Pure timber versus hybrid

In the examples of towers mentioned above steel or other metals has been used to connect members and/or to stabilize the structures. However, the amount of steel used varies a lot between the different examples. Looking at the sky walk in the Czech Republic (Figure 2.11), the trusses consists of some members in timber and some in steel and all joints are of the type where the timber members are inserted into a steel connection element. The impression this structure makes is hence very much influenced by the amount of steel used. The tower at Ermitage Saint-Antoine (Figure 2.7 and Figure 2.10) can be considered the opposite. With bolts going through the glulam members to hold them together, the only steel that is visible is the head of the bolt on one side and the washer and nut on the other.

There are two aspects to regard in the question of pure timber versus steel timber hybrids. One aspect is the functional one. Efficient material use, i.e. that the right material should be used in the right place, is part of this. This applies to connection details as well as the actual structural members, where for example a steel wire can be a much more effective way to handle tension than the corresponding timber member. Aspects such as fire safety also come in here, where steel weakens very quickly if subjected to high temperatures but not protected, whereas timber develops an outer charred layer that protects the remainder of the cross section. So, for the function, safety and efficiency of the load bearing structure, a combination of steel and timber may be the best.

The other aspect is the aesthetical one. The Pyramidenkogel tower (Figure 2.31) can be used as an example. In that tower only the columns are made of timber and the lateral and bracing members as well as the stairs are made of steel. For a timber construction that can be considered a lot of steel, but from an architectural point of view this extensive use of steel enhances the columns. These are experienced as one vertical body. Had more members been of timber, the impression from up close and especially from within the tower would have been more that of wood, but the vertical direction and the silhouette of the tower would have been compromised.

2.7.2 Expression

The truss towers have very different expressions. What can be established is that lattice structures can obtain very different shapes and architectural expressions. The post and beam structures are more similar to each other as structures. From an architectural point of view it is more interesting to look at the claddings of these towers. The old Swedish towers are more like tall red houses, but the Norwegian tower is interesting. From a distance it looks quite solid and from the inside the interior may seem neglected, but it lights up like a lantern at night, making the load bearing structure visible from far away (Figure 2.30), an effect that is made possible by the sparse cladding. Regarding the plate and slab towers, plate towers doesn't seem to exist for observation purposes. The stacked tower examples are both variations on the double helix, framed in different ways to keep the structure stable. Finally, the arch towers are quite similar in the way they carry at least vertical load, but very different in the experience they provide. The Swedish tower is a stable and fairly solid tower, while the German tower creates a big space on its inside, which is experienced from the walk path along its perimeter. All types of structures, aside from the plate structures, has proven possible to leave open, i.e. cladding and actual walls are optional, which is a great thing when aiming at providing a view.

Apart from these observations, regarding architecture there is also always a larger context to consider. In the case of an observation tower there is the relation of the building to the site as well as to all places from which the tower can be seen. In short, an observation tower is not just a means to providing a view, it is also a sculpture in the landscape.

Architecture is a lot about the experience and who can use the tower is crucial to who can experience what it has to offer. Therefore, accessibility should be considered. Ramps may be the obvious solution. The Observation tower in the Bavarian Forest National Park (Figure 2.40) is an example of this. As ramps require a fairly low inclination they have a big impact on the width of the structure. If the idea that the tower isn't accessible to all is accepted, then it can still be accessible to many if the stairs are carefully designed. Stairs of low inclination, with good railings, sufficient amounts of landings with benches to sit down on and enough space for those who are faster to pass could be enough for an elderly to feel comfortable taking on the challenge of going up. A solution where a lower part of the tower is accessible to all could also be an option.

3 Timber as a Construction Material

There are many species of trees. Each species exhibits its own set of properties, regarding visual aspects as well as structural. The properties of the material also vary depending on where the tree grew. Temperature, weather, density of the forest among other factors influence the speed of growth, whether the tree is straight or not and so on, which in turn affect shape and strength of the material. In addition, the properties vary within the tree, especially between heartwood and sapwood (Zwerger, 2011).

How the tree is treated once it has been felled also affects the properties of the final timber product. Today, drying is an absolute must before timber is used in construction. Artificial drying is the most common method today and timber is dried to a specified moisture content. However, historically timber has been air-dried for different periods of time, with or without the bark left on, depending on the species and for what the material was meant to be used. Before that, until late Gothic times, timber wasn't dried at all, but was used green in construction. Regardless if and how timber is dried before use, the one thing that will happen when a tree is cut down is that it will lose its natural supply of water from the ground via the roots. The timber will then begin to lose moisture and dry until it is in equilibrium with its surroundings. As the timber dries it will decrease in volume. The sapwood contains more water than the heartwood and will hence undergo a larger volume change and the shrinkage is also different in radial direction compared to vertical direction. Historically, this was taken into account by allowing the timber to dry in place in a construction. Once the timber had reached its final state in terms of volume, things were adjusted from there. Windows and doors of the size appropriate to the dried structure were placed in their designated holes, or the structure was dismantled, adjusted and reassembled to achieve the desired measurements (Zwerger, 2011).

In modern timber construction timber is not looked upon with this attention to the individual tree and its properties. Instead, timber is cut and classified according to a system with the aim of providing modern products that are dependable and that can therefore be prescribed by a structural engineer for a specific use in a specific place so that the actual work can be carried out by a construction worker without any of the involved having to actually pay attention to how to use a specific tree for a specific purpose. One can say that this modern system has eliminated the need for the traditional carpenter's skill set. On the other hand, it is also a system that is a necessity in the building industry today. However, it is important to be aware of the pros and cons of both the traditional and the modern ways of doing things to move forward and develop new and better methods and techniques.

3.1 Timber products and production methods today

This thesis aims to develop a modern timber observation tower that can be built by hand. Emphasis is put on making the structure consist of smaller pieces and an easily understood assembly process. Though innovation is highly appreciated, the rules and regulations set up by the European Committee for Standardization (2008, 2009a, b & c, 2010) in Eurocode as well as national regulations have to be followed. This means that all structural parts of the tower have to be built from classified materials in accordance with the construction rules. However, more ornamental parts could possibly use older methods in both choice of material and building technique.

The structural timber products available today are numerous. There is sawn solid timber from hardwood and softwood, cross sections consisting of 2-4 pieces of timber glued together, glued laminated timber, plywood, laminated veneer lumber (LVL), blockboard, oriented strand board (OSB) and various other boards made up of wood or wood mixed with other materials (Volz, 2004a). Another timber product is cross laminated timber (CLT). In the examples of built towers presented in Chapter 2, the majority of the towers are built of either sawn solid timber or glulam. There are a couple of examples of towers built from CLT too. What can be said for the towers built from sawn solid timber and glulam is that there is not a particular type of towers that is built using one material or the other, but there is rather a mix of old and new towers within each type of structure. Of course, the oldest towers are built of sawn solid timber as glulam was not yet available at the time of construction, but for the more recent projects it was simply the most suitable material that was chosen.

This thesis aims at showing ways in which the Swedish timber can be used in construction. Therefore, only timber products that can be produced from tree species found in Sweden are considered. The Swedish forests cover 70% of the land areas within the country and this percentage keeps increasing and has been increasing for the past century. The forests consist of predominately three species that make up 93% of all forest. These species are spruce (42%), pine (39%) and birch (12%). The remaining 7% of the Swedish forests are made up of other hardwood species. The Swedish forest is thus dominated by softwood (Svenskt trä, n.d.c).

Modern production methods enable the fabrication of products that far exceed what would be possible with just sawing from logs. Finger joints make it possible to make members that are infinitely long. Gluing pieces together makes it possible to create larger cross sections that are stronger than ordinary sawn solid timber as only pieces of the highest quality can be chosen and the parts that have defects can be sorted out. Gluing also enables the production of board materials.

There is a scale from industrial prefabrication of whole structures that are then only assembled on site to the historical way of cutting trees on site and making the best out of them. In this tower project, it seems rational to use products such as sawn solid timber, glulam and/or CLT for the load bearing structure, to ensure that the regulations are followed. In terms of prefabrication however, what is done in a factory or a workshop and what is done at the construction site would have to be determined by the design of the structure.

3.2 Weather, fungi and insect protection

Moisture can be a threat to timber constructions. Therefore, a moisture content of 20% has been set up as a maximum limit that can be allowed without there being a risk of fungi or insects that may discolor and/or destroy the wood. Moisture also create changes in the volume of timber, which means that changes in moisture content may cause swelling and shrinking that can damage the structure. To keep the moisture content at acceptable levels structures should be built up in such a way that their parts are either protected by other parts or placed in such a way that water from rain etc. will run off and allow the material to dry. Where it is not possible to avoid water and/or moisture reaching the wood, e.g. in outdoor floors, species that are more naturally resistant should be chosen. As a last resort treating wood with chemicals may be an option to ensure durability. There is a difference in the need for protection of timber members depending on if they are load bearing or not and if they are easily accessed for inspection or not. The more important a member is for a structure and the more difficult it is to inspect the member, the higher the requirements are for protection and the choice of a durable material (Volz, 2004b).

Small cracks appear naturally in wood, especially as it dries. These become entry points for both moisture and insects. Engineered timber products such as glulam run a lower risk of splitting than solid timber and is hence at a lower risk for damage due to moisture and insects. As mentioned above, volume changes due to moisture may also cause problematic deformations. However, volume changes are proportional to the size of the cross section. Therefore, smaller cross sections are appropriate to use for elements that are subjected to weather. It is also important to ensure that the timber is kept at the right moisture content level before it becomes part of a structure. For example, if the timber has been stored in direct sunlight it may have dried too much and therefore cracked or if it has been stored on the ground it may have reached a too high moisture content and fungi may have started to grow. It is also preferable that the timber is at the same moisture level at the time of construction as it is meant to be during the life span of the structure. This expected moisture content level varies depending on the conditions the element will be in in the ready structure, from the very dry conditions inside a heated structure to the moist conditions of a completely unprotected element. The structure of an observation tower can be considered to be exposed to the weather on all sides, which means that the moisture content at installation should be 18±3% (Volz, 2004b).

Heartwood is weather protected in itself. This is especially true for older timber. Unfortunately, due to changes in the Swedish forestry industry during the second half of the 20th century, the quality of Swedish timber has declined and the amount of heartwood is less in the trees that are growing today than it was before the 1950's (Svensson, 2016). There are also ways to treat wood to achieve protection. For example, the Korkesaari tower presented in Section 2.1.2 is built with wood that has been treated with a balm based on linen oil (arcspace.com, 2004). Other examples are heat treatment and various chemical preservatives. But regardless if the wood is treated or not, there are essentially two rules that should be followed to protect wood from damage due to moisture without chemicals. The first rule is to keep water away from the structure. The other one is to ensure that if the wood is subjected to water, the water can run off and/or evaporate so that the wood can return to a dry state.

3.3 Students as the construction crew

The idea is for the observation tower to be built within the scope of local educational programs. This means that the construction crew will mainly consist of students, whom will have no or very limited experience of such work. These students are the reason why a structure that can be assembled by hand from smaller elements is sought. With smaller elements, the need for heavy machinery is reduced or eliminated, which makes the construction site safer, but above all means that the students will really build the tower themselves and hence learn more.

The building techniques as well as the timber products available have developed over time. What is possible today is much more advanced than it was a century ago. However, as the tower should be built by the students, that sets certain limitations and requirements for the assembly of the structure, especially the joinery. This means that those working at the construction site will just be learning the basic properties of timber, such that it is much stronger in both tension and compression parallel to the grain than it is perpendicular to the grain. They will also be learning such things as the importance of edge distance for fasteners and the fasteners shouldn't be placed too close together. This doesn't mean that the structure to be built has to be simple and understandable at a first glance, but the joinery and the construction process has to be clear and uncomplicated.

Projects where wooden observation towers have been built with student participation exist. Two of the examples among the examples presented in this thesis are such projects. The gridshell in Helsinki (Section 2.1.2) is one of these. It was erected by an international team of 8 architecture students. It has over 600 joints, but is not dependent on all of them. In fact, if the shell were to be damaged at some point, the structure would still be able to carry the load (Meyhöfer, 2008). The ability of the structure to accommodate new load paths is great. Such a quality does of course contribute to resilience in any structure, but perhaps it is especially important in a project that is built by inexperienced workers, such as students.

The other example is the stacked tower in the Czech Republic (Section 2.3.1). Regarding the construction process not much information is available. In fact, all that was found was this quote from the architect: ”It is all so easy that I built the tower with the help of a group of young people – students. Even so, there are a few important things one needs to know. So, please – don't build without us!” (e-MRAK, 2014). Each piece in this structure has to be put in the right place and the cables that keep it all in place have to be attached to the tower and anchored to the ground. Still, the structure is simple, it is just a pile of timber, and therefore functioned well for students to build.

4 Design and Analysis Methods

The design and analysis work within this thesis will shift in terms of method throughout the work. Early on in a project, a conceptual design can be carried out using small physical models and/or simple digital modeling and the analysis may consist primarily of reasoning. As the project develops more detailed modeling, physical and/or digital, and more advanced analysis is required. Below is an overview of the design and analysis methods used in this thesis as well as how the results have been evaluated.

4.1 Conceptual design

A tower is always in a way a sculpture. An observation tower is meant to provide a view from the tower, but it also becomes something to look at, both from afar and up close. Looking at the possible structural systems of the reference projects presented in Chapter 2 and using them as a starting point can be one way of entering a design phase, but to instead look at the intention of the tower, what one wants it to do or to look like, may be a more interesting and innovative way to begin. Then, when the first sketches are coming along, the reference projects can guide in defining the concept of the structural system.

Some of the built examples presented in Chapter 2 had these types of interesting ideas behind their design. For example, at the Pyramidenkogel tower, presented in Section 2.2, there is a sign at the base of the tower explaining how the architect drew inspiration from the curves of a female body and the posture of a ballerina (Figure 4.1). Other examples are the Graswarder bird observation tower, which is resembling a sitting bird (Figure 2.23), and the egg shaped tower in the Bavarian Forest National Park, who's shape allows it to cage three trees that can therefore be viewed up close all the way from the ground to the top (Figure 2.40). Another approach is the more symbolic way that can be seen in the Ribbon Chapel, where the idea of two lives being intertwined has been translated into two paths for two people about to be joined in matrimony (Figure 2.41).

So, for the conceptual design of an observation tower one could imagine several different possible starting points. One could be the graciousness of a ballerina, the shape of a sitting bird or the will to experience and investigate a group of trees. One could also imagine the intention of having different paths for people going up and down or a tower where everyone can get up, even with wheelchairs or strollers. Working like this, the starting point would be an intended experience and a movement. The load bearing structure and the way that is chosen would come afterwards. However, in performing this conceptual design it is of course important to be aware of the structure and its behavior so that the concept becomes one that is both architecturally and structurally viable.

In this case, it is an observation tower that is going to be designed. What is important in the tower is not that it is a certain type of structure, but that people can get up and enjoy the view. Therefore, the starting point could be this movement up the tower. If this movement is a spiraling one, like a long ramp, then the question is how the vertical loads are carried in such a tower. There are three ways to consider the relation between the movement, which the spiral describes, and the load bearing structure (Figure 4.2). The first alternative, to the left, is that the movement carries itself. A way to solve this could be to use the same principle as in the Bhutan bridge (Chapter 2, Section 2.5), i.e. there is one spiral that reaches all the way to the top of the tower and below that one is a number of spirals of decreasing length where each new spiral supports the one above and is supported by the one beneath.

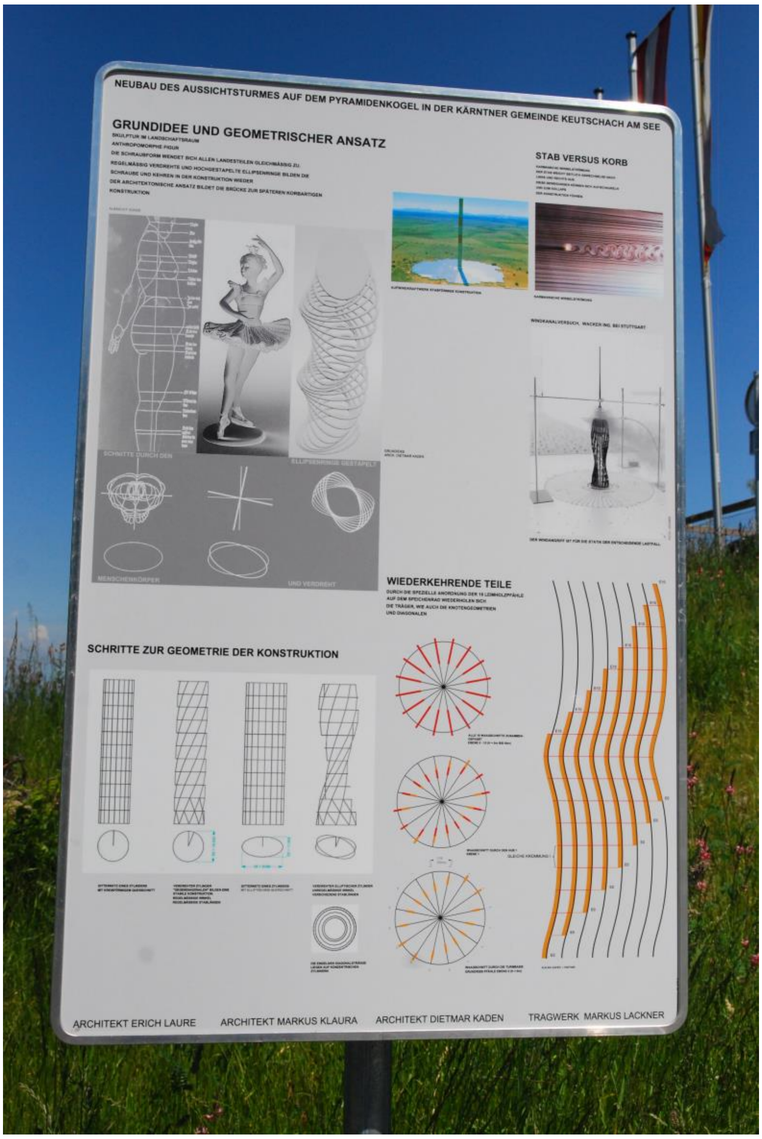


Figure 4.1 The inspiration behind the shape of the Pyramidenkogel tower is explained in a sign at the base of the tower. Author's own copyright.

The second alternative, in the middle, is where the structure interacts with the movement. It could for example be a hyperbolic structure as in the image and either the shape of the structure or the movement could be adjusted to better fit together. The tower at Ermitage Saint Antoine (Chapter 2, Section 2.1.1) is an example among the reference projects where structure and movement are well integrated. In that example, the movement, i.e. stairs and landings, make up vital parts of the trusses that together make up the load bearing structure of the tower.

The third alternative, to the right, is a structure that supports, but is separate from, the movement. The Sky Walk (Chapter 2, Section 2.1.1) is an example of such a configuration, where the frame structure of triangular trusses make up a clearly defined load bearing structure onto which the much more free formed walk path is attached. This solution could look forced, but it can also be a beautiful solution where the movement is emphasized by the fact that the structure isn't integrated. Though the movement is the same in these three cases, the overall impression of the tower is very different. There are of course better or worse solutions for quantifiable reasons such as material and production cost, but a big part of the decision has to do with aesthetics and simply what one wants the tower to look like.

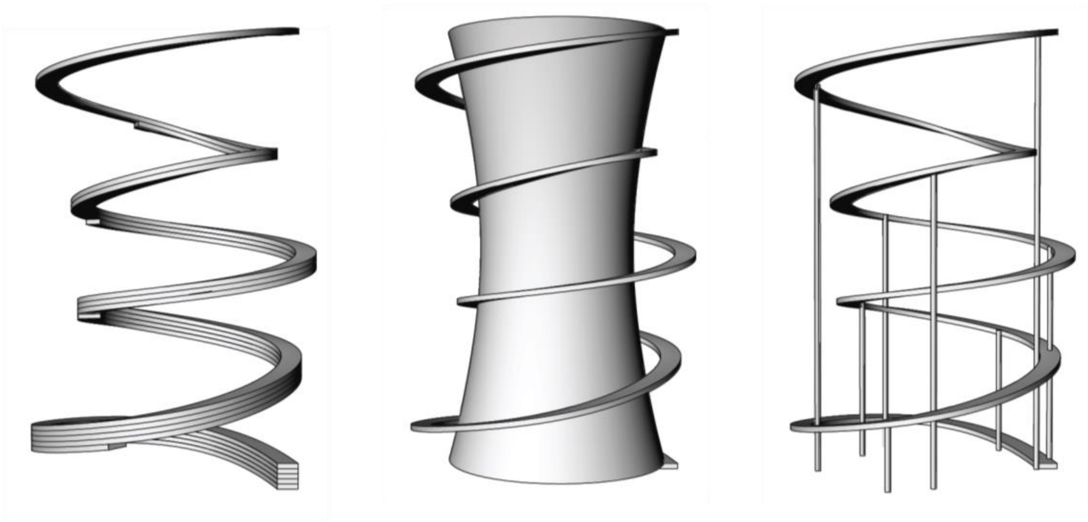


Figure 4.2 Three ways of considering the relation between movement and structure. Author's own copyright.

In early stages of design, the understanding of how a structure works, what the force patterns look like and the answer to the question "what happens if?" are important. There has to be a dialogue between architecture (the movement or the function of the tower) and structural engineering (the load bearing structure) where both aspects are considered in the design. The understanding of why something functions or not, how it can be improved, what materials and what shapes function and how the structure behaves under excessive loads are important. Though inspiration can be found from typical solutions, a catalogue of references can never replace the understanding of the specific situation. In a conceptual phase, performing exact analysis or just establishing that something doesn't work is useless, instead estimating how the structure responds and considering what can be done to solve problems and improve performance is the way forward (Olsson, 2005).

4.2 Physical model

Initially, physical models can be used to generate ideas and to try out initial concepts. In the following work, the materials utilized will be primarily EPS, XPS, steel wire, steel mesh, plastic strips, sewing thread and thin cardboard. In early sketch models built to generate ideas, the model materials do not have to symbolize any specific real material, instead the material that is found most convenient to work with to realize a specific idea in the shortest amount of time may be chosen. Afterwards, when reviewing and discussing such models, different points of view should be lifted to find the interesting aspects of the models. These aspects may be related to shape of the material, contrast between materials, space defining elements and so on. At this point the meaning of the choices made in terms of model materials may be discussed and contribute to further development of ideas. As the ideas develop, so should the models, and then the of choice of model material can start to become more important. Developing and refining a concept in physical model may mean switching to work in a larger scale, where more detail can be achieved.

4.3 Digital modeling and analysis

Various computer software has been utilized throughout the process to visualize and analyze the various structural concepts and the final structure. Initially, the simple 3D modeling software SketchUp was used to develop an idea of what the initial concepts could look. As the concepts developed, a more advanced modeling tool was needed and a switch to the 3D modeling software Rhinoceros was made.

Rhinoceros was used for some of the development of the more promising concepts, primarily for the models used to determine wind loads and to create models for export to FEM-Design, a software to perform structural analysis of 3D models using the finite element method, which was used for all structural analysis. After the final choice of a concept, Rhinoceros was used for all 3D modeling. The parametric design plugin Grasshopper was used along with Rhinoceros to define the structure based on a system of curves, which is described in Chapter 7, Sections 7.1 and 7.2. The benefit of using parametric design is that when, in this case, one of these curves was adjusted, the whole 3D model was automatically adjusted accordingly, which enabled a more effective workflow and hence allowed for a quicker development of the project.

4.4 Design criteria

Design criteria was set up for the tower before the design work began. Some criteria relate to the structure and building codes, other to the function of the tower and some to the limitations and possibilities of the site.

Criteria for the structure:

- The structure should be ~25m tall (Chapter 1, Section 1.2)
- The tower should be able to withstand vertical and horizontal load as well as torsion, due to the self weight of the structure, snow and wind loads and imposed load from visitors.
- The tower should be possible to build by hand, completely or to a large extent, and with no or very limited experience regarding construction work (Chapter 1, Section 1.6).

Criteria for the function:

- Enable views over the surrounding forest landscape.
- The tower should have an eye opening effect. It should be something that draws attention.

Criteria relating to the site:

- The tower has to fit within the boundaries of the site, i.e. approximately 20 x 30 m.
- The base of the tower and the foundation must be possible to adapt to the uneven rock at the site.

Regarding the function of the tower, the criteria developed as the parallel thesis in architecture did and a new set of such criteria is presented later in Section 6.5.

5 Initial Concepts

With the references as inspiration, a process to develop structural concepts started. The process started out with sketches on paper (Figure 5.1). Various ideas started to develop, some of which seemed reasonable and others that were discarded immediately. However, the initial sketches tended to become too similar to the reference projects.

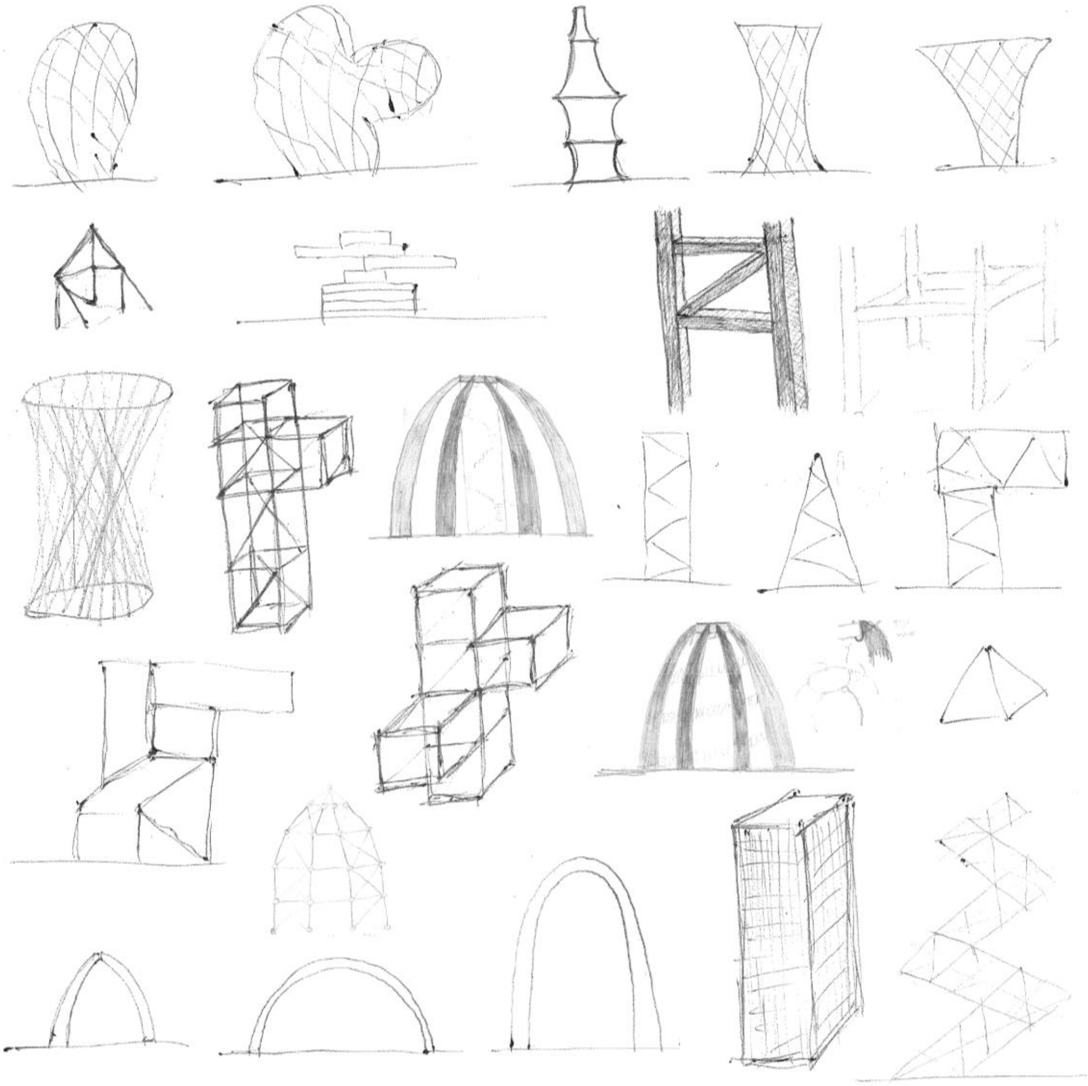


Figure 5.1 Early sketches of concept ideas. Author's own copyright.

To gather new inspiration and ideas for both the structural concepts and the architecture, or the function of the tower, two days were spent building quick sketch models (Figure 5.2 and Figure 5.3). The idea behind this workshop was to get beyond the obvious ideas. By working fast and with your hands, new ideas come up. In the end, a lot of the models may not contribute anything at all, but it is enough that some do. In addition, the models make up a library of ideas to come back to later in the process.

Figure 5.2 Quick sketch models (1/2). Author's own copyright.

Figure 5.3 Quick sketch models (2/2). Author's own copyright.

The models could be sorted in different ways and there are similarities and differences between them. Trying to organize the models in various ways, some features, architectural as well as structural, were found interesting. Among those features were:

- multiple paths
- horizontal movement
- winding shapes
- structures with changing silhouettes
- curved surfaces built up of straight elements

Considering the function of the tower and the experience the visitor would have, it was found interesting to keep working with the idea of multiple paths to develop structural concepts.

Investigating multiple paths and defining what possible options there are for such paths led to five options, four of which has the actual feature of more than one path (Figure 5.4). The “intertwined paths” was deemed the best option. The idea is that there would be two separate paths, so the visitor would choose one and stick to it and the designer would be in control of what happens along each of these paths. Along the way, the paths would have visual contact and they would meet at the top and give the visitors a new choice of which way to go down. Eventually, as the idea developed, the paths came to have different character; one adventurous and thrilling and the other more conventional.

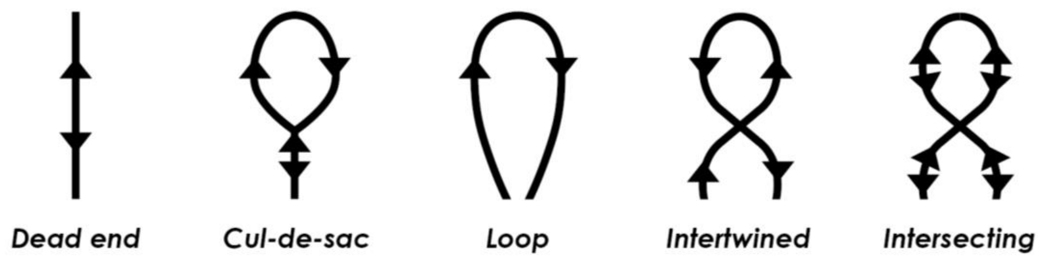


Figure 5.4 Possible options for multiple paths. Author’s own copyright.

A question that was raised was how two paths could look, without any regard to a conventional load bearing structure. Going back to look at the sketch models, a number of models were found interesting to look at as a whole tower and that triggered thoughts on how the two paths would run within these structures. Other models were interesting because of their silhouette. Some models triggered ideas about building techniques and detailing.

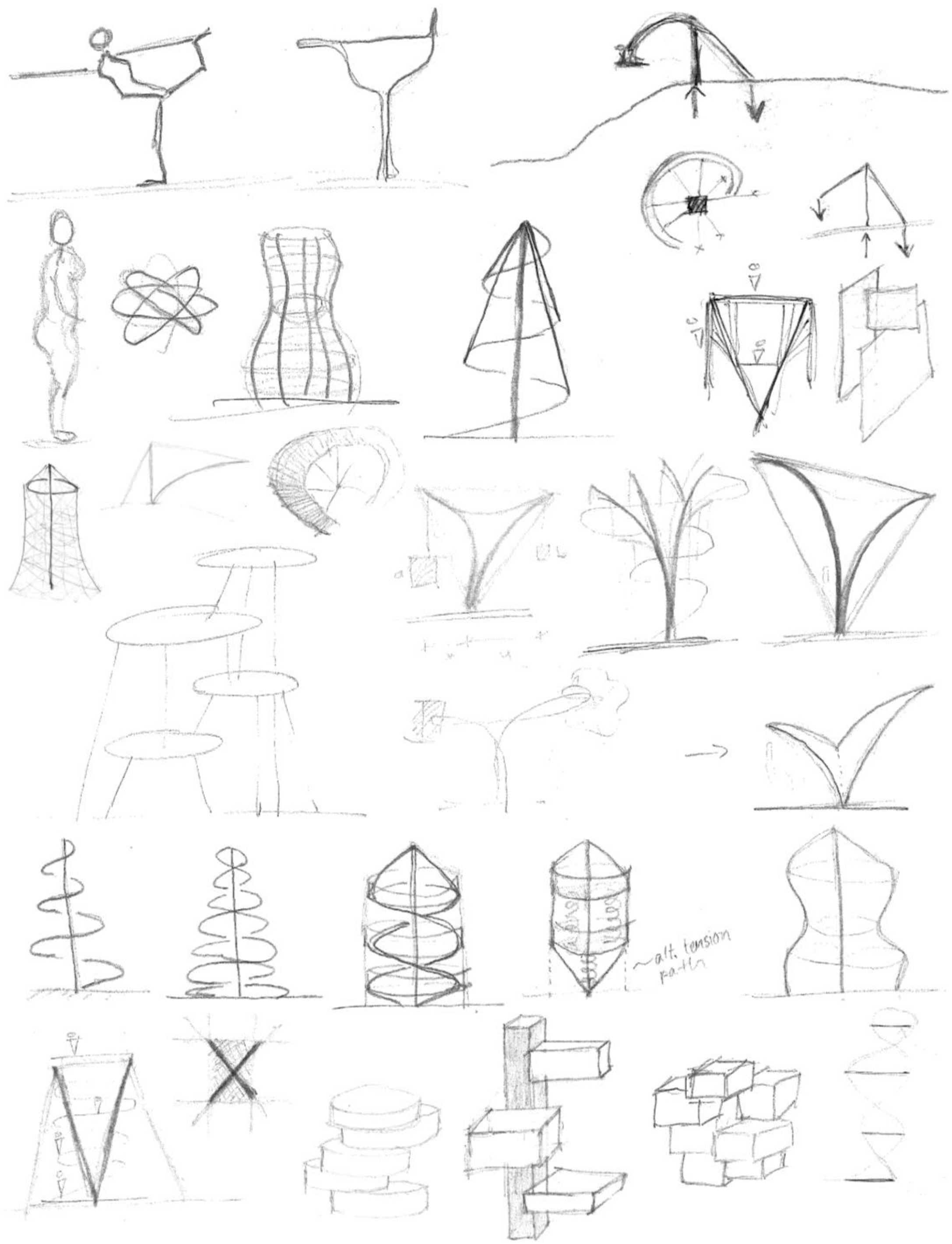


Figure 5.5 New sketches based on the inspiration from the sketch models. Author's own copyright.

The sketching continued. The ideas now started to develop into something new, not just versions of the references (Figure 5.5). Eventually, a number of more defined concepts started to take form. These concepts, which are presented below in this chapter, were investigated both in physical model and with the help of the simple 3D modeling program SketchUp. Both physical and digital models were made simple. In some cases, the two models are very much alike, in others the digital model was needed to help clarify the idea. In the digital models, no or very little regard to the size of the structural members was taken and stairs and ramps were simplified into surfaces. The idea was to provide visualizations to help argue for or against the concepts to evaluate which ones to move forward with.

For this first look at the concepts, no structural analysis was performed. Instead, the concepts were discussed in terms of what structural systems would be possible and what they could look like, following the idea that there are three possible alternatives (Chapter 4, Section 4.1). For some concepts the structure is clearer than for others, but in all cases the questions of how the structure would carry vertical and horizontal load and resist torsion are raised.

5.1 The SWIRL concept

From the idea of having two intertwined paths came the idea of simply creating two paths that swirl around each other and letting the actual paths be the tower, instead of creating a tower into which the two paths are attached. This led to the SWIRL concept (Figure 5.6).

Figure 5.6 Physical model of the SWIRL concept. Author's own copyright.

The digital model (Figure 5.7) shows an example of a tower consisting of two spirals. They're both the same, just turned 180° in relation to each other. Their outer radius is 6 m and the length of each path is approximately 140 m, measured along the center of the path. Though it may be tempting to view these paths as ramps that are wheelchair and pram friendly, they are too steep. A slope of 1:12 or 1:20 would mean a length of 300m or 200 m respectively, not counting the necessary landings. Another thing that became evident when modeling the concept digitally was the fact that it is only possible to do a certain number of rotations per spiral and place the spirals in certain ways in relation to each other without them passing too close over each other. There has to be a certain free height above the path so that the visitors can walk there. This implies that if the paths are to be made less steep, the radius must increase.

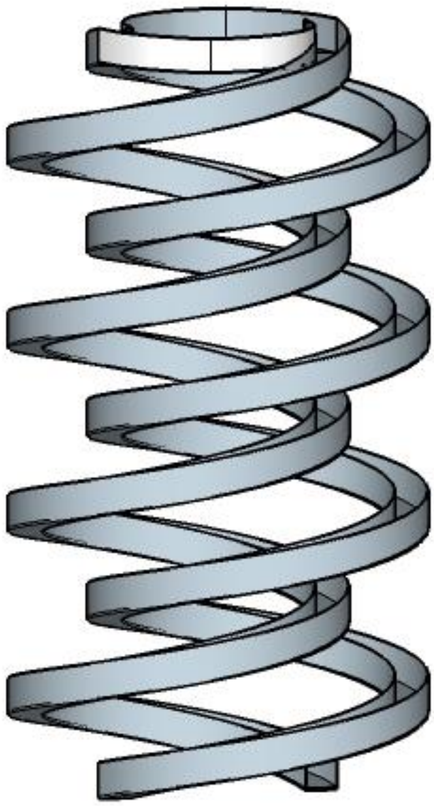


Figure 5.7 Digital model of the SWIRL concept. Author's own copyright.

The spirals in Figure 5.6 and Figure 5.7 are "screwed" together, so that they are truly intertwined. Therefore, each spiral will, in each rotation, pass by the other spiral once above and once below. Assuming that the spirals are the same, they could, depending on their cross section and height of one turn, be placed in such a way that they never touch or so that they touch once or twice in each turn. If the spirals touch they can be connected, thereby adding stiffness to the structure.

The spirals of course do not need to have neither a circular shape nor a constant shape and the two spirals can be different, as long as they don't collide. This way the tower could get a silhouette that varies from the ground to the top as well as from different sides.

The movement along two separate paths is clear in this concept. The structure is less clear. Looking back to the three ways of creating a structure, this concept is essentially the same as the example used (Figure 4.2), except now there are two spiraling paths. To summarize, this means that either the spirals are built up in such a way that they themselves become the structure. A structure such as the hyperboloid or some other space frame structure could also be fit into the spiral, so that movement and structure become well integrated. The third alternative is that the spiral is carried by a separate structure, e.g. a number of columns.

How vertical load is transferred in all of these cases is straightforward, but horizontal loads and rotations may be more difficult to grasp. Horizontal loads may come from wind, but also from moving visitors. The rotations will appear due to all sorts of loads. One way to account for this could be to simply connect the two spirals, especially if they are running in opposite directions, to achieve a certain stiffening and bracing effect.

Conclusions about the SWIRL concept:

- *Paths* - The two paths are clearly defined and not a later addition.
- *Intersections and height* - As the number of turns is limited due to the required free height above a walk path, problems may occur if the paths are different from each other.
- *Silhouette* - If the spirals are made to represent their respective character, the tower can be given a varying shape that looks different from different angles.
- *Difficult* - Not straight forward how to construct the structure without any clearly defined vertical load bearing members.
- *Foundation* - The original model only has two points on the ground. This limits the area affected by foundation work and the number of points where the structure needs to be anchored into the rock, but it also elevates the strain put on these points. A third foundation point would simplify achieving stability of the tower and is achieved if the second or third option for the structure is chosen.
- *Structural possibilities* – Though potentially possible to make the spirals become the structure, it would be much easier to achieve a stable structure if the spirals become integrated with another load bearing structure or simply carried by a separate load bearing structure.

5.2 The LAYERS concept

Another way of intertwining the paths is to let them run on either side of a plane frame wall and/or along one of two such parallel walls. The walls can be placed in a maze like structure, either with all walls connected or as units of at least two walls each, which can be seen in the concept model (Figure 5.8). Regardless of such configurations, there will be many walls placed parallel to each other so that the visitor can be either on the outside, all the way in the middle or somewhere between the LAYERS.

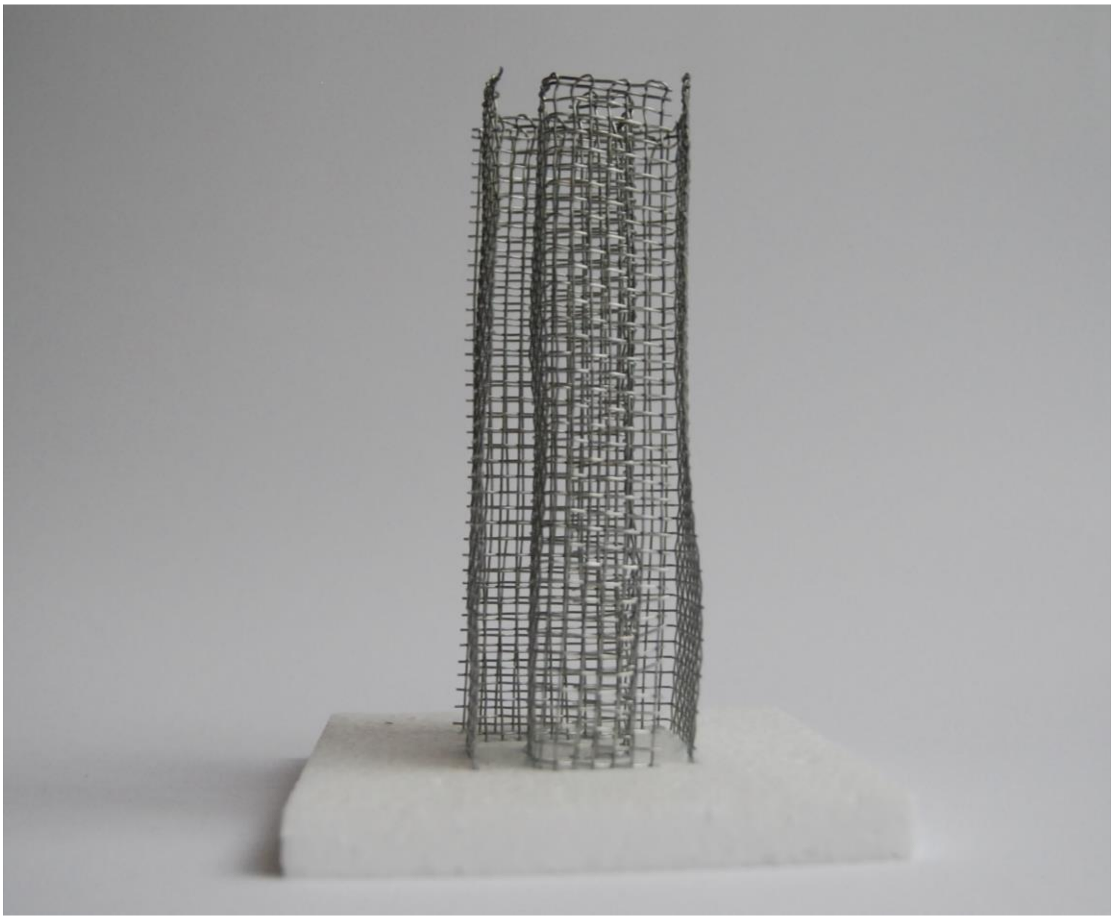


Figure 5.8 Physical model of the LAYERS concept. Author's own copyright.

A plane frame wall resists in-plane forces, but it is sensitive to forces perpendicular to the plane. With two or more walls connected at 90° angles, stability is given to the structure as the perpendicular walls provides lateral support to each other. For visitors to ascend the tower, walk paths of some kind are required. These could run from one wall to another and contribute to the lateral stabilization.

The mesh density and the dimensions of the members in the grid can vary. The desire to see through the wall to for example the other path or possibly to even be able to step through the wall to the other side can be made possible with these tools.

The concept model is an example of what such a structure, in its most basic form where all walls have grids of the same density and dimensions, could look like. One could imagine a wide variety of placements and configurations of such a structure. There can be variations in the spacing between the walls and not all walls necessarily need to have the same height, so that it is possible to have paths going over or under a wall (Figure 5.9). The example displayed by the model in Figure 5.8 corresponds to the top middle example in Figure 5.9.

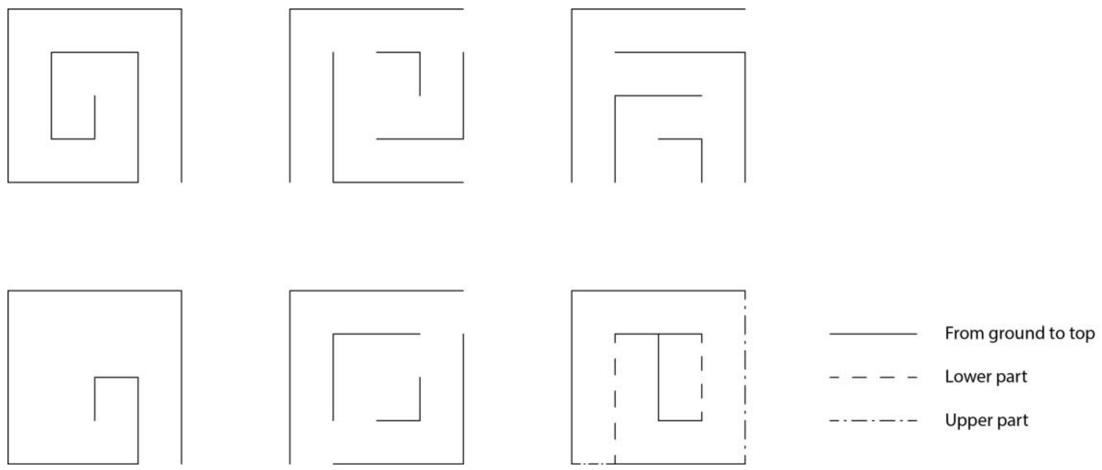


Figure 5.9 Some possible configurations for the LAYERS concept. Author's own copyright.

The setup of walls from the concept model was used to investigate what happens when two paths are implemented (Figure 5.10). In this model, all walls are connected to each other in couples, but the paths run between these couples. This means that if the paths and their connections to the walls are rigid enough they could enhance the stability of the structure.

In this concept, the movement is not as obvious as in the SWIRL concept. Instead, the movement and the experience is about the transparency of the walls. So, in a way, the structure is the primary thing and the movement is an addition. Therefore, the three alternatives from Section 4.1 do not really apply. Instead it is clear that this is the third option, i.e. there is a structure that is a separate design element from the paths that it carries.

Vertical forces will in this concept primarily be carried by the walls. Paths attached to a wall will create in plane forces in that wall. However, since the paths will be attached on one side of the wall and the force will be applied outside of the plane, there will also be a moment that causes the wall to bend or tilt, which will be resisted by a perpendicular wall. This would imply that a plate would be subject to vertical force components from paths attached to the wall and horizontal force components caused by paths attached to connected walls.

For the structure to better be able to carry horizontal forces and withstand torsion, the grids of the walls should not be designed as in the concept model, i.e.

with only vertical and horizontal members. First of all, one row and one column would need to be triangulated to achieve stability. Furthermore, it is more beneficial to have diagonal members than horizontal ones with regards to both horizontal and torsional load, like in the Bird Observation Tower on Graswarder (Section 2.1.3).

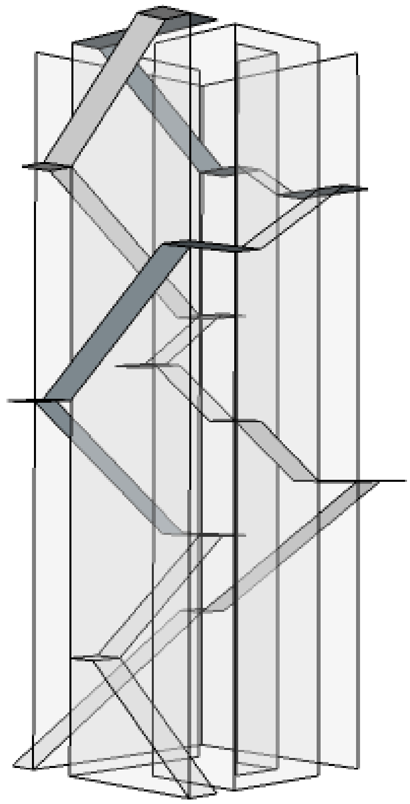


Figure 5.10 Digital model of the LAYERS concept. Author's own copyright.

How the concept resists torsion depends on the setup of walls. In the models presented above, where the walls are connected in pairs, Vlasov torsion would be dominant. If the walls would be connected into closed formations, the resistance of torsion would be much more effective and remind of the behavior of the tower at Ermitage Saint-Antoine (Section 2.1.1, Figure 2.9).

Conclusions about the LAYERS concept:

- *Straight silhouette* - This tower will look like a box from afar. The silhouette is not likely to have the desired eye opening effect.

- *Built in stability* - Two or more walls always connected to each other and stabilize each other.

- *Architecturally forced* - The tower as a sculpture of walls of different mesh densities doesn't allow for stairs and ramps to be added. When adding such elements, they appear as added elements that destroy the sculpture rather than add value.

- *Degrees of transparency* - The layers of transparent walls along with the differences in mesh density between the walls could create an interesting experience for the visitor.

- *Unconventional* - The idea of building a tower of walls like this is not something that has been found in any of the reference projects. It is innovative and could have an eye opening effect in that sense.

- *Foundation* - The tower distributes its loads onto many long lines and a relatively large area. Thereby the anchorage into the rock will be easier as the forces are distributed over a large foundation surface.

5.3 The PINE concept

Balance was something that could be found in some of the many sketch models. The thought of what balance means in the form of an observation tower led to the PINE concept (Figure 5.11). The idea is that the paths are hanging from a central column and balancing each other. This takes the shape of a pine tree, or a cone. The two winding paths are intertwined and they can swirl around in a way so that they never meet, or they can meet twice per turn, depending on whether or not the paths are winding in the same direction or not. Tensile chords running from the top of the central column to the ground keep the walk paths in place horizontally as well as vertically. This structure becomes light, so when the wind blows, the structure sways.

In the model, the paths are winding in opposite directions so that they meet twice per rotation around the central column. For the paths to not meet they have to turn in the same direction, which was tested in the digital model (Figure 5.12). In that model, the radius of the paths is evenly reduced from bottom to top so that the overall silhouette of the tower is a cone. The silhouette of this tower would of course not have to be the perfect cone, it could be more varied, as indicated in the concept model. Imagining that the two paths are more or less different the silhouette could vary both along the height of the tower and depending on from which side the tower is viewed. Just like in the SWIRL concept, attention has to be paid to the configuration of the spiraling paths so they don’t collide.

Just like in the case of the LAYERS concept, the structure is already defined in this concept, so the first alternative is not relevant. The other two alternatives, i.e. whether or not the structure and the movement are well integrated, becomes relevant for the behavior of the structure under horizontal and torsional loading, which is further discussed below.

Figure 5.11 Physical model of the PINE concept. Author's own copyright.

Vertical load will be transferred from the walk paths to the cables and down in the central column. This column will hence be in compression. To avoid buckling, its cross section will either have to be sufficiently large, or it will be necessary to find a way to brace it, perhaps by letting the walk paths leave the cable as touch the column every here and there, by intermediate slabs that could also function as landings and places to stop, or by structs between the walk paths and the column to shorten its buckling length. Horizontal load will be resisted in the pre-tensioned cables, by increased tension in the cables on one side of the structure, while the tension in the cables on the other side would decrease. To resist torsion, connecting the paths if they run in opposite directions may be one solution along the line of integrating the movement and the structure. Another solution could be to connect the cables with crosses of cables, much like the steel bracing in the Bavarian Forest National Park tower (Figure 2.40). To conclude, there is no need to design the walk paths symmetrically. Even though the initial idea of balance requires symmetry, external loads will be asymmetric and hence the structure will need to account for that. Therefore, the paths could extend differently in different directions in relation to the central column, rendering a more varied silhouette. Regardless of how the walk paths are winding, the idea of balance will still be visible in this tower.

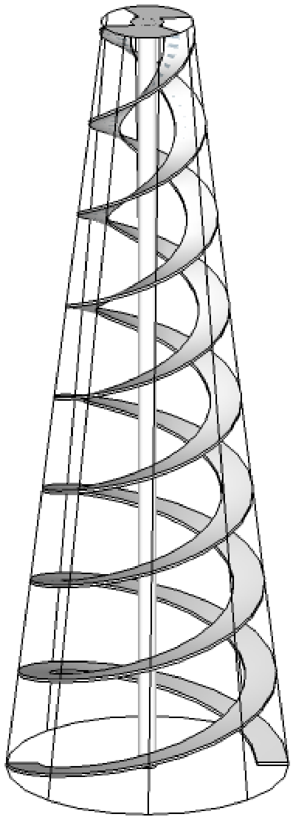


Figure 5.12 Digital model of the PINE concept. Author's own copyright.

Conclusions about the PINE concept:

- *Silhouette* - The silhouette is defined by the paths and can vary depending on their design.

- *Intertwined with less height limitations* - Unless the two paths have the exact same shape, each path can utilize the whole height of the tower if desired as the paths can wind inside and outside of each other and hence not put requirements on each other in terms of vertical distance.

- *Foundation* - Requires foundation work in many points where the tensile chords need to be anchored in the rock as well as under the central column. Each anchor point will be adapted to either tension or compression.

- *Clear division between tension and compression* - The way the system carries load is clear and easily read from the choice of material, where the cables wouldn't be able to handle anything other than tension.

5.4 The PLATES concept

From one of the many quick sketch models came an idea that didn't really start with the function. The idea behind the PLATES concept was to build a tower that is like several plates placed on top of each other (Figure 5.13).

The initial sketch model reminded more of a sculpture than a tower, but it raised the question of what it could be if it was viewed as an observation tower. To be an observation tower the stairs leading from the ground to the top is a necessity. The stairs could be attached to the plates. Perhaps they could even pass through the plates. With ideas that were much like those in the LAYERS concept (Section 5.2) about being able to attach paths to the plates, being able to sometimes see through the plates and sometimes not and to enable openings in the plates where a person could pass through, plane frame was considered a good structure and a model for the PLATES concept developed. In the model the mesh within one plate is uniform. All members have the same dimension and are spaced evenly. However, the density of the grid as well as the dimensions of the members could vary, both depending on forces and the sought visual result.

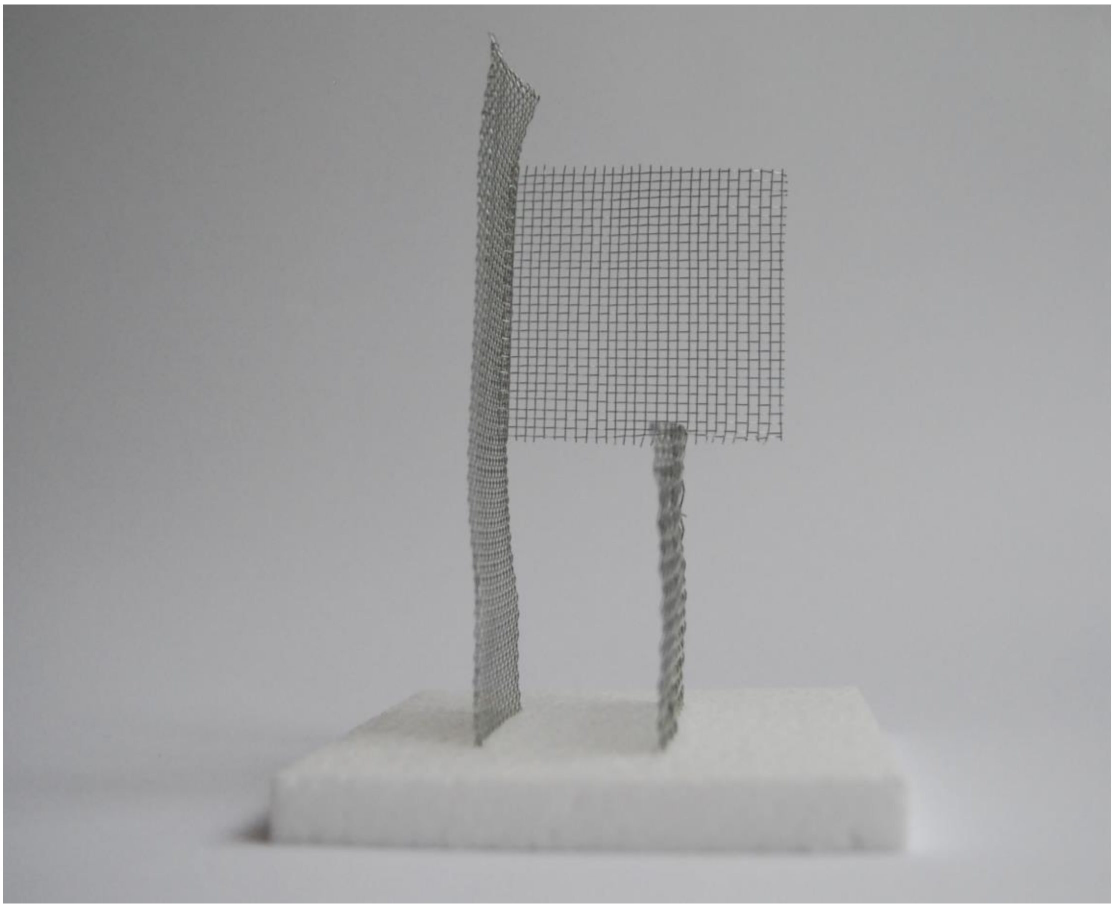


Figure 5.13 Physical model of the PLATES concept. Author's own copyright.

The walk paths cling to the sides of the plates. The two paths could be separated from the start, either by climbing up different plates or by starting from opposite ends of the same plate. The paths could also follow each other by running side by side on one side each of a plate. One way the two paths could be set up was tried out in a digital model (Figure 5.14).

Regarding the possibilities for the design of the structural system, once again this concept has similarities to the LAYERS concept. This concept doesn't allow for three possibilities, but is already the third alternative, i.e. the structure is one thing and the movement another. This could be a strength, if climbing up the tower can be made a good way to experience the sculpture of plates balancing on top of each other. In terms of how loads are transferred down to the foundation, once again there are similarities to the LAYERS concept. The walls are only stable when it comes to handling in plane forces. In the physical and digital model above there are three plates. Two of these plates are parallel, while the third is placed perpendicular to them, thereby stabilizing them while it is being stabilized by the two first walls. In this model, one of the connections between the plates is continuous, which can be assumed to be rather effective as forces can be distributed along that whole connection. The other connection however is only in one point, which means that it doesn't necessarily provide the same stabilizing effect. Such a single point connection between two plates would create a stress concentration and hence require more of the structure in and around that particular point compared to if the same load was to be transferred from one plate to the other via a continuous connection. In regard to torsion, the global structure can be compared to an open cross section, e.g. that of an I-beam (Figure 2.1).

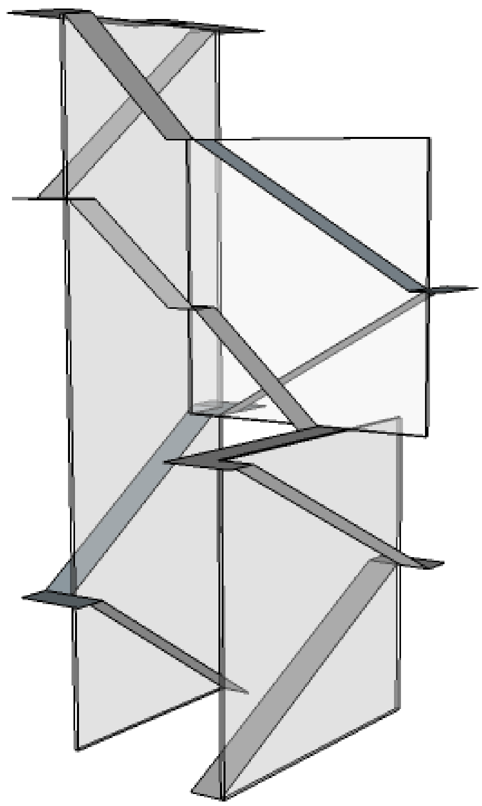


Figure 5.14 Digital model of the PLATES concept. Author's own copyright.

Conclusions about the PLATES concept:

- *Silhouette* - The multiple plates creates a megastructure that is visible from afar and onto which the walk paths can cling.

- *Weak links* - Potentially weak points in point or other limited connections between plates.

- *Architecturally forced* - The tower as a sculpture of walls of different mesh densities doesn't allow for stairs and ramps to be added. When adding such elements, they appear as just added elements and do not contribute any value to the sculptural structure.

- *Degrees of transparency* - The different plates can consist of different sized members and be different in terms of mesh density, thereby providing more or less possibilities to see through them in various directions and from various distances.

- *Unconventional* - The idea of building a tower of plates like this has not been found in any of the reference projects. It is thus something that can be seen as innovative and that could have an eye opening effect.

- *Foundation* - The tower distributes its loads onto at least two lines and. Thereby the forces that have to be transferred in each anchor point are limited.

5.5 The ROTATIONAL concept

The varying silhouette, that varies both from bottom to top and from different angles, can be interesting. This idea was one of the things that was discovered through the many quick sketch models. A thought came up through discussion about how such a varying silhouette could be imagined. With the image of the dancer from the Pyramidenkogel tower (Figure 4.1) in mind, the idea was that a path could describe a dancer. With two intertwined paths, there would be two intertwined dancers somehow joined together. These thoughts developed into the ROTATIONAL concept (Figure 5.15).

The question was how to create these dancers, that are like volumes, and their corresponding paths and how to translate them into the structure from the concept model in a controlled and logical way. Rotating a plate of a geometrical shape and placing these shapes on top of each other is a simple way of creating a path that is a spiral staircase and a volume. Letting two such piles of plates intersect can create something even more interesting and less predictable or easy to understand. However, doing so will always produce something of a monolith and something that is essentially just a staircase, potentially with two or even more paths leading from the bottom to the top (the two left figures in Figure 5.16).

Figure 5.15 Physical model of the ROTATIONAL concept. Author's own copyright.

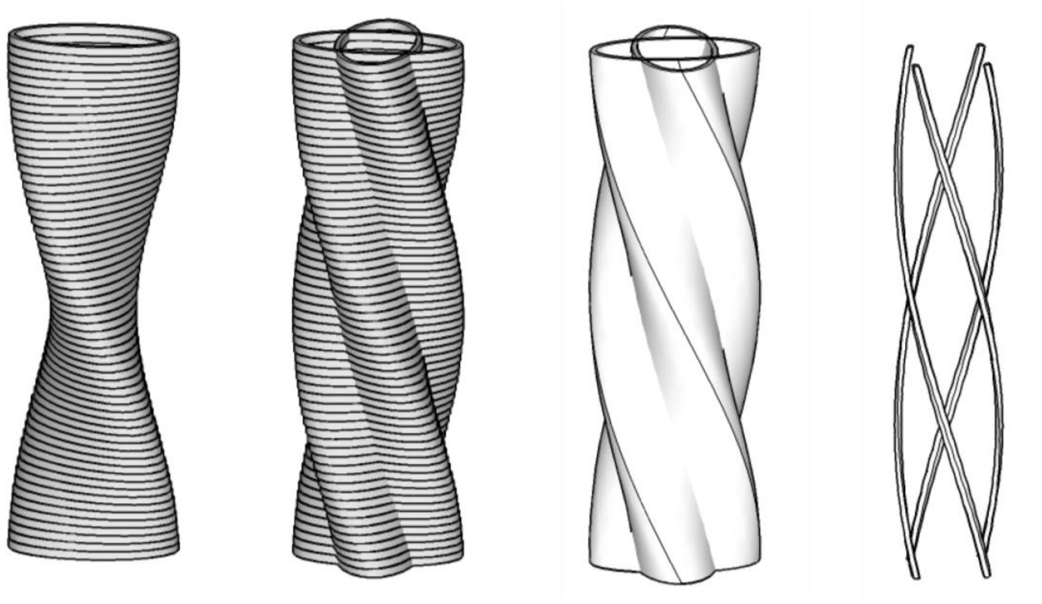


Figure 5.16 From left to right; rotating and stacking ellipses, letting two such piles intersect, turning the piles of plates into volumes and the intersection of those volumes. Author's own copyright.

If instead of being piles of plates, the piles are volumes, or rather shells, and the intersection of them can become columns that gives the tower this varying silhouette, without producing a monolith (the right two figures in Figure 5.16). The tower becomes an abstraction of the two volumes joined together. The two volumes could look the same, as in the image, but they could also be different both from each other and along the way from the bottom to the top. The walk paths would then wind around the columns, following the shape of their respective volumes (Figure 5.17).

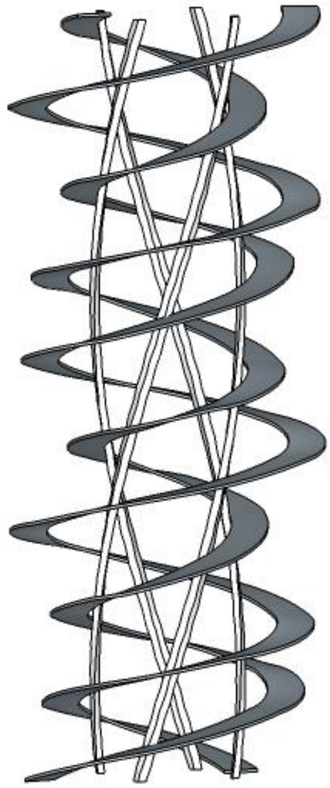


Figure 5.17 Digital model of the ROTATIONAL concept. Author's own copyright.

When it comes to the load bearing structure of this concept, the first alternative doesn't really apply, or one could say that if the movement is to be the structure in itself, then it is the same as the first alternative for the SWIRL concept. The other two alternatives are more interesting, and either one of them could be argued to work well. As this concept is based on the paths defining the structure, it becomes more a discussion of labeling it than choosing between two alternatives. The way the columns are defined, they are already integrated with the paths in a way, but it is not necessarily visible unless you know it and hence the third option, i.e. a separate structure, may be what is experienced. Either way, the vertical columns will need to be braced to avoid buckling and ensure horizontal stability and torsional stiffness. The walk paths could contribute to such stability as they touch each column once in every rotation. However, to reduce the need for moment transferring connections, purely bracing members in the opposite direction from the paths are necessary to turn the structure into a truss. Another option is of course to disregard the walk paths in terms of load bearing structure and consider them, in accordance with the third option, as something that is simply carried by a separate structure, in which case diagonals in two directions are required to turn the columns into a truss.

Conclusions about the ROTATIONAL concept:

- *Silhouette* - The more elaborate the individual rotational bodies are, the more interesting the silhouette can become.

- *Complicated* - The concept is not easy to grasp and describe geometrically. In its original shape, the columns are twisted, which would complicate fabrication. However, the columns could most likely be simplified without compromising the overall appearance of the structure, leaving the visual impression complicated, while the geometrical description, the structural analysis and the fabrication would be much simplified.

- *Unconventional, but conventional* - In one way the curving shape is rather unconventional. In another way, the structure is a truss, so though it looks complicated, the structure could quite easily be understood.

- *Foundation* - Only the four columns and the two paths touch the ground, which limits the area required for foundation work, but still distributes the loads.

5.6 The OUTSIDE/INSIDE concept

Another concept that came from the idea of balance was the OUTSIDE/INSIDE concept. It consists of a group of columns leaning slightly outwards, tied down and held in place by tensile chords. The spatial consequence of this concept is the transition from outside to inside, which gave the concept its name. The structure's perimeter is defined by the tensile cords holding the columns in place and ensuring that the whole columns are in compression. The space within the tower ranges from being primarily outside the columns at the ground level to being completely within the columns at the top of the structure, which can be seen in the concept model (Figure 5.18).

The idea is to create walk paths that takes the visitor through this change in space, so that the transition from outside to inside can be experienced. In the outside space, the walk paths can be attached to the tensile chords, making them sway as you walk or as the wind blows. Further up, as space outside and inside become more evenly distributed, the paths may be carried by both the columns and the cords, making them sway less and feel more stable. As you approach the top, the walk ways will be supported by the columns, which will provide complete stability at a point where you may need it the most, when the height above ground may be enough to render a tingling sensation in your body without the path you're walking on giving way and swaying. An example of how the paths could run was implemented in a digital model (Figure 5.19).

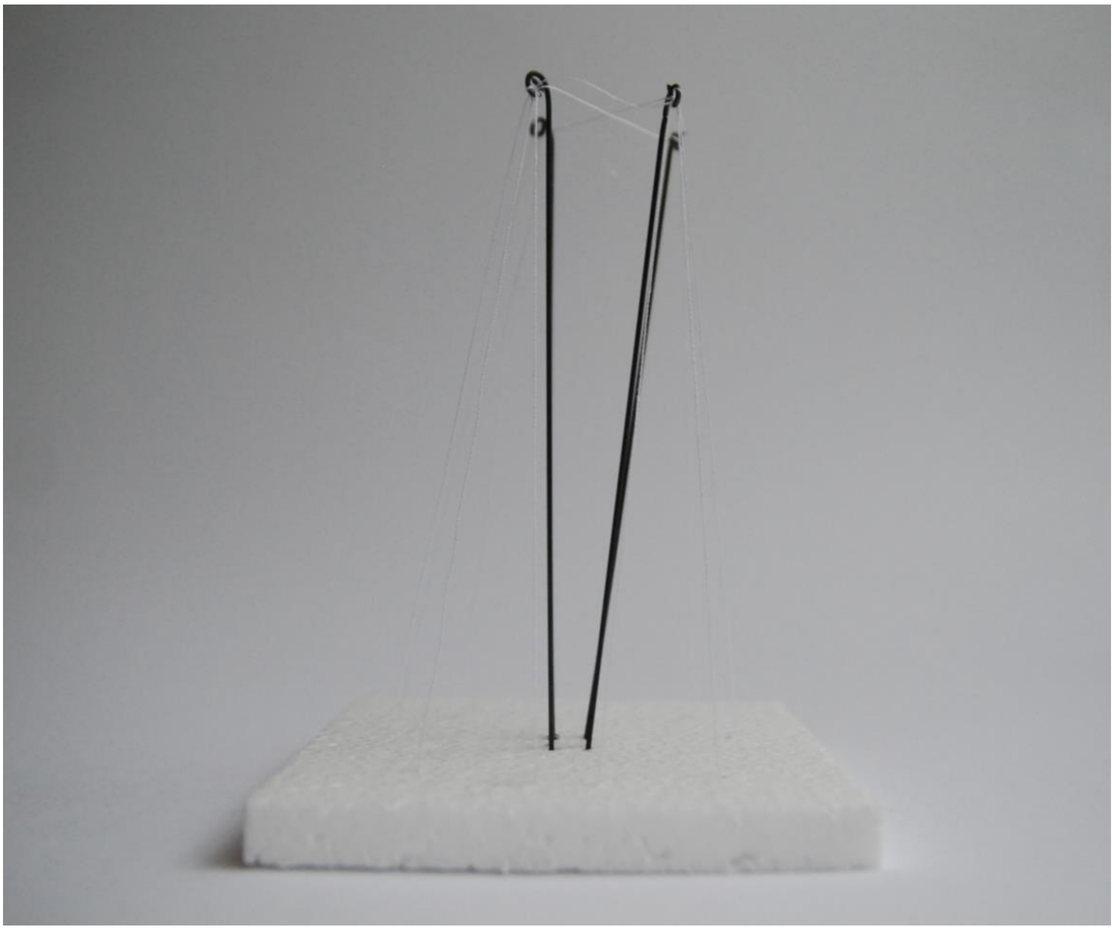


Figure 5.18 Physical model of the OUTSIDE/INSIDE concept. Author's own copyright.

The columns as well as the pre-tensioned cables are symmetrically placed in the models above, but their placement could also be asymmetrical. The structure is in this concept in a way both an integrated part of the movement and something completely separate. Integrated because without the relation between the structure and the movement the whole idea of the transition from outside to inside is lost. Separate because the structure is clearly the structure and the walk paths are something else that is added. The first alternative, i.e. that the movement is the structure, is not an option.

In terms of how load is carried, the concept bears a high resemblance to the PINE concept (Section 5.3), with vertical load being transferred from the walk paths, via the cables into the central columns and with a similar need to find a solution for the rotational stiffness and the same possibilities in terms of either using the walk paths or adding bracing cables.

In regard to buckling, just like in the PINE concept, the slender columns lack lateral support. The slenderness of the columns is elegant, but is can easily cause problems, primarily with buckling. To solve this, the columns need to be either stiffer in themselves or they need to be braced. Bracing could be provided through bracing members between the columns or by utilizing the walk paths as bracing. The columns themselves could be made stiffer by simply using a bigger cross section, which could significantly reduce the slender expression of the structure. Another option could be to give the columns a varying cross section, e.g. like in the METLA Forest Research Centre (Section 2.5).

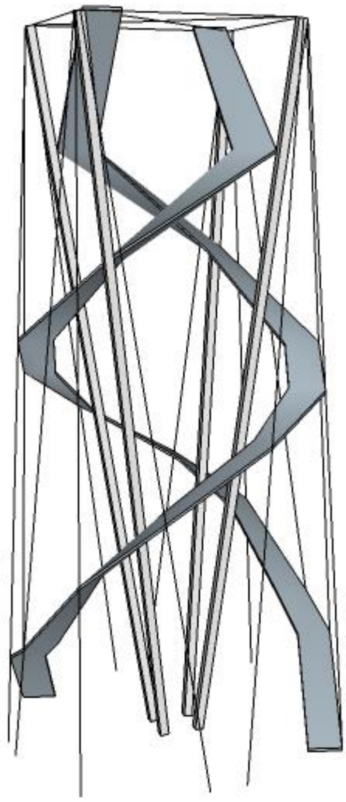


Figure 5.19 Digital model of the OUTSIDE/INSIDE concept. Author's own copyright.

Conclusions about the OUTSIDE/INSIDE concept:

- *Silhouette* - The tensile chords somewhat defines the silhouette of the tower, but from a distance they won't be seen, which means that from the ground the silhouette will be defined by the walk paths and further up by the columns.

- *Foundation needs* - Requires foundation work in many points where the tensile chords need to be anchored in the rock as well as under the central column. Each anchor point will be adapted to either tension or compression.

- *Slenderness* - The long and thin columns gives the structure an elegant and slender expression. However, the issue of buckling of long slender members in compression needs to be handled.

- *Intertwined and free* - The paths can wind quite freely as both columns and chords can be adapted in terms of placement and inclination. That way the paths are not required to have a certain inclination or to climb a certain height per rotation to allow for visitors on either that path or the other to be able to walk straight.

5.7 Comparison of the initial concepts

To choose what concepts to move forward with, the concepts shall first of all be evaluated in terms of whether or not they fulfil the criteria set up in Section 4.4. Secondly, the concepts shall be evaluated compared to each other to determine which ones to move on with.

Starting with the criteria for the structure, all concepts are designed with the thought of them being about 25 m tall so that criterion is fulfilled in all cases. All concepts have also been discussed with regards to their structural behavior and seem possible to achieve. Whether they can be built by hand from smaller elements is difficult to say at such an early stage. Some concepts have very large members, like the compressed columns in the PINE and OUTSIDE/INSIDE concepts, but those could be divided into shorter pieces. The pretensioned cables however may be difficult both to handle by hand due to their weight and to tension, but as it isn't absolutely necessary to do everything by hand this should not exclude these concepts at this stage.

Though the possibility of creating a load bearing structure for each concept has been discussed and solutions found, the SWIRL concept is a little tricky. Just like some of the other concepts essentially become the SWIRL concept when considering the movement to be the structure, the SWIRL concept itself turns into something else when the movement isn't the structure. Though the solution similar to the cantilever bridge in Bhutan is an option, it seems more reasonable to use one of the other solutions, hence rendering a different concept. For these reasons, the SWIRL concept was eliminated.

The criteria for the function states that the tower should provide a view, which all concepts have the ability to fulfill. The other criterion is that it should have an eye opening effect. Such an effect implies the realization of something unconventional and unexpected. All concepts, aside from the LAYERS concept, has the possibility to have an interesting silhouette that can give the tower attention. The LAYERS concept along with the PLATES concept both build on the innovative idea of the big walls that make up the tower, which if a better solution for the walk paths is found, could be a really interesting tower. At this stage, none of the concepts can really be excluded for not fulfilling the function related criteria.

Regarding the site, the criteria states that the towers should fit on the site. As it is approximately 20 x 30 m big, none of the concepts should present any problems regarding this. Adapting the structure to the uneven ground should not be a problem either.

To move forward, some decisions have to be made. As the criteria itself didn't help much at this stage, other aspects will have to be discussed. Besides the eye opening effect, the two separate paths up and down the tower were deemed important as it was a key factor going into the conceptual design. The SWIRL (which has been eliminated), the PINE and the ROTATIONAL concepts are the concepts that are the absolute most clear ones in terms of displaying two paths. The OUTSIDE/INSIDE can be quite clear in that aspect as well, while the LAYERS and the PLATES concepts become more of a maze where the two paths are just later additions.

Going back to the silhouette, the LAYERS concept is bad. The PLATES concept is slightly better, but it still doesn't allow for the same freedom that many of the other concepts do. SWIRL, PINE and ROTATIONAL are all concepts that are very good for creating a silhouette. The cables somewhat define the OUTSIDE/INSIDE concept, but those are so much thinner than the paths, so there is still a certain possibility to create a silhouette with the paths.

Both the LAYERS concept and the PLATES concept felt forced when the paths were integrated into the digital models. Neither concept started from the idea of the two intertwined paths, but rather from ideas of what the structure would look like, so when the paths were added, it didn't come naturally. These concepts are lacking what the other four concepts have, that is that architecture and structure is one and the same. What is interesting about them though is the possible variations in mesh density and the degrees of transparency that can be achieved from both varying the mesh and providing situations where there can be more than one wall between the visitor and the surroundings. The idea that two people can be in almost the same place, but separated by a wall, is also interesting. The PLATES concept is extra interesting as a sculpture with its large plates balancing on top of each other. These aspects of the two concepts should be further investigated. Hopefully, through model building and discussion these thoughts can developed into one new concept.

Two other concepts that should be combined are the PINE concept and the OUTSIDE/INSIDE concept. They are both based on one or many central columns that are kept in compression by pretensioned cables and where the walk paths are carried partly by the tensile chords and partly by the central column/-s. Therefore, it seems natural to combine these two concepts into one.

Finally, after comparing and evaluating the initial concepts, five of the six concepts were chosen for further work. However, as has been described above, some concepts were to be combined into one. In the end, the following 3 concepts were chosen to continue working with:

- The initial PLATES and LAYERS concepts combined into a new PLATES concept.

- ROTATIONAL
- The initial PINE and OUTSIDE/INSIDE concepts combined into a new OUTSIDE/INSIDE concept.

6 The Most Promising Concepts

After the first initial ideas and concepts were investigated, discussed and evaluated, it was time to go more into detail on the most promising concepts in search of the final concept to implement in the case study. In this chapter, the concepts will be developed to a point where a simplified analysis can be made to get a first idea of the material and dimensions necessary as well as the feasibility of the structural system as a whole. Thereafter they will be evaluated.

Among the three chosen concepts from the previous chapter, two are concepts that are to be developed from combining two of the initial concepts. The third one is already functioning as it is, but it still has development potential. Below, all three concepts will be developed through discussion and/or physical model. The concepts will then be analyzed in the commercial finite element analysis software FEM-Design to clearly show that they function and to give a first indication of the required cross sections for the structural members.

The concepts will also be discussed in terms of how they could be built. What are the element sizes and can they be made small enough to achieve the goal of building it by hand?

Finally, the concepts will again be compared to each other and evaluated based on the criteria set up in Section 4.4. With regard to the result of this evaluation, as well as what findings have been made in the architectural thesis, one concept will be deemed the best for developing even further.

The intended workflow for this chapter, to develop the concepts to a stage where the evaluation can be performed, is as follows:

- Develop physical and/or digital models to the point where there is a structural concept to analyze.
- Make digital line-models in Rhinoceros and import into Fem-Design.
- Make FEM-Design model and run an analysis using only dead load of the structure to ensure that it doesn't collapse.
- Improve line model and FEM-Design model if necessary.
- Apply loads and create load combinations in FEM-Design.
- Run the simplified analysis in FEM-Design to get preliminary dimensions of the structural elements.

Material qualities and parameters used for the analysis and dimensioning in FEM-Design are:

Service class: 2 (European Committee for Standardization, 2009c, chapter 2.3.1.3)

Glulam L40c

$\gamma_M = 1.25$ (European Committee for Standardization, 2009c, chapter 2.4.1)

$k_{cr} = 0.67$ (European Committee for Standardization, 2009c, chapter 6.1.7)

6.1 Loads and load cases

The loads that are applied in the analysis below were calculated for each concept separately, with some different assumptions for each concept depending on their geometry. However, for all concepts the basic load combinations and input data from Eurocode and the nationally decided parameters for Sweden were the same. How these common assumptions were made and loads calculated is described here below.

The dead load of the actual modeled elements is easily applied in FEM-Design. As the tower will consist of more material than so, load corresponding to the dead load of the paths was applied as well. This load, along with loads corresponding to imposed load and snow load on the paths was applied in all nodes. Wind load was omitted in a first analysis, but added in a second step. Only load cases where load was applied everywhere, i.e. no asymmetric loading, was considered. Only unfavorable loading was considered, i.e. no lifting of the structure. Asymmetric loading and lifting would need to be considered at a later stage, in a more refined analysis.

The following load combinations from Eurocode were considered (European Committee for Standardization, 2010):

6.10a. Fundamental combination, ULS STR

$$q_d = 1.35 g_k + \sum_{j \geq 1} 1.5 \psi_{0,j} q_{k,j} \tag{6.1}$$

6.10b. Fundamental combination, ULS STR

$$q_d = 0.925 \cdot 1.35 g_k + 1.5 q_{k,1} + \sum_{j \geq 1} 1.5 \psi_{0,j} q_{k,j} \tag{6.2}$$

where g_k is the dead load of the structure, $q_{k,j}$ are variable loads and $\psi_{0,j}$ are coefficients for the specific type of load. The loads and coefficients that are used for the analyses can be seen in Table 6.1. Only ultimate limit state (ULS) load combinations were considered, as serviceability limit state (SLS) would require subjective parameters such as allowed deflection, sway and vibrations to be set. The SLS parameters should be discussed with a client and investigated at a later stage in the design and analysis.

Safety class 3 is chosen because it is expected that many people may be in the structure or close by it at the same time and that a collapse can be considered to cause risk for severe injuries to people and failure of part of the structure may be considered likely to cause collapse. Safety class 3 is the highest safety class. For design at ultimate limit state (ULS), safety class is considered by multiplying the load combinations, see equations (6.1) and (6.2), by the coefficient γ_d. For safety class 3 the coefficient $\gamma_d = 1$ and will hence not affect the values rendered by the load combinations above (Boverket 2016).

Table 6.1 Loads and coefficients for first structural analysis according to Boverkets konstruktionsregler, EKS 10.

Type of load	Duration class	Value of load	ψ_0 (Boverket, 2016, p. 24)
Dead load of walk paths and top platform	Permanent	0.6 kN/m^2 *	-
Imposed load from visitors (cat C5)	Medium	5 kN/m^2 **	0.7
Snow load, s_k	Short	2.5 kN/m^2 ***	0.7
Wind load, F_w	Short	$2.5025 \cdot A_{ref}$ ****	0.3

* *An assumption that is considered to be on the safe side, i.e. a high value of the actual weight of the path.*
** *Eurocode 1 (European Committee for Standardization, 2009a, chapter 6.3.1)*
*** *Boverkets konstruktionsregler, EKS 10 (Boverket, 2016)*
**** *see explanation below*

For snow load, the load s is calculated as:

$$s = \mu_i C_e C_t s_k \tag{6.3}$$

where both the exposure coefficient C_e and the thermal coefficient C_t are equal to 1.0. The shape coefficient μ_i depends on the size and angle of the surface that is subjected to snow as well as potential obstructing objects such as walls against which snow may gather. For flat or low sloping roofs, with a slope of 0° to 30°, this factor is 0.8 (European Committee for Standardization, 2009b, chapter 5). For this first structural analysis μ_i is assumed to be 0.8, because the walk paths are assumed to be open so that there is no risk of snow drifting. In addition to this it is very unlikely that there will be visitors in the tower at the same time as there is snow.

The wind load is dependent on geographical location and type of terrain among other things. The reference wind speed in the municipality of Bengtsfors is (Boverket, 2016):

$$v_b = 24 m/s \tag{6.4}$$

For the site, terrain category III is assumed, which renders the following coefficients (European Committee for Standardization, 2008, chapter 4.3.1):

$$z_0 = 0.3\ m \tag{6.5}$$

$$z_{min} = 5\ m \tag{6.6}$$

For a building height of 25 m ($z = 25\ m$) and for the given reference wind speed and terrain category, the characteristic peak velocity pressure is (Boverket, 2016):

$$q_p(z) = 0.77\ kN/m^2 \tag{6.7}$$

$z = z_e$ is the reference height of the structure. Though a lower value for the wind pressure could be assumed for the lower parts of the structure, the value corresponding to the top of the tower is used for the whole tower at this stage in the design (European Committee for Standardization, 2008, chapter 7.2.2).

What wind load to account for in the analysis is further dependent on shape coefficients. According to the code, free standing walls where >20% of the area is openings should be regarded as trusses (European Committee for Standardization, 2008, chapter 7.4). Considering the configuration of the concepts in this study, it is deemed that all of these structures can be regarded as trusses in terms of how they catch wind, and hence the rules for free standing walls will apply.

At this stage of the design, the width of the tower, the length of the paths and so on is not set. Hence, the amount of surface area compared to openings is unknown. It is however known that regardless which concept is chosen it will be three dimensional. Therefore, the highest shape coefficient, which renders the highest force due to wind load, is chosen (European Committee for Standardization, 2008, chapter 7.11):

$$c_{f,0} = 3.25 \tag{6.8}$$

To ensure that the highest wind load is used in the analysis, no reduction should be made and the reduction factor is set to (European Committee for Standardization, 2008, chapter 7.13):

$$\psi_\lambda = 1 \tag{6.9}$$

The force coefficient of lattice structures and scaffolding is defined as (European Committee for Standardization, 2008, chapter 7.11):

$$c_f = c_{f,0} \cdot \psi_\lambda \tag{6.10}$$

Furthermore, it is assumed that (European Committee for Standardization, 2008, chapter 6.2):

$$c_s c_d = 1 \tag{6.11}$$

The wind force, F_w, on any part of the structure can then be determined using the following expression (European Committee for Standardization, 2008, chapter 5.3):

$$F_w = c_s c_d \cdot c_f \cdot q_p(z_e) \cdot A_{ref} \tag{6.12}$$

where the reference area A_{ref} is defined as (European Committee for Standardization, 2008, chapter 7.11):

$$A_{ref} = A \tag{6.13}$$

where the area A is the area of the projection of the structure on its windward side (European Committee for Standardization, 2008, chapter 7.11).

With the above mentioned numbers, the expression for the wind force becomes:

$$F_w = 1 \cdot (3.25 \cdot 1) \cdot 0.77kN/m^2 \cdot A_{ref} = 2.5025kN/m^2 \cdot A_{ref} \qquad (6.14)$$

Assumptions for reference area are made for each structure in the following sections of the chapter.

6.2 Development of the PLATES concept

There were interesting aspects of the initial concepts from which the new PLATES concept is to be developed. These aspects are the possible variations in mesh density, the degrees of transparency, that two people can be in almost the same place only separated by a wall and to create a tower from balancing large plates on top of each other. Another aspect that has to be considered is how plates carry load and how they transfer load from one plate to another. It was discussed in Chapter 5, Sections 5.2 and 5.4, how continuous connections is most effective for plates and how pointwise connecting plates may require very much from a very small area of an otherwise strong enough plate. These interesting points led to four new ideas to investigate:

- Being inside the plates instead of on the side of them.
- Letting the walls create frames instead of just walls.
- Creating boxes and stacking them on top of each other.
- Creating multiple plates that are parallel to each other.

As it felt forced from a conceptual and architectural point of view to attach walk paths to the sides of the plates, the first idea was to make them into thicker walls and to create walk paths inside them came up. By doing so, pointwise connections to other walls would also have a larger contact area compared to the initial concept due to the thicknesses of the walls. The idea came up that this concept could be a combination of vertical and horizontal plates where the movement within each plate would be limited to the two in plane dimensions, i.e. either you can move for example up and forward or forward and to the side. The models that came out of this idea can be seen in the top row in Figure 6.1.

To be able to move in three dimensions the second idea developed. That's the idea of frames (the second row in Figure 6.1). There the forces could be transferred from one plate to another within a frame via a continuous connection and between frames the contact areas could be made sufficiently large to transfer forces as well. The fact that the frame is open on two sides would direct the attention of the visitor in a certain way, e.g. forward, to the side or up.

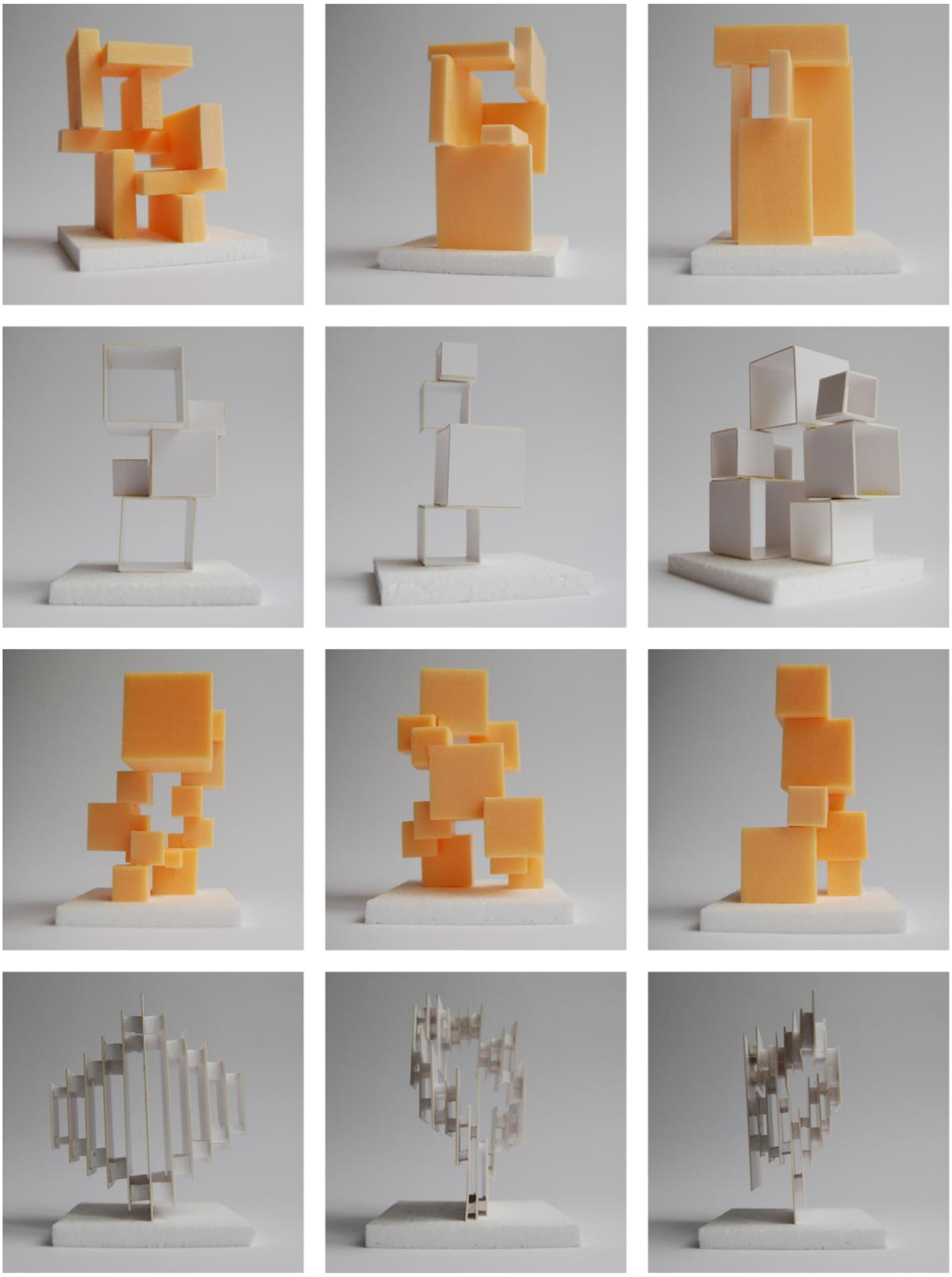


Figure 6.1 *Concept models of the further development of the PLATES concept. Author's own copyright.*

As square frames aren't necessarily stable in themselves, the third idea developed. By closing the two open sides of the frames and turning them into boxes they become stable (the third row in Figure 6.1), though at the same time the idea of opening up sides to create a direction of the space is lost.

The fourth idea was to create multiple plates that are parallel to each other (the bottom row in Figure 6.1). This idea came from the much appreciated architectural idea of being able to be in almost the same place, just separated by a wall. However, the plates in these models are all parallel, which completely eliminates the effective way in which plates transfer in plane forces over to an adjacent plate via a continuous connection and where an angle between the plates is required to handle forces in other directions than the in-plane directions.

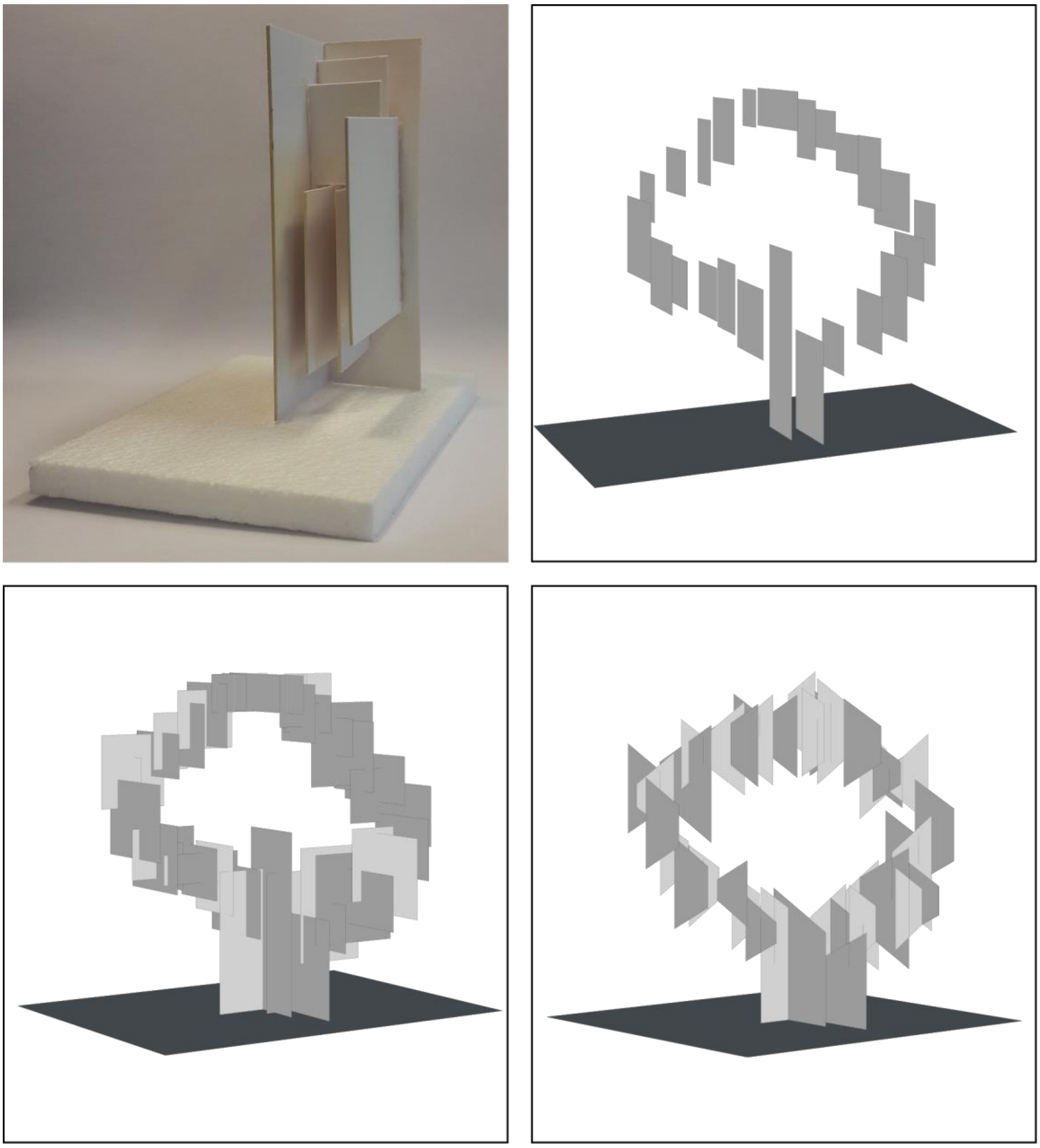


Figure 6.2 Physical and digital sketch models to further investigate offset and perpendicular plates. Author's own copyright.

Though it is structurally inefficient, the fourth idea was found to be the most interesting and innovative out of the new PLATES concept ideas. The reason for this was the possible experience in the tower, with possibilities to move along a plate and potentially through it. Another argument for this idea was the eye opening aspect, i.e. that no other observation tower seems to have been built this way. However, the concept needs load carrying elements in the direction perpendicular to the plates to actually be a structural concept. Therefore, a set of plates in that perpendicular direction was considered (Figure 6.2).

After doing these models and considering them from a structural point of view as well as how the two intertwined paths would fit, the conclusion was that this concept doesn't really allow for a clear structural system and there is no obvious way to create the paths. Of course, the structural problems could be solved if the task at hand was merely to solve the load bearing system for a given piece of architecture. However, as the task at hand is to find a load bearing system that is part of a concept for the tower, this concept does not seem to suffice, or the time required to find a solution is simply more than the time at hand. Instead, the idea of the different degrees of transparency and the possibility of designing paths that are right next to each other but still separated are kept in mind for later.

6.3 Development and analysis of the ROTATIONAL concept

The ROTATIONAL concept was the only concept that was kept as it was out of the initial concepts. That doesn't mean that there aren't other aspects to consider and things to adjust in this concept. However, the structural system of the ROTATIONAL concept is a space frame or a three dimensional truss and this first analysis of it will be performed on the initial configuration.

As the goal of this analysis is to get a first idea of what dimensions are feasible and what elements are required to make the structure stable, certain simplifications were made. First, the shape of the columns was considered. Though the shape of the columns has a clear origin in the way they were designed, their curvy shape isn't read that easily in the tower structure and hence doesn't look clearly motivated. The shape of the paths is somewhat similar in that sense. The idea this brought up was whether the paths could wind inside as well as outside of the columns. In Chapter 5, Section 5.5, the idea of having volumes that differed from bottom to top was brought up. That could give the shape of the path while the shape of the column is given by a more "average" shape, like the ones in the initial concept. The shape of the columns could also be rendered by imagining a straight column and letting the paths push it outwards or inwards, so that the tower becomes a weave of columns and paths.

Another aspect of the columns to consider is that when their shape is rendered by the intersection lines of two volumes they can become twisted. For the columns to be possible to build from smaller parts it would be preferable to adapt the shape of the columns in such a way that each segment is either straight or curved around one axis instead of two. This could be done either through an approximation of the twisting columns or by adapting the way the columns are designed from the beginning. An example of the latter method can be seen as the way that the columns of the Pyramidenkogel tower, described in Chapter 2, Section 2.2, are designed. Those columns are curved, but there is no twist or double curvature. Starting from the same volumes as in the initial concept and intersecting those with a plane instead of each other such flat columns can be achieved (Figure 6.3). Each plane gives two columns and each of these columns is like two columns rendered by the two volumes. Depending on the orientation of the plane in relation to the bodies the columns get different shapes. In the figure four planes, rotated 45° in relation to each other, are used, which renders four pairs of columns of the two different kinds that can be seen to the right in the figure.

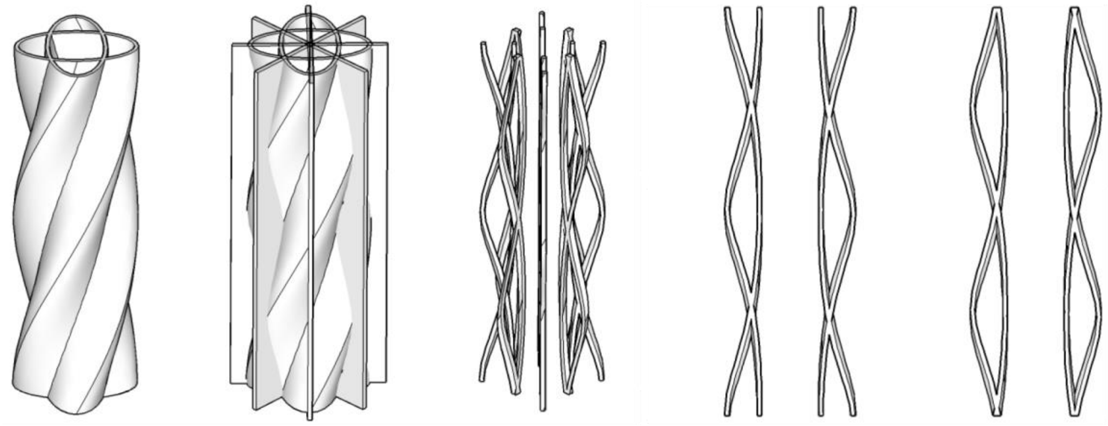


Figure 6.3 Columns from the intersection of planes and volumes. Author's own copyright.

To get an idea of the required dimensions for this tower, the model from the initial concept was analyzed in FEM-Design. A simplified model of the tower (Figure 6.4), was built up according to the following description. First, nodes were given as the points where the walk paths touch the columns. The columns were then approximated as straight elements between these nodes. The walk paths were modeled as straight diagonals between the nodes. With no more bracing units than the paths contribute, the structure could only be stable if the columns act as continuous members over the nodes, i.e. if modeled as beam elements with moment transferring joints. As timber joints are difficult to create in such a way and actual continuous columns would become heavy and with double curvature, it is preferable to consider the joints as pinned and therefore diagonals in the other direction were added to create a stable structure. In the model, all elements are modeled as simply supported truss members, i.e. bars with pinned connections.

At the bottom of the tower, the diagonals corresponding to the paths end where the path end, i.e. not at the bottom of the columns (Figure 6.5). At the top the same thing applies to the paths. The ends of the paths and the tops of the columns have also been connected using the modeling tool "fictitious bar". This type of bar is a modeling element that functions as a truss member with infinite stiffness. The top of the tower is supposed to be built as a platform and therefore will have a stiffness that is large in relation to the truss structure.

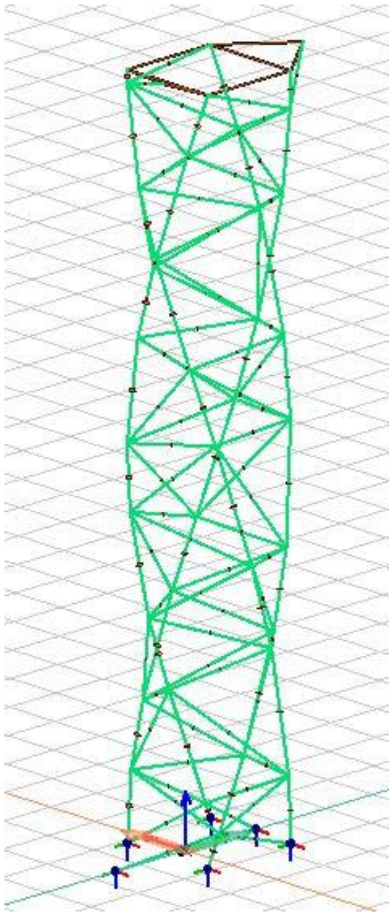


Figure 6.4 Truss model of straight elements for analysis in FEM-Design. *Author's own copyright.*

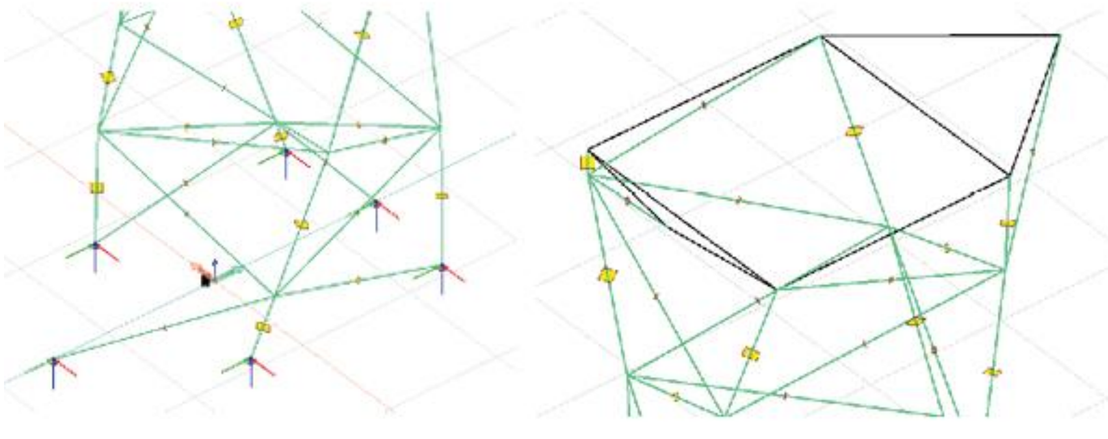
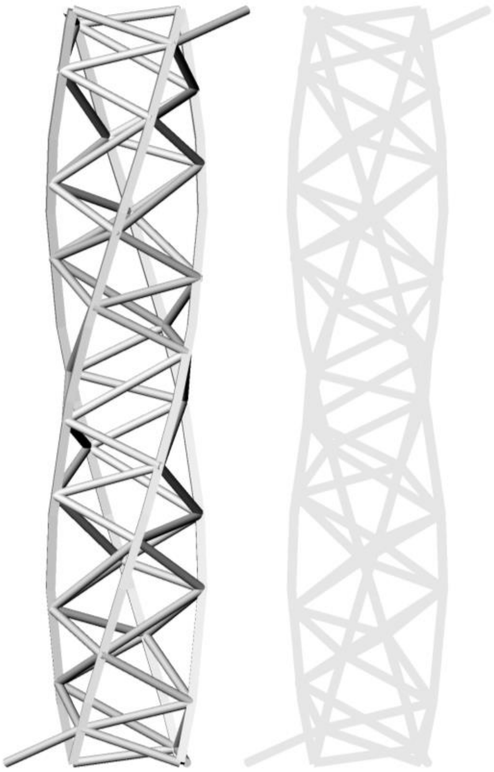


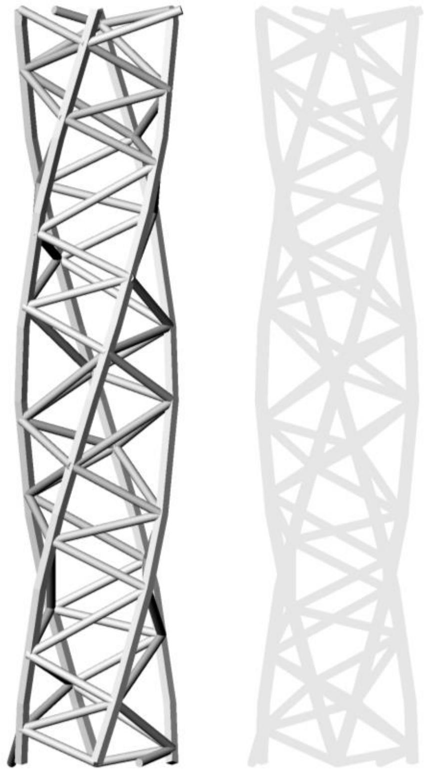
Figure 6.5 Bottom and top of the FEM-Design model. *Author's own copyright.*

The paths alternate between cantilevering out more and less from the columns. Where it is more, the length of the path from column to column is about 9.5 m and where it's less the length is about 4 m. To apply loads in the nodes, an average length of 6.75 m was considered to be the length of walk path from which the load is transferred to each node. To calculate the loads from area loads to point loads a width of 1.2 m was assumed for the walk paths. For the top platform, an area of 20 m^2 was considered and the load was divided equally between the four column tops.

The wind load was simplified in a different manner. As the walk paths were assumed to have railings made up of ribs so that the wind would mainly blow through, they were not directly taken into account. Instead, the area of the tower structure that the wind would hit was considered and multiplied by 1.2, i.e. 120% of the area subjected to wind was considered. The structural elements considered were the columns and the diagonal members corresponding to the walk paths and the additional bracing units. These structural elements were all considered to have a width of 0.3 m for this calculation. The total wind load, i.e. the area multiplied by the wind load per area, was equally distributed between all 40 nodes in the columns and applied as horizontal point loads.



$A_{ref90°} = 69.1m^2$



$A_{ref45°} = 74.2m^2$

Figure 6.6 The ROTATIONAL concept structure from two angles and the corresponding areas subjected to wind. Author's own copyright.

Two load cases were considered for wind load, one where the wind hits straight from one side, i.e. at 90° and one case where the wind hits at an angle of 45° compared to the first case. The magnitude of the load was considered to be the same for both cases. The tower structure from these two angles and the areas subjected to wind load in the two cases can be seen in Figure 6.6. The wind loads applied as well as the dead load, aside from that of the modeled structural elements, the snow load and imposed load are presented in **Fel! Ogiltig självreferens i bokmärke.**.

Table 6.2 Loads applied for the analysis of the ROTATIONAL concept.

Type of load	Point of application	How it was computed	Point load
Dead load of walk paths	All nodes where path and column meet	6.75m*1.2m*0.6kN/m^2	4.86kN
Dead load of top platform	Top nodes of columns	20m^2/4*0.6kN/m^2	3.0 kN
Imposed load on walk paths	All nodes where path and column meet	6.75m*1.2m*5kN/m^2	40.5kN
Imposed load on top platform	Top nodes of columns	20m^2/4*5kN/m^2	25kN
Snow load on walk paths	All nodes where path and column meet	6.75m*1.2m*0.8*2.5kN/m^2	16.2 kN
Snow load on top platform	Top nodes of columns	20m^2/4*0.8*2.5kN/m^2	10 kN
Wind load, 90°	All nodes	$1.2 \cdot 69.1m^2 \cdot 2.5025kN/m^2/40\ nodes$	5.2 kN
Wind load, 45°	All nodes	$1.2 \cdot 74.2m^2 \cdot 2.5025kN/m^2/40\ nodes$	5.6 kN

1st analysis - No wind load

First, an analysis was performed without applying any wind load. The structure was divided into three types of structural members; Verticals (the columns), Walk paths (the elements corresponding to the walk paths) and Bracing (the additional bracing members). The governing load case turned out to be 6.10b with imposed load as main load. The resulting required dimensions and utilization ratios can be seen in Table 6.3.

Table 6.3 The required dimensions and utilization of the structural elements without wind load applied.

Structural member	Required dimensions	Max. utilization [%]	Min. utilization [%]
Bracing	Glulam 190x180	81	2
Verticals	Glulam 215x315	90	3
Walk paths	Glulam 115x360	98	4

2nd analysis - With wind load

When wind load was applied, different load cases became governing for different structural members. In all cases 6.10b was governing, but it differed whether imposed load or wind load was the main load and in which direction the wind blew. The resulting required dimensions and utilization ratios can be seen in Table 6.4.

Table 6.4 The required dimensions and utilization of the structural members with wind load applied.

Structural member	Required dimensions	Max. utilization [%]	Min. utilization [%]
Bracing	Glulam 190x225	87	3
Verticals	Glulam 215x450	97	2
Walk paths	Glulam 165x450	98	3

Discussion

When wind load is applied, the required cross sections for the elements increases as can be expected. For the vertical elements, i.e. the columns, 450 mm may seem too big. However, as glulam is only produced in widths of up to 215 mm a wider cross section isn't possible to achieve with only one glulam beam and hence isn't an option according to the software. To get a cross section that is square, or close to square, one could consider gluing two beams with smaller cross sections together. If the two beam solution is chosen they could also be placed at a distance from each other so that elements in a different direction, e.g. the bracing units, could be placed in between. Another alternative to achieve smaller columns is of course to use more columns. Figure 6.3 describes how more columns can be rendered from the intersected volumes. With more columns, it is natural that the individual column will be slenderer.

Regarding the weight of the structural elements in the analyzed version of the concept, the analysis renders structural elements that weigh up to 184 kg. With a small group of 4-5 people that may be possible to handle, but it is not optimal. Though, with the double members or more columns, the element weights would of course decrease.

6.4 Development of the OUTSIDE/INSIDE concept

The development of the new OUTSIDE/INSIDE concept was straight forward. Combining the two concepts added some new possibilities to the OUTSIDE/INSIDE concept. The original PINE concept had a completely vertical compressed member and it also had the cables that adapted to the walk paths, i.e. the design of the paths came first and the tensile chords, i.e. the load bearing system, had to follow their shape, thus making the paths define the silhouette rather than the cables. Enabling this in the OUTSIDE/INSIDE concept is really the only significant change required to the concept to fulfill the combination of the two concepts.

Regarding the compressed members, the completely vertical one may be more effective than the tilted ones, but the tilted ones enable the journey from outside to inside. The idea that the paths decide how the cables run is more interesting than the other way around due to the silhouette, but at the same time it heightens the need for stiffness in the walk paths as they would not just be hanging from the cables chords but actually keeping the cables in their place horizontally.

Figure 6.7 Test of assymmetry and the implementation of walk paths into the OUTSIDE/INSIDE concept. Author's own copyright.

It was mentioned in the discussion about the initial OUTSIDE/INSIDE concept, see Chapter 5, Section 5.6, how the columns and cables could be placed asymmetrically. This could be something to consider for many reasons. One reason is the fact that the site is more rectangular than round or square. It can also become relevant to accommodate walk paths that extend out in various directions. To investigate this, a few models were built (Figure 6.7). In the left model, the columns are placed further apart. This gives the structure a larger support surface, which could make the structure more stable. On the other hand, this leads to the transition from outside to inside being almost diminished. It can, in terms of this spatial transition, be considered more effective to place the columns closer together and let them lean further outwards, like they do in the middle model. In the right model the columns have been placed close together and the walk paths decides what shape the cables follow. The columns have also been connected at the top with a ring, something that was initially done for practical model building reasons, but which could also be seen as a representation of the top platform and brace the compressed columns. The right model was also investigated in Rhinoceros (Figure 6.8), and in a larger physical model (Figure 6.9) to be able to see clearer how the paths could wind between the cables and columns.

It's been mentioned earlier (Chapter 5, Section 5.6) that there is a need to brace or stiffen the long vertical columns. That could be achieved either by applying purely bracing units and/or by letting the paths brace, which requires the paths to pass by and connect to the columns at certain points. These connections could not just stabilize the columns, but they would at the same time stabilize the paths, thus making them feel more stable closer to the columns, something that could work well with the idea of the spatial transition from outside to inside and what that is meant to be in terms of stability and perceived safety.

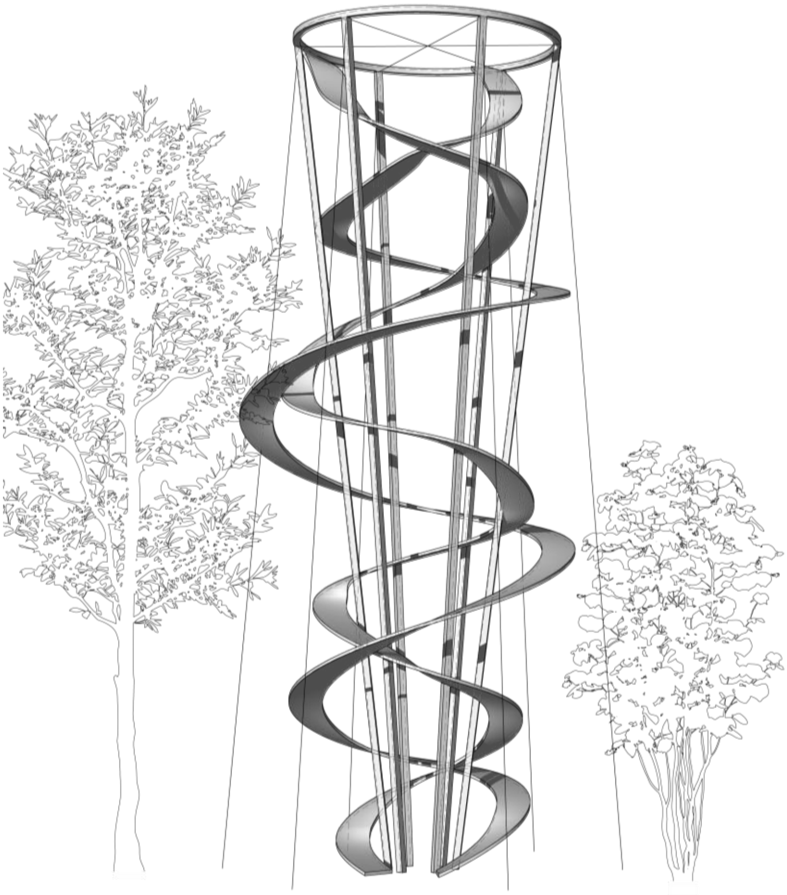


Figure 6.8 The developed concept modeled to get a clearer picture of how the paths would run in relation to columns and cables. Author's own copyright.

In analyzing this concept and the development so far, a few concerns were raised. When investigating the configuration of the paths, it became clear that the two paths would not really be intertwined, but rather parallel. The reason for this being that the different characters of the paths, desired for the intended experience of the visit to the tower, would require the thrilling path to run between the cables while the more conventional path would be restricted to the columns. This would also put certain limits on the lengths of the paths and hence affect the choice between stairs and ramps so that the accessibility of the conventional path would be restricted.

Regarding the actual construction of the tower, an important question was raised as well, namely how to get the elements in place. The columns could be cut into smaller pieces and assembled on site, but the cables would not only need to be delivered as units of their intended length, but they would need to be pretensioned with a force big enough to ensure that they would always be in tension. Though it was mentioned in the previous evaluation (Chapter 5, Section 5.7) that this shouldn't eliminate the concept, with the additional problem of the parallel rather than intertwined paths, this concept was longer a good idea.

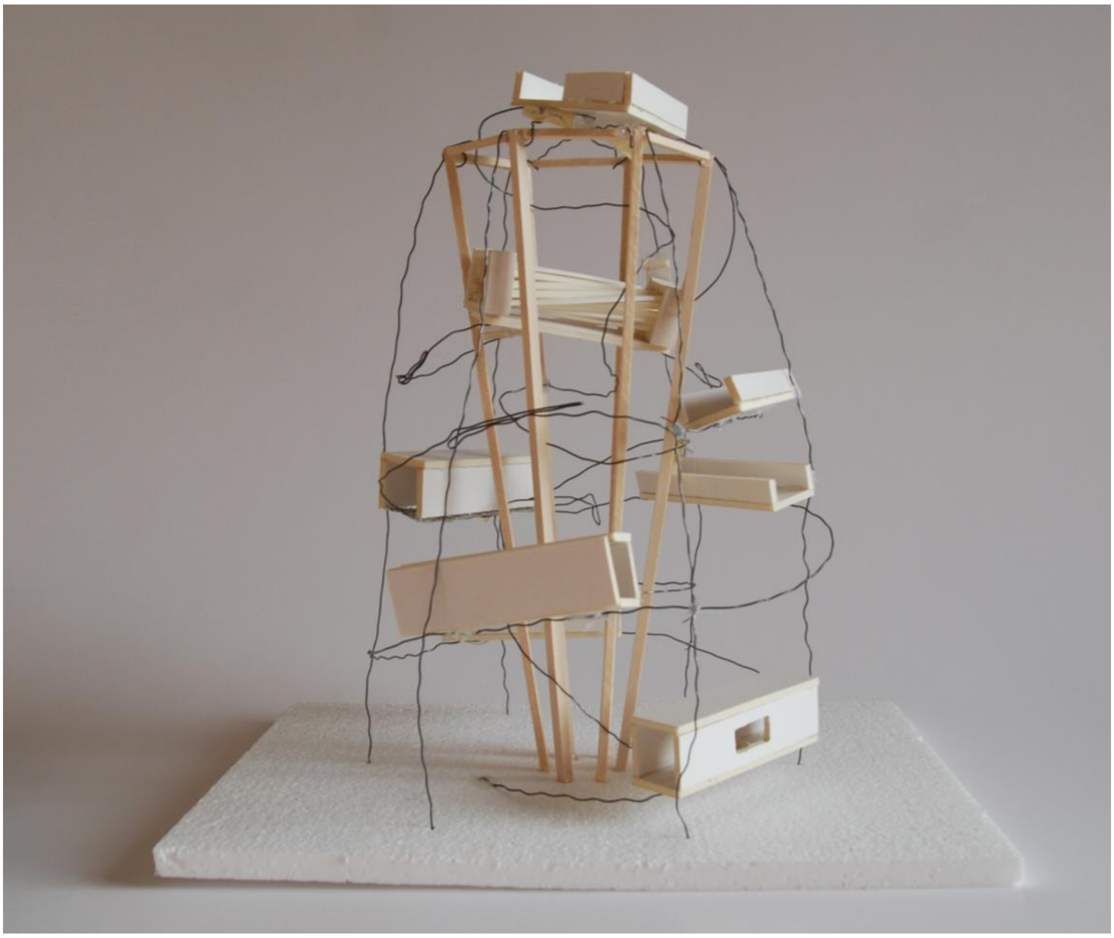


Figure 6.9 Physical model to investigate possible configurations of walk paths in the OUTSIDE/INSIDE concept. Author's own copyright.

6.4.1 Development and analysis of the alternative HYPERBOLOID concept

Though the OUTSIDE/INSIDE concept ultimately didn't develop into a desirable concept, the model with the walk paths from Figure 6.7 was still found inspirational. Looking at this model, it resembled the upper half of a hyperboloid. What if this was a hyperbolic structure? The HYPERBOLOID concept could have a small circumference at the bottom and be wider towards the top, similar to the Jüburg Hemer Landmark (Chapter 2, Section 2.1.2). With bigger, but fewer, members of the structure, the sparse impression of the original columns could be maintained and the structure would be stable in itself, with no need for cables.

To test the hyperbolic structure, a model was built in scale 1:100 (Figure 6.10). The model consists of 16 straight wooden elements, 8 leaning in one direction and 8 leaning the other way. The elements are connected two and two at the top and bottom and in three places in between. At the top and at the bottom the structure is stabilized by a circular plate made of foamboard, representing a top platform and the foundation. Though all horizontal rings but the top and bottom ones are missing, it is easy to tell from the model that the structure can become very stable. In the model, the two walk paths are represented by two steel wires that wind around the structure. In the model these wires add no load to the structure and possess no stiffness, they are only symbolic. As the hyperbolic structure is stable as a first assumption the walk paths would only be added loads and not contribute to the load bearing structure.

Figure 6.10 Physical model of the HYPERBOLOID concept. Author's own copyright.

The hyperbolic structure was modelled as a line model in Rhinoceros (Figure 6.11). The structure was given a diameter of 8 m, i.e. it was made wider and less slender than the physical model. Just like in the physical model, the paths are only symbolic and not be used in the analysis in FEM-Design. In the analysis, only the total length of the paths, estimated to 160 m, was used to compute loads from the walk paths. These loads were then equally divided between all nodes, except those at the bottom of the tower, which is a total of 32 nodes. To calculate the loads from area loads to point loads a width of 1.2 m was chosen for the walk paths. For the top platform, an area of 20 m^2 was considered and the load was divided equally between the tops of the vertical elements.

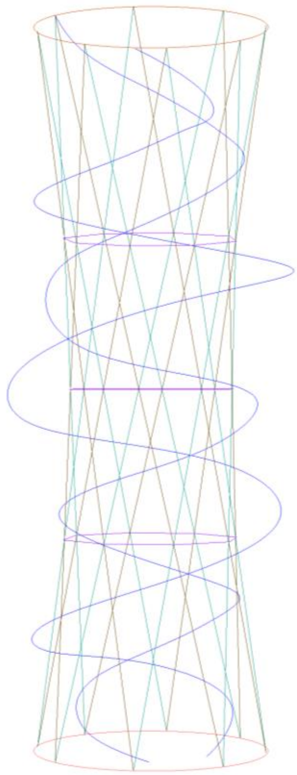
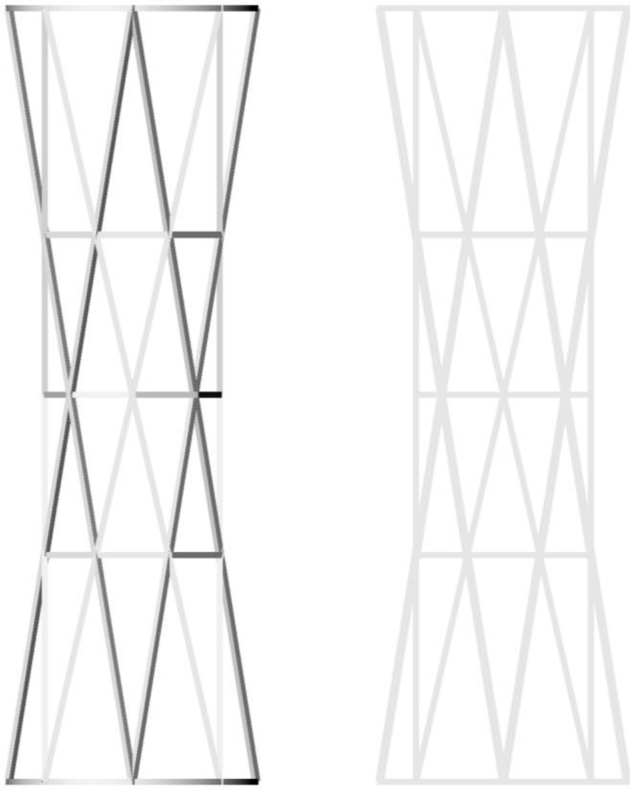


Figure 6.11 Line model for analysis in FEM-Design. Author's own copyright.



$A_{ref90°} = 51.5m^2$

Figure 6.12 The HYPERBOLOID concept structure and the corresponding area subjected to wind. Author's own copyright.

The wind load was simplified in the same way as for the ROTATIONAL concept above, with the only difference that there were no structural elements corresponding to the walk paths. The structural elements considered were the inclined elements that make up the hyperboloid and the horizontal bracing rings at the heights where the members of the hyperboloid intersect. These structural elements were all considered to have a width of 0.2 m for this calculation. The total wind load, i.e. the area multiplied by the wind load per area, was equally distributed between all 40 nodes and applied as horizontal point loads.

Only wind from one direction was considered in this concept as the area of the structure would be the same for both the case when the wind hits straight from one side and where the wind hits at an angle of 45° compared to the first case. Just like for the ROTATIONAL concept (Section 6.3), 120% of the area was assumed to be subjected to wind. The tower structure and its area used for wind load can be seen in Figure 6.12. All loads applied in the analysis, aside from the dead load of the modeled structural elements, are presented in Table 6.5.

Table 6.5 Loads applied for the analysis of the HYPERBOLOID concept.

Type of load	Point of application	How it was computed	Point load
Dead load of walk paths	All nodes except those at the	$160\ m/32\ nodes \cdot 1.2m \cdot 0.6kN/m^2$	3.6kN

	bottom		
Dead load of top platform	Top nodes of vertical elements	$20m^2/8 \cdot 0.6kN/m^2$	1.5kN
Imposed load on walk paths	All nodes except those at the bottom	$160\ m/32\ nodes\ \cdot 1.2m \cdot 5kN/m^2$	30.0kN
Imposed load on top platform	Top nodes of vertical elements	$20m^2/8 \cdot 5kN/m^2$	12.5kN
Snow load on walk paths	All nodes except those at the bottom	$160m/32nodes\ \cdot 1.2m \cdot 0.8 \cdot 2.5kN/m^2$	12 kN
Snow load on top platform	Top nodes of vertical elements	$20m^2/8 \cdot 0.8 \cdot 2.5kN/m^2$	5 kN
Wind load	All nodes	$1.2 \cdot 51.5m^2 \cdot 2.5025kN/m^2/40\ nodes$	3.9 kN

1st analysis – No wind load

First, an analysis was performed without applying any wind load. The structure was divided into two types of structural members; Verticals (the slanted members that make up the hyperboloid) and Bracing (the rings). The governing load case turned out to be 6.10b with imposed load as main load. The resulting required dimensions and utilization ratios can be seen in Table 6.6. As the structure isn't subjected to any horizontal forces and all vertical forces are applied in nodes where two slanted vertical members meet, the members of the rings are not always stressed, which can be understood from the description of the load bearing structure in the tower in Holmers-Halkenbroek (Chapter 2, Section 2.1.2).

Table 6.6 The required dimensions and utilization of the structural elements without wind load applied.

Structural member	Required dimensions	Max. utilization [%]	Min. utilization [%]
Bracing	Glulam 42x135	67	0
Verticals	Glulam 190x225	90	25

2nd analysis - With wind load

When wind load was applied, different load cases became governing for different structural members. In all cases 6.10b was governing, but it differed whether imposed load or wind load was the main. The resulting required dimensions and utilization ratios can be seen in Table 6.7.

Table 6.7 The required dimensions and utilization of the structural members with wind load applied.

Structural member	Required dimensions	Max. utilization [%]	Min. utilization [%]
Bracing	Glulam 66x90	52	4
Verticals	Glulam 215x225	96	18

Discussion

The reason for the large dimensions of the vertical members is neither compressive nor tensile strength requirements, but rather flexural buckling. There are some measures that could be considered to decrease the dimensions of the vertical elements. Adding more bracing to decrease the buckling lengths of the structural elements is one option. That could be achieved either by simply adding horizontal bracing units, e.g. halfway between the existing rings, or by inclining the vertical elements more so that the tower naturally becomes divided more times and then add bracing at these new intersections between the vertical members. The latter would also have the effect of the waist of the tower becoming narrower. Another option is to add more vertical elements. The more vertical elements there are, the slenderer each of them can be. However, the buckling lengths could still become a problem since the load on each member would be smaller but the cross section would too.

The idea that led to the development of the OUTSIDE/INSIDE concept into a hyperbolic structure was that by doing so the cables could be excluded and the structure would also be stable without additional bracing. However, for the design of the walk paths to be freer, as implied by the symbolic wires in the model (Figure 6.10), than what they are if they follow the surface of the hyperbolic it may be necessary to use compressive struts and/or cables to keep the walk paths in place. Though this doesn't change the actual path and its location, it changes the idea of the spatial concept as the transition from outside to inside along with how the path would sway when in the outside zone and carried by tensile chords and become more stable as it approaches the top and the inside zone are lost. The hyperboloid also diminishes the spatial transition as it is as wide at the bottom as it is at the top, but if only the upper half of a hyperboloid is used, the intention of the concept can be fulfilled.

6.5 Development of design criteria

As the structural concepts had developed, so had the work in the parallel architecture thesis. The architecture thesis had so far carried out what has been called “spatial investigations”. It started out considering what an observation tower can provide more than stairs leading from the ground to a viewpoint. An investigation of how to design to allow the visitor to experience certain views along the way and to focus the attention of the visitor was done. This investigation consisted of setting up the parameters that define being, among other things, over, inside, between and on top. This investigation also went into considering where these situations should be experienced in terms of height over the ground, saying that for example being over and on top requires a certain distance to the ground. Distance to the main load bearing structure, which could be perceived as secure, stable and safe, was also considered. This investigation developed into experiences with different characteristics, such as a place to stop or a thrilling experience. Eventually a system of such experiences and how they would be connected by stairs and ramps into complete paths from the ground to the top of the tower took form. From these investigations, the following criteria was obtained;

- The structure should allow for places where the visitor can stop and rest along the way to the top.
- The walk paths should consist of a mix of stairs and ramps.
- It should be possible to design walk paths close to the structure that are perceived as secure as well as paths that cantilever out and creates thrilling experiences.

Besides the above listed criteria, thought was also put into other necessary elements of the tower. Railings, landings along the walk paths and the platform at the top are such necessary elements in creating the tower. If such elements are kept in mind from the beginning, the end result has the potential of being something much better than if those things are just added at the end. That way there is a possibility of making them an integrated part of a structural system, not just additions.

6.6 Comparison of the more promising concepts

At this point, the concepts had developed further and as the parallel thesis in architecture had developed, new criteria to use in the evaluation had formed.

In investigating the PLATES concept further, it was discovered that the concept didn't lead to a structural system that was interesting for the project at hand. The PLATES concept could therefore be eliminated.

The ROTATIONAL concept was proven to be more interesting. As the overall shape of the structural system is rendered by the walk paths, the concept is really an integration of architecture and structure. At the same time, regardless of how elaborate and complicated the design of the walk paths become, the structural system will remain a truss.

The OUTSIDE/INSIDE concept was proven difficult to motivate in its original shape. Architecturally, it isn't natural for the paths to be intertwined until they approach the top and they're both close to or inside the space defined by the columns. Structurally, pretensioning of cables among other things made the concept seem irrational.

From the OUTSIDE/INSIDE concept, the HYPERBOLOID concept developed. Unfortunately, both the OUTSIDE/INSIDE concept and the HYPERBOLOID concept that followed turned into more of a structural system onto which walk paths were to be placed, rather than a system that was derived in symbiosis with the architecture. The problems due to restrictions of path lengths and that the paths become parallel in the OUTSIDE/INSIDE concept remain even as the concept developed into the HYPERBOLOID concept.

If returning to the original criteria for the structure, and the thesis questions, the structure should be possible to build by hand and by inexperienced workers. To make this possible, the structural elements have to be small enough so that they don't become too heavy. The construction process would be further simplified if the structure that is being built can be raised from the bottom up and if the walk paths can be built along with it so that the workers can stand on them while completing the next step upwards in the structure, then scaffolding can be limited or eliminated. Among the concepts presented in this chapter the truss in the ROTATIONAL concept and maybe the HYPERBOLOID structure exhibit this quality. Though the heaviest elements in the ROTATIONAL concept are on the verge of being too heavy according to the analysis, possibilities to solve this problem has been pointed out.

To sum it up, it is either the ROTATIONAL or the HYPERBOLOID concept that should be elected as the chosen concept to move further with. As the HYPERBOLOID concept exhibits problems regarding the basic idea of the intertwined paths and puts unnecessary restrictions on the length of the more conventional path, it is eliminated. So, it is the ROTATIONAL concept that is found to have the highest potential and with which the work will continue.

7 The Chosen Concept

The ROTATIONAL concept was considered the best alternative for this project for structural and architectural reasons as well as practical aspects when it comes to the construction process. However, it was also proven to be a bad concept for several reasons. One reason is of course that the structural elements become quite heavy and would be difficult to handle by hand, especially with unskilled labor. As the work within the architecture thesis progressed and more elaborate walk paths were investigated, it turned out that two walk paths with a more arbitrary shape than the ones in the initial concept do not necessary describe these volumes that intersect nicely to form columns. Neither does the intersection between the volumes and planes (Figure 6.3) work smoothly. Furthermore, the architectural expression becomes something that twists for no apparent reason, not something that lead your thoughts to the initial volumes. From there a new idea formed, intended to find a way to derive the structure in a way that would utilize the volumes in a better way.

7.1 Redeveloping a concept where the walk paths define the structure

To come up with a new version of the structural concept that would consist of smaller, and thereby lighter, elements and that would function regardless of the shape of the paths, a new idea was tried out. The idea is that each of the two walk paths is described by a curve and that curve describes a volume. The two volumes corresponding to the two paths then together create two new volumes that are the union and the intersection of the two volumes, like an outer and an inner surface (Figure 7.1). By letting the two paths run in either the same or opposite directions this idea renders four alternatives. Furthermore, the curve that describes the path and its corresponding volume can be considered to follow either the inner or the outer edge of the path, or to be located somewhere within its width (Figure 7.2). When combining the alternatives for the volumes and the alternatives for the paths, twelve options are rendered (Figure 7.3 and Figure 7.4).

There are differences and similarities among the twelve alternatives. Structurally, all the alternatives above function more or less the same. The alternatives that are based on the outer surface may be more stable than those based on the inner surface because of their lower height to width ratio, but other than that they are very similar. The paths also create differences. With both the outer and the inner surface representing the structure, paths can run freely. With the outer surface, these free paths are on the inside, while with the inner surface they're on the outside. The paths on the outside are likely to require some more attention for structural reasons as they cantilever out and creates a moment both in their connection to the structure and in the global structure as the load is applied outside of its supports. However, a solution similar to the walk paths of the Sky Walk (Figure 2.12) should solve this. From an architectural point of view the alternatives were more diverse and exhibited some interesting qualities (Figure 7.5). One of these qualities was the curves running in opposite directions, as they would naturally meet and connect the two paths visually. Another was that the paths described by a curve within the width of the path would create interesting experiences as they alternate between inside and outside the structure. Finally, the paths that run free from the structure, especially on the outside, would render thrilling experiences. Unfortunately, neither of the twelve alternatives exhibited all of these qualities.

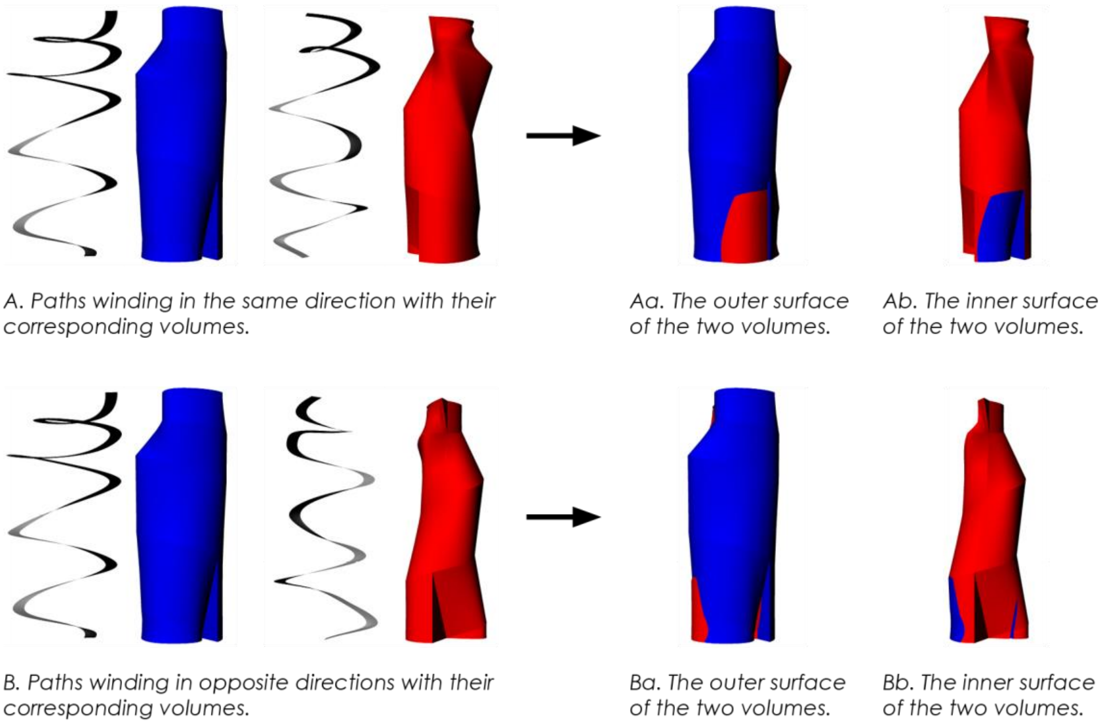


Figure 7.1 *Two volumes, each representing a path, renders four alternative combined volumes. Author's own copyright.*

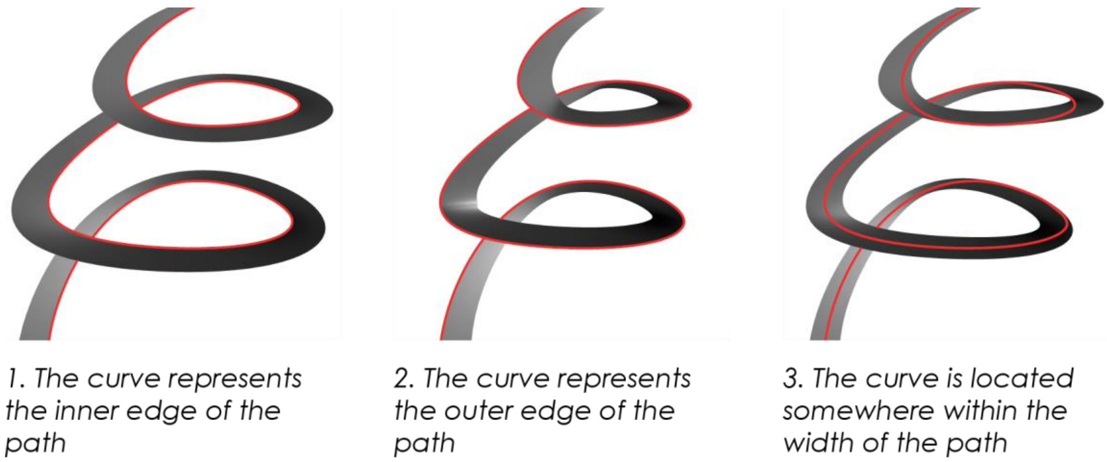
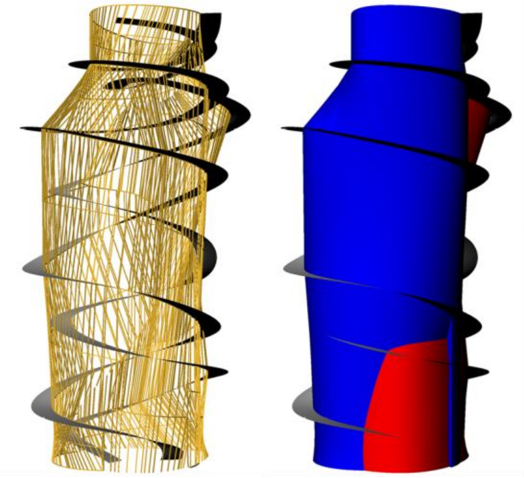
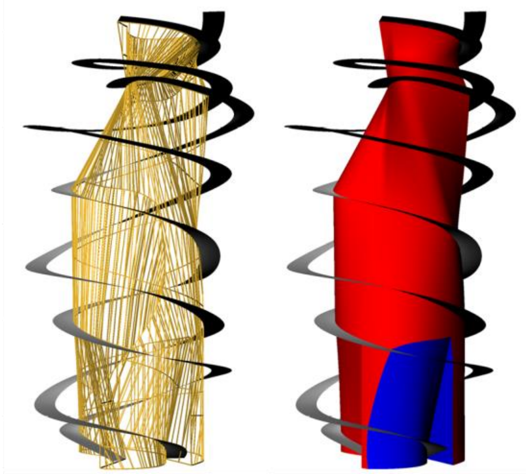


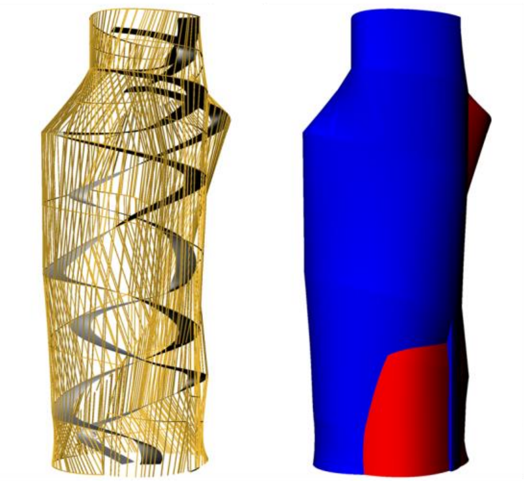
Figure 7.2 *Three alternatives for how a walk path can be described by a curve. Author's own copyright.*



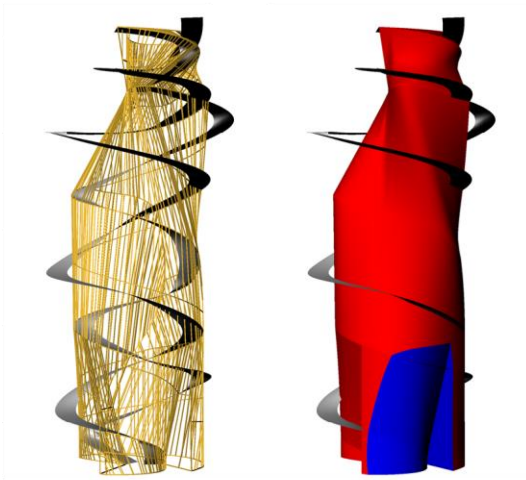
Aa1 - Same direction, outer surface, inner edge



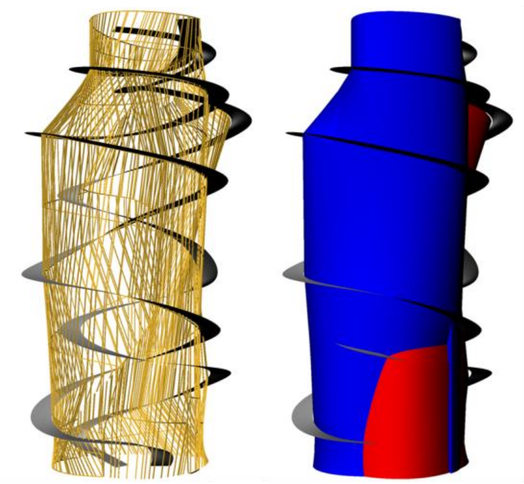
Ab1 - Same direction, inner surface, inner edge



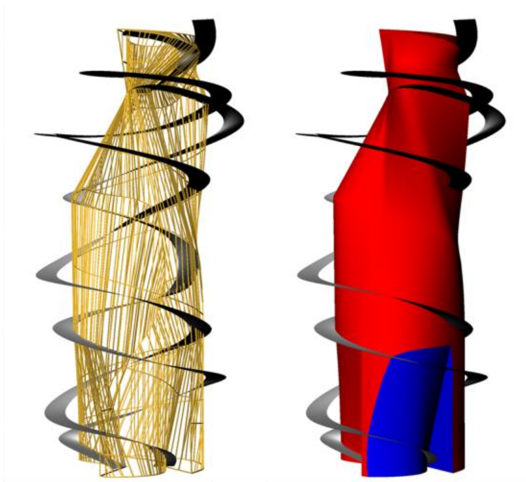
Aa2 - Same direction, outer surface, outer edge



Ab2 - Same direction, inner surface, outer edge

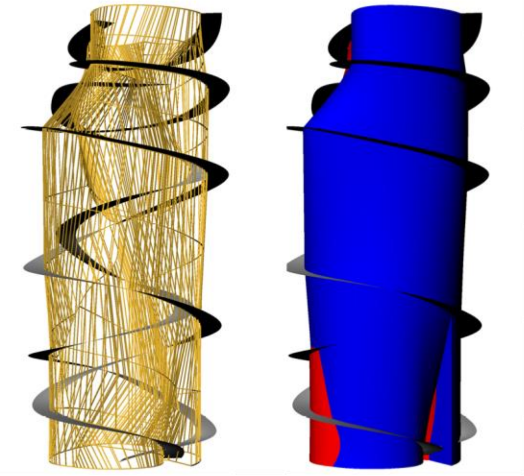


Aa3 - Same direction, outer surface, within width

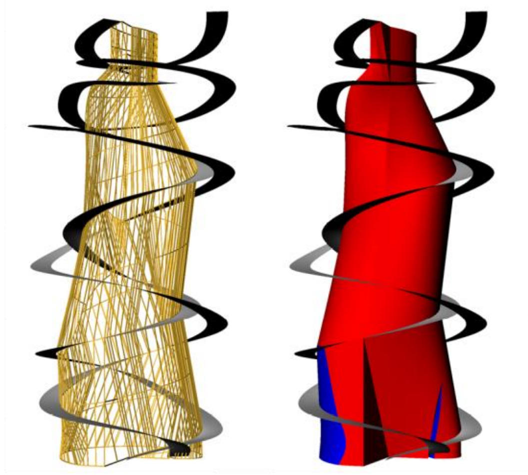


Ab3 - Same direction, inner surface, within width

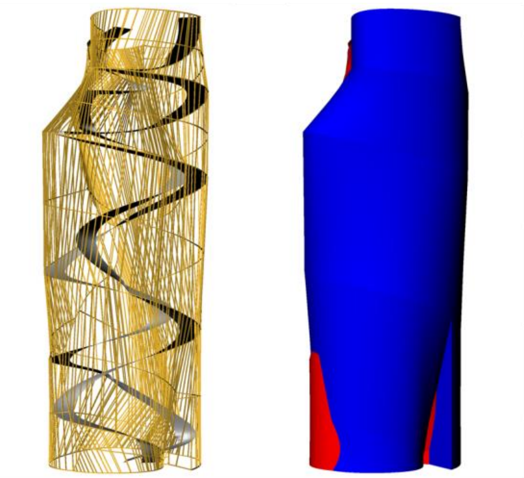
Figure 7.3 The six alternatives possible when the walk paths run in the same direction. Author's own copyright.



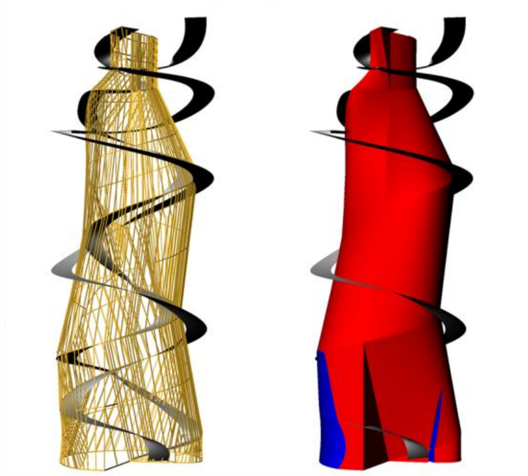
Ba1 - Opposite direction, outer surface, inner edge



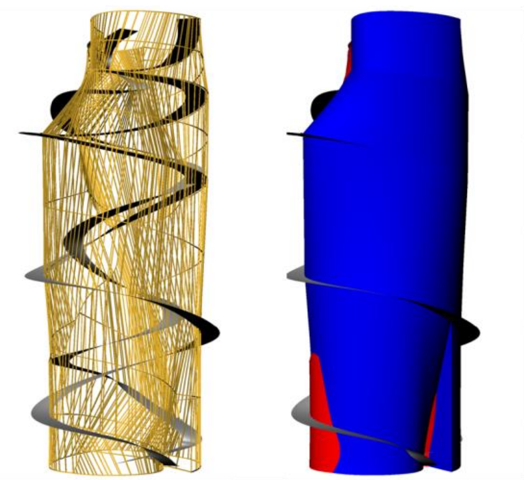
Bb1 - Opposite direction, inner surface, inner edge



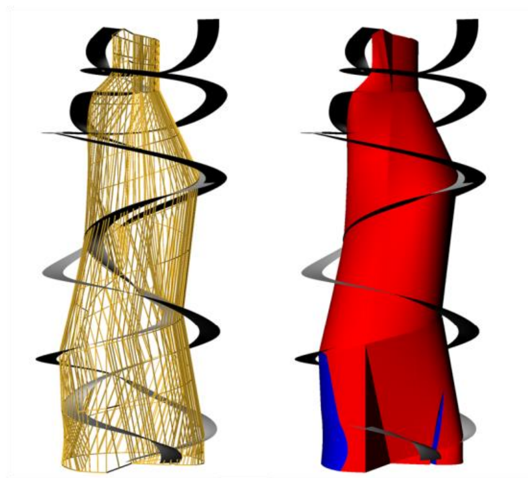
Ba2 - Opposite direction, outer surface, outer edge



Bb2 - Opposite direction, inner surface, outer edge



Ba3 - Opposite direction, outer surface, within width



Bb3 - Opposite direction, inner surface, within width

Figure 7.4 The six alternatives possible when the walk paths run in opposite direction. Author's own copyright.

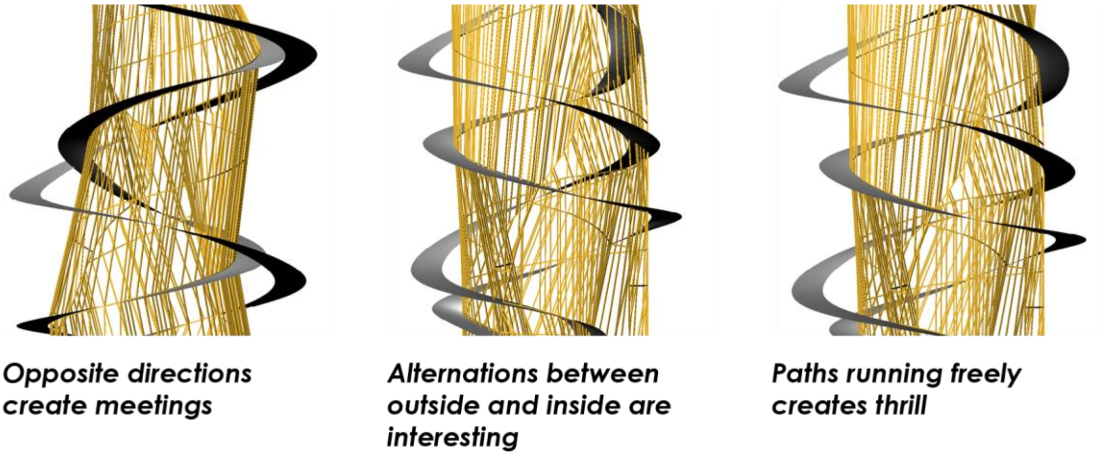


Figure 7.5 *Different interesting aspects to achieve in the structure. Author's own copyright.*

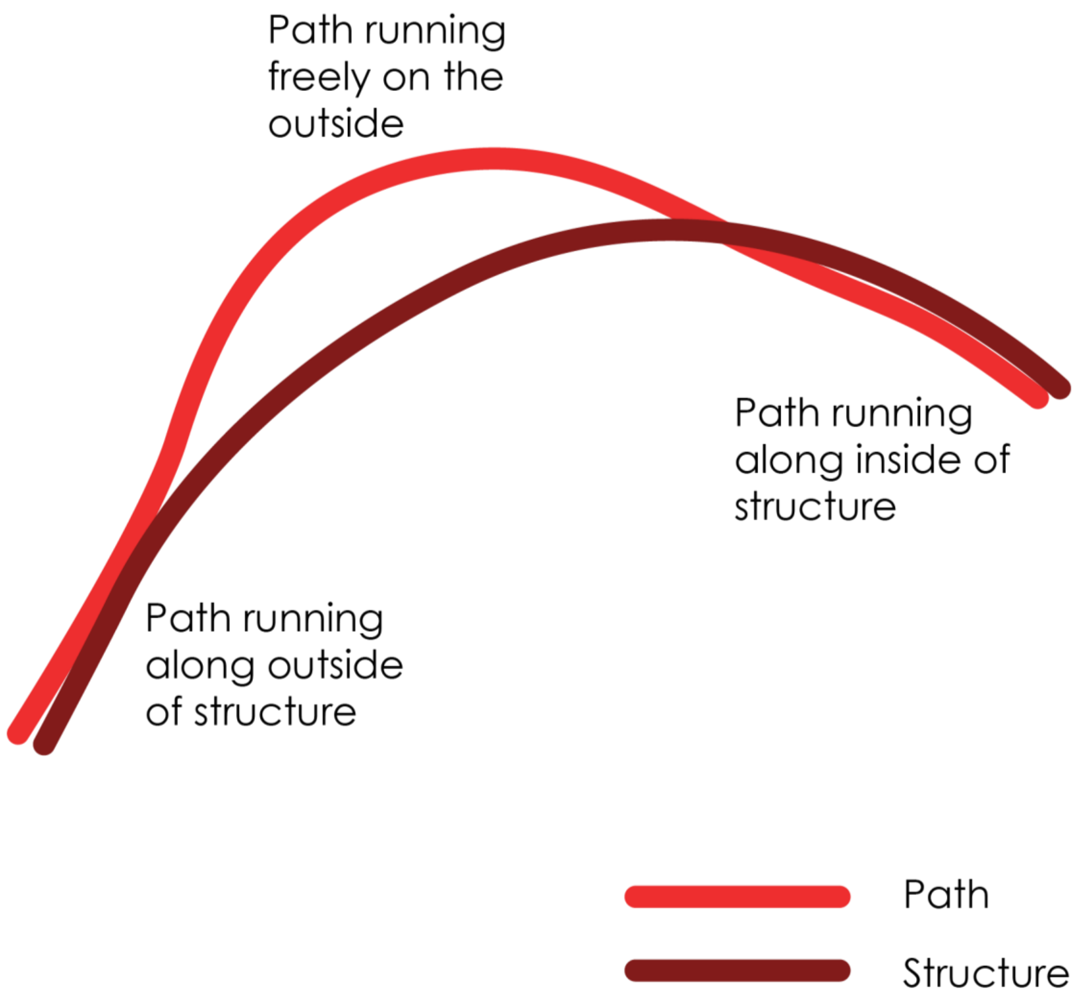


Figure 7.6 *A new conceptual idea where each path is described by a curve and the path's relationship to the structure is described by a second curve. Author's own copyright.*

To account for all of these interesting aspects, a new idea of how to define the structure had to be developed. To achieve, and be able to control, all the qualities, the relation between the walk path and the structure had to be possible to control at each point. The new idea consisted of a system where each walk path is described by a curve along the center of the path. In addition to these two curves there is another set of curves that describe the structure. So, for each walk path curve there is a structure curve, which describes the horizontal relationship between the path and the structure (Figure 7.6). This means that if the path curve and its corresponding structure curve run alongside each other, the path is running along either the inside or the outside of the structure. If the distance between the two curves is large, the path is running freely and if the two curves cross each other the path is going through the structure.

7.2 The proposal for the View of Wood observation tower

From the idea of the two curves that describe each walk path, the whole tower was developed. The parallel master's thesis in architecture developed a system of events, or experiences, examples of which can be seen in Figure 7.7, that were combined into two sequences, one for each of the two paths, and designed to give new experiences and perspectives of the site and the forest landscape. By placing these events in space on the site and connecting them with stairs and ramps into the walk paths that lead to the top of the tower, the walk path curves were defined. Depending on the event and the desired experience the structure curves could then be determined. Thereafter the structure could be defined, which is described in Sections 7.3 and 7.4. From the architecture thesis came the name of the tower as well. It is called "View of Wood" for two reasons; the first being the fact that it is a wooden structure that provides a view and the second because of its intention to bring attention to the wooden material and change the way it is viewed in modern construction.

The design of the tower (Figure 7.8) may look arbitrary in its shape, but that's not the case. The process of placing the sequences of events and their connecting paths in space and making sure that all events relate to the site in the intended way turned out to be easier said than done. Aside from the placement of the events, some other parameters had to be considered as well. The connecting paths, i.e. ramps or stairs, need to have the right length to height ratio to be walkable. Furthermore, there always has to be enough free space over the path to ensure that it is possible to walk along it, which means that a path running above it can't be too close. In the end, it turns out that there isn't much wiggle room in terms of the forming of the curves that define the paths and the structure.

In the tower, there are two paths that lead to the top of the tower. These two paths are completely separated in the sense that the visitor has to pick one and stick to it, because it isn't possible to switch along the way. However, the paths are visually connected and as they run in opposite directions they meet naturally. In addition to these two paths, there are another two paths leading into the base of the tower where the visitor can choose which path to go up. The placement of the four paths is rendered by the conditions of the site and from what directions people can be expected to arrive.

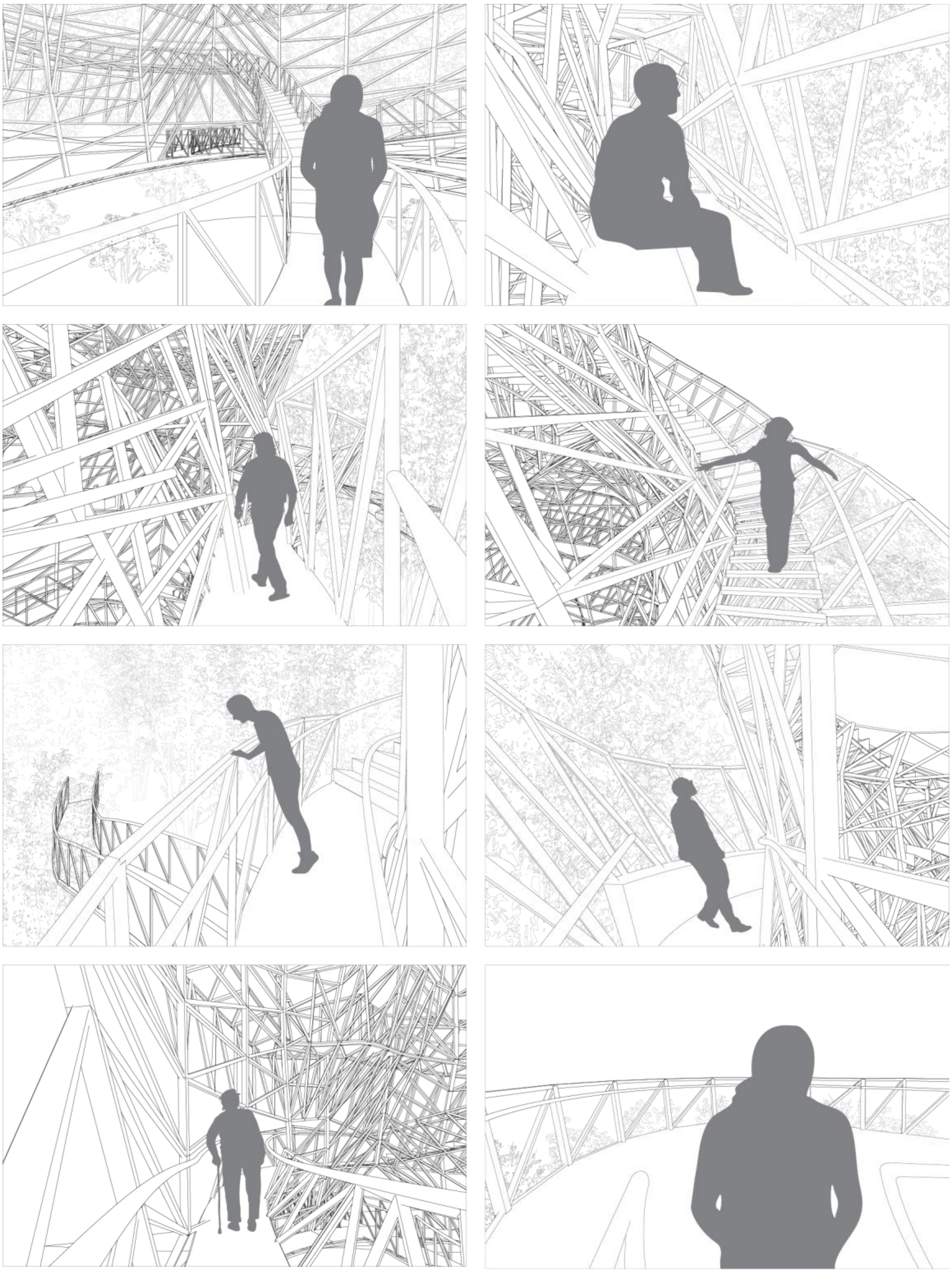


Figure 7.7 Some of the events along the walk paths up the tower. Author's own copyright.

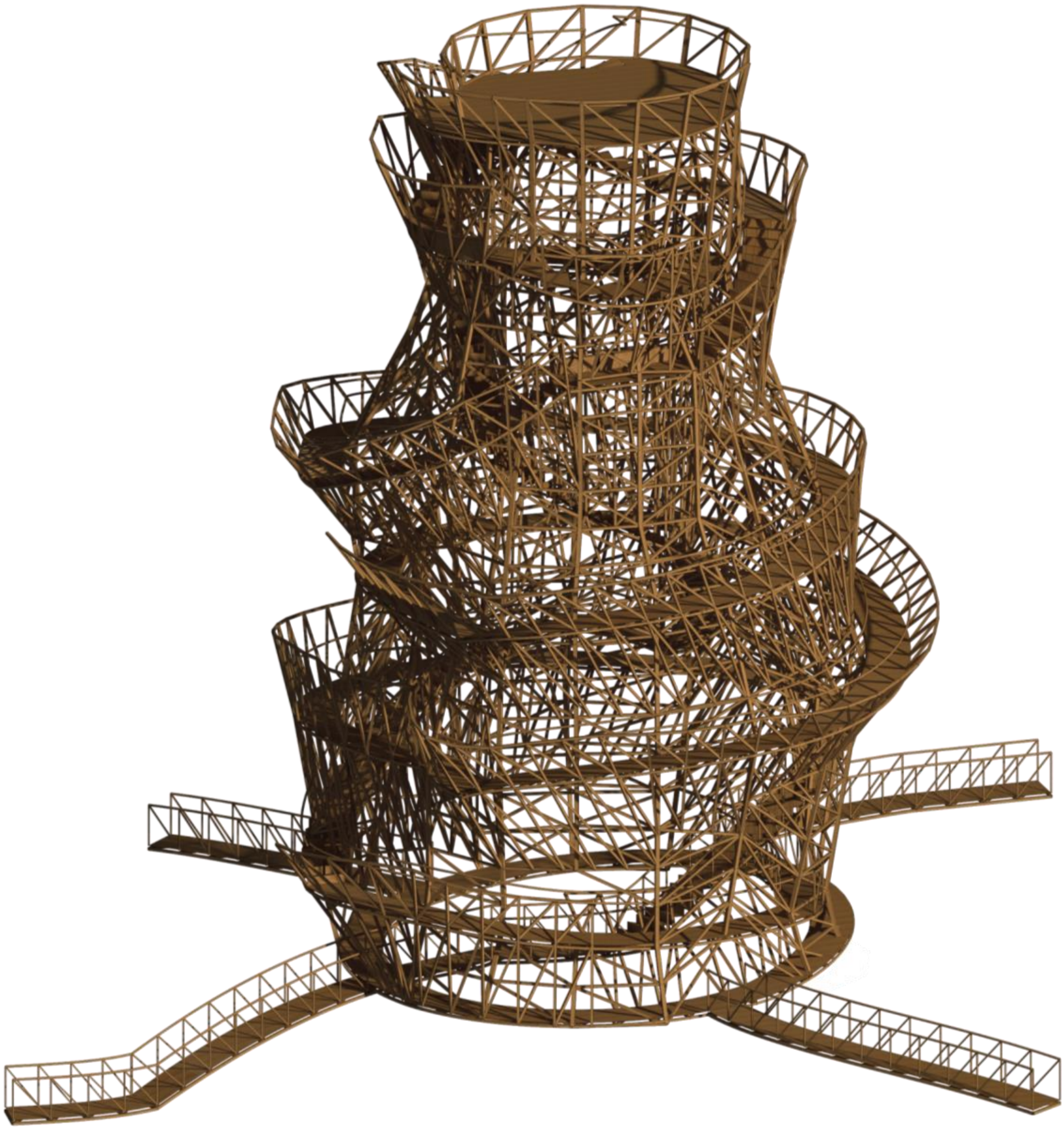


Figure 7.8 Axonometric drawing of the View of Wood observation tower. Author's own copyright.

7.3 The structure defined by the paths

The load bearing structure was developed starting with this system of two curves per path presented in Section 7.1. The curves that define the actual walk paths were defined first, based on the series of experiences for each path that had been defined in the architecture thesis. At each point along these curves the horizontal relation between the path and the structure was considered and the structure curves could be defined.

The development of the structure is described in Figure 7.9. The first image shows the two curves that describe the center of the walk paths in light blue and pink. The structure curves relate to their respective walk path curve and are depicted in dark blue and red. A structure curve may run parallel to its path curve to indicate that the path is following the structure. The two curves can also be at a larger horizontal distance to indicate the path running freely or they can cross to indicate that the path is passing through the structure.

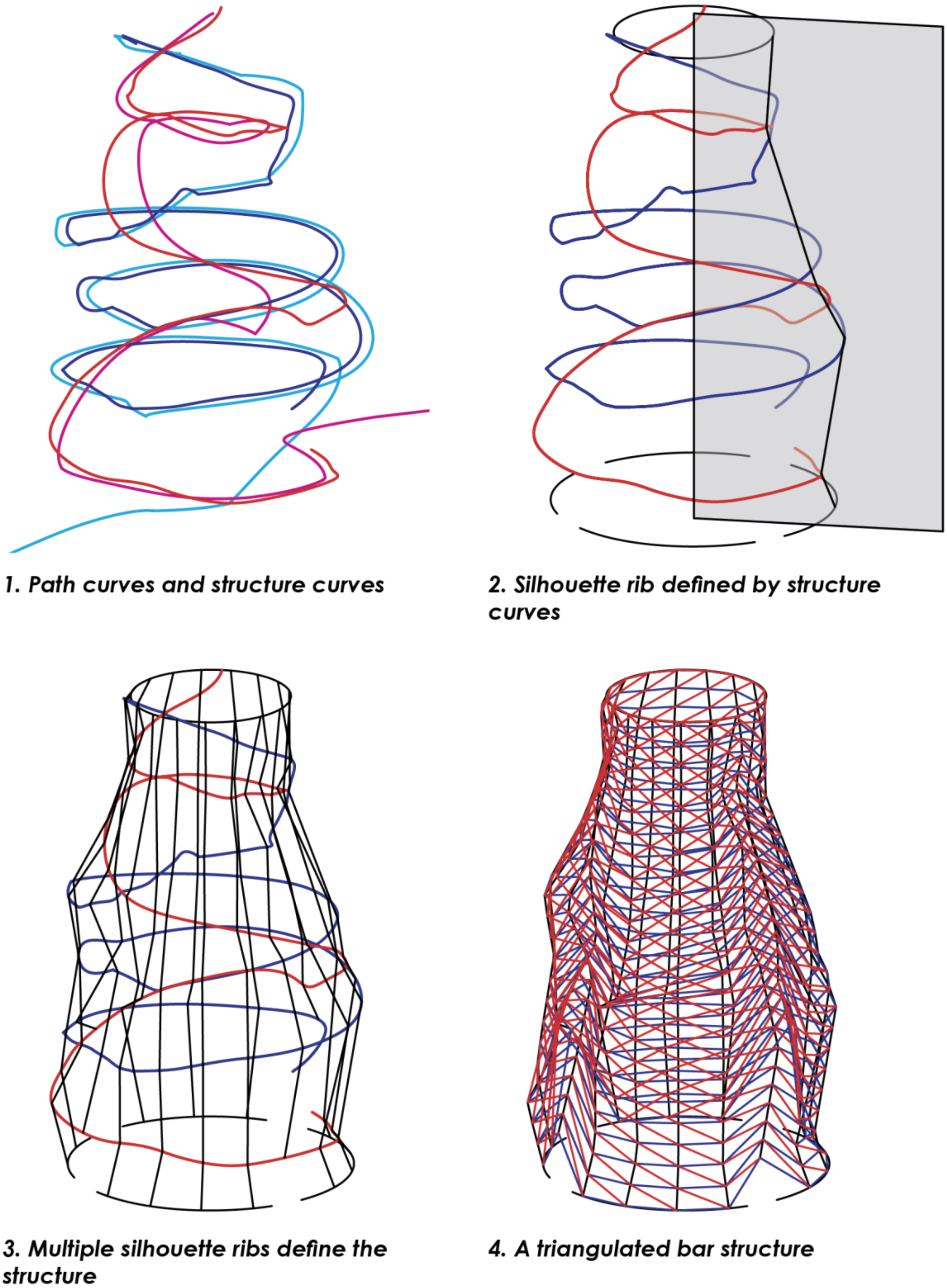


Figure 7.9 How the structure is defined with the walk paths as a starting point. Author's own copyright.

The second image explains how the ribs that describe the silhouette of the structure, and are the closest thing to vertical columns in this structure, are obtained. By intersecting the structure curves with a vertical plane, points are rendered. These points are then joined into a silhouette rib. By adding circular curves at the top and the bottom in addition to the structure curves, additional points are obtained and the rib becomes complete. The design of the walk paths show that they are both to go into the structure at the base of the tower. To ensure these openings, parts of the circular curve at the bottom is left out. By repeating the procedure with the intersection with a plane around the whole tower the other ribs are defined, which can be seen in the third image.

Finally, the ribs are divided into appropriate lengths. The nodes where this division is done are then connected horizontally and diagonally with each other. By doing so, the completely triangulated truss structure shown in the fourth image is obtained. With bars across the opening of the structure at the top, to simulate the top platform, and with pinned supports at the base of the ribs, the structure is stable.

To check the stability of the tower, two analyses were carried out using FEM-Design. First, the tower was checked against vertical loading. To do so, point loads of 5 kN were applied in all 288 nodes (the left image in Figure 7.10). The deformations that can be seen are small, just as could be expected (the left image in Figure 7.11).

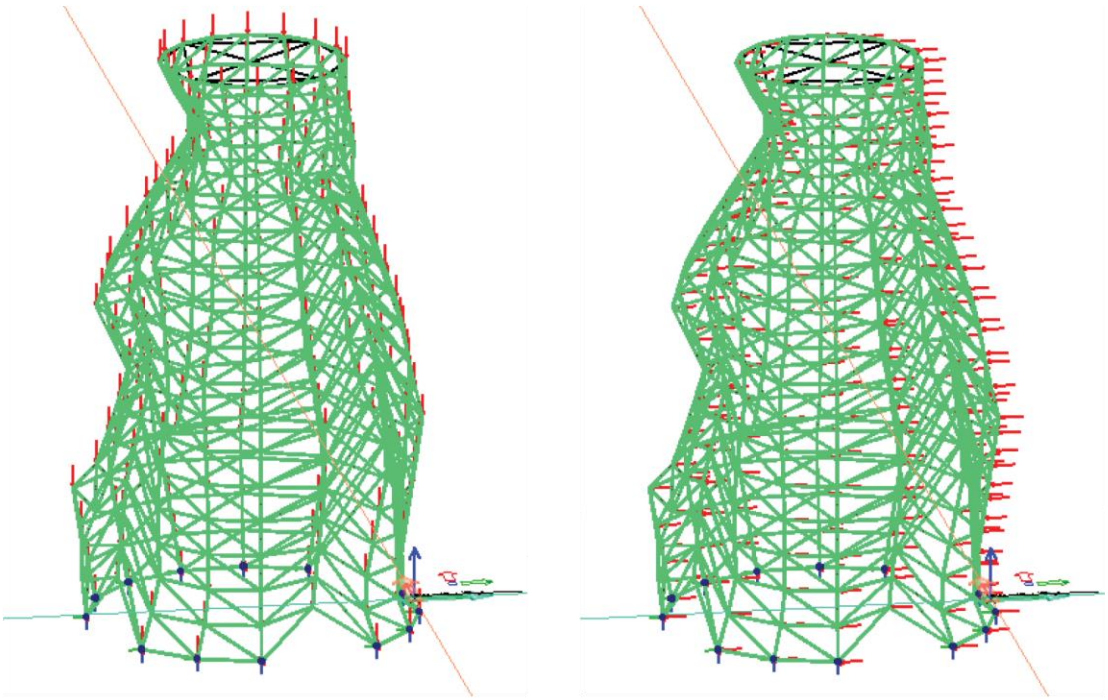


Figure 7.10 Vertical and horizontal point loads applied to analyze the stability of the structure. Author's own copyright.

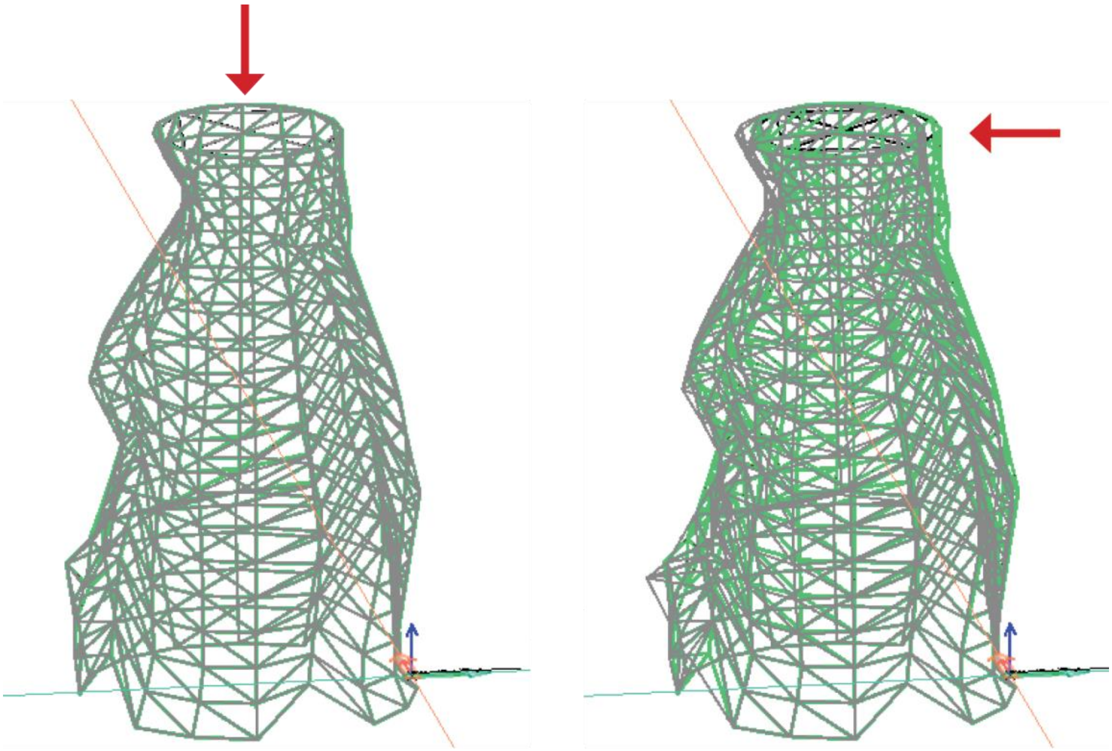


Figure 7.11 *The structure is stable against both vertical and horizontal forces. Author's own copyright.*

The second analysis was to check, the structure against horizontal loading. This time point loads were applied in all nodes as well, but their magnitude was set to 1 kN (the right image in Figure 7.10). The deformations from this type of loading are greater than for vertical loading, which could be expected. Still, the deformations were deemed reasonable both in terms of shape and magnitude (the right image in Figure 7.11).

For these analyses, all elements span node to node with pinned joints. The structural elements were modeled as glulam L40s with a 90x90 mm cross section.

Finally, though no analysis were made, the rotational behavior of the structure was considered. As the structure is tube like and completely triangulated, it is easily understood that it would function like a closed cross section. The structure of the tower could be compared to many of the reference towers presented in Chapter 2, for example the trussed beams and columns of the Sky Walk (Figure 2.12 and Figure 2.13) and the hyperbolic structure of the tower in Holmers-Halkenbroek (Figure 2.19). Hence St Venant torsion would be predominant and the structure would effectively resist torsional moments.

7.4 The structure that carries the paths

The walk paths are defined by the previously mentioned curves. Their relation to the structure is such that they are carried by the structure along one edge, leaving the other edge unsupported. Therefore, an additional part of the load bearing structure is needed to integrate the walk paths into the structure and ensure that they are sufficiently supported. In addition to the support given by the structure along one edge of the path, the other side is supported by struts that transfers the load down to a node further down in the structure (Figure 7.12). At the level of the walk path, these struts and the structure are connected by a horizontal truss onto which the actual path is placed. The struts also continue upwards to become a railing along the path.

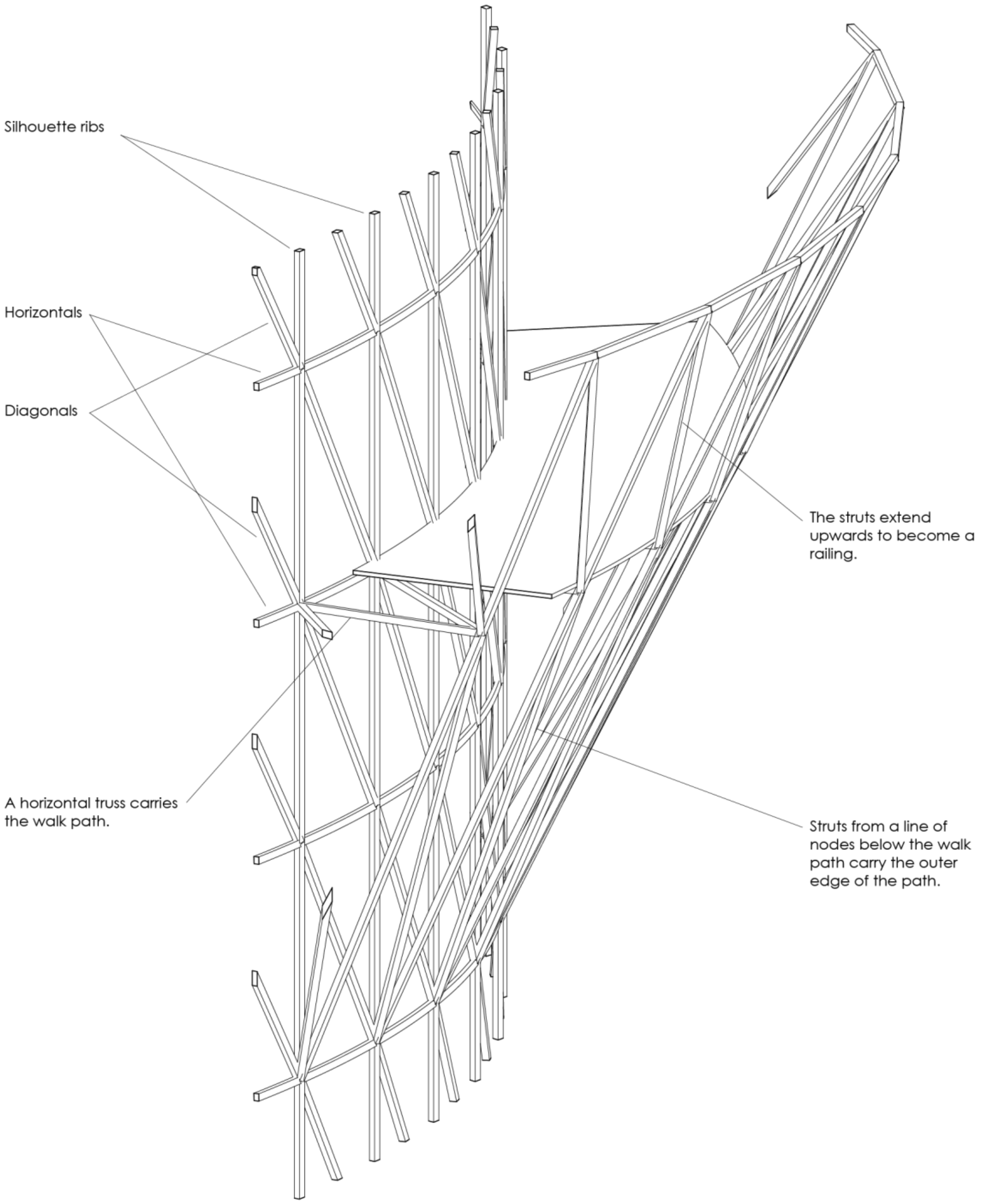


Figure 7.12 Axonometric drawing of the structure carrying the walk paths. Author's own copyright.

There are no limits to the inclination of the struts. The location of stretches of walk path below do however set some limits. The struts may not extend so far down that they interfere with the space needed above a walk path to ensure that it is possible to walk on it.

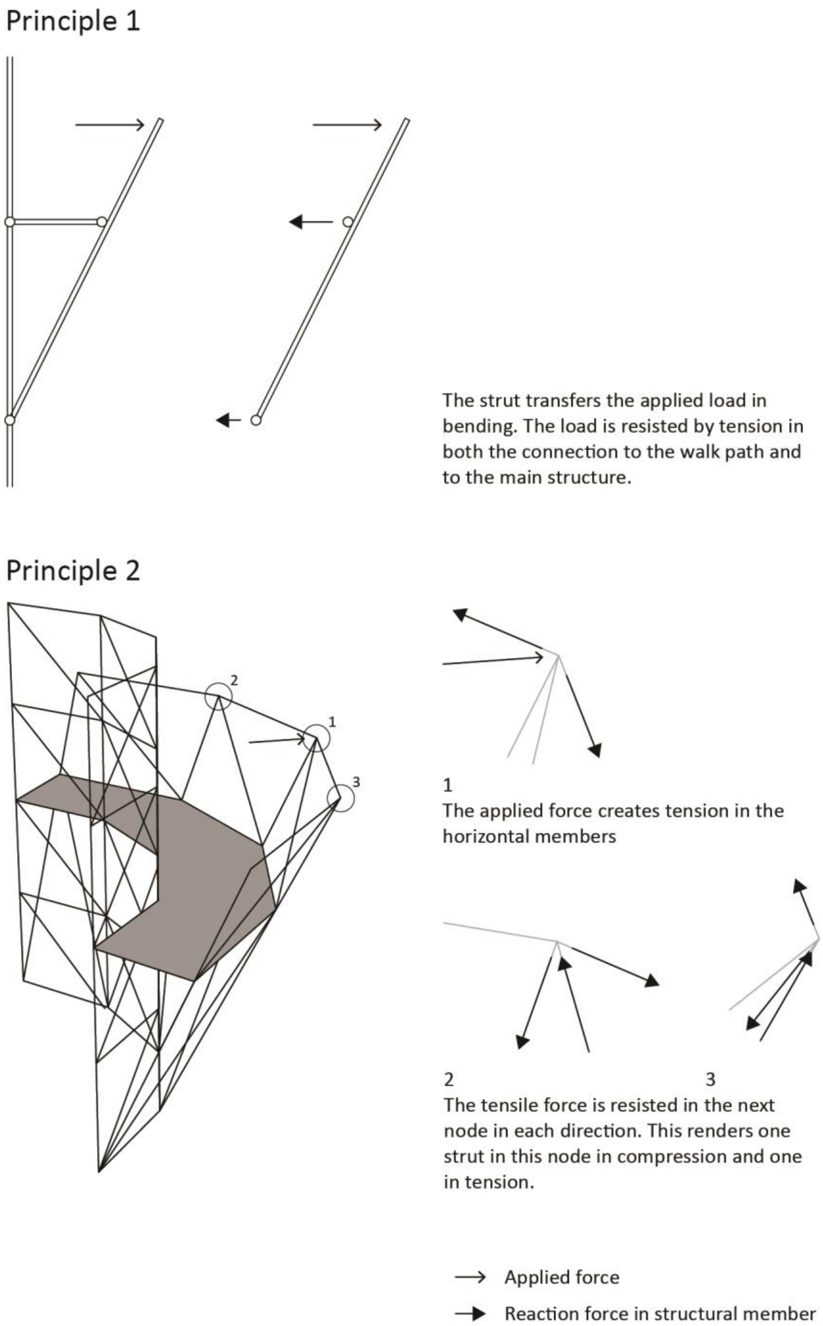


Figure 7.13 There are two principles according to which horizontal load on the railing can be resisted. Author's own copyright.

The railing will be subjected to horizontal forces from visitors holding on to the railing as they walk by and stopping to lean against it. There are two principles according to which these horizontal forces can be resisted (Figure 7.13). Following the first principle, the connections between the strut and the top of the railing and the strut and the walk path are able to transfer moments. This can be achieved by making the strut one continuous element. The horizontal force is then transferred down along the strut in bending and resisted by tension in the two connections.

The second principle benefits from the curvature of the structure. The horizontally applied force is then resisted by tension in the two connecting elements along the top of the railing. These tensile forces are in turn resisted in the next nodes in each direction along the railing. In these adjacent nodes, the tensile force renders one of the struts connecting to that node in compression and the other one in tension.

7.5 Possibilities to better define the structural grid

Dividing the ribs at a number of nodes as described in Figure 7.9 renders a grid where the placement of the nodes doesn't coincide with the meetings of the walk paths and the ribs. To achieve a better correlation between the load bearing structure and the walk paths, the nodes need to be distributed in a manner that follows the shape of the walk paths. The problem of the non-coinciding nodes and path is illustrated in Figure 7.14. As the diameter of the tower structure changes and the inclination of the paths vary along the way, the structural grid and the shape of the walk path are not completely straight as in the image, but the problem is the same.

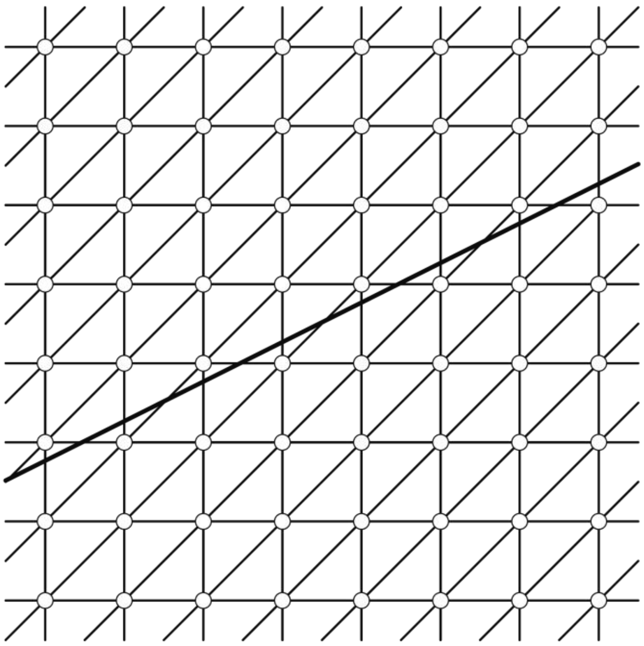


Figure 7.14 Current solution where the nodes of the structure do not coincide with the walk path (represented by the thick line). Author's own copyright.

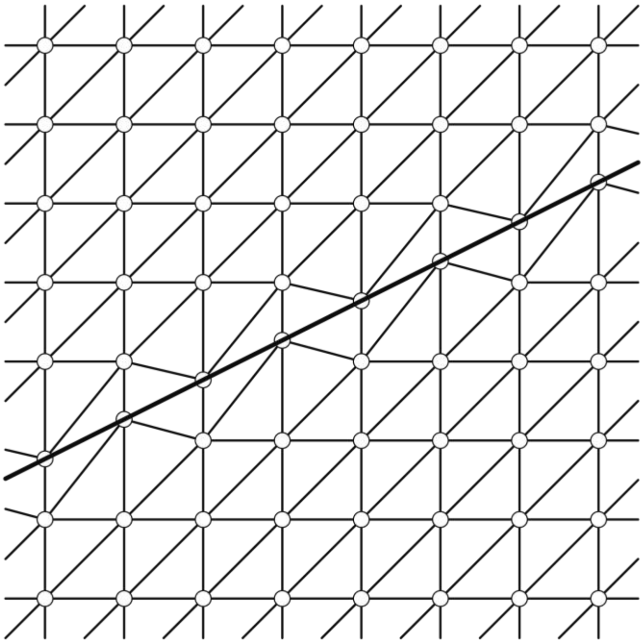


Figure 7.15 One option is to move the nodes closest to the walk so they coincide with the path. Author's own copyright.

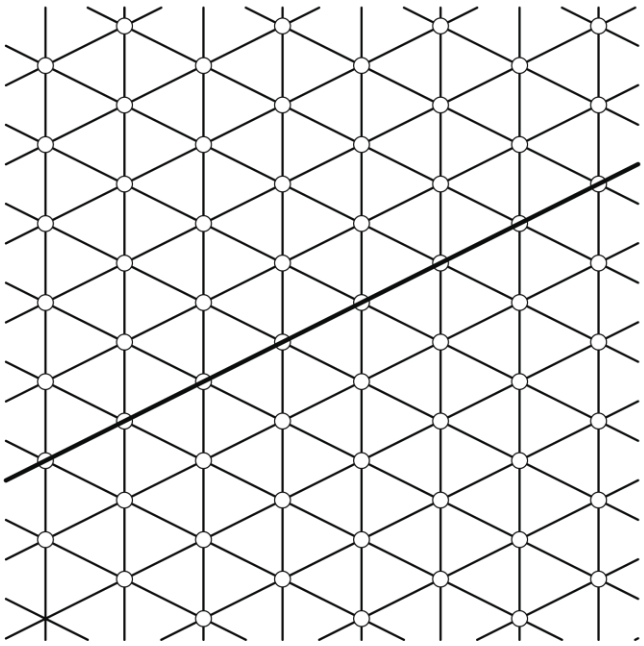


Figure 7.16 Another solution is to redefine the grid of the structure so that the members follow the direction of the path. Author's own copyright.

One way to solve this is to move nodes so they coincide with the walk path. That would mean that at every intersection between a vertical structure member and the walk path, the closest node along that vertical member, above or below the path, should be found and moved to the intersection (Figure 7.15).

Another option is to redefine the structural grid to ensure it follows the shape of the paths from the beginning. In that case, the vertical members could be defined as previously described, but instead of adding horizontal and diagonal members, the vertical members would be connected by members following the inclination of the walk paths. Figure 7.16 illustrates what this would look like with one path crossing a number of vertical members. Imagining the other path, which runs in the opposite direction, it is easy to see that it would render structural members leaning in the other direction.

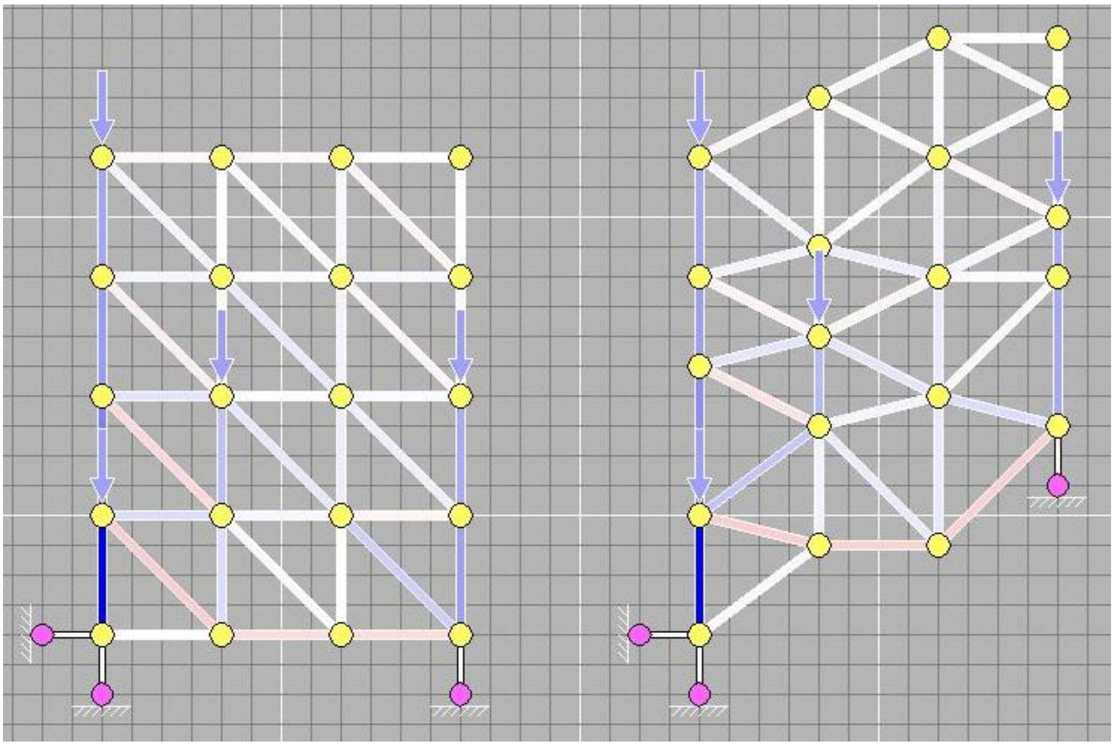


Figure 7.17 The way the structure functions remains the same if the original pattern (left) is altered (right). Author's own copyright.

Regardless of which solution is chosen, the structure would still function in the same manner as the original structure (Figure 7.17). If point loads are applied to some nodes in the original structural grid, which has vertical, horizontal and diagonal members, some members will be compressed and others tensioned, just like in any truss system. In such a system, each node has a certain connection to the rest of the system. The whole system can be described by a typology where each node is defined and each element is defined by its start and end nodes. If the nodes are shifted vertically or horizontally, their position becomes a new one, but their relation to the rest of the structure is described in the same way. Essentially, the structure remains the same in terms of behavior. To the right in the image is the same structure as to the left, but with the nodes shifted vertically in different ways. In the adapted case, the force pattern is the same as in the original, i.e. the compressed (blue) members remains compressed and the tensioned (red) members remains tensioned. So, though the stable structure developed above doesn't correspond to the shape of the walk paths, a structure of the same kind but where the nodes are shifted along the ribs to coincide with the walk paths would be stable as well. Which of the two options presented above that is chosen is a choice to be made and perhaps the second alternative, where the structure is basically redefined is a better choice from an architectural point of view, but structurally they are very similar.

A final note regarding the possibilities of how to better define the structure is to address the number of elements. The structure as it is defined above is completely triangulated, which is unnecessary from a structural point of view. What is required in addition to the vertical and the horizontal members is the equivalent of one row and one column of diagonal members. Such an adjustment could make the structure much more open and potentially require less material. It would also simplify many of the connection details as fewer elements will connect in each node.

7.6 Joinery

The question of how to assemble the structure, what elements to prefabricate and what types of fasteners to use was developed via model studies with the previously developed truss like structure as a starting point. This truss structure has nodes where 6-8 elements connect at arbitrary angles. To find a solution for how such a joint could be designed the models in Figure 7.18 were created. The idea that eventually developed was to use slotted steel plates that would be connected to each other in some sort of a hinge system.

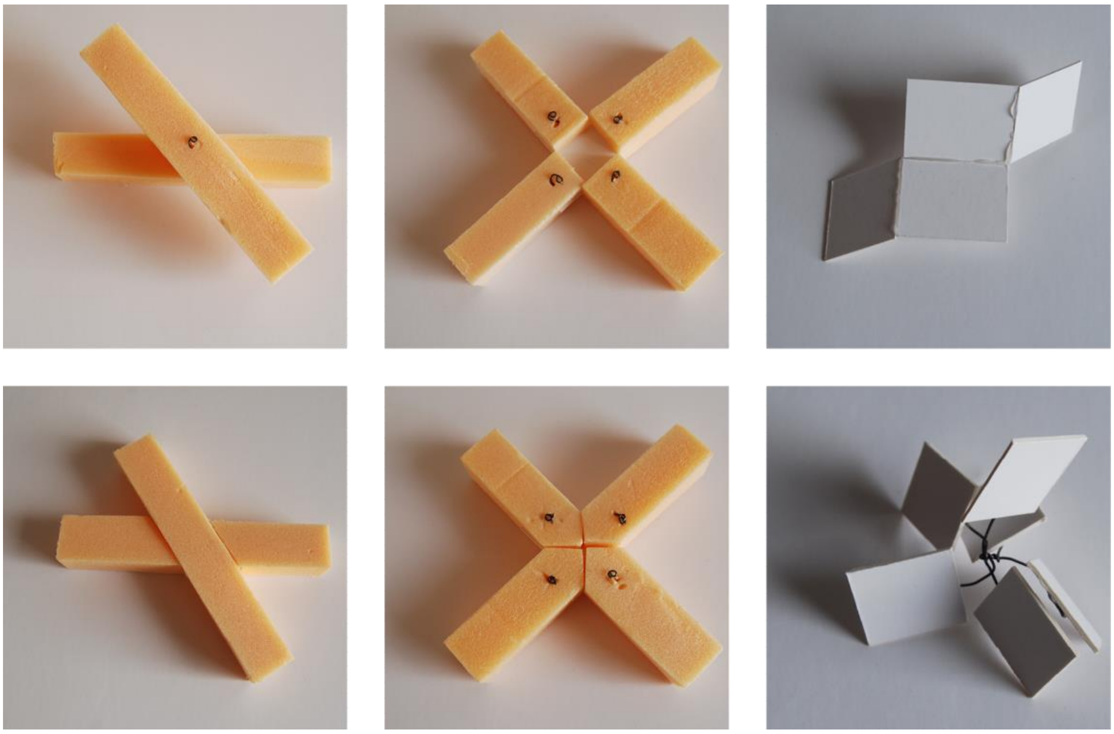


Figure 7.18 Model studies to find a general solution for the joinery in the original truss structure. Author's own copyright.

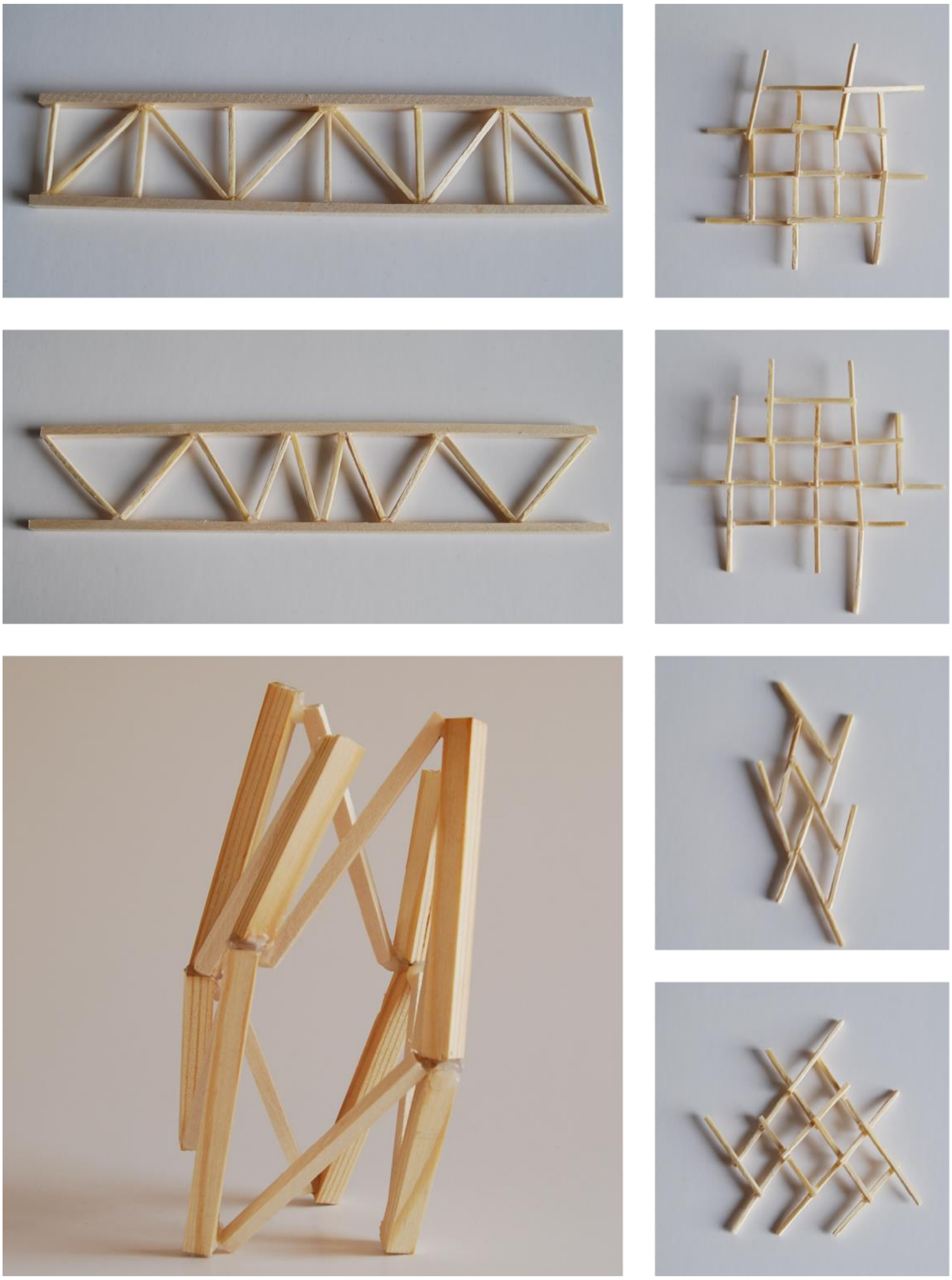


Figure 7.19 Various models to further investigate the joinery of the truss structure. Author's own copyright.

Unfortunately, it turned out to be somewhat impossible to figure out the configuration of these nodes even in a digital model. Hence, it seemed that the potential that something could go wrong on the construction site was big and the solution seemed insufficient for a real project, especially one that is to be built by students. Therefore, the model studies continued in search of a more redundant and easy to grasp solution.

In developing the ideas for the structure and joinery further, the models in Figure 7.19 were built. Ideas such as varying spacing of elements in the truss structure was considered. The twisting truss, which relates back to the initial ROTATIONAL concepts was tried out to see how elements connect to achieve the twist. As it had proven difficult to have many elements meet in a truss node in the way that was first imagined, inspiration was sought in Zollinger's lamella roof structure. This led to the models where the elements overlap in the nodes. However, that works very well with elements forming four sided holes in a structure that is rather flat. With curved elements, a more curved structure could be achieved, but it did not seem like a perfect solution for the meetings of 6-8 element that was the problem at hand.

At this point, continuous elements were considered. That way not all elements would have to span node to node. With continuous elements, a statically indeterminate structure could be achieved and a certain safety in case of faulty joinery could be built into the structure. Such a safety could be good, especially considering the intention to build the tower as part of an educational process.

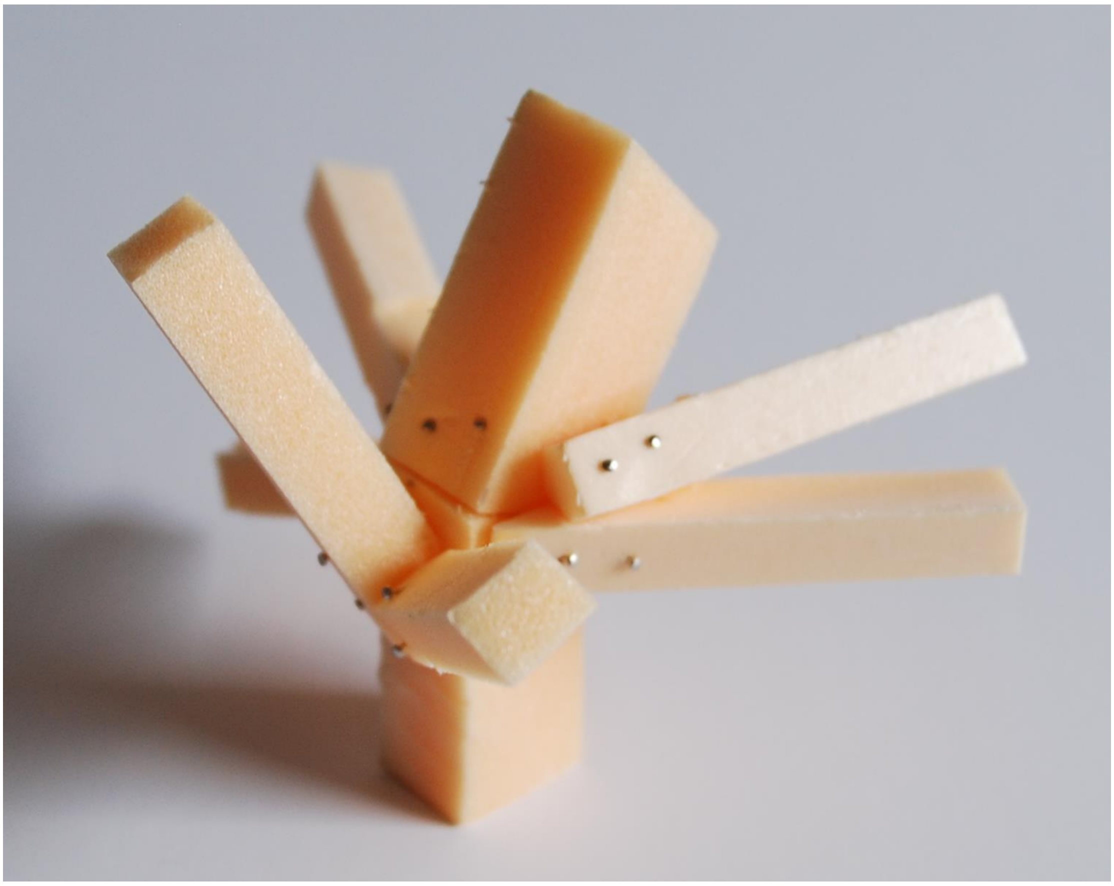


Figure 7.20 Joint inspired by wooden roller coasters. Author's own copyright.

Figure 7.21 Connection of two parts of a silhouette rib. Author's own copyright.

The first inspiration was wooden roller coasters. These structures have continuous columns that are connected by shorter members into truss like structures. With the use of five axis CNC milling, all members can be different and all cuts be made and holes drilled to ensure that it all fits together once erected on site (Jeska & Pascha, 2015). The structure of a wooden rollercoaster may look arbitrary and impossible to understand, but is in fact built up in a very clear and systematic way.

In the case of this tower, there are no clearly vertical members, but the closest thing are the silhouette ribs. An idea formed where they would be placed in the center of the nodes and the horizontal and diagonal members would be attached onto their outside. An example of such a joint, where two parts of the silhouette rib are joined in the node as well, can be seen in Figure 7.20.

To minimize the number of elements that connect in one point, the silhouette rib could be continuous over the joint and its members be connected mid span instead. If viewed more like a continuous column, the silhouette rib wouldn't be divided into more parts than is necessary for the sake of easy handling and available material dimensions. The parts of the silhouette ribs would be joined on site using slotted steel plates and bolts, which is illustrated in the model in Figure 7.21.

Working further with continuous elements and having the silhouette ribs, or vertical members, the horizontal and the diagonal members, there could be either one, two or three types of continuous members. For example, the Zollinger inspired solution could be complemented by continuous diagonal elements on each side or continuous verticals and horizontals with diagonals spanning node to node. One could also consider a structure and joinery where all members are continuous. There could then be pairs of members layered outside of each other to create a structure whose cross section is symmetric. All of these ideas for working with continuous members were developed using models (Figure 7.22).

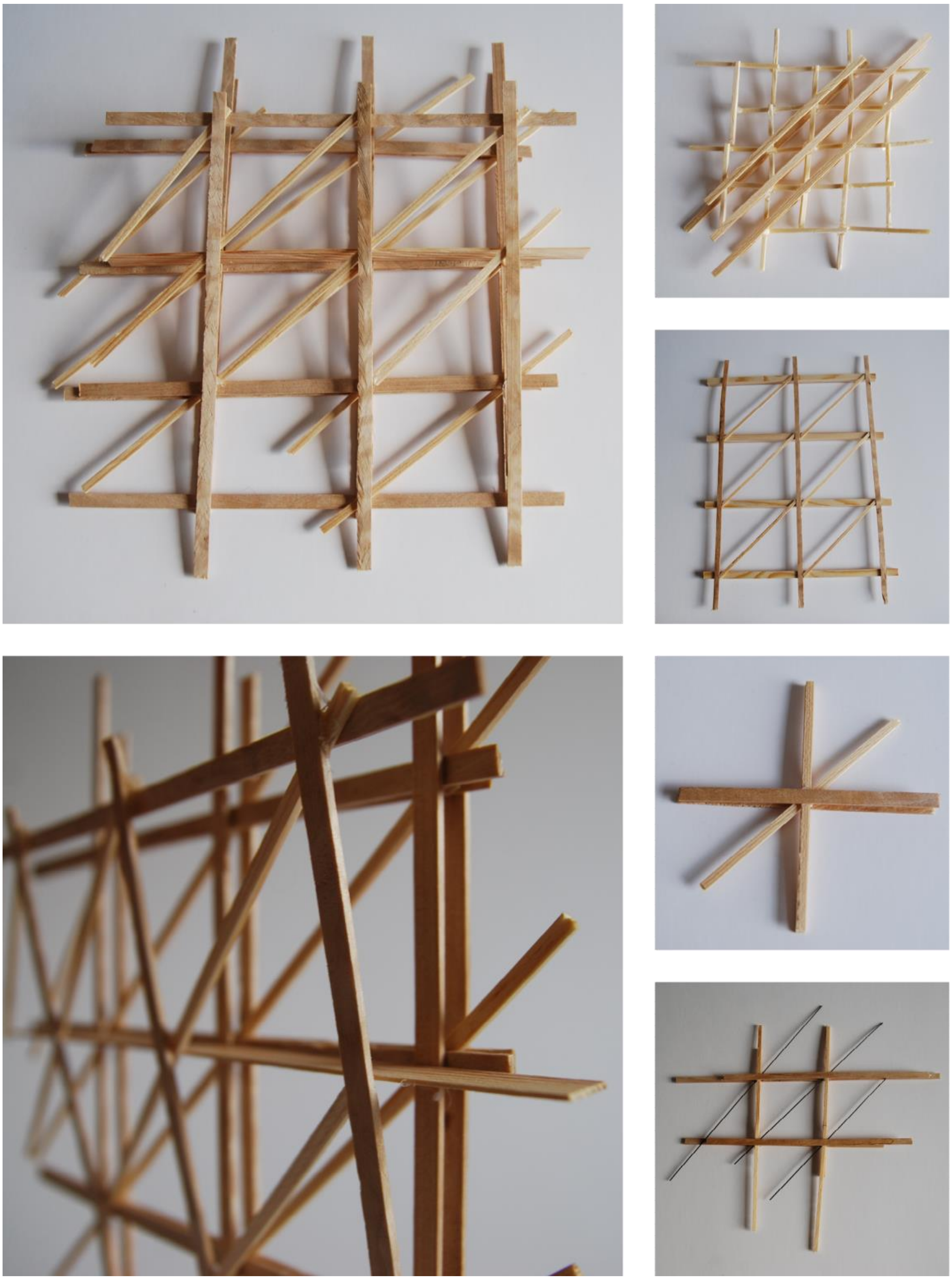


Figure 7.22 Models to investigate the structure and joinery with continuous members. Author's own copyright.

7.6.1 Alternative 1

Eventually two suggestions for possible joinery in the tower developed. The first alternative is based on the inspiration drawn from the wooden roller-coasters. It has continuous members that represent the silhouette ribs and that are connected by horizontal and diagonal members spanning from node to node.

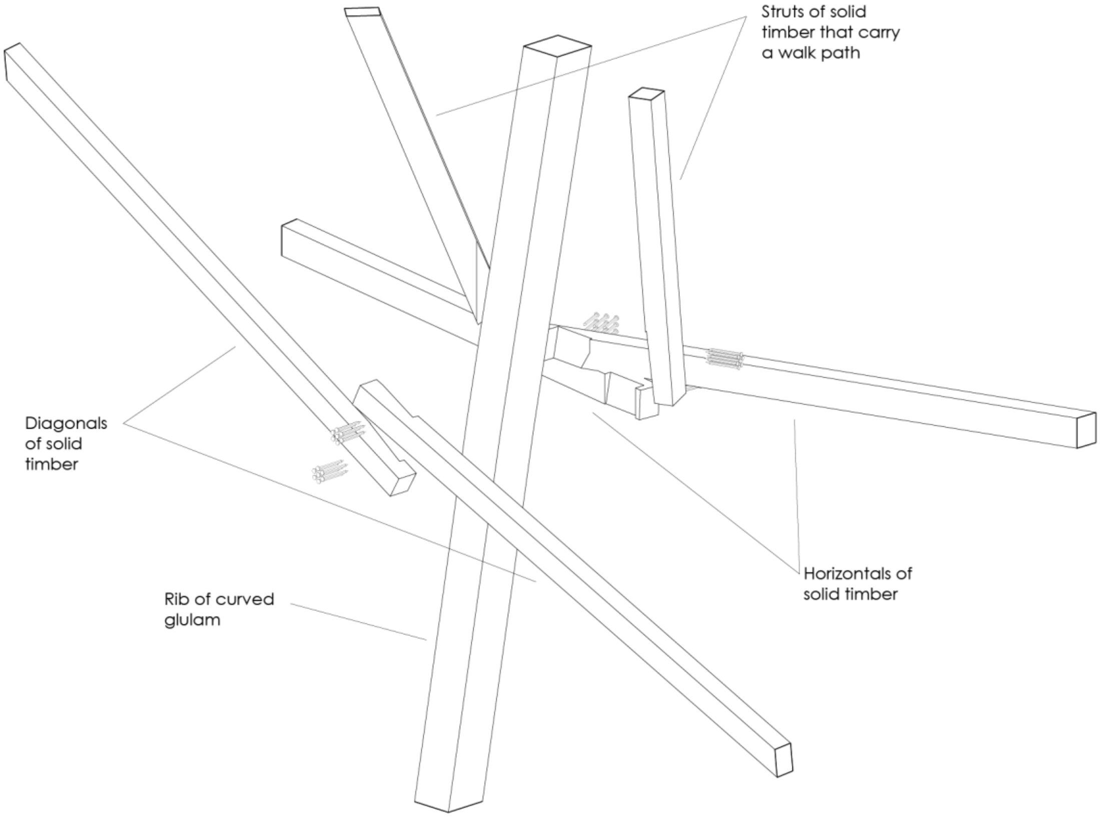


Figure 7.23 Exploded axonometric drawing of the Alternative 1 joint. Author's own copyright.

All members will be prefabricated and provided with markings to ensure that they are placed in the right place in the structure. Through CNC milling, each shorter member will be cut to fit in the right angle onto the silhouette ribs. Just like the horizontal and diagonal members, the struts to carry the walk paths will be precut and marked for attachment onto the ribs. For the actual assembly, any necessary pre-drilling will be done in the prefabrication process and markings will be made for all fasteners. Once on site, the structure will be assembled as indicated in Figure 7.23.

When designing the joints, it is necessary to consider how it may be affected by moisture. Therefore, all members must be placed in such a way that no pockets that may gather moisture are created. When it rains or in case of condensation, the water must be able to run off so that the timber is allowed to dry. The assembled joint (Figure 7.24) shows how the elements fit together so that no hazardous water pockets are created and thereby the risk of moisture damage, which would shorten the service life of the structure, is minimized.

The silhouette ribs would be prefabricated in parts. The size of these parts would depend on what length is deemed possible to handle on site, due to size as well as weight, and what dimensions are available. These parts would then be assembled on site using slotted steel plates and bolts (Figure 7.25).

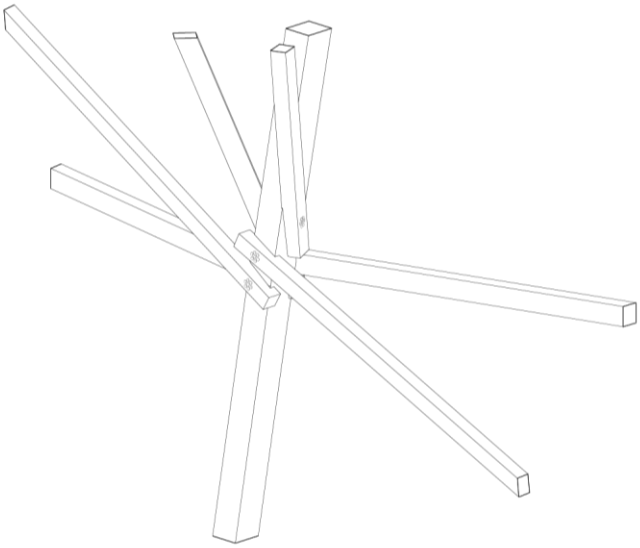


Figure 7.24 The assembled Alternative 1 joint. Author's own copyright.

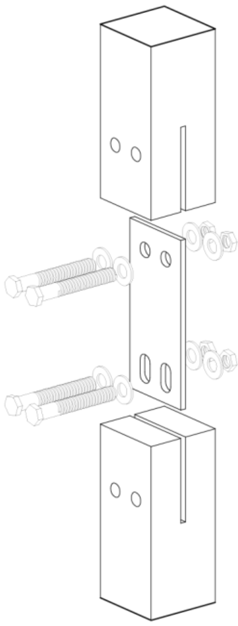


Figure 7.25 The elements of the ribs are assembled on site using slotted plates and bolts. Author's own copyright.

The idea for the attachment of the horizontal and diagonal members onto the ribs is to use nails. However, depending on the dimensions of the members and the forces to be transmitted, it may prove insufficient. An alternative to achieve stronger connections could be to use bulldog plates and screws (Figure 7.26).

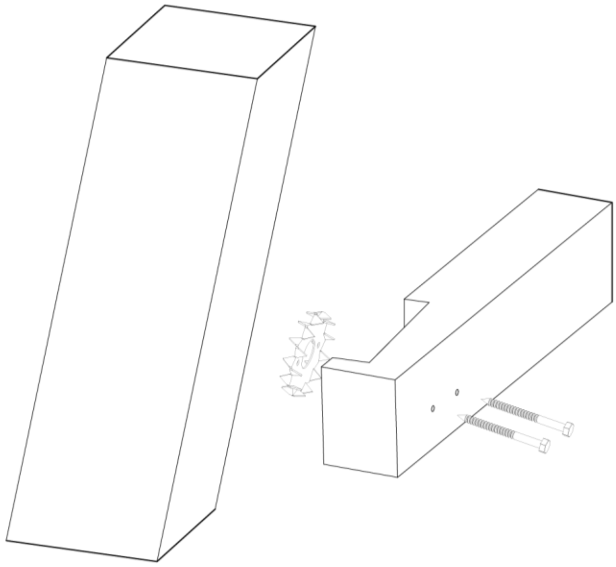


Figure 7.26 An alternative to the nailed connections could be to use bulldog plates and screws. Author's own copyright.

7.6.2 Alternative 2

The second alternative for the joinery has only continuous members. The silhouette ribs, or verticals, and the horizontals consist of pairs of parallel members, while there are only single members that make up the diagonals. These single diagonals are placed centrally with one of the horizontal members on either side and one of the vertical members on either side of that.

All members would be cut to their appropriate lengths and provided with markings in a prefabrication process. Depending on their dimensions and the material, they may be steam bent to easily fit together into the tower structure. In the same fashion, the struts that are to carry the walk paths would be cut, marked and bent so that they could be introduced into the structure with ease.

All members would receive drilled holes for the joinery as part of the prefabrication process. That way, they could be assembled on site using a bolt (Figure 7.27). Struts are created by letting the rib member on that side of the structure bend out. A new member of the rib is introduced to continue upwards. That way even the struts become part of the continuous members (Figure 7.28).

The double members contribute to a safe structure. Aside from the fact that the members are continuous, which in itself implies that the structure is statically indeterminate and that loads can find alternative ways if required, the double members ensure that if something was to happen to one member in a pair, the other member could still function to transfer at least part of the load along the intended path.

The risk of moisture damage and ensuring that water can't gather anywhere to cause such damage is important for this joint as well. However, as all members are continuous through all joints, water that runs along one member will simply continue and pass through the joint. Hence, water collecting in corners of the joints will not be a problem.

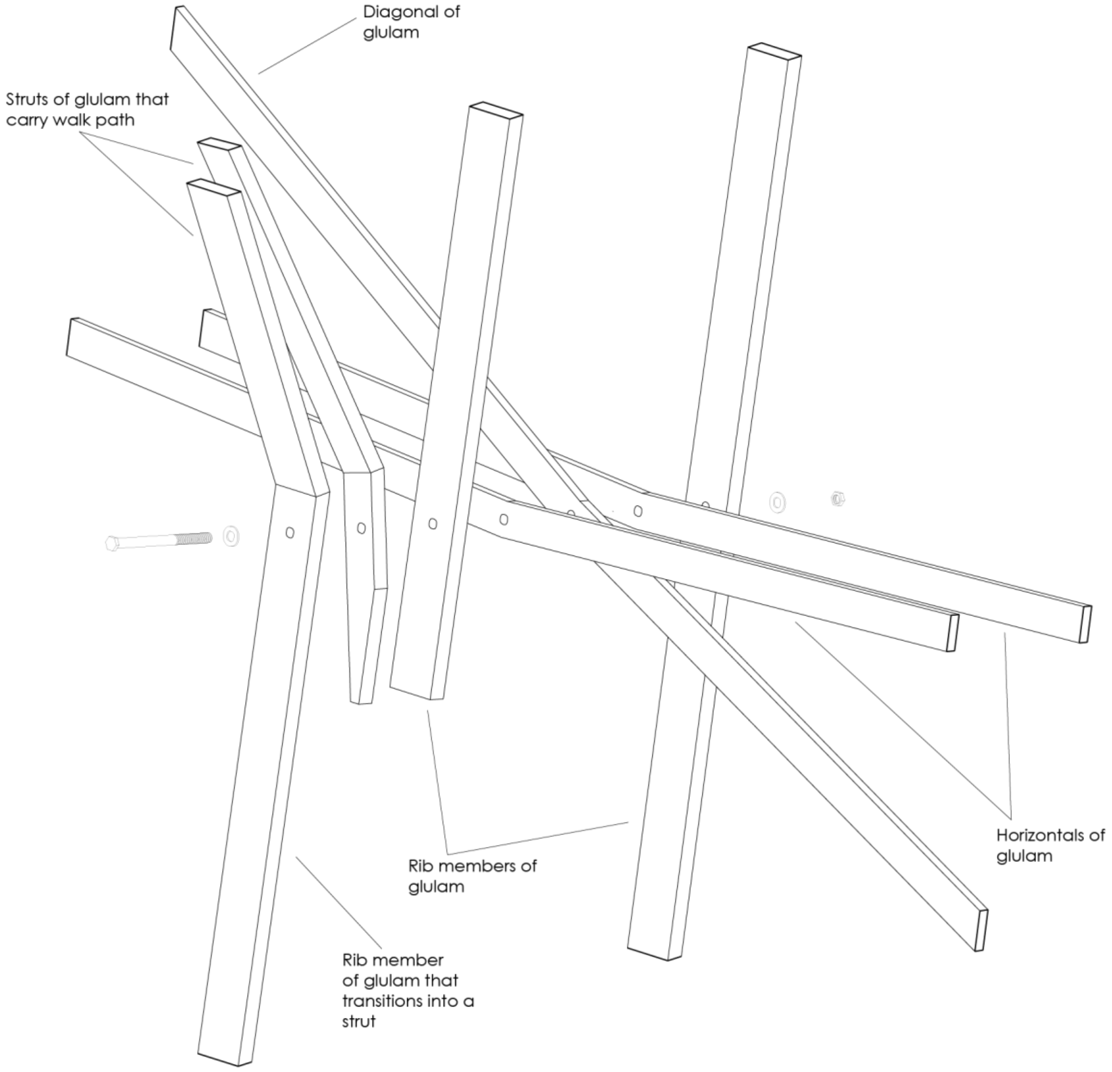


Figure 7.27 Exploded axonometric drawing of the Alternative 2 joint. Author's own copyright.

The continuous members will of course have to be assembled from shorter parts on site (Figure 7.29). The idea is that one member in a pair is to always be continuous. This means that the joints along the two members of the pair are offset in relation to each other. A joint consists of a block, the thickness of which is equal to the space between the members which is created by intermediate members in other directions, into which the parts to be connected as well as the continuous member of the pair are screwed.

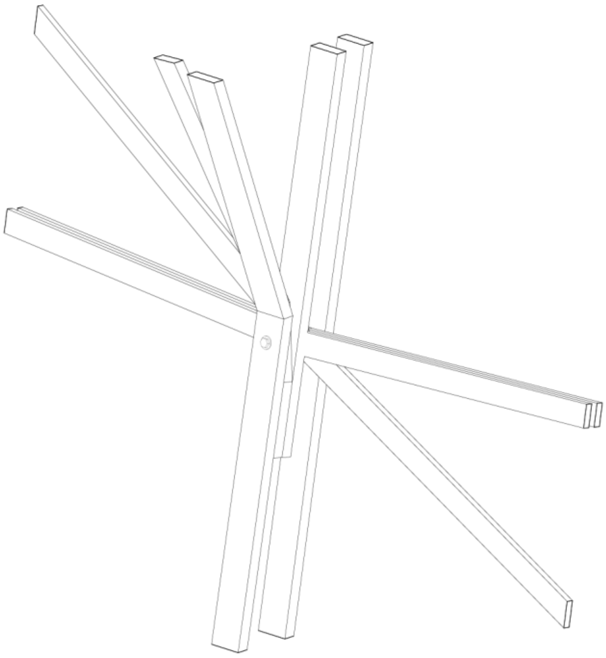


Figure 7.28 The assembled Alternative 2 joint. Author's own copyright.

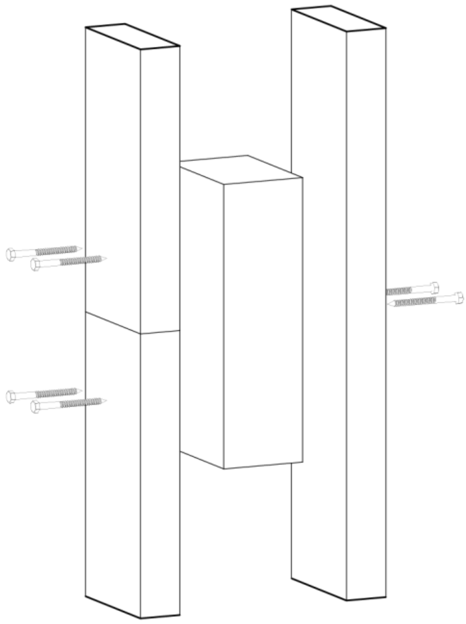


Figure 7.29 Concept for the connection of parts of a continuous member. Author's own copyright.

To create a different visual impression or to make the structure less thick, the centrally placed diagonal members could be made of steel (Figure 7.30). In that case, a custom made steel plate is placed centrally in the node. Steel bars, spanning node to node, are then welded onto these plates on site.

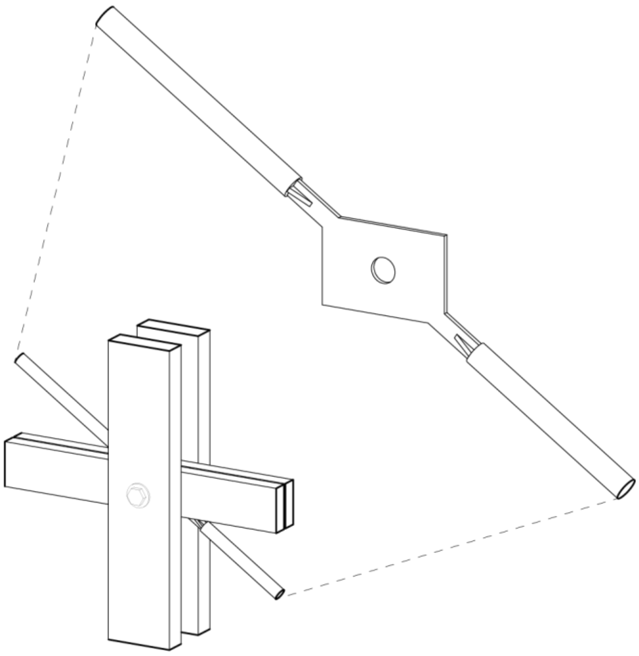


Figure 7.30 The diagonal members could also be made of steel. Author's own copyright.

8 Conclusions and reflections

Initially, a clear goal for the design was to work with structures that can be built by hand and by inexperienced workers as an educational experience. However, during the process, structures along a gradient from those that can be built entirely by hand to those that require cranes and such for the load bearing structure to be mounted has been considered. What is important is that traditional techniques and knowledge are kept alive so that modern technique can build upon that. That way the trade of carpentry can evolve in times where industrialized timber building is becoming increasingly popular.

To increase the knowledge and to obtain the education for the involved in the project, an aim is to create a project within which students from various schools can participate, not just in the design on paper, but in the actual construction process. With that said, it is not the actual possibility to be able to build everything by hand that is the goal, but to be able to provide learning opportunities, which is easier the more of the work that can be done by the students. For that purpose, the question of how much can be built by hand within a concept has been raised continuously throughout the process.

8.1 The answer to the problem

Looking back at the thesis questions presented in Chapter 1, Section 1.1.4, the development of the structural concepts presented in this thesis has continuously been developed with the question of element sizes in mind with the aim at finding a solution that would require no, or very little, heavy lifting done by machines. The final proposal for a tower structure is one that consists of only smaller elements in a structure that is built up in a very logical way and which can be adjusted to consist of more and smaller elements or fewer and larger elements. That way a balance can be found between what is possible to handle by hand, what material and dimensions are available and the desired visual expression of the tower.

The question about connection details brought the proposal further along. The proposed tower has a statically determined truss like structure, which implies pinned joints that turned out to be very difficult to achieve. So, to get past this and to at the same time achieve a more redundant structure, an investigation into joinery and structures with continuous elements begun. This led to two proposed alternatives for joinery and the configuration of the tower structure. Both alternatives would be possible to assemble by hand. With the help of a prefabrication process, the joinery would be self-explanatory to a high degree and thereby suitable for a construction project with inexperienced labor.

So, in terms of answering the questions set up for the thesis, the work has, in close collaboration with the parallel master's thesis in architecture, developed a system to define a structure that is possible to build by hand. This system could be used to develop an observation tower at any site. The shape of the tower would vary depending on the configuration of the walk paths and their corresponding structure curves, but the actual structure would function in the same way.

Regarding the case study and the wishes of the land owner, the proposed structure can adapt to the shape of the ground. The base of the tower doesn’t have to be completely leveled, instead the lattice can be shaped to follow the rock at its bottom. The proposed configuration of the structure is quite wide in relation to its height and would therefore be fairly stable, which would simplify the anchoring into the rock. The accessibility aspect was also mentioned. As the land owner want all their museum visitors to be able to appreciate the tower as well, that stairs and ramps have a good height to length ratio is important, which is handled in the setup of the curves that describe the walk paths. Furthermore, railings become an integrated part of the structure onto which handrails can be mounted to ensure a comfortable walk up the tower.

8.2 The collaboration with architecture

Aside from carrying out a conceptual design for an observation tower to find the answers to the thesis questions, a big part of the thesis has been the collaboration with the parallel master’s thesis in architecture. That thesis has had a completely different starting point. Though both theses have been considering the planned observation tower in Bengtsfors as a case study, the approaches have been very different. While this thesis started with inspiration of previously built structures to, with those references in mind, go on to derive possible concepts for a timber observation tower, the architecture thesis started with the possible experiences within an observation tower. The architecture thesis started out by identifying situations in which a visitor could be on his or her way up the tower and how to design these situations to ensure that the visitors focus is on a certain thing or in a certain direction. For example, the parameters believed to control the experiences of being over, under, inside and on top were investigated. The next step was to identify how to place these situations in relation to each other and how they affect each other. Thereafter, these sequences of experiences were combined with the more promising concepts in Chapter 6.

The architecture thesis focused a lot on the experience of the forest, the source of the timber, and the possibility to draw attention to timber construction through this experience. Meanwhile, this thesis focused more on the element sizes and the possibility to build the tower by hand and by inexperienced workers. The site itself was interesting from an architectural point of view because of how to place the events in the tower so that the desired views and experiences would be achieved. From a structural point of view, the size of the site, the adaptation to the uneven ground and the need to anchor into the rock was of larger importance.

About halfway through the thesis, the final concept for the load bearing structure was chosen (Chapter 6, Section 6.6). For both structural and architectural reasons, it was desired to develop this concept further. It is the combination of these aspects that led the development of the concept to the final proposal for the structure (Chapter 7).

A very important aspect of this collaboration is of course that both theses we're carried out by the same student. It was never two parallel projects, but rather one big project where different aspects and different steps in the process were presented in different ways in the two theses. With that said, the collaboration has functioned well and the influence of one thesis on the other is believed to have had a positive effect on both theses. The two theses have, as mentioned above, had different focuses and from the beginning it wasn't clear how they would contribute to each other. However, very quickly findings from one investigation within one thesis became input and feedback for another investigation within the other thesis and so on. Working on both the structural concept and the experience in parallel has functioned as a constant eye opener in giving input back and forth and ensuring that attention was paid to things that would have otherwise likely been missed. At times, the two theses have been quite independent of each other, but in the end, the input and feedback between them has been key in obtaining the result that is the proposal for the View of Wood observation tower. Without the two theses being carried out in parallel and guiding each other through decisions, the result would have been something completely different.

8.3 What is left to do

This thesis work ends with two alternatives for the joinery of the tower for the case study. Neither of these alternatives is consistent with the tower structure at this point. Therefore, a next iteration would have to include going back to implement these alternatives for the joinery into the structure and evaluate the architectural and structural consequences. Furthermore, the definition of the structure itself needs to be developed according to one of the options presented in Chapter 7, Section 7.4. Eventually it will also be necessary to start considering if and where to use structural timber, glulam and so on. For the tower in the case study to be ready to build, the following have to be done:

- Redefine or adjust the structure so that there always are nodes to attach the walk paths to.

- Implement the two alternatives for the joinery into the structure and evaluate the architectural and structural consequences of the two in search of the best solution for this tower.

- Consider what type of timber material to use where, if any members should be steel and what those choices mean in terms of dimensions of the members, spacings in the structural grid and visual expression.

- Carry out careful structural analysis using all required load cases to determine the required dimensions of all structural members.

- Carry out analysis of the joinery to determine what type of fasteners to use, how many etc. As it has been determined that the truss like system where the centers of all members meet in one single point isn't achievable, it will be necessary to consider the effects causes by eccentricity in the joints.

- Investigate how to build the tower from the bottom up in a way where the structure is always stable and where a system of scaffolding helps ensure the safety of the workers and make it possible to, with simple equipment, lift all elements into their designated place in the structure for assembly.

- Integrate a system of net, e.g. thin steel nets, into the railings and the structure along the walk paths to ensure that the visitors are safe.

- Design the foundation.

In addition to the above, which relates to the design and erection of the structure as well as the safety of the visitors, there are some aspects regarding experience and visual expression to consider as well. Among those are another iteration of the design of the experiences along the walk paths and the attachment of the handrails onto the railings and the structure.

In a broader perspective, looking at what the result of this thesis can be used for other than the case study, the following can be said:

- The concept of the tower, with the two walk paths that define the structure, could be implemented on any site if desired.

- A complex structure can be designed in such a way that it can be built of smaller, easy to handle, elements and with joinery that is easy to grasp and hence such a complex project can be broken down into something that is suitable for education.

8.4 The next step within the case study

The intention from the beginning was for the workshops and the courses in and around Bengtsfors to take place during the year of 2016. However, none of this has started yet when this thesis work is ending in spring, 2017. Therefore, the workshops did not become a part of this thesis work. Perhaps, given that the project is continued, this thesis and the architecture thesis may instead become a starting point for workshops and courses.

The hope still stands that the project will become reality. If and when that happens, the proposed design of this thesis and the architecture thesis could be the first proposal for the tower. By following the steps set up above, final drawings for the prefabrication and construction could be developed for this tower.

Before the actual construction process can start, the local education has to begin. The students that are to build the tower must receive basic education within construction, which will hopefully include the previously mentioned workshops.

In the end, the intention is that this project will teach a trade to a group of students to build a local and skilled workforce in Bengtsfors and Dalsland. The intention is also that the tower will draw attention, both as an educational project involving a long array of stakeholders and as a built object. If that can be achieved, the interest in timber as a construction material can grow and the idea of a project like this can spread. As a continuation, if more projects like this get started, the Swedish carpentry skills can be regained and kept as a basis for the development of our future timber building.

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