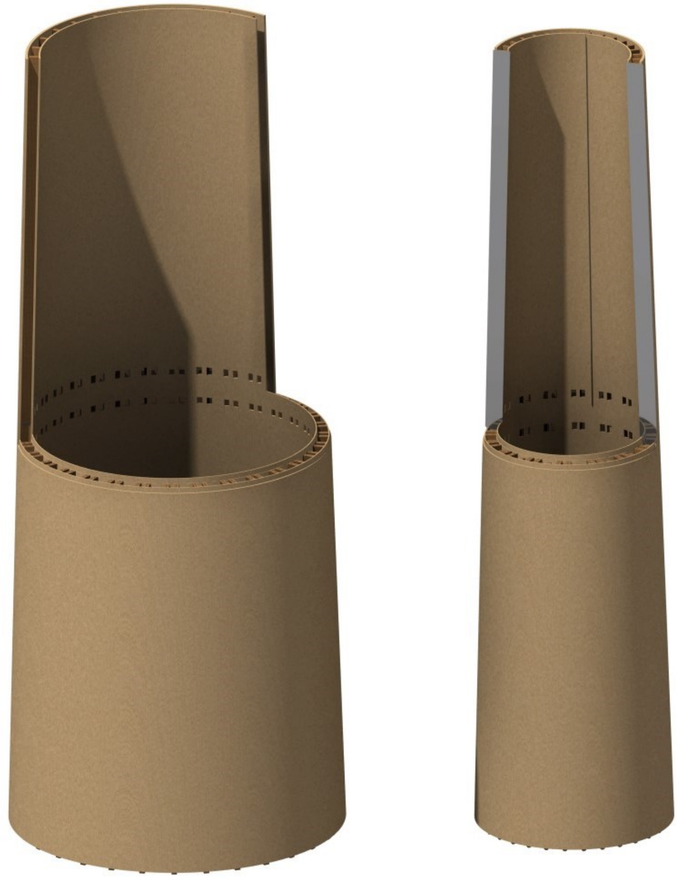

Joining Solution for a Wooden Wind Turbine Tower

Master's thesis in Product Development

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Department of Industrial and Material Science
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2018

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Cover:Render of a conceptual solution.

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Abstract

This report describes the development of a joining solution for a wooden wind turbine tower. It has been carried out in collaboration with Modvion AB.

Taller towers for wind turbines significantly increase the efficiency of the wind turbines, which increase the need for a wider base. Due to transport restrictions, it is hard to transport a tower with a base wider than 4,5 meters. In order to overcome this, a segmented tower that allows assembly on site could be used. The tower developed by Modvion will be delivered to the assembly site in partial circle panels. These panels will be assembled on site, first by constructing the different levels. The tower will then be built by stacking the levels on top of each other. The task of this thesis is to develop the joints for joining the panels into levels, as well as the joints between the levels. In order for this tower design to work, the joints between the panels need to be made strong and stiff enough to ensure that the tower can withstand the forces that wind turbine towers are exposed to.

To be able to find a working solution, a requirement specification was established after a pre-study that includes the properties of wood, different joining methods and the loads associated with a wind turbine tower. With the requirements in mind, a number of concepts were generated. These concepts were carefully analysed and evaluated by using various decision methods. The most promising concepts were further developed to find a final system of solutions.

The outcome of the project is a system of solutions. These solutions are illustrated by CAD-models and a MATLAB program that calculate the dimensions for the joint depending on the load case and size of the tower. However, some further development will be needed to confirm the effectiveness of the solution.

Keywords:Wind turbine tower, Joint, Wood structures, Engineered Wood Products, Glue, Dowel, Bolt.

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- Per-Johan Persson, our contact at Moelven, who helped us with the manufacturing possibilities of our concepts.
- Hamidreza Abedi, Ph.D. at the Division of Fluid Dynamics at Chalmers, who helped us with questions about the aerodynamic loads.

Oskar Ekblad, Oskar Strömblad, Gothenburg, June 2018.

Contents

1 Introduction

This report is a master thesis at Chalmers University of Technology in collaboration with the company Modvion AB. Below called Modvion, Modvion is a small startup company that has developed a design of a segmented wind turbine tower made out of wooden panels. The purpose of the thesis is to develop suitable joining solutions for these panels. A large number of solutions were generated in the early stages, and later on, some were eliminated as they were put through rigorous tests and evaluations. In the end, one system of solutions were developed and analysed carefully.

This thesis was primarily carried out using the methodology of “The Value Model” (*Lindstedt and Burenius (2013)*) which is regularly used for development projects at the school of mechanical engineering at Chalmers.

1.1 Background

It is well known within the wind power industry that taller wind turbines can produce a lot more power than shorter ones, due to the higher wind speeds and the larger blade dimensions. However, building taller towers has many associated difficulties, mainly transport. Traditionally, wind turbine towers are built by stacking large conical steel segments on top of each other. As the tower grows taller, the base needs to be widened. This trend has reached a point where the segments that make up the towers cant be transported on regular roads, as they have height and width limits, this is due to lane width and bridge heights. In Sweden, the maximum height of a vehicle is 4.5 metres (*Moberg and Skagersjö (2004, p.23)*). Since traditional towers are made up of several levels, each one requires special transportation, which rapidly increases the cost. Today this is usually solved by keeping the base diameter at around 4.5 meters and increasing the wall thickness of the tower. This solution is not very weight efficient though.

Because of the reasons above, Modvion believes that today’s wind turbine towers have reached their limit regarding height, and they have therefore developed a significantly different solution to get around this problem. The profile of the tower is still conical, but each level is split up into either eight or four panels which are then assembled into a conical structure. The advantage of this is that the panels can be made small enough to be transported by conventional means (see Figure 1) , while the assembled tower is significantly wider, which means that it becomes significantly stronger in regards to the amount of material used.

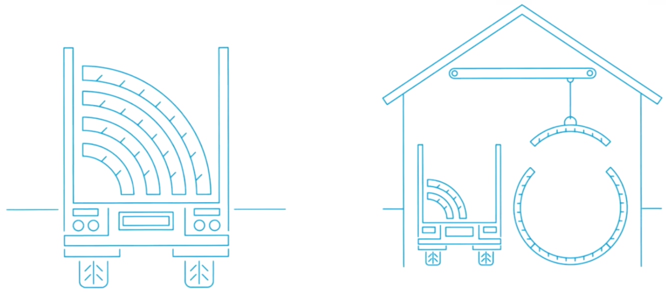


Figure 1: Transport and assembly

One of the advantages of metals as a construction material is that it can be shaped into large, solid, continuous shapes. Since this tower is supposed to be segmented, this advantage is less prominent. Therefore, Modvion has looked at other alternatives and have concluded that wood is a very promising material for this project. In ideal conditions, wood is several times stronger than steel adjusted for their densities (see calculations on page 10). One of the problems with wood though, is that it is anisotropic, which means that it has different properties in different directions. Because of this, as well as irregularities and imperfections, wood is rarely used as a construction-material at a large scale. However, with the introduction of engineered woods, such as LVL (Laminated Veneer Lumber) and CLT (Cross Laminated Timber), many of these problems are taken care of. These materials are made by laminating boards or veneers to tweak the characteristics and reduce the impacts of imperfections. This ability to create more reliable and predictable construction elements means that they can be analysed and used much like the other materials used in the industry.

1.2 Aim

The project aims to develop a joining solution for the design of a segmented wooden tower for a wind turbine. This solution will be validated through CAD design and structural analysis.

1.3 Limitations

- Analysis conducted, will focus on concept validation rather than detailed analysis.
- The cost analysis will be of a simplified type, with the objective to compare different solutions to each another.
- No detailed drawings will be delivered, models will be used to show and validate concepts.
- Joints to the foundation and turbine housing will not be examined.

1.4 Stakeholders

- Future investors in wind turbine energy production are seen as the largest stakeholder in this project, as wind turbines built with this solution might be a more cost-efficient energy producer, and therefore a better investment.
- The energy sector, as the increased cost efficiency would mean that wind power is a more viable large-scale energy producer.
- The wind turbine suppliers, to be able to sell the towers a collaboration with a wind turbine supplier is necessary.
- The assembly personnel erecting the towers, as this solution could result in a more complex assembly routine which might create a higher risk of errors.
- The wood industry, as this would open up a new market for the use of wood. This would also serve as an example of the capabilities of wood for future projects in other sectors.
- Transport companies, as transportation of these panels would be significantly easier, as compared to the towers used today.

1.5 Specification of issues under investigation

The joining concepts in question will have to be developed to meet many requirements in different parts of the value chain. Different stakeholders are affected in each part, which means that all parts need to be addressed to create complete customer satisfaction.

The joining solution has to:

- Hold the panels together securely to form a strong structure that can withstand the forces involved over time.
- Be produced in such a way that the costs are kept at an acceptable level.
- Not compromise the envisioned transportation solution.
- Allow the tower to be assembled on site using available tools and machinery.
- Be able to be serviced and inspected.

1.6 Tower geometry

The general tower geometry, and a detailed view of a panel is illustrated in Figure 2. The panel consist of an inner and outer Laminated Veneer Lumber (LVL) sheet, that are joined with glulam beams, 32 in total. For explanation of glulam beams and LVL see page 12. In the case of this project, a 150 meter tower with 12,5 meter base diameter is used as a reference geometry, divided into ten levels. At the first seven levels, eight panels are used to create a level, and in the last three levels four panels will be used.

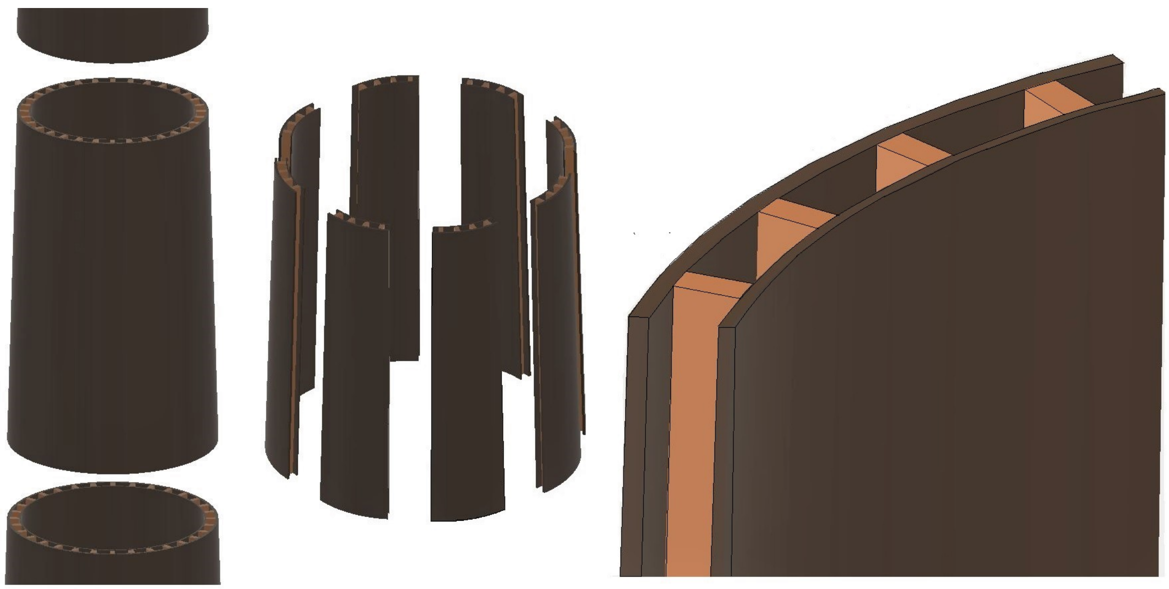


Figure 2: Tower geometry

2 Methodology

The general methodology used during this project is the so called Value Model. This method emphasises maximising value to the customer and the stakeholders in every part of the product lifecycle. The value model gives guidance in both a holistic and a detail perspective (*Lindstedt and Burenius (2013)*). Customer value can be summarised as performance divided by cost. In order to maximise this, the performance of the product has to be increased while keeping the costs at a reasonable level.

2.1 Research

In order to develop effective solutions, research had to be made on the factors that affect them. These include wood characteristics, current joining solutions and general information regardning wind power. To gain knowledge about the factors that will affect the wood; such as anisotropy, effects of moisture and fatigue, a literature study was conducted. Special effort was put on studying wood as an engineering material. This is due to its unique properties and the fact that it does not share the same mechanical characteristics as the materials that are part of the standard engineering curriculum. Emphasis was also put on examining the joining solutions that are used in different industries today. A patent search was conducted to search for inspiration regarding different types of locking mechanisms and joining systems. Searches were also conducted to avoid possible infringements.

2.2 Stakeholder analysis

In order to identify and understand the needs of different stakeholders, interviews and visits were held with representatives from each of them. The most important contacts were:

- Moelven Töreboda AB. Below called Moelven. The factory that Modvion is planning to use to manufacture the wood panels. A factory visit was arranged in order to view the production facility and discuss solutions with their engineers. Since then, they have been helpful in discussing designs and production techniques.

- Rabbalshede Kraft AB. Wind turbine park planner. An email discussion was held in order to understand the needs of during the assembly phase.

2.3 Requirements

In order to understand the demands and wishes for the product, it is important to establish a requirement specification. A requirement specification should be complete and give an overview of the overall expected performance of the product (*Johannesson et al. (2013, p.157-159)*). It should be written in a neutral manner that allows a range of solutions. The requirements should be strong and verifiable. The requirements are divided into wishes and demands. Demands need to be fulfilled in order to have a working product while wishes are not necessary but give increased customer value. Some of the requirements are measurable and have an exact value, while other describes a function that the system needs to provide.

2.4 Concept generation

To generate and evaluate ideas structured development methods were used during the development of the final solution. At the beginning of the concept generation, the joining systems will be divided into different functions. From these functions, a number of ideas will generate concepts that later will be evaluated. After the evaluation the number of concepts will be narrowed down by using structural methods. This process is illustrated in Figure 3.

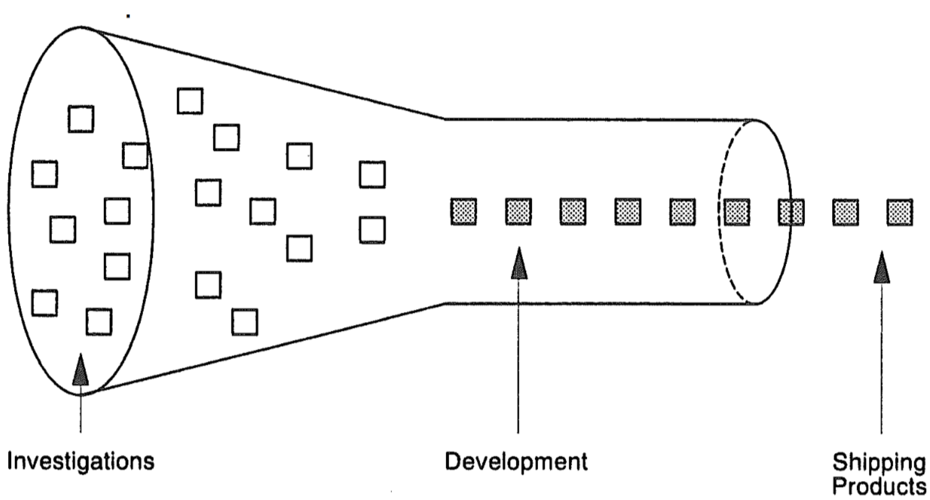


Figure 3: The development funnel (*Ulrich and Eppinger (2012, p. 58-59)*)

During the concept generation, a number of ideas were generated through brainstorming. Brainstorming is a method to generate a high quantity of ideas (*Åsa Wikberg-Nilsson et al. (2015, p. 34)*). Before the brainstorming session begins, it is important to have clearly stated functions that the generated concepts need to solve. The method aims to generate as many ideas as possible, both realistic and unrealistic. To be able to be creative, criticism of the concepts should be avoided in this step (*Åsa Wikberg-Nilsson et al. (2015, p. 35)*). The generated ideas cover both sub-systems and more complete solutions.

2.5 Concept selection

The generated concepts from the brainstorming were evaluated to decide which concept has the highest potential. The evaluation is done by first eliminating the non-feasible concepts and in a later stage compare the remaining concepts in a number of set criteria.

2.5.1 Elimination matrix

An elimination matrix is a systematical tool to narrow down the number of concepts (*Johannesson et al. (2013, p. 183)*). To pass the elimination matrix, the concepts need to be realistic and be able to solve the functions associated with the product.

2.5.2 Pugh selection matrix

Pugh selection matrix is used to compare the remaining concepts against each other in an objective manner considering selected criteria (*Johannesson et al. (2013, p. 184)*). The criteria should cover different categories to get a wide picture of the concepts. The selected concept is compared to a reference concept, see Figure 4. If the compared concept is more suitable than the reference concept, it will get the score '+', if it is less suitable it get a '-' and if it is equally good it will get the score 0. The sum of the scores is added so that the concept gets a net score. The remaining concepts will be compared to the reference in the same way. After the first comparison, the reference concept is shifted to another and the comparing process repeats. The total score of the concepts can be compared to get a rank between the concepts.

	Concepts						
Criteria	A	B	C	D	E	F	G
Cost	-	+	-	0	+	+	-
Effectiveness	-	+	+	+	+	+	0
Speed	-	0	-	+	+	+	0
Portability	+	+	+	+	+	+	+
Mani ability	0	+	-	+	+	+	0
Total Weight	-2	4	-1	4	5	5	0

Figure 4: Example of Pugh Matrix (*Wikipedia (2014)*)

In a ordinary Pugh matrix, each criteria is equally important, which in reality might not be the case. To get a more representative picture of the performance, a weighted Pugh Matrix has been used as well. In a weighted Pugh matrix the score for the concepts considering a selected criteria gets multiplied by the weight of the selected criteria (*Johannesson et al. (2013, p. 185)*). This might lead to a new rank between the concepts.

The weights for the criteria used in the weighted Pugh matrix can be settled in different ways. In this case a weighting matrix has been used. A weighting matrix is a structured way to compare the importance between the different criteria (*Johannesson et al. (2013, p. 188)*). The first row and the first column in the matrix contains all the criteria. The selected criteria is then compared to all the other criteria. If the selected criteria is more important than the compared, it will get the score 1, if it is equally important it will get 0.5 and if it is less important it get get the score 0. The score for each of the criteria will get summed to get a total score, which gives the weight for the criteria.

2.6 Result validation

The selected solutions will be evaluated in order to confirm that they fulfill the requirements and are feasible. Several measures will be taken to validate the different concepts. CAD-models will be created to verify that the geometries will work together to form a solid structure. Mathematical models for the forces acting on the tower levels will be developed to find the critical design demands for the joints. Later, the joints will be dimensioned in detail and analysed; this will be done using MATLAB to iterate several joining concepts for multiple joints.

3 Pre-study

Before the development of the joining solution could begin, a pre-study had to be executed in order to gain knowledge of the materials and systems that are involved in this project.

3.1 Wood

As this project puts great emphasis on the fact that the tower is supposed to be made of wood, it is necessary to research its capabilities and characteristics. In this research, there is a need to separate raw wood from the EWPs (Engineered Wood Products) that are to be used in the final design of the tower. The properties and characteristics of raw wood are essential to grasp to understand how EWPs work and how their properties can be altered to suit different applications (*Thelandersson and Larsen (2003, p.81-84)*). Wood has been an essential construction material for millennia, mostly because of its abundance and the ease of shaping it to suitable construction elements. Its use as a construction material has decreased dramatically during the past century, in favor of materials such as steel and concrete. While this evolution has enabled higher and more dramatic buildings, certain advantages of wood still make it preferable in a few applications.

3.1.1 Fibres/Anisotropy

Wood is a fibrous material; this means that it has fibres running along the length of the material which provides additional strength compared to the base material. These fibres consist of cellulose fibres, which run along a matrix of lignin. This combination creates a sort of composite material, where the cellulose fibres resist tension and the lignin resist compression. These are essential to the strength of the wood. In fact, in the load case of a bending beam (which is the case of the tower), a wooden beam is ideally many times stronger and stiffer than a steel beam of the same weight (*Thelandersson and Larsen (2003, p.15-18)*). The material index, see Equation 1 and 2, describes how well a material perform in a specific loading case (*Ashby (1999, p.85-93)*). In this cases a higher material index indicates that it is stronger and stiffer in relation to its weight, for the load case of a bending beam. See Table 1.

$$M_{Stiffness} = \sqrt{E}/\rho \quad (1)$$

$$M_{Yieldstrength} = \sqrt{\sigma}/\rho \quad (2)$$

	Spruce	Mild steel
Stiffness, E (GPa)	15	210
Yield strength, σ (MPa)	45	250
Density, ρ (kg/m^3)	500	7850
$M_{Stiffness}$	244.9	58.4
$M_{Yieldstrength}$	13.4	2

Table 1: Material properties

Unfortunately, things are not that simple, while the fibres provide the wood with a lot of its strength, it is also the reason for it being a so-called anisotropic material. As the fibres only run in one direction, the material behaves anisotropically, meaning that it has different properties when loaded in different directions. When a wooden element is loaded along the fibres, it is about 50 times stiffer and 30 times stronger compared to the same element loaded perpendicular to the grain(*Gross (2016, p.23)*). This means that it is critical to align wooden element correctly in the design in order to use the material to its maximum potential. The cellulose fibres also play a part in making failure in wood brittle when loaded beyond its limit. When wood is loaded in tension beyond its limit, the cellulose fibres snap without much strain, creating brittle failure. When loaded in compression, it is slightly more ductile, as the lignin carries most of the load.

3.1.2 Wood fatigue

Like most materials, wood can experience fatigue failure under certain loading conditions. These conditions are more complex than the ones affecting fatigue in most materials. In traditional fatigue theory, only stress amplitude and NOC (number of cycles) affect the TTF(time to failure). When studying fatigue in wood, another factor is in play, TUL (Time Under Load). Because wood is viscoelastic, the frequency of the load affects the fatigue properties. The exact correlations of these parameters are still being researched and the models used have not been completely experimentally verified (*Thelandersson and Larsen (2003, p.144)*). Three surfaces can be seen in Figure 5, where three different characteristics can be seen. Because of the complexity of this, the project will not include fatigue analysis of the wood itself. Instead, all wood elements used in the joints will be dimensioned so that the stresses are not significantly higher than those found in the analysis of a seamless tower. This means that the the proposed solutions will rely on the fatigue asumptions made by Modvion prior to this project.

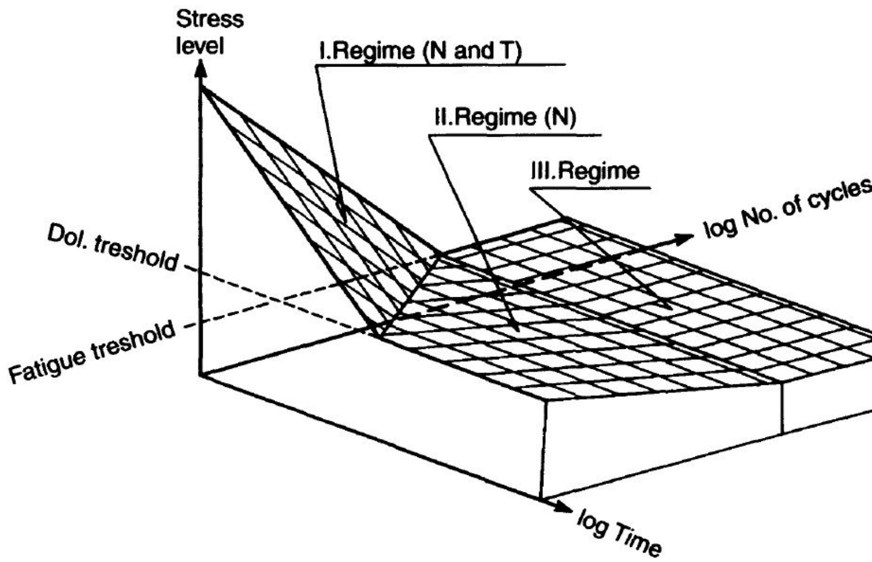


Figure 5: Fatigue characteristics for wood (*Thelandersson and Larsen (2003, p.144)*)

3.1.3 Moisture

Wood is hygroscopic, which means that it interacts with the humidity of the surrounding air. Because of this, wooden construction elements can vary in moisture content during their lifespan. This variation in moisture content results in swelling and shrinking of the wood. These shifts are not uniform though, the shifts perpendicular to fibres are around 20 times larger compared to the shift along the fibres (*Thelandersson and Larsen (2003, p.153)*). The shift in moisture content (MC) can be modeled with equation 3:

$$\Delta l = \Delta MC \cdot a \cdot l \tag{3}$$

Where l is the unit length, MC is the moisture content in the wood and a is the expansion factor for the specific wood and direction. The glulam beams used in this case, has an expansion factor of 0.002 across the grain and 0.0001 along the grain (*Crocetti (2016, p.7)*). However, the moisture content is rarely uniform in a wood element. The moisture in the wood is transported through diffusion, which is a slow process. This means that different parts of the same element will have different moisture contents at any given time. These differences can create warps and cracks since parts of the same element swell at different rates and create internal stresses.

3.1.4 EWPs

As mentioned earlier EWP is the combined name of wood products that are made by laminating veneers and beams of wood into larger construction elements. These elements have different properties compared to regular wood. Their properties can be altered to behave in different ways depending on how they are made. A good example of this is plywood and LVL, they are both made by laminating thin wood veneers together, but while the veneers in LVL are all stacked with the fibres in the same direction, in plywood, they are laminated perpendicularly. This means that with the same base material, two different construction materials can be created. The plywood behaves in a more isotropic manner but with somewhat lower ideal mechanical properties. LVL is still anisotropic, but eliminates weak points and retains the ideal mechanical properties(*Thelandersson and Larsen (2003, p.153)*). The EWPs that are to be used in this project are so called glulam beams and LVL sheets.

Glulam beams

Glulam beams are wooden beams laminated together to form larger beams. This has many advantages, one of which is that larger beams of nearly any dimension can be created, they can also be formed into curved shapes which enables more types of designs. Another advantage is that localized weak points such as knots and small cracks do not go through the entire beam, which means that the strength of the material increases. When making glulam beams, wooden beams are machined to a precise flatness and glued together. Increasing the thickness of the beam is relatively easy, as there is a lot of surface area for the glue to adhere to. To create the desired length, however, the surface area is limited. Therefore the lengthwise joints are usually made using finger joints. Which help transfer the loads between the beans as well as create a larger surface area between them (*Gross (2016, p.7)*).

LVL-sheets

As mentioned above, LVL-sheets are large laminated panels where most of the fibres are running in the same direction. This is suitable when the forces in the application are predictable, and high strength is only needed in one direction. As with the glulam beams, LVL-sheets can be made in large, intricate shapes, and while doing so, knots and other weak spots are spread out and layered so that they have less impact on the overall strength of the sheet (*Thelandersson and Larsen (2003, p.93-95)*). The LVL-sheets used in this project are laminated with 20% of the fibres running perpendicular to the rest, this is done to reduce the sensitivity of the design.

3.2 Joints

The purpose of the thesis is to develop joining solutions. Even though the final product may not use existing joining concepts, it will likely use elements of them, such as dowels or glue. Therefore it is important to understand how the different joining techniques in the industry work and interact with the wood. The stiffnesses of a few common wood joints can be seen in Figure 6.

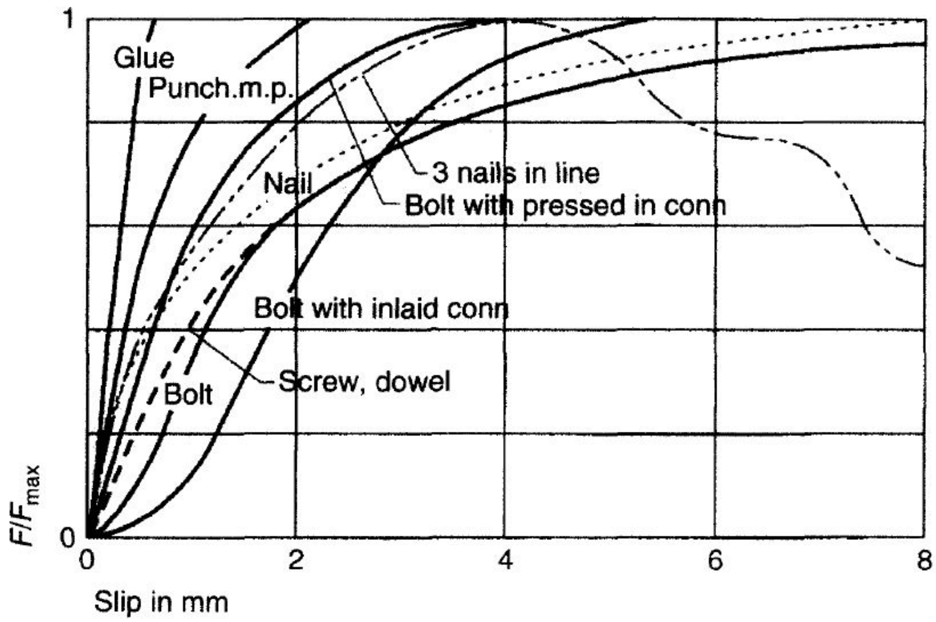
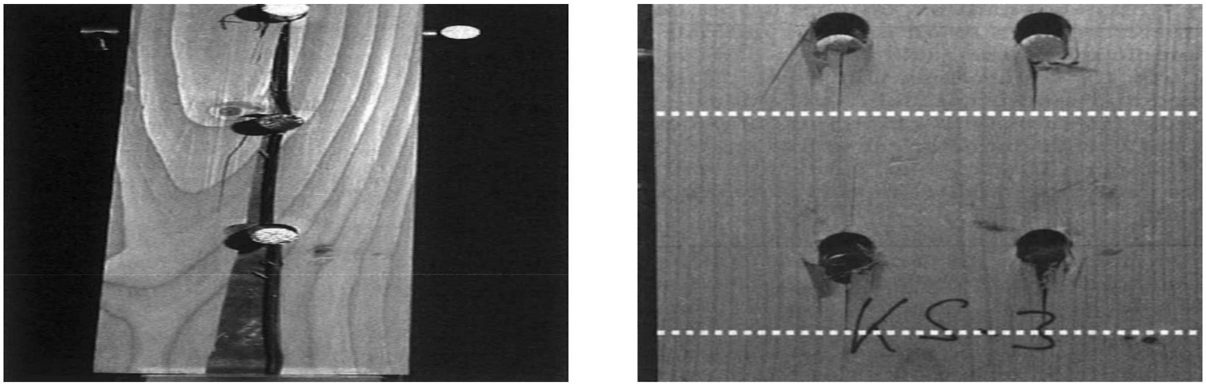


Figure 6: Joint stiffnesses *Thelandersson and Larsen (2003, p.313)*

3.2.1 Dowels

There are numerous types of dowel joints being used in wood construction, but they all work using the same principle. Two beams or similar construction elements are attached to one another by a dowel type fastener that runs through both of the elements. This dowel can be a screw, nail or other forms of designs depending on the application. The forces are transferred between the beams through the dowel, which means that it can be subjected to a great deal of force. Several dowels are usually used in a single joint in order to distribute the load over many elements. Different dowels work in different ways, a cylindrical dowel will transfer force over its perpendicular area, while a self-tapping screw can transfer loads lengthwise through its threads. Self tapping screws can also be used to reinforce wooden beams by preventing splitting, see Figure 7.



(a) Without screws (b) With screws (dotted lines)

Figure 7: Crack prevention with screws, load is applied in vertical direction (*Thelandersson and Larsen (2003, p.323-324)*)

The load carrying capacity of a single, cylindrical dowel is found by equation 4 (*Crocetti (2016, p.55-56)*). Each of the variables in the equation 4 can be found in Table 2.

$$R_k = 1.15 \cdot \sqrt{\frac{2 \cdot \beta}{1 + \beta}} \cdot \sqrt{2 \cdot M_{y,k} \cdot f_{h,1,k} \cdot d} \tag{4}$$

Variable	**Meaning**
R_k	Carrying capacity
$M_{y,k}$	Dowel strength
$f_{h,1,k}$	Hole strength
β	Hole strength factor between elements
d	Dowel diameter

Table 2: Variables for calculating the carrying capacity of a single dowel

These equations derives from Eurocode 5, a European standard that describes how the design of timber structures should be managed within the European Union (*Eurocode*).
Failures in dowel joints are complex, as both the dowel and the wood fail in unison and each has multiple modes of failure, illustrated in Figure 8. This makes failure difficult to model and design against, because of this, a generous safety factor is usually introduced.

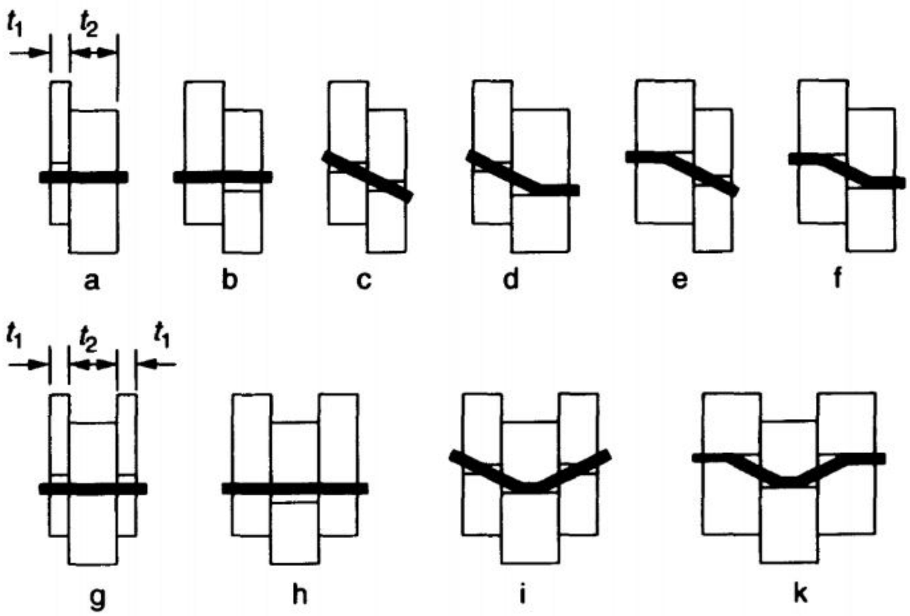


Figure 8: Failure modes in dowel joints (*Thelandersson and Larsen (2003, p.318)*)

3.2.2 Bolts

Even though bolts can be considered as a type of dowel when loaded perpendicularly, they behave in a completely different manner when they are pretensioned and loaded axially. When a bolt is pretensioned around a part, the bolt extends, and the part is compressed. This results in static forces and deformations, the forces and deformations are proportional to the stiffnesses of the elements, where the deformation increases linearly with the force. When forces are applied to the joint during use, they will also induce deformations. Both of these deformations interact according to the stiffnesses of the elements, and this affects the forces that each element is subjected to. These joints can be modeled using the F/δ equations (*Mägi et al. (2017, p.80)*). The angle of the sloped lines in Figure 9 correspond to the stiffnesses of the elements; steeper means stiffer. The one extending from origo is the bolt stiffness, and the other is the clamped part.

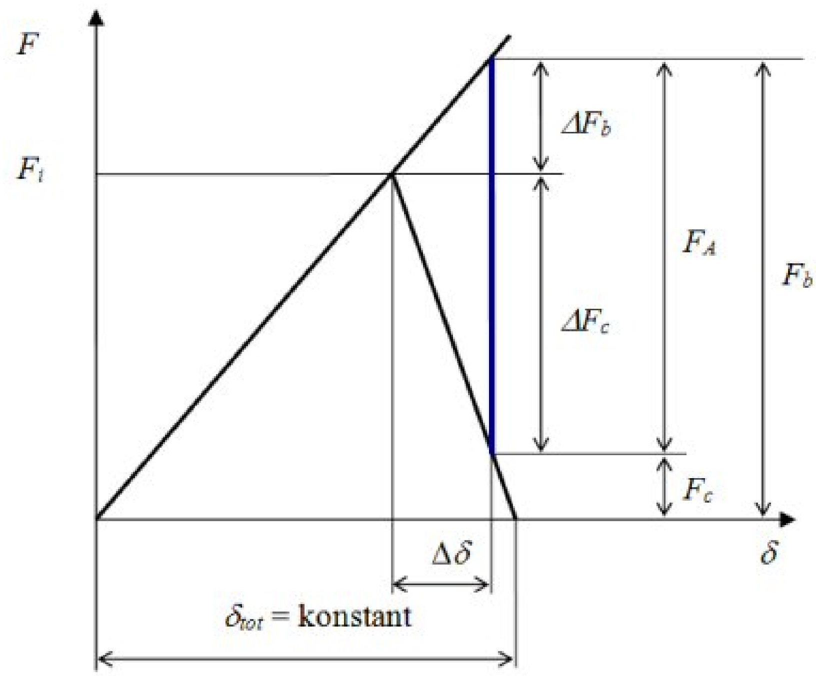


Figure 9: F/δ diagram *Swedish Fastener Network (2018)*

F_t =pretension force F_A =Applied force F_C =Clamping force F_b =bolt force
ΔF_c = Lowered clamp force ΔF_b =Increased bolt force $\Delta\delta$ =Joint deformation

The pretension force is chosen depending on the application, usually as a factor of the bolts failure limit. Common modes of failure to consider when designing these joints are bolt fatigue and joint disconnection. Bolt fatigue is developed when $\Delta F_b =$ is too large; this is best avoided by decreasing the stiffness of the bolt and increasing the stiffness of the part. Disconnection happens when F_C approaches zero and the clamped parts no longer make contact, this is avoided by ensuring a high pretension, which may require a larger bolt dimension (*Mägi et al. (2017)*).

3.2.3 Glue

Glue is extremely common in wood construction. However, it is mainly used when manufacturing different construction elements in factories, rather than as a means of assembling elements into a building. However, while it is challenging to use glue while assembling larger elements, it is a method worth exploring. As with all joining types, they can be used in different ways depending on the application, but they share a number of characteristics. Glue is the stiffest wood joint possible (see Figure 6), which is generally desirable, but it also means that it is unsuitable in joints where a certain amount of deformation is expected.

The stiffness of glue also means that glue joints may prevent the movements brought on by moisture, which in turn may lead to cracks. Glue can be used in combination with screws and interlocking flanges to create a strong joint, in this case, the glue is the active joining agent, while the screws or flanges work by distributing the glue and the forces between the elements. It is not possible to combine for example screws and glue in the hopes of strengthening the joint itself. Since they have drastically different stiffnesses, they are not compatible (*Thelandersson and Larsen (2003, p.313)*).

3.2.4 Glued rods

While it may seem that glued rods are just a combination of bolts/dowels and glue, that combination creates a joint that can be used in ways that neither of the two can on their own. It combines the stiffness of the glue, with the versatility of bolts, enabling several joining solutions that would be difficult to create otherwise. On a fundamental level, they function much like their respective parents, but there are many specific equations for different applications of this joint type (*Thelandersson and Larsen (2003, p.356-371)*).

3.3 Wind power

The use of wind power is increasing globally, the global production capacity has seen an annual growth of 12.6% in the latest years (*GWEC (2017)*). In Sweden, wind power accounts for 9% of the total energy production in 2016 (*Energimyndigheten (2017, p.8)*). As the wind speed is higher at higher altitude, taller towers enable better system efficiency. The produced energy is directly proportional to the cube of the wind velocity. A higher tower also enables larger diameters of the rotor blades and turbines which can produce more energy (*Manwell et al. (2010)*).

3.3.1 Current tower designs

Steel tube tower
While there are some variations in tower designs in the industry, the overwhelming majority follow the steel tube design principle. The tower is made up of conical steel elements with internal flanges welded onto the top and bottom (*Engström et al. (2010, p.19)*). These are then stacked so that the flanges meet and can be bolted together. These bolts have to be tightened with immense forces, demanding flat interfaces between the flanges, reliable characteristics from the bolt grease and consistent torque from the tools. Failure to achieve the desired bolt pretension force can result in poor fatigue resistance. This leads to increased cyclic loads which over time results in failure of the bolt and the collapse of the tower (*Statens Haverikommision (2017, p.33)*).

Concrete towers
Concrete towers is a design which is quite different compared to the steel tube. Their main advantage is that the levels can be moulded on site. This solves a lot of the transportation problems, as the levels can be made wider, but the transportation of concrete can be made in regular concrete trucks. Concrete can withstand high compression forces, but it is weak in tension. To get around this problem, the entire tower can be compressed using steel tensioning cables (*Engström et al. (2010, p.26)*), ensuring that the concrete is always kept in compression. While it has been proven that tall towers can be made using this design, they require a lot of concrete. This means that they are not the most environmentally friendly solution, which many argue is the main goal of building wind turbines in the first place.

Modular steel towers
The idea of building modular towers is not unexplored. One company that is exploring this option is Northstar (*Northstar (2018)*). Their design is similar to Modvion's in some ways, mainly in how they piece together levels which are then stacked. Each level is made up of six steel panels. These are bolted together using friction joints. This is a tried and reliable joining concept, but it requires a lot of bolts, which leads to a complicated assembly process.

3.4 Loads

Many different loads act on a wind turbine tower, and each one can lead to failure if not considered properly. When joining a segmented wind turbine tower such as this, the tangential joints will have to be designed to carry loads that are regularly carried by a solid steel cross-section. Therefore, there is a need to investigate the different loads in order not to overlook the ones that are not critical in a traditional design.

In this part, only the generic equations will be presented. As factors like bending moment and cross-sectional properties vary along the height of the tower. Illustrations of the load cases can be found in Appendix A.

- **F** the force applied at the top of the tower
- **I** Second moment of inertia, cross sectional property
- **Q** Static moment of area, cross-sectional property
- **b** Cross sectional thickness
- Δh Distance from the point of measurement to the top of the tower
- **M** Bending moment
- **y** Distance from the cross-section center to the point of stress measurement

- F_J Force on joint, the amount of force a vertical joint is expected to withstand
- A_{SJ} Section area that one joint is expected to support
- A_τ Tangential section area

3.4.1 Static load

When the tower is assembled, it will have to support its own weight plus the weight of a turbine. For a 150m tower with the imagined cross section, this is about 500 tonnes plus about 350 additional tonnes from the turbine and rotor (*Siemens (2012)*). This load is of least concern, as it is applied strictly vertically from the top, it does not primarily target the joints the same way that the other loads do. It does require the cross section to be buckling resistant and stiff enough to not deform.

3.4.2 Bending moment

The wind acting on the rotor causes a load of about 1 MN (for the reference geometry) to be applied at the center of rotation. This load results in a bending moment that runs along the tower. This moment is affected by the load on the rotor and the distance at the point of measurement from the top, increasing further down the tower. This moment will put stress on the vertical joints, as they are the ones that join the levels of the tower lengthwise and keep the moment from tipping the tower. The bending moment is calcualted with equation 5.

$$M = F \cdot \Delta h \tag{5}$$

The resulting stresses in the structure are calculated with equation 6:

$$\sigma = (M \cdot y)/I \tag{6}$$

These are equations for an ideal beam, subject to a point load at the end. This is not an entirely accurate representation of a wind turbine though. Apart from the load on the rotor, a force will also be created as the wind acts on the rest of the tower, creating a pressure differential between the front and rear. This force is low and difficult to model, to compensate for this, a safety factor is used on the rotor force. To establish the amount of force each joint has to carry, this stress is multiplied by the cross-sectional area that a joint is expected to support. That area is equal to the section area of a beam and the section area of the LVL sheets halfway to the next beams. This is calculated with equation 7.

$$F_j = \sigma \cdot A_{SJ} \tag{7}$$

3.4.3 Shear force

When the tower is bending, a shear force will be applied between the tangentially joined panels. This is due to the skewing that appears as the structure bends. This load is present in all structures exposed to bending. In traditional wind turbine tower design, shear forces are handled by the cross section itself, and will not primarily affect the joints. In this tower, the shear forces will have to be transferred by the tangential joints.

The shear stress is dependant on the force applied at the top of the tower, as well as three cross-sectional properties, as shown in equation 8.

$$\tau = (V \cdot Q)/(I \cdot b \tag{8}$$

The total shear force acting on the joint as a result of this is calculated with equation 9:

$$F_\tau = \tau \cdot A_\tau \tag{9}$$

3.4.4 Cyclic loads

The cyclic load is a result of the rotation of the rotor which causes vibrations. The primary loads from this are known as 1P and 3P (*Hau (2006, p.422-428)*). The imbalance in the rotor causes the 1p load. Just like in a car, when a wheel is unbalanced, the rotation causes cyclic loads as the center of mass rotates around the axle. This load is usually quite small as the rotor is carefully balanced after the assembly. The 3P load is caused when a rotor arm passes by the tower and initiates strong turbulence. This turbulence causes powerful vibrations, which makes it important to have the natural frequency of the tower separated from the 3P frequency. Vibrations like this affect all joints, making it very important to consider fatigue strength for them.

4 Concept generation

This chapter describes the concept generation phase. Firstly, the design requirements are described, followed by the presentation of initial concept suggestions, and the subsequent selection thereof. In order to create a large number of joining concepts, several brainstorming sessions were carried out. These were done in a free manner, using whiteboard drawings to illustrate and initially develop the concepts. The solutions were divided into two variants, tangential and vertical; these are then placed into sub-categories based on their working principle. Tangential joints are the ones that join several panels into one level; vertical joints are the ones that join the stacked levels into a taller structure. The different joints work in unison to create a stiff structure, and some of the concepts might not be compatible in this regard.

All the intitial concepts can be found in Appendix B.

4.1 Requirements

To understand the needs and requirements of the joining solution a requirement specification has been established. The specification has the following categories: Structural integrity, assembly, service and miscellaneous. The requirements derive from different sources, like Modvion, transportation restriction and observations made on the wind power industry. The evaluation of the requirements is done in different ways, mostly decided by the geometrical design.
The complete requirement specification can be found in Appendix C. The following list list the most crucial requirements:

The joints need to:

- Handle the shear force and bending moment deriving from a 1 MN rotor force.
- Be weather resistant over time.
- Be manageable to assemble, only using standard tools and allowing pre-assemble of levels on site.
- Be resistant against impact during handling and assembly.
- Enable stacking of levels without the need to work from the outside of the tower.
- Allow service and replacement of vertical fastening elements.
- Be manufacturable with available methods.
- Be designed for a lifespan of 20 years.
- Cost less than 15% of the total tower cost.

4.2 Initial tangential concepts

The tangential concepts can be carried out using many versions of panel designs. Looking at the cross-section of the tower, it consists of two LVL tubes with glulam beams holding them together, see Figure 10. When dividing a level into symmetrical panels, the cuts can be made in several different ways, each with their advantages and disadvantages (the panels are made separately, and no cut has to be made, but it is an intuitive way of visualising the joint design and assembly). The example showcased in the reference model places the cut in between two glulam beams, only splitting the LVL-sheets. Another quite simple solution would be to split a beam in two, essentially leaving half a beam at either end. There are, of course, many more possibilities, some of which are listed below as part of joining concepts. The concepts shown below are the results of brainstorming sessions and initial refinement.

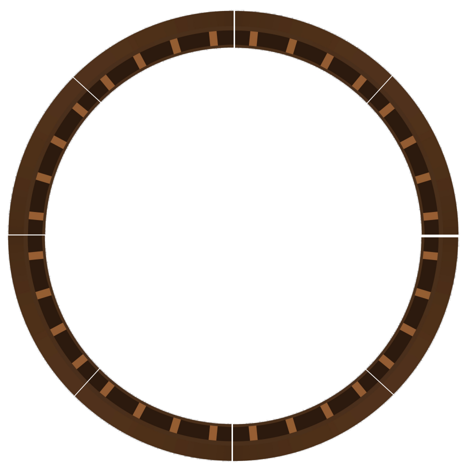


Figure 10: Gaps show joints

While these concepts are primarily used as tangential joints to pair panels into segments, similar concepts will also be considered as part solutions for the vertical joints.

4.2.1 Panel cuts

The concepts that are shown below work by dividing the cross section in different ways to create overlaps that enable the panels to be joined.

LVL stair-A

As the LVL-sheets are made up of several different layers (five on the outside and three on the inside), these can be aligned in a manner resembling a stair formation. This creates a joint where the panels have a decent amount of contact area, as well as an interlocking effect.

When the panels are put in place, they are nailed, screwed or glued together.
Positives: No added weight on panel, cheap, interlocking edge.
Negatives: Brittle edge, fairly difficult to align in assembly.
Development needed: Length of each step, size, and spacing of nails

Shared beam-B

On one side of the panel, the beam is exposed halfway, leaving room for the LVL-sheets on the other side to be put around it. This enables nails to be put through the LVL and into the beam, which ensures a tight fastening.
Positives: No added weight on panel, cheap, interlocking edge.
Negative: long piece of self supporting LVL, asymmetrical panel, slight widening of panel.
Development needed: Size of joining beam, size and spacing of bolts, support for LVL-sheet.

Asymmetrical shared beam-C

The fastening principle is the same as in the previous concept, but the inner and outer LVL-sheets are attached to different beams. This is a structural advantage as the joint does not run straight through the wall, instead, it is divided in two "cuts" where each cut is supported by a solid panel beside it.
Positives: No added weight on panel, cheap, interlocking edge, divided split line.
Negatives: long piece of self supporting LVL, asymmetrical panel, large widening of panel.
Development needed: Size of joining beam, size and spacing of bolts, support for LVL-sheets.

Male-female LVL ends-D

One LVL layer on each side is extended outwards to make a male connection. On the opposite side, the same layer is offset inwards to make a female connection. These are interlocked and nailed together.
Positives: Minimal change to panel,
Negatives: Load carrying capacity, brittle edge.
Development needed: Dimensions of layer extension, nail fastening.

4.2.2 Introduce sheets

The concepts that are shown here work by introducing structural sheets that overlap the joining panels. These can be made in different materials and attached in different ways.

Sandwich-E
Slits are cut into the LVL-sheets. Sheets of either wood, steel, or a hybrid of the two can then be inserted into the slits of two joining panels. They are then fastened with either glue or bolts.
Positives: No added weight on panel, enable steel reinforcement, stiff, guiding during assembly.
Negatives: Complex geometry to model, may require glue.
Development needed: Size and number of slits and sheets, slit tolerances, glue assembly.

Cover panel-F
At each end of the panel, the last layer of LVL does not run all the way to the edge. This enables another panel to overlap both joining panels while sitting flush against the surface.
Positives: No added weight on panel, cheap, wide edge panel.
Negatives: Relatively weak joint, lots of extra panels in assembly.
Development needed: Size of joining panels, size and spacing of bolts, variants of joining panels.

4.2.3 Friction joints

These concepts work by introducing steel surfaces around the joint so that friction bonds can be made between them.

Steel side-G
The side of each panel is covered with a steel plate that creates flanges on both the inside and outside. When two panes are joined, these flanges are bolted together to form a friction bond.
Positives: Very strong joint, steel plate protects panel edges.
Negatives: Added weight, cost, altered shape complicates transport, altered shape might increase wind load.
Development needed: Dimensions of steel plate, bolt parameters, bolt force, surface treatment of plate, steel to wood glue.

L profile-H
Similar to G, this concept works by friction bond, but instead of covering the entire side with a steel plate, the ends of the LVL sheets are paired with an L profile that creates the flanges.
Positives: Strong bond, steel plate protects panel edges.

Negatives: Added weight, cost, self supporting LVL, strength of bracket to panel bond, altered shape might increase wind load.
Development needed: Dimensions of steel profile, steel to wood glue, screw parameters.

4.2.4 Clamped beam

These concepts work by splitting the cross-section of the tower through the beams, then clamping them together.

Bolt through beam-I
The inside LVL-sheet has holes cut in it that enables bolts to be driven through the end beam of two panels.
Positives: No added weight on panel, few but strong bolts are used.
Negatives: Weakening of structure from holes, bolt compression on wood, shear direction perpendicular to bolt.
Development needed: Size of joining beam, size, and spacing of bolts, tensioning force of bolts.

Staples-J
Slits are cut beside the end beams of the panels. This enables a staple like bracket to be put through the slits and encircle the beam at the joint and squeeze it together. The ends of the staple can then be bolted together.
Positives: Simple component, accessible with tools.
Negatives: Unsure friction between beams, weakening of panels, holes in exterior panel increase risk of weather damage.
Development needed: Dimensions of steel staple, bolt parameters, sealing hole.

4.2.5 Miscellaneous

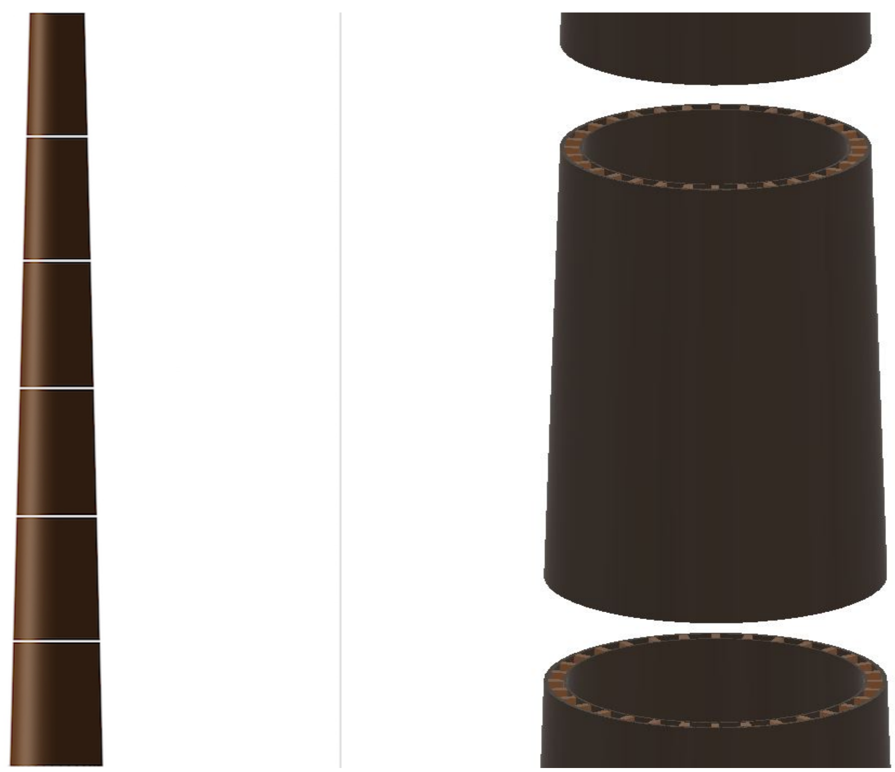
H profile-K
On the edge of the LVL-sheets, a steel profile is attached. In this case, it is an H (or a wide I) profile. The profile covered side is matched with the free side of the other panel, which is then bolted or glued in place with the profile.
Positives: Little modifications of panels
Negatives: Some added weight, cost, difficult to match profile with the panel, joint strength.
Development needed: Dimensions of steel profile, attachment method.

Toothed wall-L
At the ends of the panel, teeth are pre-made that interlock in the adjacent panel. This means that two panels are pushed together tangentially to form a joint, glue or nails are used to

fixate, but wont carry much load.
Positives: No added weight on panel, interlocking edge, contact area perpendicular to the shear direction.
Negatives: Brittle teeth, complex LVL cutting, difficulty of assembly, fine tolerances might be needed.
Development needed: Size of teeth, size and spacing of bolts, manufacturing method of teeth, need for an extra supporting beam

4.3 Initial vertical concepts

The vertical joints join stacked levels to make the tower taller. A crane lifts a pre-assembled level on top of another. They are then joined using one of these concepts. The interfaces for these joints are illustrated in Figure 11.



(a) Splitting lines (b) Levels

Figure 11: Vertical joints

4.3.1 Wood flange

End beam-M
In the top and bottom ends of each panel a curved glulam beam is fixed together with the vertical beams. When the levels are stacked, the end beams can be bolted together. To be

able to perform this operation, an assembly window in the inner LVL is necessary.
Positives: Little change of weight, no change of outer dimensions of the panels, bolts are axially loaded.
Negatives: The end beams will be loaded perpendicular to the fibres, steel reinforcement might be needed, need for hole in inner LVL.
Development needed: Examine load direction in beam, possible reinforcement.

End beam with guide beam-N
Fairly similar to end beam, but said end beam is also equipped with guiding beams to guide the stacked level into the correct place.
Positives: Large area for bolt attachment, little change of weight, provides guiding during assembly.
Negatives: The end beams will be loaded perpendicular to the fibres, fairly intricate manufacturing, interference during stacking.
Development needed: Examine load direction in beam, edge cut to enable guiding.

Boot-O
On the top and bottom edges of the panels, a block of wood, resembling a boot is glued. This creates internal flanges that meet up as the levels are stacked. The connecting flanges are then bolted together as they would be in a conventional tower design.
Positives: Large area for bolt attachment, easy assembly.
Negatives: Cumbersome geometry, complicates stacking during transport, unsure strength of joint.
Development needed: Design to transfer force, attachment to panel, bolt parameters.

4.3.2 Vertical beam bolts

Side beam-P
Each beam in the panel has two side beams glued at each end. When the levels are stacked each beam will be standing on top of another, aligning the side beams perfectly and enabling long bolts to be put through. In order for this to work, assembly windows will have to be cut in the inside sheet of LVL.
Positives: Simple and cheap, even tension over beam.
Negatives: Fairly intricate assembly, slight weakening of internal structure.
Development needed: Bolt parameters, Dimensions of beam.

Guide beam-Q
Functions much like the previous concept, but the side beams on the lower panel extends beyond the top edge of the panel, creating a guided slot for the lowering panel to drop into.
Positives: Simple and cheap, even tension over beam, guiding during stacking.

Negatives: Fairly intricate assembly, slight weakening of internal structure, interference during stacking.
Development needed: Bolt parameters, edge cut to enable guiding.

Bolt inside beam-R
The beams are vertically connected with bolts inside the beam. To be able to do so, a hole in the beams and LVL is necessary. The beam holes can be reinforced with steel.
Positives: Minimal change of overall structure, cheap, even tension over beam.
Negatives: Weaker beams.
Development needed: Beam reinforcement, glued or inserted bolts.

4.3.3 Steel flange

Profile flange-S
At the top and bottom a bended T-profile is glued to the inner and outer LVL. The T-profile is creating a flange that can be bolted together after stacking the levels.
Positives: Easy to assemble, relatively large area for bolts.
Negatives: Expensive and complicated profiles, does not connect the vertical beams, the thickness of the LVL limits the size of the flange, need for assembling on the outside of the tower.
Development needed: Dimensions of profiles, curvature, bolt parameters.

Plate flange-T
Shaped like a traditional flange in wind turbine tower design, a plate is attached to the top and bottom of the panels, matching its neighbour as they are stacked, enabling bolts to tighten them together. As this tower has an unusually wide cross-section, the flange will probably have to extend both inside and outside of the tower to create a uniform pressure over the joint area.
Positives: Tried conventional design, strong bond.
Negatives: Very expensive, very heavy, complicates geometry.
Development needed: Plate dimensions, bolt parameters.

4.3.4 Miscellaneous

Block-U
Between the panel beams, blocks of wood are placed and fastened into the panel. These blocks form teeth that interlock with the next panel during stacking. The blocks are then fastened into the top panel using bolts.

Positives: Durable geometry, provides guiding during assembly.
Negatives: Complex block shape, bolts loaded perpendicurarly.
Development needed: Assess geometrical difficulty, joint strength.

Steel side sandwich-V
This is a complementing concept that requires the tangential joint concept "steel side" to be used. When two levels are stacked, their tangential edges are supposed to align. This creates a steel flange that runs along the tower, enabling additional plates to be used to create friction joints at the vertical edges.
Positives: Strong bond, using available geometry.
Negatives: Requires aligned edges, fixation but no tension.
Development needed: Shear effect of aligning panels, carrying capacity.

4.4 Concept selection

The next part of the development chain is the concept selection. Here, all proposed concepts are compared to each other, as well as the requirements listed in the requirement specification. This is done using elimination and selection matrices.

4.4.1 Elimination

An Elimination Matrix was created to reduce the number of concepts the concept selection phase. The matrix includes five criteria: cost, transport, the complexity of manufacturing, joint strength and assembly. As earlier, the concepts are divided into tangential and vertical joints. The different concepts are evaluated to see if they fulfill the criteria or not. If the concept fulfills all criteria, it passes to the next phase, if it does not, it will be eliminated. In some cases, further research is needed, in which case the concept passes.
For the tangential joints, eight concepts passed the elimination matrix for further evaluation. See Table 3.

	A	B	C	D	E	F	G	H	I	J	K	D
Concepts/ Criteria	LVL stair	Shared Beam	Assym. Sh. Beam	Male/Female LV	Sandwich	Cover panel	Steel side	L-profile	Bolt through be	Staple	H-profile	Toothed wall
Cost												
Transport												
Complexity of manufacturing												
Joint strength												
Assembly												
Keep	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No	No	No	Yes

	Pass
	Research needed
	Fail

Table 3: Elimination tangential joints

The following list explains why the eliminated concepts did not pass:

- Concept F, Cover panel, will not be strong enough. Limited sheet thickness for bolt joint. No area perpendicular to shear direction.

- Concept I, Bolt through beam, will not be strong enough. The shear force will load the bolts perpendicularly.
- Concept J, Staple, will not be strong enough. It will be difficult to achieve enough friction between the beams, in which case, the bolts are loaded perpendicularly.
- Concept K, H-profile will be too expensive. There are no standard profiles in the required dimension, which will lead to a high cost.

For the vertical joints, only four concepts passed the elimination matrix for the concept selection phase. See Table 4.

	M	N	O	P	Q	R	S	T	U	V
Concepts/ Criteria	End beam	End beam with guide beam	Boot	Side beam	Guide beam	Bolt inside beam	Profile flange	Plate flange	Block	Steel side sandwich
Cost										
Transport										
Complexity of manufacturing										
Joint strength										
Assembly										
Keep	No	No	No	Yes	Yes	No	No	Yes	No	Yes

	Pass
	Research needed
	Fail

Table 4: Elimination vertical joints

The following list explains why the eliminated concepts did not pass:

- Concept M, End beam, will not be strong enough. The end beam will be loaded in its weak direction. This could be fixed with steel reinforcements, but it will lead to an unnecessarily complex solution.
- Concept N, End beam with guide beam, will not be strong enough. It is loaded in the same way as concept M, in the beams weak direction.
- Concept O, Boot, will not be strong enough, similar to concept M and P, it will be loaded in the weak direction of the glulam beam. It will also have a complex geometry, unique for every level which will lead to a high cost.
- Concept R, Bolt inside beam, will not be strong enough, the holes will weaken the beams too much.
- Concept S, Profile flange, will be too expensive. It will need a high quantity of complex profiles, unique for every level.
- Concept U, Block, will be too complex to manufacture, to get a good contact with all surfaces fine tolerances will be needed, unique blocks for all levels.

4.4.2 Concept selection

Pugh's concept selection matrices were used to evaluate and compare the remaining concepts to decide the most promising ones. During the first screenings, a regular Pugh matrix was used and in a later stage, a weighted Pugh matrix. The Pugh matrices can be found in Appendix D. For the weighted Pugh matrix, a weighting matrix was used to determine the weights for each of the criteria. In total there are eleven criteria, which are compared to each other. The weighting showed that the most important criteria are stiffness/strength and weather resistance. The weighting matrix can be found in Appendix E. Since there are 11 criteria, the highest possible weight from a weighting matrix is 10.

The matrices evaluate the concepts based on the following criteria:

Cost: The added cost for the joint compared to an unmodified model. Cost is always important, but in this case the remaining concepts are already assumed to be able to meet the cost target. Because of this the difference in cost between the concepts is of medium importance. The weight for this criteria is set to 4.

Shock resistance: How sturdy the panel is to hits and bumps during handling. Because of the consequences if an element gets damaged, the weight of this criteria is set to 7.

Size: The added size compared to an unmodified panel. All maximum dimensions are stated in the requirement specification, which the remaining concepts fulfill. The change in size gives a minor advantage due to easier transportation. The weight for for this criteria is set to 3.

Weight: The added weight for the joint compared to an unmodified panel. The added weight is assumed to be of less importance, as long as it fulfills the requirements. Due to this, the weight for this criteria is set to 1,5.

Manufacturing: The complexity of manufacturing for the panels and joint. A less complex manufacturing decrease the risk of defects and errors. Since the requirements are already fulfilled, the weight for this requirement is set to 4.

Serviceability: The ability to perform a service and replace elements. Due to the importance of replacing element without affecting the structure, the weight for the criteria is set to a relatively high 7,5.

Stiffness/strength: The stiffness and strength of the joint. Since the consequence of a weak joint is complete failure of the tower, the weight for this criteria is set to 10.

Assembly: How difficult and time consuming the joint is to assemble. This is an important criteria because a simpler assembly reduce the risks of errors which is a major benefit. Therefore, the weight value for this criteria is set to 7.

Environmental sustainability: How environmentally sustainable the solution is. This criteria is considered to be of less importance because the joints should be a minor part of the total environmental impact of the tower. Therefore this criteria is set to 0,5.

Safety: How safe the joining solution is during handling and assembly. Safety is a large concern, but the differences between the concepts are small, so the weight for this criteria is set to 2.

Weather resistance: How well the concept can handle weather effects over time. Weather resistance are considered to be of high importance due to the consequences if the requirements are not fulfilled, giving it a weight of 8,5.

Tangential concept selection

For the tangential joints, two screening processes were conducted to give a fair representation. To ensure a difference between the screenings, concepts with a great diversity in characteristics were selected as references in the different screenings. In the first screening, concept A (LVL-stair), was used as the reference and in the second screening concept G (Steel side) was used as the reference. For the first screenings with the non-weighted matrices, it was hard to draw conclusions as the net scores were quite similar. When using the weighted matrices the difference in total score is larger and more conclusions could be made (see Appendix D).

After the last screening, four concepts were eliminated, and four concepts remain for further development. The four remaining tangential concepts are:

- Concept A: LVL stair.
- Concept E: Sandwich.
- Concept G: Steel side.
- Concept L: Toothed wall.

Vertical concept selection

The vertical concepts were evaluated in the same way as the tangential ones. In the first screening, concept P (Side beam), was used as the reference and in the second screening concept T (Plate flange) was used as the reference. From the first screening with the non-weighted matrices, some conclusions could be made. When using the weighted matrices, the result was similar. Concept P (side beam) and concept Q (Guide beam) (see Figure 12) appear to be the most advantageous. These concepts are similar, and concept Q has the same structure as concept N, but concept Q has a slightly simplified assembly. Due to this, only the concept Guide beam (Q) is carried forward for further development.

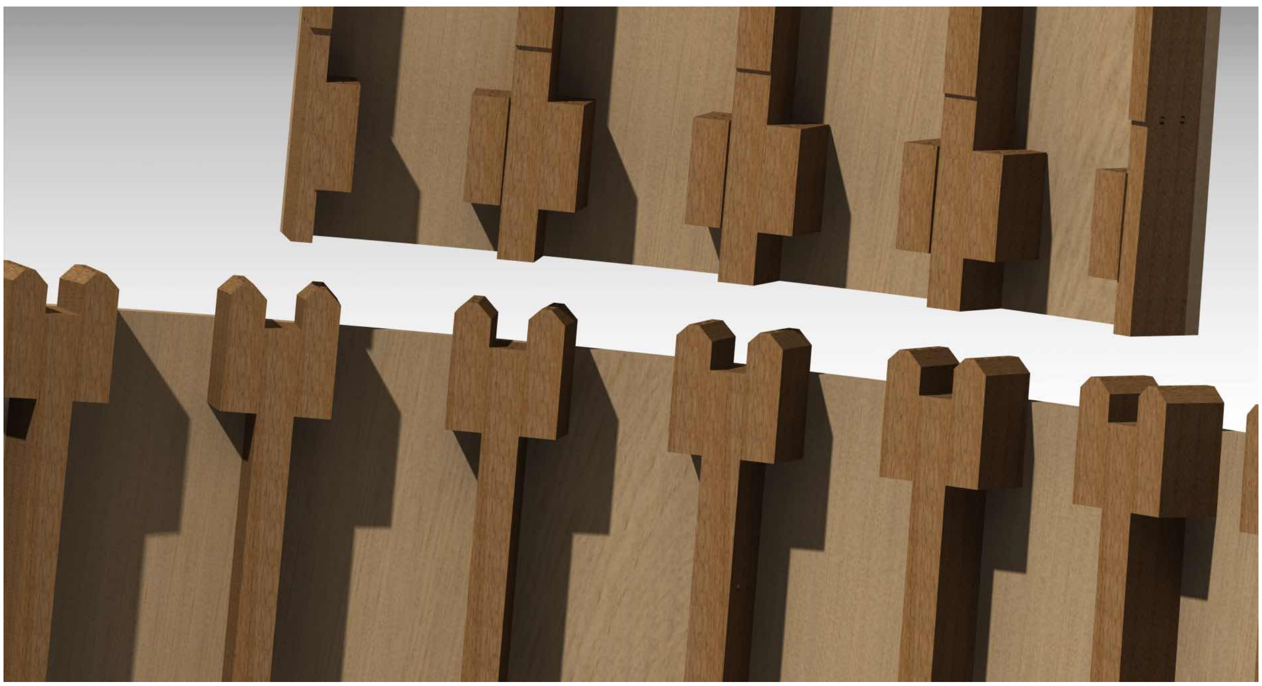


Figure 12: Guide beam concept

5 Development

In this chapter, each of the developed concepts that made it through the selection will be developed further to make a fair assessment of them when it is time to choose the final concepts. During this phase, emphasis will be put on the significant technical challenges and how they can be solved for the final solution.

5.1 Overall refinement

5.1.1 Tangential joints

The tangential joints join the levels prior to stacking. The main load that is being transferred is shear forces as the tower bends.

LVL-stair

This concept works by interlocking panels with the stair geometry, and then join them with nails illustrated in Figure 13. Nails work on dowel principle, which is a common technique in the construction industry. However, these equations rely on the assumption that the load carrying potential increases linearly with the number of dowels, but in reality, this is not true. As the nail pattern tightens, the ideal strength of the joint is lowered. This means that the nail spacing will have to be kept at a reasonable level to expect the load carrying capabilities that are found in the equations. The strength factor of the material decides the step length of the stair formation. In order to get a sufficient contact patch without complicating the assembly, a step length of 10 cm is chosen.

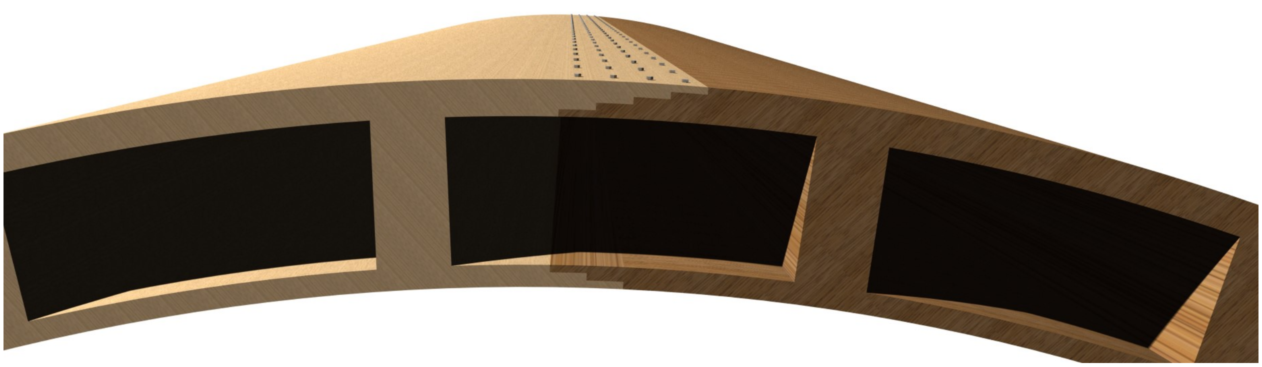


Figure 13: Stair concept

Alternatively, the joint could be made using glue, using nails or screws only as a form of clamping. If this concept is carried out correctly, the joint is very stiff and enables the tower level to behave almost like a continuous element. The main difficulty of this concept is creating a temporary factory that can meet the requirements involved when gluing large construction elements. This includes keeping a suitable moisture level, overall cleanliness and clamping ability over the entire glue joint.

As this is an unproven method, glue will not be examined further. Even though it has great potential, the development needed is deemed to be outside of the scope of this thesis. This means that the nailed LVL-stair will be carried forward as a strong candidate while glue LVL-stair will be put to the side as a recommendation for further research at another time.

Toothed wall

In this concept, the teeth interlock and effectively transfer the shear loads between one another, see Figure 14. For this to work in the final solution, teeth have to be designed that can transfer enough shear loads while not creating large stress concentrations. This concept requires that the teeth be cut with quite fine precision, as they will have to distribute the load over all teeth evenly. This creates a conflict of manufacturing time/load carrying which is more substantial than that of the other concepts. Another tradeoff is assembly time. Load carrying potential increases as the teeth interlocking get tighter, but this also makes the assembly more difficult. These tradeoffs, as well as the experimental nature of the joint, leads to the conclusion that this concept will not be developed further.

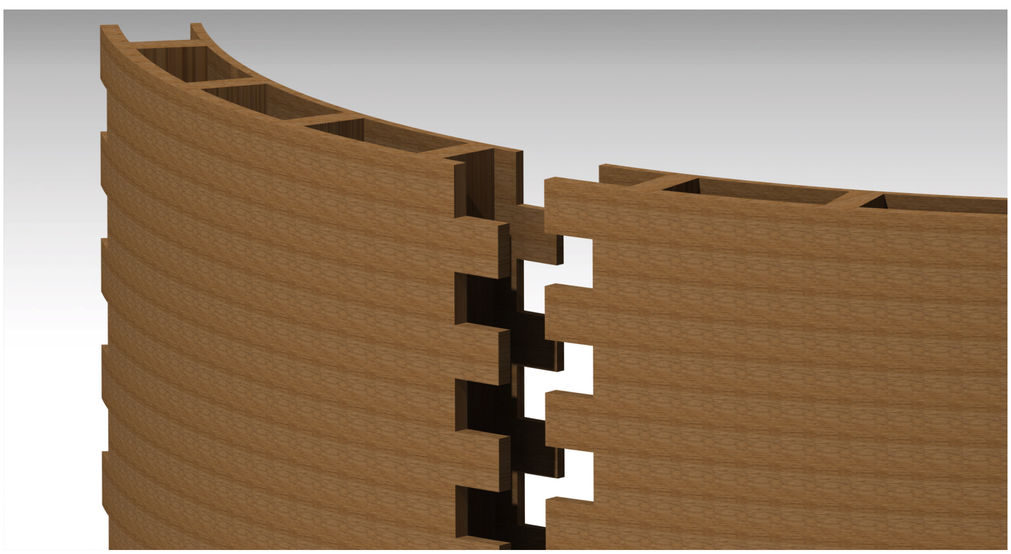


Figure 14: Toothed wall

Sandwich

The sandwich concept works by cutting a slit into the side of the LVL sheets and sandwiching steel plates that join two panels together, see Figure 15. These plates have pre-drilled holes across the entire surface. This means that when the plate is pressed into the slit with glue, the glue fills the holes and create a dowel effect when the glue dries. The gluing process needs to be thoroughly investigated to assess whether or not it is a suitable method to use in under those circumstances.

The size and spacing of the plates also need to be considered carefully to maximize the load carrying capacity while keeping cost and weight down. This is a concept with potential, however, its dependence on glue requires the focus of the thesis to change direction, as stated in the previous concept. The concept will not be developed further, but will be recommended for investigation at another time.

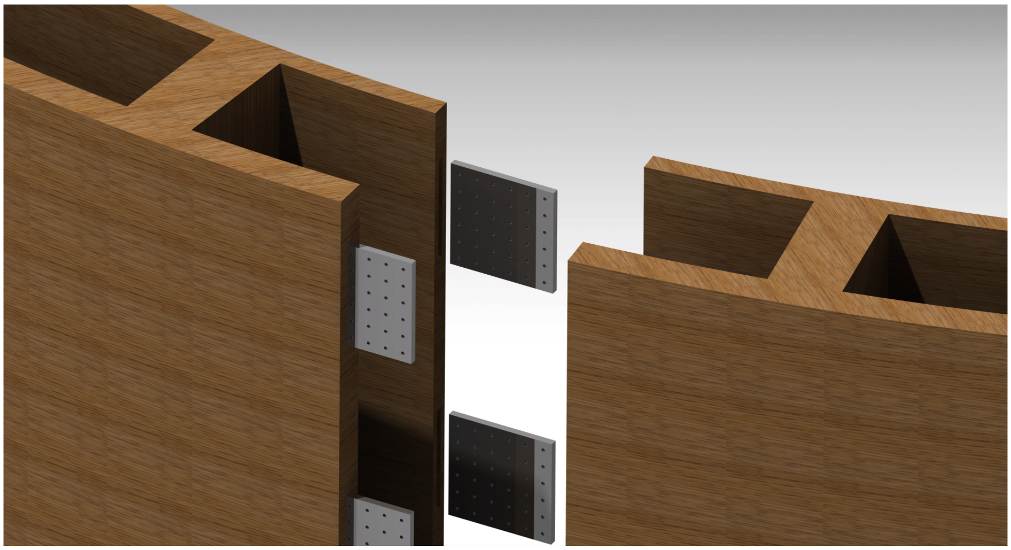


Figure 15: Sandwich

Steel side

The steel side concept works by dressing the edge of the panels in steel plates that are then bolted onto one another to create a friction bond, see Figure 16. For this to work, the dimensions of the plates and the size and number of bolts has to be examined further. The glue that bonds the steel to the wooden panel has to be examined to assess its strength and longevity. As most of the cost of this concept is the steel plates, it is necessary to examine different geometries of these plates to minimize the weight while keeping an adequate contact surface between the steel and the panel.

As this concept creates an external flange on the tower, it looks like it might catch a lot of wind and contribute to larger forces on the tower. After consulting an expert on the subject though, this does not seem to be a problem (*Hamidreza Abedi*). At the bottom of the tower, the moment arm is short enough that it wont contribute to any large bending moment. At the top of the tower, where the rotor acts, the airflow is so turbulent that it wont attach to any surfaces, and thus will not contribute to increased forces in a high level.

Another factor that might affect this joining concept is moisture expansion. As mentioned in the pre-study, wood expands when exposed to moisture, the steel will not deform under similar conditions though. This means that if the beam attached to the steel plate expands, the bond between them will experience a lot of stress. To prevent this, the joint and the wood around it will have to be sealed thoroughly. Wood expansion is most prominent in the direction perpendicular to the wood fibres. As the steel plates run along the fibres, this effect will probably not contribute to any large stresses.

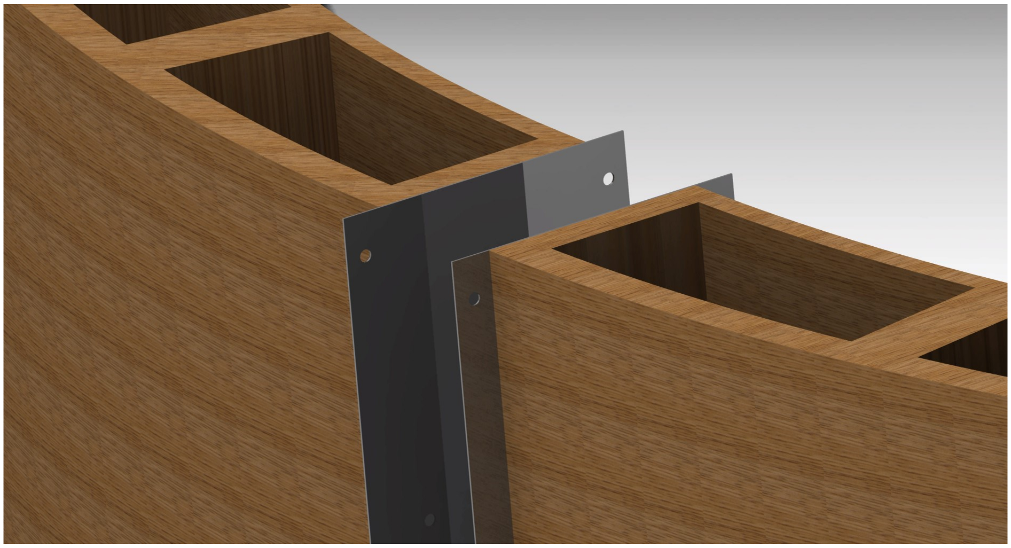


Figure 16: Steel side

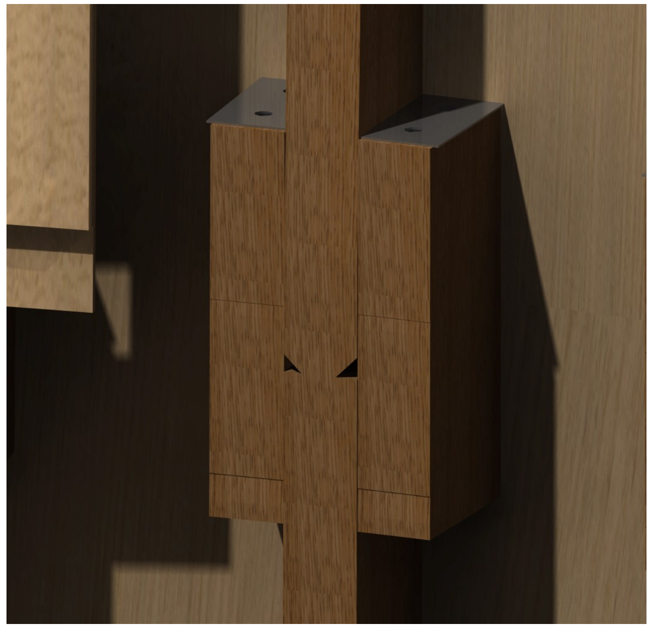
5.1.2 Primary vertical joint

In order to stack and join the segments on top of one another, vertical joints have to be implemented. These are the main load-carrying joints as the tower is pushed by the wind.

Reinforced guide beam

In the cross-section, there are 32 glulam beams sandwiched between two LVL sheets. The guide beam concept works by attaching shorter beam segments at either side of these beams, thus creating a block where bolts can be attatched, see Figure 17a and Figure 17b. The beams are reinforced with thick steel tubes to stiffen the joint. The main purpose of this is to reduce the fatigue stress in the bolts as the tower is put under fluctuating loads over its lifetime. The attached beams create a guiding slot for the next level to lock into as the center beam is slightly offset, thus ensuring that the bolt holes line up as intended. This is done slightly differently to what was proposed in the initial concept. The guide beams are placed flush with the panel edge, while the panel beams are lowered slightly. This makes it easier to ensure that the guide beams to make contact, which is crucial to make sure that both steel tubes work as a single part in the bolt joint. To access the nuts and bolts in the assembly phase, windows are cut in the inner LVL-sheet (see Figure 18). These can later be reinforced with plywood boards to reduce the effect of stress concentrations.

(a) Beam reinforcement



(b) Complete reinforcement

Figure 17: Beam reinforcements, shown without inner LVL-sheet

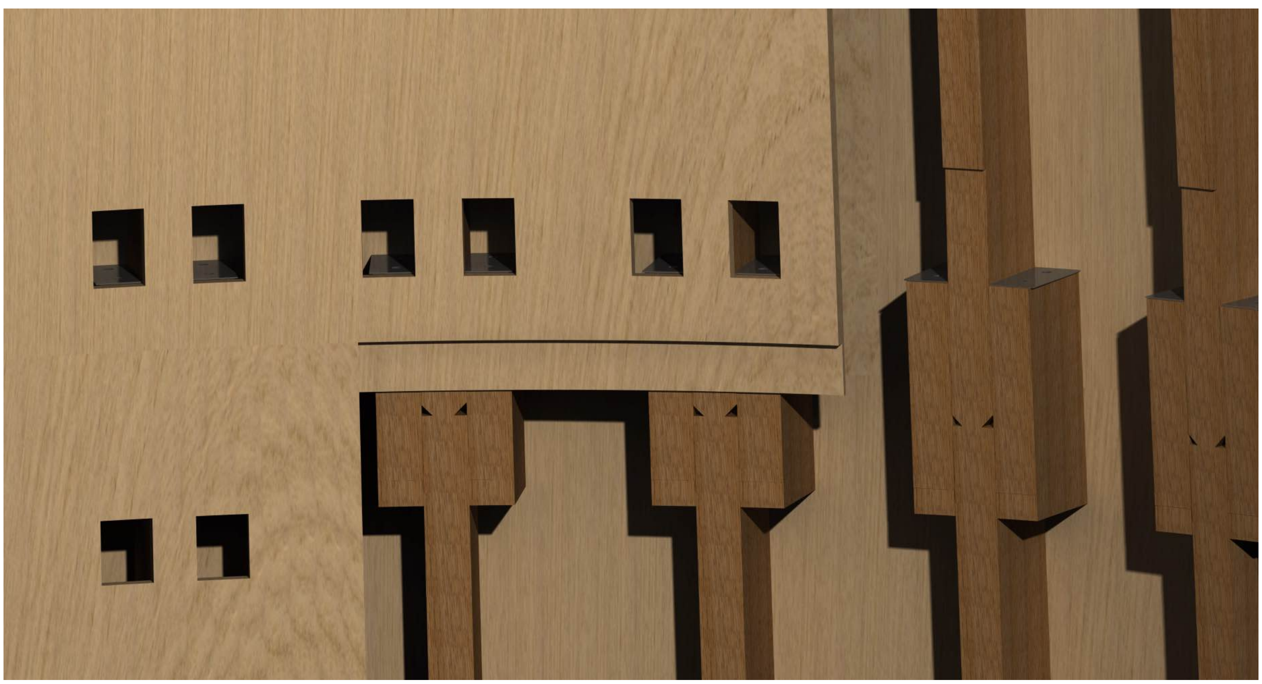


Figure 18: Assembly windows and guide beams

5.1.3 Vertical LVL joint

The vertical joining concept presented above should be enough to keep the segments together under load. However, as the joints are only placed around the beams, the stress distribution is not homogeneous over the tower, which is not ideal. Since the load on the joints are calculated using the assumption of stress distributions on a homogeneous tower, using only these joints might affect the load distribution in such a way that those models are made incorrect. Therefore, there is a need to join the LVL sheets at the vertical joints as well, enabling a more even stress distribution. This joint will also create a seal to prevent moisture from getting into the tower.

However, there are a few problems to consider when designing these joints. When stacking conical elements, it is difficult to create geometries that overlap without inducing clash. When the segments are standing, waiting to be lifted for stacking, it would be desirable for them to be self-supporting, without the need for supporting elements. If the lowest part of the LVL sheet is made thin, this may weaken the bottom face enough so that such elements are needed. This joint will not primarily transfer loads, but rather to make the two levels behave more homogeneously. The problem with load transfer around the LVL is that it is almost impossible for the LVL joint and the bolt joint to "share" the load in a way that both joints can handle. All joints depend on some form of stiffness/deformation correlation. If the LVL joint is stiffer than the bolt joint, it might be loaded to failure before the bolt joint is put under enough deformation to absorb the bulk of the load.

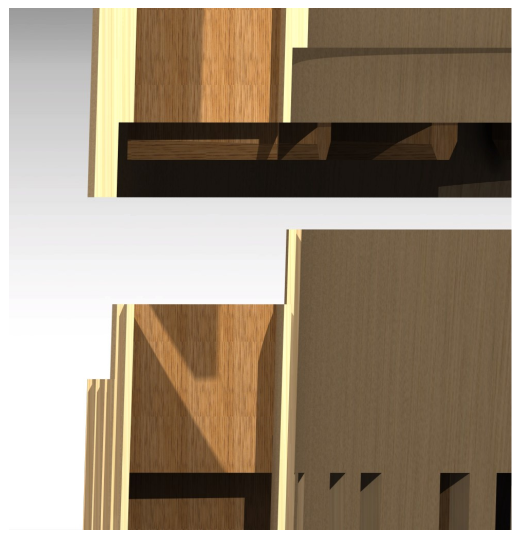


Figure 19: Two level LVL-offset

LVL-stair

Just like with the tangential stair concept. Offsetting the LVL-layers to create a stair formation gives a good contact patch to form either a nail or glue bond. This does have the drawback of having quite complex geometry, which is disadvantageous while stacking, and it also weakens the base for when it is pre-assembled and waiting to be stacked.

Two level LVL-offset

Similar to the LVL-stair, but instead of offsetting each layer of the LVL, only two levels are used in the offset. This simplifies the geometry, enabling an easier stacking and a more robust base (see Figure 19).

5.2 Load carrying calculations

At this point, models for the load carrying potential of the concepts was established to design the joints for the forces involved.

5.2.1 Nail LVL-stair

As mentioned earlier, the LVL-stair concept transfers loads using nails. A simplified picture of the nail spacing can be found in Appendix F. This distribution means that each row contains 13 nails. Using standard equations for dowels in wood construction, the load carrying capacity R_k for a nail is calculated with equation 10:

$$R_k = 1.15 \cdot \sqrt{\frac{2 \cdot \beta}{1 + \beta}} \cdot \sqrt{2 \cdot M_{y,k} \cdot f_{h,1,k} \cdot d} \tag{10}$$

The values of the used variables are found in equations 11-13

$$f_{h,1,k} = 0.082 \cdot d^{-0.3} \cdot \rho_{k,1} \tag{11}$$

$$f_{h,2,k} = 0.082 \cdot d^{-0.3} \cdot \rho_{k,2} \tag{12}$$

$$\beta = \frac{f_{h,1,k}}{f_{h,2,k}} \tag{13}$$

Where $f_{h,1,k} f_{h,2,k}$ refers to the hole strength of the two panels that are supposed to be joined To be able to carry the full load capacity a minimum panel thickness is required. It is calculated with equation 14:

$$t_{i,req} = 1.15 \cdot (2 \cdot \sqrt{\frac{\beta}{1 + \beta} + 2}) \cdot \sqrt{\frac{M_{y,k}}{f_{h,i,k} \cdot d}} \tag{14}$$

If the minimum required thickness is not met, only a fraction of the full load capacity will be achieved, equal to the fraction of the actual thickness divided by the required thickness.

The nail distance is crucially important in this design to ensure that the joint keeps its ideal characteristics. In Eurocode 5, there are standards put in place to make sure that nails are not placed tighter than the panel can handle. The crucial distance can be calculated using equation 15.

Nail center distance parallel to grain:
α= angle to grain, d=nail diameter.

$$dist = (7 + 8cos(\alpha))d \tag{15}$$

This means that when nails are placed perfectly parallel to the grain, a distance of 15d between the nails is enough to ensure that they do not weaken the overall structure. When placed perpendicular to the grain, 7d is sufficient. This measurement also applies to edge distance.

5.2.2 Steel side

The steel side concept functions just like a traditional slip critical bolt connection, assuming that the glue joint between the wooden panel and the steel plate is strong enough to withstand the forces. The equation 16 finds the load carrying potential of such a joint.

$$R = 1.13 \cdot \mu \cdot T_b \cdot n_s \tag{16}$$

Where R is the slip resistance, μ is the friction coefficient between the plates, T_b is the bolt pretension and n_s is the number of bolts in the connection. Using this equation, it is easy to establish the number of bolts needed to secure the panels together. Bolts of a certain dimension are recommended to have a pretension between 55-90% of its breaking load. Using 70%, which is Eurocode 5 standard (*Boverket (2011)*), the only variables that dictate the resistance of the joint is the number of bolts, bolt size and quality.

5.2.3 Reinforced guide beam

Based on the joint model, the loads put on the bolts can be assumed to be completely linear, enabling standard F/δ equations to be used (equation 17-19).

$$F_N = F_j/4 \tag{17}$$

$$F_s = F_T + F_N \cdot (c_s/(c_s + c_k)) \tag{18}$$

$$F_A = F_N \cdot (c_s/(c_s + c_k)) \tag{19}$$

F_s is the total amount of force that the bolt is exposed to, F_T is the bolt pretension, F_N is the load that is applied to the joint as the tower is put under load, F_A is the amplitude of the fluctuating bolt load, c_s is the bolt stiffness and c_k is the stiffness of the clamped part. Each beam in the cross section is supported by four bolts, as seen in the concept pictures. Therefore, a fourth of the load exerted over a joint area is exerted on a single bolt, as seen in equation 17.

A common mode of failure in bolt joints is fatigue stress, caused by fluctuating loads over time. As the load on the joint fluctuates, so does the force on the bolts. In order to achieve a low fluctuating load, the clamped part should be much stiffer than the bolt. Because of this, the steel tubes were introduced into the design.

The guide beam which is the anchoring point of the bolts is glued in contact with the supporting beam and the outer LVL-sheet. This contact area will transfer the load of two bolts from the side to the central beam. To improve the cost-effectiveness, the length of these side beams should be proportional to the load applied to the joint, as they decide the length of the bolts and tubes.

5.2.4 Vertical LVL-joint

As both vertical LVL-joining concepts function using the same principle, they will be analysed the same way. The bulk of the forces are supposed to be carried by the bolt joints in the concept mentioned above. The bolts work by traditional force/deformation correlation, which means that the LVL-joint will have to deform as much without failure. This deformation is small, but not negligible. A traditional wood glue joint would be too stiff, and nails require assembly work on the outside of the tower. A suitable compromise would be to use a sealant type bond, it can be applied prior to stacking, they are not as stiff as regular wood glue but are reasonably strong. A sealant with suitable characteristics need to be established to verify the effectiveness of this concept.

5.3 Development conclusions

From the development of both the overall geometries and load carrying components, the following conclusions can be made:

Nail LVL-stair: This concept has a quite simple geometry with no complicated construction elements. The nail fastening follows the standards put forward in Eurocode 5, which simplifies the permitting process for a new design.
The concept results in a strong enough bond at most levels. At the highest levels though, the required number of nails results in a nail spacing which is too tight, resulting in a weakened joint. Since many nails are used, the assembly time is essential to consider. Even though the materials and production methods are cost-effective, the extended assembly time may result in a higher cost for the overall solution.

Toothed wall: As mentioned earlier, the toothed wall concept will not be developed further. The main reason being its reliance on fine tolerances to distribute an even load along the joint. These tolerances would also complicate the assembly. Since the factors joint strength/Assembly time are in direct conflict with each other, this is not deemed to be a suitable concept to use, and therefore, no load carrying calculations were developed.

Sandwich: The sandwich concept was an experimental design with the advantage of introducing stronger materials into the cross section around the joint. Even though these steel sandwich plates are strong enough to cope with the shear forces, the load transfer between the panels is uncertain. Because of this, as well as the reliance of glue, this concept was set aside as a recommendation for further research.

Steel side: The steel side concept uses a conventional construction method relying on friction. It creates a strong bond, capable of withstanding the forces at all levels of the tower. Therefore, the biggest question mark in this concept is the glue that bonds the steel plate to the wood panel. Because of the large surface area between the wood and the steel, this is deemed to be manageable. One of the problems with this concept is that the steel plate becomes expensive as it is supposed to cover all panel sides. This might be a necessary sacrifice though, as the shear forces are higher at the top, where the joints need to be especially stiff to hold the turbine securely.

Reinforced guide beam: This concept has changed significantly during the development. The introduction of steel tubes is a complex but necessary addition to stiffen the joint to the point where fatigue stress is no longer a problem. The interface plane where two levels meet is an area that requires fine tolerances for this concept to work as intended. The steel tubes on either side have to make contact for them to transfer the loads between one another and behave as a single part. This creates a problem when the joint is loaded in compression. If the supporting beams are misaligned with the rest of the top level, they might take up most of the compressing load. This puts a lot of stress on the glue joint to the supporting beam. Therefore, the manufacturing tolerances will have to be fairly fine for this concept to work.

Two level LVL-offset: The purpose of this joint is to make the tower behave more uniformly as well as create a seal from the outside elements. They will carry some load as the tower is put under stress, but they are to be designed so that the primary vertical joint will take the bulk of the load. The most reasonable joining agent identified is a sealant type bond as it provides enough strength without increasing stiffness or relying on external assembly.

Final development conclusions

The concepts that are carried forward for detailed development are LVL-stair, and Steel side for the tangential joints. For the vertical joints; Reinforced guide beam and two level LVL-step will be used.

6 Results

In this chapter, the final joining solution will be presented. A complete description of all joining concepts will be included, along with a description of the MATLAB program used to calculate the appropriate fastening elements in each concept. Lastly, results from an example case will be presented.

6.1 Concept description

As mentioned in the previous chapter, two solutions for the tangential joints were carried forward, one solution for the primary vertical joint, and one solution for the vertical LVL joint. Two geometries of joints were modeled in cad. The joints between lowest two levels, to show the size of the bottom level and display how the concepts work there. The second model shows the joint between level 7 and 8. This was chosen for a number of reasons. It is where the tangential joint transition from LVL-stair to steel side. Level 7 is made up of 8 panels, whereas level 8 is made up of 4. These factors, combined with the intricacy of a smaller tower diameter result in a complex geometry. This geometry had to be verified to prove the feasibility of the chosen concepts.

6.1.1 Tangential joints

In order to create a cost-effective and durable tower design. Two tangential joining solutions had to be combined. Since the forces in these joints vary a lot from top to bottom, the choice to combine two concepts with different characteristics was not unexpected.

LVL-stair
The LVL-stair concept is mostly unchanged from what was presented in the concept generation phase. The inner and outer walls of the panels are made up of layers of LVL-sheets. Offsetting these layers one by one creates a stair formation that enables the panel to interlock with an identical panel on the opposite side, see Figure 20. These steps on the LVL-stair are used as a fastening area for nails. The amount of nails used in the joint is directly proportional to the shear force exerted on the tower. As the force increases along the height of the tower, the nail spacing tightens at the higher levels. To accommodate this, a tight nail pattern was developed (see Appendix E) which accommodate a large number of nails in the given area, while retaining the necessary spacing to keep their ideal strength. The cost of nails is the only factor affecting the cost estimation in this study. This concept becomes increasingly complex further up the tower. The diameter of the tower decreases, while the width of the stair is constant. This means that the stair overlap will interfere with beams and assembly windows if it is used high up the tower. This means that the stair geometry is aborted at certain areas (see Figure 21).

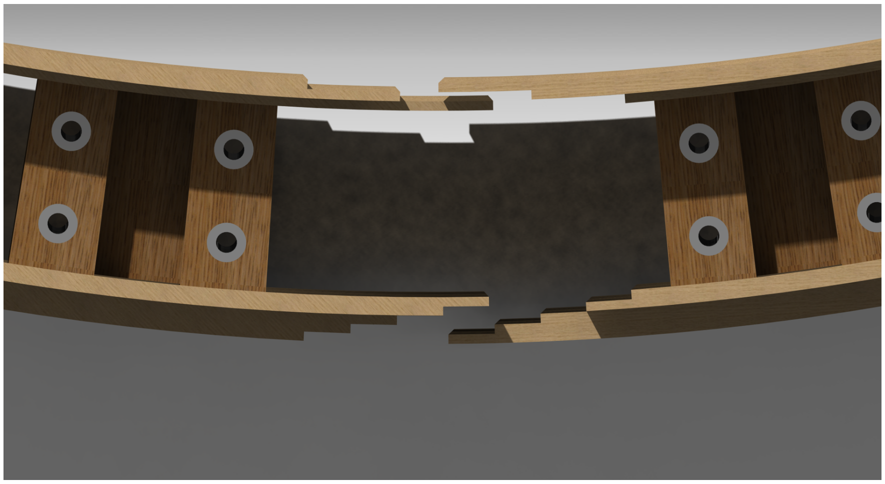


Figure 20: Stair concept

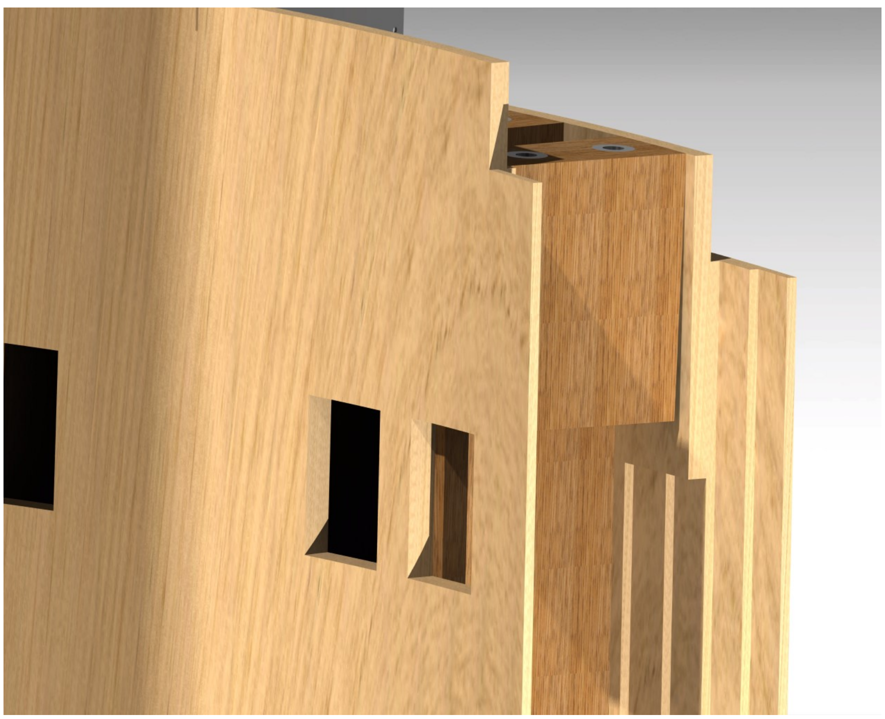
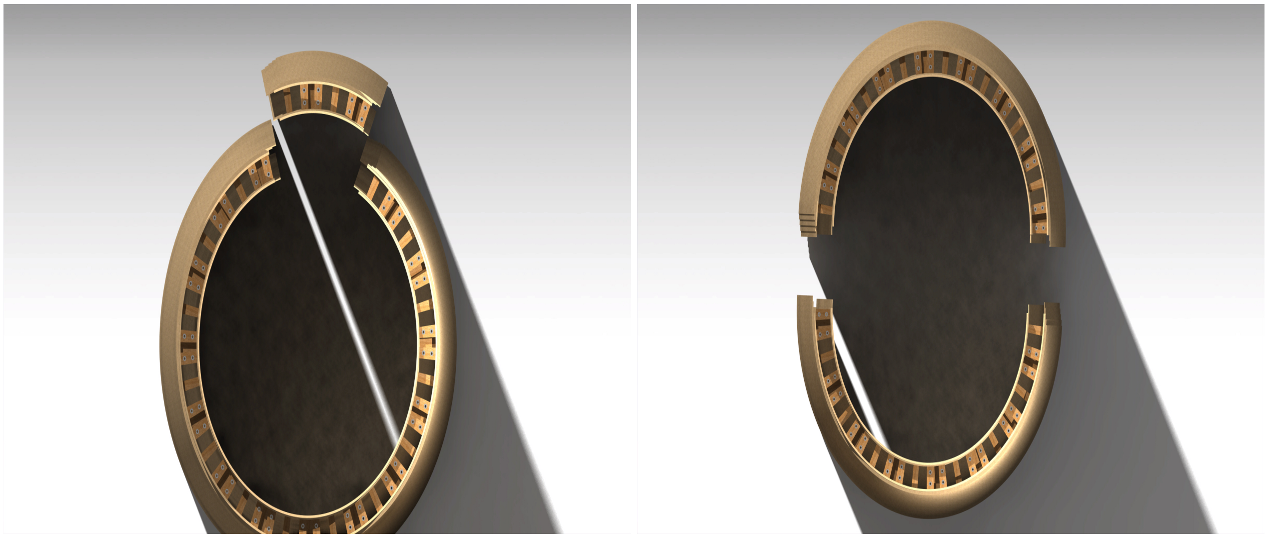


Figure 21: Top view of LVL stair

There are also other assembly difficulties that has to be addressed. One such problem, is the fact that the panels can not be assembled one by one until they form a complete segment (see Figure 22a), the interlocking geometries prevent that. One possible solution is to assemble halves which are then stacked on top of each other (see Figure 22b). This puts higher demands on lifting equipment in terms of weight and precision.



(a) Assembly clash (b) Stacking halves

Figure 22: LVL-stair assembly

As the shear force grows with the height of the tower, the nail spacing of this concept approaches a point where the ideal strength of an individual nail is lowered. This means that for a tall tower, a different concept with a higher potential strength has to be used for the top levels.

Steel-side

The steel side concept works using the principles of a slip critical friction joint, where two steel plates are bolted together and the resulting clamping force creates enough friction to hold them in place (see Figure 23). This creates a bond that is significantly stronger than that of the LVL-stair, so it can easily be designed to withstand the shear forces at the top of the tower. This concept is significantly more expensive compared to the LVL-stair though (at least regarding material cost), this means that the steel side concept should only be used when the LVL-stair is not strong enough.

Figure 23: Steel side

6.1.2 Vertical joints

Reinforced guide beam

This concept is deemed to be strong and versatile enough to be used over the entire height of the tower. At the bottom of the tower, each panel is made of 4 beams (8 at the top), each of these beams are equipped with short guide beams on either side while the middle one is lowered slightly, creating guiding slots for the beams of the next segment to lock into (see Figure 24). At the top levels, where the distance between the beams get critical, every other beam are equipped with guide beams (see Figure 25). When two levels have been stacked, the guide beams are in contact with each other, and a thin steel plate is put between them, this is done to prevent the fibres in the end grain from sinking into each other. At this stage, bolts are put through both of the side beams to join the two segments together. To be able to access the bolts, windows are cut in the inner LVL-sheet (see Figure 26). In order to achieve a bolt joint that is stiff enough, thick steel tubes are glued in place to reinforce the bolt holes. These are then topped with reinforcing steel plates on both sides to distribute the forces and prevent the bolt to excerpt too much shear stress around the tube. It is essential to ensure that the guide beams make contact upon stacking; otherwise, the tubes will not work together. However, if they are placed too close to each other and make a stronger contact than the rest of the cross section, they will transfer high compression loads as well, which is not ideal.

Figure 24: Removed LVL, shows stacking

Figure 25: Vertical joint at the top

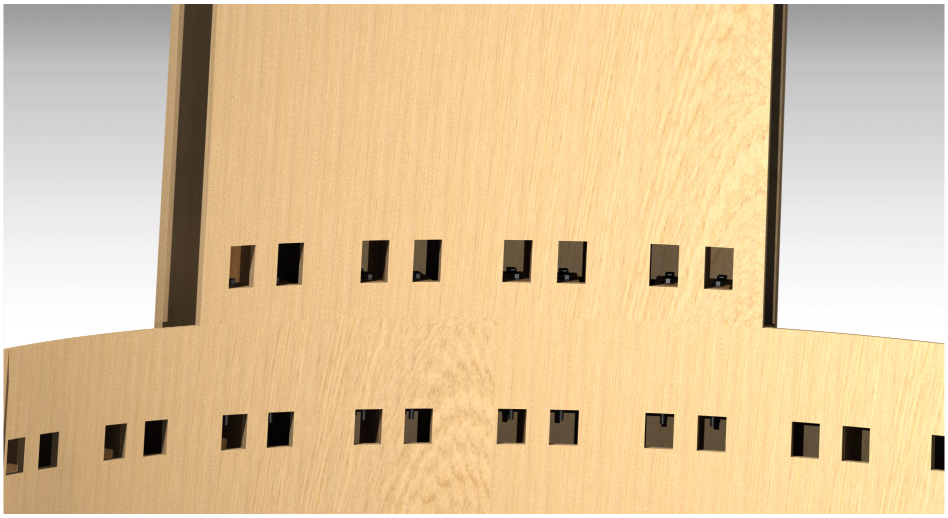


Figure 26: Assembly windows

The length of the guide beams is dependant on the required glue area to bind them to the rest of the tower. The bolt loads will have to be transferred to the tower via these glue bonds. Therefore, the required length of these beams will vary over the height of the tower. The guide beams are bonded to the panel beams and the outer LVL-sheet (see Figure 27), the inner LVL-sheet is not used in order to ease the manufacturing.

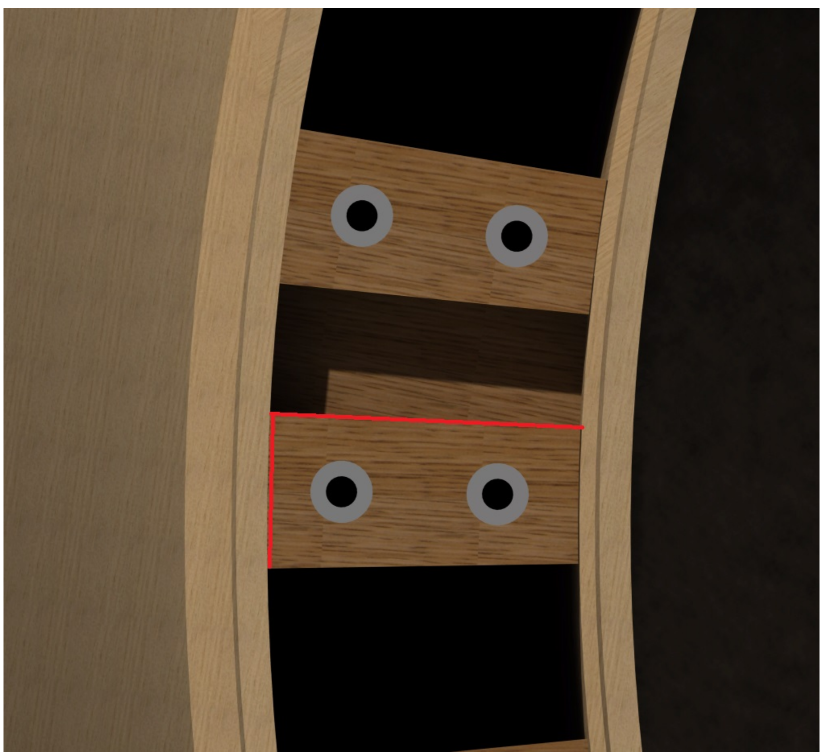


Figure 27: Glue areas for guide beams

Two level LVL step

The previous joint is strong enough to withstand the expected forces on the tower. However, as those joints are only located at the beams, there is a risk of creating an uneven stress distribution in the tower. To get around this, the LVL-sheets are also joined when the segments are stacked, see Figure 28. By carrying a small part of the load, it is not vital to the carrying capacity of the joint, but it will even out the stress distribution around the joint, enabling a more efficient material use. As mentioned in the development chapter, the stiffness of this joint is crucial to its behaviour.

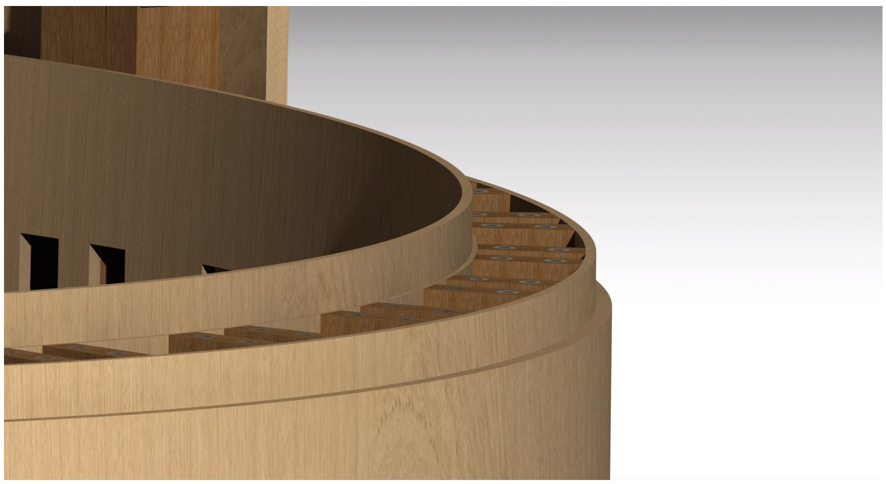


Figure 28: Vertical LVL-joint

6.2 MATLAB program

The second part of the delivery of this thesis is a MATLAB code that calculates the required dimensions of the fastening elements of these concepts, based on a pre-determined load case. The user can alter the size of the tower, the number of levels, the force that is applied to the rotor, safety factors and costs of material. From this, the program calculates the required dimensions of the fastening elements of each joint and returns the most cost-effective solution.

6.2.1 Tangential joints

When calculating the strength for the LVL-stair, the joint force is divided by the carrying capacity of the chosen nail. This returns the number of nails needed for the joint in question. Using the developed nail pattern, the nail spacings are calculated. These are then compared to the critical nail distances found by the equations in Eurocode 5. If the nail distance is lower than what Eurocode 5 requires, the steel side concept is used. The calculations for the steel side is similar, but each bolt has a much higher carrying capacity than the nails used in the LVL-stair, resulting in fewer bolts, and an increased spacing. The program returns the used joining concept, the number of fasteners, the fastener spacing, and the material cost. This is done for each level of the tower.

6.2.2 Vertical joints

The vertical joining concept is more complex than the tangential one. The program calculates the required length of the guide beam to avoid shear failure, which subsequently decides the length of the bolt. In the following bolt calculations, each bolt dimension can be paired with several tube dimensions, all combinations of these are tested. The bolt-tube combinations that hold up to the forces are compared from a cost perspective, and the cheapest one is chosen.

6.2.3 Example case

In this chapter, the program will perform calculations on a tower with a height of 150 m, split into ten levels, it has a base diameter of 12.5 m, a top diameter of 4 m, and a rotor force of 1 MN. The cost for bolts, nuts, and washers is set to 40 SEK/kg. For the steel plates and tubes, the cost is set to 15 SEK/kg.

Tangential results

Level	Nr. of joints	Solution	Distance	Fasteners	Cost
1	8	LVL-stair	110	9884	5930
2	8	LVL-stair	101	10838	6502
3	8	LVL-stair	92	11990	7193
4	8	LVL-stair	83	13405	8043
5	8	LVL-stair	73	15185	9111
6	8	LVL-stair	64	17484	10491
7	8	LVL-stair	55	20559	12336
8	4	Steel side	110	900	54520
9	4	Steel side	88	1088	55874
10	4	Steel side	66	1368	58061

Table 5: Tangential results

The total cost for the tangential joints is: 228 000 SEK
The total weight of the tangential joints is 15.2 tonnes

Table 5 above shows the results of the tangential joints. The number of joints is equal to the number of panels needed on the level, this is dependant on the panel width. In this scenario, both the LVL-stair and steel side concepts are used in the tower, this is due to the high shear forces in the top. For the LVL-stair, distance refers to the diagonal distance d_d (see Appendix E). This is the distance which is at risk of ending up below the safety limit for nail patterns. In the steel side concept, distance refers to the center distance between the fastening bolts. Fasteners refers to the number of fasteners needed to join all panels into a complete level, whether they are nails or bolts. The estimated cost includes the cost of fasteners as well as the steel plates used in the steel side concept.

Vertical results

Joint nr.	Nr of bolts	Bolt Ø	Bolt L.	Bolt wgt.	Tube inner Ø	Tube outer Ø	Cost
1	128	36	1300	10.6	45	80	140860
2	128	36	1200	9.8	45	80	131560
3	128	36	1200	9.8	45	80	131532
4	128	42	1100	12.3	50	80	111785
5	128	42	1000	11.2	50	80	103233
6	128	36	1000	8.2	45	70	94948
7	64	36	1400	11.4	45	85	96139
8	64	36	1100	9.0	45	80	61233
9	64	30	800	4.6	40	65	34184

Table 6: Vertical results

The total cost for the vertical joints is: 905 500 SEK
The total weight of the vertical joints is 47.3 tonnes

Table 6 above shows the results of the vertical joints. As only joints between tower segments were examined, 10 levels result in 9 joints between them. The number of bolts used in a joint depends on the number of guide beams used. As seen in figure Figure 25, guide beams can be placed on every other beam rater than all of them. This is done when there is not enough available space. In this case, the transition from 128 to 64 bolts coincide with the transition from 8 to 4 panels in a level, this is not always the case though. The bolt length is chosen based on the length of the guide beams. The bolt diameter and the tube dimensions are chosen as a combination based on the cheapest solution that meet the requirements. The cost estimation includes the cost of bolts and tubes.

The total cost for all the joints is 1 133 500 SEK
The total weight of all the joints is 62.5 tonnes

7 Recommendations

This thesis has put forward a recommended solution to join panels for the construction of a wind turbine tower. Even though this solution is well designed and dimensioned using generous safety factors, there are still many uncertainties that have to be investigated before these are mature enough to be used in an actual tower. Firstly, regarding the structural calculations of the joints, many assumptions on their behaviour have been made. Secondly, even though the joining concepts have taken manufacturing and assembly into consideration, a lot of work will have to be put into refining them to make this a cost-effective tower design. This chapter gives a few recommendations regarding further development of the results of this thesis, as well as further work for Modvion in general.

7.1 Refinement of proposed concepts

The concepts proposed in this thesis have been validated using structural calculations adhering to Eurocode standards. While this has validated the crucial parts of the designs, a lot of details have to be investigated further for them to be considered finished.

7.1.1 Stiffness

While the calculations show that these joints are strong enough to hold the panels together under load, questions regarding their stiffness will have to be answered. As mentioned in most chapters, all joints work using some form of a force/deformation correlation. If the joint in question is not stiff enough, it will have to deform significantly in order to excerpt the required amount of force. The vertical bolt connection has standardised equations to calculate the stiffness, the nail joints are more difficult though. In general, nails are not a particularly stiff joint since both the nail and the hole edge will deform slightly upon loading. However, with a nail pattern as tight as this, and rigid boundaries at either side of the joint, their behaviour is difficult to model. In order to test the stiffness of this joint, some form of experiments will have to be made. If the joints reduce the stiffness of the tower, it may result in increased top displacement and a lowered resonance frequency, which in turn make the tower more unstable.

7.1.2 Steel-wood combination

Several parts of the presented solutions rely on a design combining wood and steel. This is done in order to strengthen and stiffen the design locally to increase the performance of the joint. This is an area that requires a lot of research to establish the behaviour of these components. Since wood and steel have significantly different stiffnesses, they behave differently when put under load.

A component that is crucial in this respect is the guide beam in the vertical bolt joint. For the bolt joint to work as intended, steel tubes were introduced to stiffen the clamped part. These steel tubes are glued into pre-drilled holes in the beams. This will not be enough to hold it in place though. The shear stresses that act around the tubes-wood bond are greater than the maximum shear stress of the wood, unless the beams are made significantly longer. To get around this, thick steel plates were put on either side of the beam, sandwiching the bolt joint. This is done in order to distribute the bolt forces from the tubes into the guide beams. This works well as a concept, but the detailed behaviour of the combined materials will have to be analysed to verify that this is a suitable solution.

Another solution that has to be analysed in regards to this is, of course, the steel side joint. The steel-steel connection is a tried and reliable joint, but when combined with wood like this, there are many more things to consider. The most obvious problem to investigate is the strength of the glue bond. Wood-wood glue joints are regarded to be just as strong as a continuous wood element if done properly. Wood-steel glue joints are not as common and, therefore add a level of uncertainty. Another area that might need further research is the moisture expansion, when exposed to moisture, wood expands while steel does not. If the panels are not sealed properly, their expansion will result in stresses in the glue bond to the steel side. Therefore, there might be a need to investigate the properties of the sealing agent over time to establish the longevity of this joint.

7.2 Development of adjacent systems

This thesis has focused on developing joining solutions from a structural integrity perspective. For this tower design to work, several adjacent systems have to be developed to make the tower a feasible solution for wind turbines in the future.

7.2.1 Transport

One of the main reasons why this tower design is deemed beneficial over competing designs is the ease of transportation. As the panels have a manageable size, they can be transported on regular trucks, eliminating the need for massive convoys closing down roads. The transportation issue is not solved merely by managing the width of the panels though. There are many more details to consider, both technical and logistical. To make the transportation as efficient as possible, several panels need to be able to be transported at once on the same truck. While doing so, they need to be able to withstand the handling required to be placed on, and taken off the trucks. A study investigating transport and handling would therefore be a suitable research area going forward.

7.2.2 Assembly

The assembly process of this tower is a critical factor to make this design work. During the development of the presented solutions, the conceptual assembly process was taken into account. However, this process needs to undergo detailed design and meticulous planning to make it efficient. The presented vertical joining solution functions much like the joints used today, enabling a fairly smooth transition. The tangential joints however, are an entirely new solution, as joints of this geometry is not really used elsewhere. As with the transportation, a detailed study refining this process is required to make this tower design efficient. This would include material handling, assembly jigs, tools, and personnel management.

8 Discussion and conclusions

The methods and techniques used in this project have proved useful and the project has gone according to plan, but there is always a risk of uncertainties in explorative research like this. This chapter lists and reflects on a few of the factors that may contribute to this uncertainty.

Whether or not the best possible concepts were chosen is a difficult question to answer. No matter how much effort is put into the different phases, one can never be certain to have thought of everything. Because of this, Modvion should always be open to explore alternative solutions that were not covered in this project, especially with an application as new as this. As the project went into the final development phase, one of the factors that lead to the choice of the final concepts was the fact that they were less experimental in their nature than their rivals. For example, using glue as a means of assembly at a construction site is not common and brings a lot of uncertainty along with it. Developing a joining solution relying on glue would require the focus to be shifted towards the handling and chemistry of glue, which is outside of the scope of this thesis. Instead, the chosen concepts rely heavily on traditional mechanical fasteners used in creative ways. Although this is not guaranteed to be the best solution, it enabled a deeper analysis to be made. To summarise this, a few glue-based concepts are recommended for further research if Modvion deem it necessary, while the selected concepts have been analysed and documented in greater detail.

The developed concepts often met concern from Moelven, mainly because they require finer manufacturing tolerances than what Moelven are used to in their regular projects. This is difficult to get around though. As this tower faces severely stronger loads than the buildings they usually design, higher demands are required. Therefore, it is unrealistic to expect that their usual routines are up to this task. Moelven's regular work consists of pre-fabricating bespoke glulam beams for buildings, where the tolerance requirements are quite coarse. Constructing a tower like this is a different job altogether, which would require them to alter their manufacturing process. Transitions like that are challenging for manufacturers, it might require them to change tools, machines, and working procedures. Making this transition might be necessary for them though. Being able to deliver more complex and involved components is usually a good way to expand the business and increase the economic margins. Ultimately this is a decision Moelven has to make themselves, if they are not willing to make changes to improve their manufacturing Modvion may have to look elsewhere.

During the course of the project, companies, and people of interest were contacted to gain knowledge of details regarding their respective specialties, this did not always work out though. A few of the contacted people have been very helpful with sharing information, others have not responded at all. This creates gaps in the acquired information, which in turn means that the information had to be collected from secondary sources, or even assumptions. The information in question is not fundamental to the project, but rather details that affect the result in a mild degree. An example of this is the cost estimations of the bolts. Bolt manufacturers Friedbergs and Cooper&Turner were contacted for quotes on bolts. They supply bolts to many wind turbine builders and were the first choice of information on the topic. When they failed to respond, contact was made with Chinese companies, who were happy to deliver quotes. As there may be concerns regarding the quality of cheap bolts from China, the estimated cost for the bolts was substantially increased for the final result. Other areas of research with similar outcomes are assembly and service personnel, as well as glue manufacturers.

The cost calculations conducted only factor in material cost at the moment, which is a good start, but it does not show the whole picture. Comparing the steel side and LVL-stair for example; it is obvious that the steel side has a higher material cost. However, the LVL-stair requires 5-10 times more fasteners, which increases the assembly time. These are different fasteners with different characteristics, which adds another level of complexity to the analysis. Assembly time is crucial in the cost-effectiveness of this tower, as the machinery on site can be hugely expensive.
The elements in the vertical joints are chosen based on the cheapest solution that can withstand the forces. One factor which is not factored into this is the advantage of having fewer unique components. The results from this case resulted in 8 unique bolts and tubes for 9 joints. The advantage of having fewer unique components is difficult to measure, as it is mainly a logistical advantage.

As stated in the introduction, joints to the foundation and turbine housing were not examined. This is because the demands are quite different and it would require three separate development paths. However, it is not impossible that the proposed vertical joining concept can be modified to work as either of those.

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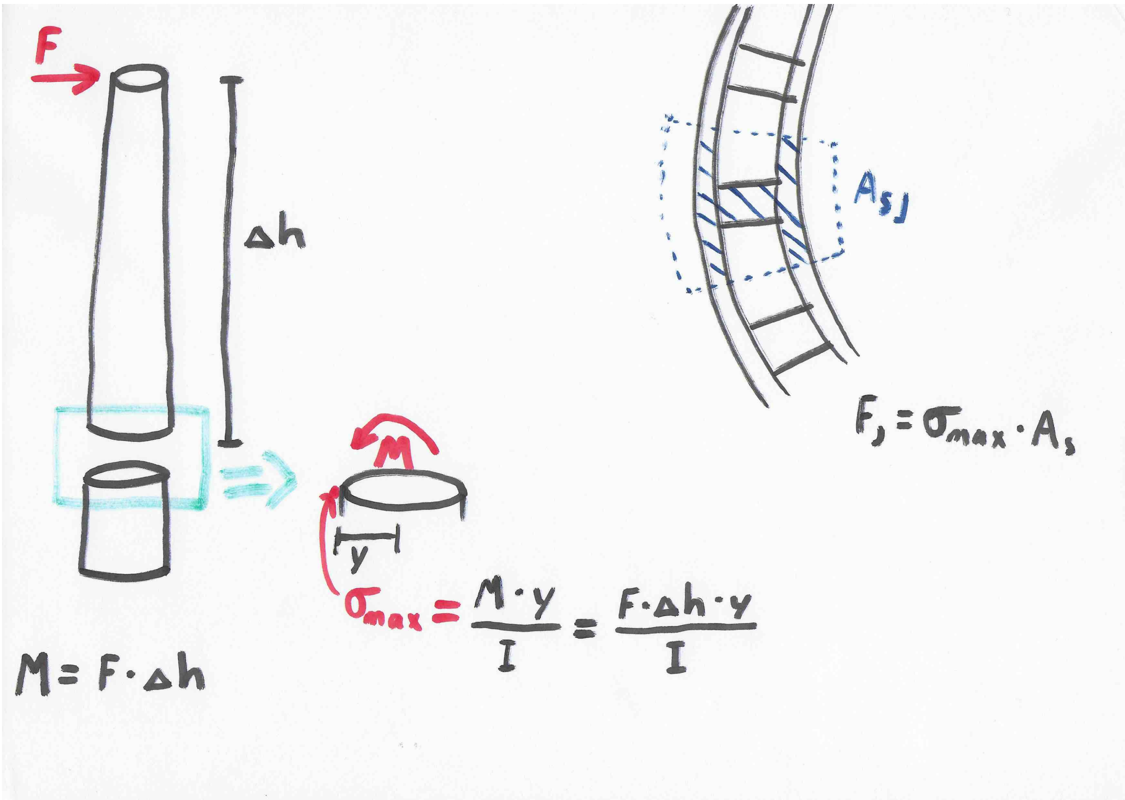
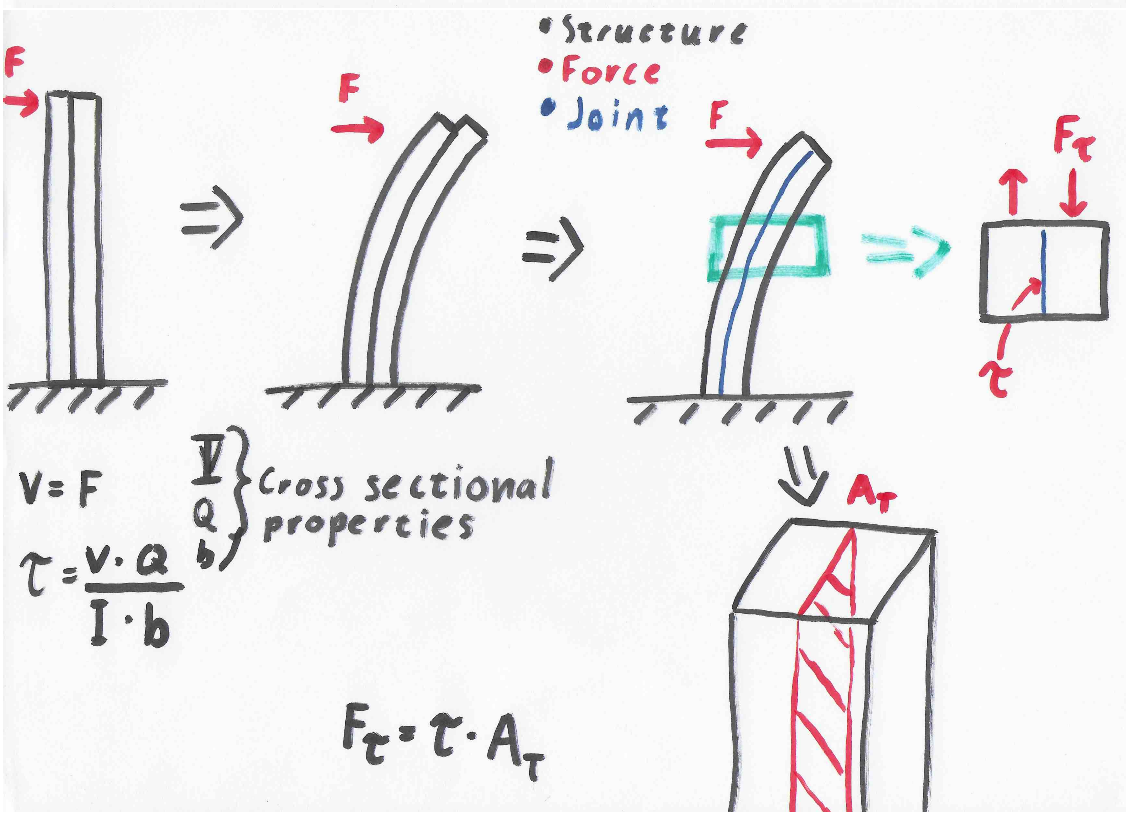
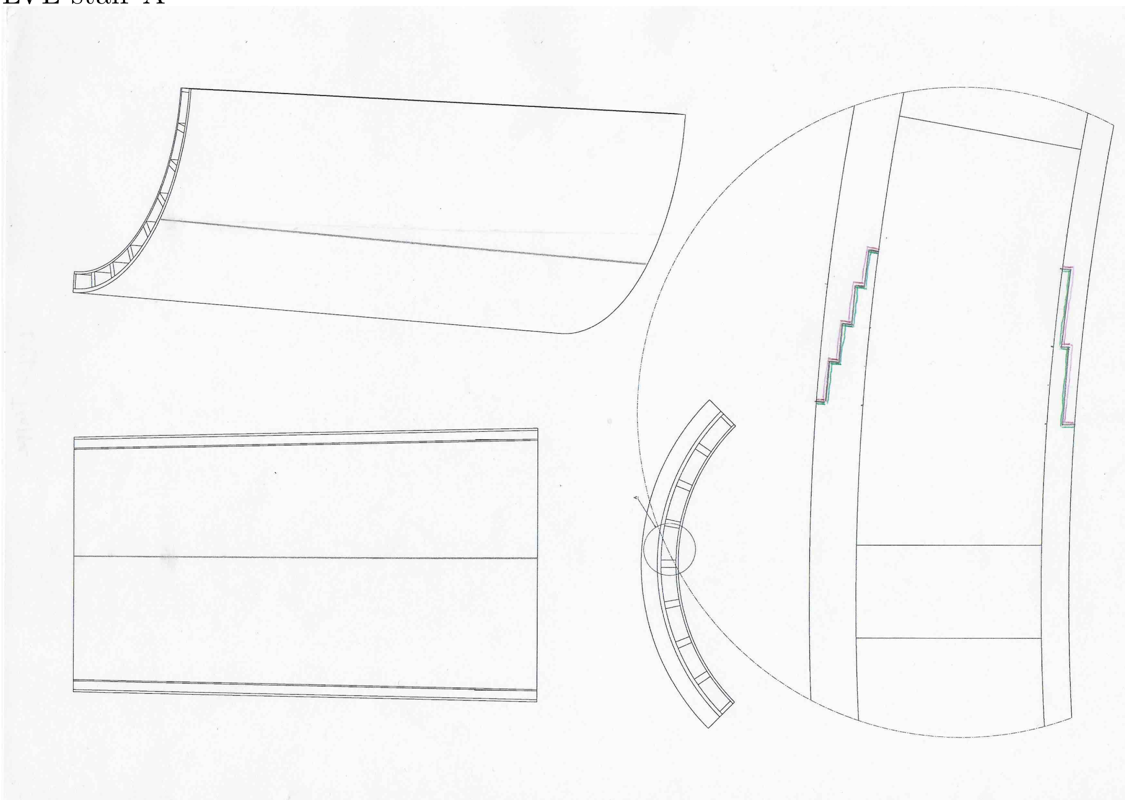
A Load calculations



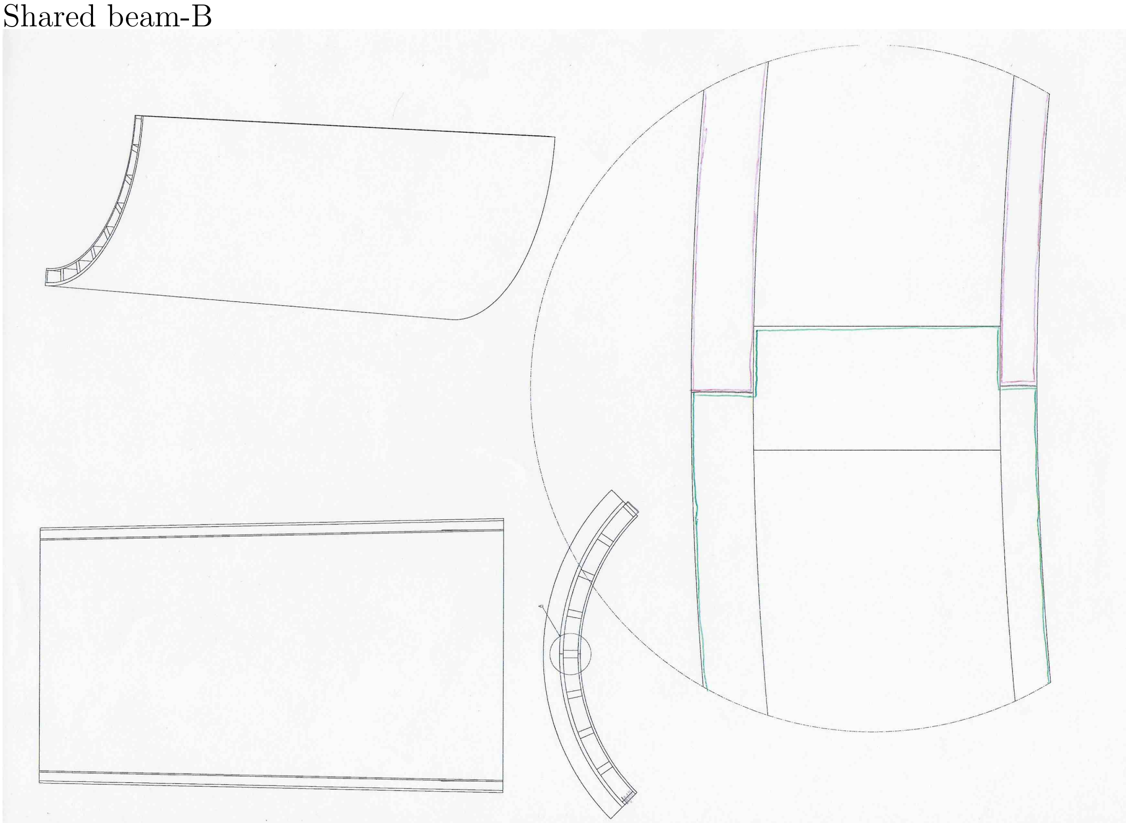


B Intital concepts

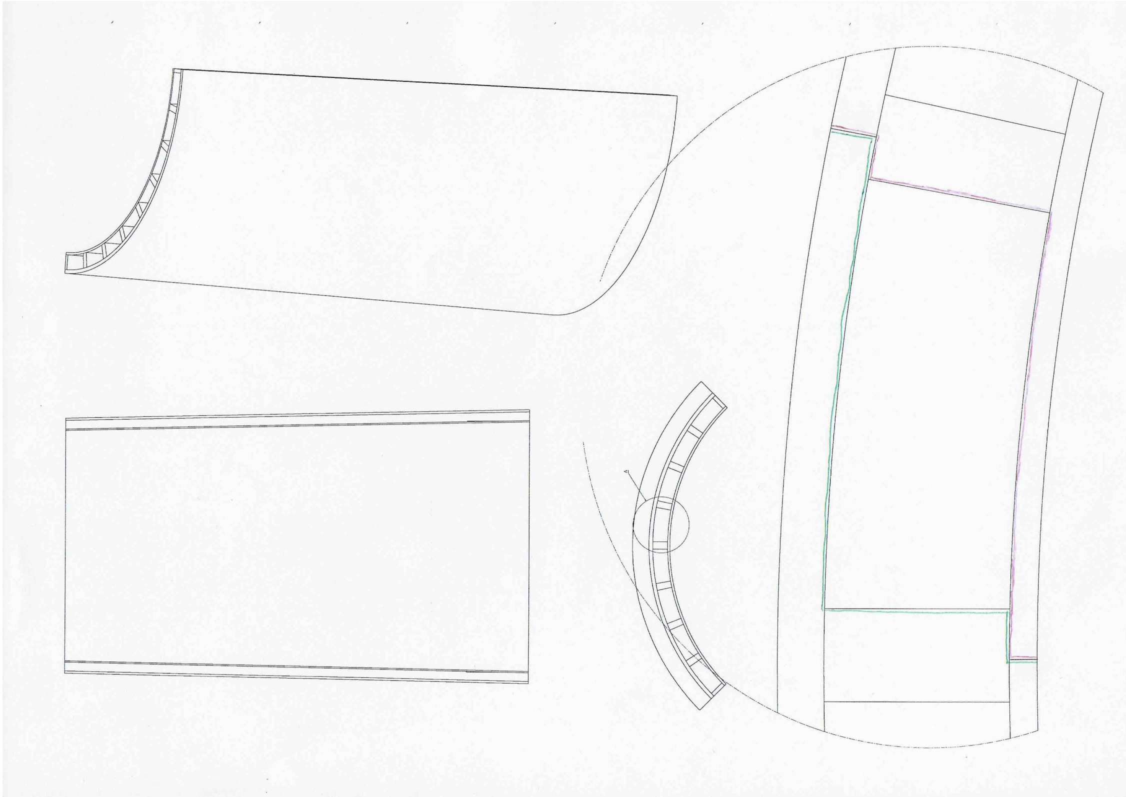
LVL-stair-A



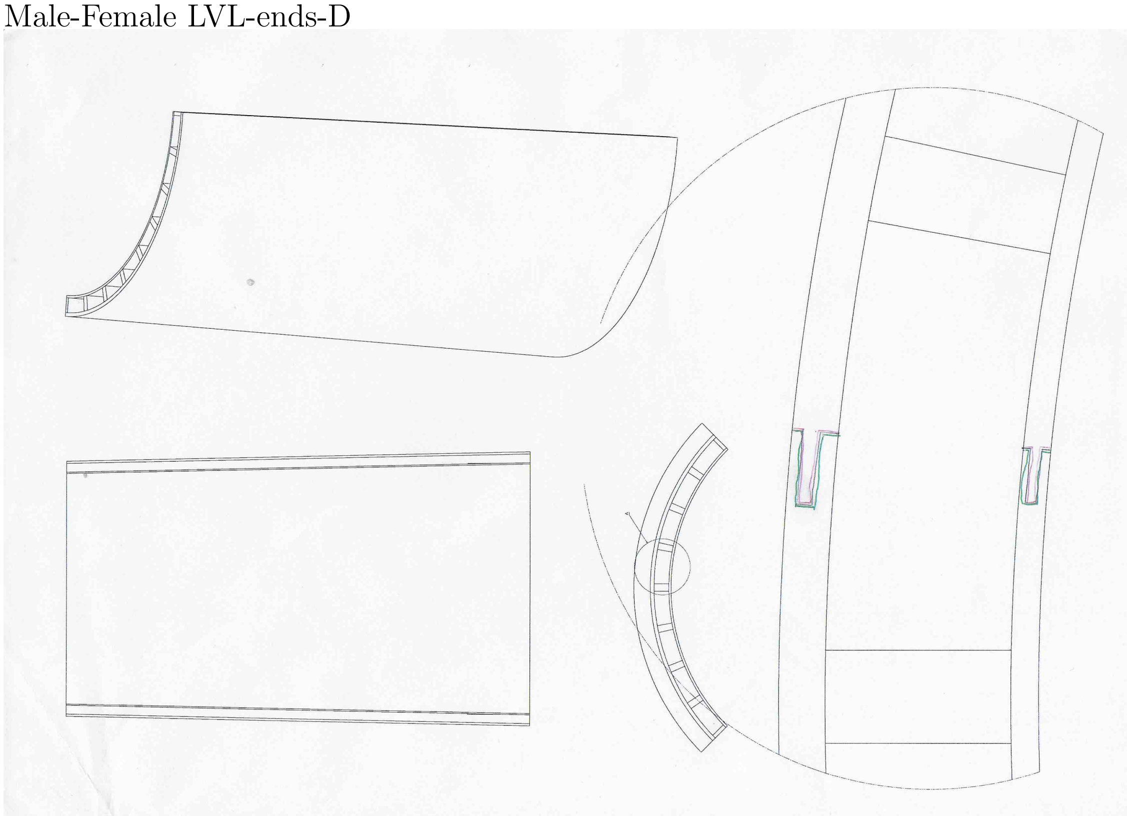
Shared beam-B



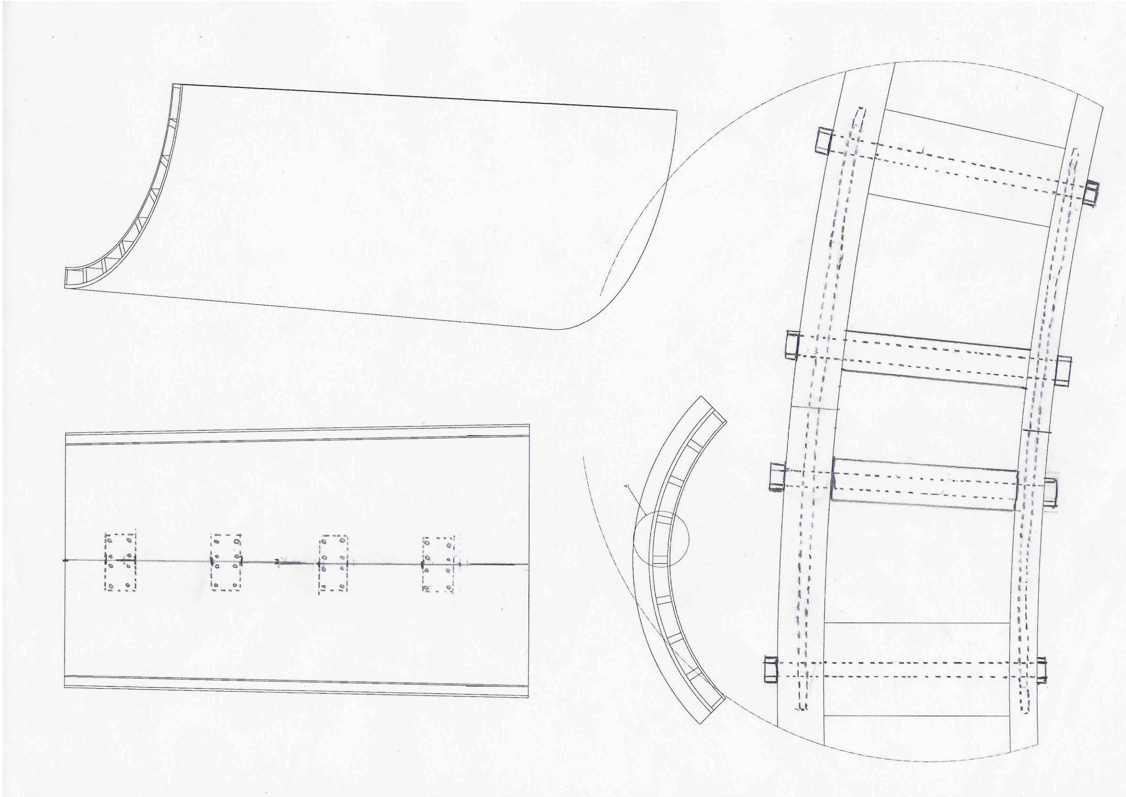
Asymmetrical shared beam-C:



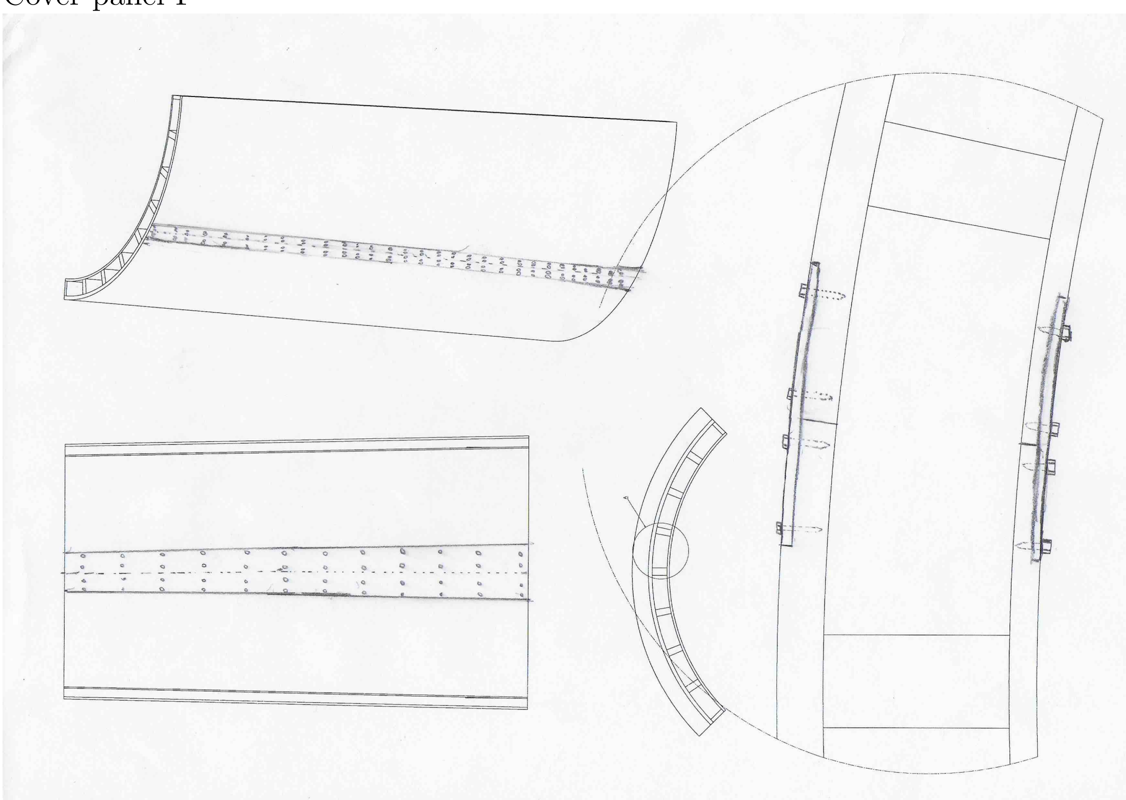
Male-Female LVL-ends-D



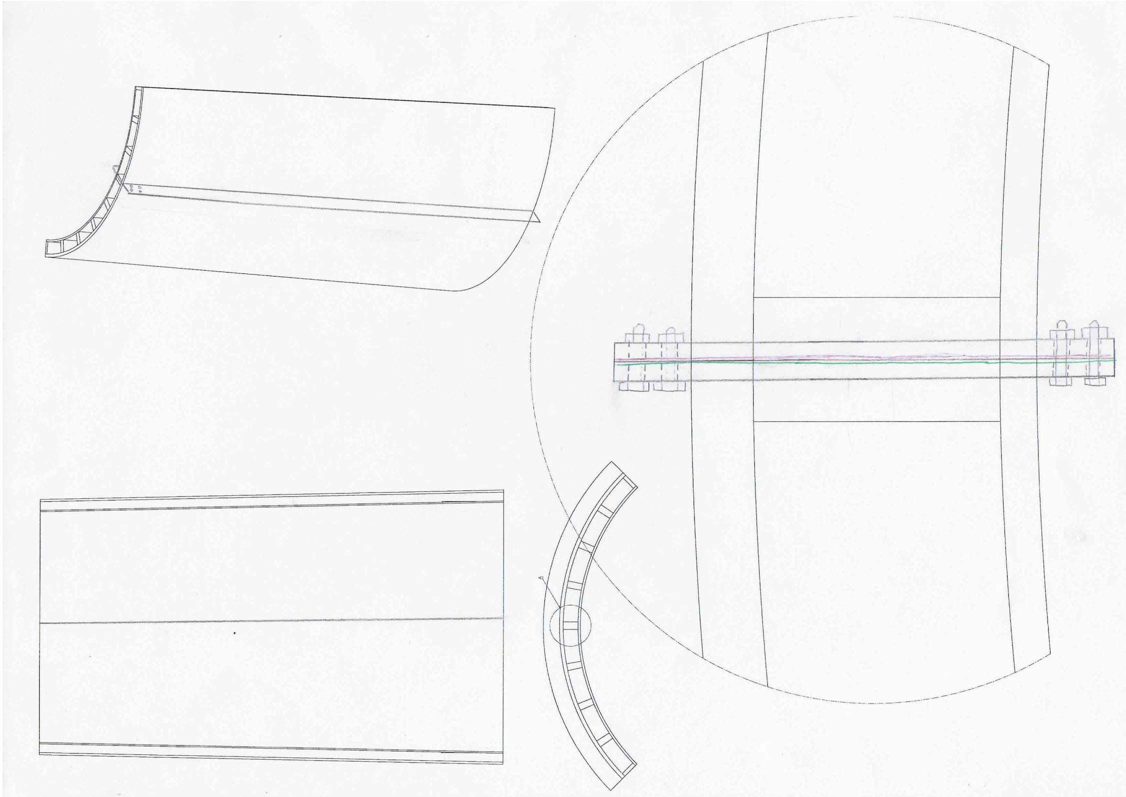
Sandwich-E



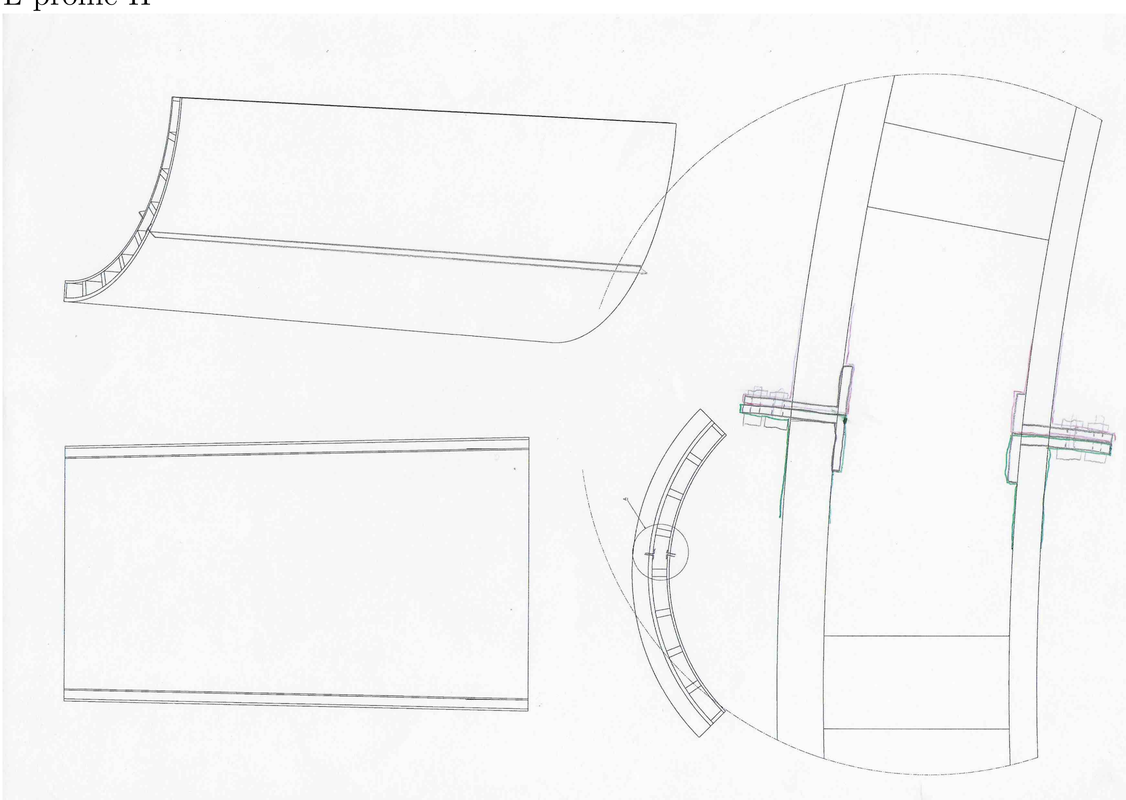
Cover panel-F



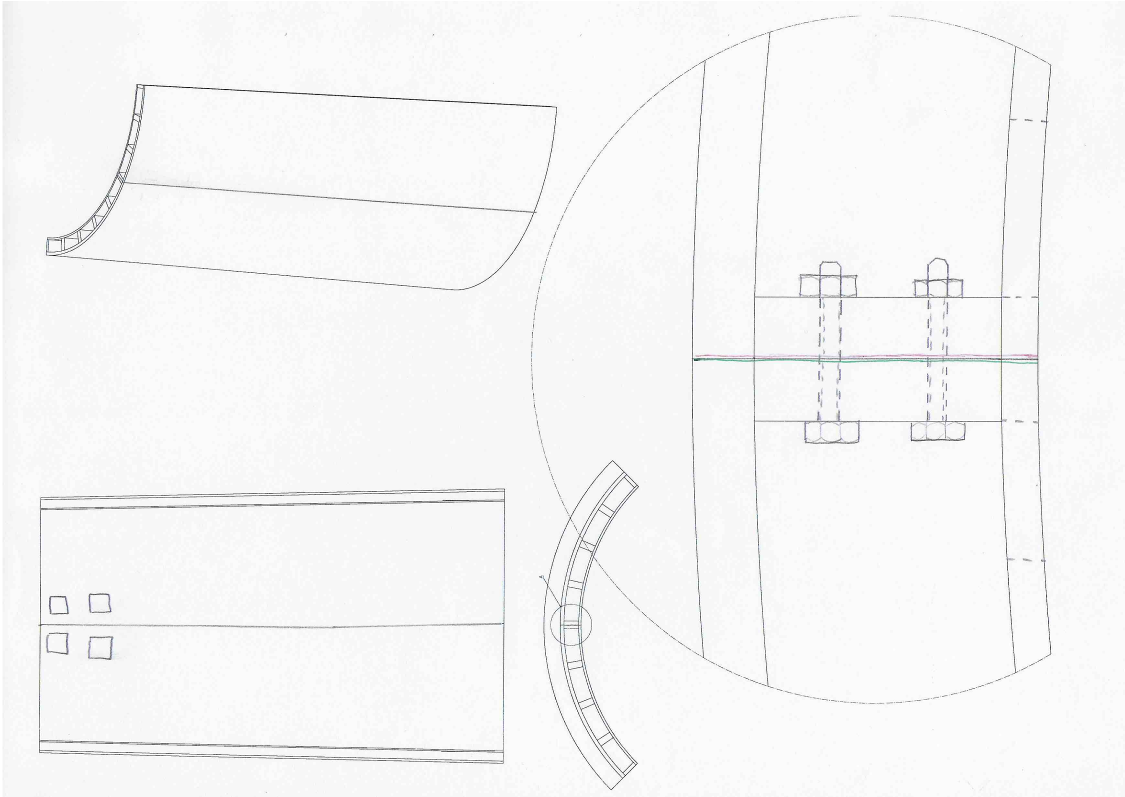
Steel side-G



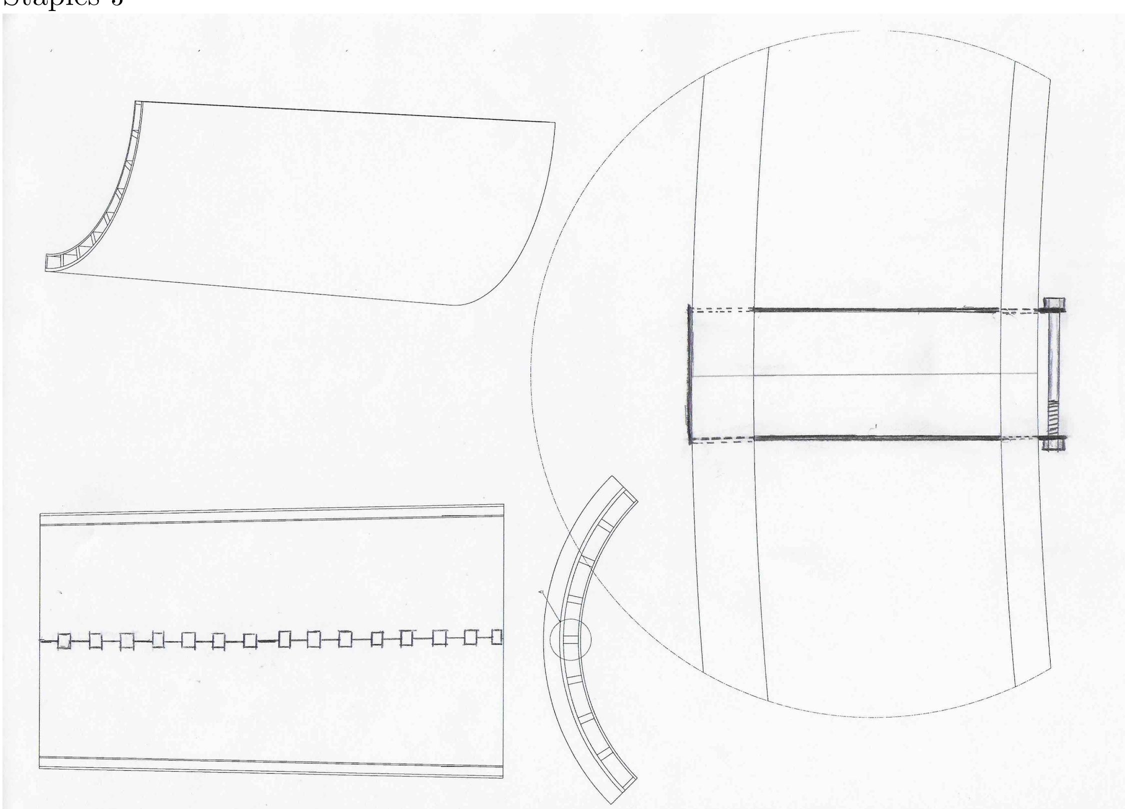
L-profile-H



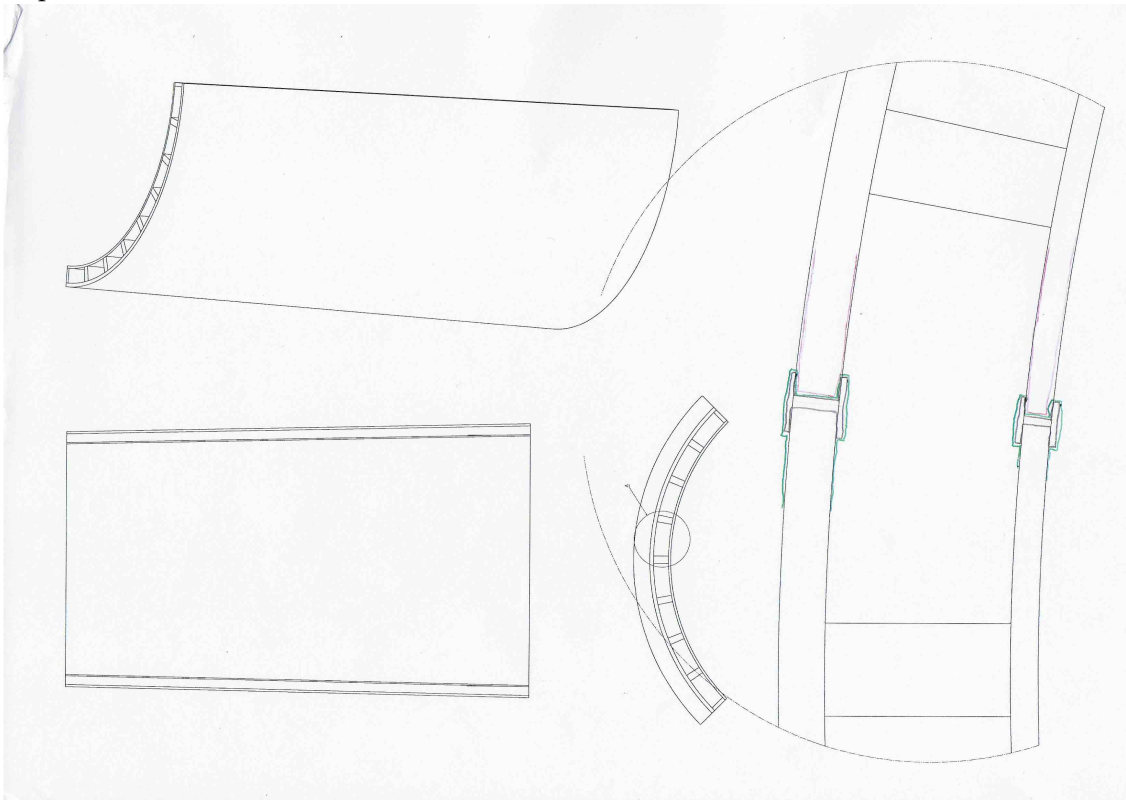
Bolt through beam-I



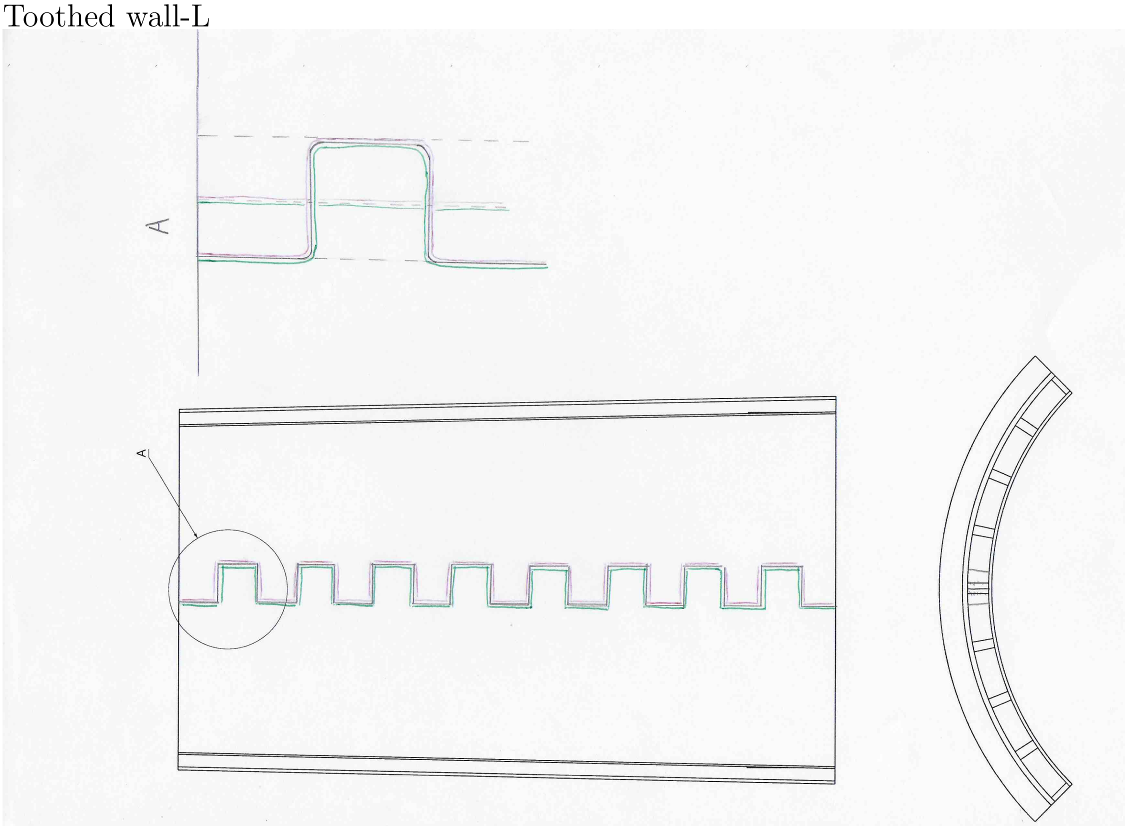
Staples-J



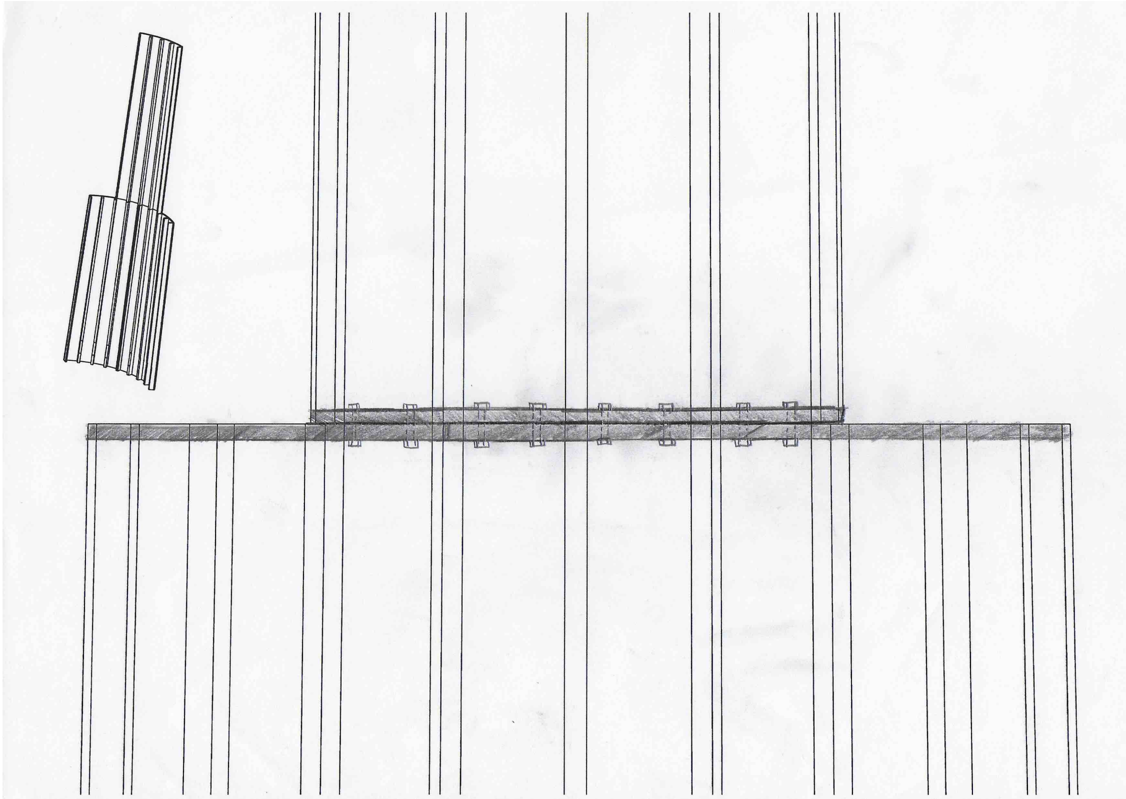
H-profile-K



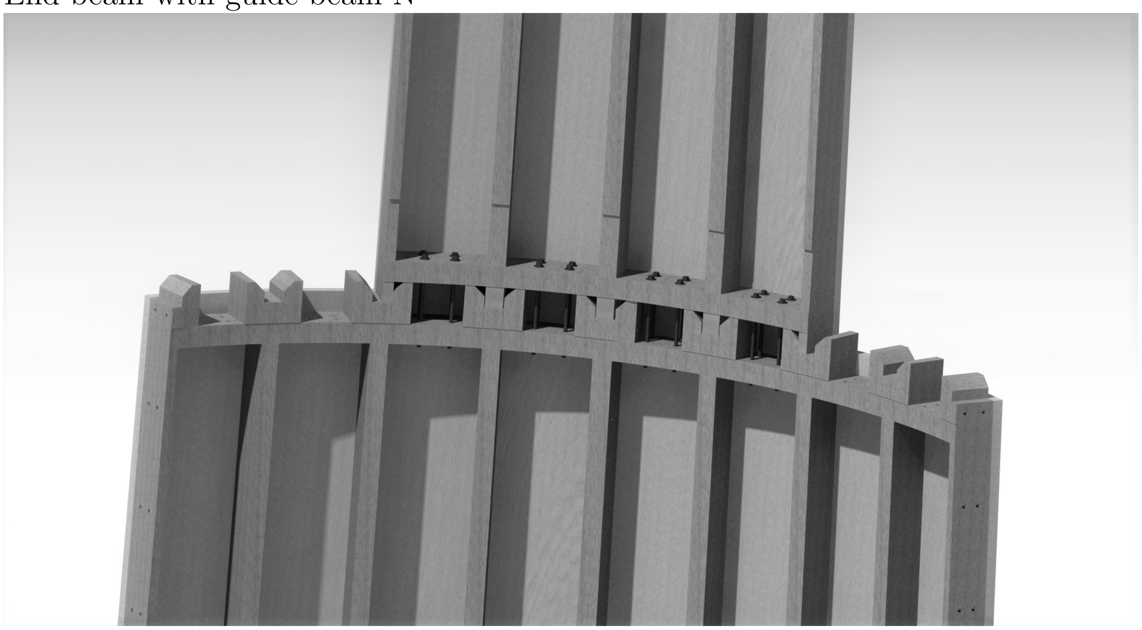
Toothed wall-L



End beam-M

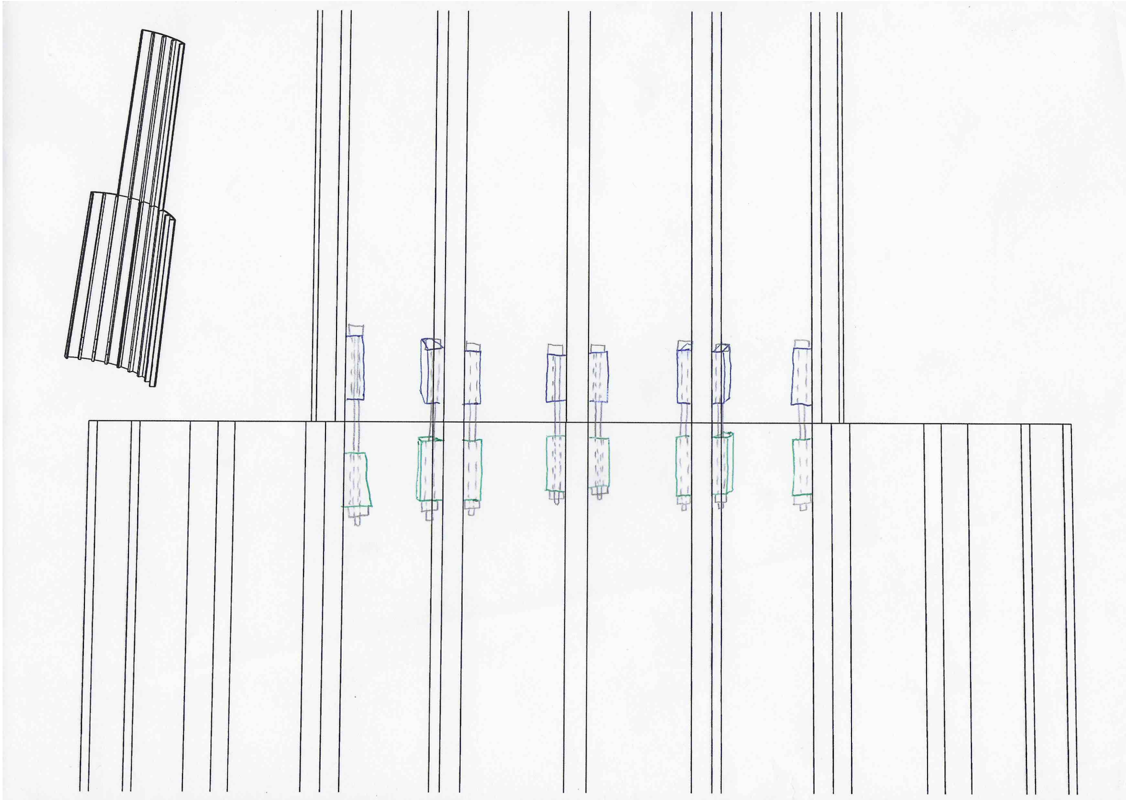


End beam with guide beam-N

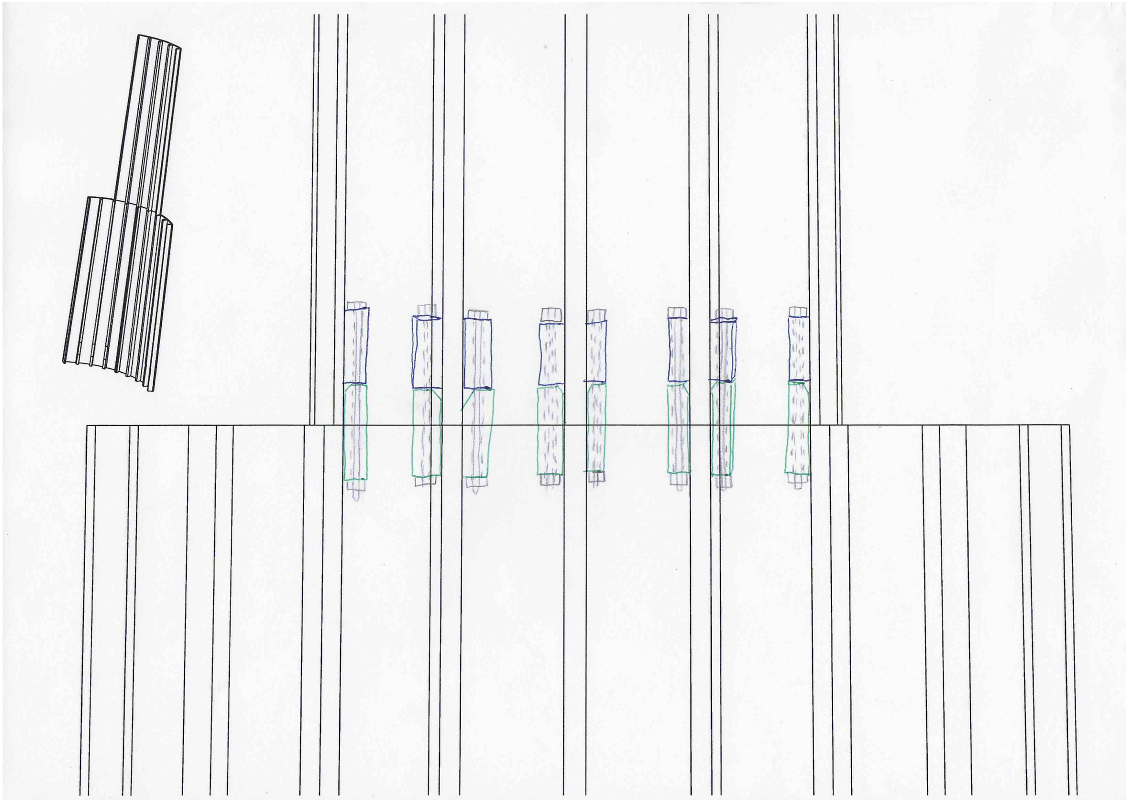


Boot-O

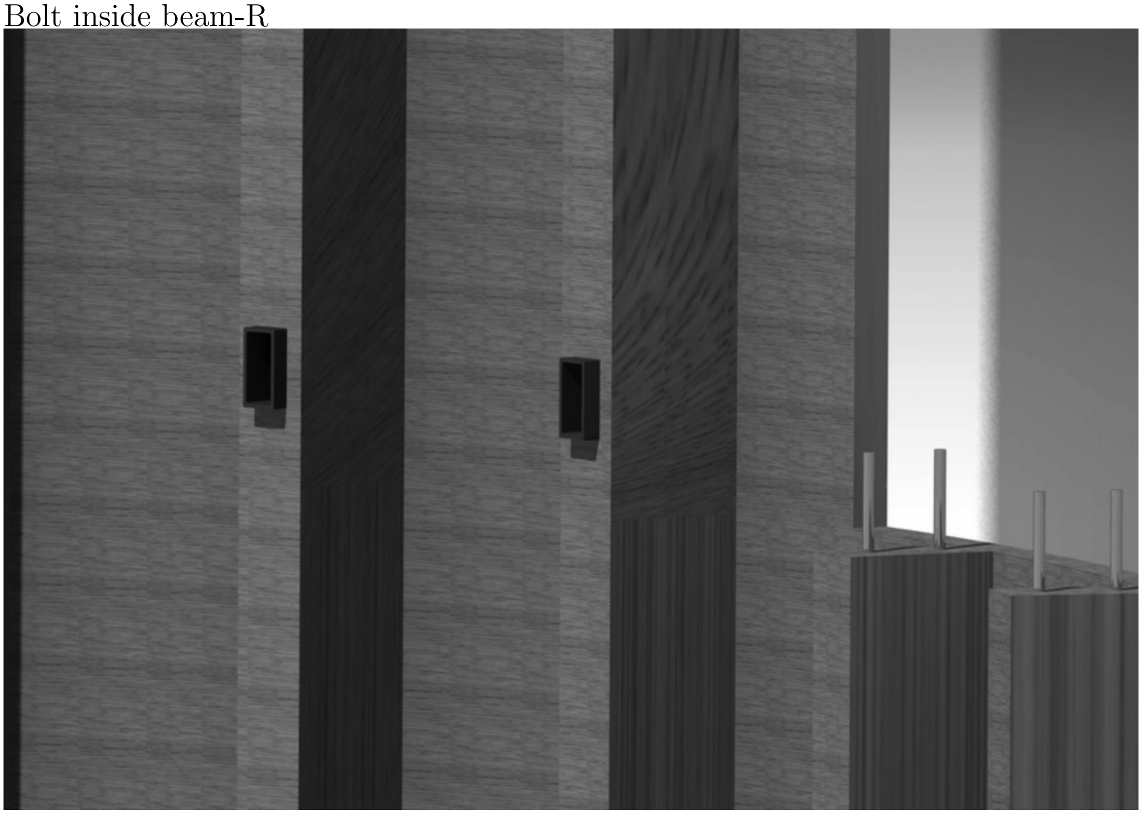
Side beam-P



Guide beam-Q



Bolt inside beam-R



Profile flange-S

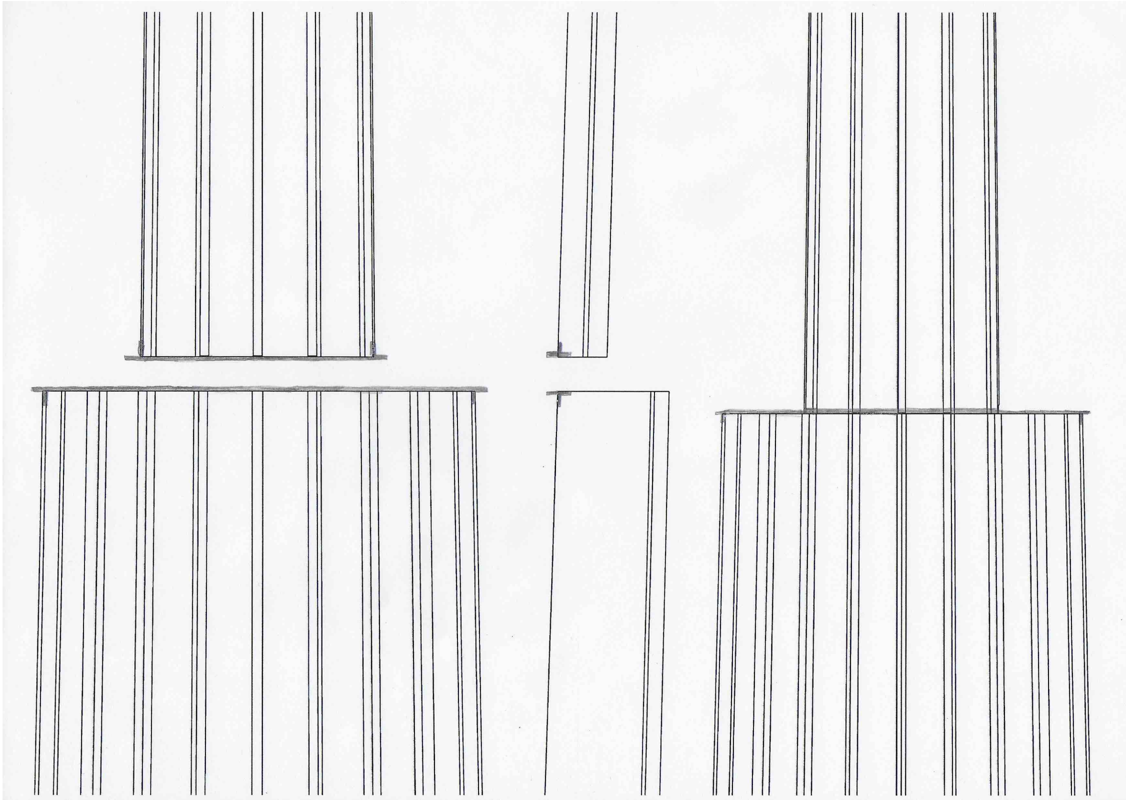
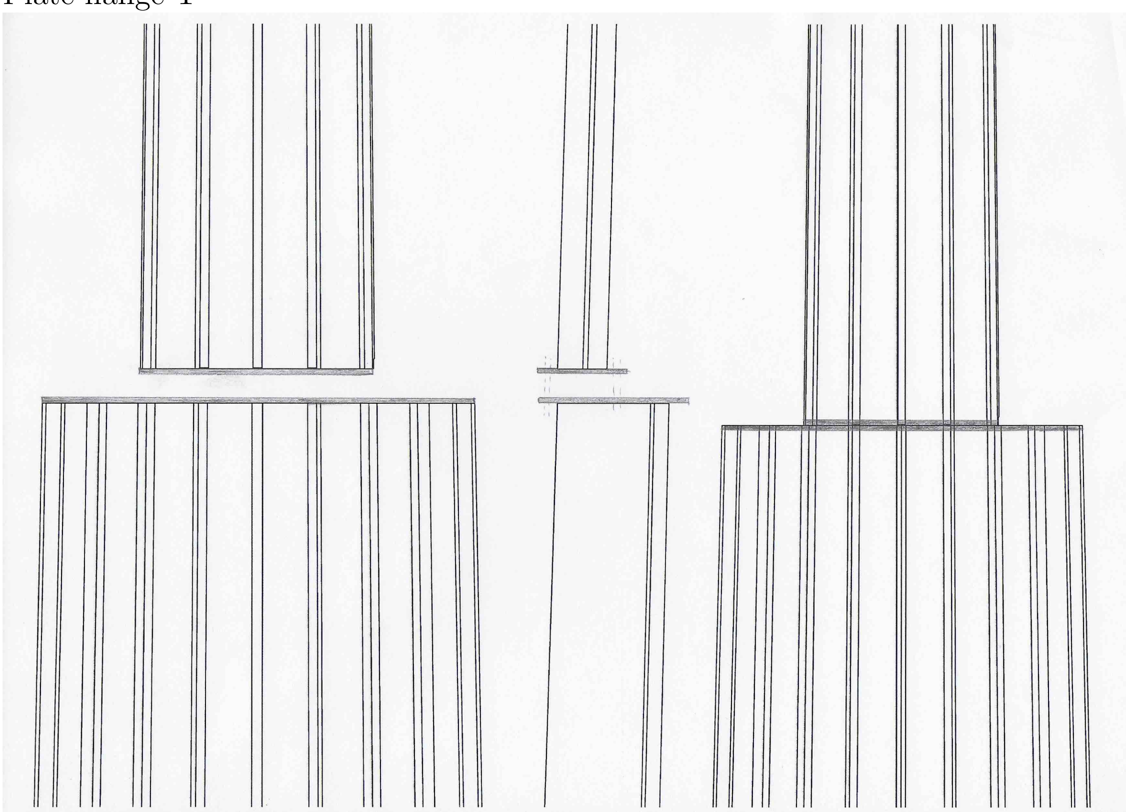
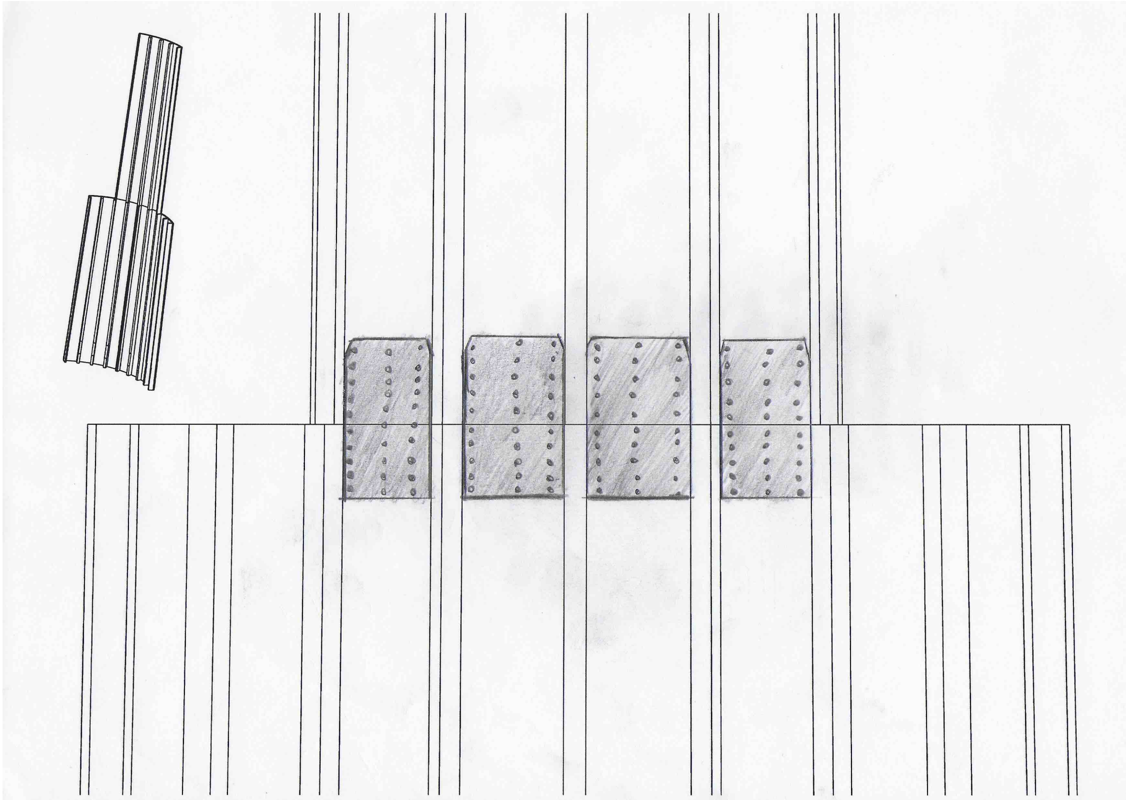


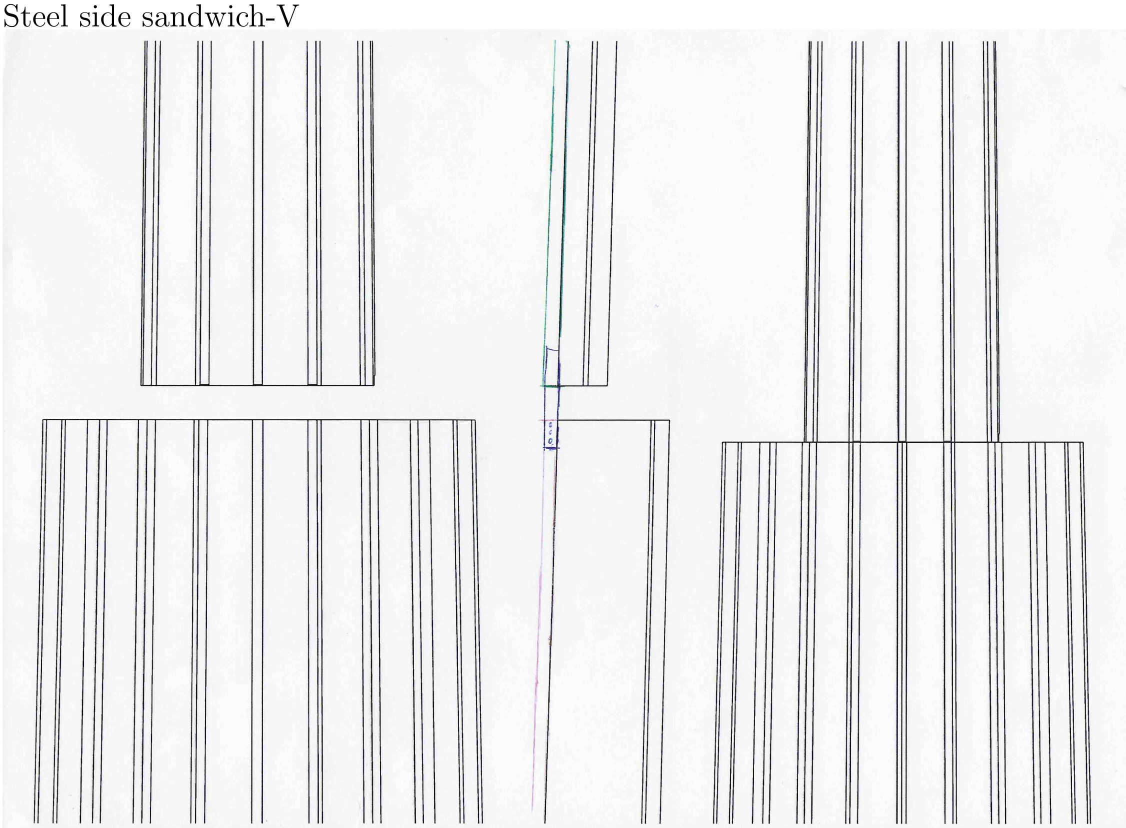
Plate flange-T



Block-U



Steel side sandwich-V



C Requirement specification

1. Structural intigrity			
Requirement (Criterion)	**Demand/Wish**	**Value**	**Evaluation / Verification**
Rotor force	D	1 MN	Calculations
Symmetry of contruction	D		Geometrical design
Maximum weight of joints, proportion of total weight	D	20%	Calculations
Maximum weight of joints, proportion of total weight	W	10%	Calculations
Allow movement of the wood structure	D		Geometrical design
Not initiate rot	D		Geometrical design
Designed to prevent collection of water	D		Geometrical design
Prevent local buckling of the segments	D		Geometrical design

2. Assembly			
Requirement (Criterion)	**Demand/Wish**	**Value**	**Evaluation / Verification**
Allow pre-assembly of the levels	D		Geometrical design
Only standard tools needed	W		Research
Resistant to impacts during assembly	D		Geometrical design
Stable when stacking levels	D		Geometrical design
Reasonable assembly potential	D		Geometrical design
Allow lift by crane	D		Geometrical design
Few unique type of fasteners	W		Geometrical design
No assembly from the outside when stacking the levels	D		Geometrical design

3. Service			
Requirement (Criterion)	**Demand/Wish**	**Value**	**Evaluation / Verification**
Design to simplify an inspection	D		Geometrical design
Simple replacement of fastening elements	D		Geometrical design

5. Miscellaneous			
Requirement (Criterion)	**Demand/Wish**	**Value**	**Evaluation / Verification**
Maximum width	D	5 m	Geometrical design
Maximum length	D	20 m	Geometrical design
Maximum material cost of joints, proportion of totat co	D	15%	Cost estimations
Maximum material cost of joints, proportion of totat co	W	10%	Cost estimations
Reasonable complexity of manufacturing	D		Geometrical design
Enable a lifespan	D	20 years	Estimations

D Pugh matrix

Pugh matrix for tangential concepts:

	A	B	C	D	E	H	J	L
Cost	*	+	+	-	-	-	-	+
Shock proof	R	0	-	+	+	+	+	-
Size	E	0	-	0	+	0	0	+
Weight	F	0	0	0	0	-	-	0
Manufacturing	E	+	+	-	-	0	0	+
Serviceability	R	0	0	0	0	+	+	0
Stiffness/strength	E	−1	0	0	0	+	+	-
Assembly	N	+	-	+	-	+	+	0
Environmental sustainability	C	0	0	0	0	-	-	0
Safety	E	0	0	0	0	0	0	0
Weather resistant	*	0	0	+	+	-	-	-
SUM +		3	2	3	3	4	4	3
Sum -		1	3	2	3	4	4	3
Sum 0		7	6	6	5	3	3	5
Net result	0	2	−1	1	0	0	0	0

	A	B	C	D	E	H	J	L
Cost	+	+	+	+	+	*	0	+
Shock proof	-	-	-	-	0	R	-	-
Size	0	+	-	+	+	E	0	-
Weight	+	+	-	+	+	F	0	+
Manufacturing	0	+	+	0	+	E	-	+
Serviceability	-	-	-	-	-	R	0	-
Stiffness/strength	-	-	-	-	-	E	-	-
Assembly	-	-	-	-	-	N	0	-
Environmental sustainability	+	+	+	+	+	C	0	+
Safety	0	0	0	0	0	E	0	0
Weather resistant	+	0	0	0	0	*	0	0
SUM +	4	5	3	4	5		0	4
Sum -	4	4	6	4	3		3	5
Sum 0	3	2	2	3	3	11	8	2
Net result	0	1	−3	0	2	0	−3	−1

Weighted Pugh matrix for tangential concepts:

	A			B			C			D			E			H			J			L		
	+/-	Weightning	Total	+/-	Weightning	Total	+/-	Weightning	Total	+/-	Weightning	Total	+/-	Weightning	Total	+/-	Weightning	Total	+/-	Weightning	Total	+/-	Weightning	Total
Cost	*	*	*	1	4	4	1	4	4	−1	4	−4	−1	4	−4	−1	4	−4	−1	4	−4	1	4	4
Shock proof	*	R	*	0	7	0	−1	7	−7	1	7	7	1	7	7	1	7	7	1	7	7	−1	7	−7
Size	*	E	*	0	3	0	−1	3	−3	0	3	0	1	3	3	0	3	0	0	3	0	1	3	3
Weight	*	F	*	0	1,5	0	0	1,5	0	0	1,5	0	0	1,5	0	−1	1,5	−1,5	−1	1,5	−1,5	1	1,5	1,5
Manufacturing	*	E	*	1	4	4	1	4	4	−1	4	−4	−1	4	−4	0	4	0	0	4	0	1	4	4
Serviceability	*	R	*	0	7,5	0	0	7,5	0	0	7,5	0	0	7,5	0	1	7,5	7,5	1	7,5	7,5	0	7,5	0
Stiffness/strength	*	E	*	−1	10	−10	0	10	0	0	10	0	0	10	0	1	10	10	1	10	10	−1	10	−10
Assembly	*	N	*	1	7	7	−1	7	−7	1	7	7	−1	7	−7	1	7	7	1	7	7	0	7	0
Environmental sustainability	*	C	*	0	0,5	0	0	0,5	0	0	0,5	0	0	0,5	0	−1	0,5	−0,5	−1	0,5	−0,5	0	0,5	0
Safety	*	E	*	0	2	0	0	2	0	0	2	0	0	2	0	0	2	0	0	2	0	0	2	0
Weather resistant	*	*	*	0	8,5	0	0	8,5	0	1	8,5	8,5	1	8,5	8,5	−1	8,5	−8,5	−1	8,5	−8,5	0	8,5	0
SUM			0			5			−9			14,5			3,5			17			17			−4,5

	A	Weighting		B	Weighting		C	Weighting		D	Weighting		E	Weighting		H	Weighting		J	Weighting		L	Weighting	Total
Cost	1	4	4	1	4	4	1	4	4	1	4	4	1	4	4	*	4	*	−1	4	−4	1	4	4
Shock proof	−1	7	−7	−1	7	−7	−1	7	−7	−1	7	−7	0	7	0	R	7	*	−1	7	−7	−1	7	−7
Size	0	3	0	1	3	3	−1	3	−3	1	3	3	1	3	3	E	3	*	0	3	0	−1	3	−3
Weight	1	1,5	1,5	1	1,5	1,5	−1	1,5	−1,5	1	1,5	1,5	1	1,5	1,5	F	1,5	*	0	1,5	0	1	1,5	1,5
Manufacturing	0	4	0	1	4	4	1	4	4	0	4	0	1	4	4	E	4	*	−1	4	−4	1	4	4
Serviceability	−1	7,5	−7,5	−1	7,5	−7,5	−1	7,5	−7,5	−1	7,5	−7,5	−1	7,5	−7,5	R	7,5	*	0	7,5	0	−1	7,5	−7,5
Stiffness/strength	0	10	0	−1	10	−10	−1	10	−10	−1	10	−10	−1	10	−10	E	10	*	−1	10	−10	−1	10	−10
Assembly	−1	7	−7	−1	7	−7	−1	7	−7	−1	7	−7	−1	7	−7	N	7	*	0	7	0	−1	7	−7
Environmental sustainability	1	0,5	0,5	1	0,5	0,5	1	0,5	0,5	1	0,5	0,5	1	0,5	0,5	C	0,5	*	0	0,5	0	1	0,5	0,5
Safety	0	2	0	0	2	0	0	2	0	0	2	0	0	2	0	E	2	*	0	2	0	0	2	0
Weather resistant	1	8,5	8,5	0	8,5	0	0	8,5	0	0	8,5	0	0	8,5	0	*	8,5	*	0	8,5	0	0	8,5	0
SUM			−7			−18,5			−27,5			−22,5			−11,5			0			−25			−24,5

Pugh matrix for vertical concepts:

	N	O	T	V
Cost	*	0	-	+
Shock proof	R	0	-	0
Size	E	0	-	0
Weight	F	0	-	0
Manufacturing	E	0	-	0
Serviceability	R	0	+	-
Stiffness/strength	E	0	+	-
Assembly	N	+	-	-
Environmental sustainabil	C	0	-	0
Safety	E	0	-	0
Weather resistant	*	0	-	-
SUM +	0	1	2	1
Sum -	0	0	9	4
Sum 0	11	10	0	6
Net result	0	1	−7	−3

	N	O	T	V
Cost	+	+	*	+
Shock proof	+	+	R	0
Size	+	+	E	0
Weight	+	+	F	1
Manufacturing	+	+	E	1
Serviceability	-	-	R	-
Stiffness/strength	-	-	E	-
Assembly	+	+	N	-
Environmental sustainabil	+	+	C	0
Safety	+	+	E	0
Weather resistant	+	+	*	-
SUM +	9	9		3
Sum -	2	2		4
Sum 0	0	0		4
Net result	7	7	0	−1

Weighted Pugh matrix for vertical concepts:

	N			O			T			V		
	+/-	Weightning	Total	+/-	Weightning	Total	+/-	Weightning	Total	+/-	Weightning	Total
Cost	*	*	*	0	4	0	−1	4	−4	1	4	4
Shock proof	*	R	*	0	7	0	−1	7	−7	0	7	0
Size	*	E	*	0	3	0	−1	3	−3	0	3	0
Weight	*	F	*	0	1,5	0	−1	1,5	−1,5	0	1,5	0
Manufacturing	*	E	*	0	4	0	−1	4	−4	0	4	0
Serviceability	*	R	*	0	7,5	0	1	7,5	7,5	−1	7,5	−7,5
Stiffness/strength	*	E	*	1	10	10	1	10	10	−1	10	−10
Assembly	*	N	*	1	7	7	−1	7	−7	−1	7	−7
Environmental sustainability	*	C	*	0	0,5	0	−1	0,5	−0,5	0	0,5	0
Safety	*	E	*	0	2	0	−1	2	−2	0	2	0
Weather resistant	*	*	*	0	8,5	0	−1	8,5	−8,5	−1	8,5	−8,5
SUM			0			17			−20			−29

	N			O			T			V		
	+/-	Weightning	Total	+/-	Weightning	Total	+/-	Weightning	Total	+/-	Weightning	Total
Cost	1	4	4	1	4	4	*	*	*	1	4	4
Shock proof	1	7	7	1	7	7	*	R	*	0	7	0
Size	1	3	3	1	3	3	*	E	*	0	3	0
Weight	1	1,5	1,5	1	1,5	1,5	*	F	*	1	1,5	1,5
Manufacturing	1	4	4	1	4	4	*	E	*	1	4	4
Serviceability	−1	7,5	−7,5	−1	7,5	−7,5	*	R	*	−1	7,5	−7,5
Stiffness/strength	−1	10	−10	−1	10	−10	*	E	*	−1	10	−10
Assembly	1	7	7	1	7	7	*	N	*	−1	7	−7
Environmental sustainability	1	0,5	0,5	1	0,5	0,5	*	C	*	1	0,5	0,5
Safety	1	2	2	1	2	2	*	E	*	0	2	0
Weather resistant	1	8,5	8,5	1	8,5	8,5	*	*	*	−1	8,5	−8,5
			20			20			0			−23

E Weighting matrix

	Cost	Shock proof	Size	Weight	Manufacturing	Serviceability	Stiffness/Streng	Assembly	Env. sustainability	Safety	Wea. resistant	Weighting
Cost		0	0,5	1	1	0	0	0	1	0,5	0	**4**
Shock proof	1		1	1	1	0,5	0	0,5	1	1	0	**7**
Size	0,5	0		1	0	0	0	0	1	0,5	0	**3**
Weight	0	0	0		0	0	0	0	0,5	1	0	**1,5**
Manufacturing	0	0	1	1		0	0	0	1	1	0	**4**
Serviceability	1	0,5	1	1	1		0	0,5	1	1	0,5	**7,5**
Stiffness/strength	1	1	1	1	1	1		1	1	1	1	**10**
Assembly	1	0,5	1	1	1	0,5	0		1	1	0	**7**
Environmental sustainability	0	0	0	0,5	0	0	0	0		0	0	**0,5**
Safety	0,5	0	0,5	0	0	0	0	0	1		0	**2**
Weather resistant	1	1	1	1	1	0,5	0	1	1	1		**8,5**

F Nail pattern