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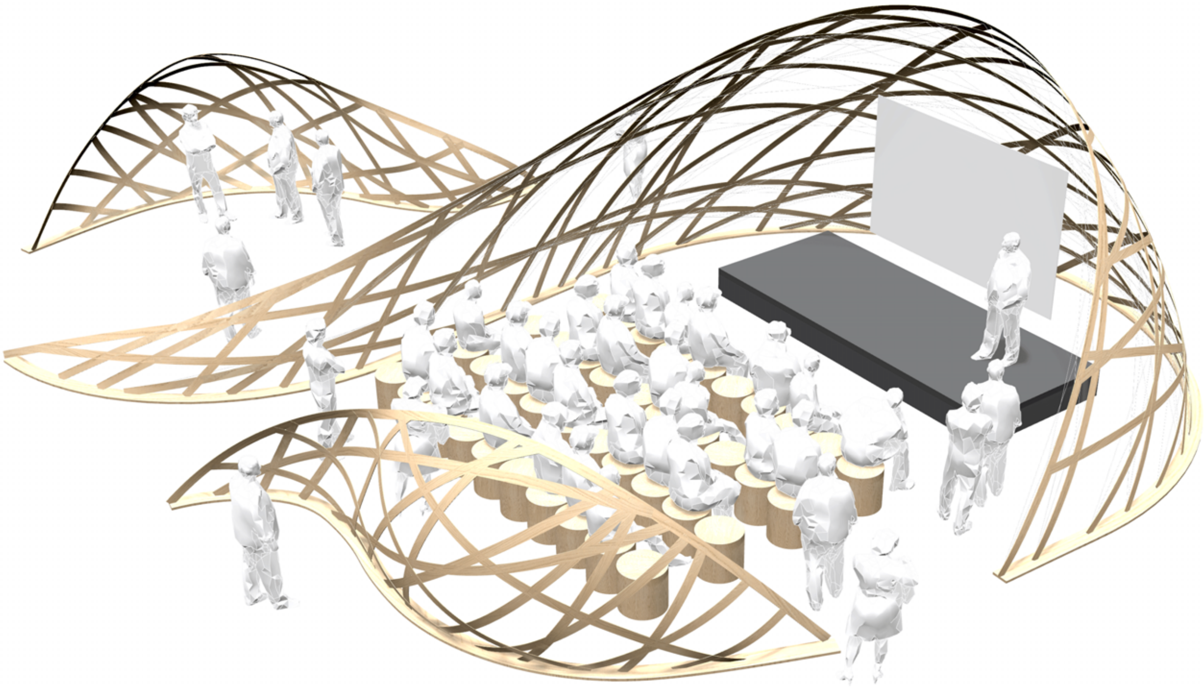

STRESSING TIMBER

An exploration of the use of prestressing in timber structures through the design of a lecture pavilion

Master's thesis in Structural Engineering and Building Technology

JOHANNA ISAKSSON
MATTIAS SKEPPSTEDT

Department of Architecture and Civil Engineering
Chalmers University of Technology
Gothenburg, Sweden 2018

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Cover: Visualisation of final pavilion design.

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Abstract

From the late 60's, timber gridshells have fascinated architects and engineers alike with their ability to cover large spaces with minimum material, expense and environmental impact. However, with long-term creep deformations, thin cross sections and high elasticity, timber shells face potential stability issues. Historically, prestressing systems have been shown to prevent instability modes in unstable structures. This thesis explores the potential use of prestressing in timber structures through the design of a lecture pavilion. The purpose is both to investigate the possible benefits of prestressing and to evaluate constructive design research as a method for driving structural engineering research. This is done through an iterative design process exploring, evaluating and further developing possible concepts into a viable design proposal. Based on context, production and relevance for the research question an actively bent geodesic gridshell is chosen as the most suitable concept at the end of the conceptual design phase. Digital analysis and physical tests are then interactively combined to study and implement various modelling and analysis techniques, prestress configurations and connection details. It is found that an internal prestressing system can significantly increase the stability of elastic bending-active gridshells in terms of eigenfrequencies. Reflections on the constructive design research approach suggest that it is a useful method for exploring new structural concepts. There is also a discussion on the level of openness in the design question and the resulting consequences for the design.

Keywords: timber, prestress, gridshell, research by design, active bending, geodesics, connection details

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Johanna Isaksson and Mattias Skeppstedt, Gothenburg, June 2018

Contents

List of Figures

List of Tables

1

Introduction

From their first appearances in the late 60's, timber gridshells have caught the fascination of architects and engineers alike. With their light weight, beautiful patterns and natural material they serve exceptionally well for covering large spaces with minimum material, expense and environmental impact. In later years, actively bent gridshells have become increasingly popular owing to the ease of fabrication and transportation of the initially straight laths. However, with long-term creep deformations, thin cross sections and high elasticity, timber shells face potential stability issues. Historically, prestressing systems have been shown to prevent instability modes in unstable structures, and could therefore be a potential method for increasing the shell stability. Along the lines of "constructive design research", a full-scale pavilion will be designed in this thesis to test the viability of prestressing timber structures.

This section will give an introduction to the history of shells in architecture, the benefits of prestressing and constructive design research. Furthermore, the local context for the intended pavilion will be introduced. Finally, the purpose and limitations of this thesis will be outlined.

1.1 Shells in architecture

Shells are ideal shapes for achieving strong structures with a minimum of material usage, as exemplified by their abundance in nature (e.g. sea shells, sea urchins, mussels). Likewise, shells can be found in various areas of everyday life, such as kitchen sieves (Figure 1.1). The form of a shell is in direct relation with the flow of forces. In the ideal shell there is no bending under self-weight, only axial compression and tension (Adriaenssens et al., 2014). However, as soon as live loads are introduced, bending and torsion occurs.

(a) Sea urchin, structural inspiration for the ICD-ITKE Research Pavilion 2015-16

(b) Kitchen sieve (Adriaenssens et al., 2014)

Figure 1.1: Examples of shell structures

In architecture and structural engineering, shells have been adapted in a variety of fashions, from continuous structures like Heinz Isler's concrete cupolas at highway service area Deitingen, to timber gridshells like the Mannheim Multihalle (Figure 1.2). As evident by this, the shell can be a continuous surface or constructed by a grid of discrete members, forming a gridshell. Following simplicity of production, timber shells are often constructed as gridshells, whereas for example concrete shells are normally continuous surfaces. Chilton and Tang (2017) gives a thorough exposé of gridshell theory and design. Traditionally, gridshells were defined as planar grids of rods with constant spacing between rigid joints, that form a spatially curved framework (Hennicke, 1974). With time however, the term has widened and can be more generally described as a shell with holes, where the structure is concentrated into strips (Johnson, 2000).

(a) Highway service area Deitingen south, Heinz Isler, 1968 (*Highway service area Deitingen south*, n.d.)

(b) Mannheim Multihalle, Frei Otto, 1974 (Werkarchiv Frei Otto im Südwestdeutschen, n.d.)

Figure 1.2: Early examples of shell structures

Mannheim Multihalle was one of the earliest examples of timber gridshells. Since then, a large variety have been constructed, ranging from engineered glulam shells like the Clubhouse for the Haesley Nine Bridges Golf Resort in Yeoju, South Korea, to bamboo structures like the ZBC Bamboo Pavilion in Hong Kong (Figure 1.3).

(a) Clubhouse for the Haesley Nine Bridges Golf Resort, Shigeru Ban, 2009 (Hirai, 2014)

(b) ZBC Bamboo Pavilion, The Chinese University of Hong Kong School of Architecture, 2015 (Ng, 2016)

Figure 1.3: Later examples of shell structures

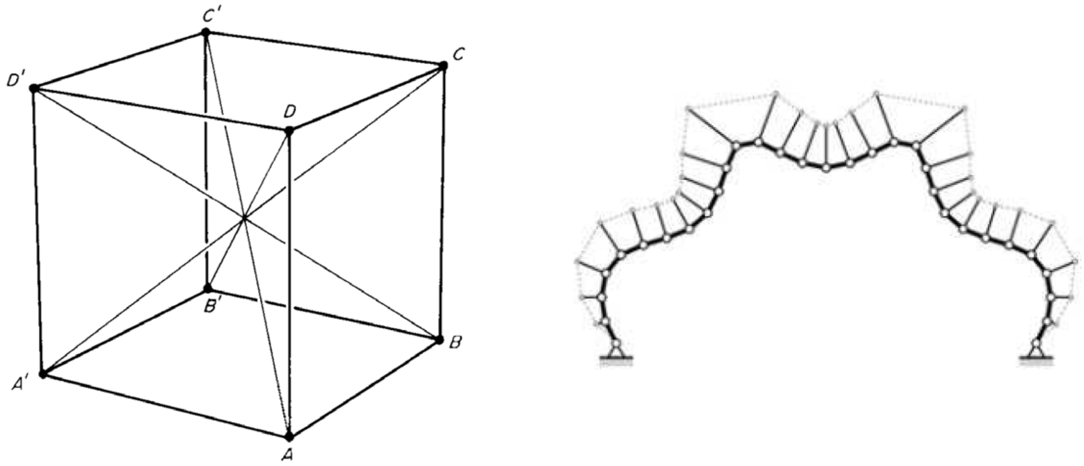
1.2 Stability and prestress

The global stability of a gridshell is generally determined by its ability to resist local and global buckling. Local buckling relates to individual buckling of a lath segment between its points of support, while global buckling describes collapse of the entire or large parts of the structure. The latter occurs as a consequence of local buckling or by the combined effects of displacements and rotations in the structure. In gridshells, local buckling is generally of less importance, since the large number of alternative load paths provides good redundancy.

The general rule of thumb is that for a shell to be able to carry only in compression, the thrust line must lie within the middle third of the cross-section (Heyman, 1996). It follows that buckling occurs more easily for a thin and shallow arch than for a thicker and higher one. Furthermore, if the shell is of lightweight material, the influence of a point load on the thrust line is larger. However, if the permanent load on the structure is increased, for example by prestressing, the influence of the imposed load is reduced, making the load bearing capacity of the shell higher. A shell with a small structural height, like a thin two-layer timber gridshell, will instead have to rely on bending to carry point loads.

In the case of timber gridshells, material-related factors like creep and high strength-to-weight ratio also play a significant role for stability. Long-term creep deformations under self-weight may lead to a loss of structural integrity, as the structure gradually deviates from its optimal shape towards a buckling mode (Adriaenssens et al., 2014). By the use of prestress, some deformations may be prevented so as to lessen the destabilizing effects.

The low weight of timber also gives rise to dynamic issues that are not present in structures composed of heavier materials such as concrete or brick. Prestressing may prevent this phenomenon, in line with the principle of “tensegrity”, where self-stress can be used to stiffen the instability modes present in structures with fewer bars than what is necessary to satisfy Maxwell’s rules for the construction of stiff frames (Calladine, 1978). Furthermore, prestressing might allow for more complex structures and shapes, that would otherwise be impossible to obtain, such as the post-tensioned arbitrary geometries demonstrated by Todisco et al. (2015) (Figure 1.4).



(a) Diagonal stiff members fixed by prestressed cable frame (Calladine, 1978)

(b) Arbitrary geometry created with post-tensioning (Todisco et al., 2015)

Figure 1.4: Examples of prestressing in structures

At Chalmers, a PhD thesis within the Architecture and Engineering Research Group focuses on the use of prestressing to improve stability of timber structures. Prestressing of timber can be found in a variety of traditional usages, such as the skins of a timber framed kayak, the string of a bow (Figure 1.5) or the net of a tennis racket. Translating this to a shell, prestressing could be applied for example by a fabric wrapping or by an internal net of cables (Figure 1.6). A prestressed wrapping would improve the stability of the shell by increasing the permanent load in the system, thereby reducing the impact of punctual loads, while an internal net of cables would provide geometrical stiffness.

(a) Canoe with textile membrane (Seawolf Kayak, n.d.)

(b) Traditional bow and arrow (*Red Oak Pyramid Bow*, 2010)

Figure 1.5: Examples of prestressed timber structures

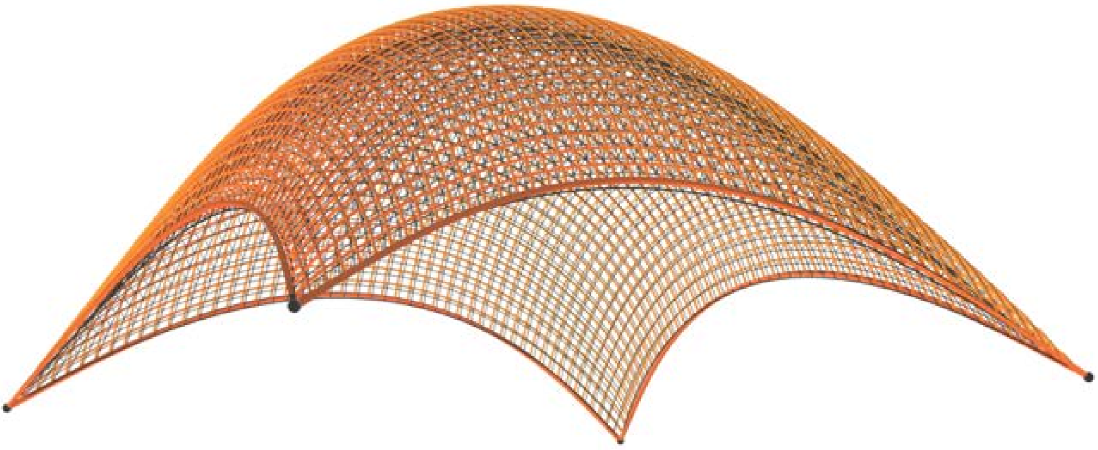


Figure 1.6: Prestressing of a gridshell by an internal net of cables (Ander et al., 2017)

1.3 Research by design

A useful method for exploring new structural concepts and ideas is to put them into practice in physical models of different scales. Koskinen et al. (2011) talk about "constructive design research", in which construction is used as the key to achieve knowledge, based on the idea of "research by design" (Frayling, 1993/4). By not separating planning and doing, the researcher encounters more practical problems that drive knowledge generation in different ways than the traditional academic approach. Pavilions are often used as a means of implementing structural design research in a full-scale but manageable size, with examples in the research pavilions created each year at the University of Stuttgart (see eg. Schwinn et al., 2016) and the compressive shells constructed by the Block Research Group at ETH in Zurich (see eg. Rippmann et al., 2016).

1.4 The Wood Products & Technology fair

The Wood Products & Technology fair is a large biannual trade fair and meeting place for all aspects of wood industry, including raw material, processing, research and finished products. It brings together suppliers, industry and academia for trading, dialogue and seminars for four days.

The fair takes place at the Swedish Exhibition and Congress Centre of Gothenburg (Svenska Mässan), a large exhibition space in Gothenburg that hosts several large fairs each year. For the Wood Fusion lecture area, a pavilion is to be designed including a presentation podium and seating space for 40-80 people. The pavilion will be located in the C-hall (marked blue in Figure 1.7), which is an area of the fair that will be focused on the furniture industry.

Figure 1.7: Plan of the exhibition space at Svenska mässan

The space provided for the pavilion is a rectangular area of 18x14 metres, in which some margins should be included to provide space between the pavilion and the walking paths. It is located in one corner of the fair between the entrance and a cafe, as shown in Figure 1.8. Thus it can be assumed that the flow of visitors past the pavilion will be quite large, and that people will enter the pavilion area from all sides.

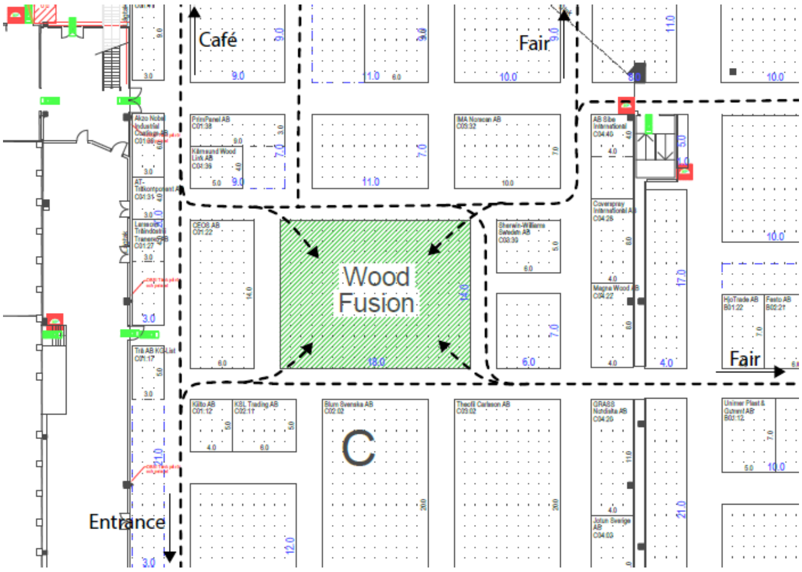


Figure 1.8: Close-up of the pavilion area, called "Wood Fusion"

Prior to the fair there is a period of eight days during which the pavilion can be erected. There is also a possibility that the pavilion could be displayed at other venues after the fair, wherefore it might need to be dismantled and rebuilt again.

1.5 Purpose

The purpose of this thesis is to study the structural benefits of prestressing in timber structures through design of a lecture pavilion. The thesis will also investigate the principle of research by design as a method for structural engineering research and explore the design process of an unconventional structure, from conceptual design to structural analysis and detailing.

1.6 Limitations

The project will focus on the design of the pavilion, from concept phase to detail drawing from a holistic perspective. Principles for production, construction and continued life for the pavilion will be planned, but the actual construction will be outside of the time frame of the thesis. Economy, coordination and logistics aspects will not be considered.

After the conceptual phase, one final concept will be chosen for further development. Other combinations of timber and prestress will therefore only be studied on a conceptual level.

Creep deformations is an important topic in timber constructions, not least when prestressing is involved. The possible advantages and disadvantages of prestressing on the effects of creep on the pavilion will however not be studied in this thesis, since the pavilion will only stand for a few days.

1.7 Outline of the report

The first part of the report is an introduction into the subject of shells in architecture, their stability and the potential stabilising qualities of prestressing. The benefit of research by design is discussed and the local context of the Wood Products & Technology fair is introduced.

Following the introduction, the design method and theory behind conceptual design is described. Then, the report is organised as a process description, starting out from the conceptual design face and finishing in the final design. In the initial phases, the final structural system and principles are unknown, and as the design progresses theoretical choices are based on the results of the previous phases. For continuity, the relevant theory is therefore introduced at the point in the report when it is implemented.

In the initial conceptual design phase, various structural, spatial and material ideas are investigated and evaluated. Evaluation criteria are developed based on the local context and stakeholder's demands. Finally, one winning concept for the pavilion is chosen.

In the preliminary design phase, methods for modelling and analysis of the chosen concept are investigated and implemented. The stabilising effects of prestressing are then tested and applied to the pavilion. Connection details are also investigated and evaluated based on structural and aesthetic qualities.

In the final design chapter, the finished design is materialised into a stiffness-scaled physical model. A plan for fabrication and erection of the full-scale pavilion is also presented.

Finally, a discussion on the work and results is presented together with suggestions for future work.

2

Design method

In order to implement constructive design research as outlined in Section 1.3, a pavilion was to be designed in this thesis. The design process was divided into conceptual design, preliminary design and final design as described in this chapter.

In structural and architectural design a conceptual design phase is often used to generate ideas and compare different solutions before going into detail design. Corres-Peiretti (2013) discusses the principles behind conceptual design that were introduced in the fib Model Code for Concrete Structures (2010). Conceptual design is described as a method for choosing the most appropriate solution for a particular problem, based on the various requirements posed by local context, production etc. Corres-Peiretti also cites the preface to the symposium papers for a symposium on conceptual design organised by Jörg Schlaich in 1996, stressing the importance of conceptual design for qualitative structural design: "The overall quality of many structures today leaves much to be desired. The rapid technological progress does not reflect adequately in their variety, beauty and sensitivity. Too often, structural engineers neglect the creative conceptual design phase by repeating standard designs and not sufficiently contributing with [their] own ideas to the fruitful collaboration with architects. Engineers thus often waste the chance to create building culture".

Corres-Peiretti furthermore describes the general process of conceptual design as set out at the fib Model Code kick-off meeting in Lausanne 2004. The process starts in gathering of inputs such as site data, service criteria and performance requirements. Various activities are then suggested for developing design proposals, using different design and sketching tools. Iteration between activities and evaluation follows until an approved final concept is chosen, which is then the basis for the design for the project.

In the course Structural Design at Chalmers University of Technology, a methodology for the conceptual design is presented based on three iterative steps: the intuitive phase, the intentional phase and the evaluation phase. This methodology was also implemented in this thesis. Each step is described in more detail in Chapter 3.

The conceptual design was followed by preliminary design, in which the chosen concept was further developed into a viable design proposal. The preliminary design consisted of the evaluation and choice of suitable modelling and analysis methods, the development of the structural system, the structural analysis and the development of connection details, resulting in the final design proposal.

Finally, in the final design phase, a stiffness-scaled physical model was built in order to gain better understanding of the final design. The model highlighted potential issues construction and proved a good starting point for discussions and improvements to the design before the fair. A plan for production and fabrication was also formulated. The entire design process is described in Figure 2.1.

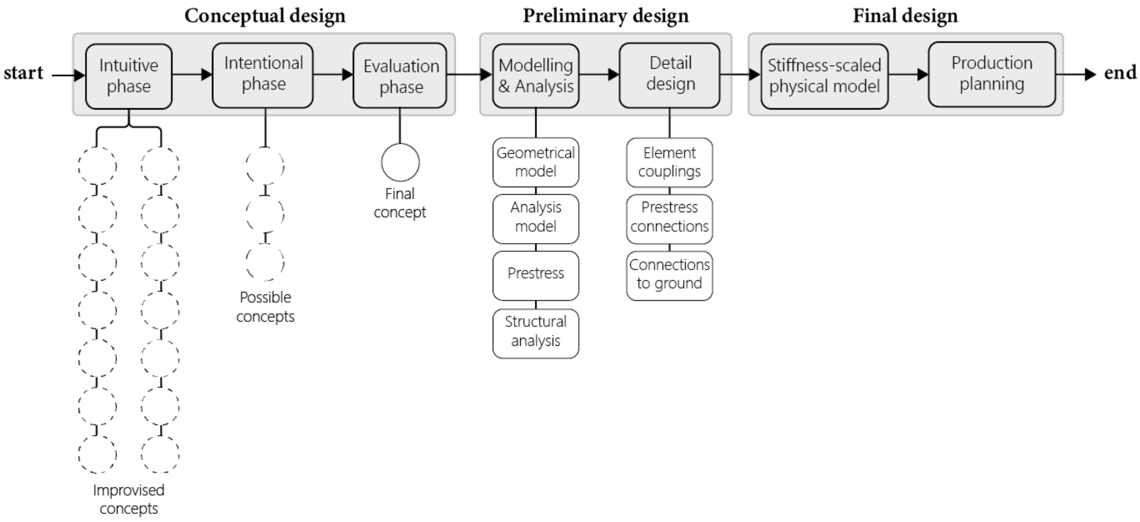


Figure 2.1: Design process

3

Conceptual design

The conceptual design of the pavilion took an iterative form in three stages, where several concepts were created, evaluated and developed into one final design proposal based on the methodology described in the course memo for the course Structural Design at Chalmers University of Technology (Nilenius, 2017). The first, *intuitive*, phase was a loosely-defined phase aimed at producing a range of interesting ideas to investigate further. In the second, *intentional*, phase a number of promising concepts were chosen and developed. In the final phase, the *evaluation* phase, a design goal was formulated and a final concept established.

During the conceptual design, seminars were used as a means of evaluating the concepts together with evaluation criteria that aimed to quantify the qualities of each concept.

3.1 Intuitive phase

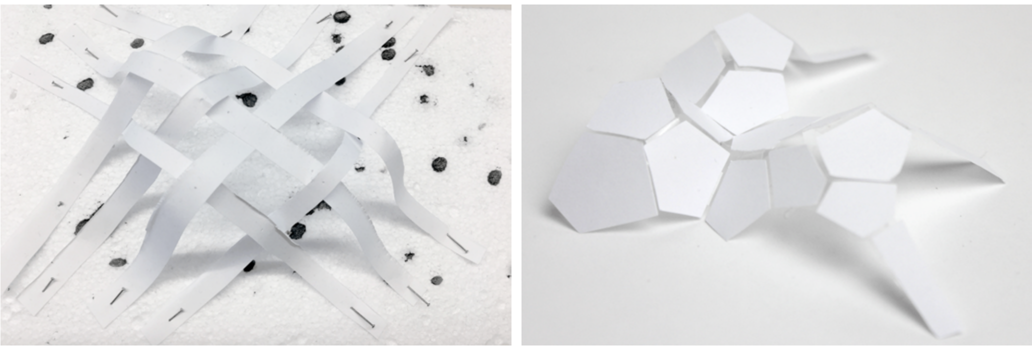
In the intuitive phase, a series of *improvised* concepts were created. The purpose was to capture and generate ideas in physical models, wherefore the models should be at a low level of detail and rather suggest than define ideas. Structural and spatial concepts were investigated separately with the aim of not letting spatial demands impose on the structural concepts and vice-versa in this early stage. By evaluating all concepts together at the end, the most promising combinations could be identified.

3.1.1 Structure

The structural concepts aimed to freely investigate shell structures and the use of prestress to improve or change structural behaviour. Various types of shells were identified and while the prestressing concepts were often investigated in isolation, they could all be imagined as implemented on one or other of the shell types.

Shells in timber can be constructed in a variety of fashions. Pre-curved beams or thin elastic laths can be used to achieve a curved shape with continuous laths

(Figure 3.1a). Straight laths can be used to create a hyperbolic paraboloid and similar shapes. Individual panels can also be created and joined together to create a curved, segmented shell (Figure 3.1b). Shell-like shapes could also be created by placing arches next to each other.



(a) Shell formed by continuous laths **(b)** Segmented shell

Figure 3.1: Various methods of constructing shells

Figure 3.2 shows an arch with an added external prestressing system. The cables provide extra geometrical stiffness to the structure together with increased structural height and separation of compressive and tensile stresses, making it less sensitive to loading.

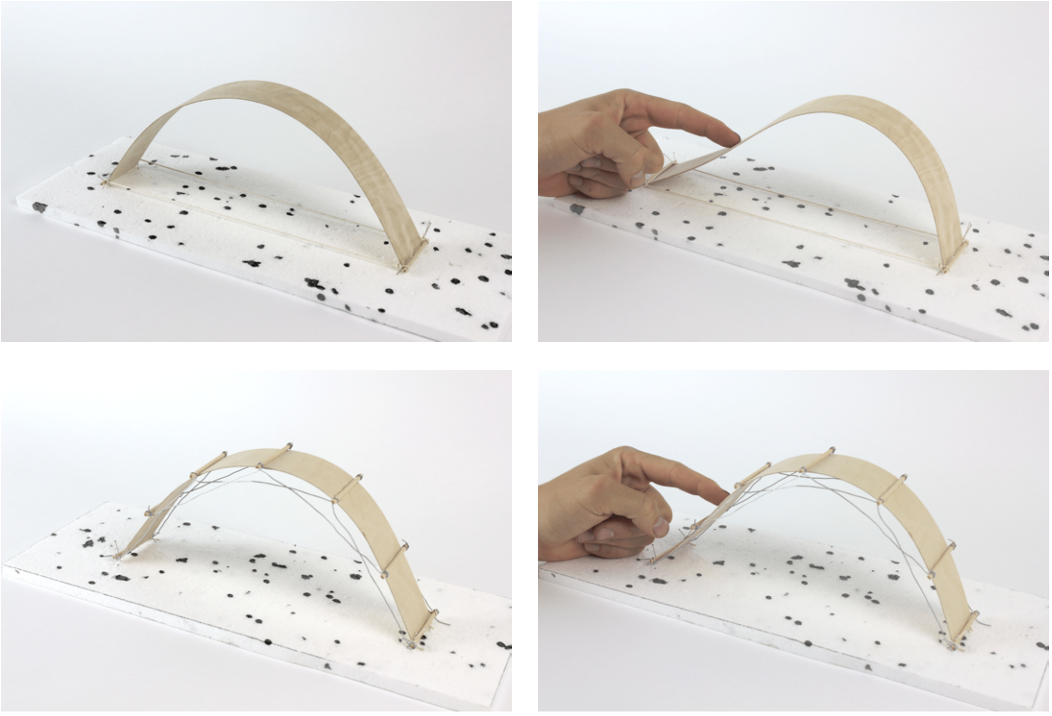


Figure 3.2: Two-dimensional arch with and without external prestressing system

The principle of using prestress to create stability is also employed in the idea of tensegrity. The system relies on isolated compression elements suspended in a tension system which together create a self-stabilising system where the compression elements put the cables in tension and vice-versa. As demonstrated in Figure 3.3 the opposite, an internal prestressing system, does not produce a stable system.

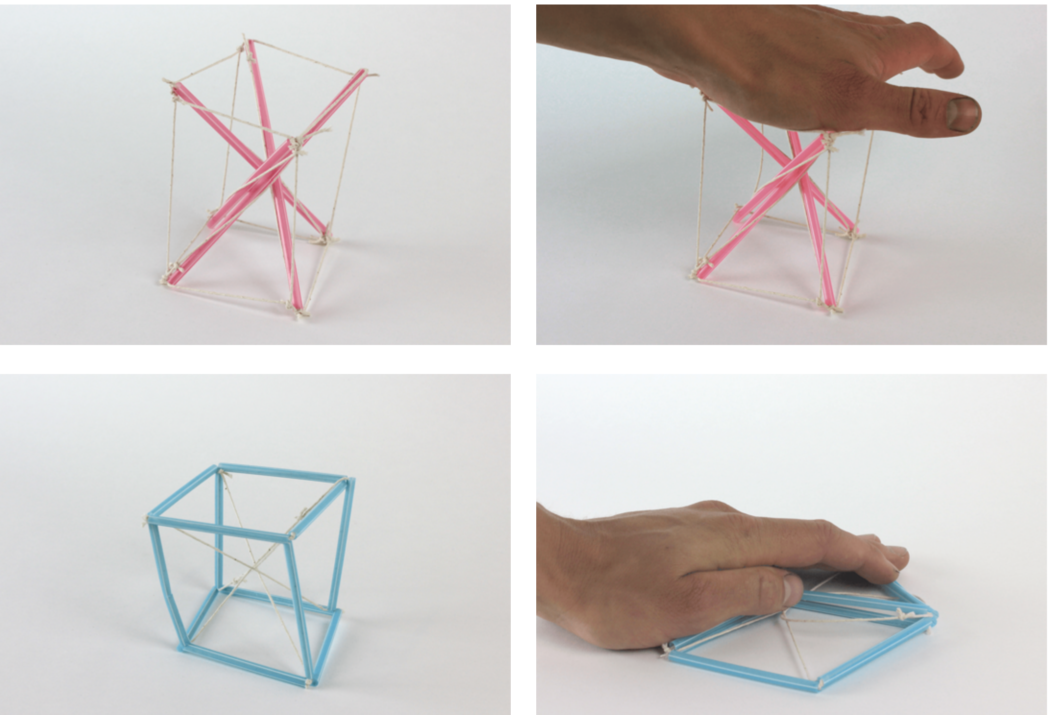


Figure 3.3: Stability with various prestressing systems

In a similar manner, a prestressing chord can create a self-correcting behaviour in a structure (Figure 3.4). In this model, the cable will always pull the structure into the upright position in the picture to the left, as any other position forces an extension in the cable.

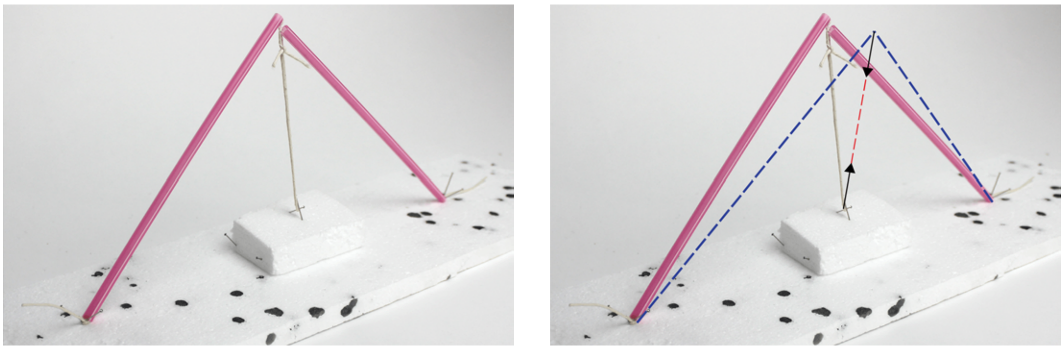
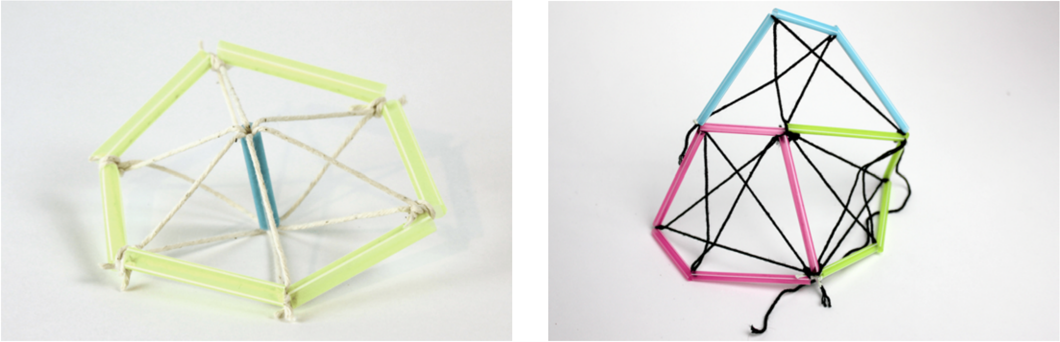


Figure 3.4: Self-correcting behaviour

Prestressing could also be used to create lightweight, self-sustaining modules, such as the bike wheel or web-like modules similar to a dragonfly wing where all compression and tension members are in one layer (Ander et al., 2017) (Figure 3.5).



(a) Bike wheel module **(b)** Dragonfly module

Figure 3.5: Lightweight modules for segmented shells

The idea of fairly flat, modular pieces and tensegrity can be combined by a system of panels and cables, similar to the 99 failures pavilion in Tokyo (2013) and Cecil Balmonds H_Edge structure (2006), where the panels in their simplest form have to be crosses that transfer compressive forces, and the cables serves the purpose of lifting the force from one panel to the next (Figure 3.6). The system could then be used to create vaulted shells or walls.

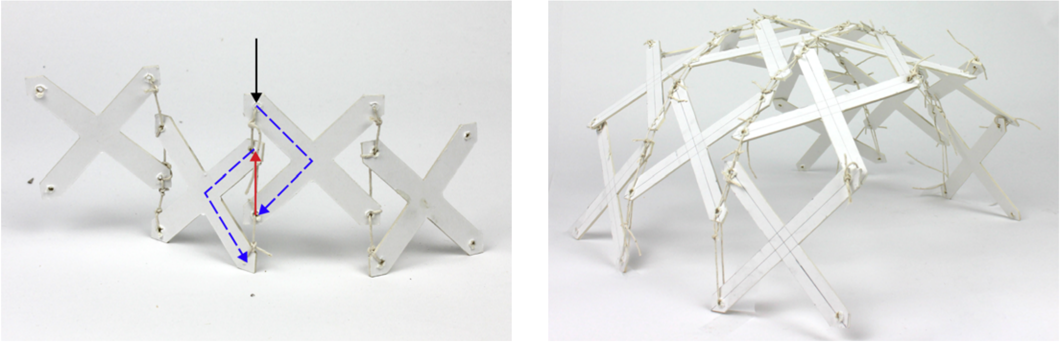


Figure 3.6: Tensegrity system using compression crosses and tension cables

External prestressing can also be used to create funicular shapes that defer from gravity-formed hanging chain and arch shapes, as demonstrated by Todisco et al. (2015). Examples of such structures are shown in Figure 3.7.

Figure 3.7: Funicular shapes altered with external prestressing

A different way of employing cables in the structure could be to balance opposing arches against each other (Figure 3.8).

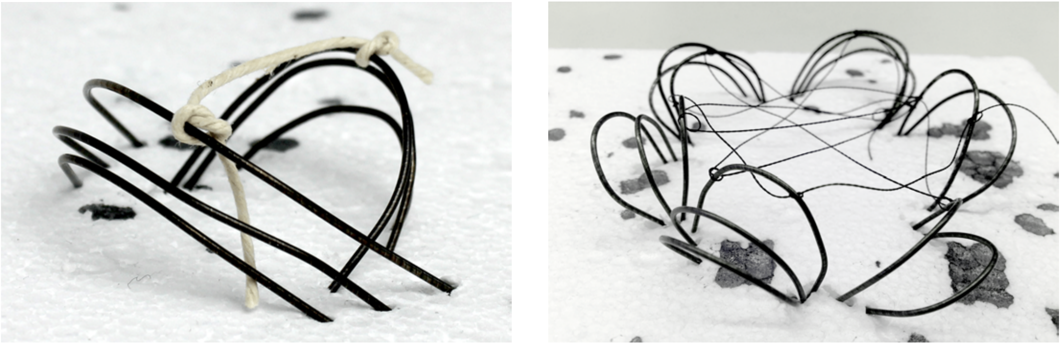


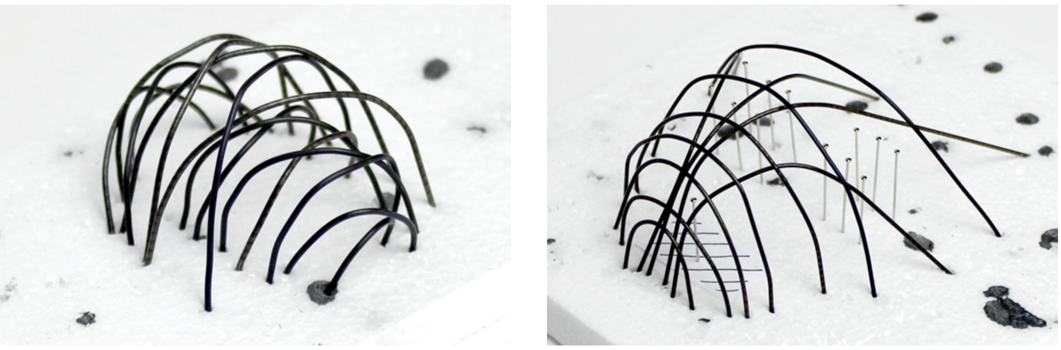
Figure 3.8: Opposing arches balanced with tension cables

3.1.2 Space

The spatial concepts were aimed at investigating the spatial experience created by parameters such as shape, level of openness, focus and number of supports. The concepts should therefore be viewed as representations of shapes, that could just as well be created by a gridshell, a modular structure or a continuous surface, rather than an indication of the type of structural system.

An important parameter to study for a lecture space in a busy environment like a fair is the level of openness, i.e. how much protection the pavilion offers. At the same time, the pavilion should also invite passing visitors to stop an listen to the ongoing presentations.

Looking at the two extremes, the pavilion could either be a fairly closed space where the visitors have to enter in order to see what is going on (Figure 3.9a), or a shell that opens up behind the audience to make it very easy to listen in to a presentation without entering or sitting down. With a gradually increasing density of the shell, protection of the lecture space could still be achieved (Figure 3.9b).

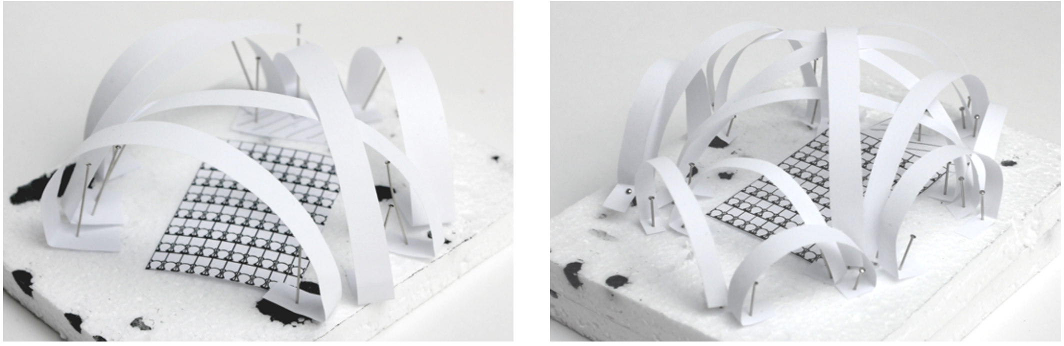


(a) Closed shell where the visitor must enter to see what is going on

(b) Open shell where the visitor can listen to a presentation without entering

Figure 3.9: Degrees of openness with different boundary conditions

Considering a shell that opens up in several directions, the level of protection would largely be governed by the number and placements of openings. The walls could also be continuous pieces of the shell (Figure 3.10a), or created by the assembly of several small supports, similar to a group of tree trunks (Figure 3.10b).

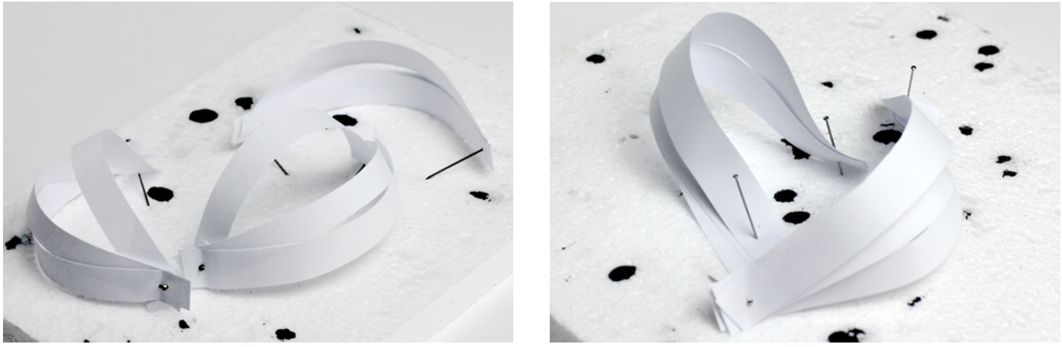


(a) Shell with few supports and large openings

(b) Shell with many supports and small openings

Figure 3.10: Degrees of protection with different boundary conditions

Another way of shielding lecture space from the fair could be by a collection of smaller shells that form screens. By varying the spacing and distribution of the shells, different levels of openness can be achieved (Figure 3.11).



(a) Three screens forming a semi-open space

(b) Two screens forming a fairly closed space

Figure 3.11: Degrees of openness with different boundary conditions

The shape of the pavilion could also be used to create more than a space for lecture, such as an exterior space for people to sit down (Figure 3.12a) or a walkable space surrounding the lecture space (Figure 3.12b).

(a) Sweeping shell forming a space for people on the outside

(b) Torus shell forming a walkable space arounf the lecture space

Figure 3.12: Shells forming extra spaces in addition to the lecture space

3.1.3 Seminar 1

At the end of the intuitive phase, a seminar was held to discuss the various concepts and the design process. A summary of important points that were discussed is presented in this section.

One of the topics that were covered was the materiality of wood. In the context of a wood and technology fair, it is desirable that the structure emphasises the unique properties of wood. One way to do this is to use different kind of wood in different parts of the structure depending on the properties required, another could be to create a structure that uses the high strength-to-weight ratio or the elastic bending capability in wooden laths.

General aims for the structural design were also discussed, with emphasis on simplicity and elegance. Since the pavilion aims to investigate the influence of using prestressing elements, the structural behaviour should be clearly readable in the structure. Furthermore, a certain degree of effortlessness in the structural design is to be aimed for. If the solution looks to complicated, the structural benefits becomes less clear.

On a more practical note, the size and arrangement of openings to the lecture space were discussed. It was concluded that for the purpose of the fair, a fairly open shell is desirable in order to attract audience for the lecture. Nevertheless, the lecture space should still direct the focus towards the stage by shielding the audience somewhat from the surroundings.

3.2 Intentional phase

In the intentional phase, the demands posed by the local context and by stakeholders were allowed to influence the design. Based on those, a series of evaluation criteria were developed to differentiate between the concepts developed in the intuitive phase. The most promising concepts were then developed further into *possible* concepts that could all be feasible pavilion designs.

3.2.1 Demands

In order to identify the various demands on the pavilion, both the local context and the interest of stakeholders in the project were studied, based on the method set out by Nilenius (2017). Firstly, a series of demand categories were established, such as accessibility, attraction and comfort. These are shown on the topmost row in Tables 3.1 and 3.2. Next, the context was broken down into five areas such as spatial context, social context, cultural context etc. These are listed in the left column in Table 3.1. Each demand category was then analysed based on the context areas to find the relevant demands. Finally, the three most important demands were chosen, as marked in bold text in the table.

Table 3.1: Contextual demands

	Accessibility	Attraction and event	Comfort for audience	Structural and material efficiency	Manufacture, assembly and recycling	Operation
Spatial	Easy entrance and exit for visitors	Interesting space	Good visibility		Limited area for assembly	Invite passing visitors to stop
Setting	Openings in line with people flow		Protection from busy fair environment	Minimise supports anchored in the floor	**Buildable in short time**	Not interfere with surrounding space
Social		Attraction point at the fair	Easy to stop and listen	Low material usage	Recyclable material	
Historic		Reference to traditional timber construction in Gothenburg		Reference to historic shell structures		
Cultural		**Innovative timber design**			**Reuse of pavilion after fair**	

A similar approach was used for the stakeholders' demands. Relevant stakeholders for the project were identified together with their possible demands based on the demand categories, as shown in Table 3.2. The three most important demands are again marked in bold.

Table 3.2: Stakeholders' demands

	Accessibility	Attraction and event	Comfort for audience	Structural and material efficiency	Manufacture, assembly and recycling	Operation
Svenska mässan	Easy entrance and exit for visitors	**Attract visitors - create a "landmark" for the fair**				Easy evacuation
Chalmers		Visible force pattern		**Investigate a new type of structure**	Reusable after fair	Structural safety
Visitors			**Comfortable, good acoustics and visibility**			Feel safe, limited deflections
Exhibitors		Attract visitors to the room			No interference with surrounding area during assembly	
Wood manufacturer		Nice detailing and finish		Modular, repetitive components or low-level processing of members		
Speaker						Good lecture space

3.2.2 General intention and evaluation criteria

Based on the analysis of contextual and stakeholder's demands, a general intention for the pavilion could be formulated as follows: *The pavilion should be a landmark structure that promotes new methods for using timber as a construction material.*

Based on the general intention and demands, a series of evaluation criteria were developed for evaluation of the concepts from the intuitive phase. The criteria should be such that the differentiate the concepts from each other, and thus not include criteria and demands that all concepts fulfil by default. The criteria were divided into spatial and structural criteria, so as to allow separate evaluation of the two concept categories. The criteria and an explanatory text are shown in Table 3.3.

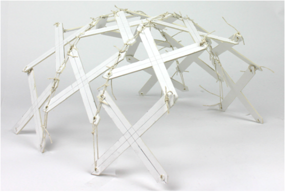
Table 3.3: Evaluation criteria

Spatial criteria	**Explanation**
Wow-factor	The pavilion should be a landmark for the fair
Easy access	It should be easy for passing visitors to see what is going on in the pavilion and to stop and listen
Protection	The pavilion should shield the lecture space from the busy fair and provide a focused lecture space
Buildability	The shape should promote easy assembly by for example simple shape, limited height and short member length

Structural criteria	**Explanation**
Innovative	The structural system should be innovative
Use of timber	The structural system should take advantage of the material properties of timber
Prefabrication	The more of the structure that can be prefabricated, the better
Buildability	The structural system should allow easy assembly by not requiring too complex connection details etc.

The structural and spatial concepts from the intuitive phase were then evaluated according to the evaluation criteria. They were given a score between zero and two depending on how well they were found to fulfil the criteria. The evaluation matrices are shown in Table 3.4 and 3.5. Important deciding factors between the structural concepts proved to be use of timber and buildability. The top-scoring structural concepts are the tensegrity concept (Number 1), the non-funicular arch (Number 2) and the opposing balancing arches (Number 6). For the spatial concepts, wow-factor and easy access were the most important factors, with the sweeping shell (Number 2), the forest-like shell (Number 4) and the long-span shell (Number 5) coming out on top.

Table 3.4: Evaluation matrix for structural concepts

			
Number	1	2	3
Innovative	+	++	++
Use of timber	+	+	
Prefabrication	++	+	
Buildability	+	+	
Sum	**5**	**7**	**2**
	Uses tensegrity in a more spatial way than many tensegrity sculptures today. Could be used to create various shapes like shells, vaults and screen walls. However a few similar structures exist. Modules can be prefabricated by cut-out timber panels or crossed timber laths. Assembly might be difficult with many different modules. Needs to be lifted into place after assembly.	Innovative way of creating new funicular shapes with a few historic examples. Does not use timber properties if the compression members are separate blocks but could potentially be created by active bending of timber laths. Arches could then be placed in a sequence or interlaced into a gridshell. Parts can be prefabricated, but long timber laths would have to be joined on site. Unclear assembly process.	Interesting new type of structure but little background research to build on. Not making particular use of timber properties and uncertain fabrication and assembly.

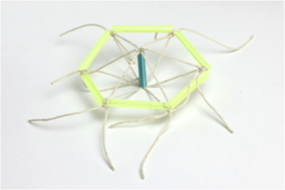
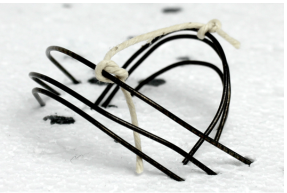
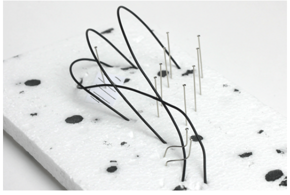
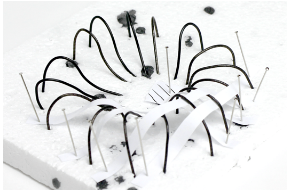
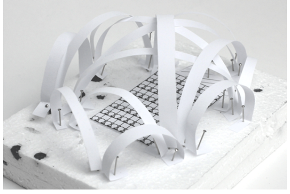
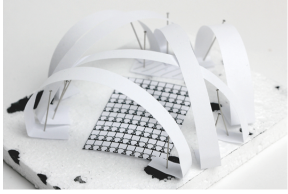
			
Number	4	5	6
Innovative		++	+
Use of timber			++
Prefabrication	++	+	
Buildability	++		++
Sum	**4**	**3**	**5**
	Not so innovative as a structure compared to others, but combining several bicycle modules to a shell could be interesting. Not making particular use of timber properties. Modules can be prefabricated and assembly should be straightforward.	Could create an innovative and interesting structure if expanding the self-correcting concept to a larger system. Not making particular use of timber properties. Elements could be prefabricated depending on length, and possibly all identical to facilitate sorting on site. Assembly unclear.	Not really an innovative structural concept, but could create a fascinating balance. Uses the bending capacity of timber in an interesting way. Timber laths would have to be joined together on site to achieve the necessary lengths. Should be quite easy to build on site by raising the opposing arches together.

Table 3.5: Evaluation matrix for spatial concepts

			
Number	1	2	3
Wow-factor		++	
Easy access	+	++	
Protection	+	+	++
Buildability	++	+	+
Sum	**4**	**6**	**4**
	Not so fascinating shell shape, but creates a nice exchange between openness and protection. Should be comparably easy to build since it does not span over the lecture space.	Nice sweeping shape that could be extended with other smaller pieces. Creates additional spaces on the outside that could be used for exhibition. Offers some protection for the stage while still easily accessible. Could be more difficult to build because of longer spans.	Offers both a circular space to experience the pavilion and an inner, focused lecture space. Could be more difficult to attract passing visitors. Shorter spans should make it easy to build but needs to be quite big to allow sufficient central space.

			
Number	4	5	6
Wow-factor	++	++	+
Easy access	++	++	
Protection	+		++
Buildability	+	+	
Sum	**6**	**5**	**4**
	Creates a nice forest-like room with the many supports and a ceiling that could filter light similar to interwoven tree branches. Allows visitors to see in and still protects the space. Could be difficult to build with long spans.	A more open space with long impressive spans. Makes it easy for a lot of people to stop and listen in the openings but does not offer a lot of protection. Could be difficult to build with long spans.	Intriguing space where the visitor has to enter to find out what is inside. Offers a lot of protection but might have a difficult time attracting visitors to the lectures. Needs to be quite big and have long spans which could be difficult to build.

3.2.3 Possible concepts

After the evaluation, the most promising concepts were further developed in order to achieve a set of *possible* concepts. These concepts should have a clearer answer of how structure, space and material are related and how they can be constructed. The possible concepts do not need to build directly on the concepts from the intuitive phase, they can just as well be new concepts inspired by the findings in the intuitive phase and the evaluation.

For the first possible concept, the tensegrity structure (Table 3.4, Number 1) was combined with the sweeping shape (Table 3.5, Number 2). The large sweeping shell shields the lecture space on one side but also opens up and allows people to stop by and listen from the other side. Smaller screens with the same structure can be used to define additional spaces for conversation or exhibitions related to the pavilion (Figure 3.13). The degree of porosity in the structure could be varied by changing the size and shape of the panels and openings, for example making it more closed behind the stage and more open in other places.

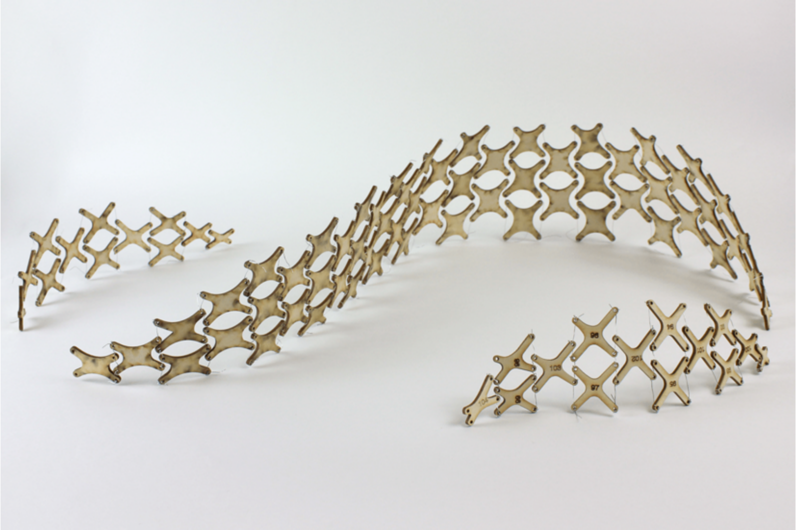


Figure 3.13: Developed tensegrity concept

The type of panels to use for the compression elements were a topic for discussion. Flat, solid panels as indicated in Figure 3.13 could be easily pre-fabricated by cutting out plywood sheets. The panels could then be stacked on top of each other and transported onto site. However, such a panel does not really demonstrate the material properties of timber and could just as easily be constructed in steel or plastic. It would also create excessive material waste from the cutting out of the panels. For the purpose of the timber fair, interesting use of timber was been an important design criteria from the start and therefore other possible panel types were investigated. Two such elements are shown in Figure 3.14. However, the panel in Figure 3.14a deforms extensively under in-plane compression which is not suitable for the tensegrity structure. With less elastic timber laths it might work. Another alternative element could be simply connecting two straight timber laths into a cross as in Figure 3.14b, which would result in minimal material waste and very low cost. However, a rigid nodal connection in the middle would then be needed, which could be difficult to achieve for timber laths.

Construction-wise, this concept would allow pre-fabrication of all elements. On site, the panels would then need to be connected with prestressing cables. Most likely, the structure would then need to be lifted in place by a crane or similar, which could prove difficult in the fair hall.

(a) Panel alternative 1 **(b)** Panel alternative 2

Figure 3.14: Panel alternatives

The second concept combined the the idea of long open spans (Table 3.5, Number 5) and non-funicular arch shapes (Table 3.4, Number 2). An interlaced grid of actively bent timber laths stretches over the entire lecture space, with an internal prestressing system that modifies the shape compared to a funicular shell structure in order to achieve a more vertical meeting with the ground (Figure 3.15). In that way, less space is lost at the perimeters of the shell as it gains height quickly. The prestressing system could either be timber or cables (Figure 3.16). Apart form changing the shape of the structure, the prestressing system also takes up horizontal forces, creating a self-sustaining shell without large horizontal reactions. Lateral stability is achieved through the interconnecting timber laths.

Figure 3.15: Developed actively bent lath concept

The construction could be quite troublesome due to the long span of each lath, especially interconnecting several overlapping laths and their respective prestressing systems. Depending on the bending stiffness of the laths, small or high forces would be introduced in the system. With stiff laths, similar to a bow and arrow, large forces would be released if a lath breaks which could have grave consequences. With a less stiff lath, sufficient stability might not be achieved in the system.

Figure 3.16: Prestressing systems

The last concept combines the idea of using screens to shield off the area (Table 3.5, Number 1) with arches balancing against each other (Table 3.4, Number 6). This concept allows a great variety of how the room can be composed, by varying the placement and angles between the screens. One configuration is two shells with low porosity placed close to each other with entrances like the Figure 3.17. One has to walk in through the shielded entrance to explore the room and the lecture inside.

The structure is composed by continuous plywood laths that are actively bent around the shell. The vertical forces will be taken up by a number of tension elements that are holding the arches in balance. The laths in one arch will connect to two supports which will be subjected to high lateral forces due to the spring back force in the bent laths.

As for the production, this will require a substantial amount of on site construction since the wood elements need to joined together to create the continuous laths. The cables have to be fixed to laths in their upright position which will require work at high heights.

In light of the large horizontal support forces and potential risks during construction and consequences of potential member failure, this concept was ruled out in favour of further developing the other concepts before the evaluation phase. Nevertheless, none of these issues would be unsolvable.

Figure 3.17: Counterweighted shells

3.2.4 Seminar 2

At the end of the intentional phase, another seminar was held to discuss the various concepts and the design process. A summary of important points that were discussed is presented in this section.

The main topic on the seminar was structural stability. The models were discussed and physically tested to understand possible instability problems and how prestressing could prevent these.

Model building as a means of exploring structures was also discussed. Complex shell structures are difficult to predict numerically and analytically and therefore the model building can be very informative. When building structural models, there is a distinction between scale independent and scale dependent models. To the first counts compression structures such as domes and vault, which rely on the fact the compressing forces are kept within the structure. These can be represented by models in various scales with high accuracy. As for scale dependent models, for example models that rely on the stiffness of a beam, the rules are different. Because the weight of the element depends linearly on thickness while stiffness depends on thickness raised to the power of three, these two need to be scaled separately (Adriaenssens et al., 2014).

One way to further develop the spatial appreciation of a model is to place scale figures in the model and take pictures inside. When looking at the pictures of the models, the perspective is changed to the appropriate scale and is therefore very informative.

3.3 Evaluation phase

In the evaluation phase, the concepts from the intentional phase were critically reviewed and developed. The design intention was developed to a design goal and possible risks were identified and assessed. The purpose was to form the basis for an informed choice of final concept and lay the foundation for further development.

3.3.1 Design goal

The pavilion should be a landmark structure for the timber fair, emphasising new ways of using timber in structures. It should also create a semi-focused lecture space, framing the stage but still allow passing visitors to stop by and listen.

3.3.2 Prioritised context and demands

In Table 3.6 the two final concepts are evaluated. In this evaluation, the concepts were given zero, one or two plus signs depending on how well they were judged to fulfil the various criteria. The result is evaluated in subsection 3.3.4.

Table 3.6: Evaluation matrix

				
	Points	Comments	Points	Comments
Innovative structure		Fascinating structure but similar examples exist. Potential to develop into more innovative panels.	++	Long span and use of prestressing, potential use of timber for the prestressing element. Allows more direct evaluation of influence of prestress.
Production of elements		Works well for prefabrication. Time consuming cutting of panels with much material waste. The cutting of the plywood boards process will be time consuming. Difficult to create spare pieces if all panels are unique.	+	Easy cutting of laths with minimal material waste. Each lath needs to be created by joining several shorter pieces because of limited plywood board length. Repetitiveness can be achieved by only varying the length of the end pieces. Surplus elements can easily be produced in advance to replace broken elements.
Prefabrication	+	All elements can be prefabricated and mounted on site.		Laths can be pre-cut but need to be joined to their full length on site.
Interesting use of timber		Not making use of properties specific to timber	++	Making use of the elasticity and light weight of timber to span long distance with minimum material.
Construction	+	Easy assembly of panels by laying them out flat and connecting them with cables of predefined length. Potentially difficult to lift with crane or winch in the roof girders.		Complicated building process with interwoven laths and prestressing. Could potentially be performed by weaving the pattern flat on the ground and then lifted up incrementally and connecting the tension elements. Another alternative is mounting a complete lath arch on the ground and then turning it up in to its final position. This will however create problems with weaving the laths together.
Material efficiency		Material waste in cutting process. This could be minimised by optimising the sawing pattern.	++	High material efficiency due to minimised cross sections and separation of compression and tension elements.
Possibility for reuse	+	Easy dismantling by flattening to ground and disconnecting the tension cable from the panels.		Complicated to dismantle because of interconnectivity and interdependancy between laths and prestressing. Potentially high forces in elements. Laths will need to be disassembled into smaller pieces for transport.
Lecture space	++	Focused lecture space which still allows passing visitors to stop by and listen		Nice pattern from the crossing laths but less focused lecture space with the open sides
Sum	**5**		**7**	

3.3.3 Risk assessment

The pavilion will be subjected to loads such as people leaning against it or pushing it to test its stability. This will have to be taken into account in further analysis for any of the concepts. There could also be a risk, even if it is rather unlikely, that a person attempts to climb in the structure. This would be dangerous and possibly lead to collapse. For the bending active structure, it would be quite difficult to climb but for the tensegrity perhaps rather tempting. Other severe accidental loads, such as a fork lift crashing in the pavilion, is difficult to design the structure for but the risk is also assumed to be low.

In terms of structural redundancy, both concepts allow alternative force paths if an element breaks. In the case of the tensegrity concept, breakage will most likely lead to part of the structure sinking slightly. The actively bent structure might get more severe consequences in case of a lath breaking. Prestressing long timber laths could be hazardous if high stresses are induced in the elements. If an element breaks, the failure is brittle and a high amount of energy will immediately be released, like an arrow is released from a bow. However, if the induced stresses in the system are in fact not so high, the forces released will be low and the structure will probably not be very affected by a lath breaking.

During construction, pieces might break and need replacing. For the bending active structure, it will be easy to produce extra pieces in advance since most of the pieces are identical for all the laths. On the other hand could the construction phase be complicated since there are numerous of laths to be erected in a complex pattern, especially if the pavilion spans over the entire lecture space. The concept will require well planned and performed construction at site, whereas the construction for the tensegrity concept would most likely be easier as lined out in Table 3.6.

3.3.4 Final concept

The bending active concept got the highest overall score in the evaluation in Table 3.6, scoring high on innovativeness, use of timber and material efficiency. It is also the concept that is most suited to evaluate the structural benefits of prestressing. The tensegrity concept however got a much better score on lecture space. Based on this and the potential risks of constructing such a long span, it is decided to go forward with a combination of the two: an actively bent geodesic gridshell with internal prestressing cables with the sweeping shape from the tensegrity concept.

In terms of material, Finnish birch plywood is chosen for both structural and aesthetic reasons. Plywood is an engineered product with little natural variation such as knots and varying grain direction, which both gives it a very nice appearance and makes it ideal for bending-active structures. The small amount of defects are reinforced by adjacent veneers (Bass et al., 1995), compared to other timber products where knots could easily cause unexpected failure under bending.

4

Preliminary design phase

The preliminary design phase consists of the structural analysis and detail design of the final concept. In this chapter, suitable modelling and analysis techniques are first discussed and chosen. Then, the design is developed and analysed. Finally, possible connection details are identified, tested and evaluated.

4.1 Modelling and analysis methods

This section describes the choice of suitable modelling and analysis methods for the pavilion. A method for finding curves on a surface that can be clad by timber laths is presented, followed by an evaluation of various methods for applying the stresses induced by active bending in an analysis model.

4.1.1 Geodesic splines

When modelling a gridshell with timber laths, it is important to find curves for the timber laths that are achievable in reality. With thin, wide laths for example, a curve needs to be found that only has curvature about one axis. Orienting timber laths along geodesic lines on a surface is a good way of avoiding curvature about two axes, used by for example Julius Natterer in his ribbed timber shells (Herzog, 2004). Struik (1950) defines geodesic lines as "curves of zero geodesic curvature", meaning that at each point along the curve the curvature vector coincides with the normal curvature vector of the surface. This can be visualised by wrapping a strip of paper over a smooth surface - a geodesic line is a line along which the strip can run without wrinkling (Figure 4.1).

Geodesics can be defined in several ways. Most common perhaps is the line of shortest distance between two points of a surface. Struik (1950) however provides the alternative definition that a geodesic is uniquely determined by a starting point and a tangent at that point, and that through every point of the surface there is a geodesic in every direction. The definitions and underlying theory are thorougly described by Adiels (2017). The two definitions together provide a large degree of freedom in the design of a geodesic gridshell, giving control either over the endpoints

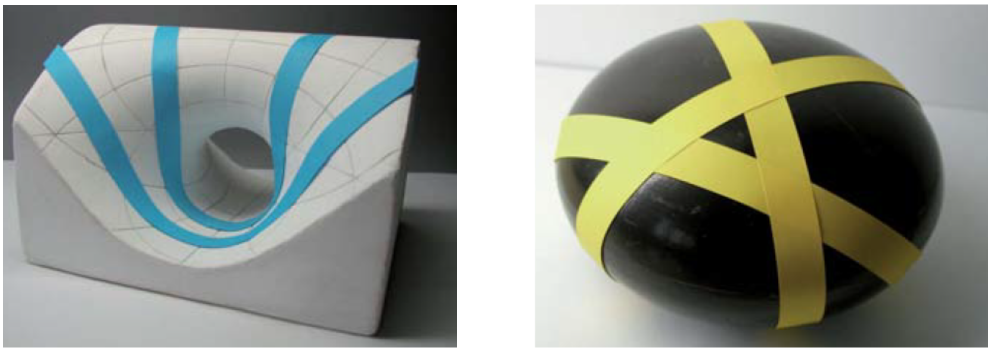


Figure 4.1: Strips of paper wrapped over surfaces illustrating geodesic lines (Herzog, 2004)

or the direction of the laths. However, this also means that each geodesic will need its individual controls.

For this thesis, both methods described above were implemented in the 3D software Rhinoceros using the parametric modelling plugin Grasshopper. The shortest distance method already exists as a Grasshopper component, using the `Surface.ShortPath()` method to find the shortest path on the surface between two input points. The second method based on a start point and tangent vector was implemented in an approximate manner with a custom `C#` script, iteratively taking steps on the surface based on the tangent vector and the surface normal. The script can be found in Appendix 1.

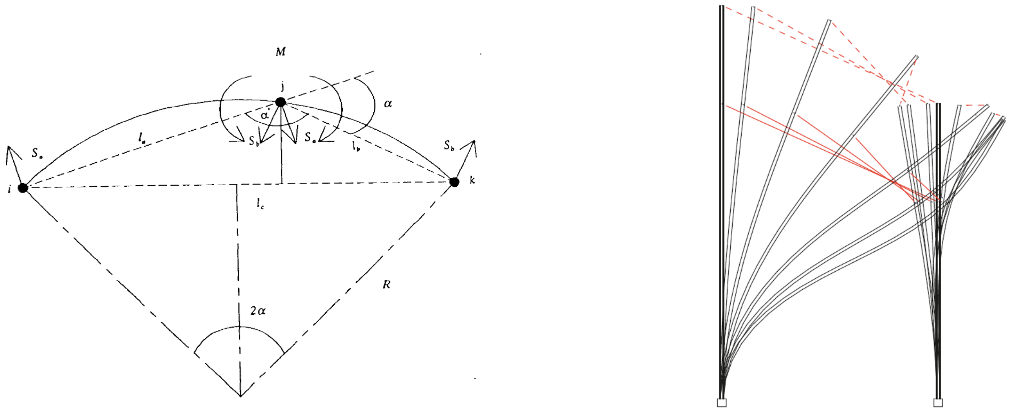
4.1.2 Active bending

Constructed from initially straight laths, actively bent gridshells have a built-in stress state where the elements seeks to spring back to their initial state. Various methods exists for modelling this in a structural model. Adriaenssens (2000) describes a three degree of freedom (3DOF) dynamic relaxation approach in which three consecutive nodes in a spline are analysed together to find the bending moment acting on the middle node (Figure 4.2a). The moment can then be translated into shear forces acting on the three nodes, which are added to the nodal forces in the analysis.

However, the 3DOF approach for a single spline does not take the cross-sectional orientation of the element into account, and thus can only accurately model rods with circular cross sections. For the UWE Research Pavilion (Harding et al., 2017), both a 3DOF spline model and a finite element model were used. The 3DOF model was implemented in the Grasshopper plugins K2Engineering and Kangaroo2, using particle-based physics simulations for formfinding. The finite element model was created in the finite elements solver Karamba, another Grasshopper plugin. The purpose of this was to capture the active bending stresses with the 3DOF model and the biaxial bending stiffness with the finite elements model. The cross section of the 3DOF model and corresponding behaviour was then calibrated against the Karamba model until a fairly matching behaviour was achieved (C. Brandt-Olsen, personal communication, March 23, 2018).

A way of extending the 3DOF method to considering non-circular cross sections could possibly be to use an orientation input for each arc segment or considering two crossing splines simultaneously (i. e. a five node cross element rather than a three node arc) (C. Williams, personal communication, March 20, 2018).

Another method developed by Lienhard (2014) is the elastic cable approach (Figure 4.2b) in which an iterative FE analysis is used. A fictional elastic cable pulls the end of an initially straight beam into a curved shape, thus explicitly introducing the bending stresses and geometric stiffening in the element.



(a) 3DOF approach (Adriaenssens, 2000)

(b) Elastic cable approach (Lienhard, 2014)

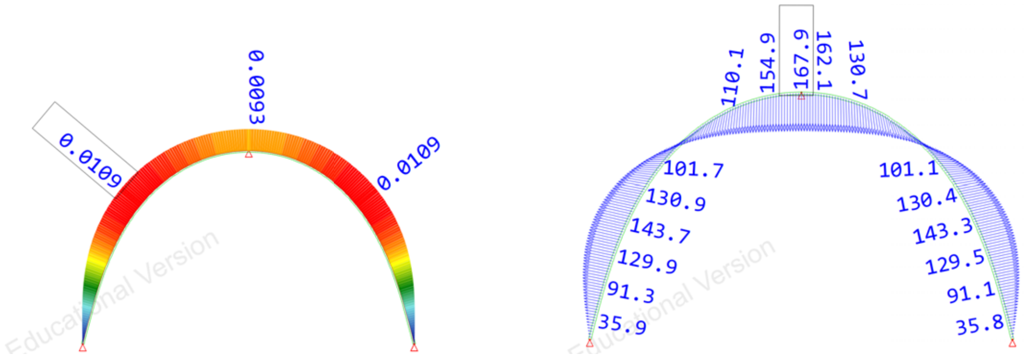
Figure 4.2: Methods for modelling of actively bent splines

Yet another method could be to derive the internal moments in the structure from the curvature of the splines. This is implemented in a new function called ACTB in the FE analysis program SOFiSTiK (Bellmann, 2017) which calculates the internal bending prestress of a curved beam that corresponds to it initially being straight and stress free. The program computes the curvature of the beam and derives the corresponding internal bending stresses.

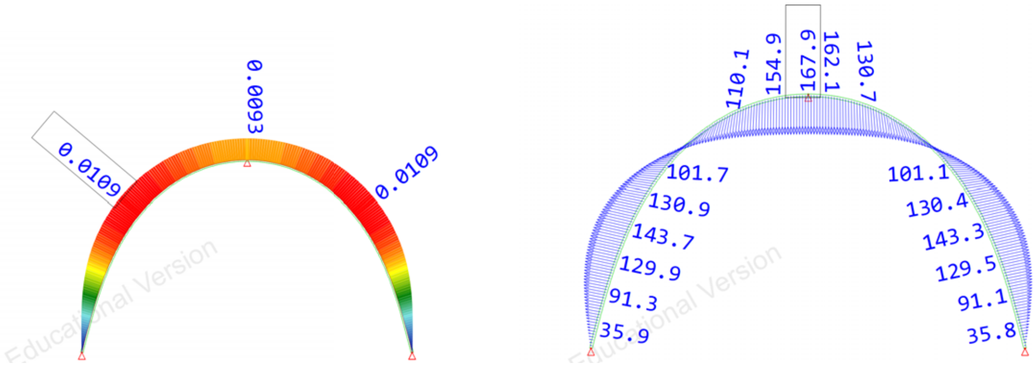
Figure 4.3 presents a comparison between the different modelling approaches; an initially straight lath bent with the elastic cable approach, an initially curved lath without induced stresses and an initially curved lath with the ACTB input. Each model is also subjected to self-weight. The geometry studied is a 10 m long and 6.5 mm thick birch plywood lath with 5 plies that is bent to a support distance of 6 m.

The comparison shows that the elastic cable approach and the ACTB function produces identical results. The benefit in the ACTB approach is the possibility to start with an already curved shape. Even if the initial geometry is not an elastica shape (i.e. a shape obtained by bending a straight element), the ACTB input will push it into one (Bellman, 2017).

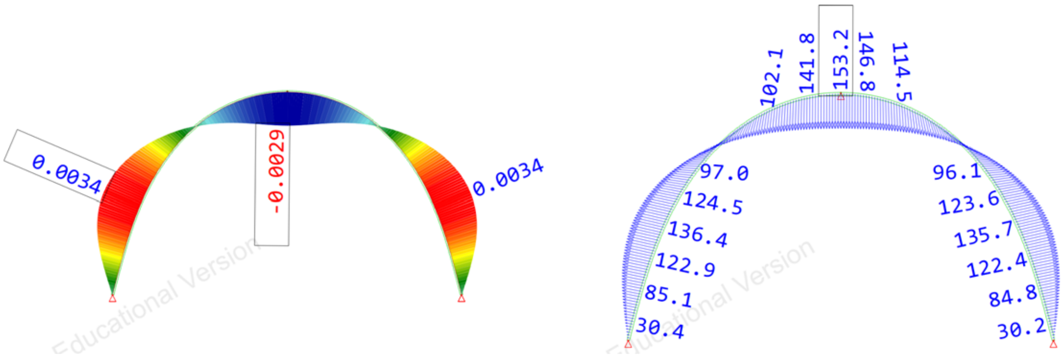
Finally it can be seen that without initial bending stresses the shape of the resulting moment diagram is significantly different. The displacements, however, are quite close to the displacements with initial bending stress, and it is also important to note that the bending stresses induced by the bending are not very large in this model. Thanks to the simplicity of using the ACTB method, starting from the already-curved shape and back-tracing the bending stresses, this method is chosen for the further analyses.



(a) Active bending prestress from elastic cable approach



(b) Active bending prestress from ACTB feature in Sofistik



(c) No active bending prestress

Figure 4.3: Resulting bending moments (kNm) and displacements (mm) for various modelling methods under self-weight

4.2 Stability and prestressing

This section describes methods for evaluating the stability of a structure and prestents a two-dimensional study of the stabilising effects of an external prestressing system.

4.2.1 Stability

Many of the earlier gridshells were two-way rectangular grids, which by nature are foldable (Chilton & Tang, 2017). In Mannheim Multihalle, diagonal bracing cables were used to achieve in-plane stiffness, and in the Weald and Downland gridshell external diagonal cladding rails performed the same task. In the Savill Garden gridshell, it was plywood panels. In recent years, stiffness has instead been achieved through other geometrical configurations, where the laths form a triangulated, self-stabilising pattern. This method will be used for the pavilion in this thesis, creating a lath pattern with sufficient amount of triangles to achieve stability.

In actively bent gridshells, the need for elastic bending creates an additional conflict between stiffness and stability. While a low stiffness is needed for the elastic bending, this also makes the structure sensitive to deformation. Lienhard (2014) describes two methods for analysing the stability of bending active structures; analysis of the general behaviour using eigenfrequency analysis, and analysis of a particular load bearing mechanism by comparing deflections. The two methods are used to investigate the difference in behaviour between the so called "geometric nonlinear case" including the bending stresses from elastic bending and the "reference geometry case" without the bending stresses. In the eigenfrequency analysis the two cases are introduced by the means of a primary load case, which includes dead load and the bending stresses.

In Sofistik, eigenfrequency analysis can be implemented with such a primary load case, which gives the eigenfrequencies of the system under the stresses of the primary load case (SOFiSTiK, 2018). An eigenfrequency analysis on the resulting structure from the different methods in Figure 4.2 show that including the bending prestress gives somewhat higher eigenvalues (Table 4.1).

Table 4.1: Eigenvalues for various modelling methods

Modelling method	Mode 1	Mode 2	Mode 3
Elastic cable approach	0.33 Hz	0.62 Hz	1.18 Hz
No bending prestress	0.25 Hz	0.54 Hz	1.03 Hz
ACTB	0.33 Hz	0.62 Hz	1.18 Hz

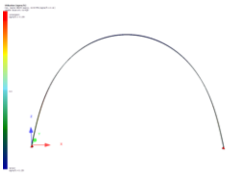
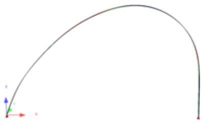
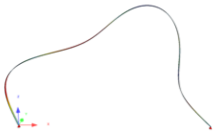
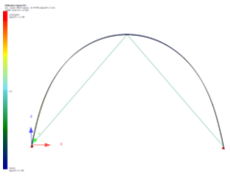
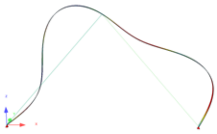
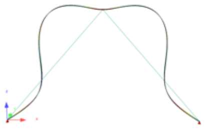
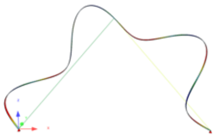
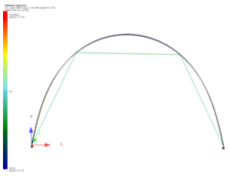
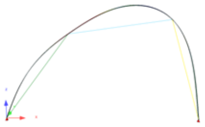
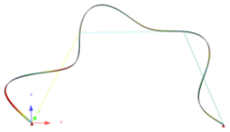
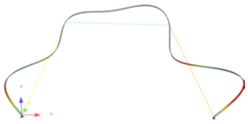
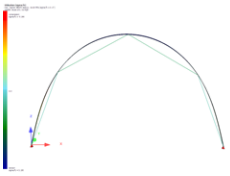
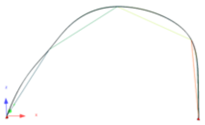
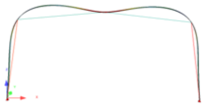
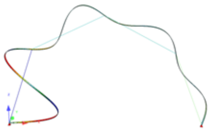
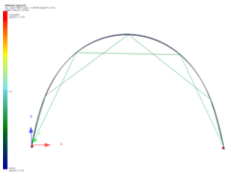
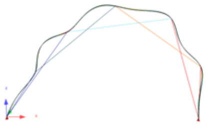
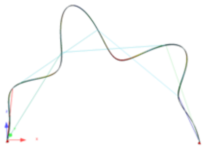
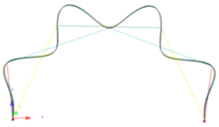
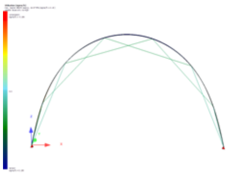
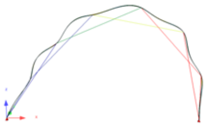
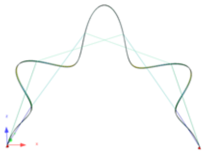
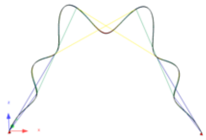
4.2.2 Prestressing

The combination of bending active structures and tensile elements are often referred to as "Hybrid bending active structures". These structures obtain an increased level of efficiency which are described by Aitoh and Okada (1999) by "passive and active effects". The passive effects are the creation of a balanced system and bracing effects, while the active are stress control of the system, control of displacements and increased geometrical stiffness. The active effects are dependent on the level of prestress applied to the tension members.

A tensile system such as a membrane can also be used to modify the curvature of the bending active elements, either for architectural reasons or to achieve a more uniform stress-distribution, as described by Alpermann and Gengnagel (2013). Tensile elements can also be used to restrain actively bent elements to each other in for example columns or beams. Converesely, bending active elements can also be used to shape membrane structures (Mele et al., 2013). Alexandrou and Phocas (2017) suggest using a system of cables that can be used both for the erection of the actively bent structure and for stabilising it once erected. By shortening of the cables and subsequent deformation of the bending active members, prestress is introduced simultaneously in the whole system.

The geometrical stiffening caused by a system of cables can be studied through eigenvalue analysis, as described in Section 4.2.1. Table 4.2 shows the eigenfrequencies of a bending active arc for an increasing number of equal length cable segments. It can be seen that the cable system increases the stiffness in the system and that the eigenfrequencies rise with increasing number of cable segments.

Table 4.2: Eigenfrequencies for different cable configurations

System	Eigenmode 1	Eigenmode 2	Eigenmode 3
 **0 cable segments**	 0.54 Hz	 1.65 Hz	 2.43 Hz
 **2 cable segments**	 1.43 Hz	 1.88 Hz	 3.91 Hz
 **3 cable segments**	 0.56 Hz	 3.83 Hz	 4.21 Hz
 **4 cable segments**	 0.67 Hz	 1.76 Hz	 7.24 Hz
 **6 cable segments**	 2.41 Hz	 5.09 Hz	 6.17 Hz
 **7 cable segments**	 2.32 Hz	 6.52 Hz	 7.14 Hz

4.3 Structural analysis

As outlined above, the geometry for the structural model was defined parametrically in Grasshopper. The text input required for creating the same geometry with the Sofistik text editor Teddy could then easily be generated within Grasshopper, allowing quick feedback between analysis and modelling. In Sofisik, buckling safety, deformations, eigenfrequencies and load carrying capacity during prestressing, in ultimate limit state and under accidental load were analysed. Utilisation levels were verified separately in Mathcad. The workflow is described in Figure 4.4.

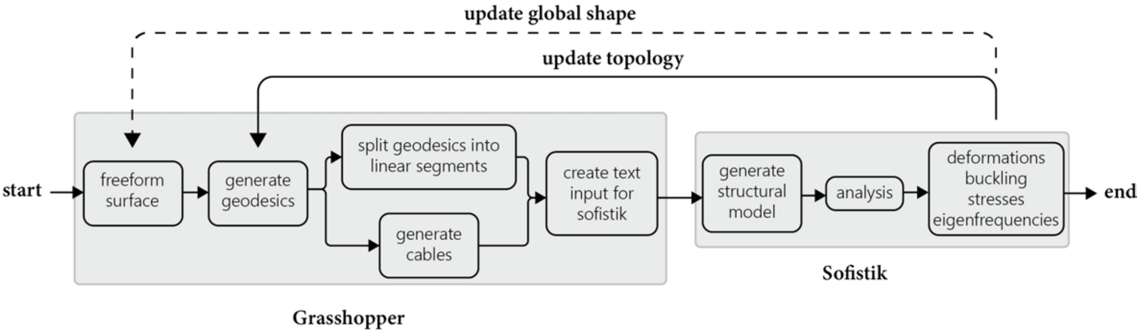
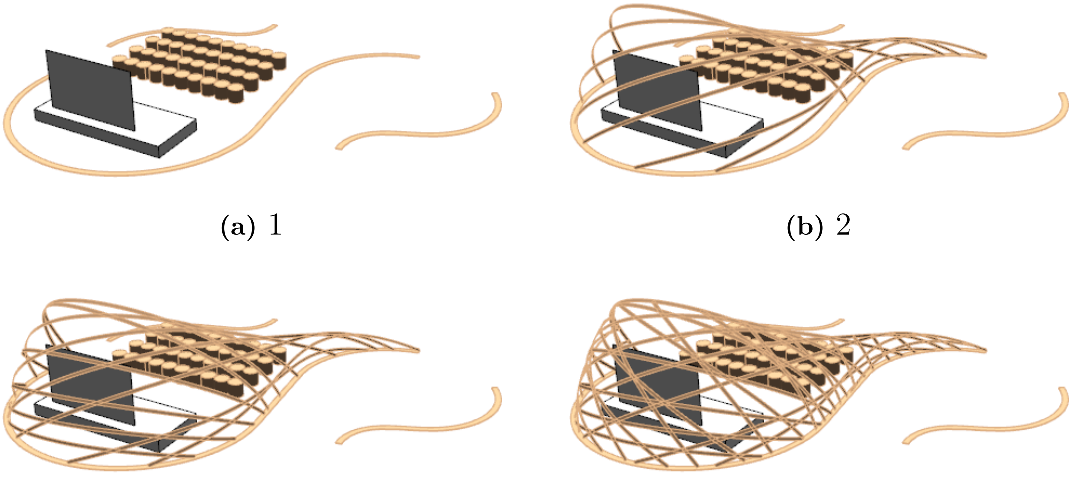


Figure 4.4: Computational workflow

4.3.1 Topology and stability

The final topology of the structure was found iteratively, starting out from shape defining floor-to-floor laths and then successively adding additional laths to prevent movement were deformations were large as shown in Figure 4.5.



(a) 1

(b) 2

(c) 3

(d) 4

Figure 4.5: Successive creation of laths

Prestressing cables were then added to increase the stability of the structure, as monitored by increase in eigenfrequency. A cable pattern similar to the most successful one in the cable study was adopted with a spacing chosen so as to not intrude too much on the space inside the pavilion but still allow sufficient increase in geometrical stiffness. The cables were only placed along the floor-to-floor laths, as prestressing along the interrupted laths might introduce unwanted stresses along the free edge of the structure. The final structural system is shown in Figure 4.6.

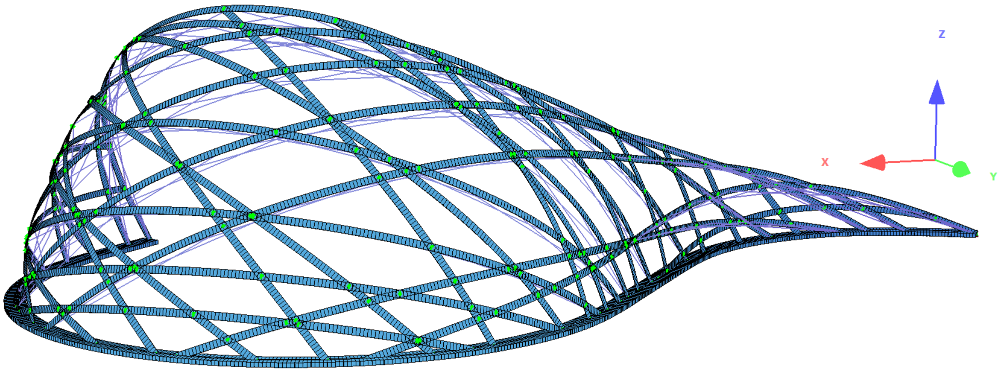


Figure 4.6: Structural system

4.3.2 Joints and support conditions

The laths are connected to the floor plate with a spring that is super-stiff axially and laterally, imitating a pinned connection. The floor plate is supported vertically all around and pinned in three locations; both ends and once in the middle.

To accurately model a single-bolt connection the joints between the laths needed to restrain vertical and lateral movement but allow in-plane rotation. Furthermore, thanks to the width of the lath's cross section, some rotational restraint around the local y-axis of each lath could also be imagined, forcing the two laths to rotate together. To achieve such a connection, spring elements were used that can be given axial, lateral and rotational stiffness. Three springs were placed in each joint (Figure 4.7): one along the normal of the plane of the joint, super-stiff axially and laterally but free to rotate, and two along the local y-axes of each lath with some rotational stiffness to prevent individual rotation of the laths.

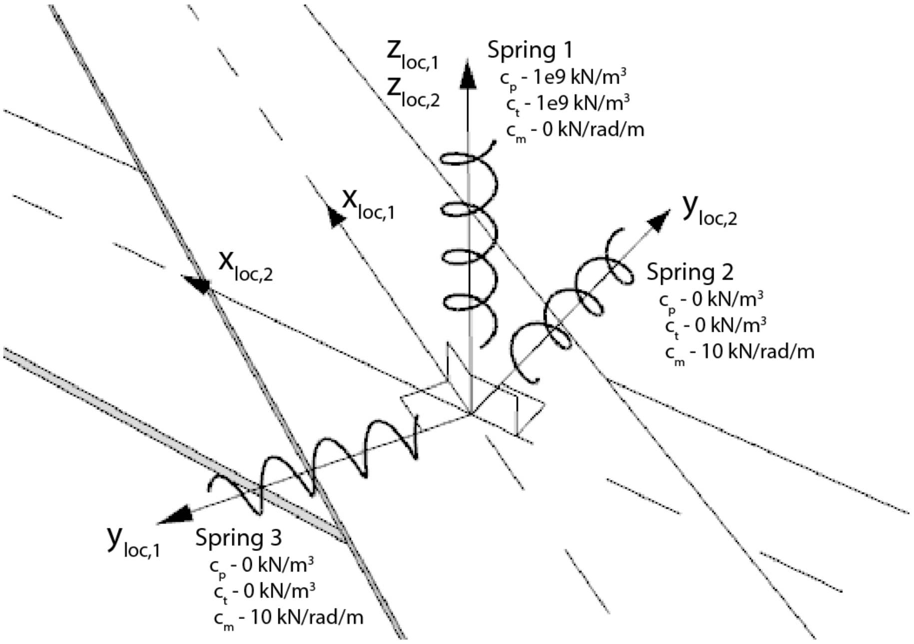


Figure 4.7: Direction and stiffness of springs in coupling joint between laths

4.3.3 Material

A 6.5 mm Finnish birch plywood with 5 plies was used for the laths. Its strength and stiffness properties are listed in Table 4.3.

Table 4.3: Material properties for 6.5 mm Finnish birch plywood

Bending parallel to grain	$f_{m,0,k}$	50.9	N/mm^2
Bending perpendicular to grain	$f_{m,90,k}$	29.0	N/mm^2
Compression parallel to grain	$f_{c,0,k}$	29.3	N/mm^2
Compression perpendicular to grain	$f_{c,90,k}$	22.8	N/mm^2
Tension parallel to grain	$f_{t,0,k}$	42.2	N/mm^2
Tension perpendicular to grain	$f_{t,90,k}$	32.8	N/mm^2
Panel shear	$f_{v,k}$	9.5	N/mm^2
Mean modulus of elasticity parallel to grain	$E_{m,0,mean}$	12737	N/mm^2
Mean modulus of elasticity perpendicular to grain	$E_{m,90,mean}$	1029	N/mm^2

For the floor plate, the material properties for three 21 mm Finnish birch plywood sheets stacked on top of each other was used. For the prestressing cables, the exact material to be used was unknown at this point. Therefore, S235 steel was conservatively used.

4.3.4 Cross sections

The timber laths were modelled with solid rectangular cross sections of 6.5x100 mm. The cables were modelled as 4 mm diameter VVS-2 locked coil cables. The floor plate was modelled as a solid, U-shaped cross section 300 mm wide and 63 mm high width 130 mm flanges.

4.3.5 Loads

The main loads acting on the structure will be the self-weight of the laths, the stresses introduced by the active bending and the prestress in the cables. Since the pavilion will be placed indoors, no wind or or snow need to be considered. However, the effects of accidental loads similar to someone pushing on it by hand are studied by the means of point loads at a height of about 1.5 meters. Four different placements of accidental load were tested in separate load cases (Figure 4.8. The locations were chosen so as to test the structure from different directions, and where it seemed most sensitive in the eigenvalue analysis.

The accidental loads were taken as 0.25 kN, based on manual tests of the magnitudes of load arising when a full-grown person leans against a wall. The cable prestress was set to 0.1 kN based on what seems a reasonable load to manually prestress the cables to.

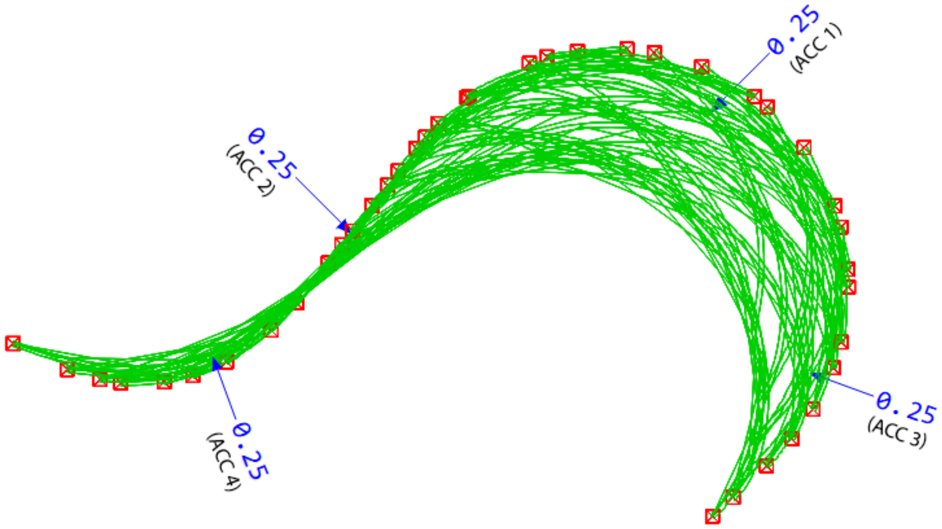


Figure 4.8: Placements of accidental loads and the name of their load cases

4.3.6 Load cases

When the pavilion is built, its shape will deform somewhat compared to the geometrical model. Firstly, some relaxation will occur under self-weight to an equilibrium shape and secondly, additional deformation will happen as the cables are prestressed. This is portrayed in the loadcases as two serviceability limit state (SLS) analyses; one with dead load (DL) and one with dead load and prestress (PS). On this deformed and stressed geometry, ultimate limit state (ULS) and accidental load (ACC) analyses cases are then based. The relationship between the analyses is shown in Figure 4.9 and Table 4.4.

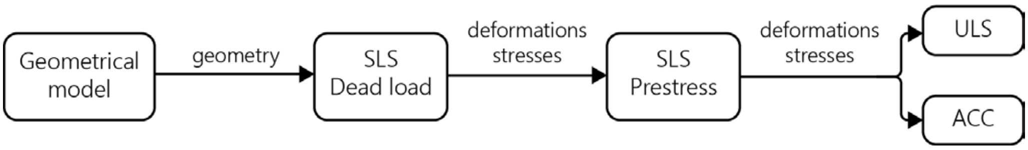
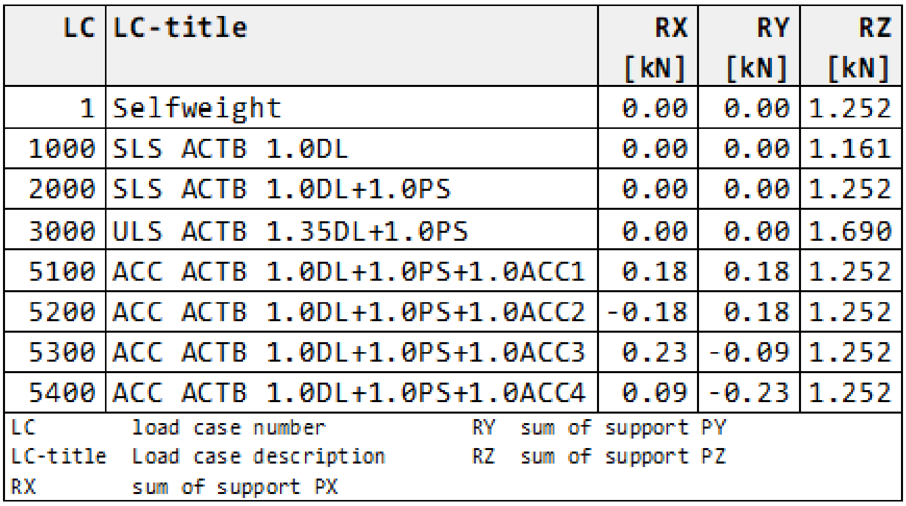


Figure 4.9: Analysis sequence, where each load case is based on the results of the previous one

Table 4.4: Load cases



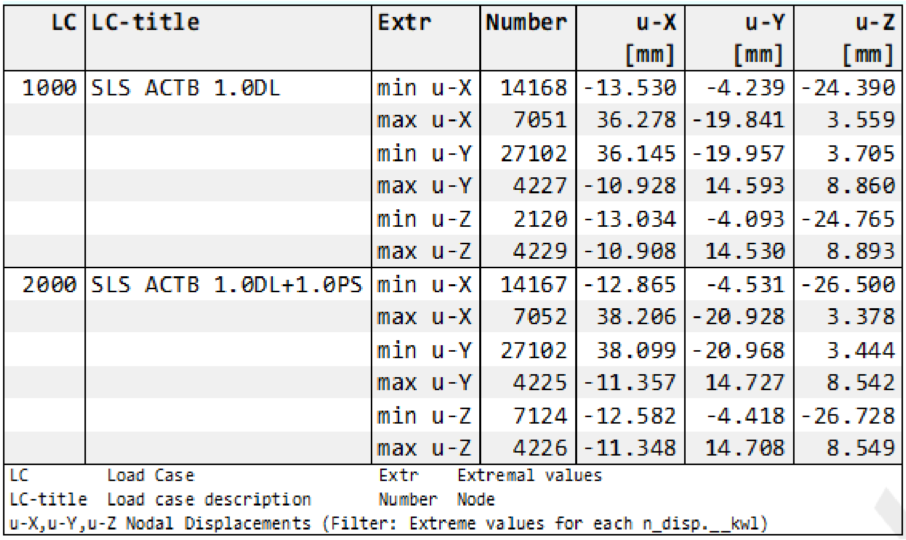
LC	LC-title	RX [kN]	RY [kN]	RZ [kN]
1	Selfweight	0.00	0.00	1.252
1000	SLS ACTB 1.0DL	0.00	0.00	1.161
2000	SLS ACTB 1.0DL+1.0PS	0.00	0.00	1.252
3000	ULS ACTB 1.35DL+1.0PS	0.00	0.00	1.690
5100	ACC ACTB 1.0DL+1.0PS+1.0ACC1	0.18	0.18	1.252
5200	ACC ACTB 1.0DL+1.0PS+1.0ACC2	-0.18	0.18	1.252
5300	ACC ACTB 1.0DL+1.0PS+1.0ACC3	0.23	-0.09	1.252
5400	ACC ACTB 1.0DL+1.0PS+1.0ACC4	0.09	-0.23	1.252

LC	load case number	RY	sum of support PY
LC-title	Load case description	RZ	sum of support PZ
RX	sum of support PX		

4.3.7 Movements

As explained in the previous section, movement in the structure is expected when it relaxes under dead load and when the cables are prestressed. The resulting maximum nodal displacements are shown in Table 4.5.

Table 4.5: Maximum nodal displacements under dead load and prestress



LC	LC-title	Extr	Number	u-X [mm]	u-Y [mm]	u-Z [mm]
1000	SLS ACTB 1.0DL	min u-X	14168	-13.530	-4.239	-24.390
		max u-X	7051	36.278	-19.841	3.559
		min u-Y	27102	36.145	-19.957	3.705
		max u-Y	4227	-10.928	14.593	8.860
		min u-Z	2120	-13.034	-4.093	-24.765
		max u-Z	4229	-10.908	14.530	8.893
2000	SLS ACTB 1.0DL+1.0PS	min u-X	14167	-12.865	-4.531	-26.500
		max u-X	7052	38.206	-20.928	3.378
		min u-Y	27102	38.099	-20.968	3.444
		max u-Y	4225	-11.357	14.727	8.542
		min u-Z	7124	-12.582	-4.418	-26.728
		max u-Z	4226	-11.348	14.708	8.549

LC Load Case
Extr Extremal values
LC-title Load case description
Number Node
u-X,u-Y,u-Z Nodal Displacements (Filter: Extreme values for each n_disp.__kwl)

4.3.8 Member utilisation

The load-bearing capacity of the timber laths were verified for torsion, combined bending and axial tension and combined bending and axial compression according to EN 1995-1-1 (Eurocode 5).

The design value of a strength property in timber is given by Equation 4.1 according to 2.4.1(1)P in Eurocode 5.

$$R_d = k_{mod}\frac{R_k}{\gamma_m} \tag{4.1}$$

where:

R_k	is the characteristic value of a load-carrying capacity;
γ_m	is the partial factor for a material property;
k_{mod}	is a modification factor taking into account the effect of the duration of load and moisture content.

The partial factor γ_m for plywood is given in Table 2.3 in Eurocode 5 as 1.2 for fundamental combinations and 1.0 for accidental combinations.

Values for the modification factor k_{mod} is given by Table 3.1 in Eurocode 5. As the pavilion will stand indoors, the service class is 1. If the load-combination has actions belonging to different load-duration classes, the k_{mod} value corresponding to the shortest duration should be chosen. Therefore, it was taken as 1.0 for accidental loads. Because the pavilion will only stand for about a week, the load-duration class for ultimate limit state was taken between "Short term action" and "Medium action" as 0.85.

For torsion, equation 4.2 according to Eurocode 5 6.1.8(1)P should be satisfied.

$$\tau_{tor,d} \leq k_{shape} f_{v,d} \tag{4.2}$$

with $k_{shape} = min \begin{cases} 1 + 0.15\dfrac{h}{b} \\ 2.0 \end{cases}$ for rectangular cross sections

where:

$\tau_{tor,d}$	is the design torsional stress;
$f_{v,d}$	is the design shear strength;
k_{shape}	is a factor depending on the shape of the cross section;
h	is the larger cross-sectional dimension;
b	is the smaller cross-sectional dimension.

For combined bending and axial tension, expression 4.3 and 4.4 according to to Eurocode 5 6.2.3(1)P should be satisfied:

$$\frac{\sigma_{t,0,d}}{f_{t,0,d}} + \frac{\sigma_{m,y,d}}{f_{m,y,d}} + k_m \frac{\sigma_{m,z,d}}{f_{m,z,d}} \leq 1 \tag{4.3}$$

$$\frac{\sigma_{t,0,d}}{f_{t,0,d}} + k_m \frac{\sigma_{m,y,d}}{f_{m,y,d}} + \frac{\sigma_{m,z,d}}{f_{m,z,d}} \leq 1 \tag{4.4}$$

where k_m is 1.0 for plywood according to 6.1.6 in Eurocode 5. For plywood, there is no tabulated data for bending about the strong axis (in-plane bending), as plywood is normally used in large sheets. Bending can be approximated as a stress couple of tension and compression on either side of the cross sectional neutral axis. Therefore, the lowest strength value between $f_{c,0,k}$, $f_{c,90,k}$, $f_{t,0,k}$ and $f_{t,90,k}$ was used as a conservative approximation for $f_{m,z,k}$.

For combined bending and axial compression, expression 4.5 and 4.6 according to Eurocode 5 6.2.4(1)P should be satisfied:

$$\left(\frac{\sigma_{c,0,d}}{f_{c,0,d}}\right)^2 + \frac{\sigma_{m,y,d}}{f_{m,y,d}} + k_m \frac{\sigma_{m,z,d}}{f_{m,z,d}} \leq 1 \tag{4.5}$$

$$\left(\frac{\sigma_{c,0,d}}{f_{c,0,d}}\right)^2 + k_m \frac{\sigma_{m,y,d}}{f_{m,y,d}} + \frac{\sigma_{m,z,d}}{f_{m,z,d}} \leq 1 \tag{4.6}$$

where k_m is 1.0 for plywood according to Eurocode 5 6.1.6.

The floor plate is verified for pure in-plane bending according to 4.7.

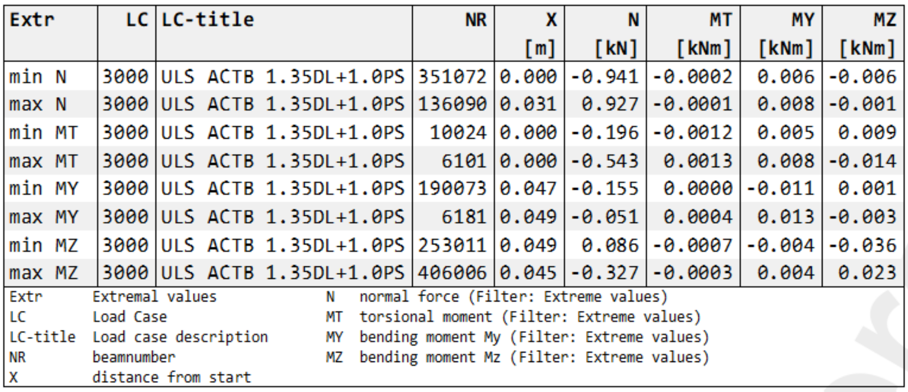
$$\frac{\sigma_{m,z,d}}{f_{m,z,d}} \leq 1 \tag{4.7}$$

The axial utilisation in the prestressing cables was verified according to EN 1993-1-1 (Eurocode 3).

4.3.8.1 Ultimate limit state

The extreme values for axial forces, bending about weak and strong axis and torsion in ultimate limit state are shown in Table 4.6. Each line represents an extreme value, as indicated in the left column. The "NR" and "X" columns show in which beam and at which point the extreme value occurs, and the right columns show the actual value together with the other sectional forces in the same point to be used for combination checks.

Table 4.6: Maximum forces in ultimate limit state analysis



Extr	LC	LC-title	NR	X [m]	N [kN]	MT [kNm]	MY [kNm]	MZ [kNm]
min N	3000	ULS ACTB 1.35DL+1.0PS	351072	0.000	-0.941	-0.0002	0.006	-0.006
max N	3000	ULS ACTB 1.35DL+1.0PS	136090	0.031	0.927	-0.0001	0.008	-0.001
min MT	3000	ULS ACTB 1.35DL+1.0PS	10024	0.000	-0.196	-0.0012	0.005	0.009
max MT	3000	ULS ACTB 1.35DL+1.0PS	6101	0.000	-0.543	0.0013	0.008	-0.014
min MY	3000	ULS ACTB 1.35DL+1.0PS	190073	0.047	-0.155	0.0000	-0.011	0.001
max MY	3000	ULS ACTB 1.35DL+1.0PS	6181	0.049	-0.051	0.0004	0.013	-0.003
min MZ	3000	ULS ACTB 1.35DL+1.0PS	253011	0.049	0.086	-0.0007	-0.004	-0.036
max MZ	3000	ULS ACTB 1.35DL+1.0PS	406006	0.045	-0.327	-0.0003	0.004	0.023

Extr	Extremal values	N	normal force (Filter: Extreme values)
LC	Load Case	MT	torsional moment (Filter: Extreme values)
LC-title	Load case description	MY	bending moment My (Filter: Extreme values)
NR	beamnumber	MZ	bending moment Mz (Filter: Extreme values)
X	distance from start		

The resulting utilisation levels according to the checks in Section 4.3.8 are shown in Table 4.7.

Table 4.7: Utilisation levels in ultimate limit state

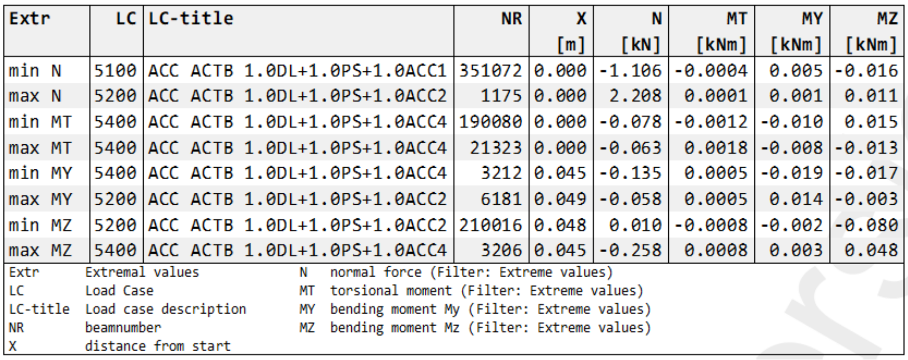
Case	Extreme value	Utilisation level
Combined bending and tension	Max N	0.404
Combined bending and compression	Min N	0.302
Combined bending and compression	Max MY	0.586
Combined bending and compression	Max MZ	0.381
Torsion	Max T	0.616

Theoretically, some other point could have a higher combined value, but since the utilisation level is fairly low, it is assumed that no such point would be critical.

4.3.8.2 Accidental loads

Similar to ultimate limit state, the extreme values for axial forces, bending about weak and strong axis and torsion under accidental load are shown in Table 4.8. Each line represents an extreme value, as indicated in the left column. The "LC" and "LC-title" columns indicates for which of the accidental loads the extreme value occurs.The "NR" and "X" columns show in which beam and at which point the extreme value occurs, and the right columns show the actual value together with the other sectional forces in the same point to be used for combination checks.

Table 4.8: Maximum forces in accidental load case analysis



Extr	LC	LC-title	NR	X [m]	N [kN]	MT [kNm]	MY [kNm]	MZ [kNm]
min N	5100	ACC ACTB 1.0DL+1.0PS+1.0ACC1	351072	0.000	-1.106	-0.0004	0.005	-0.016
max N	5200	ACC ACTB 1.0DL+1.0PS+1.0ACC2	1175	0.000	2.208	0.0001	0.001	0.011
min MT	5400	ACC ACTB 1.0DL+1.0PS+1.0ACC4	190080	0.000	-0.078	-0.0012	-0.010	0.015
max MT	5400	ACC ACTB 1.0DL+1.0PS+1.0ACC4	21323	0.000	-0.063	0.0018	-0.008	-0.013
min MY	5400	ACC ACTB 1.0DL+1.0PS+1.0ACC4	3212	0.045	-0.135	0.0005	-0.019	-0.017
max MY	5200	ACC ACTB 1.0DL+1.0PS+1.0ACC2	6181	0.049	-0.058	0.0005	0.014	-0.003
min MZ	5200	ACC ACTB 1.0DL+1.0PS+1.0ACC2	210016	0.048	0.010	-0.0008	-0.002	-0.080
max MZ	5400	ACC ACTB 1.0DL+1.0PS+1.0ACC4	3206	0.045	-0.258	0.0008	0.003	0.048

Extr	Extremal values	N	normal force (Filter: Extreme values)
LC	Load Case	MT	torsional moment (Filter: Extreme values)
LC-title	Load case description	MY	bending moment My (Filter: Extreme values)
NR	beamnumber	MZ	bending moment Mz (Filter: Extreme values)
X	distance from start		

The resulting utilisation levels according to the checks in Section 4.3.8 are shown in Table 4.9.

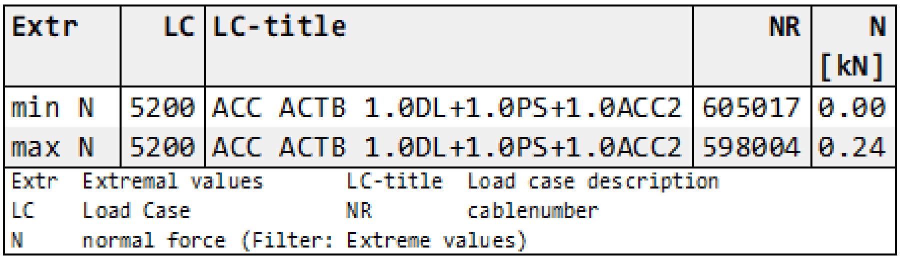
Table 4.9: Utilisation levels under accidental load

Case	Extreme value	Utilisation level
Combined bending and tension	Max N	0.156
Combined bending and compression	Min N	0.223
Combined bending and compression	Max MY	0.634
Combined bending and compression	Max MZ	0.386
Torsion	Max T	0.711

4.3.8.3 Cable utilisation

The maximum axial forces in the cables are shown in Table 4.10, with a resulting maximum utilisation level of about 20%.

Table 4.10: Maximum cable forces



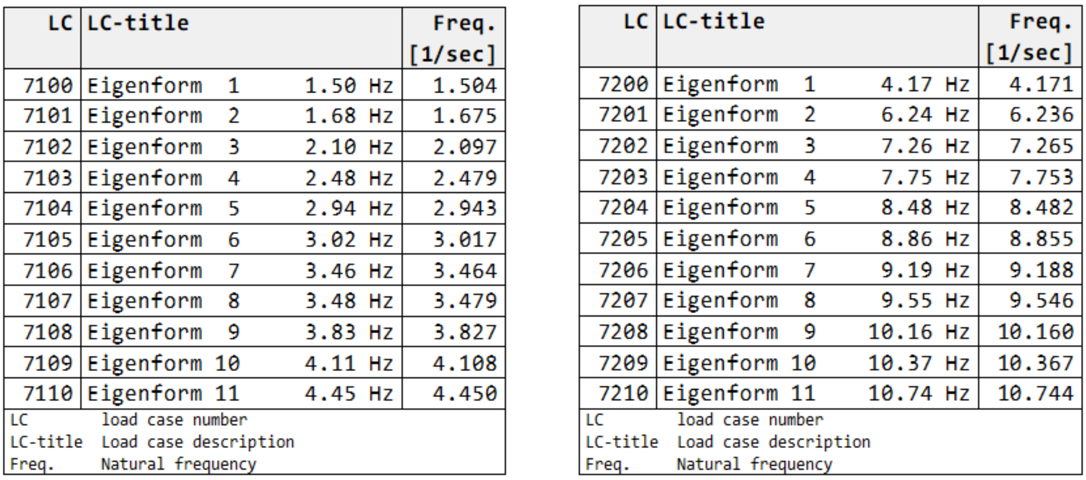
Extr	LC	LC-title	NR	N [kN]
min N	5200	ACC ACTB 1.0DL+1.0PS+1.0ACC2	605017	0.00
max N	5200	ACC ACTB 1.0DL+1.0PS+1.0ACC2	598004	0.24

Extr	Extremal values	LC-title	Load case description
LC	Load Case	NR	cablenumber
N	normal force (Filter: Extreme values)		

4.3.9 Eigenvalue analysis

Eigenvalues with and without cables included in the structural model are shown in Table 4.11. As intended, the cables provide a significant increase in eigenvalue and thereby stiffness. For reference, the first six mode shapes are shown in Figure 4.10.

Table 4.11: Eigenvalues without and with cables, showing the increase in stability using cables



(a) Without cables

LC	LC-title	Freq. [1/sec]
7100	Eigenform 1 1.50 Hz	1.504
7101	Eigenform 2 1.68 Hz	1.675
7102	Eigenform 3 2.10 Hz	2.097
7103	Eigenform 4 2.48 Hz	2.479
7104	Eigenform 5 2.94 Hz	2.943
7105	Eigenform 6 3.02 Hz	3.017
7106	Eigenform 7 3.46 Hz	3.464
7107	Eigenform 8 3.48 Hz	3.479
7108	Eigenform 9 3.83 Hz	3.827
7109	Eigenform 10 4.11 Hz	4.108
7110	Eigenform 11 4.45 Hz	4.450

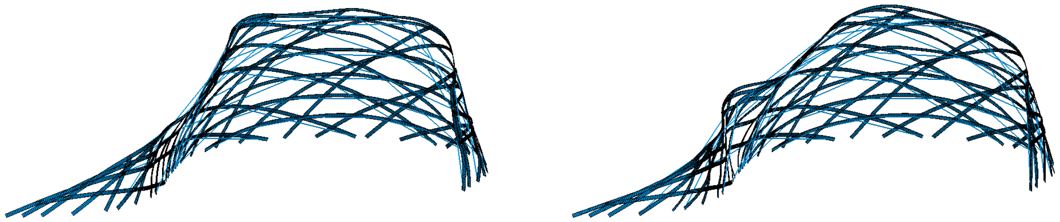
LC	load case number
LC-title	Load case description
Freq.	Natural frequency

(b) With cables

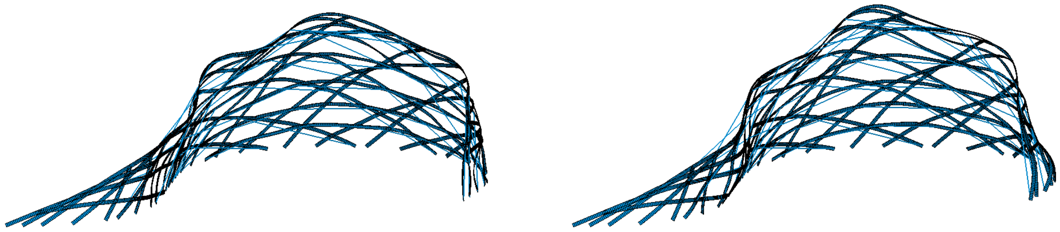
LC	LC-title	Freq. [1/sec]
7200	Eigenform 1 4.17 Hz	4.171
7201	Eigenform 2 6.24 Hz	6.236
7202	Eigenform 3 7.26 Hz	7.265
7203	Eigenform 4 7.75 Hz	7.753
7204	Eigenform 5 8.48 Hz	8.482
7205	Eigenform 6 8.86 Hz	8.855
7206	Eigenform 7 9.19 Hz	9.188
7207	Eigenform 8 9.55 Hz	9.546
7208	Eigenform 9 10.16 Hz	10.160
7209	Eigenform 10 10.37 Hz	10.367
7210	Eigenform 11 10.74 Hz	10.744

LC	load case number
LC-title	Load case description
Freq.	Natural frequency

(a) Mode 1 (b) Mode 2



(c) Mode 3 (d) Mode 4



(e) Mode 5 (f) Mode 6

Figure 4.10: The first six eigenmodes of the pavilion with prestressing cables

4.3.10 Buckling

A linear buckling eigenvalue analysis was carried out for the ultimate limit state and accidental load cases. The resulting buckling load factors are shown in Table 4.12, showing that buckling does not occur before about twice the load for any load case. For future work, it would be of interest to perform nonlinear buckling analysis to evaluate the effects of potential negative post-critical buckling behaviour.

Table 4.12: Buckling load factors

Loadcase	**Buckling load factor**
ULS	3.72
ACC1	3.90
ACC2	1.81
ACC3	3.15
ACC4	2.66

4.3.11 Floor plate

Just like the rest of the structure, the floor plate is expected to deform under self-weight and prestress. The horizontal displacements of the floor plate under SLS are shown in Figure 4.11. As previously described, the floor plate was modelled as bolted in the two ends and in the middle. Potentially more locations could be bolted in order to decrease the displacements induced by prestressing.

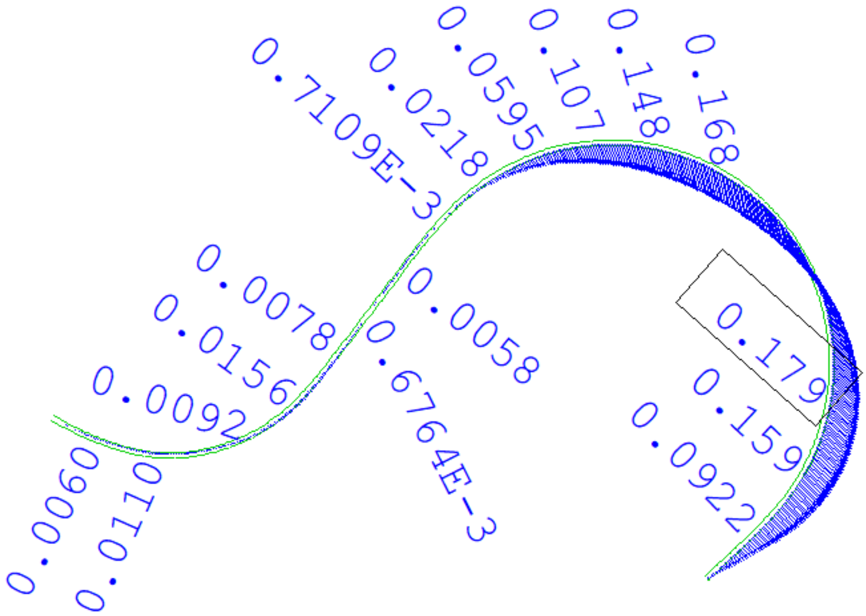
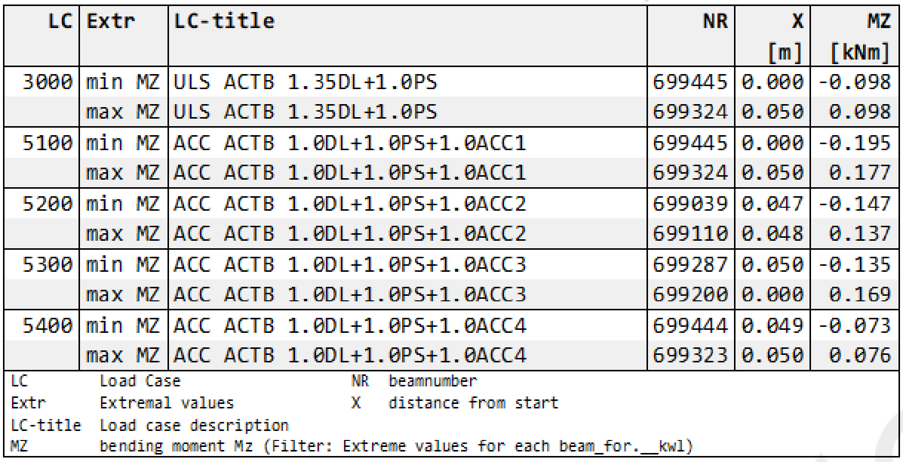


Figure 4.11: Nodal displacements [m] of floor plate under dead load and prestress

The maximum bending moments in the floor plate under ULS and ACC are shown in Table 4.13. The moment capacity is calculated to 25 kNm, resulting in a utilisation of 1%.

Table 4.13: Maximum bending moments about strong axis in floor plate



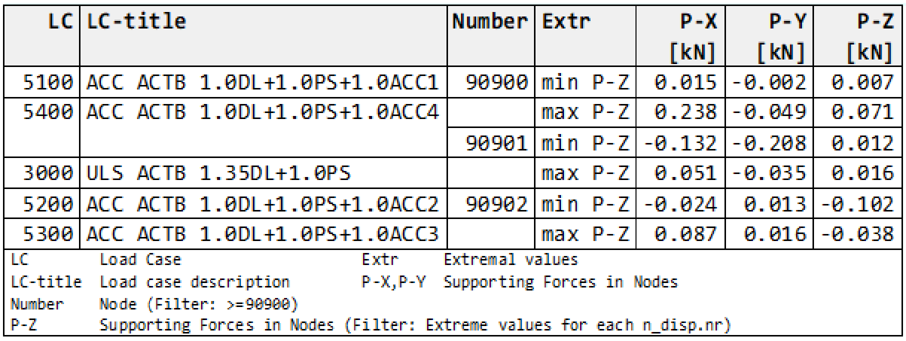
LC	Extr	LC-title	NR	X [m]	MZ [kNm]
3000	min MZ	ULS ACTB 1.35DL+1.0PS	699445	0.000	-0.098
	max MZ	ULS ACTB 1.35DL+1.0PS	699324	0.050	0.098
5100	min MZ	ACC ACTB 1.0DL+1.0PS+1.0ACC1	699445	0.000	-0.195
	max MZ	ACC ACTB 1.0DL+1.0PS+1.0ACC1	699324	0.050	0.177
5200	min MZ	ACC ACTB 1.0DL+1.0PS+1.0ACC2	699039	0.047	-0.147
	max MZ	ACC ACTB 1.0DL+1.0PS+1.0ACC2	699110	0.048	0.137
5300	min MZ	ACC ACTB 1.0DL+1.0PS+1.0ACC3	699287	0.050	-0.135
	max MZ	ACC ACTB 1.0DL+1.0PS+1.0ACC3	699200	0.000	0.169
5400	min MZ	ACC ACTB 1.0DL+1.0PS+1.0ACC4	699444	0.049	-0.073
	max MZ	ACC ACTB 1.0DL+1.0PS+1.0ACC4	699323	0.050	0.076

LC Load Case NR beamnumber
Extr Extremal values X distance from start
LC-title Load case description
MZ bending moment Mz (Filter: Extreme values for each beam_for.__kwl)

4.3.12 Support reactions

The maximum support reactions in global directions at the points where the floor plate is bolted to the ground are shown in Table 4.14. The vertical support reactions in all nodes along the floor plate are shown in Figure 4.12, showing potential areas for uplift in red. Since no continuous uplift occurs along a longer stretch of the floor plate, it is expected that these uplift forces will be handled by the structure.

Table 4.14: Maximum support forces in floor plate attachment points under all loads



LC	LC-title	Number	Extr	P-X [kN]	P-Y [kN]	P-Z [kN]
5100	ACC ACTB 1.0DL+1.0PS+1.0ACC1	90900	min P-Z	0.015	-0.002	0.007
5400	ACC ACTB 1.0DL+1.0PS+1.0ACC4		max P-Z	0.238	-0.049	0.071
		90901	min P-Z	-0.132	-0.208	0.012
3000	ULS ACTB 1.35DL+1.0PS		max P-Z	0.051	-0.035	0.016
5200	ACC ACTB 1.0DL+1.0PS+1.0ACC2	90902	min P-Z	-0.024	0.013	-0.102
5300	ACC ACTB 1.0DL+1.0PS+1.0ACC3		max P-Z	0.087	0.016	-0.038

LC Load Case

LC-title Load case description

Number Node (Filter: >=90900)

P-Z Supporting Forces in Nodes (Filter: Extreme values for each n_disp.nr)

Extr Extremal values

P-X,P-Y Supporting Forces in Nodes

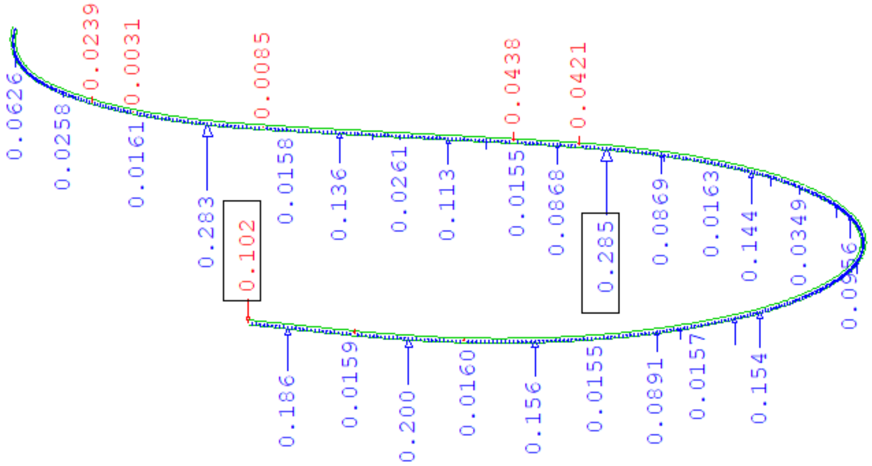


Figure 4.12: Support reactions [kN] in all nodes along floor plate under ULS, uplift in red

4.4 Detail design

In the design of the connection details, it is important that they allow and prevent movements as intended. Furthermore, for the purpose of this pavilion, subtle connections are sought, so as to give the impression of continuous laths. The pavilion will be placed in the part of the fair with focus on furniture industry, wherefore it is also important with a high level of finish on the details and material. A study of joint designs and metal fasteners was conducted as described in this section to test various options based on both structural performance and aesthetics.

4.4.1 Joint design

There are numerous of ways to join two laths together. Previously built pavilions as well as traditional Japanese and Swedish craftsmanship was studied to find inspiration for the design in this pavilion (Figure 4.13).

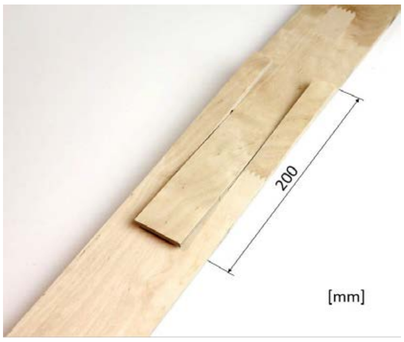
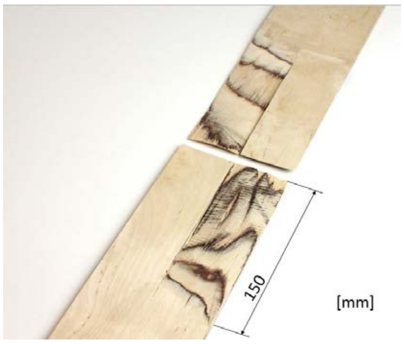
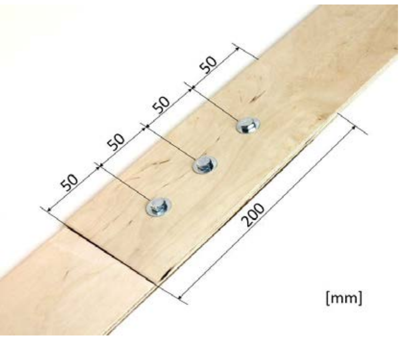
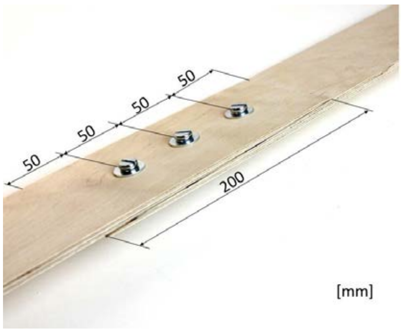
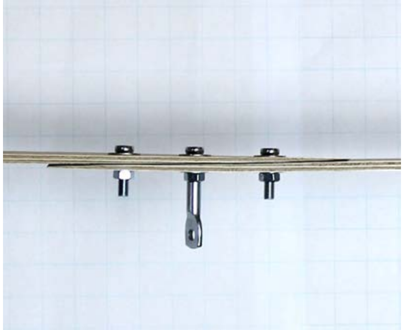
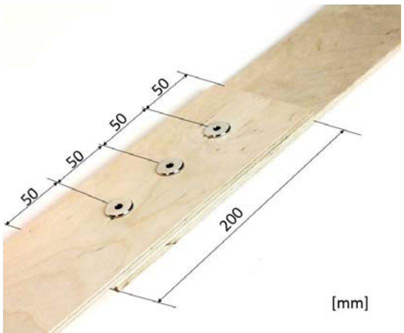
(a) Joint in Earth Center Forest Garden Grid Shell (Grant, 2017)

(b) Japanese wood joint

Figure 4.13: Examples of wood joints

A series of different joints were designed in this study. The goal was to find a refined connection which minimise the need for metal fasteners and potentially allows the centre lines of two connecting elements to meet. If the two centre lines meet at the same level there is no visible overlap with increased thickness, making the lath feel smooth and continuous. Additionally, the production and assembly should be fast and reliable. The designs are presented in table 4.15.

Table 4.15: Connection design

1			Complicated connection to build. Small slots are cut out in order for the laths to connect to each other without metal fastenings.
2			All wood connection with two opposed triangles bevelled out from each lath. Inspired by traditional Japanese craftsmanship.
3			Two plies are routed out from each connecting lath, which are placed on top of each other. Connected with standard hexagon bolts.
4			The end of each lath is bevelled in to a long and thin triangle. The triangle allows the centre line of the elements to meet.
5			Two laths simply placed on top of each other and connected with polished hex key bolts with flat head

The most critical load case for the laths in the pavilion is bending. The designs presented in Table 4.15 were therefore subjected to a three point bending test. The laths were placed on a rig with a span of 120 cm between the simply supported end supports and the joint in the middle of the span, see Figure 4.14. Behind the rig, a grid was placed in order to evaluate the curvature and the deflection. A load was placed in the middle of the joint and incrementally increased until the lath breaks. After each load increment a photo was taken.

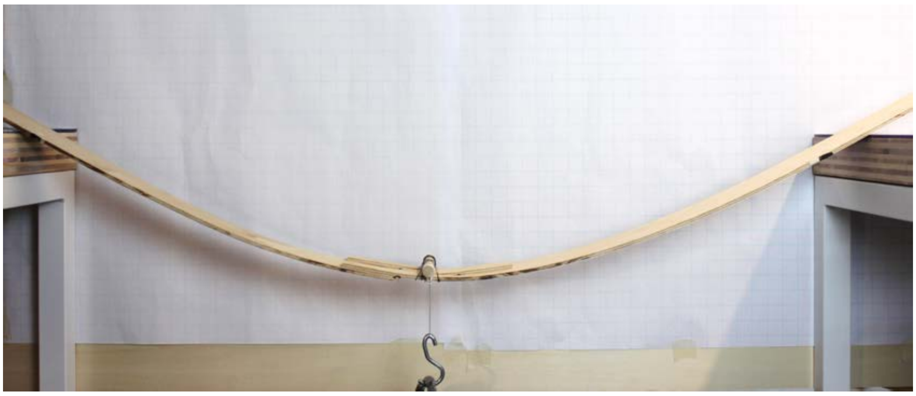


Figure 4.14: Test rig with bending of a lath with joint

There was a wide spread in moment capacity between the different designs. The strongest is Number 5 in Table 4.15, which is also the easiest to produce. This is the only joint that did not break in test. The lath reached the end of the test rig with under a load of 50 Nm. The second strongest was Number 1, which is on the other hand the most complex to produce. The rest of the designs had a capacity which was far from satisfactory, collapsing already at small loads.

Alternative Number 5 was chosen in order to benefit from the strength of the material and not introduce an impairment in the joints. The simplicity during production was also in favour for this solution. It was also judged that the increased thickness at the overlap did not affect the aesthetics of the joint substantially.

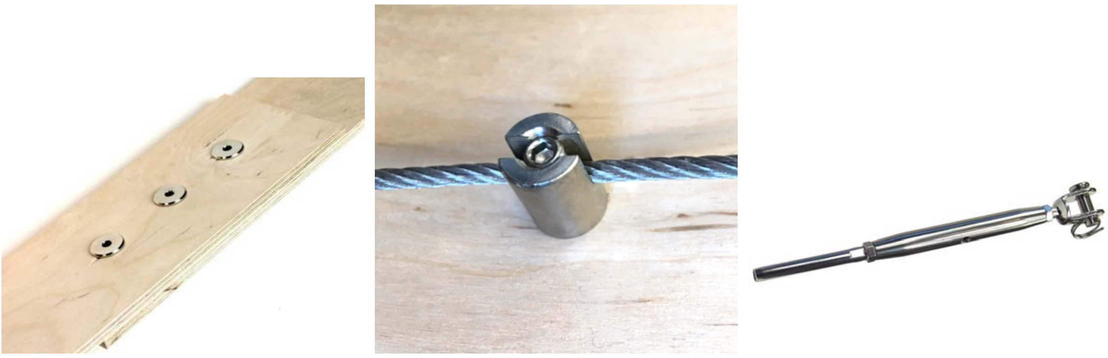
The strength of the connection was calculated according to Eurocode 5 SS-EN 1995-1-1. The bolts were placed closer to the edge than what is recommended in Eurocode so as to keep laths from opening up from each other when subjected to bending. Therefore, the calculated strength value was also compared to a bending tests. The test gave the satisfactory result of 50 Nm.

4.4.2 Metal fasteners

A wide variety of fasteners was studied to find a suitable solution. Most of the standard hardware products are not refined enough for the application. Therefore the search was broadened to special applications such as kitchens, doors and furniture. The solution that was found best fitting for the pavilion is presented in Figure 4.15a. This fastener will be used to join the continuous laths described in subsection 4.4.1 and at the intersection of two crossing laths.

A set of wire ropes with a dimension of 3 mm will be used to prestress the structure. These are continuous and follow the laths that go from floor to floor. Along the lath the wire rope will be attached with a wire rope clamp presented in Figure 4.15b which clamp the wire without letting it slip. The wire rope clamp will be fastened with a M6 screw.

The wires need to be adjusted after being mounted in the structure to allow for adjustments of the shape of the pavilion that will occur when the prestress is applied. To be able to perform this adjustment, turnbuckles will be placed on each wire rope which can be turned until the desired tension is reached (Figure 4.15c).



(a) Metal fasteners **(b)** Wire rope clamp **(c)** Turnbuckle connector

Figure 4.15: Details of fasteners

4.4.3 Floor plate

The floor plate will be 300 mm wide and built by three layers of 21 mm plywood. The first layer will be the full width and on top of this there will be two layers with a gap between. In this gap the laths will meet the floor plate at a slight angle see Figure 4.16. In order to make a continuous plate along the pavilion the layers will overlap each other so that they can be bolted together.

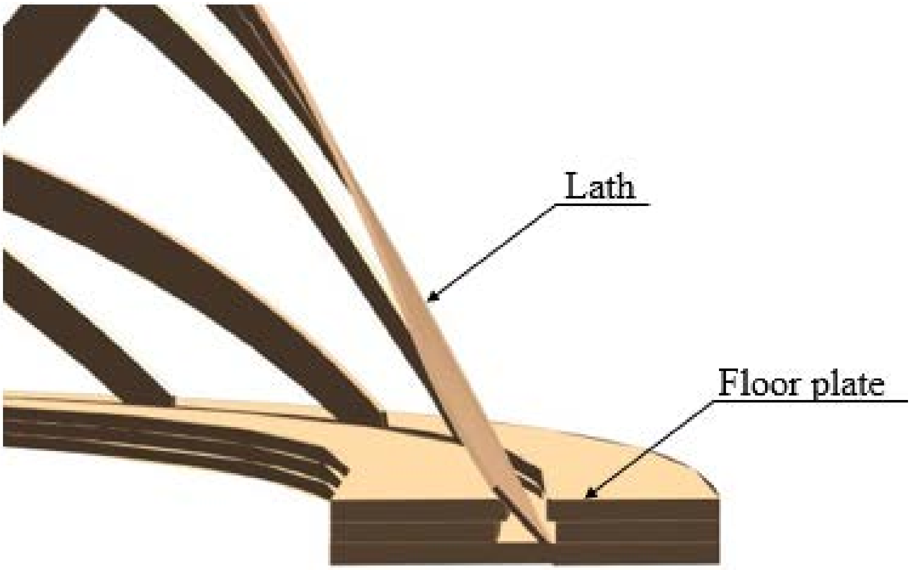


Figure 4.16: Floor plate

5

Final Design

In the final design phase, a stiffness-scaled physical model is realised in order to improve understanding and identify possible construction issues in the final design proposal. Then, a plan for production and erection is presented. Finally, a risk assessment is conducted, highlighting potential risks with the design.

5.1 Final design

In order to obtain an increased understanding of the behaviour of a structure, a stiffness-scaled physical model can be created. The idea is to scale the thickness of the elements differently from the span, in order to obtain a model where weight and stiffness relates to each other in the same way as in the full-scale structure. The relationship is not direct, since stiffness relates to the thickness raised to the power of three. One can find a unit-independent relationship between stiffness and weight as displayed in Equation 5.1 (C. Williams, personal communication, March 20, 2018). In the stiffness-scaled model, this relationship should have the same value as in the 1:1 structure. Given that, the necessary thickness for a given span or vice-versa in a scale model can be found.

$$\frac{Et^3}{\rho g t S^3} \tag{5.1}$$

where:

E is the Young's modulus [MPa];
t is the thickness [m];
ρ is the density [kg/m^3];
g is the standard acceleration due to gravity [m/s^2];
S is the span [m];

With this method, a scale model was constructed. The material used was 1.5 mm thick air plane plywood, with a modulus of elasticity of about 1000 N/mm^2. Based on that thickness and modulus of elasticity, Equation 5.1 gave a 1:10 scale for the overall model.

The laths for the model were cut out with a laser cutter. The cutting drawings for the machine were created in Grasshopper, measuring each lath and marking out where it crossed other laths and where cables attached to it. Furthermore, the laths were split according to where they need to be spliced in the full-scale pavilion, i.e. every 2.4 m. Each lath segment was numbered and each joint was marked with a number corresponding to which element it should be joined to. In that way, the model could easily be assembled without drawings, simply based on the numbering. Metal wire was used for all connections, since larger connection details would be too heavy compared to the scale of the model.

First, the ground beam was assembled. In the scale model, it was created of just two layers of 3 mm plywood without the central rail cut out for the lath connections (Figure 5.1a). The laths were assembled into their full lengths (Figure 5.1b), and then attached to the model.

(a) Ground beam assembly **(b)** Lath assembly

Figure 5.1: First stages of model assembly

The model was supported in the middle when the first laths were attached (Figure 5.2a), but soon gained enough stiffness to stand by itself (Figure 5.2b). The weaving, i.e. which element should go on top of which, was chosen on the spot based on what seemed most suitable.

(a) Initial support **(b)** Self-supporting structure

Figure 5.2: Lath attachment

When all laths were mounted, the cables were attached (Figure 5.3). It was impossible to judge what tension went into the cables, and consequently some cables became slack and the shape of the structure was somewhat affected. However, the overall effect of the cables was clearly stiffening for the structure. The finished model can be seen in Figure 5.4.

Figure 5.3: Cable attachment

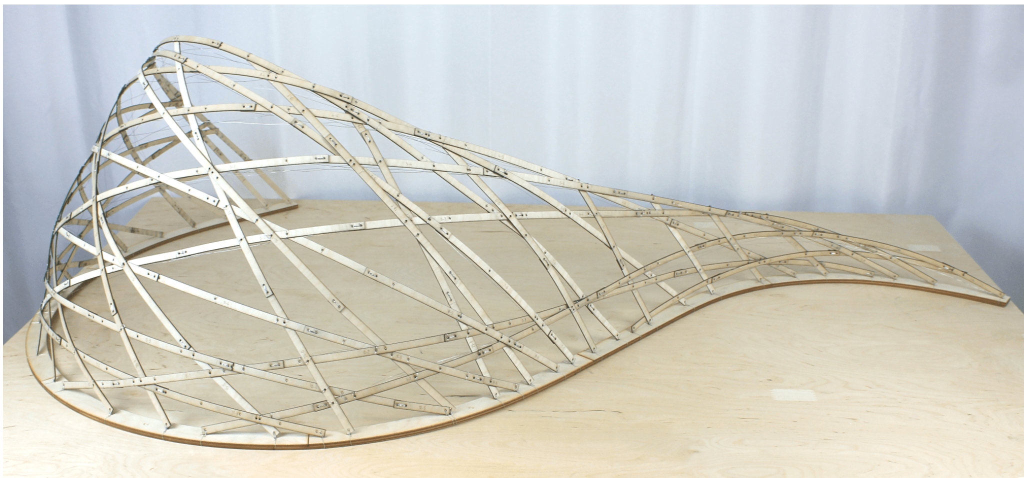


Figure 5.4: Finished model

The model provided a series of good teachings. Firstly, it was interesting to see how floppy the laths were when assembled into their full lengths, more like a strip of paper than a timber lath. Then, when all the laths were mounted on the structure, they actually together provided a fairly large stiffness. When the cables finally came on, the structure became very stiff, with only local deformations of one lath when pushing it.

Secondly, it quickly became clear that both the placement of the lath splice overlaps, the side of the lath that the overlap is placed on and the weaving played important parts in how smooth the couplings between the laths became (Figure 5.5). For the construction of the full-scale pavilion, the scale model should provide a good study material for potential adjustments.

Figure 5.5: Overlap, weaving and lath coupling

Thirdly, it proved to be quite difficult to determine which cable should go on top of which so as to not have any cables pushing on the others. Because the cables are small and many it is also difficult to create a good system for monitoring this but it would be advisable for the construction of the full pavilion.

Finally, the model showed uplift in the ends when point loads were applied somewhere along it, similar to what was seen in the analysis model (Figure 4.12). While this did not affect the overall stability, it is not desirable in the full-scale pavilion. Therefore, the potential vertical support possibilities in the bolts to the ground should be investigated.

Other than that, the scale model provided a good confirmation of the analytical results, with a large increase in stiffness when the cables were installed.

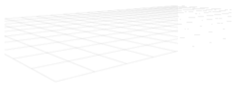
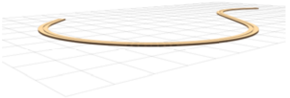
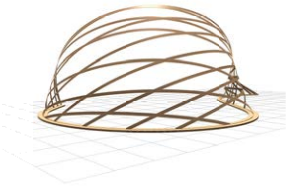
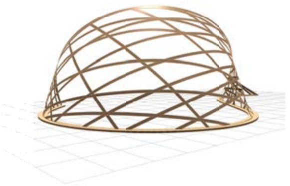
5.2 Production and erection sequence

There is a time period of eight days prior to the fair's opening that will be allocated for building the pavilion on site. Before this, the elements will have been prefabricated to lengths that are suitable for transportation. This section describes the envisaged prefabrication and erection process of the pavilion.

The wood elements in the pavilion will be prefabricated at the wood shop at Chalmers University of Technology. The laths will be sawed out of 2.4 m long plywood sheets using a vertical panel saw. The first and last element of each lath are of individual length, while the ones in between are the same length, which will speed up production. Holes will be drilled for the coupling between the lath segments, joints between crossing laths and cable connections. A drill press with a jig that helps to place the drill at the right location should be used for this. The jig will also speed up the drilling process since no measuring is required.

The construction on site will be divided into five steps. These are presented in Table 5.1.

Table 5.1: Erection sequence

1		A grid or control points are drawn on the ground in order to orientate the structure's position.
2		The prefabricated elements are sorted and assembled on site. The CNC-cut foundation is bolted to the ground and the laths joint together flat on the ground. The holes for the bolts are drilled.
3		The laths that reaches from ground to ground are first added so that they are crossing each other and creating a woven pattern. At the intersection points are they connected with a bolt. Struts are used as scaffolding to support the structure during this phase.
4		The vertically oriented laths are added last. When all the laths are mounted, the structure is stable and the scaffolding can be removed.
5		The prestressing system is added. All the cables are added before the wires are stressed to the correct amount of tension.

Once the structure is erected, the prestressing wire ropes will be added. These will be mounted one wire rope at the time starting from one side of a lath and then connecting it to the wire rope clamps until it reaches the end of the the lath. After the wire rope is connected at all points along the lath, the wire will be contracted using a winch until a certain level of stress is induced in the system.

The final stress level will be controlled by a wire tension gauge designed for sailing boats. This process will be repeated for all the wires until the whole structure is prestressed. At this time, the tension in the wire ropes will probably have changed from the initially set and need to be adjusted with the turnbuckles. When the tension is satisfactory the wire clamps will be tightened.

5.3 Risk assessment

The risks discussed in the concept phase (Section 3.3.3) were considered when further developing the final design. The pavilion is balancing on what is possible to build safely since the material utilisation is high and the eigenfrequencies relatively low. It is not unlikely that something could break, wherefore focus has been on minimising the consequences of such an event. The major risks are presented in Table 5.2. Table 5.3 has been used to evaluate the risks.

One of the most important design principles for risk mitigation throughout the design of the pavilion has been redundancy. Because of the inherent structural variations in wood as a construction material, a special emphasis has been placed on creating a design that allows for potential local failures in the structure. This was accomplished by making sure that if a lath breaks, the force can find new ways in the the structure. This means that the pavilion may deform but not collapse in case of a local failure.

Another critical risk factor to consider was the amount of prestressing added to the system. The level of prestress was kept low in order to avoid a situation where large forces are released if an element breaks.

The final major design concern with regards to risk assessment was keeping the span size as small as possible while maintaining the original design idea. This was intended to aid both the construction and the structural performance. A long span could be problematic at construction, since the structure would need to be supported by a large amount of scaffolding and work would have to be carried out at high heights.

One risk that was difficult to avoid was people leaning against the structure or pushing it. Therefore, the pavilion needed to be able to withstand this kind of loads, which was analysed in Section 4.3.8.2 where it was found to not be problematic.

Table 5.2: Risk assessment

Event	**Probability (0-2)**	**Consequence (0-2)**	**Risk (0-4)**
Local failure in single element	1	1	2
A person pushing the pavilion	2	0	2
People climbing in the structure	0	2	2
Failure during construction	1	1	2
Failure during dismantling	1	1	2

Table 5.3: Risk verification

		Consequence		
		0 Minor	1 Moderate	2 Major
Probability	0 Unlikely	0 Acceptable low	1 Acceptable low	2 Acceptable medium
	1 Likely	1 Acceptable low	2 Acceptable medium	3 Unacceptable high
	2 Very likely	2 Acceptable medium	3 Unacceptable high	4 Unacceptable extreme

6

Discussion

The following chapter contains reflections on the results and methods presented in this thesis, followed by a section with suggestions for future work.

6.1 Reflections

This sections firstly reflects on the general method used in this thesis, the so-called research by design. The particular design process used is also discussed. Then, reflections on modelling and analysis techniques and performing detail design for unconventional structures are presented. Finally the benefits of prestressing found in this thesis are discussed.

6.1.1 Research by design

This thesis started out in a very open manner, with the aim of applying research by design on the wide topic of prestressing timber. Without much specific literature to base the research on, the interpretation of research by design became very literal, with a thorough conceptual design phase trying out the various possibilities in timber, prestress and the combination of the two. Driven by the design process, the need for deeper knowledge in various subjects then became apparent. Some in-depth knowledge was gained within the scope of the thesis, but several topics for future study was also found. It appears that research by design is a very useful tool for approaching a new subject and finding topics for detailed studies. Furthermore, these topics will all have arisen from actual design problems, giving them a practical relevance.

However, it can also be noted that many interesting concepts were found in the conceptual phase that were not carried forward for various reasons. In some of the cases, these concepts would just have needed a bit more development to be perceived as viable design options. While the concepts are interesting in themselves, it might be argued that a narrower initial scope might have allowed the conceptual phase to dive deeper into a particular type of timber prestressing. In that way, an even more daring use of prestress might have found its way into the final pavilion design, such as changing the shape of the structure with prestress or a different type of prestressing material. The open conceptual phase on the other hand is clearly very useful for finding various interesting ways of using prestress in timber, which could also have been an interesting thesis topic.

Another benefit inherent in constructive design research is the way it forces the engineer to make use of their engineering understanding in novel ways. In the design of an unconventional structure, it is less straight-forward but crucial to gain understanding of how the forces travel through the structure and how these paths can be affected by the design of a connection detail or change in typology. It is the authors' belief that such an understanding will help the engineer in the design of all types of structures, enabling optimisation and detailed control of the stress patterns in the structure.

6.1.2 Design process

The particular design process applied in this thesis, with an iterative conceptual design phase followed by a preliminary design phase, appears to be a good way of generating and evaluating different ideas. A large variety of early concepts were developed and with the help of evaluation criteria based on local context and stakeholders' demands a suitable design for the pavilion could be found. By starting out with separate concepts for space and structure, both aspects could be addressed without limiting each other, enabling a freer discussion of each.

However, the various and sometimes conflicting evaluation criteria were also a limitation in the design process. For example the demand for a good lecture space could prevent the choice of an interesting structural concept, because no suitable spatial concept could be found to match it. In a real design project it is naturally important to find a solution that fulfil both criteria. In the design of a pavilion however, it might be beneficial to instead choose one governing evaluation criteria. It might for example be decided that for the purpose of a timber fair, the most important aspect is to show an innovative use of timber, and then an interesting structural concept might be chosen despite not creating the best lecture space, or vice-versa.

6.1.3 Modelling and analysis

Since the structure was initially undefined, the process of choosing suitable modelling and analysis methods became a large part of the thesis. It quickly became apparent that no single method for modelling active-bending elements exist, but rather a range of techniques suitable in different situations. An implementation of bi-axial bending in a Grasshopper plugin would be very useful for instant feedback. The tools available today are either only modelling active bending with the 3DOF methods, thus unable to accurately model non-circular cross-sections, or only providing bi-axial bending but no means of applying active bending in an already-bent structure. However, the easy export to Sofistik gives the full potential of an FE analysis software while still providing quick feedback. Baking all functionality into one software might not be the most efficient in terms of analysis time, wherefore easy export between different software might actually be the best method.

6.1.4 Detail design

The goals set in the joint detail study were to find a solution utilising either only wood without metal fasteners, or a solution where the centre line of two connecting laths meet at the same level. At the same time the joint should not only be rigid, but also fast and reliable to build. After building the joint prototypes and load testing them, it was clear that these requirements were conflicting and that it would be difficult to find a solution that fulfilled all of them. This is partly due to the fact that the pavilion is such a complex structure with difficult couplings between intersecting laths. In addition, it would not be reasonable to spend the considerable amount of time that most of the prototype joints in the study took to produce for a pavilion that will stand for such a short time.

Although none of the joint prototypes successfully met both the structural requirements and the wish for an aesthetically subtle joint design, the final design of the joints is believed to be successful and well suited for the project. It fulfils the structural demands and is still visually appealing with the high finish hex bolts.

6.1.5 Benefits of prestressing

Both the single arch cable studies and the analysis of the full pavilion show significant increases in stability in terms of eigenvalues using a prestressing cable system. It is however difficult to physically comprehend the relationship between increase in eigenfrequency and increase in stability, i.e. what level of increase is needed to actually make the the structure give the impression of being stable. Nevertheless, the prestressing clearly has potential to stabilise otherwise unstable structures.

Local deformations are less aided by the prestressing system, which could possibly be handled by shorter distances between the cable support points.

As shown in the detail design section, the necessary connection details are simple and using prestressing cables could therefore be a feasible method for increasing stability of bending active structures.

6.2 Suggestions for future work

This section describes a few topics that were encountered during the work with this thesis. These would be interesting and relevant for further study.

6.2.1 Interesting concepts

Several interesting concepts were found during the conceptual design phase, that for various reasons were found unsuitable for the pavilion designed in this thesis. Nevertheless, they would be interesting for further studies of ways of combining prestress and timber.

One very interesting concept is the bow-and-arrow principle where timber is used also for the bow-string. The bow-string bends the bow, while the bow puts tension in the bow-string, thereby creating a self-equilibrated load system without horizontal support reactions. In a stiff wood, this creates a very stable system just because of the bending stiffness of the bow. In a very flexible wood, several attachment points between the bow and the string and length differences between the two could be used to create interesting shapes while at the same time providing higher stiffness.

Along the same lines, a prestressing system could be used according to the principles presented by Todisco et al. (2015) to create free-form shapes in timber vaults.

The X-shape tensegrity system would also be interesting to develop further, perhaps finding a way of using specific timber properties to improve the structural properties.

6.2.2 Benefits of prestressing

In this thesis, it is shown that an internal system of prestressed cables provide increased stability in bending active gridshells. It would however be interesting to look into other types of structures, both shells and different typologies, and see what the benefits of prestressing are there. It would also be useful to study the relationship between eigenfrequency and stability.

6.2.3 Modelling

In terms of modelling, but unrelated to prestressing, both tools for easy generation and control of geodesic lines on freeform surfaces and for modelling of active bending in Grasshopper would be very useful in early design of active-bending gridshells.

6.2.4 Creep

A topic not addressed in this thesis is the long-term creep deformations present in timber structures. It would be interesting to investigate in what way creep would influence the stress in a prestressed timber structure, but also if the prestressing can actually be used to lessen the effects of creep deformation.

7

Conclusion

This thesis aimed to test the method of research by design to investigate the topic of prestressing timber, which was done through the design of a prestressed timber pavilion. Through a conceptual design process, a range of methods for combining prestress and timber were found, of which several would be interesting for future research. The concepts were evaluated based on a set of criteria reflecting the local context and stakeholders' demands for this particular project, resulting in the choice of a final design proposal.

This proposal was then further developed in a preliminary design phase, where methods for modelling and analysis were investigated and implemented. It was found that no single good method for modelling of active bending exists, but a suitable method for this project was chosen. Connection details were also researched, tested and developed for the specific needs of the structure, resulting in simple details with an adequate structural capacity and rapid construction. A suitable configuration for the prestressing system was found, and it was shown that it gave a significant increase in the structure's global stiffness in terms of eigenfrequencies.

Through the conceptual and preliminary design phases, a range of interesting concepts for prestressing timber structures were found, together with various topics for detailed studies, suggesting that research by design is a useful method for investigation of a new type of structural system.

References

Adiels, E. (2017). *Structural influence of the geometry of masonry vaults - brick tiling patterns for compression shells using geodesic coordinates* (Master's thesis). Department of Applied Mechanics, Chalmers University of Technology, Gothenburg, Sweden, no: 2016:88.

Adriaenssens, S. (2000). *Stressed Spline Structures* (PhD thesis). University of Bath.

Adriaenssens, S., Block, P., Veenendaal, D., & Williams, C. (2014). *Shell Structures for Architecture.* New York: Routledge.

Aitoh, M., & Okada, A. (1999). The role of string in hybrid string structure. *Engineering Structures 21*, 756-769.

Alexandrou, K., & Phocas, M. C. (2017). Hybrid bending-active structures with multiple cables. In *Proceedings of the IASS Annual Symposium 2017 "Interfaces: architecture.engineering.science".*

Alpermann, H., & Gengnagel, C. (2013). Restraining actively-bent structures by membranes. In *VI International Conference on Textile Composites and Inflatable Structures (Structural Membranes 2013).*

Ander, M., Sehlström, A., Shepherd, P., & Williams, C. J. K. (2017). Prestressed gridshell structures. In *Proceedings of the IASS Annual Symposium 2017.*

Bass, H., Aune, P., Choo, B., Görlacher, R., Griffiths, D., Hilson, B., … Steck, G. (1995). *Timber engineering - step 1.* Deventer: Salland De Lange.

Bellman, J. (2017). Active bending starting on curved architectural shape. In *VIII International Conference on Textile Composites and Inflatable Structures Structural membranes 2017* (p. 265-274).

Calladine, C. R. (1978). Buckminster Fuller's "tensegrity" structures and Clerk Maxwell's rules for the construction of stiff frames. *International Journal of Solids and Structures*, *14*, pp. 161-172.

Chilton, J., & Tang, G. (2017). *Timber gridshells.* Routledge.

Corres-Peiretti, H. (2013). Sound engineering through conceptual design according to the fib model code 2010. *Structural concrete*, *14*(2).

Frayling, C. (1993/4). Research in Art and Design. *Royal College of Art Research Papers*, *1*(1).

Grant, A. (2017). *Earth centre forest garden grid shells.* [Online image] Retrieved March 28, 2018 from `http://grant-associates.uk.com/approach/earth-centre-forest-garden-grid-shells`.

Harding, J. E., Hills, S., Brandt-Olsen, C., & Melville, S. (2017). The UWE Research

Pavilion 2016. In *Proceedings of the IASS Annual Symposium 2017.*

Hennicke, J. (1974). *IL 10: Gitterschalen / Grid Shells.* Institute for Lightweight Structures.

Herzog, T. (2004). *Timber construction manual.* Birkhäuser.

Heyman, J. (1996). *Elements of the Theory of Structures.* Cambridge University Press.

Highway service area deitingen south. (n.d.). [Online image] Retrieved May 3, 2018 from `https://78.media.tumblr.com/1bad4eaea6a0e9c6615716bfd138ba20/tumblr_om6iseg5AU1tw598eo1_1280.jpg`.

Hirai, H. (2014). *Clubhouse for the haesley nine bridges golf resort.* [Online image] Retrieved May 3, 2018 from `https://www.archdaily.com/490241/nine-bridges-country-club-shigeru-ban-architects/53325861c07a80cb6b0000a2-nine-bridges-country-club-shigeru-ban-architects-photo`.

Johnson, S. (2000). *Gridshells and the contruction process.* [online] Weald & Downland Living Museum. Available at: `http://www.wealddown.co.uk/explore/buildings/further-reading/gridshells-construction-process/` [Accessed 18 Dec. 2017].

Koskinen, I., Zimmerman, T., Binder, T., Redstrom, J., & Wensveen, S. (2011). *Design research through practice.* Waltham: Elsevier Inc.

Lienhard, J. (2014). *Bending-Active Structures* (PhD thesis). University of Stuttgart.

Mele, T. V., Laet, L. D., Veenendaal, D., Mollaert, M., & Block, P. (2013). Shaping Tension Structures with Actively Bent Linear Elements. *International Journal of Space Structures*, *28*(3&4), 127-135.

Ng, K. (2016). *Zcb bamboo pavilion.* [Online image] Retrieved May 3, 2018 from `https://www.archdaily.com/800173/zcb-bamboo-pavilion-the-chinese-university-of-hong-kong-school-of-architecture/5837dc93e58ece83500000fa-zcb-bamboo-pavilion-the-chinese-university-of-hong-kong-school-of-architecture-photo`.

Nilenius, F. (2017). *Course assignments for BOM170 - Structural Design.* (Course assignments, Chalmers University of Technology, Gothenburg)

Red oak pyramid bow. (2010). [Online image] Retrieved May 3, 2018 from `http://www.instructables.com/id/Red-Oak-Pyramid-Bow/`.

Rippmann, M., Mele, T. V., Popescu, M., Augustynowicz, E., Echenagucia, T. M., Barentin, C. C., ... Block, P. (2016, September). The Armadillo Vault: computational design and digital fabrication of a freeform stone shell. In *Advances in architectural geometry 2016* (pp. 344–363).

Schwinn, T., Krieg, O. D., & Menges, A. (2016). Robotic sewing: A textile approach towards the computational design and fabrication of lightweight timber shells. In *Acadia 2016.*

Seawolf Kayak. (n.d.). [Online image] Retrieved May 3, 2018 from `https://seawolfkayak.com/`.

SOFiSTiK. (2018). ASE General Static Analysis of Finite Element Structures [Computer software manual].

Struik, D. J. (1950). *Lectures on classical differential geometry.* Cambridge: Addson-Wesley.

Todisco, L., Fivet, C., Corres-Peiretti, H., & Mueller, C. (2015). Design and exploration of externally post-tensioned structures using graphic statics. *Journal of the International Association for Shell and Spatial Structures*, *56*, 249-258.

Werkarchiv Frei Otto im Südwestdeutschen. (n.d.). *Multihalle mannheim.* [Online image] Retrieved May 3, 2018 from `http://www.archplus.net/home/news/7,1-13346,1,0.html`.

A

Appendix 1

The following script shows a simple way of obtaining an approximation of a geodesic on a surface starting from a point and a direction vector. The step size governs the precision of the approximation.

```
private void Runscript(Surface srf, Point3d pt, Vector3d vec, double
   ↪ step, ref object geodesicPts)
{
    double tol = 0.0001;

    if(pt.DistanceTo(new Point3d(0, 0, 0)) > tol)
    {
      // Create list for points on geodesic line
      List<Point3d> ptList = new List<Point3d>();

      // Get closest point on surface to start point
      double u,v;
      srf.ClosestPoint(pt, out u, out v);
      Point3d srfPt = srf.PointAt(u, v);
      ptList.Add(srfPt);

      // Get start vector on surface
      Plane vecPlane = new Plane(pt,vec,Vector3d.ZAxis);
      Curve[] intersectionCurves;
      Point3d[] intersectionPoints;
      Rhino.Geometry.Intersect.Intersection.BrepPlane(srf.ToBrep(),
         ↪ vecPlane, tol, out intersectionCurves, out
         ↪ intersectionPoints);
      vec = intersectionCurves[0].TangentAt(0);
      vec.Unitize();

      for (int i = 0; i < 1000; i++)
      {
        // Get surface plane at point
```

```
        Plane frame;
        srf.FrameAt(u, v, out frame);
        Vector3d planeNormal = frame.Normal;

        // Take step along vector
        Point3d ptNext = srfPt + vec * step;

        // Project to surface along surface normal of previous point
        Point3d ptTemp1 = ptNext - planeNormal*100*step;
        Point3d ptTemp2 = ptNext + planeNormal*100*step;
        Line tempLine = new Line(ptTemp1, ptTemp2);

        Curve[] overlapCurves;
        if(!Rhino.Geometry.Intersect.Intersection.CurveBrep(tempLine.
           ↪ ToNurbsCurve(), srf.ToBrep(), tol, out overlapCurves,
           ↪ out intersectionPoints))
                    break;

                Point3d ptProj;
                try{
                    ptProj = intersectionPoints[0];}
                catch{
                    break;}

        // Get new vector
        vec = ptProj - srfPt;
        vec.Unitize();

        // Get new point and add to list
        srf.ClosestPoint(ptProj, out u, out v);
        srfPt = srf.PointAt(u, v);
        ptList.Add(srfPt);
      }

      geodesicPts = ptList;

    }
}
```