Hygromorphic Timber

Passive curving method for multi-layer structural timber floor elements

Msc Graduation Thesis Report

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MSc Architecture Urbanism and Building Technology
Master Track - Building Technology

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ABSTRACT

Due to carbon emissions and increased global temperatures, the need for carbon neutral materials is rising. As of 2024, the use of timber is growing rapidly. Still, timber is not the preferred material in the construction sector. As modern architecture is getting more complex geometries, 'fluid' construction materials like steel and concrete dominate the building sites. As timber has a straight geometry, making curved and complex shapes is not desirable. However, timber is a porous and hygroscopic material, it can absorb water from its surroundings and become more flexible. This characteristic has been utilized for over many centuries. By processing glulam or lvl beams or columns with steam or adhesives and clamps, curved structural elements can be manufactured. However, these bending methods are energy- and work-intensive and result in products which are not sustainable in terms of re-usability, recyclebility, etc. Furthermore, curved structural elements can be more efficient in terms of load distribution and material usage than the rectangular and straight counterpart. This thesis aims to research and develop complex structural curved floor elements produced with passive self-shaping.

After an initial bi-layer self-shaping test, multiple different typologies were designed, tested and compared with a conventional capped ceiling. Interconnections, treatment processes, assembly orders and timber species were investigated. For an efficient capped ceiling floor element, the curvature height to width ratio should be between 1/8 and 1/12. The elements designed and tested with both a water and a moisture treatment showed a maximum ratio of 1/45 or 26.8% of the 1/12 ratio. Meaning that it is possible to manufacture and produce a complex self-shaping floor element. There is much potential for the structural floor elements to reach the 1/12 ratio, however this could not be achieved during this research thesis.

Key words - Hygromorphic timber, Curved construction, Moisture content, Relative humidity, Passive bending, Active bending, Bi-layer, Timber construction, Timber typology, Self-shaping

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Furthermore, I would like to thank my parents, fellow students and friend who supported and helped me along these past weeks. Without there help, writing this thesis would have been an impossible task.

CONTENT

Introduction

Goals & Questions

1

The title of this master's thesis called; "Hygromorphic Timber - Passive curving method for multi-layer structural timber floor elements", enlightens the prosperity of & innovative thinking in timber properties and characteristics in order to contribute to a more circular and sustainable timber construction sector. The circularity in the design will merge different aspects like reuse, disassembly, reduce together. Conducting this research is a mandatory component for earning a master's degree within the Building Technology specialization of the MSc Architecture, Urbanism, and Building Sciences tracks at TU Delft. Structural Design & Mechanics and Product Design will be the scope of the thesis, with Stijn Brancart and Gilbert Koskamp consulting me for these chairs of program respectively.

1.1 *Type of architecture*

The typology of buildings is equivalent and shaped by the spirit of time. Simple huts primarily made from organic materials like timber, clay and animal materials in prehistoric times to robust and stable structures of wonder during the Egyptian times, the technology of the time influenced the way architecture was formed. The Romans were able to make incredible curved and round structures like the pantheon, with concrete. The Romans discovered that by combining lime and pozzolanic substances like volcanic ash with volcanic tuff and other aggregates, a durable, strong and moldable material could be created (Seymour et al., 2023). However, this construction knowledge was lost after the collapse of the Roman Empire, and this stable construction method could only be matched centuries later.

After the industrial revolution, concrete and steel production allowed to build structures in more profound and curved ways. This fascination of curved and organic free-form structures is part of the current structural typology. Architectural firms like Zaha Hadid Architects and Niko Architects are just an example of the many firms specialized in designing organic, curved and complex structures. As seen in figure 2, the Heydar Aliyev Cultural Centre located in Baku, Azerbaijan, is arguably the pinnacle of current organic and curved architecture. Steel and concrete are combined to make a curved architectural masterpiece, a landmark. Interestingly, arguably the oldest building material, timber is not a conventional construction material anymore.

There is a relation between innovation in the construction sector and the driving factor for new architectural topologies. These innovation can be on construction and building level. However the materials themselves can be researched and developed to have an impact on the type of architecture.

Figure 2: Heydar Aliyev structure. (Dispenza, 2011)

1.2 Problem statement

The construction and building sector significantly contributes to total global emissions, with an estimated impact of approximately 5.7 billion tons of CO_2, representing a range between 23% and 30% of the annual global emissions, as indicated by Huang et al. (2018) and Zhang et al. (2019). The 5.7 billion tons of CO_2 is linked to the life cycle energy and consist of two factors; The operational energy which is used for the occupation of the building and the embodied energy, used for construction, renovation and maintenance.

As the global human populations continues to expand, there is a corresponding demand for increased build environment. In the absence of changes to the current construction methodology, the global carbon footprint of the building sector is set to escalate. In times of potential human induced global warming effects, this continues process of current construction methods is ethically questionable.

Architectural issue

Complex building forms become more conventional in current times. From external steel diagrid structures to internal 3d printed columns, the architectural design is evolving in complexity (Willmann et al., 2016). This evolution happens rapidly, and the material adaptation needs to develop just as fast. As mentioned before, the Heydar Aliyev Cultural Centre located in Baku is arguably the embodiment of the current architectural evolution. A competition, set out by the Azerbaijan government, demanded a cultural centre which opposed the rigid and monumental Soviet architecture. Zaha Hadid Archtitects designed a building perpendicular to the profound present building environment.

However, the fluid motion of the exterior results in a lack of efficiency. By achieving this groundbreaking innovative and modern geometry, a reinforced concrete core structure with a steel shell was build. While these materials are affordable and commonly utilized, they pose environmental pollution concerns and lack viable options for circularity (Hradil et al., 2014). Architecture is progressing towards complex and modern geometries; however, the conventional building materials and construction methods fail to make a positive contribution to this transformation.

Material issue

To address the rising carbon footprint in the built environment, the choice to persist with materials that emit carbon rather than adopting carbon-neutral alternatives raises questions. Human engineered materials like steel and concrete contribute significantly to high concentrations of CO_2, NO_2, and other greenhouse gases. Transitioning from these unsustainable emitting materials to less environmentally impactful options, such as timber, presents a pathway for meaningful change.
Timber is an organic material which absorbs carbon dioxide in order to grow. In other words, the material has a negative carbon footprint. According to the Arbor Day Foundation, a mature tree can absorb approximately 21 kilograms of CO_2 per year. This would suggest that due to the global warming crisis, timber would be the most used construction material.

Nevertheless, due to long-standing fire safety concerns, the utilization of timber in the construction sector decreased, particular when reliable and safe alternatives like concrete and steel were widely available (Smith en Snow, 2008). While recent legislations have enhanced fire safety measures for timber, a substantial surge in timber usage has not been realised. This reluctance may stem from the timbers industry's challenges in meeting the growing demand for complex curved architectural designs, resulting in its continued insignificance when compared to steel and concrete (Grönquist et al., 2019)

As seen in figure 3, curving timber is a knowledge known to men for over many centuries. Not only ships implemented curved timber, also wooden barrels or the productions of bows are examples of the possibility to bend timber in desirable geometries. Currently, there are two conventional methods for bending timber. Cold bending which involves the use of clamps, glue, and a mold, while warm bending requires the timber to be steamed to increase its flexibility. Subsequently, the timber can be shaped into the desired geometry.
Both options are undesirable in their own way, labour intensive or using energy to make steam. Although, the production and design of complex curved timber elements can be realised, the method to do so is far from sustainable.

Circularity issue

Concrete, steel and other resources can become scarcer, therefore developing an efficient structural building element is key. Timber is known as an 'infinite' recourse, due to the fact that it grows back. Curved elements are known for being efficient in terms of load distribution and material usage. By combining both the material and the geometry in a new structural typologies may make the building construction sector more circular and sustainable.

Hygromorphic materials are known to absorb water. Timber is such a material, and will expend or shrink when moisture enters or leaves the material (Okuda en Sekida, 2001). Several studies have demonstrated the feasibility of achieving passive bending in timber through moisture control. An illustrative example is the Urbach Tower, depicted in Figure 4, where the University of Stuttgart successfully managed the swelling and bending of timber panels, resulting in a remarkable structural landmark standing over 14 meters tall. While bi-layer panels have been effectively curved using this method, it is noteworthy that various structural topologies employed in the construction sector can undergo alteration through passive bending techniques. The potential applications extend beyond bi-layer panels, suggesting a broader scope for innovation and transformative possibilities in timber construction.

Figure 3: The Oseberg Ship. (Ulleland, 2011)

Structural elements such as floor elements or columns and beams have not received extensive research attention in the context of hygromorphic bending. To make a substantial impact on the timber construction sector, it is crucial to carefully select the appropriate element for research and development. Identifying which timber element can be effectively replaced by sustainable, curved hygromorphic elements has the potential to revolutionize construction practices, thereby positively influencing the building industry. Moreover, existing studies have predominantly focused on the bending of bi-layer elements, neglecting the aspect of straightening these elements to enhance their usability and flexibility. Actively incorporating both bending and straightening processes for timber elements can positively impact their lifespan and contribute to the effectiveness of 'R'-strategies.

This thesis investigates the feasibility of bending a timber element using hygromorphic effects to enhance the versatility of the element. Through an examination of 'R'-strategies, various timber structural elements, curving methods, and the utilization of curved elements, a deeper comprehension of the issue can be achieved.

1.3 Design goals

A climate neutral society in 2050, this is the ultimate goal for the Netherlands. Achieving a way of life without excessive carbon emissions. This objective necessitates transformation in every sector, including the construction industry. However, the construction sector is characterized by conservatism, where alterations in production and building methods are infrequent. Despite the sector's resistance to adopting new technologies, there is a pressing need for change (Khan et al., 2023). The adoption of timber as a more conventional building material faces challenges in gaining traction, primarily due to competition from relatively inexpensive and well-established materials such as steel and concrete.
The objective of this master's thesis in the building technology sector is to develop a universally applicable, passively curved structural timber element. The aim is to encourage architectural firms, contracting companies, constructional design studios, and other stakeholders to embrace sustainable approaches in both design and construction practices.

The primary focus of this thesis will centre on the passive curvature of structural elements endowed with hygromorphic properties. Various alternatives, including boxfloor elements, solid timber beams, LVL-beams, GLT-beams and others, will be thoroughly examined and considered. The secondary emphasis of this thesis involves altering the sustainable characteristics of timber, with the aim of minimizing the consumption of drying energy, adhesive usage, and waste management, aligning with the principles of 'R'-strategies. Following the research-by-design principle, this thesis will investigate the materials behaviour and will base its conclusions on physical results.

1.4 Research questions

To understand the overall complex issue and guide the research into the right direction the main question needs to be answered. The primary research question for this thesis encompasses the objectives of creating a new self-shaped typology:

How can curved structural floor elements be created based on self-curving hygromorphic bi-layers?

The sub-research questions support the thesis research by elaborating different sub elements of the main thesis:

How can curved timber elements be implemented in the build environment?

How do structural curved typologies contribute to sustainable architectural designs?

How will hygromorphic characteristics curve structural timber elements?

How does the assembly-order influence the self-shaping curvature height?

Figure 4: The Urbach tower. (ICD/ITKE University of Stuttgart., 2019)

1.5 *Methodology*

This chapter will embark upon how the methodology was employed during the study. An explanation is given on the area of the study, and the reasons for this particular area. These chapters will elaborate on the research by design and approach, sample procedures, methods for data collection and analysation, and material validation.

Research design

As described by Kothari (2004), research design is the conceptual structure within which the research is conducted; it collects data and analyses it, which are relevant to the study. The design is made up of hypothesis final data analysis and operational implications. Due to the fact that practical experiments will likely happen later on, the approach and type of design are influenced. Furthermore, research by design plays a key role in understanding and developing new insights. Trying to create new building structures by research through design consequently has an impact on the overall research design. The research design for this study therefore will use an ethnography type of design to ensure a reliable outcome.

Research approach

According to Kothari (2004) the research approach can be divided into qualitative and quantitative approach. A quantitative research approach is achieved by qualitative data collection, usually provided by a survey, questionnaire or a different kind of input source. Respondents can also add additional information in order to provide more depth to the given quantitatively response. The qualitatively research approach focuses on the researches ability to subjectively assess information and results. This research will follow a qualitative approach, due to the fact that input and results are collected by test.

Type of design

As the qualitative approaches is most suited as a research approach for this study, the type of design may depend on multiple criteria. Due to the research by design, real-life models will be constructed and tested, not only by strength but also by form, looks, usability. These different results will lead to understanding the study problems. The Quasi-experimental design type may be adequate to guide the study to a relevant and reliable conclusion. The quasi-experimental design type has multiple purposes and characteristics. Outcomes are compared to pre-existing sample groups.

Data collection method

As stated before, the aim of this study is to design a new circular and sustainable curved structural typology by using hygromorphic properties. Physical sciences, which uses scientific instruments to collect data, will contribute to this eventual aim. Data like strength, pressure, deformation can all be measured by the physical science method. However, these measurements can only be conducted by the right equipment. The TU Delft has multiple science labs where tests can take place. There, physical appearances can be measured.

Academic development

Research into the development of self-shaping hygromorphic timber elements is not new; therefore, this thesis must contribute something novel to the field to avoid redundancy. While the development of self-shaping bi-layers is well-documented and researched, the exploration of multi-layer structural elements is relatively unexplored. In this thesis, various typologies of boxfloor elements are examined and further enhanced to exhibit self-shaping characteristics. Through real-life testing, conclusions will be drawn regarding the feasibility of manufacturing efficient self-shaping beam or boxfloor elements.

The primary distinction from previous research lies in the interaction between the elements themselves rather than solely focusing on the shape or curvature produced by a bi-layer. Questions such as whether the elements can enhance or constrain curvature, differences in the introduction of moisture into the wood, and which shapes display promise in curvature are explored. Figure 5 illustrates the difference of this thesis compared to other relevant research, highlighting a significant difference in the product design and ultimately leading to new outcomes.

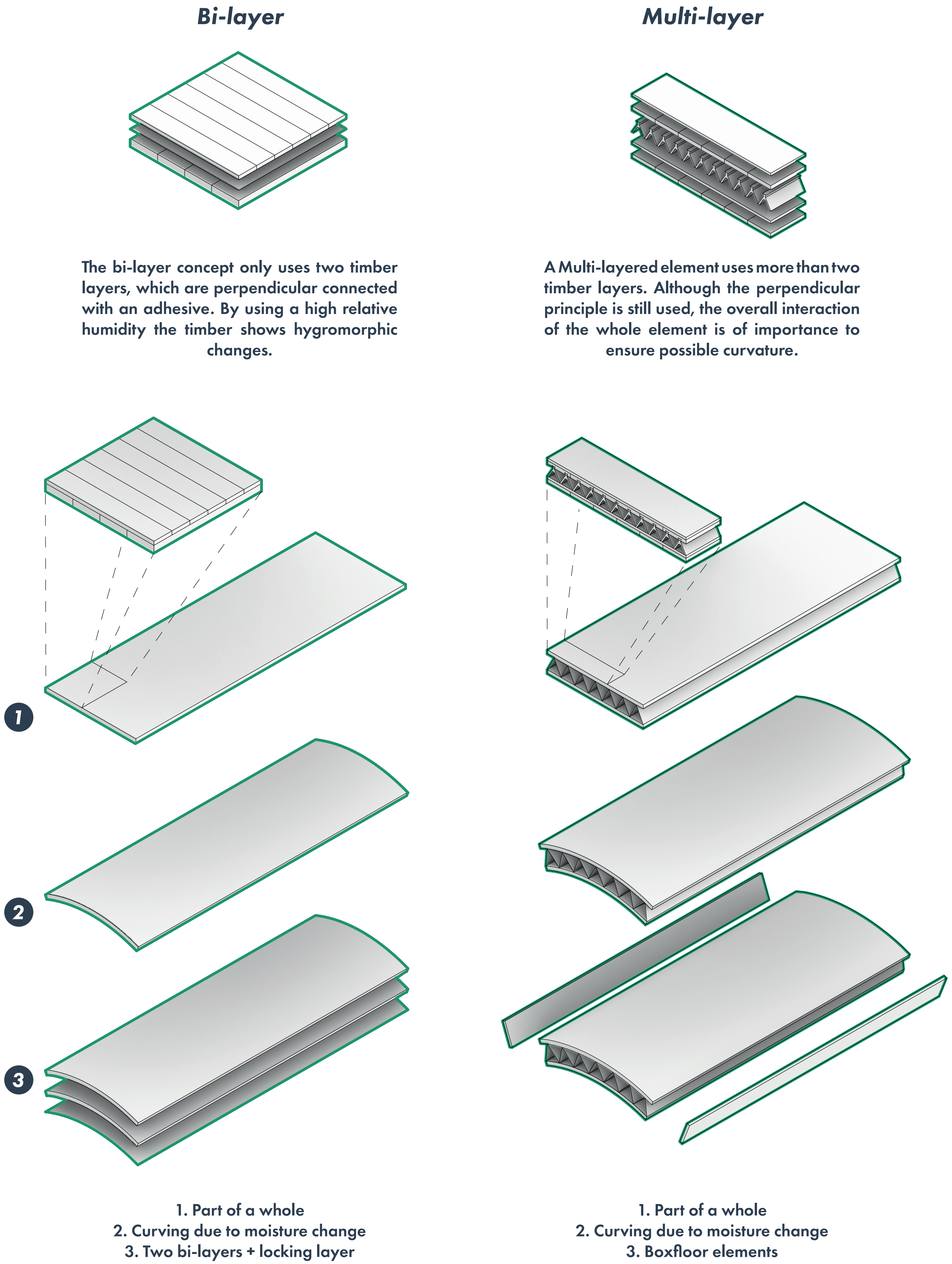


Figure 5: Methodology comparison

Sustainability

Circular product design

2

In a world undergoing drastic changes driven by escalating emission levels, the selection of the appropriate building material holds the potential to positively influence this transformation. It is widely acknowledged that industrial materials such as concrete and steel contribute significantly to excessive CO_2, NO_2, and other hazardous emissions. Nevertheless, these construction materials are the most widely utilized globally. Converting towards less pollutant alternatives, like timber, is a viable option. However, timber bears an unfounded stigma. While it possesses the capability to absorb CO_2 and produce O_2, resulting in a carbon-positive footprint, the sustainability of timber lacks prosperity. Waste management practices and design decisions play a role in distorting the overall picture. These aspects will be explained in the subsequent chapter.

2.1 *Drying emissions*

Logistics within the timber sector presents a challenge, with emissions produced by transporting cargo between forest, kiln, and building site, necessitating the use of motor-powered vehicles such as trucks, trains, and shipping boats. It is worth noting that this logistical challenge is not exclusive to the timber sector and is similarly relevant to the concrete and steel industries. Consequently, this aspect of the timber sector is deemed irrelevant to the scope of this thesis research, focused on designing more sustainable elements.
When a tree is freshly cut its moisture content varies between as little as 40% to values over 200%. When the tree is deprived of its natural supply of water through the roots, it dries to the surrounding moisture content at around 6% in dry environments and 20% in humid climates, provided that the material is protected form direct water contact such as rain and other moist materials. It is expected for timber to shrink when dried below the fibre saturation point (Langrish en Walker, 2006).

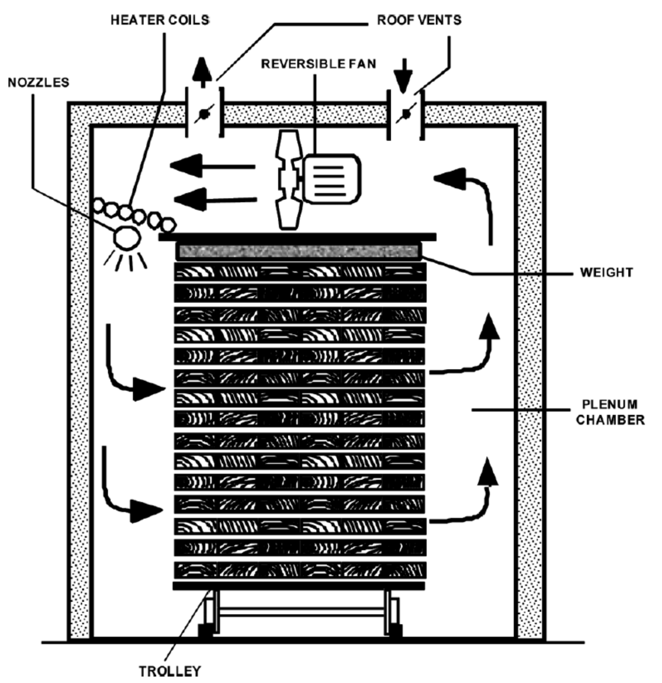


Figure 7: Details and process of conventional drying kilns. (Perré et al., 2012)

In order to safely use timber for the building environment, it needs to be dry. Unexpected moisture in timber results in unwanted mold forming, deformation, splitting due to internal stresses and loss in structural strength (Langrish en Walker, 2006). Different drying methods exist, like using drying kilns or air-drying stocks. Kilns are the most conventional way to reduce moisture in timber due to economical and time factors (Perré et al., 2012, Langrish en Walker, 2006). Air-drying can cost precious time, as it can take months or even years for stocks to dry, which consequently makes this method economically uninviting.

In general, kilns are closed buildings where humidity, temperature and air flow can be controlled. As seen in figure 7, a conventional kiln commonly has fans for circulating the air, heating coils for air temperature regulation, roof vents for moisture control and water or steam nozzles as extra humidity measures. These steam or water nozzles are mainly used in the beginning of the drying process (Perré et al., 2012) . The heating coils and steam nozzles in the kilns, however, use different kinds of pollutants like gas, coals or waste wood to generate the energy needed to reduce the moisture in the timber stock. (Langrish en Walker, 2006). This amount of energy is related to the time required for a specific timber characteristics. Depending on the type of timber, thickness of the boards and the days it needs to be dried, the average energy needed to dry timber is around 2.73kWh.kg1 (Perré et al., 2012).

Many existing bending techniques necessitate the re-moistening of dried timber to facilitate the curving of elements. This repetitive drying process leads to the generation of excessive emissions. Exploring the potential integration of the curving method with the initial drying phase holds promise for reducing the overall carbon footprint of timber. However, it is crucial to acknowledge that the drying process is necessary to ensure a reliable and adequate quality of timber, and as such, it remains an essential step that cannot be bypassed.

2.2 *Waste*

The way the build environment is constructed & designed has a significant impact on how sustainable a material is. By reducing the need for materials due to structural optimisation or improving the structural element typology, material waste in the building sector can be lowered. As seen in figure 8, 5% of concrete and 1% of steel used as a building's structural frame ends up at landfills. This percentage is admirable for materials known for its lack of sustainability. Contradictory, approximately 58% of all timber building structural elements end up at landfills (Hradil et al., 2014). While the material itself is sustainable, the issue lies in how we handle and treat it. A-wood is known as unprocessed timber and can be commonly found in the packaging industry. In 2015, A-wood was responsible for 124 kilotons of waste wood. B-wood is usually a construction type of timber, like multiplex and triplex or LVL and CLT. In 2015, B-wood was the largest contributor to annually national timber waste in the Netherlands, with over 1250 kilotons of waste. It has to be said that the B-wood waste flow consist of a combination of A-wood, B-wood and timber packaging (van Bruggen & van der Zwaag, 2017).

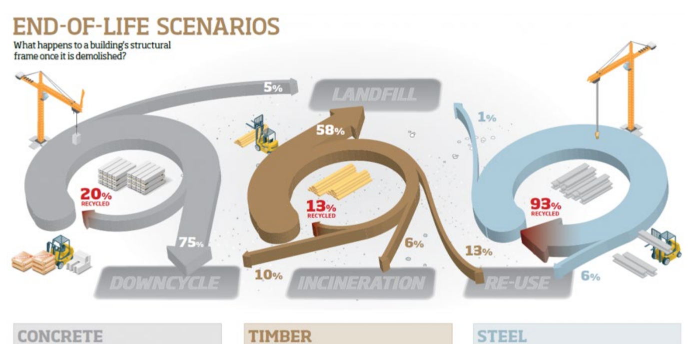


Figure 8: An example of end-of-life scenarios for concrete, timber and steel from building. (Hradil et al., 2014)

Eco-efficiency emerges as a potential solution for minimizing overall timber waste, embodying the principle of accomplishing more with fewer resources. It encompasses two essential components: eco-innovation and resource efficiency. Resource efficiency, a sub-part of eco-efficiency, involves the more effective (re)use of resources within the economy. Simultaneously, the development and utilization of elements that promote the optimal use of resources constitute eco-innovation (Hradil et al., 2014).

Addressing the challenge of reducing the 1250 kilotons of timber deposited in waste landfills involves tackling various obstacles. Among these challenges is the increase in the production of curved timber elements, leading to an excess of waste. The conventional bending method does not serve as a practice for waste reduction. Processes like molding and reshaping through cutting, all contribute to generating excessive waste, much of which ultimately finds its way to landfills.
However, innovative forming methods are known to reduce waste material by milling (Grönquist et al., 2019). Hygromorphic bending is an eco-innovate forming method, which utilises the expansion and shrinkage of timber due to relative moisture content within its fibres and cells. As a result, the inherent self-forming properties in the timber element eliminate the need for molds. Furthermore, efficient typologies can be constructed and designed which may reduce the usage of the material itself.

The timber sector encounters a significant challenge in mitigating waste at the end of the product life cycle. As mentioned earlier, the current 58% of timber ending up in landfills requires reduction, while alternative pathways depicted in Figure 8 must be expanded. Promoting practices such as down-cycling, reusing, and recycling is vital for decreasing overall waste generated by the timber sector and enhancing its sustainability. Terms like "reusing" and "recycling" are part of a terminology used in the sustainability sector to increase the overall life-time of products.

2.3 'R'-Strategies

The PBL Netherlands Environmental Assessment Agency published a report outlining nine strategies, referred to as the "R-strategies," designed to diminish raw material consumption and minimize waste production (PBL Netherlands Environmental Assessment Agency, 2018). The term R-strategies is well known in the circular design sector. The term can be divided in 3 different circular approaches that divine the different steps towards a more sustainable product.

Smart manufacturing is the first circular approach and require the largest mentality shift in order to make a significant impact. Refuse, Rethink and Reduce form the base of this first approach. Refuse aims to make elements expendable and thus creating a void only to be filled by a different element or completely cancelling its function. Rethink implies a focus on maximizing a products utilisation. Lastly, producing elements with fewer raw material applies to reduce (Ioannou, 2023). The second circular approach aims to prolong the product's service-life by improving the Reuse, Repair, Refurbish, Remanufacture and Repurpose opportunities. Reuse endeavours to achieve that different users employ discarded products for the same purpose. Repair pursues the philosophy of preserving broken elements in its original state. Refurbish and remanufacturing mainly have the same objective, modernize old products by replacing old part or dismantling the product itself. Finally, the use of old products in new functions follows the idea of repurposing.

At last, the third stage of the R-strategies which is focused on end-of-life scenarios. The last two strategies are recycle and recover. Recycling implicates processing of materials derived from discarded products. Although, this is the most recognized R-strategy, its feasibility is not always assured. In numerous instances, it is energy-intensive and necessitates chemical or mechanical treatment. Recover is the final strategy and is irreversible. Energy is being extracted out of the material by burning, and therefore destroying the material.

As seen in figure 9, the nine circularity strategies are shown in chronological order, from beginning to end of life. The timber construction elements are not known for their circular properties. As mentioned in chapter 2.2, over 58% of all structural timber elements end up at landfills, and usually being incinerated to recover energy. Yet, there are a many opportunities to change this non-circular stigma. The process of manufacturing and designing new structural elements can be re-thought. By making typologies more efficient, the total amount of material used in an element can perhaps be reduced.

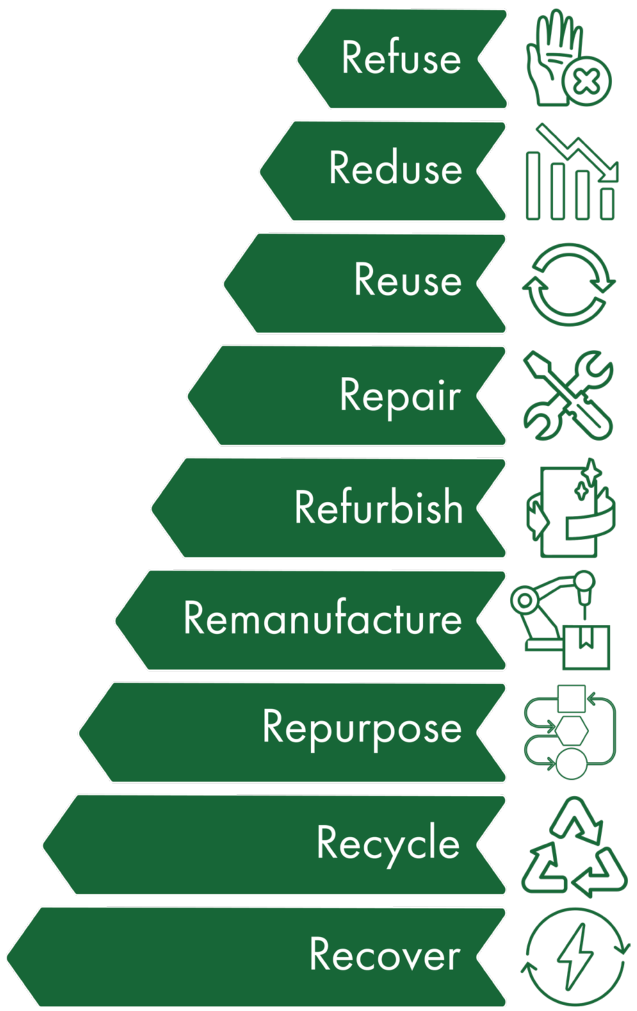


Figure 9: The nine 'R'-strategies

Nonetheless, these curved structural timber elements, such as floor elements, LVL or GLT, employ various adhesives to bind different layers together and form a robust and stable beam or column. The question arises: How harmful are these adhesives to structural stability and, furthermore, to the principles of the R strategies?

2.4 Adhesives

One of the downsides of a wooden log is its dimensions. The dimensions of concrete and steel are relatively fluid and therefore can be produced in the form which is desirable. However timber dimensions are fixed to the shape of the original tree trunk. Though the years, different structural timber elements were designed & developed to be compatible with their concrete or steel counterparts. A few of these elements are; Cross laminated timber slabs (CLT), glue laminated timber beams (GLT) or laminated veneer lumber elements (LVL). These elements are all constructed of multiple different timber parts bound together with adhesives.

One of the first patented adhesive technology is the 'Hertzer Method', dating from the 1900s (figure 10). The adhesive used in the system had only an interior purpose, as the adhesive was not waterproof due to its high humidity weakness. Further adhesive technology development, resulted in the creation of synthetic resin adhesives, capable to resist water and encouraged the usage of glulam timber structural elements in exterior projects like bridges or high humidity environments like swimming-pools (Moody et al., 1999).

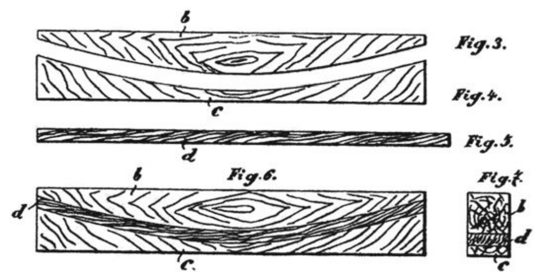


Figure 10 Otto Hetzer's patent. (Hetzer, 1905)

The current glulam manufacturing sector uses multiple types of adhesives. The most commonly used adhesives for lamination bonding are: phenolic and aminoplastic adhesives, one-component polyurethane (PUR) moisture curing adhesives and emulsion polymer isocyanate (EPI) adhesives (Ong, 2015).
There are different adhesive classification types, determined by the end-use in the three different service classes; type I or II. Service class 1 is an interior atmosphere where the fast majority of softwoods does not exceed an average moisture content of 12%. The second service class is a protected exterior environment, like roofs, where the average softwood does not exceeds more than 20% moisture content. Service class 3 describes an exterior atmosphere where the average moisture content of timber does not exceeds the service class 2 value.

Although, by using adhesives on timber elements they are compatible with their steel and concrete counterparts, the use of adhesives can have major drawbacks, especially in the R-strategy sector. By using adhesives to bond different timber elements together, the overall structural element becomes a solid part. This means multiple circularity strategies are excluded. Especially the reuse and refurbishing of curved timber elements, the research scope this thesis is focusing on, is effected. Still, adhesives are needed to maintain a strong structure shape. Therefore, excluding adhesives all together is not an option.

So, the main contributors for timber to be an unsustainable materials are the drying process, the amount of waste created by the way of designing and producing, use of adhesives and the lacking mentality to introduce the R strategies into the product design methods. Curving timber with hygromorphic properties may solve part of these issues, as it can reduce drying emissions, is less wasteful as conventional curving methods and can integrate the R strategies into its design and production method. Here the question arises; *How do structural curved topologies contribute to sustainable architectural designs?*

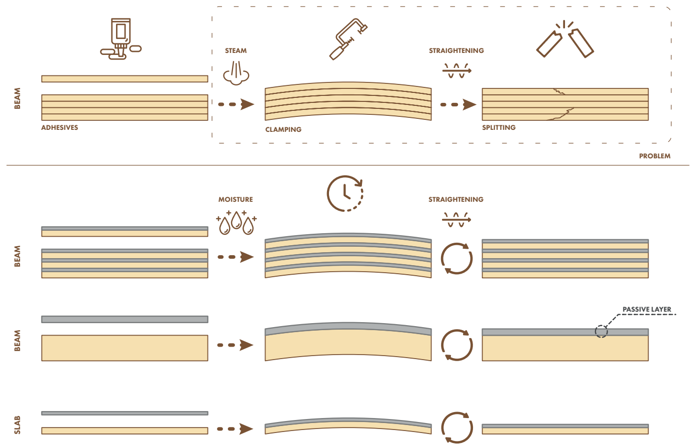


Figure 11: Strategies to design and develop sustainable structural timber elements.

Typology

Elements & Shaping

3

As there are multiple sustainable opportunities for timber, the typology and how we implement timber elements in the build environment can have an significant impact. To understand where sustainable steps can be made, the different timber elements need to be known. Most of these topologies have a straight geometry. The amount of options for curved elements are negligible. The method to curve timber and the purpose of curved timber elements has shifted into a more modern approach. Furthermore, new techniques to curve timber are being researched and developed.
This chapter will describe the conventional structural typologies and there curved possibilities, as well as the state of the art passive curving method, called hygromorphic expansion bending. How is it utilised and what is passive/active bending?

3.1 *Conventional typologies*

Throughout centuries, timber has been a main material in the construction industry. Its wide availability, organic nature, semi-straight form, and inherent strength make it an ideal material for crafting rigid structures. Initially, due to the natural geometry of tree trunks, columns and beams emerged as fundamental structural typologies. As technology advanced, processing methods evolved, allowing for the transformation of logs into slabs and smaller pieces. This breakthrough facilitated a increase in structural typologies, leading to the widespread availability of floor and roof panels, as well as the development of innovative structural elements.

In the construction industry, timber applications can be broadly categorized into two subcategories: mass timber systems and lightweight timber frame systems. Mass timber components are engineered timber elements utilized as the primary structural system in buildings. These components comprise smaller parts bonded together to form rigid load-bearing elements such as beams, columns, and panels. Over the past two decades, there has been a notable increase in the global popularity of mass timber components, driven by their sustainable and carbon-positive attributes (Thistleton, 2023). The enhanced load-bearing capacities of these engineered elements have significantly expanded their implementation range. Moreover, the prefabrication of these elements off-site provides increased processing opportunities. Currently, the three most utilized mass timber elements in mid- to high-rise buildings are panellized systems, post-and-beam systems, and volumetric modular systems.

Lightweight timber frame components represent adaptable and efficient systems crafted from standardized structural sawn timber, combined with sheet panels such as plywood or OSB. These components are favoured in the construction sector due to their cost efficiency, construction speed, quality, and availability. Off-site manufacturing is the predominant construction method, where sawn timber elements are assembled using nails or screws to construct stairs, walls, floor, and roof slabs, essentially forming the 'skeleton' of a structure. While site assembly may still be required, lightweight timber systems are recognized for their safety, sustainability, and efficiency, particularly in low-rise constructions (Thistleton, 2023).

As seen in figure 13, an overview of the most conventional structural timber typologies used in the build environment are showcased. This thesis focuses on developing and researching passively curved mass timber or slab components.

3.2 *Beams*

Beams are known for supporting roofs, floors, and spanning large distances. A conventional beam has a rectangular geometry and can span several meters. Wooden beams used to be made from one solid timber piece. In the late 1800s one of the first glulam elements were created (Issa en Kmeid, 2005). After this moment in time, the method of using glulam timber is more conventional. In the 1980s, the use of glulam was booming, with countries like Finland, Norway and Denmark using over 8,000 m3 of glulam per million inhabitants (Abbott en Whale,1987). Currently LVL and GLT beams are the preferred choice in constructing timber buildings (Thistleton, 2023). LVL and GLT beams are constructed by stacking multiple wooden elements and using an adhesive to bind them all together, however there are distinctive differences in each option.

Laminated Veneer Lumber

LVL is an engineered mass timber elements consisting of veneer layers. These thin layers, usually 3mm thick, are extracted form a log by rotary- or plain-cutting, creating veneer slabs parallel or perpendicular with the grain (Holstov, Morris, et al., 2015b). This cutting method is done under heat and pressure. LVL is known to be one of the strongest mass timber components and is roughly twice as strong as its steel counterpart, in proportion to weight (Thistleton, 2023). LVL beams can both be manufactured in softwood and hardwood. However, the type of wood has effect on the overall geometric dimensions. Hardwood LVL beams can be produced up to 18m x 1360mm x 300mm. Softwood LVL beams can be manufactured with a longer overall span, but a smaller width; max. 24.5m x 2400mm x 75mm.

The production of LVL beams is not bound to a specific timber species. The hardwood elements can be produced with beech and birch whereas the softwood components include larch, fir, spruce and pine. For the manufacturing of LVL the mandated European standards BS EN 14374 and BS EN 14279 are required.

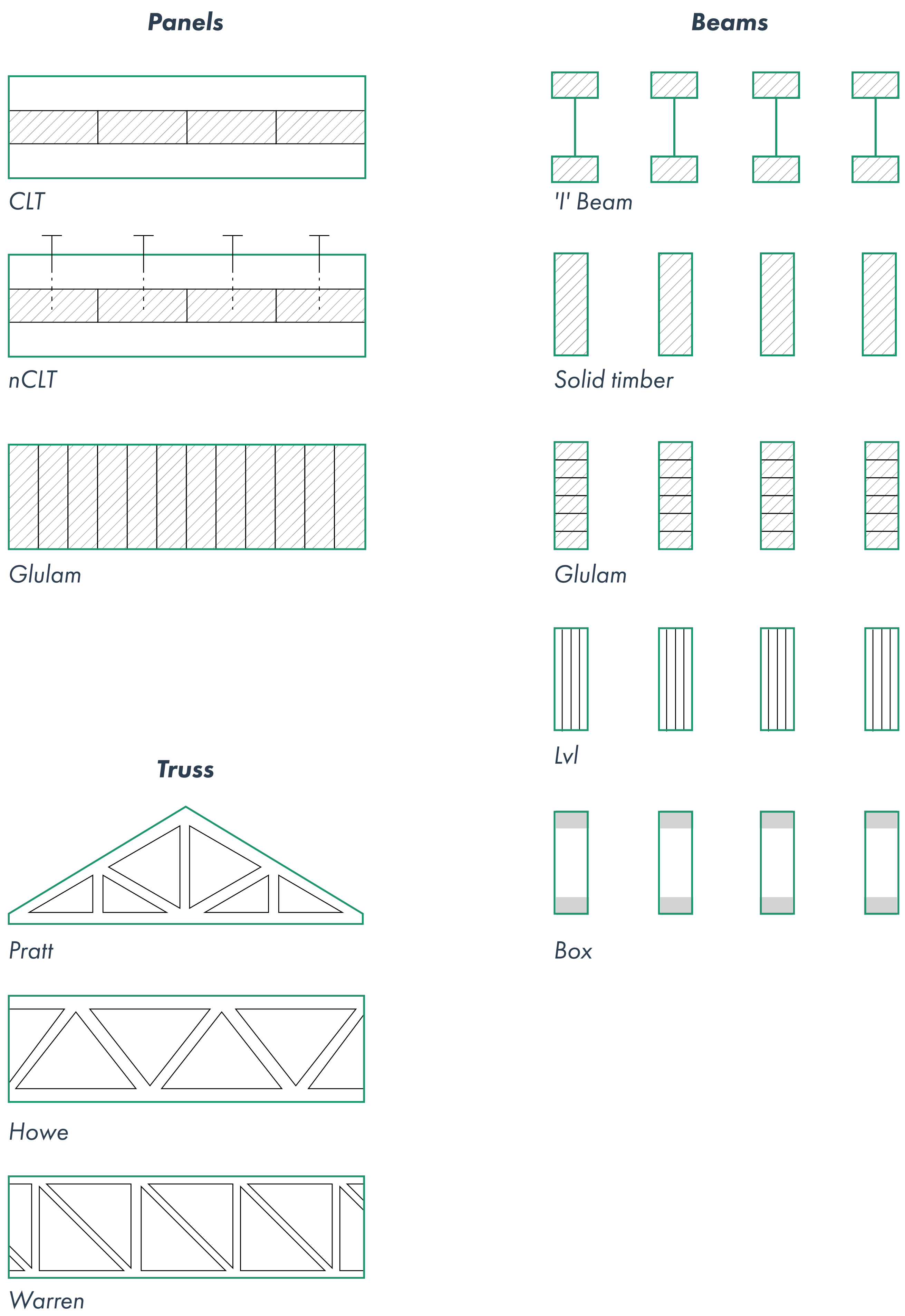


Figure 13: Different structural timber typologies

Glued Laminated Timber

GLT also known as glulam or glued laminated timber, is a mass timber structural element which is manufactured by bonding timber planks together with adhesives, thus creating beams and columns. The strength graded timber elements, usually interlinked with finger-joints, are glued parallel of each other to form a beam. GLT beams are commonly used to span large distances and therefore can replace steel and concrete. Conventionally the geometry is straight, however curved alternatives are also being used in the construction world.

GLT beams are typically manufactured with a width increment of 40mm, and they come in standard sizes ranging from 80mm to 280mm. Additionally, the height of these beams does not exceed 1280mm, and their maximum span is 18 meters. However, it's worth noting that customizing the shape and size of GLT beams is not uncommon. There are multiple strength classes available; GL24, Gl28, GL32 and GL36. It should be noted that every element utilized in a GLT beam must bear a CE marking, as mandated by European standards BS EN 14080 (Thistleton, 2023). The commonly used wood species in GLT beams for interior use include spruce, fir, larch, and pine.

3.3 Columns

Columns are used to transfer loads and additional forces to the foundation. The most efficient transfer pathway is linear, resulting in straight typologies found in almost every utility building and residential developments over 5 stories. However in single story buildings, like terraced houses, columns are unconventional . Nevertheless, curved or bend columns is not unheard of. Lukkaroinen Architects responsible for the Pudasjärvi School design, designed the largest known log building in the world. Inside the campus, different columns types are used, from standard straight columns to Y-shaped timber elements. They also developed a 4-way curved column contraption reaching a height of over 11 meters (Figure 14). These glulam columns, manufactured by Kontio, all have the same curvature (Pudasjärvi Log Campus | Lukkaroinen, 2023). Timber columns could also be manufactured with laminated veneer lumber. By shifting the slabs grain in the optimal direction, LVL could function as a beam and as a column.

Considering the current negligible demand for curved columns, the potential impact of sustainable passively curved columns is also limited. Therefore, the column typology will not be the primary focus of this hygromorphic curved timber thesis.

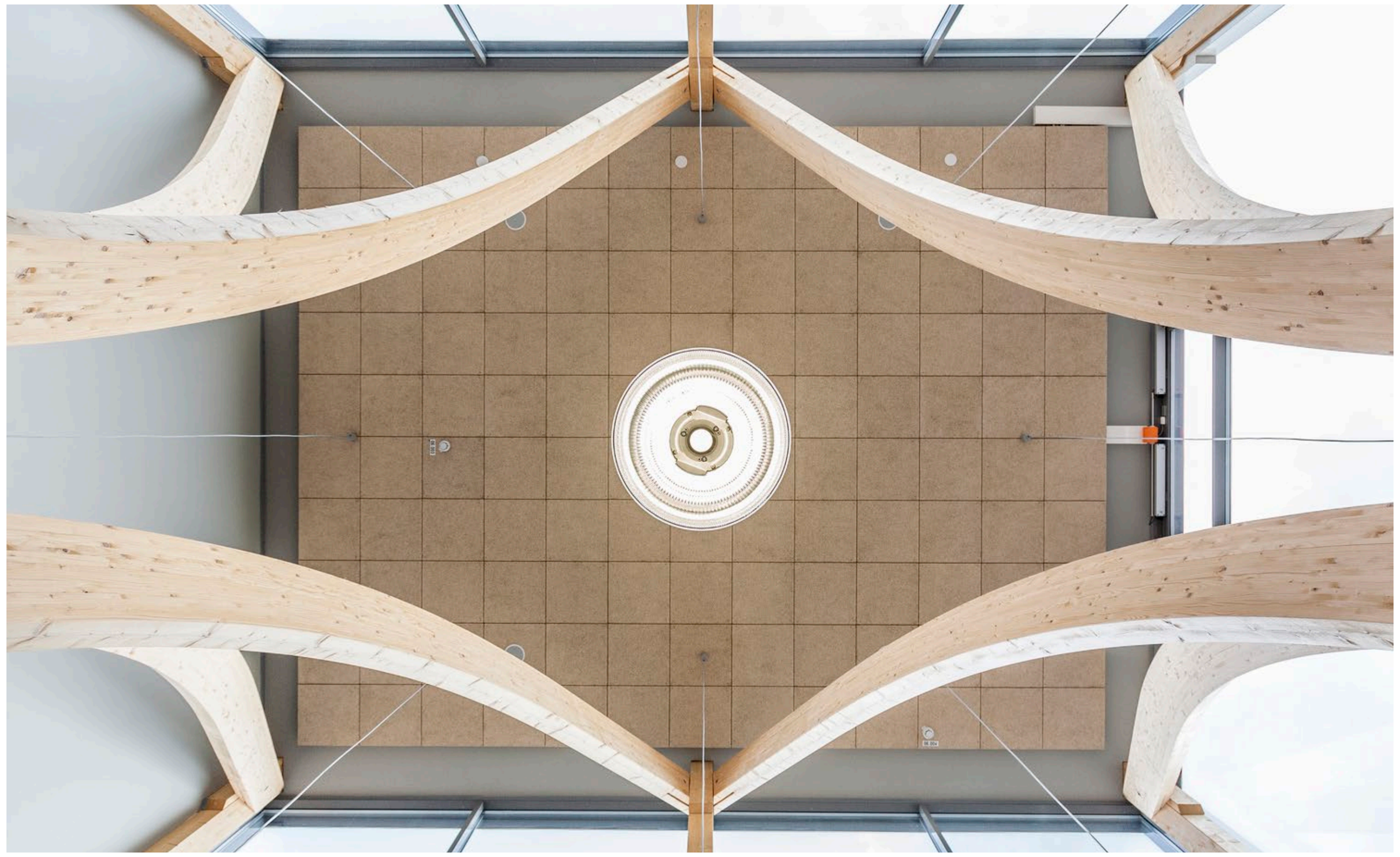


Figure 14: Curved columns (RA-studio Raimo Ahonen, z.d.).

3.4 Slabs

Panels are commonly used as floor and wall systems, but can also function as structural stair material or be used in finished facade elements. The most profound panel system is Cross Laminated Timber (CLT). In the 19th century, the first development of products with laminar laminated timber were made (Brandner et al., 2016). This research and manufacturing mainly took place in central Europe, specifically in Germany, Austria and Switzerland. Over the past few decades, the production intensity was increased from small scale to industrial manufacturing. This is partly caused by the introduction of the CLT European product standard EN 16351 (Brandner et al., 2016; Thistleton, 2023). Another contributor to the increase of production is the fact that CLT panels can compete with reinforced concrete. Moreover, the sawmill industry was motivated to find a more efficient use of side-boards (Brandner et al., 2016). Furthermore, CLT is also included in the Eurocode 5. Worldwide production in 2014 increased to 625.000m³ and as of 2020 this production grew to over 2.000.000m³, as seen in figure 15 (Muszynski et al., 2020).

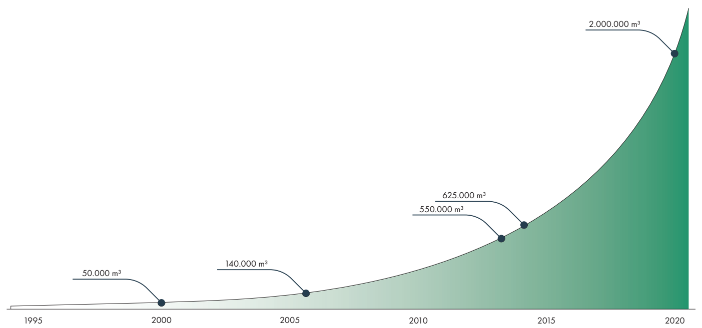


Figure 15: Worldwide CLT production (Muszynski et al., 2020).

Although the manufacturing of CLT elements is comparable with glulam, in terms of structural integrity CLT can span in different directions whereas glulam elements cannot. CLT is manufactured by a perpendicular layering method of boards or panels, usually 20 to 40 mm thick, glued and pressed together. Common dimensions of the engineered timber product are a length of up to 18 meters, thickness of 300 to 400 mm and a width of approximately 3 meters. CLT panels are standardised with uneven layers, where 3, 5 and 7 layers are most conventional (Thistleton, 2023).

Materials used in CLT panels are adhesives and timber. The kind of timber species may very, however the most commonly utilized timber species are; Pine, Spruce, Fir and Larch. CLT panels have different strength gradings, nevertheless CL24h and CL28h are standard, whith $f_{t,0,l,k}$ = 14.0 N/mm² and $E_{0,l,mean}$ = 11.000 N/mm². Bendingstrength is higher as tensile strength with 24 and 14 respectively (Brandner et al., 2016).

Over the past few years, the research and development of hygromorphic curved timber elements was implemented in bi-layer elements. This development shows great potential. Therefore, developing and research in CLT elements is less attractive due to the fast availability of papers. Panels will therefore be excluded in this master thesis, due to the absence of a research gap. However, more complex multi-layer and floor elements could be developed further.

3.4 Truss

Truss systems are a structural typology often used to span large distances. Due to this specific characteristic, the use of truss system is limited. Truss systems can be implemented in large warehouses, airports, gymnastic-halls, etc. Also, smaller timber truss systems can be found in roof structures for houses, with smaller span distances. The geometry of truss systems differ, as there are multiple different truss typologies. For larger distances, a conventional Howe, Pratt or Warren truss is typically used. Truss systems for roofing usually have more profound geometries, like the Queen post, Fan or Arch system. Most truss types contain straight elements, some mounted diagonally, still curved elements are not the conventional construction element in trusses.

Only the Arch system shows some form of curved element in the geometry. This makes the overall potential for curved timber elements insignificant, besides the use of truss systems is limited. It is advisable to exclude truss systems in this master thesis' research as per the last arguments.

3.5 *Curved timber*

The efficient distribution of loads through curved geometries is a well-established principle. This concept can be harnessed by incorporating curved geometries into the built environment. Even in ancient Roman times, curved and round objects were utilized, as exemplified by the Pantheon. Still, this geometry was realised with liquid concrete. The curving of solid timber objects was only achieved several centuries ago. In modern construction practices, the preference is often for the easiest and safest options. Clients typically request timber products to be as uniform as possible, with the need for reliable and stable characteristics to compete with materials like steel or concrete (Teischinger et al., 2023). The most traditional form of timber elements is the straight typology, largely influenced by the natural geometry of its source, the log (Bader and Ormarsson, 2023). Nevertheless, the straight typology is suboptimal and leads to the excessive use of material, a concern that can be mitigated by selecting the appropriate form (Strozzi et al., 2018) (Aziz et al., 2023). As seen in figure 16, curved capped ceilings use less material than a conventional rectangular slab. This principle of arched and curved elements being more efficient in terms of material usage and load distribution can be used in the timber sector. However, the method to bend different typologies may vary and be unsustainable. In the current timber sector there are two sub-categories in timber curving techniques; Active bending and Passive bending.

3.6 *Active bending*

As stated before, timber elements are often straight configurations. This is because of the source material, a regular tree. However moist timber becomes relatively flexible. This means that shaping timber into different configurations is possible. The earliest instances of curved timber elements date back centuries, exemplified by objects like curved bows, wooden barrels, and bent wooden plates on ships (Sandberg et al., 2023). As evidenced by these historical examples, the utilization of curved timber elements has been predominantly observed in everyday objects rather than in the built environment, where their structural significance is considerably less pronounced.

Conventional bending

It is widely understood that elements with structural significance typically exhibit larger dimensions. Given the interconnection between the second moment of inertia and the energy required to bend an element, a larger cross-sectional area necessitates more energy. The second moment of inertia is related to the width and thickness of an element. However, double the height is not equal to double the force needed, as height (h) will effect the I_y by the power of 3.

$$I_y = \frac{wh^3}{12} \tag{3.1}$$

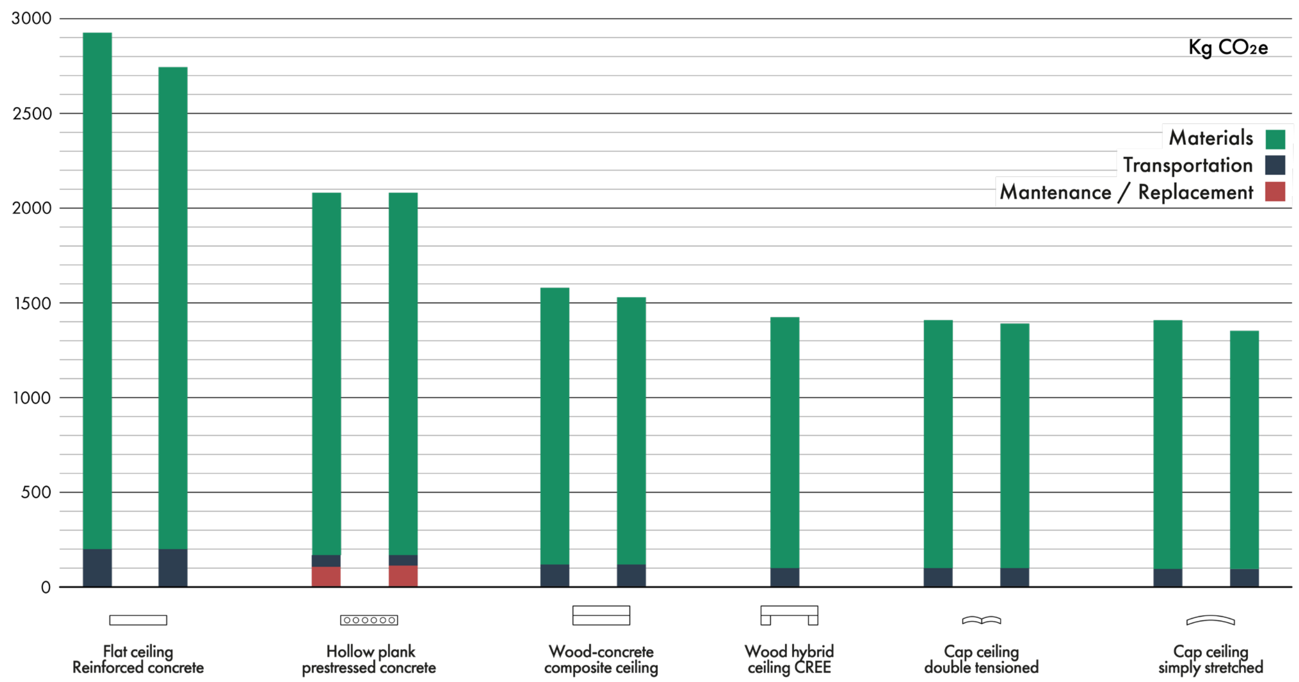


Figure 16: CO_2 emissions per slab configuration (Aziz et al., 2023).

Consequently, solid timber pieces are prone to shattering or breaking when subjected to bending forces. The phenomenon of timber elements shattering or splitting under applied forces was observed by engineers centuries ago. However, when timber elements are moist, either freshly cut or having been in contact with water, they exhibit plasticization (Wright et al., 2013). This led to the practice of placing timber in humid environments to enhance its flexibility. It is essential to note that the optimal temperature for these humid environments should not exceed 160°C, usually produced by steam, as temperatures beyond this threshold may lead to a loss of strength (Sandberg et al., 2023). Furthermore, traditional atmospheric steaming is undesirable due to its non-uniformity, time-intensive nature, and the potential for failure. Achieving uniform plasticization, resulting in less brittle timber, can be accomplished through the utilization of vacuum steam technology (Wright et al., 2013). Kiln-dried timber is favoured as bending material because it contains minimal moisture, reducing the risks of splitting and checking. However, the dry state of the material necessitates increased steaming time. This phenomenon can be attributed to diffusion, a process wherein molecules can move to different areas through molecular pathways. Timber's intricate longitudinally and radially oriented molecular pathways result in rate-limited diffusion (Wright et al., 2013).

Glulam

The most conventional types of glulam are; Laminated veneer lumber (LVL), Cross laminated timber (CLT) and Glued Laminated Timber (GLT/Glulam). As seen in figure 17, the dimensions and directions of the timber elements differ per topology. Due to the two different slab orientations, CLT thrives in spanning in multiple directions and therefore mainly used as floor & roof slabs. LVL consist of paper thin timber slabs, cut from a log, glued together. Positively, almost all the material of a log is used, however lots of adhesives are used. Floor slab as well as beams can be produced with this topology.

As per Bhooshan et al. (2023b), the glulam lamella can achieve a radius of curvature that is 200 times the thickness of the lamella. The inherent flexibility of the lamella, even during the gluing process, provides the opportunity for curving large structural timber elements (Bhooshan et al., 2023b). However, the prolonged drying period of adhesives necessitates careful clamping planning for lamella bending. This factor significantly influences the overall flexibility and the speed at which the desired curvature can be achieved.

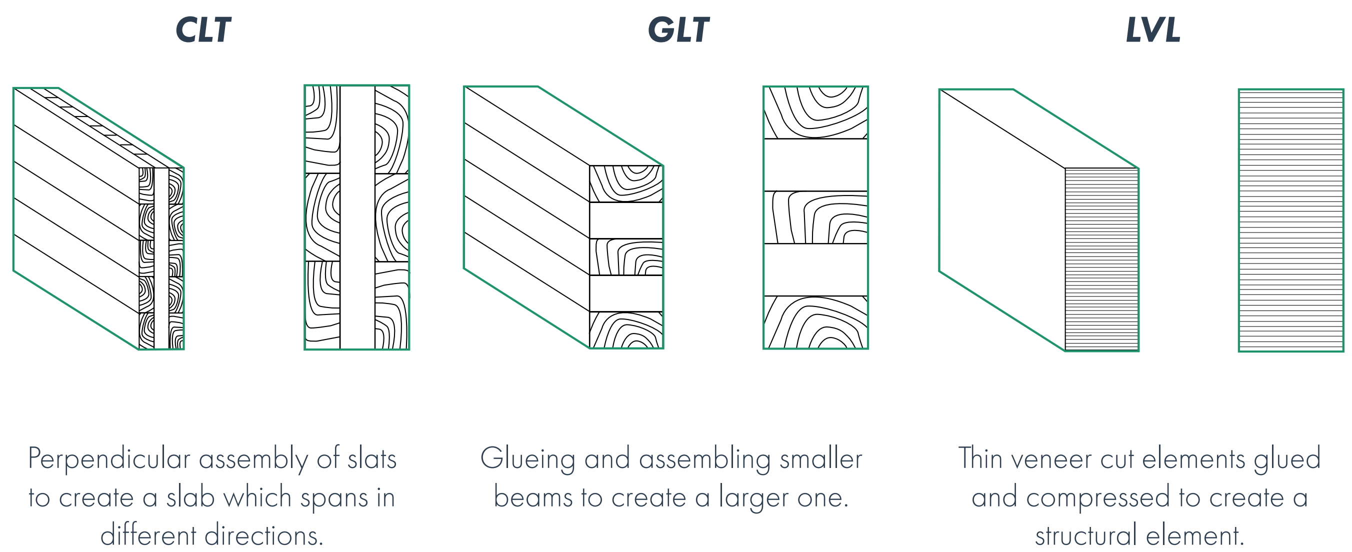


Figure 17: Different engineered timber elements

3.7 *Passive bending*

As outlined in chapter 3.6, exposing timber to moisture induces flexibility through plasticization. Traditionally, wood was actively shaped through various methods. However, in recent decades, numerous studies have shown that by harnessing the hygromorphic characteristics inherent in wood, timber can also be bent passively. Hygromorphic characteristics can be best illustrated by examining pine cones. Pine cones exhibit the ability to open or close in response to weather conditions influenced by moisture levels, facilitating the dispersal of seeds. The pine cones consist of bi-layers, two distinct layers, which undergo noticeable dimensional changes when exposed to moisture. Consequently, the scales open in dry conditions and close in humid or wet environments (Holstov, Bridgens, et al., 2015b).
The concept of utilizing bi-layers to achieve passive curvature in timber is increasingly being developed and implemented. In this approach, a timber layer is combined with a perpendicular passive layer, which may also be of wooden origin. Timber undergoes hygroexpansion, an increase in size, in high relative humidity environments (Holstov, Morris, et al., 2015b). Once hygroexpansion has occurred, the passive layer is bonded to the active layer using adhesives. The adhesive binder interlinks the two layers, creating a cohesive bi-layer element. When the bi-layer has established a strong interconnection, the slab can be relocated from the 'controlled' high relative humidity environment to its intended placement location. Subsequent changes in relative humidity cause the active layer to experience hygroshrinkage, leading to a reduction in volume. However, the passive layer remains unchanged, resulting in internal tension. This internal tension gives rise to the bending of the structure.

The exploration of reverse hygromorphic bending, where a dry timber slab expands in a high relative humidity environment, leading to curvature, has not received extensive research and development. Additionally, the practical application of hygromorphic curved elements is limited in the building environment. This limitation may stem from the recent development of hygromorphic timber as a method. Notably, the projects implemented thus far are predominantly artistic in nature and have not yet seen widespread structural implementation in the built environment. This research concentrates on exploring the feasibility of implementing hygromorphic bending in floor elements.

3.8 *Implementations*

The concept of a curved bi-layer composite holds potential for application in the timber construction sector. The production of curved timber structural elements using this approach offers a low-tech and cost-effective alternative to the labor-intensive and energy-intensive active bending methods (Holstov, Bridgens, et al., 2015b). Furthermore, as the element is the final structure material and the shaping mechanism, the necessity for large machinery and frameworks is greatly reduced (Wood et al., 2020). Currently different hygromorphic curved elements are being build, with different implementations.

Façade projects

Research conducted by Holstov, Bridgens, et al. (2015b) investigated the response and movability of facade panels. In humid outdoor conditions, the facade would close, while in dry periods, it would open, as depicted in figure 18. This dynamic behaviour means that during dry, sunny periods, a building could utilize natural ventilation, whereas in humid periods, the facade would close, halting natural ventilation. Importantly, this is achieved through a low-cost mechanism.

Structural projects

The ETH Zürich and Stuttgart university designed and developed the Urbach Tower (Figure 19). This structural landmark project is made of timber slabs curved with the hygromorphic bi-layer principle. This project shows the different possibilities and opportunities with passively curved timber (Wood et al., 2020). This research serves as a pioneer in the advancement of material-driven self-shaping fabrication. Double-curved self-shaping timber geometries have become achievable, potentially serving as a stepping stone towards greater integration of timber in the increasingly complex world of architecture. Another illustrative example of research by design involving hygromorphic timber is the 'HYGROSHELL', as depicted in Figure 20 While this geometry lacks structural capacity and can be classified as an 'Artwork,' its impact extends to influencing subsequent structural developments through the knowledge acquired via practical research. However, it is essential to note that this research thesis specifically focuses on further designing structural elements for the built environment, making 'artwork' applications less relevant.

Floor & roof-slabs

Construction typologies and elements which are used in every construction building are roofs and floors. Floors and roofs have a large impact on the overall embedded emissions of a structure. Floors are made to be level, however the construction underneath does not have to meet this requirement. As Grönquist et al. (2019) stated, structurally efficient curved geometries are easily designed. Still the production and manufacturing is intensive and uses excessive machining. Nevertheless, the ability to produce passively curved floor elements by hygromorphic abilities has been researched by Grönquist et al. (2019). Yet, it only looked at solid elements and not a typology optimisation or form finding.

Beams & columns

Straight rectangular beams are the most conventional structural typology used in the building environment. Nevertheless this geometry is unsustainable in terms of material usage, due to its typology (Strozzi et al., 2018). The ability of timber to be curved, and therefore designing curved beams, could be beneficial. However, beams and columns are rarely used in a conventional house. Utility constructions on the other hand use this construction topology more often.

The downside of designing curved timber elements with hygromorphic properties, is the relation between area and curvature. The greater the thickness of the wood elements, the higher the second moment of area. This increases the bending stiffness, which in result lowers the total curvature (Grönquist et al., 2019). This explains the lack of research focused on hygromorphic curved solid timber elements. However, there is a research gap aimed on complex multi-layered solid timber elements. By joining multiple bi-layer elements and curving the whole joint element, a new typology could be designed.

Figure 18: Hygromorphic Skin Prototype, Holstov (2015)

Figure 19: The Urbach tower. (ICD/ITKE University of Stuttgart., 2019)

Figure 20 Hygroshell. (ICD Research Buildings / Prototypes Chicago, USA, 2023)

Details

Material properties

4

Trees absorb water through the development of a complex root system underground. This intricate root system enhances the overall absorption area, thereby increasing moisture intake. The capacity of timber to absorb water has been recognized and utilized for practical purposes for many centuries. The intake of moisture or excessive water makes timber more flexible, a characteristic that can be harnessed for various practical applications. While this ability has been acknowledged for an extended period, the detailed understanding of the mechanisms behind why and how water is absorbed has been known for a relatively short time.

This chapter will delve into both the macro and micro levels of timber, exploring the workings of wood cells and fibres. The goal is to gain a comprehensive understanding of how timber absorbs water, why it becomes more flexible with a high moisture content, and how this flexibility can be strategically manipulated to passively bend structural timber elements in our favour.

4.1 *Micro & Macro*

Timber, like other bio-based materials, can attract water from its surroundings and absorb it within the material structure, therefore making the material porous and hygroscopic (Thybring et al., 2022). The quantity of water in the timber is related to the moisture content, which is affected by the relative humidity and temperature. Once the absorbed water is in the material, it can be transported to or placed in the macro-void structure or to the cell walls, the storage location is decided by the relative humidity.

Bound water

Water is predominantly taken up in cell walls, when the hygroscopic range of 0% to 97% relative humidity is reached. The water molecules present within the cell walls of wood are commonly called "bound water". This bound water interacts with the cell-wall polymers. As Thybring and Fredriksson (2023) stated, the behaviour of water within cells falls between a liquid state as well as a solid ice-like state. However, this behaviour will shift more to a liquid state as the concentration of water in the cell-wall increases. So, when the water concentration increases within timber, and thereby within the cell-walls, the cell-walls will be more flexible due to a shift from solid to liquid state water. Consequently, because of this phenomenon, the flexibility of the overall material would increase (Thybring en Fredriksson, 2023).

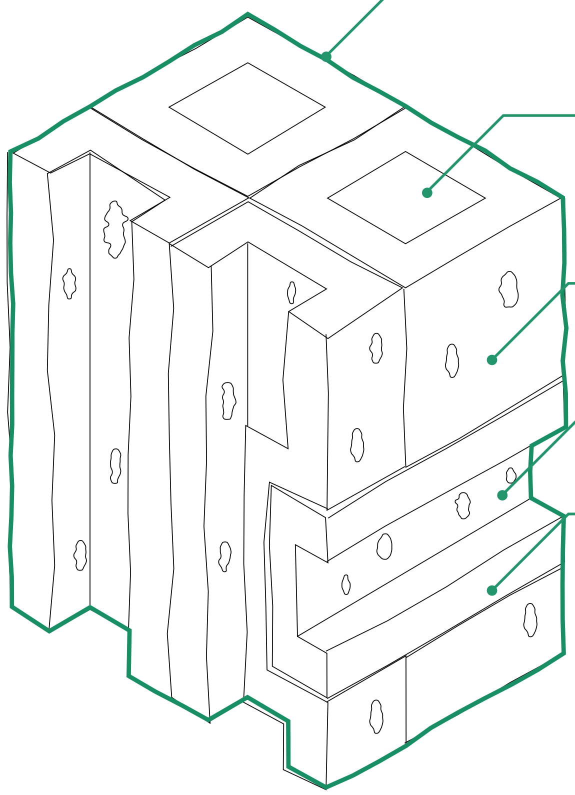


Figure 22: Timber cell composition (Hill, 2021).

Capillary water

Water could also be present and stored outside cell walls. When an environment has high relative humidity levels, also called an over-hygroscopic range where relative humidity exceeds 98%, capillary condensation of liquid water in macrovoids like pit chambers and cell lumina becomes more dominant (Thybring en Fredriksson, 2023). Capillary condensation is a process where water-vapour, below saturation vapour pressure, is condensed in pores (Thybring en Fredriksson, 2023). Capillary condensation (CC) happens at relatively low humidities in small pores, rather than large pores. Cell lumina are usually 10 - 40 µm in size and will only fill by CC above 99.99% RH. CC in pit chambers, which can be classed as smaller voids, occurs at a slightly lower relative humidity (Thybring en Fredriksson, 2023).

Drying

When timber dries the bound water and the capillary water, stored in the longitudinal cells, needs to exit the material. Parenchyma cells, also known as the macroscopic flow-pathways or radial cells, are responsible of transporting this water to exit the material. The arrangement of the Parenchyma cells depend on if the timber is hardwood or softwood. The longitudinal cells form an interconnected system by small openings in the cell walls, called pits. The connection between the longitudinal cells and the parenchyma cells are made possible by tracheid, which is a more efficient way of water management, as seen in figure 22 (Hill, 2021).
Some wood species have natural valves on the pits and tracheids as a defense machenism to prevent drying out or if it gets wounded. These notorious wood species are referred to as refractory species. One of the famous species with this property is spruce. According to Moya et al. (2009) it takes over 700h or 29 days for wetwoods in the radial direction to reach an equilibrium moisture content, this has to be taken into account when the testing phase starts, due to planning reasons.

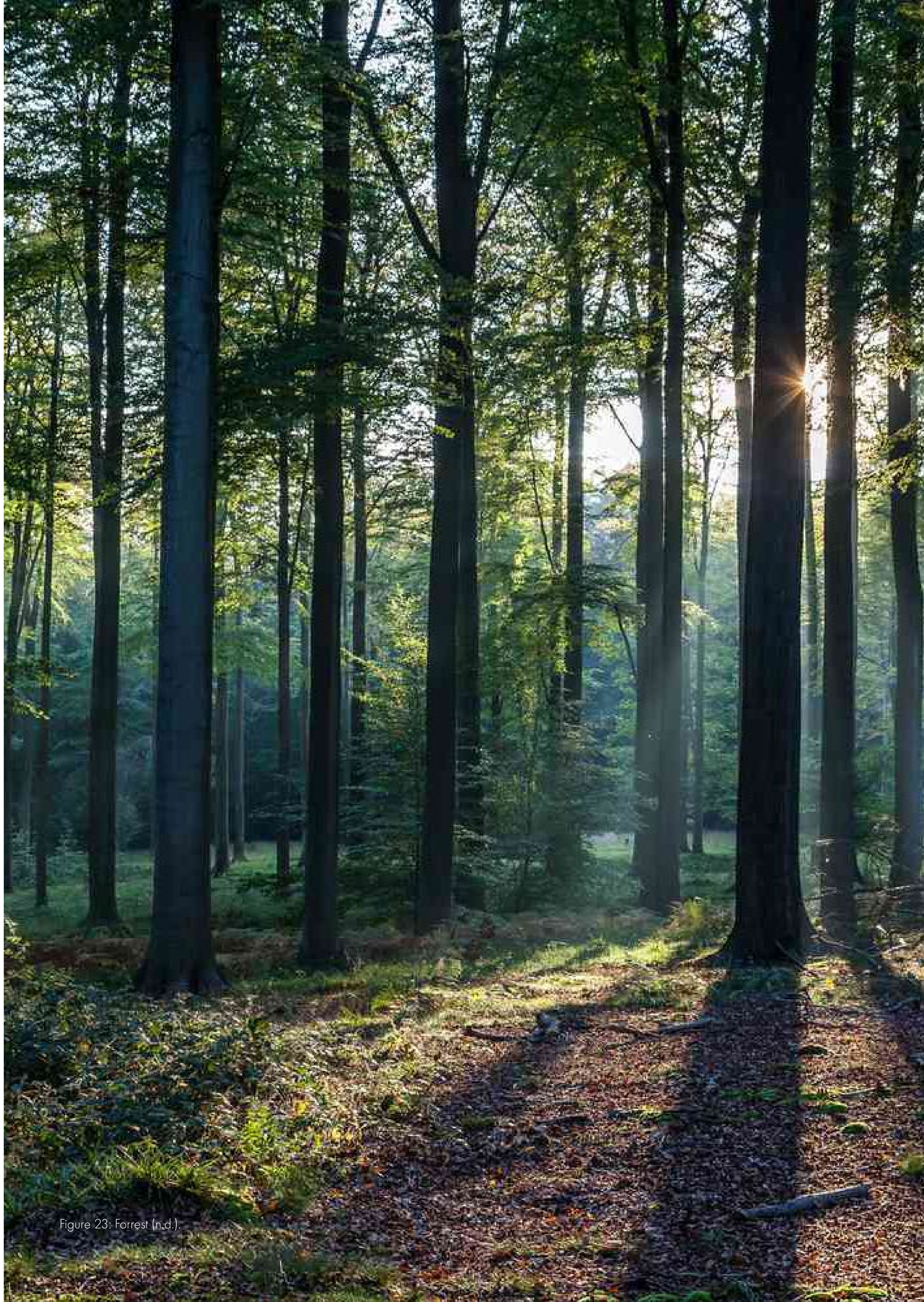


Figure 23: Forrest (n.d.).

4.2 Moisture content

The moisture content in timber can not only be observed but also be measured. This amount can be determined by the ratio:

$$\omega = \frac{m_{\mathrm{w}}}{m_{\mathrm{dry}}} \tag{4.1}$$

Where moisture content is W (g g-1), Mw (g) is water mass, and Mdry (g) is dry mass. It has to be said, that the moisture amount measured is the sum of moisture in the cells and in the macrovoids.

Sorption isotherms is the term describing the relation between moisture content of a material and the water state's equilibrium with the ambient climate at a constant temperature. Timber can experience both hygroscopic and over-hygroscopic ranges. The hygroscopic range is linked too the moisture concentration in timber interlinked with the bound water in the cell walls and is influenced by the density of the timber species. Hardwoods have a higher cell density, therefore they have more cell walls and thus can have a higher moisture concentration.

Hygroscopic range is between 0% and 97%-98% relative humidity. The over-hygroscopic range is >98% relative humidity. In the over-hygroscopic range capillary condensation in the macrovoids dominates the water intake and is related to the bulk density, lower density means more macrovoid volume resulting in more volume available for water. Due to large shifts in moisture content, the sorption isotherms of the over-hygroscopic range is plotted logarithmic as a function of water potential or pore water pressure. As seen in figure 24, the sorption isotherm of both Beech and Norway spruce is seen (Thybring en Fredriksson, 2023).

Furthermore, temperature also has an significant impact on the overall sorption isotherm. Due to higher temperatures the relative humidity in different timber samples will decrease in both the hygroscopic and over-hygroscopic range. This change in the over-hygroscopic range may be explained by the surface tension of water which is also temperature dependent (Thybring en Fredriksson, 2023). These graphs are measured and plotted during controlled environments. The Heritage department of Architecture at the Technical University of Delft has moisture chambers where the relative humidity can be controlled. These chambers will be used to conduct an experiment to passively bend timber with the sorption isotherm properties. The results of this experiment will be elaborated on further in chapter 7.

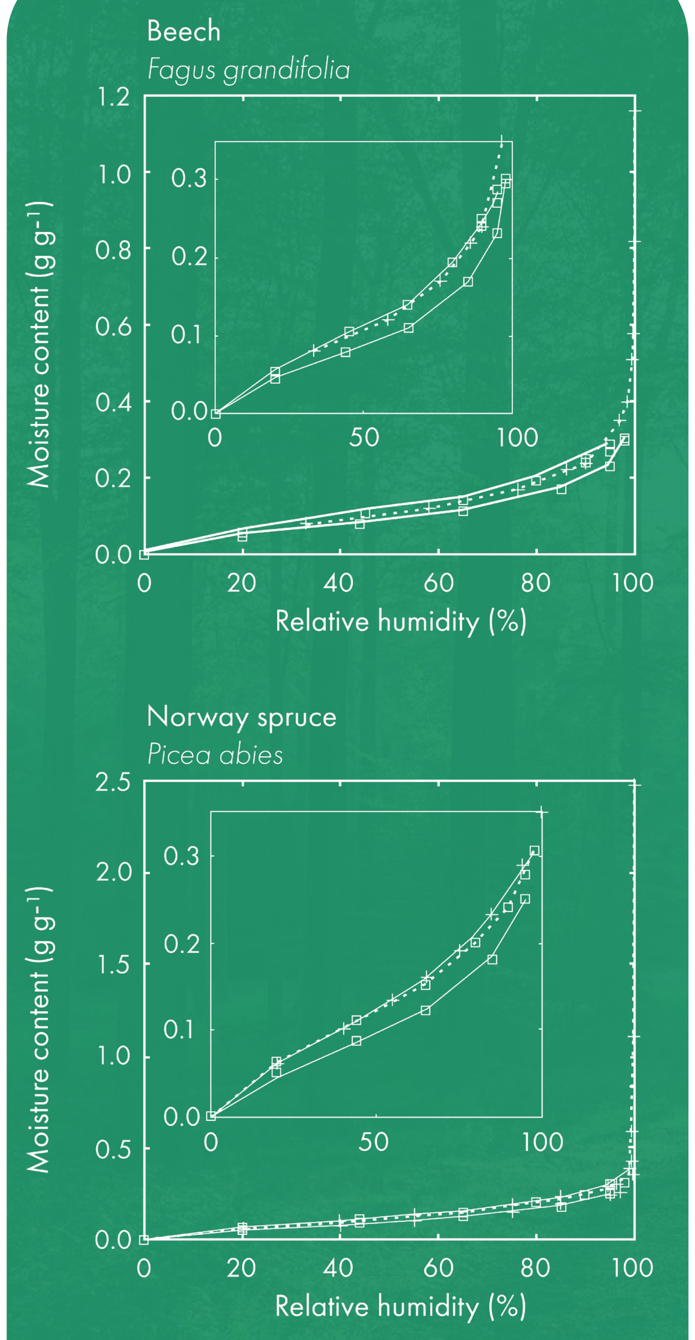


Figure 24: Moisture content and relative humidity relation in timber (Thybring en Fredriksson, 2023).

4.3 Hygroexpansion

The dimensions of wood depend on its moisture levels. The volume of timber will increase during water absorption, this is known as swelling. Consequently the dimensions and volume will decrease until its minimum in a dry-state during desorption. This is known as shrinkage. This swelling and shrinkage is not proportional in each direction, which makes wood an anisotropy material. There is a link between dimension changes and the orientation of microfibrils. Microfibrils are membrane-bound enzymes, and can be found in timber cells (Okuda en Sekida, 2001). The timber cells are orientated in the longitudinal dimension, as seen in figure 23. Consequently swelling and shrinkage in this longitudinal direction is less due to the swelling and shrinkage happening in the cell-walls, where water is stored. The transverse direction is affected greater than the longitudinal direction.

This swelling is indicated in percentages. As seen in figure 25, the tangential swelling is approx. 10%, whereas the radial swelling is around 5%. The longitudinal swelling can be neglected, as the swelling is 0.2%. This swelling and shrinkage is seen as a problem in the build environment. For example facade cladding can rupture and tear due to inefficient designing. Nevertheless, this swelling and shrinkage can perhaps be seen as a solution, with passive hygromorphic curving. The type of wood can influence the percentages. On average softwoods swell less than hardwoods. This could be related by the density of the microfibrils.

Log anisotropy

Due to the fact that timber is an anisotropic material, the original location of timber elements in the log can influence the overall form the element will take when shrinking of swelling. The more centred the wooden piece was located, the less curving is possible. As shown in figure 26, making the right decisions in cutting timber elements from logs has a substantial influence on the overall form-finding with passive curving due to swelling and shrinkage. The most effective passive bending timber batch is situated near the exterior of the logs.

Furthermore, different wood species exhibit varying anisotropic values for shrinkage and swelling. There is a distinctive difference in earlywood and latewood. During the beginning of the growth season trees produce wide, thin-wall earlywood fibres. Later in the season the tree develops thin, thick-wall latewood fibers. These two distinct fibres contribute to the distinctive circular rings structure in timber. The latewood rings are darker than their earlywood counterparts (Bertaud en Holmbom, 2004). Moreover, due to the narrow, thick-wall characteristics of latewood, it is stiff in nature. Earlywood on the other hand is more flexible. According to Thybring en Fredriksson (2023), earlywood has a considerably higher anisotropy than latewood. This product can therefore be useful. The dimensional shrinking and

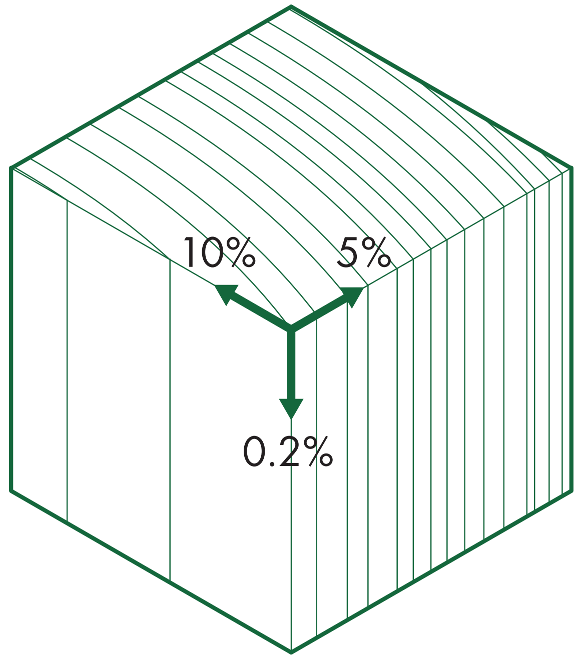


Figure 25: Anisotropy swelling percentages of timber (Thybring en Fredriksson, 2023).

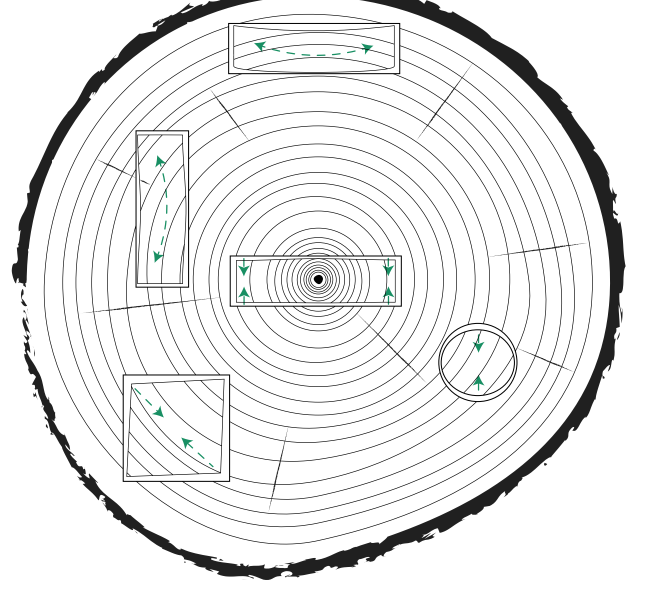


Figure 26: Maximum responsiveness of timber elements in a log. (Thybring en Fredriksson, 2023).

swelling changes in timber exhibit a linear correlation with the equilibrium moisture content within the range of 0.05 - 0.20 g/g. Also, as seen in figure 26, wooden elements closer to the exterior show significant larger shrinkage and swelling changes.
In figure 27 an overview is structured with different timber species and their characteristics. This overview will help make choose the right timber specimen when conducting research and develop prototypes. This overview highlights multiple properties.

Maximum responsiveness

Although the earlywood can be effective for employing hygroexpansion, according to Holstov et al. (2015) maximum responsiveness in timber can be achieved by utilizing the tangential direction in the active layer. This can be achieved by rejecting quarter-cut veneer and choosing optimized rotary-cut or plain-cut veneer. Rotary-cut or plain-cut veneer is a cutting method where thin slabs are cut along the log or parallel with the grain. Rotary-cut veneer shows greater hygroexpansion due to exact alignment along the distinctive circular growth rings. Furthermore, this cutting method is less expensive compared to the other methods, and has the ability to produce large sheets. However, this does not mean that LVL beams could have a promising opportunity in becoming a viable option to passively curve large structural timber elements. Due to the fact that Holstov et al. (2015) looked at single sheet optimisations whereas this research thesis looks as multi-layered structural elements.

To conclude and answering the question: "How will hygromorphic characteristics curve structural timber elements?", Wood can absorb and desorp water and moisture from its surroundings making it an hygroscopic material. During this hygroscopic phenomenon, the wood cells increase in size. This expansion in size is different in each direction making timber an anisotropic material as well. The largest dimension change occur in the tangential direction, with approximately 10%. This could be utilised in the production of passively curved objects. The position and shape of the utilised timber elements in the original log have an significant impact on how the element want to show hygroexpension. It is advisable to use timber close to the exterior of the log, due to the greatest swelling and shrinkage change observable.

Timber species and their chraracteristics

Timber species	Max. swelling %[1] [L]	[R]	[T]	Max. cell-wall MC[1] [g g⁻¹]	Density[2] [Kg m⁻³]	Growth-rate[3]	
Softwoods							
Norway Spruce *Picea abies*	0,3	3,7	8,5	0,38 - 0,52	377	M-F	
European red pine *Pinus sylvestris*	0,3	4,2	8,3	0,36	339	F	
Douglas fir *Pseudotsuga menziesii*	0,2	5,0	8,0	0,46 - 0,62	412	M	
Hardwoods							
European Beech *Fagus sylvatica*	0,4	6,2	13,4	0,31 - 0,35	554	S-M	
European ash *Fraxinus excelsior*	-	4,8	7,8	0,35 - 0,39	564	S-M	
Sycamore maple *Acer pseudoplatanus*	-	4,8	12,3	0,34 - 0,41	522	S-M	
Pedunculate oak *Quercus robur*	0,4	4,6	10,9	-	561	S-M	

1) Maximum swelling % and Maximum cell-wall moisture content (Thybring en Fredriksson., 2023). 2) Density properties per timber species (Niemz et al., 2023). 3) Growth rate: S ≤ 12" per year, M = 13"-24" per year, F ≥25" per year (Tree Guide - Arbor Day Foundation, z.d.). Fig 1-7: Keila-Paldiski (2011), Mickaël Delcey (2012) Rasbak (2007), Willow (2009), Tony Holkham (2019), Willow (2007), Snowmanradio (2012).

Preparations

Laboratory

5

5.1 Tools

To conduct a practical experiment, different measures have to be taken in order to be trustworthy. The Architecture faculty of the technical university of Delft is in possession of multiple measuring equipment and devices which can regulate relative moisture content. Also the workshop can be used to process the timber elements. Obtaining the right timber specimen is therefore the main struggle in conducting the research.

Timber specimen

Obtaining timber samples or better, usable timber specimen from manufacturers is the main goal. Many different timber producers claim to be generous in distributing small timber samples, however small samples are not particularly desired for this research. A freshly cut slab of any species of timber would help in conducting research. However, manufacturers are not eager to hand over such valuable material. After contacting companies like Derix, Heko, & Metsä the search for timber was still on, as they could not provide what was needed.

Moisture lab

As stated before, the architectural faculty of the TU Delft has a moisture laboratory. This laboratory, located in the basement, houses equipment used to control relative humidity with salt concentrations, drying-ovens for elements of different materials and measure moisture content of the research design elements.

The equipment to control the relative humidity is a basic refrigerator with a 300mm x 400mm x 450mm dimensions for timber elements to be induced by moisture. The limited refrigerator dimensions restrict the overall research design element's dimension. At the bottom, space is reserved for a small plastic box containing a salt-concentration. There are different plastic boxes containing different concentrations to create different relative humidity percentages. A little ventilator, connected to the power grid and placed in the door of the refrigerator, will function throughout the whole research. The ventilator will evenly distributing the relative humidity. The refrigerators work continuously, influencing the time spend in the laboratory. Once the timber elements are placed inside the refrigerator, constant supervision is not necessary.

The laboratory also has equipment to measure dilation and moisture content of the timber used in the experiments. The moisture content can be measured with a precision scale. It should be noted that both the dry-state weight as well as the saturated-state should be weighted, to make calculations. The idea was to measure the dilation of the elements by a digital probe and linear encoder from Solartron Metrology / Ametek. This device, capable of measuring on a sub-micron scale, could help during the research period. However as the device is complex, time should be reserved to understand and known it. This was to complicated, so the devise was not used.

Workshop

When the timber arrives from the company who send it, the timber needs to be processed into the right dimensions. The workshop at the architecture faculty has multiple tools to achieve these desired dimensions. The saw table can cut the thicker hardwoods, under supervision of the staff. The thinner pieces and the softwoods can be cut manually into the right sizes by the machines available in the workshop.

Figure 29: Moisture Lab TU Delft Architecture

5.2 *Typologies*

The experiment in the laboratory is more than just physical testing. The idea is to first start with research by design, after which a digital model is used to predict what will happen to the different design options, considering shrinkage, expansion, curvature. Because the actual physical testing will be conducted with scale models, approximately 1:3, this could affect the dimension changes as well as the overall goal, which is curvature. In total 2 different options and an neutral, case 0, option will be researched. This does not mean that only 3 physical test will be conducted.

Research by design

The first step towards actual testing in the laboratory is knowing what to test. As this research thesis is focused on developing a structural curved multi-layered timber element, the scope has been created. After designing different typologies, 5 distinct geometries were picked to be developed further. As seen in figure 35, these 5 different options are:

- Sandwich (1+n+1)
- Double passive (2+n+1)
- Neutral (1+x+n)
- Spacer (1+n+x+n)
- Multi-layer (1+n)

The n-layer stands for the active layer, which is the primary reason for the passive self-shaping. The x-layer refers to a material which does not contribute to the curving whatsoever, but is used to create height.

Sandwich slab

As seen in many different developed hygromorphic elements, a passive layer is added to create internal stresses when the active layer shrinks due to reducing wood moisture content. However, these passive layers are always connected on one side, and there is only one. The idea to implement 2 passive layers to create some sort of sandwich panel came from the hybrid GLT beams. These beams have different timber species at the exterior and the interior, or at the top-bottom and inside. Usually hardwood is located at the external zone, where higher stresses occur and softwood type elements are used in the interior. The main challenge with this configuration may be the curvature. Due to the one-side trademark of the conventional bi-layer slabs, the curvature direction can be predicted. When a passive layer is used on both sides of the slab, the curvature can be cancelled, or be reduced due to increased internal forces. The slab may also split in one of the two passive layers. As these layers are less thick than the active layer. Due to these reasons, the sandwich slab will not be researched in the laboratory.

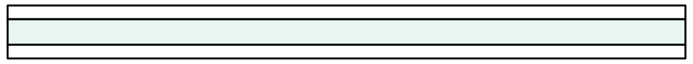


Figure 30: Sandwich

Double passive slab

The double passive slab arises from the sandwich slab. However, the double slab contains 3 passive layers which results in at least 2 passive layers on one side. This change removes the possibility for cancellation, as the slab is not symmetrical anymore. Still the question remains, how will this increase in passive layer mass influence the overall curvature? As there is no direct answer to this question in relevant literature, the aim is to research this in the laboratory and the digital model.

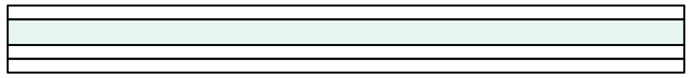


Figure 31: Double passive

Neutral

The neutral typology presents an intriguing theoretical option. The idea of utilizing a material that provides both stiffness and flexibility to facilitate self-shaping curvature holds promise. However, the practical challenge lies in finding such a material. Given the numerous uncertainties surrounding the neutral material and the significant time investment required to identify the right one, it is deemed impractical to pursue this option further. As a result, it will be excluded from consideration in selecting the typologies to be further developed.

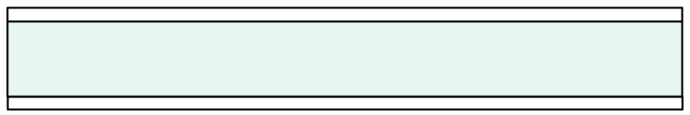


Figure 32: Neutral

Spacers

The idea to make use of spacers is more out-of-the-box thinking and can perhaps be integrated into a building due to installation gaps for shafts, etc. The principle of spacers to increase heights in beam can be seen in the steel beam sector. By using castellated steel beams (to increase depth of the section) and introducing spacer plates, an octagonal opening is created (Al-Thabhawee & Al-Kannoon, 2018). The elements are welded together, however the problem is, how can this principle be implemented as a construction typology with timber as a building material. Should the spacer material also be timber, or can it be made from a different material? There are still a few questions which needs to be answered in order to get an understanding of how things work. Still, due to its creative and innovative nature the spacer option will be developed further as it looks the most different and interesting.

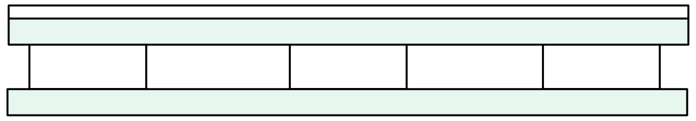


Figure 33: Spacer

Multi-layer slab

The multi-layer slab is the most recognisable and conventional option. This configuration has been researched, developed and used already in multiple occasions. However, the multi-layer slab has only been used with no more than 2.5 layers. The shape-stable curved slabs are manufactured by interlinking two self-shaped bi-layers and an locking layer, which usually has been cold bended, to create a structural slab (Grönquist et al., 2019).
Nevertheless, the possibility to combine more than two bi-layers has not been investigated. This principle can be crucial in finding a stable multi layer structural element. Therefore, this topology of connecting more than 3 multi-layer slabs together will be researched and experimented with in the laboratory, if there is time because the main focus is with the spacer typology.

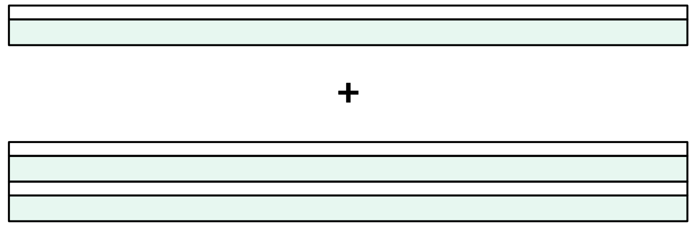


Figure 34: Multi-layer

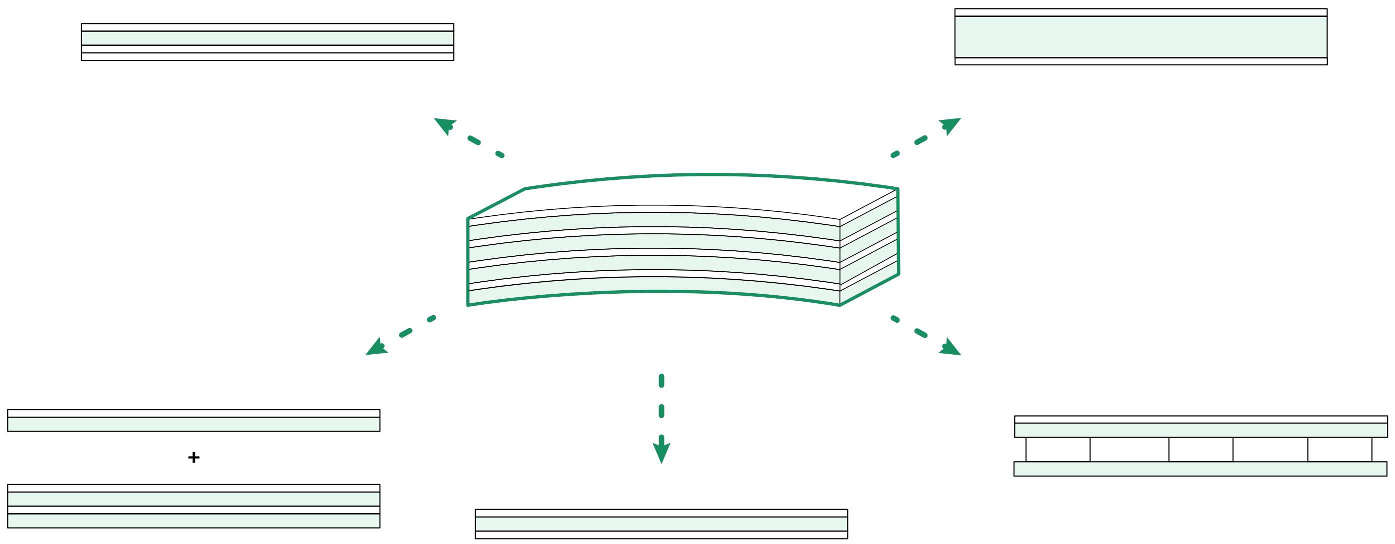


Figure 35: Different typologies from multi-layer concept

5.3 Plan set-up

Before beginning the experiments, a few aspects should be adressed in order to start properly.

Digital model

There are multiple ways to implement a digital model on the overall research and development. One of the goals for this research was to develop an interactive FEM model, which could show curvature during different parameters. By making such a digital model in a perfect environment, the curvature of different typologies could be predicted and reflected onto the realistic imperfect world. After consulting and practising with the set-up of a similar digital model, a challenge occurred.
Developing such a model, is a study on its own. This is however not the goal for this master research study. Therefore the use of an analytic model with graphs and formulas could help the development. By making an interactive parametric model in grasshopper, the basics can be predicted.

Physical testing

Physical testing is a key part of the research conducted in this master thesis. The physical testing can be divided into 2 sub-testing parts. The relative humidity and wood moisture content testing to induce curvature in a laboratory, and the potential load and strength experiment at a testing ground. First the creation of curved elements is needed. This experimenting needs to be conducted in a controlled environment, with the right equipment and materials in the laboratory in the basement of the TU Delft architecture faculty. To see how the scaled models compare to conventional timber and steel beams, a strength test could be done to see how efficient and sustainable the new configurations are. These test can take place in the TU Delft campus with expensive tools or with general loads.

The material

The decision for a specific timber species, used during testing, is influenced by multiple factors and parameters. The most dominant factor influencing the decision is the swelling percentage of the specific timber species. Softwoods like spruce and pine are known to have a less significant swelling percentage than hardwoods like oak and beech (Thybring en Fredriksson, 2023). As stated in chapter 4.3, Beech swells by 6.2% or 0.2 % g/g[1] in the radial direction and 13.4% or 0.41 % g/g[1] in the tangential direction. As these percentile are significantly higher as softwoods, experimenting shows great potential to maximize curvature in multi-layer elements.

Furthermore, beech (*Fagus sylvatica*) is one of the most dominant and abundant hardwood species in central Europe (Pramreiter & Grabner, 2023). Nevertheless, European beech is lagging behind on other wood species in the construction sector, due to poor decay resistance and dimensional stability. However, as the demand for sustainable materials increases, the rise of beech in the construction sector may increase as well.
Norway spruce (*Picea abies*) is a softwood and used as a construction wood in continental Europe, therefore making it economically relevant. Due to its fast-growing nature and straight and slender topology, the relevance increases even more. Moreover, the standardised timber processing industry is configurated for this type of softwood timber, making large-scale production and manufacturing possible. Still, the swelling percentage is significantly less compared to beech, with a reduced difference of almost 40% (Thybring en Fredriksson, 2023). This affects the possible overall curvature.

A combination of both species could be one of the testing configurations. Due to the fact that the elements will be multi-layered, hardwood could be used at the bottom and top, like an hybrid GLT glulam beam. Therefore, both European beech and Norway spruce will be used as testing materials in the laboratory.

5.4 Analytical model

To gain insight on how the different typologies will behave during induced moisture curving, multiple options are available to show this self-curving. Physical testing is the most obvious method. However, there are multiple ways to make digital models, and even these models can differ from 3d elements, FEM models or graphs based on formulas based on literature. These options are analytical models, and implement formulas and equations to describe or predict the behaviour of multi-layer self curving elements.

FEM & 3D models

Making FEM & 3D models predicting curvature based on internal forces is hard. As it shows, creating these types of models are Ph.D. studies on there own, and therefore unrealistic to achieve in a master thesis. Attempts were made to achieve something, however the results were not desirable and reliable. Due to these reasons, the FEM & 3D models where put on hold, and the focus was set to an analytical model.

Analytical model

The first attempt at creating a graph where moisture content in timber is plotted against curvature. This graph was created in the coding software Python, and was based on research by Grönquist et al. (2019). During this research the bi-layer principle of Timoshenko was used. The Timoshenko formula, Eqs 6.1, is based on a metal bi-layer element, and the curvature could be extracted. Although this formula is based on metal bi-layers, the properties of the right timber species can be implemented to find the curvature of a timber bi-layer. The curvature of a timber bi-layer element is related to the difference in moisture content. Current models assume a proportionality factor K, where K is the function of moisture (K = K(w)). K incorporates the effects of geometry and material characteristics for any bilayer, as seen in Eq 6.1,

$$k \approx k_0 \left[\frac{h_1 + h_2}{2} + \frac{2(E_1 I_1 + E_2 I)_2}{h_1 + h_2} \left(\frac{1}{E_1 h_1} + \frac{1}{E_2 h_2} \right) \right]^{-1} (\alpha_2 - \alpha_1) \tag{6.1}$$

where $I_1 = h^3{}_1/12$ and $I_2 = h^3{}_2/12$ are the area moment of inertia. h_1 and h_2 are the height of the active and passive layer respectively. α_1 and α_2 are the swelling coefficients, these values differ per timber species and direction. For beech wood, conventional values are α_L = 0.0001, α_R = 0.0019 and α_T = 0.0040 in $\%^{-1}$. E_1 and E_2 is considered to be the Youngh modulus, where the value is species dependent as well.

By using this formula in Python, a computational result for the curvature can be found. However, the length, curve-height, etc., are still unknown. To visualise the self shaping phenomenon of bi-layers based on the Timoshenko formula, Rhino7 and Grasshopper is used.

The visualisation model uses basic geometry, as seen in figure 31. As K is the solution from the Timoshenko formula, it can be used to find angle θ. S is the length of the overall element, which is known. By using different formulas, the height of the curved bi-layer element and the exact length can be determined.

$$\theta = k \cdot S \tag{6.2}$$

$$S = \theta \cdot r \tag{6.3}$$

$$h = \frac{c}{2} \cdot tan\left(\frac{\theta}{4}\right) \tag{6.4}$$

$$C = 2R\,sin\left(\frac{\theta}{2}\right) \tag{6.5}$$

As seen in Eqs 6.2 to 6.5, by extracting k or curvature from the Timoshenko formula, the angle of the element with a certain length S can be determined. Once this angle is known, the radius r, curve-height h and curve -length can be calculated. Curve length c will always have a smaller length than the original length S.

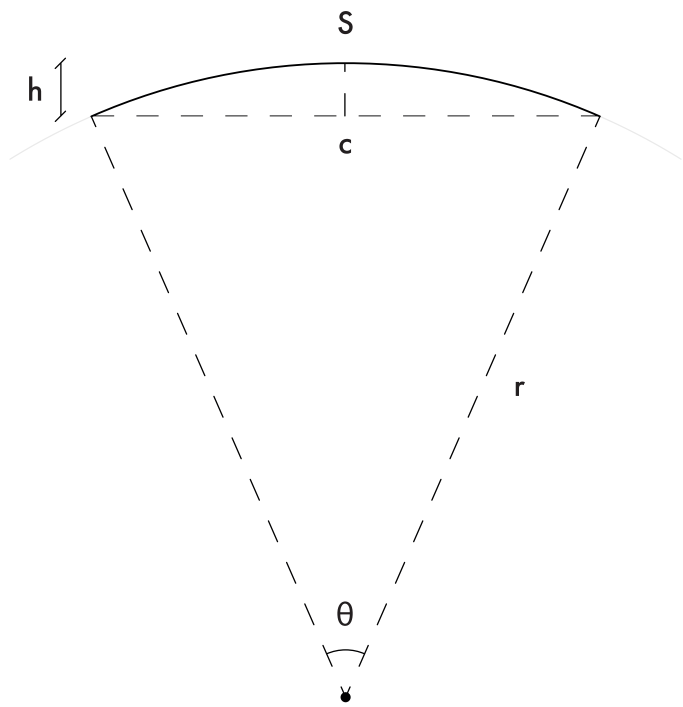


Figure 36: Timoshenko bi-layer curve height

A parametric model has been made in Grasshopper which shows every curve height and curve length per S. Also the Young modulus, swelling-coefficient and height per layer can be changed. This results in an interactive parametric wooden bilayer, as seen in figure 37 and 38, the whole grasshopper code can be found in the appendix.

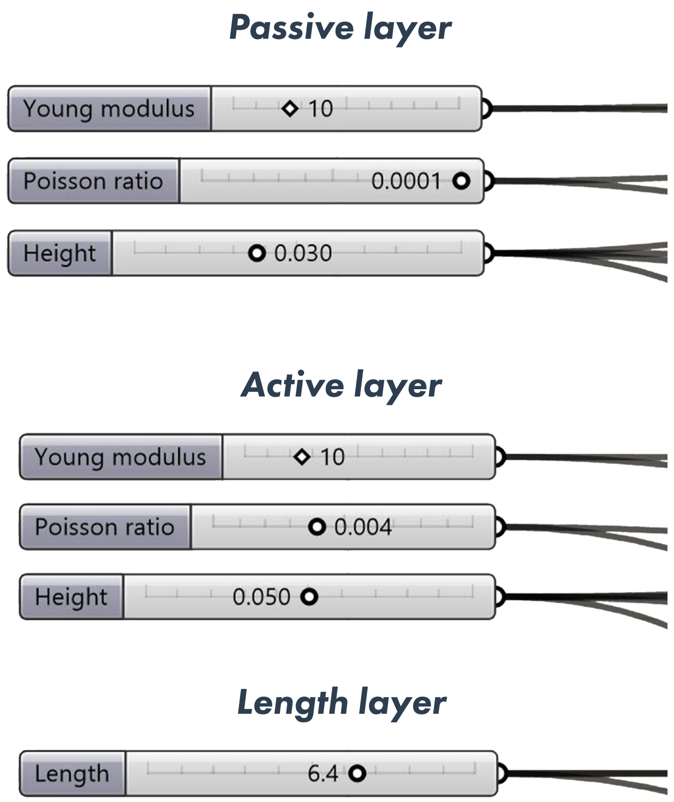


Figure 37: Parameters for analytical model

Making a parametric wooden bilayer model has been achieved, nevertheless a multi-layer model is more complicated. Implementing the different typologies seen in the next chapter is a challenge. It has been decided to only make this bi-layer parametric model. The complex multi-layer typologies will be judged by physical appearance and real life performance, as an parametric model is to complex and not the main focus of this thesis.

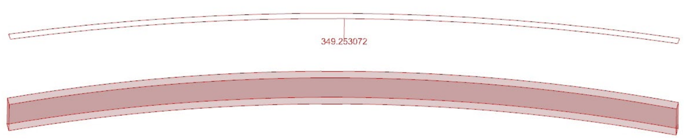


Figure 38: Curvature of bi-layer

Designing Development

6

6.1 Spacer

The challenge with a spacer slab typology is the eventual self-shaping curvature achievable. As there is just one active layer in the composite which causes curving, the self-shaping phenomenon can be greatly reduced or not occur at all when lots of passive material is added into the overall element. This due to the curvature being related to the moment of inertia which is related to the overall section area.
Therefore the idea of implementing spacers was created. There are multiple ways to fill the 'void' created when the height is increased. Simple rectangular timber blocks and experimental 4d cross-section printing methods are some of the possibilities as a spacer typology.

6.1.1 Blocks

When a solid element curves, internal stresses occur. Depending on the type of material and the use of different materials in an element the overall curvature can be influenced. When blocks are used instead of a solid continues element, the stresses will not happen as the material is not compressed. As a consequence, less force is needed to curve the element.

However, as there is less material and flexibility is increased, strength and load bearing capacity is negatively impacted. This phenomenon of decreased strength will be applicable for other spacer typologies.

Figure 40: CLT boxfloor element. (Best wood Schneider, n.d.)

6.1.2 4D-Printing

Recently, an innovative state-of-the-art printing method has been developed where self-shaping capacities can be up-scaled. By rotating the axis before printing, the design and fabrication of self-shaping mono-material systems is enabled (Şahin et al., 2023). By focusing on the self-shaping prosperity and topology optimisation, an efficient filling can be designed, where structural integrity and strength are a top priority. By creating cells in the cross-sectional depth, based on the large-flowered butterwort (*Pinguicula grandiflora*), shape changing is made possible. Still, this method focusses on a niche part of the overall end goal, which is a sustainable and widely usable self-shaped mass timber element. By implementing a futuristic like manufacturing principle, the mass production and adoption of curved mass timber elements will be discredit.

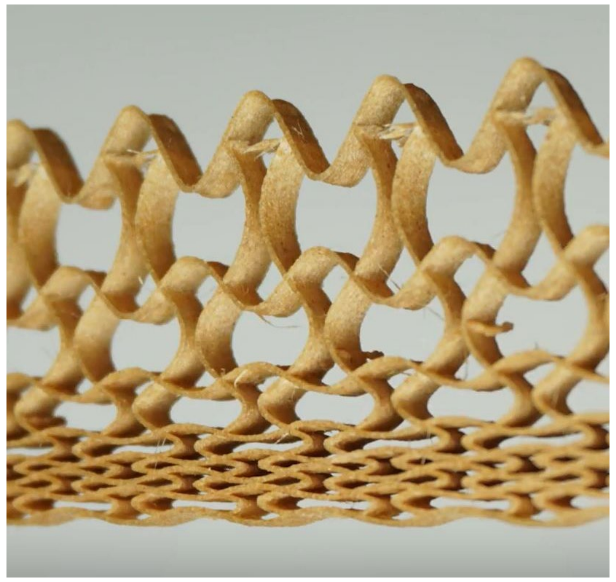


Figure 41 4D printing (Sahin., et al, 2023)

6.1.3 Kerf-bending

Kerfing or kerf-bending is a curving method mainly used in carpentry. As carpentry requires small radius curves, numerous methods have been developed to achieve this. In a nutshell, by systematic removing parts of a rigid material at strategic locations, the structure becomes more flexible, making bending possible. This characteristic can be used as filling between the bi-layer component and the locking layer, creating a flexible 'height increaser'. However, as a result of removing or cutting parts of the material, gaps arise. These gaps may face large stress concentrations, making the material more fragile (Lorenzoni & Da Silva, 2022).

Figure 42 Kerf-bending. (Brudeli, 2022)

6.1.4 Kielsteg

Boxfloor elements are compact configurations and can span multiple meters. These configurations change, depending on the manufacturer. One of the most profound systems is the Kerto-ripa boxfloor element. By combining straight and rectangular timber elements, a strong structural floor element is created. Kielsteg developed a method to create rigid floor elements, with less material. By combining and connecting thin, diagonally placed, timber boards, a triangular cell structure is created. The fact that the elements are so rigid, makes self-shaping a challenge. However, by combining certain options together, a new passively bend option may arise. These options will be tested in the laboratory, and will be judged on multiple parameters and criteria.

Figure 43: Kielsteg boxfloor (Koskamp, 2019)

6.2 *Sketching & Designing*

The many different spacer typologies described in the last chapter, were taken as a benchmark for the newly developed typologies. As the self-shaping criteria is dominant in the decision-making for shape, orientation and geometry, each typology is unique. Sub-groups were eventually created, based on matching properties. The figures show the spacers and the second self-shaping layer, the primary self-shaping layer above the spacer has been made transparent.

Straights

The block typology is the dominant contributor to the idea and inspiration of the first 3 configurations. All 3 are slightly different from each other, but share the same parent. The 3 options are called; Traffic, Convergent & Tube. The Traffic and Convergent typologies both use blocks to create height, where the orientation of the blocks play a key role in providing structural strength and allowing self-shaping curvature. The Tube typology is based on interconnecting the blocks with a hollow of solid tube like element, thus creating a guider for proper curvature shaping.

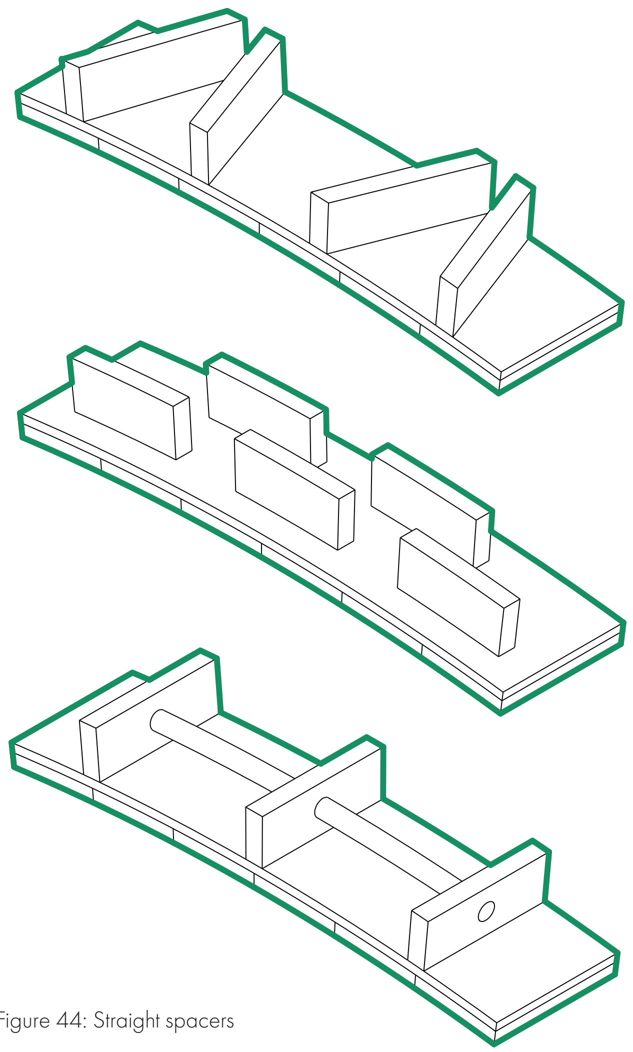


Figure 44: Straight spacers

Trusses

Trusses are used often in the building sector, as they are a strong and reliable form of construction. The Kielsteg boxfloor element uses the principle of a truss, and the newly designed Y-shape and Gulf elements do so too. The Gulf typology makes use of a sinus-wave extruded element which has many contact point with the primary and secondary self-shaping layer.

The Y-shaped element employs multiple inverted components that can be manoeuvred into position, thereby increasing the circularity of the design. When these Y-shaped elements are positioned adjacent to one another, they form a continuous triangle grid. However, this arrangement may compromise the overall self-shaping ability of the element.

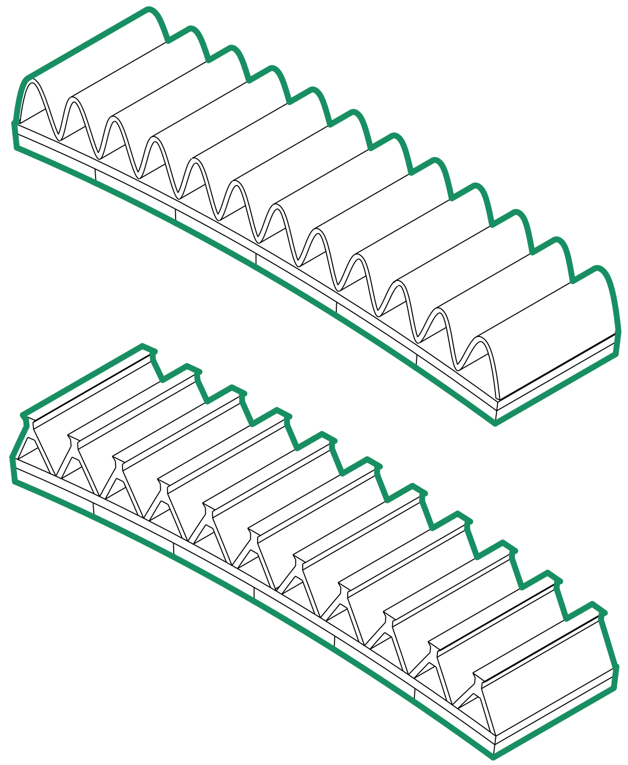


Figure 45: Truss spacers

It's important to note the interplay between strength and curvature; a stronger element tends to resist curvature induced by self-shaping. Conversely, increasing self-shaping capabilities may weaken the structural integrity of the element, which is not desirable for a structural component.

Comb

The Comb configuration stems from the kerf-bending principle. By removing material from the spacer, it can become more flexible in a certain direction. In this design, material has been selectively removed from the underside of the spacer, allowing for increased flexibility. However, it could be argued that removing material from the top as well would be beneficial. As a element is bend, tension at the top and pressure at the bottom occur. The pressure ensures compression of the fins, which can act as a locking mechanism. By removing material from the top, the top part of the Comb experiences reduced tension, resulting in easier curvature and self-shaping.

However, it's important to consider the drawbacks of removing material from the Comb. Excessive bending or sagging may occur, especially under heavy loads placed on the structural element.

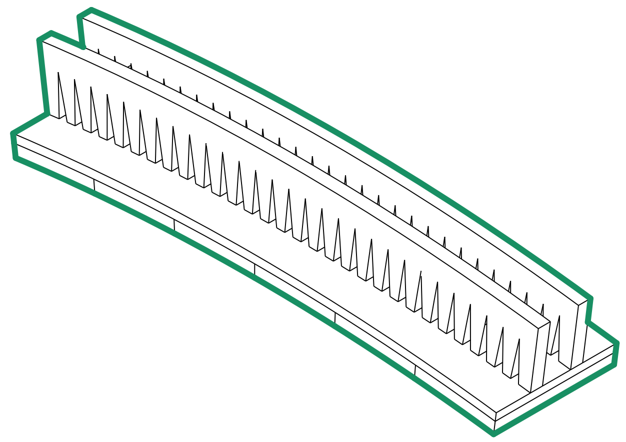


Figure 46: Comb spacer

Rods

Taking inspiration from the intricate 4D-printing technique, the Rod principle is characterized by the utilization of numerous poles that establish connections between the primary and secondary layers. Currently, these poles are randomly positioned and arranged linearly. However, this configuration is subject to change depending on optimization or Finite Element Method (FEM) studies projected onto the poles. The angles of selected poles may change to enhance lateral stability, while certain areas may require a higher density of poles to accommodate larger load flows. This adaptability underscores the potential for dynamic optimization and customization within the Rods principle framework.

Indeed, while the poles effectively distribute floor loads from the first to the second layer, they themselves do not contribute significantly to stiffness. This limitation may pose challenges when dealing with real-life dead and live loads.

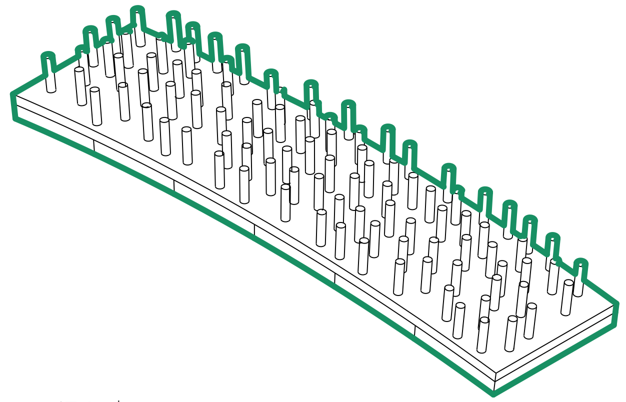


Figure 47: Rod spacer

6.3 Selection

To make an informed decision on which typology to further develop and potentially test, it's necessary to establish specific parameters. The structural element must comply to these conventional specifications before progressing from conceptual sketches to physical models.

Manufacturing

In 2024, the capability to manufacture nearly anything exists, but the challenge lies in balancing speed, cost, and quality. This dilemma is often referred to as the iron triangle because achieving excellence in all three areas simultaneously is unattainable. Structural elements, in particular, cannot compromise on quality as they must adhere to timber NEN-EN standards. However, given the time required for timber to reach equilibrium and increase Wood Moisture Content (WMC), time becomes a critical factor. Thus, the primary aim is to reduce manufacturing time, even though this may result in increased costs for the end product. The manufacturing threshold is linked to how easy the spacer elements can be produced.

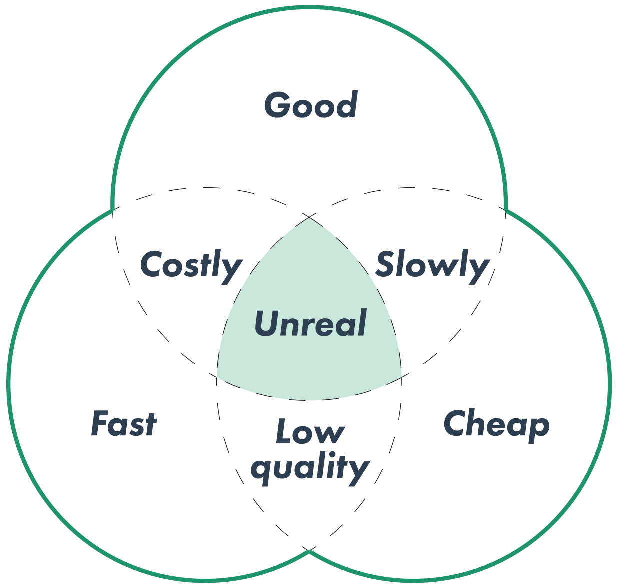


Figure 48: Iron triangle

Structurally

Conclusions about structural integrity can not be made before load testing has been done. However, design choices influence the stiffness and strength of the overall element, therefore an indication of the structural performance can be estimated. One of those indications is geometry. Triangles are desirable in making robust and strong elements. Furthermore, design choices made to increase lateral stability is desired. This could be done by non-linear elements or shifted and angulated elements.

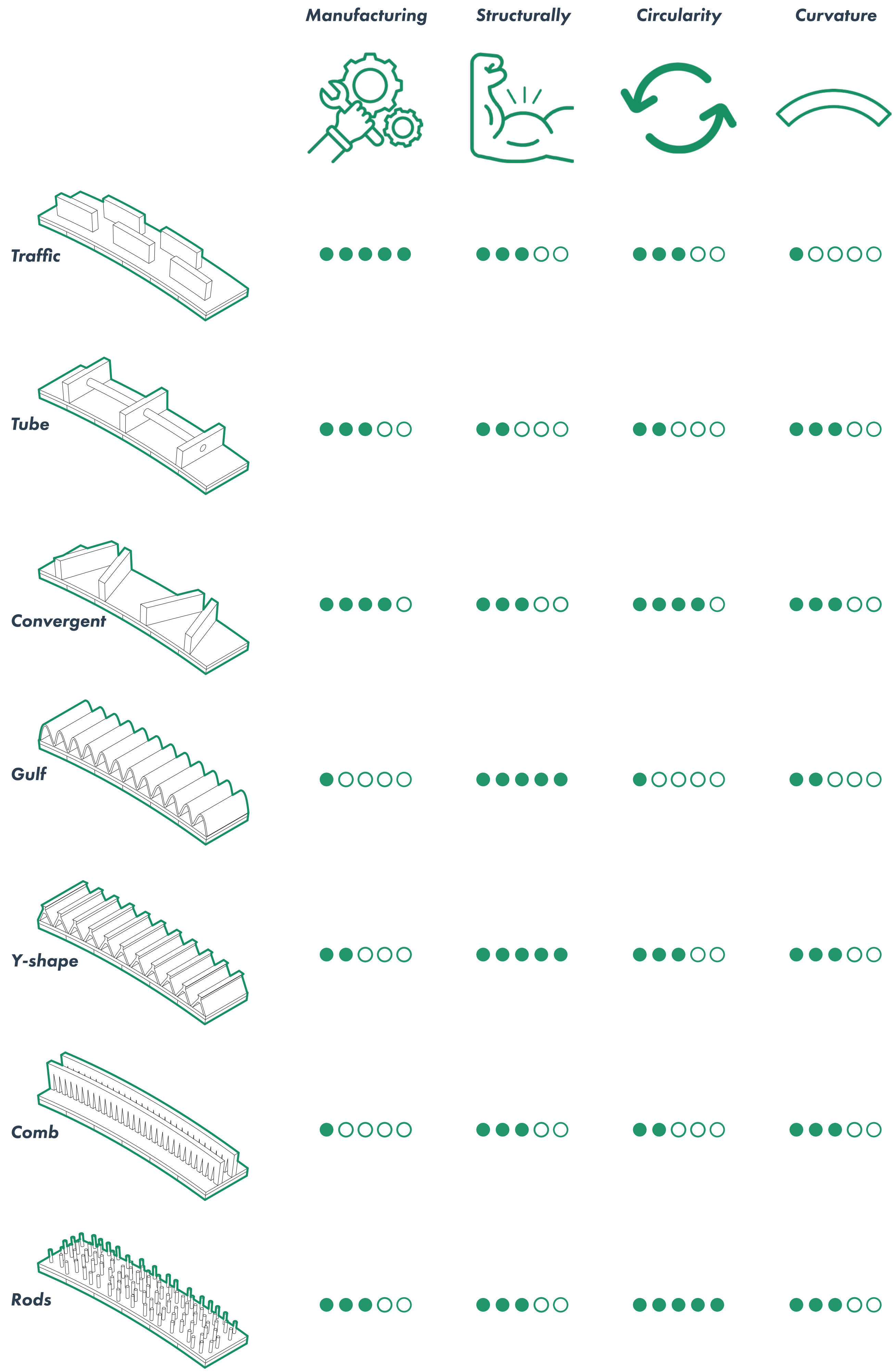
Circularity

Products can by made circular when the R-strategies are integrated into the design. As stated in Chapter 2, the R-strategies consist of a group of 9 terms, related to the life-time of a product. If a design can be refurbished or parts of the spacer filling be replaced, the circularity score increases. This also works with recyclebility or repair of elements. Think of demounting and replacing pieces. Due to the self-shaping nature of the elements, the spacer fillings can become fixed in place. Glue is therefore unnecessary. All these little things effect the circularity result.

Curvature

There exists a correlation between structural stiffness and the potential for curvature. Generally, the stronger an element, the less curvature it can achieve. Moreover, large geometries, particularly orientated in the span or curvature direction, tend to reduce curvature. Therefore, minimizing material usage is essential for maximizing self-shaping capabilities. However, it's worth noting that having significant amounts of material but limited contact points may favor the element's capacity for self-shaping.

These four terms; Manufacturing, Structurally, Circularity & Curvature, form the benchmark of choosing the right typologies to workout and test. As seen in figure 49, the Convergent and Y-shape options show high potential to be selected. Therefore, these 2 types are being worked out further.



	Manufacturing	Structurally	Circularity	Curvature
Traffic	●●●●●	●●●○○	●●●○○	●○○○○
Tube	●●●○○	●●○○○	●●○○○	●●●○○
Convergent	●●●●○	●●●○○	●●●●○	●●●○○
Gulf	●○○○○	●●●●●	●○○○○	●●○○○
Y-shape	●●○○○	●●●●●	●●●○○	●●●○○
Comb	●○○○○	●●●○○	●●○○○	●●●○○
Rods	●●●○○	●●●○○	●●●●●	●●●○○

Figure 49: Typology comparison

6.4 Elaboration

The idea of creating a combination of a boxfloor element and a beam-like structure was not intended, yet using the term spacer, by definition a boxfloor element is in the picture. At first, the Kielsteg geometry was a main source of inspiration during the development phase. Kielsteg combines a conventional boxfloor outside while making a zigzag pattern as a filling, resulting in a strong, lightweight and robust structural floor element which can spans up-to 13 meters. The orientation of the fins, which is the filling, indicate the span direction of the overall mass-timber element.
Solid beams do not have oriented fillings, the material itself appoints the shape and span direction. In timber, the fibre orientation is imported during development or manufacturing of a beam. By this precedent, the spacer should follow the span direction. However by doing so, the element will become too stiff which causes problems to arise for self-shaping. Therefore the locking layer will play a key role in maintaining a stable and strong structure as the spacer fillings do not contribute as much to the overall structural strength if designed incorrectly. As seen in figure 40, the spacer fillings have a similar structural approach, however the design and mechanism are completely different.

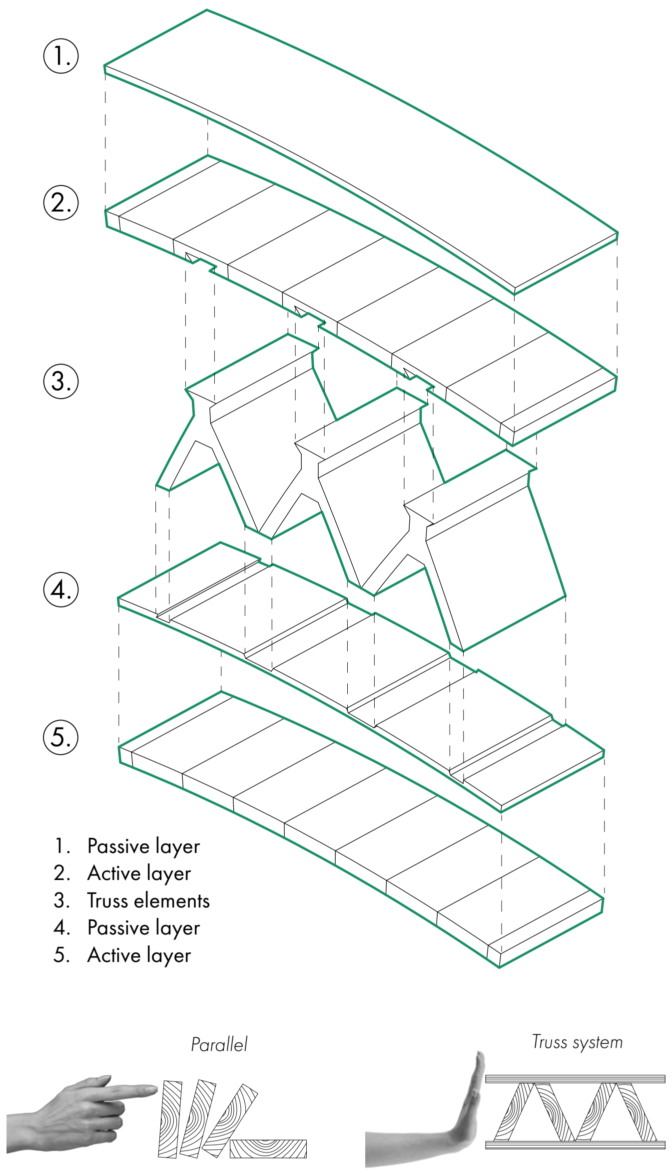


Figure 50: Truss elements

Truss system blocks

A truss system can embody different geometries and forms. Nevertheless, truss systems have almost always something in common; diagonal beams or elements play a major role in ensuring lateral stability. It is widely acknowledged that triangles are one of the strongest geometries used in the construction sector. Bridges and diagrids are great examples in the build environment which showcase the use of the triangle topology as a construction geometry. Lateral stability can become a challenge, as the height of the element is increased by the use of spacer fillings. Furthermore, due to the fact that the height of the structural element with a spacer filling is increased, consequently also will its centre of mass rise. The higher a centre of mass of an object, results in a less stable object.

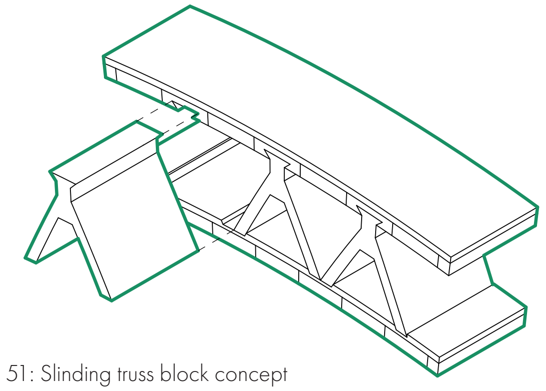


Figure 51: Slinding truss block concept

Therefore a reversed Y-shaped object is used as a filling. By placing the Y-shaped elements next to each other, an interlinked triangle grid will be created. Moreover, the fillings will contain a sliding mechanism, creating a more circular product, contributing to a sustainable construction sector. The challenge however is developing the details to ensure a safe, low-tech and low-maintenance product. As the timber pieces will expand and shrink due to different WMC. Also the second bi-layer should seamlessly connect with the Y-shaped fillings above. Only than a symbiotic relation between the bi-layers and the spacer filling can be made.

Convergent blocks

A simpler and less technologically advanced option is employing convergent blocks. Unlike traditional methods where spacers are placed parallel to each other, convergent or divergent blocks are positioned at angles towards each other. This arrangement creates triangular shapes within the structure, enhancing stability. By restricting rotational freedom through the orientation of these blocks, the mass timber element gains increased lateral stability.

Upon examining the geometry of the element, it bears resemblance to a 'vierendeel' truss. This type of truss lacks diagonal elements, rendering it a versatile shape. The openings within this structure can serve as pathways for mechanical building components such as air ducts, pipes, and lighting fixtures. Additionally, the absence of complex shapes simplifies the design, enhancing its low-tech and low-maintenance qualities. This observation was further confirmed during the preparation stages for testing and construction. The assembly of components for the convergent option notably required less time as expected. This efficiency should be duly considered when determining the optimal topology for mass production.

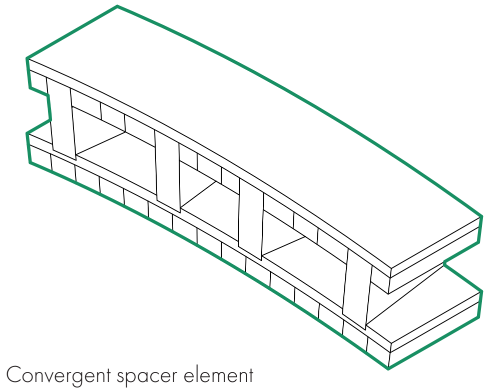


Figure52: Convergent spacer element

In the convergent design, a sliding mechanism is slated for implementation to enhance stability. However, this addition moves the element away from its original low-tech and low-maintenance attributes. Additionally, adjustments to the second passive layer are necessary to ensure precise placement of the spacer fillings.

These adjustments can be achieved by employing a milling machine. This sophisticated tool operates by removing material using a spinning bit, effectively cutting away timber to achieve the desired modifications.

Additionally, modifications to the second passive layer are imperative to guarantee the precise placement of spacer fillings. Also, the locking layer should be integrated in the design.

Overall, the convergent block approach offers a simpler and less technologically intensive alternative. Its resemblance to a 'vierendeel' truss allows for enhanced stability and versatility, while its simple geometry facilitates ease of construction and maintenance. This underscores the importance of considering efficiency alongside technological advancements when selecting the optimal topology for mass production

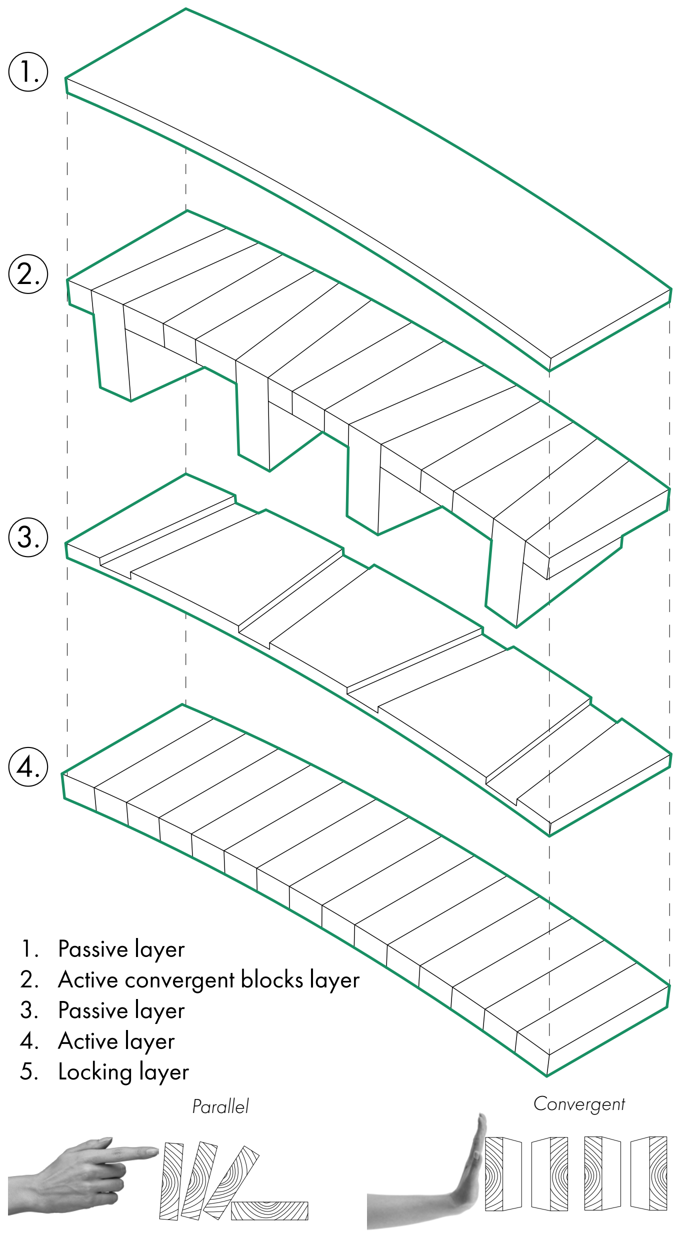


Figure 53: Convergent elements

6.5 Self-locking

A recurring challenge with all developed typologies is the requirement for a locking layer. While the typologies demonstrate sufficient strength to bend autonomously, they tend to deform when subjected to loads. The locking layer plays a crucial role in preventing deflection or sagging of the structural element under these loads. However, manufacturing the locking layer involves a different, more energy-intensive process compared to the passive or active layers. Nevertheless, there is theoretical potential to bypass the need for a locking layer by exploring alternative designs of the spacer filling.

It is known that the active layer expends when placed in high RH environments. Consequently, timber shows shrinkage when placed in a low RH environment. In the winter, people tend to heat the building to reach an comfortable indoor temperature, meaning that the RH will decline. During summer times, air-conditioning and other measures are just to cool the building, which increases the RH. Still, on average the indoor relative humidity is around 40-60% for residential buildings (Psomas et al., 2021).

Designing an interlocking mechanism within the spacer filling typologies that leverages changes in relative humidity (RH) could potentially eliminate the need for a separate locking layer. After the adhesive period, the element can be subjected to a low RH environment of approximately 10%. As the timber pieces shrink in response to the low RH, the interlocking mechanism can engage, securing the element in its desired shape. Subsequently, the element can be placed in a mean indoor RH environment, causing some swelling again. During these two steps, the locking mechanism would effectively fasten, providing structural stability without requiring a dedicated locking layer. This approach could streamline the manufacturing process and reduce energy-intensive manufacturing methods associated with traditional locking layers.

This process of fastening during the different steps can be seen in figure 54. The interlocking mechanism can be as complex as needed, yet simple designs may work as well. Moving part should be avoided, as they tend to break more easily.

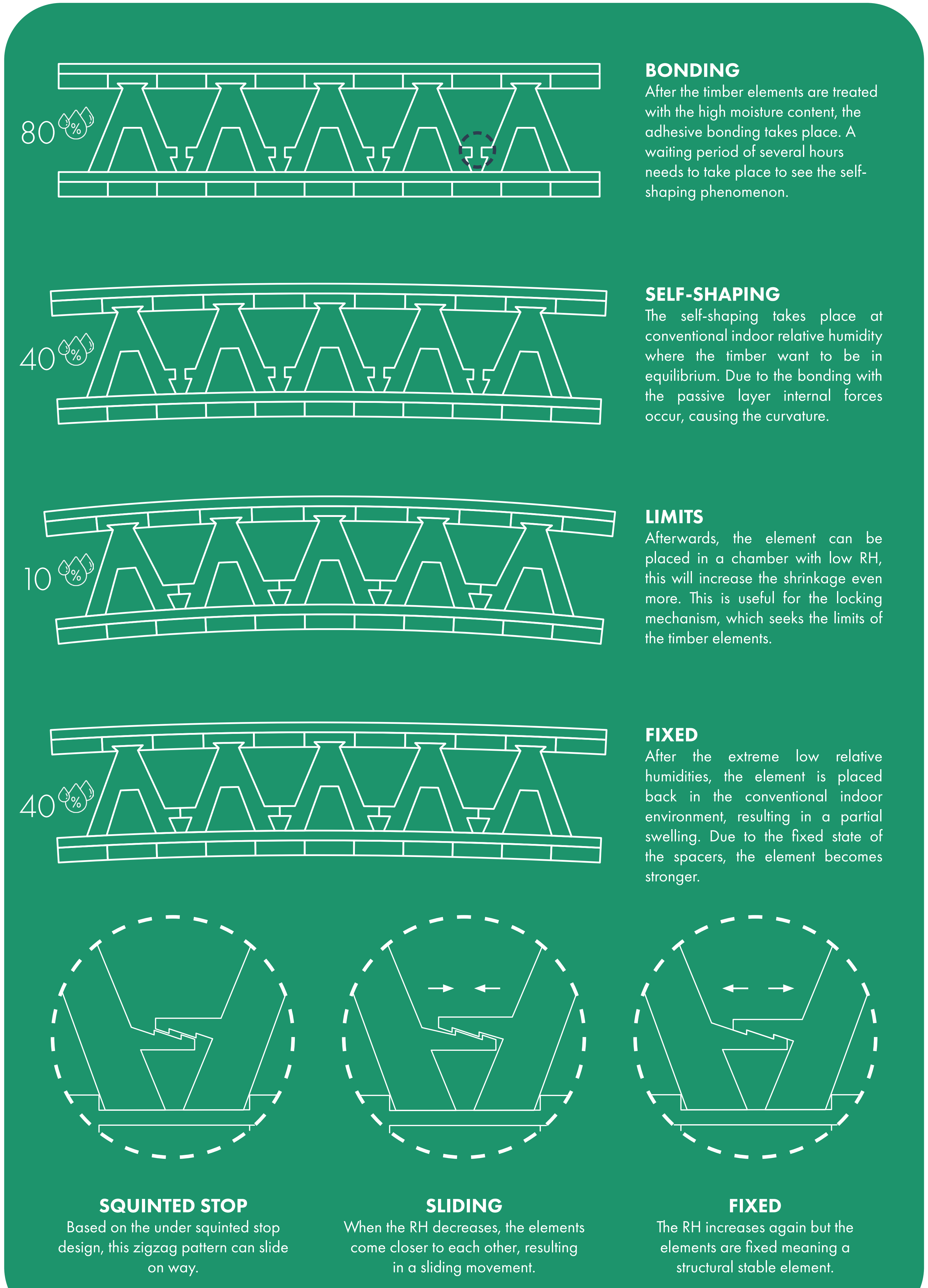


Figure 54: Theoretical locking mechanism

6.6 Multi-layer

The principle of a multi-layered structure is not new. As stated earlier, CLT or LVL typologies consist of many timber layers which can been glue together. There already exist examples of passive self-shaping multi-layers, most prominently the Urbach tower. By combining 2 bi-layers and a locking layer, a 90mm thick CLT element is created. However, the methodology of creating a self-shaped CLT element is of importance, and more specific the assembly of the elements. As seen in figure 46, the bi-layers are passively curved separate from each other. Only when the finale curvature is reached, the 2 bi-layers are combined with an actively bended locking layer. After assembly, the solid structure can be used to create an observation tower, as they did in Germany (Figure 55). However, this separate curving is more time consuming and work intensive than assembling the element as a whole. Furthermore, more space needs to be reserved for drying two elements as compared to one combined element. This raises the question if it is possible to passively curve a multi-layered element as a whole?

Figure 55: The Urbach tower. (ICD/ITKE University of Stuttgart., 2019)

6.7 Sketching & Designing

The multi-layer principle speaks for itself. Combining two passive layers and two active layers during the drying period could still make passive self-shaping feasible. Therefore, the most straight forward approach is to combine these elements during the drying period.

Simple multi-layer.

Combining passive and active layers to create the whole elements has been done before. However, combining them during the drying period before the self-shaping has set in yet, has not been done before. Although it can have its advantages of less time consuming and less space needs, there could be a problem consearning the hard and soft woods. As hardwoods have a slower drying time than softwoods, by combining the two and enclose the hardwoods, moisture can be trapped inside, making the changes of fungi or mold forming significantly higher.

Interlocking

There could be a possibility to remove the adhesive layer between the first and second bi-layer by implementing an interlocking system, which effectiveness starts when the self-shaping phenomenon happens. As seen in figure 56, as the lower plane of the first bi-layer has a smaller curve radius as the upper plane of the second bi-layer, they rub against each other. By designing an element, for example dowels, which makes this interlocking system work, glue usage can be reduced by 1/3. A challenge with such an interlocking system may be safety. When humidity changes, the element will expend, shrink, move. If the connections may loosen, the whole element becomes unstable and its structural integrity is lost.

It has to be said that this typology is not thoroughly researched and developed, due to the already existing nature of the geometry. Still, the principle of assembly before drying has an added value, which could perhaps be beneficial for the overall aim of the research.

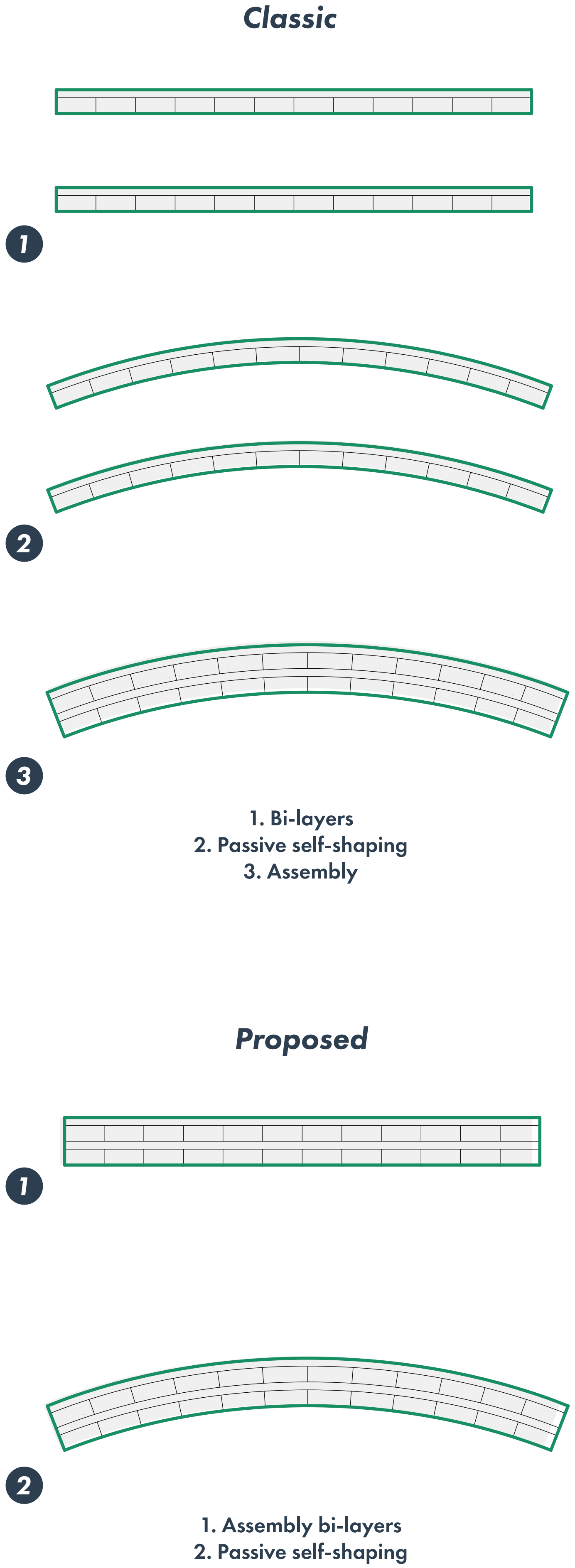


Figure 56: Assembly methods multi-layer

Testing

p h a s e

7

Once the material was prepared and the test set-up documented, the testing phase of the master thesis research could begin. The material used during the first experiments were gifted by Gilbert Koskamp's architectural firm OvO, located in Amsterdam. The facilities used during the experiments were made available by Barbara Lubelli from the heritage department at the architectural faculty in Delft.

The fact that the research gap in this particular field of mass timber is dominantly present, the research testing conducted must be reliable. Furthermore, as the analytical models only mention or describe the bi-layer typology, only by physical testing conclusions can be drawn.

7.1 Scope

The first physical test focused on a 'simple' bi-layer construction. Due to the fact that the analytical model can be a theoretical reference based on formulas based on literature, a comparison and conclusion can already be made. Furthermore, the first bi-layer component can be compared to other bi-layer components developed during similar research testing. After the primary bi-layer test, the different designed typologies are explored in their self-shaping capacity. These typologies exploit multiple structural design options.

Figure 58: Visualisation of used spruce wood during bi-layer test.

Bi-layer

The timber used in the initial first test was standard spruce wood, acquired by the local hardware store. These slats, with a maximum length of 1200mm, where cut to the right size in order to construct a bi-layer element. The first step taken during the physical testing was determining the wood moisture content or WMC. This was done by measuring the weight of the element and comparing this to the dry-state weight of this particular timber species. As seen in Figure 59, the elements with the corresponding WMC are shown. In total, 18 blocks were placed inside the controlled high humidity chamber.
The relative humidity in the chamber was controlled by a salt concentration, Potassium chloride (KCl), creating a humid environment of ±85% relative humidity. The ventilator distributes the moisture proportionally. During a 5.5 day period the RH and temperature were measured by an easy-log USB (Apendix). During the 5.5 day period, the timber absorbed moisture, resulting in an average WMC increase of ±4,58%. During this period, multiple measurements were conducted in order to get an profound insight on absorption ratios. These moist blocks are bonded with the passive layer, which had an WMC of around ±8%, as it was placed in a regular indoor environment. When the active timber blocks are relocated from the high relative humidity environment to a standard indoor environment, they will try to find an equilibrium with the relative humidity of the indoor environment, therefore the adhesive process needs to be conduced rapidly. The adhesive used in the first test is a standard water resistance wood adhesive. This adhesive is known for withstanding high moisture concentrations. When the two layers are glued together, the bi-layer needs to dry, which eventually shows self-shaping. The analytic model predicted a curving height of about 40 mm by a bi-layer length of 1200 mm. The first physical bi-layer model shows a curving height of around 10 mm, which is around 25%.
This difference in actual and analytic curvature can maybe be explained by the 'low' 85% RH which does not seek the maximum expansion of the timber block. Furthermore, the glueing time was obstructed by a fire alarm, which went on for over 1,5 hours. Also the time in the high RH can be argued to be not sufficient enough, thus the blocks possibly did not reach the maximum expansion potential. All these factors can contribute to a lower curvature height than predicted. Still, the first goal of creating self-shaping has been achieved, making a clear path towards manufacturing the newly designed topologies.

Typologies

To pursuit the goal of developing a self-shaping multi-layer structural element, design aspects have to be refined. Reaching the final goal takes steps and for this part in the thesis, these steps consist of sketching, refining, re-developing which eventually leads to progress.
The aim is to see how the timber and overall element react every time a new sub-part is added. As seen in Figure 60, the bi-layer is the baseline from where the next steps can be taken from. In this figure the spacer element is still unidentified. After sketch-designing based on existing structural principals, over half a dozen 'prototypes' were created and two types are going to be developed further. The spacer typologies consist of a top layer, a spacer layer and a bottom layer and afterwards a locking layer is added for stability reasons. However, the development process is not linear. As challenges occur and eventual results be lacking the preferred outcome, changes can be made to optimise the element and thus creating a near prefect self-shaping structural element.

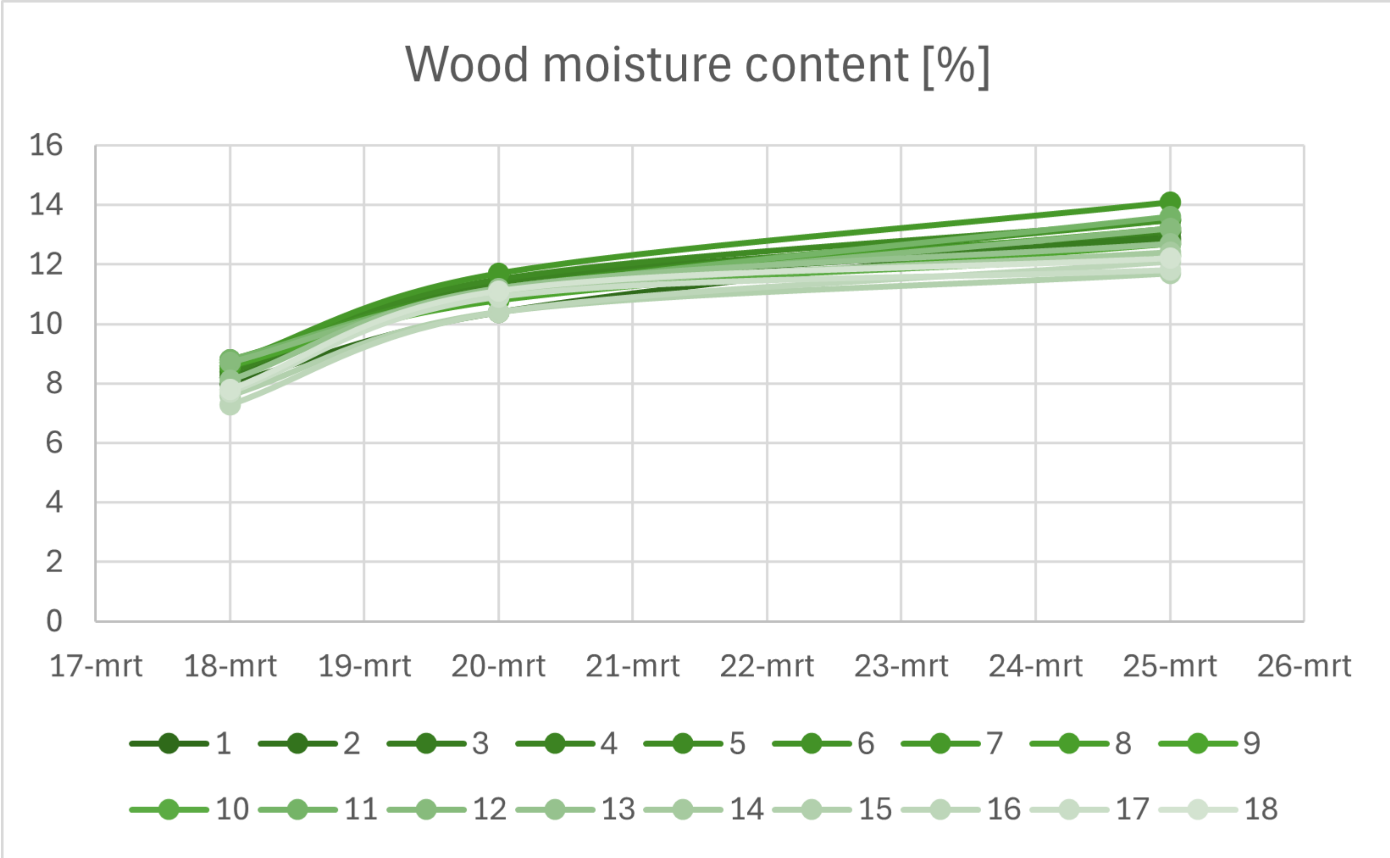


Figure 59: Wood moisture increase over a 7 day period [%]

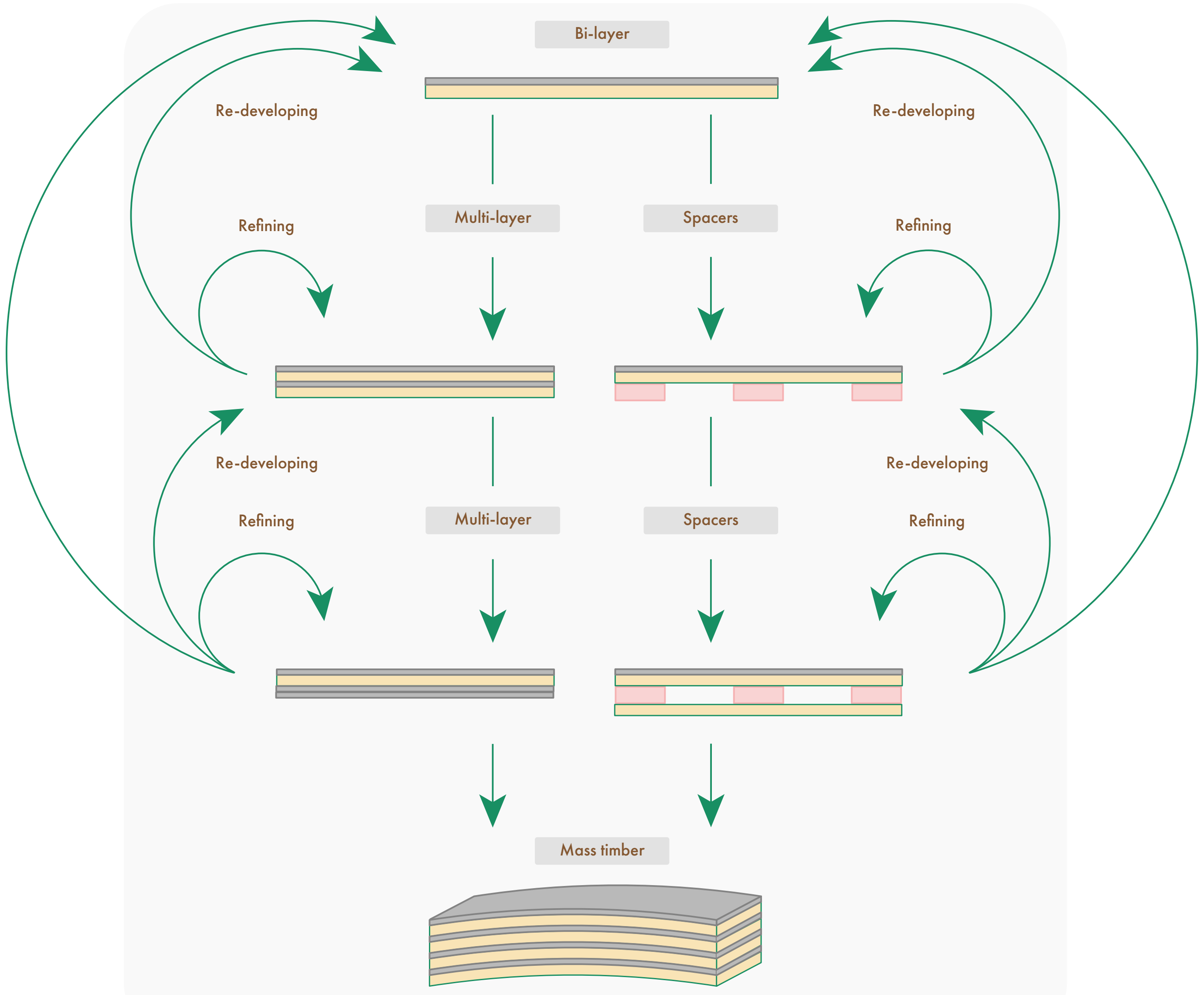


Figure 60: Process of manufacturing the end goal

7.2 Timber

Before the testing phase can start, the right timber specimen had to be obtained. The first introduction test, a simple bi-layer configuration, was realised with standard spruce timber from the local hardware store, as stated before. However, to conduct a realistic experiment, the right species of timber should be used. Softwood is widely available. Hardwood on the other hand is a more scarce and expensive product for the common man. Therefore many companies were contacted to find some leftover timber, sadly without results.

My second mentor Gilbert Koskamp gave contact details of Lorin Brasser, who could help in the search for the right specimen. After going back-and-forth exchanging information about the goal and aim of this thesis, I went to Westpoort Amsterdam to meet Lorin in person. Without question Lorin and Santiago, an employee and former TU Delft student, helped me in finding the right timber. It so happened that there was an old batch of hardwood still laying around. From Beech, Ash and Oak. Furthermore, there were also multiple softwood planks, with Douglas fir as the most prominent species. In total over 30kg of pieces were loaded and taken to the architecture faculty in Delft.

A challenge with all the different types of soft- and hardwood pieces is that not for every piece the original species is known. This makes controlled experimenting and testing harder and less accurate, as the properties like expansion rate are unknown. Furthermore, the pieces were leftovers, meaning that their quality was not desirable. As seen in figure 62, large knots, cracks and imperfections are present in the timber pieces. Although this wood can still be used, it does influence the overall outcome and results of the experiments. Also, some pieces were glued, screwed and painted, which may effect the overall result as well.

Yet, I am grateful that I got the opportunity to meet with Lorin and Santiago, and for their generosity in contributing to this thesis by supplying the much needed timber.

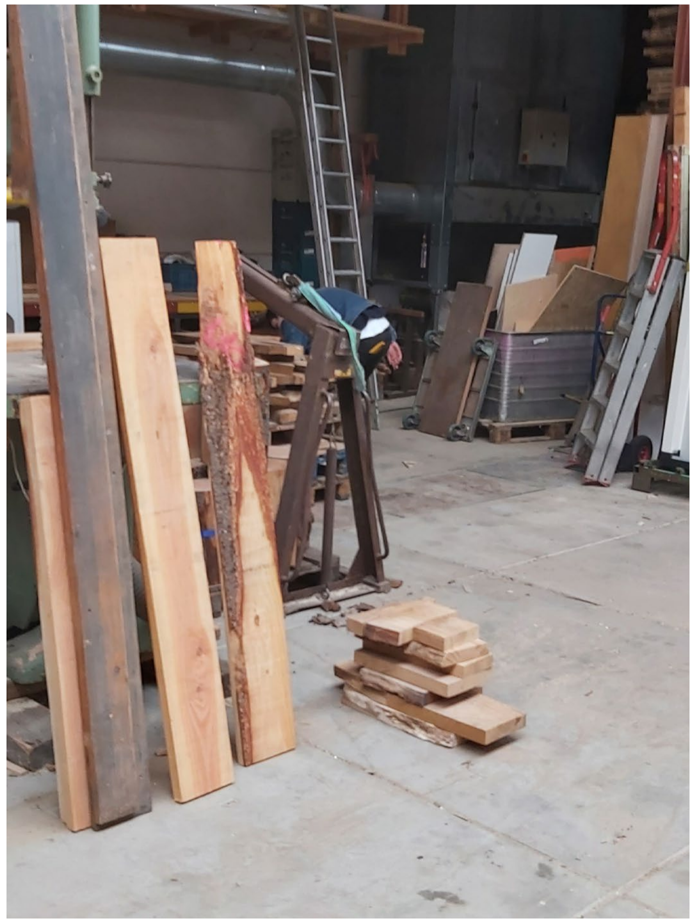


Figure 61: Selection of usable timber

Figure 62: Selected timber

Figure 63: Timber artwork at the hangar

7.3 Testing

After the initial first test had an positive self-shaping outcome and different types of soft- and hardwoods were acquired, larger and complex typologies could be made. For the second test, larger Douglas Fir elements were cut and shaped to be implemented as a spacer typology.

Spacer testing

For the second hygromorphic test, enough blocks were cut to make 3 different typologies. At first these blocks were placed in the fridge with potassium nitrate (KNO_3) to create a RH of ±95%. After 2 days of moisture treatment, the smaller elements were placed in a bucket of water. By placing the elements in water, the hygro-expansion time may be shortened. The RH over the whole 5,5 days did not exceed 80%, and the blocks increased in weight by approximately 10 grams. The smaller blocks which were splaced in water increased in weight by over 50 grams. Furthermore, their size was significantly increased as well. After the 5,5 days, the elements were glued together. After a resting and drying period of 2 days, the self-shaping results were disappointing. A few problems occurred which caused the disappointing non-present self-shaping outcome in both bi-layers.

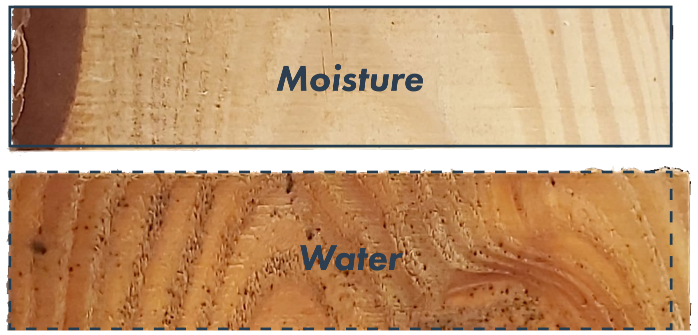


Figure 64: Expension difference moisture vs. water

Smaller blocks

The smaller blocks were originally used scrap wood with some kind of paint coating. This coating made adhesive joining hard. In the days after the joining, seen in figure 56, the boards detached from the passive layer although they had been properly glued and clamped. Due to the detaching, the self-shaping did not happen. Also the glue became an issue. As it is not a structural glue, its strength may have caused problems as well. The strength of the cupping of the boards was stronger than the adhesive, resulting in an invalid test result.

Larger blocks

The large blocks were only placed in the fridge for a reason. A test block was placed in water and showed significant expansion. However when the block dried, large cracks and chaps were noticed. This resulted in a weaker and fragile timber blocks, which could not be used in a spacer bi-layer.

Nevertheless, the fridge-blocks never showed any curvature as well (Figure 69), while they were attached properly to the passive layer. One possibility of no self-shaping is the thickness of the passive layer. Although the proportions are 1:2 for passive and active, the passive layer is very stiff.

Figure 65: Crack forming due to water treatment

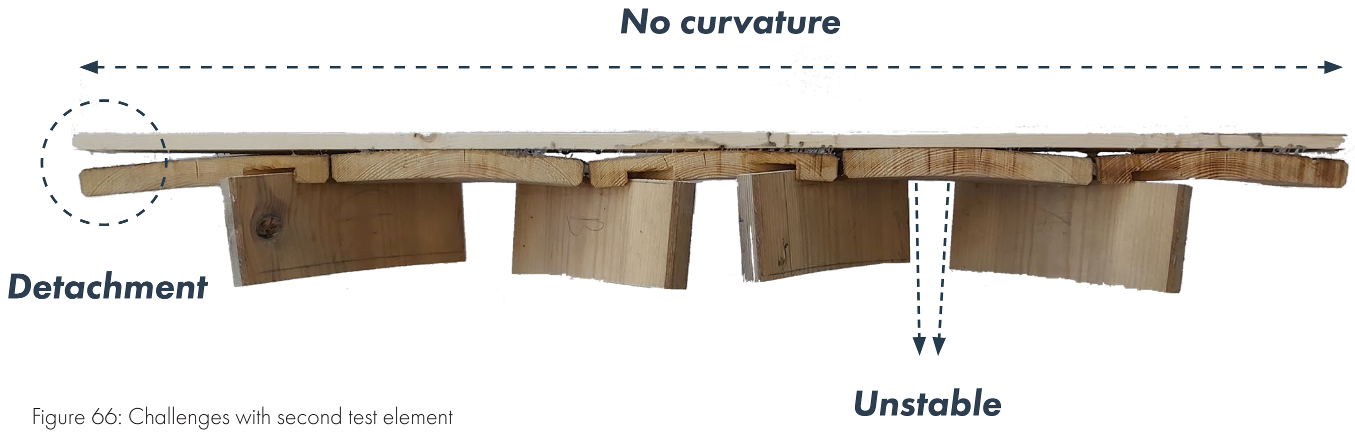


Figure 66: Challenges with second test element

Figure 67: Detached elements due to excessive curving.

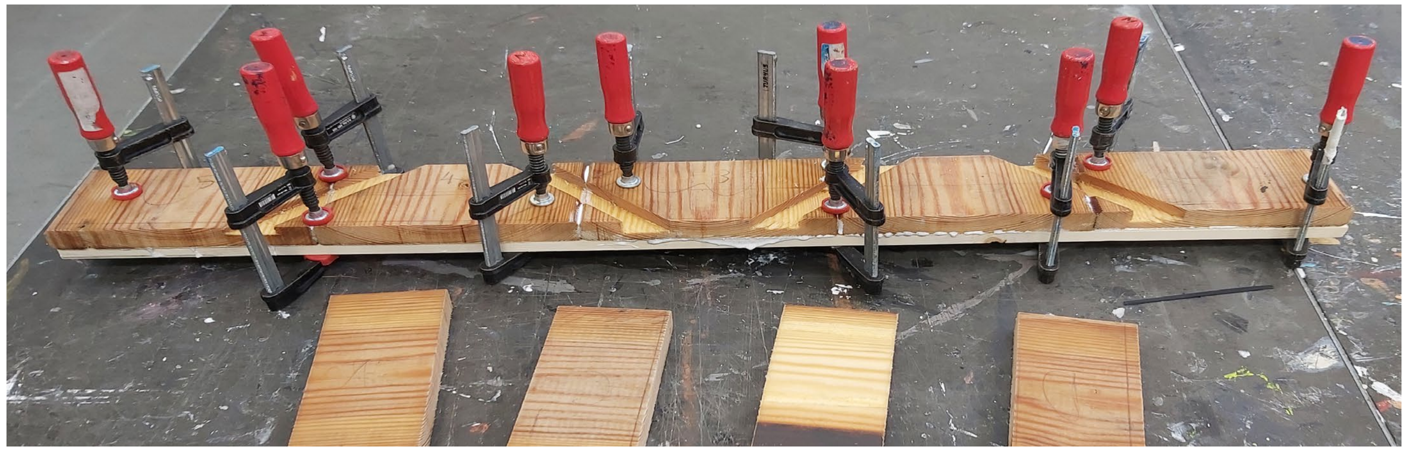


Figure 68: Assembly process

Figure 69: Large blocks showing no curvature

These disappointing results meant that the self-shaping process had to be rethought and re-develop. Because, going from a promising first test to no self-shaping in the second test is problematic and should be investigated.

Re-developing

The simple bi-layer of the first test has already been proven to work. Therefore, the third test was done with the same type of timber used in the first test. Two simple spacer typologies, a combination between the convergent and the tube options, were made. These two elements had the same dimensions, timber species and process time, however the hygroexpansion method was different. One of the two active layers was placed in a relative humidity whereas the other active layer was placed inside a bucket of water. This difference in process is necessary to understand why test 2 was a failure. Therefore three control groups with four specimen were made to measure and document findings. The bucket group will be called A-group, the fridge group is B-group, and the test specimen where nothing happened will be called T-group.

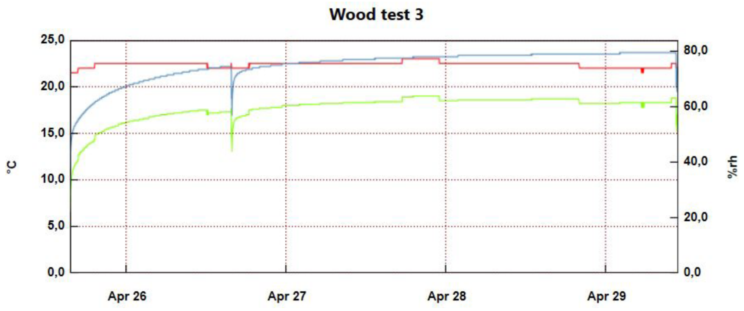


Figure 70: Temperature and humidity during test 3

Over a period of 4 days, the A- and B-group were treated with water and high relative humidity respectively. Again, the RH did not exceed the 80% margin over the testing period, seen in figure 70. The appearance of the A- and B-group was significantly different, see figure 61. The water group expanded more than the B-group, this would also suggest more shrinkage and thus more self-shaping curvature. Furthermore, for this third test a new adhesive was used. This transparent construction effervescent glue based on a polyurethane formula by bison is stronger than the conventional timber glue used in the first two test. The two different active layers were both bounded within 1 hour, which reduces the curvature rate change.

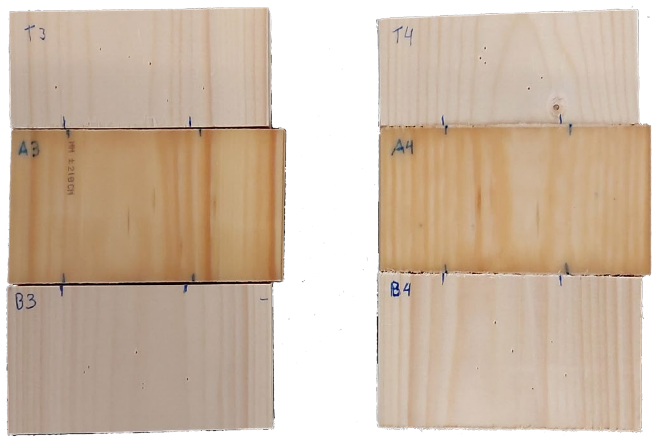


Figure 71: T-group compared with A- and B-group

When the two elements were glued, the drying period starts. Both elements were placed in the same location. The A-group, which showed greater hygroexpansion due to the water, had no significant curvature after 24 hours, whereas the B-group showed self-shaping. Only after 48 hours, self-shaping became noticeable for the A-group. As seen in figure 72, moisture treatment resulted in more self-shaping compared to water treatment, meaning that using water processed timber elements is not advisable. The causation for limited curvature can not be blamed on the adhesive bonding, as a stronger glue was used than before.
A plausible reason for the lack of curvature by the A-group may be the stiffness of the timber after the water bath. The blocks became significantly weaker which can weaken the connection of the timber with the adhesive. This could also be the reason why the elements in the second test failed. The glue was weaker, the timber became weaker and the passive layer was thicker meaning more internal forces are needed to bend the element.

After 24 hours, the B-group exhibited self-shaping curvature comparable to the first test. This observation is significant, considering that less space was allocated for the active layer due to the presence of spacer blocks. Additionally, the curvature observed confirms that the large blocks used in the second test may be insufficiently strong to bend a thick board effectively.

Furthermore, the active layer blocks were attached to each other. In the first test, the blocks were glued next to one another, but due to hygroshrinkage, gaps occurred. Therefore, during this test the active layers were glued

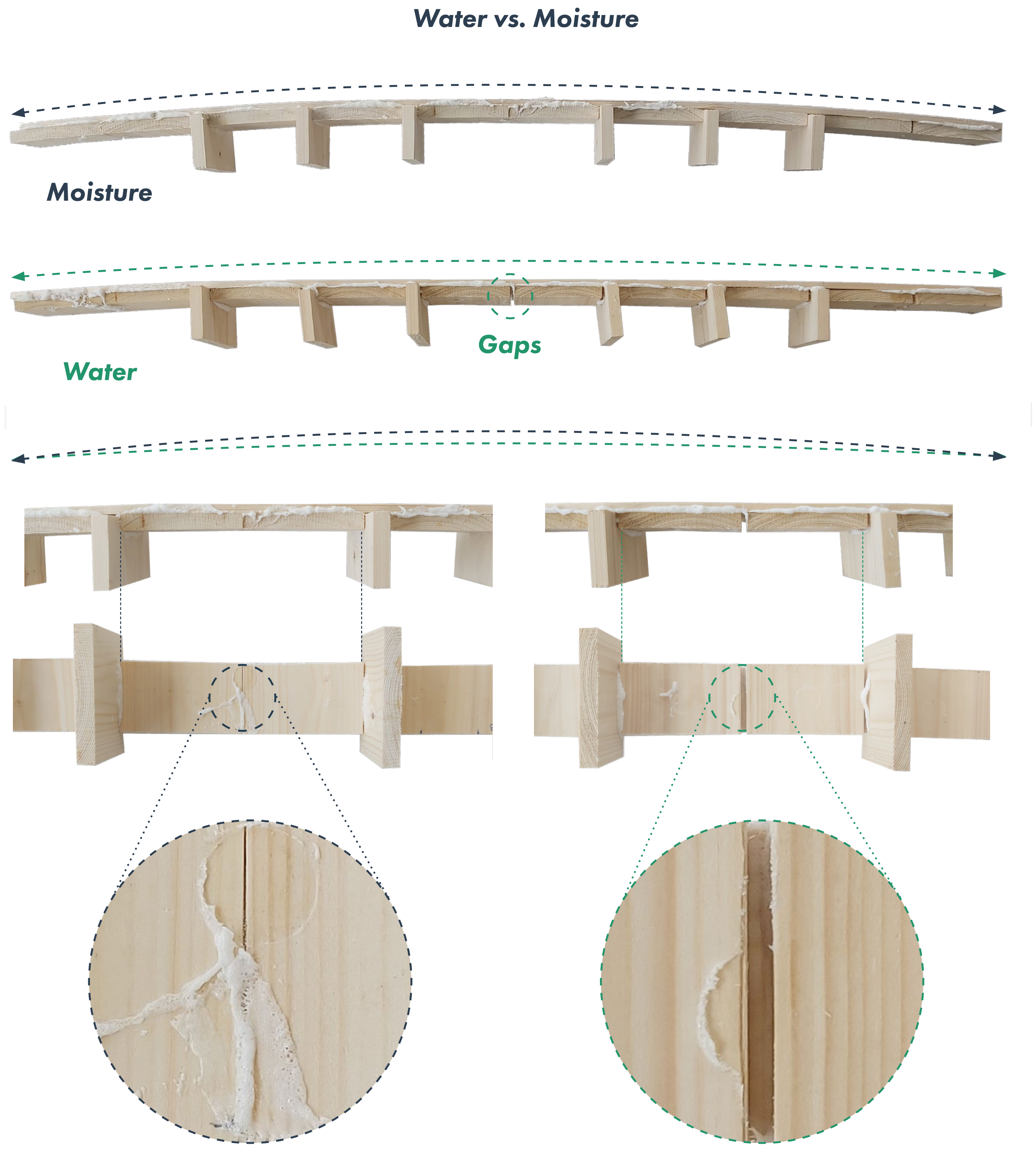


Figure 72: Self-shaping difference between water and moisture treatment.

to each other. As seen in figure 72, the moisture treated blocks stayed interlinked. However, the moisture blocks detached. This has influence on the self-shaping because internal forces, inter connections, were lost, plausibly resulting in less self-shaping curvature.

In light of this new information, the next test will exclusively utilize blocks treated with high relative humidity and the stronger polyurethane effervescent adhesive. Additionally, the thickness of the passive layer will remain unchanged for the time being. However, further development of the typologies will involve adding a bottom bi-layer in the next step.

Boxfloor element

The results from the third test showed that a bi-layer with spacer element can self-shape. The next step towards a complex self-shaping multi-layer is the addition of the second bi-layer at the bottom, creating a boxfloor geometry. For this fourth test, the convergent geometry was created, thus making a realistic version of the typology developed in the sketch & design phase. The approach for this new element was the same as for the moisture treated bi-layer in the third test, as this element showed promising curvature.

As seen in figure 75, after a moisture period of several days, and a drying period of 24 hours, the element showed significant curvature. Both the lower as the upper bi-layer and the spacer elements were assembled and connected before self-shaping started. As this test was a success, the next step was the change the active layer blocks from spruce softwood to beech hardwood (Figure 66). However, a problem arose.

Figure 73: Sawing hardwood at the Architecture faculty

While sawing the hardwood, it became clear that the status of the timber was in worse condition than previously thought. Two of the eight pieces broke in half, the material was fragile. This ofcourse influences the self-shaping result. Furthermore, the treatment time was the same as for the softwood. As stated in chapter 4, due to the higher density of hardwoods, it takes a significant longer time to reach water state's equilibrium. This means that the hardwood did not reach its maximum hygroexpansion. Resulting in a curvature which is less compared to the boxfloor element which consisted solely of softwood in the first few days. After a significantly longer drying period the curvature of the hardwood element increased. As seen in figure 77, the curvature of the boxfloor element properly changed. This may be caused by the same principle as to why hardwood takes a longer time to reach an equilibrium.

Multi-layer

Simultaneously as the hardwood test, a multi-layer test was conducted. This test had significant added value, as it could show the impact of assembling element before and after the drying self-shaping period. As mentioned in chapter 6.7, conventional hygro-curved elements were assembled after the self-shaping happened. The idea to assemble the whole element at once, was to reduce waiting time, workload and space use. As seen in figure 78, no self-shaping occurred. This means that the assembly is to stiff for the active layers to curve, when attached to one another. This could also mean that the curvature height in both boxfloor elements is limited by

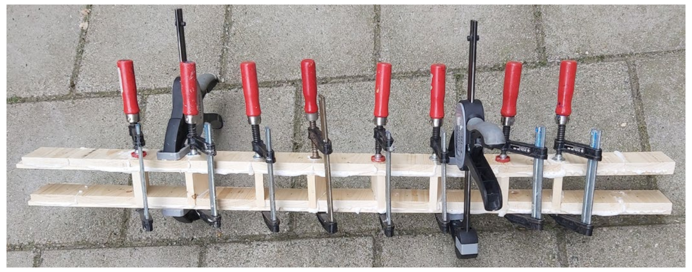


Figure 74: Direct assembly of boxfloor element

the assembly procedure. Hypothetically speaking, if the assembly of the upper spacer bi-layer with the lower bi-layer happens after the drying period, when self-shaping occurs, than potentially the curvature height can increase even further.

After the p4 a test was conducted to investigate the potential for this different assembly order. By shifting from element assembly to bi-layer assembly, the potential curvature height could be affected positively. As seen in figure 80, the result shows the highest curvature achieved yet. This can be traced back to the high salt-concentration RH of 95% and the extended treatment time of the active layer blocks. In total almost 30 mm of curve height was achieved, meaning 27,7% of the 1/12 capped ceiling ratio has been reached. Due to the fact that the element is longer, the curvature will therefore be higher. However, how will this curvature be affected when the top bi-layer with the spacer elements is assembled?

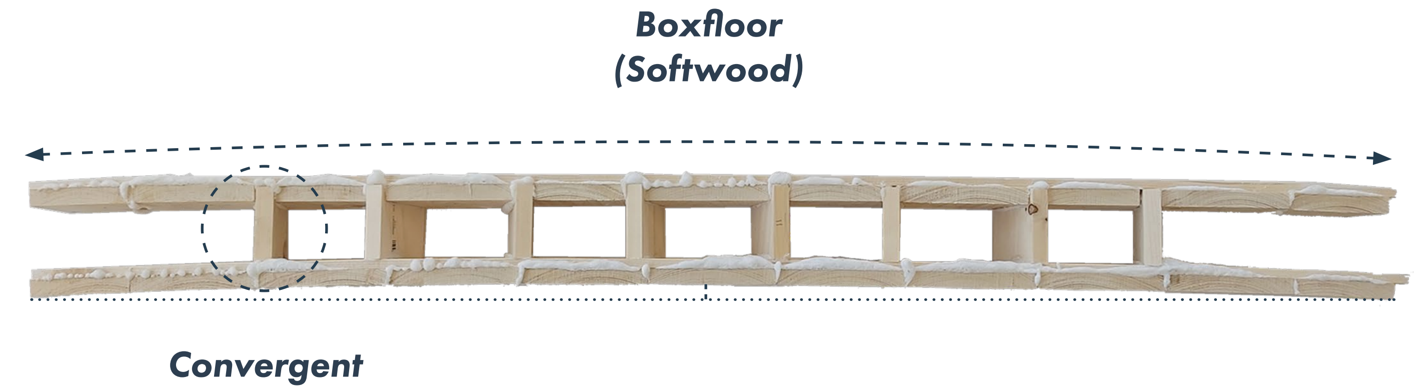


Figure 75: First curved boxfloor element with self-shaping principle.

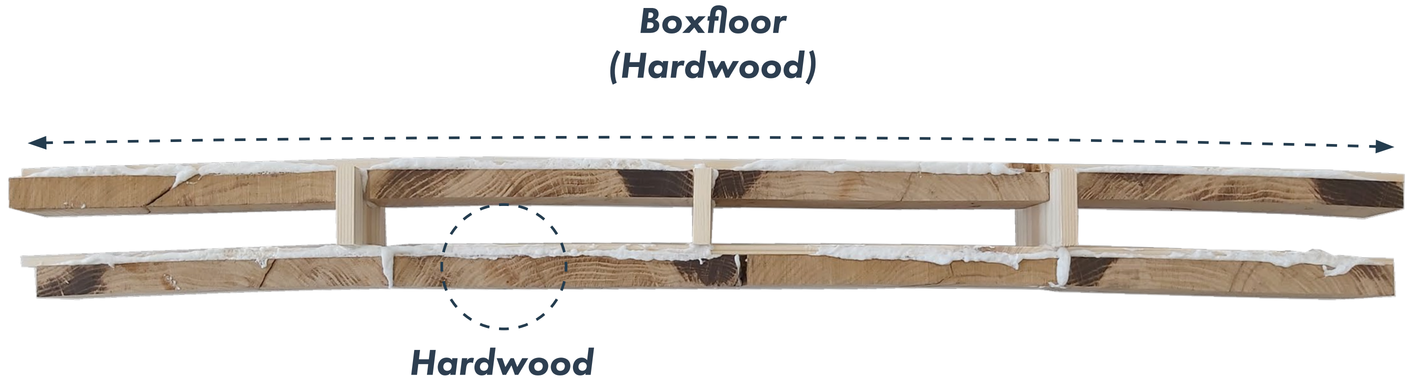


Figure 76: First curved hardwood boxfloor element with self-shaping principle.

Figure 77: Increased curvature after significant 'drying'-time.

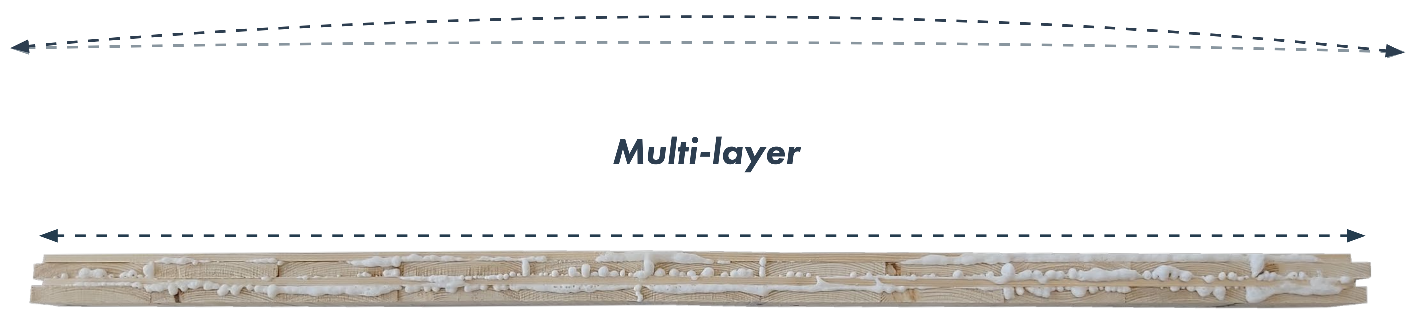


Figure 78: Multi-layer self-shaping test

By shifting the assembly order from whole to pieces, the curvature should be affected positively. The upper bi-layer with the integrated spacer elements had an overall self-shaping curvature of around 30mm as well. Therefore, in these two test the curvature is minimally or not at all limited by the reserved contact area with the passive layer by the spacer blocks.

Dovetail

A key element in hypothetically increasing the potential self-shaping curvature is the design and implementation of connections. As the hygromporhic curving only happens due to a strict connection between the passive and active layer and an interlinkage, connections have significant influences on the geometric outcome. The connection between the passive and active layers has been investigated and improved. However, the joining of the active layers themselves, can be improved on.

As seen in previous test outcomes, the active layers detach from each other during hygro-shrinkage. It could be argued that if the elements stay connected to each other, the curving forces become stronger, resulting in a greater self-shaping curvature. This connection-form can be made in different shapes, however in the timber industry conventional wood-to-wood connection types already exist. One of those types is the dovetail connection. This type of connection assemble and bind two pieces in two directions (x- & y-axis) as seen in figure 79. As the active-layer elements essentially work only in the x-axis, the dovetail connection has great potential to increase the self-shaping curvature. Furthermore, the dovetail connection is a relatively low-tech and low-cost connection type, making it suitable for being implemented in the typologies.

The dimensions of these dovetails can be based on literature. For this digital example 4 dovetail were used with a neck width of 15mm, head width of 32mm and neck length of 30mm (Park et al., 2010). The direction of the dovetails should be placed carefully, as tension will play a key role during the self-shaping process.

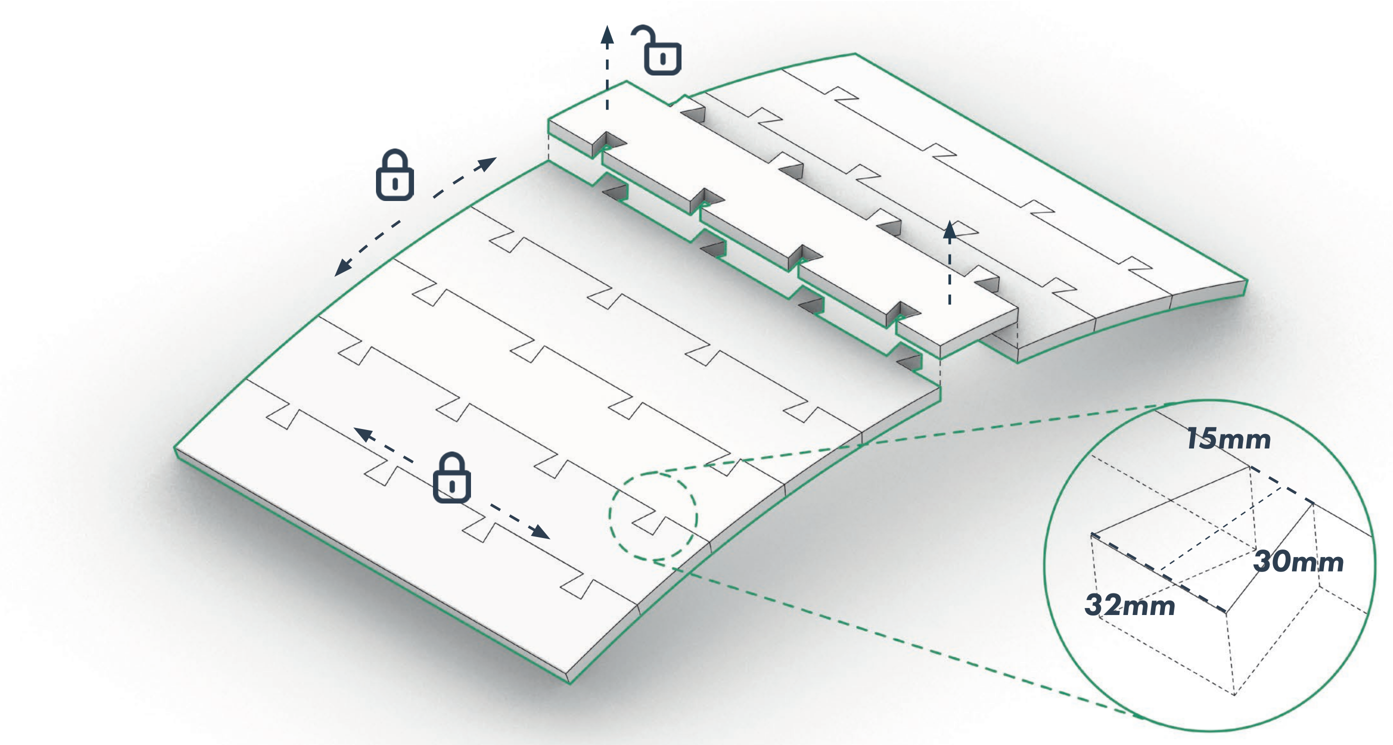


Figure 79: Dovetail principle

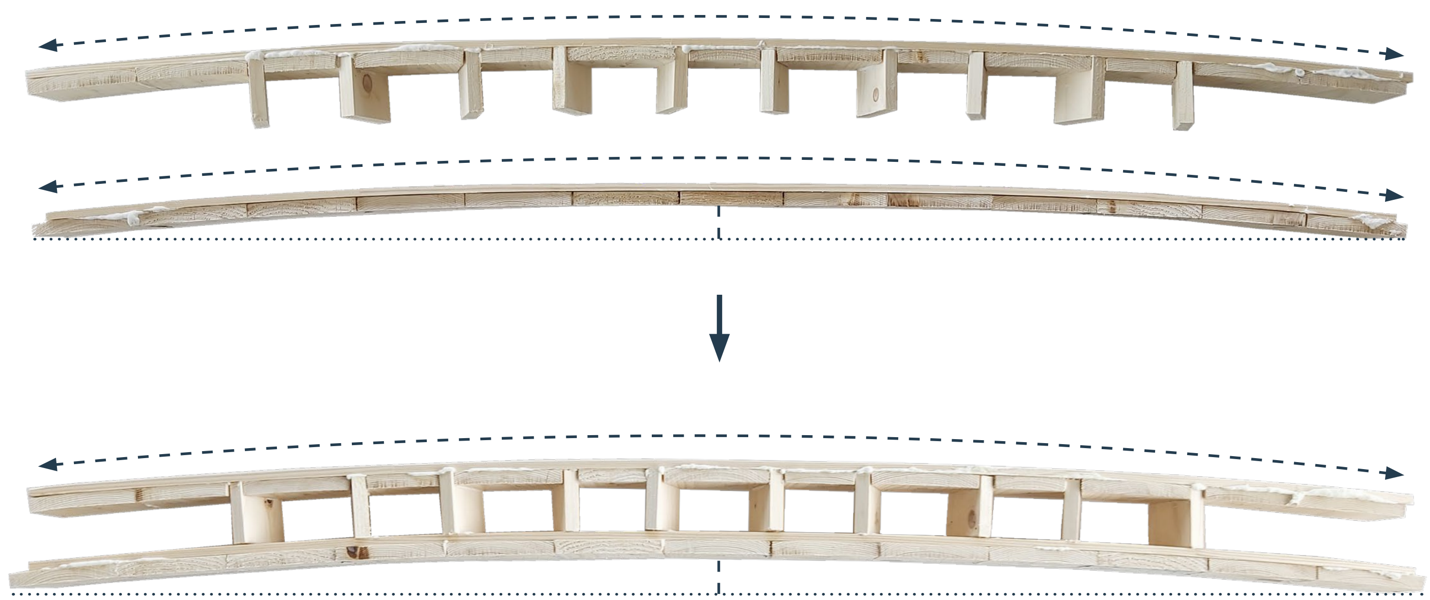


Figure 80: Highest curve height achieved during testing with different assembly order

7.4 Results

The study demonstrates that hygromorphic self-shaping with timber is possible for typologies more complex than a conventional wooden bi-layer.
During the second test, two different methodologies where used on larger and thicker elements. One element was treated with high relative humidity (A) while the other was based on expansion when placed in water (B). The observations might suggest that water treatment is more superior in creating self-shaping curvature due to its significant hygroexpension. However, the results showed that the water treated elements showed no element curvature. Moreover, the results of test A as B were surprising as both elements showed no curvature as an element.

The third test, consisting of two bi-layer elements with spacer geometries and two different treatment processes, showed curvature again. The water treated element showed 11,8 mm curvature height which is 13.6% of the desired height. The moisture treated element showed 22,4mm curvature height or 1/45 curvature per length unit which is only 26.8% of the desirable curvature compared to a capped ceiling but double that of the water treated element. The fourth test was focused on a boxfloor element. The boxfloor element showed a maximum curve height of 5mm or 1/197 curvature per length unit. When compared to the desirable 1/12 curvature per length unit for a standard capped ceiling, the result is at 6.1% of the desirable curvature.
The fifth test consisted of both a hardwood boxfloor element and a multi-layer element. The multi-layer element never curved. The hardwood element curved 4mm during the first few days. However, as the time to reach an equilibrium is longer for hardwood, the self-shaping period would therefore also be longer. After a 'drying' period of over 30 days, the boxfloor element showed a curvature height of over 25mm. Although this is not as much curvature as what was achieved with the softwood counterpart, it is promising that the hardwood element reached 25mm curvature height while being only treated for less than 7 days. Which is in relatively less than the softwood blocks.

Furthermore, a dovetail connection type can be used to enhance the self-shaping outcome of an element, as it would prevent a common phenomenon of detaching between the active-layer blocks.

Implementation

Actualizing

8

As it is possible to make complexe self-shaping structural elements, how will these elements be implemented or used in the construction sector? By investigating the manufacutring process, a business model and regulations for structural timber elements in Europe, a more complete product can be made.

8.1 Context

To really compete with the established structural timber sector, a thought out product and business model are needed. How will the business manufacture its product, which regulations and safety concerns are there with this new product? Arguably the most important, how will the cash-flow be generated?

Floor package

In floor structures, the structural element is just one component of a multi-layered system, each serving different functions such as sound or thermal insulation, leveling with screed, moisture prevention with plastic layers, etc. While this thesis focuses solely on the structural product, it's essential to acknowledge its role within the larger assembly.
A challenge with curved typologies is ensuring the overall package remains level, as curved or crooked flooring is undesirable. One solution is to implement a filling layer to address this issue. The filling material must be flexible and moldable, such as sand. Despite potential challenges related to weight, sand is an excellent filling material that can effectively level the floor package. Additionally, sand can provide sound insulation benefits, further enhancing the functionality of the floor structure.

Connections

Creating a cohesive and interconnected system with the boxfloor product presents a significant challenge, particularly when considering its implementation across entire floors. Existing boxfloor products utilize various connection methods. These methods often involve steel beams or wood-to-wood connections, specifically designed for linear boxfloor products. However, the introduction of the newly designed self-shaping product, which is curved, poses difficulties in achieving seamless interconnections.One potential solution to this challenge lies in leveraging old capped ceilings. By incorporating a beam between the boxfloor elements, shaped at the appropriate angle to accommodate the curved product, seamless integration can be achieved. Capped ceilings are known to possess a curvature height of up to 1/8 of their span (Aziz et al., 2023), making them a viable solution for addressing this specific problem.

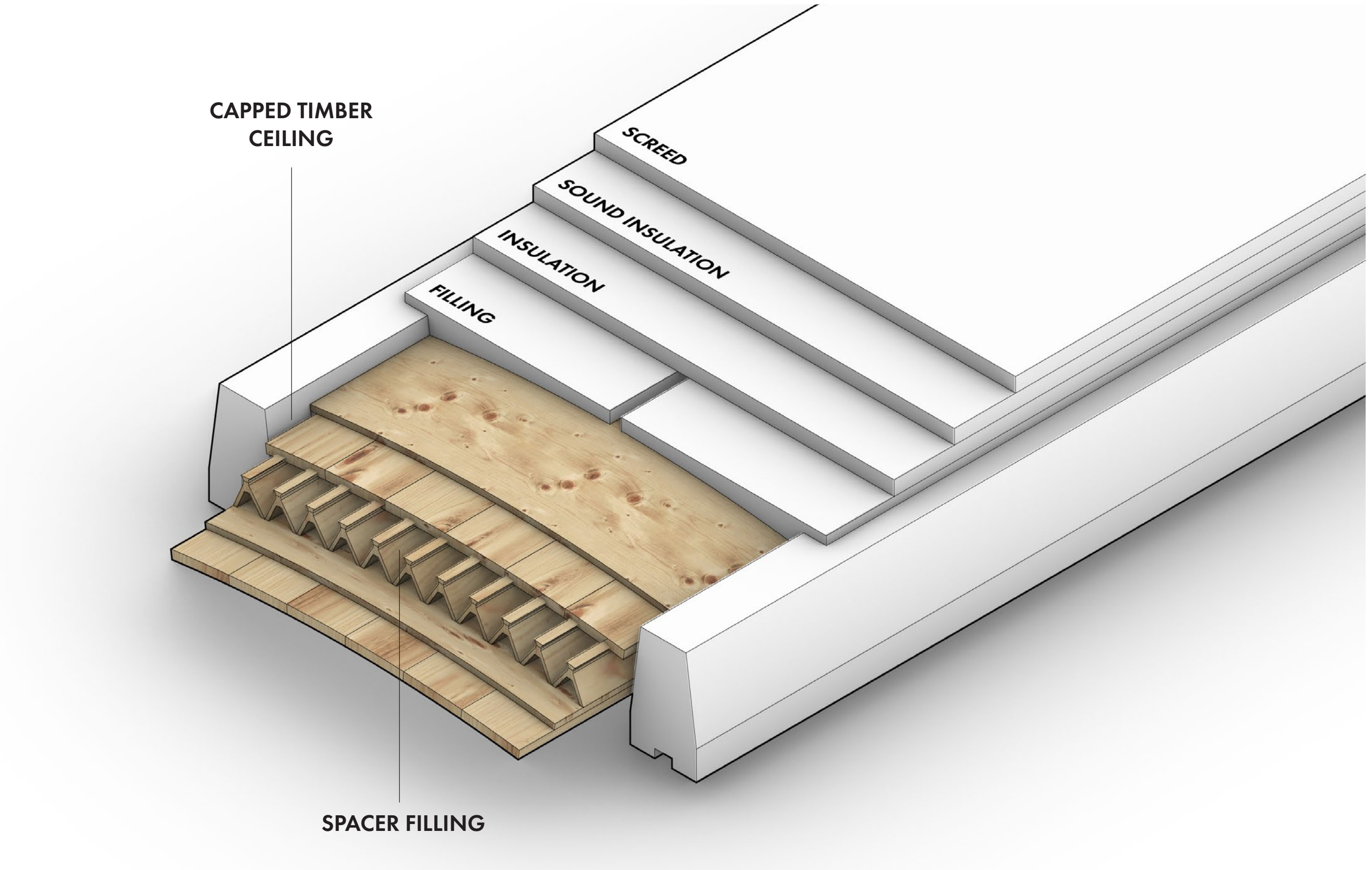


Figure 82: Hypothetical curved timber capped floor element

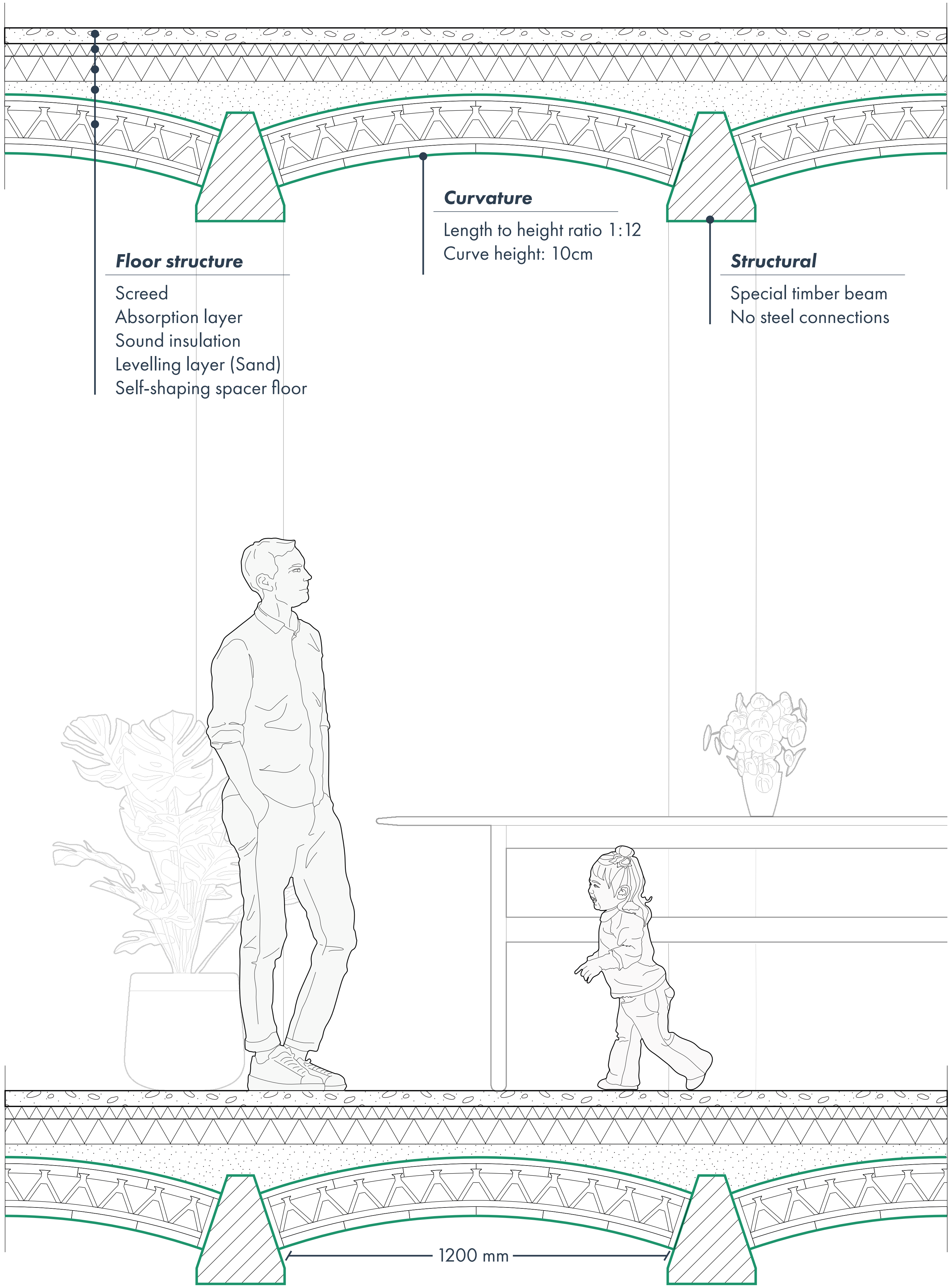


Figure 83: Cross-section of hypothetical curved timber capped floor element

8.2 Manufacturing

When a new product becomes available on the market, it needs to comply with many regulations. Furthermore, it's geometry or form needs to be widely accepted in order to compete with the existing product stock. Also, it need to produce a profitable cashflow, which is linked to the cost of manufacturing and the revenue earned by selling the product itself. How does the manufacturing process from producers of boxfloor- and mass timber elements work?

European timber

As stated, the type of timber influences the curvature of the element. The optimal situation is to use locally produced timber. Think of old beech or ash trees in historic city centres in the Netherlands which dead during a storm, or farming the unhealthy monocultured forests which would make the forests healthier. This could be an reliable option during the start of the manufacturing process, as the demand for the product is not significant yet. However, this process is time consuming and could be expensive. Therefore, when the product needs to be manufactured in bulk it may not be best option.

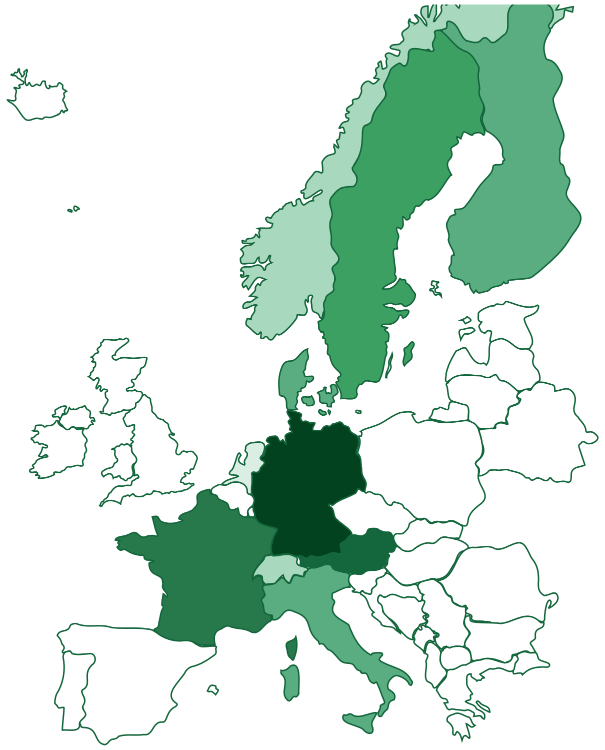


Figure 84: Dominant timber producers in Europe

As seen in figure 84, Germany is a dominant timber producer in Europe. They offer multiple kinds of softwoods and hardwood, and can therefore be an important player during the start of production and manufacturing.

Although the timber logistics is complicated, forming and self-shaping the product itself is also a challenge.

Moisture chambers

During testing, the elements could all be made with just an small refrigerator and some glue and clamps. Also, a bucket of water was used. All these tools could facilitate the manufacturing of 1.2m long models. When the bulk production of life-size 1:1 scale models begins, the right facilities are needed. Large closed environmental chambers are needed to ensure the timber reaches an equilibrium with the artificial relative humidity, created by using a specific salt solution. After the timber is moist and enlarged enough, it should be connected with the passive layer quickly. Time is of the essence during this production step, due to the shrinkage rate of the high wood moisture content timber. The longer the timber is out of the high relative humidity chamber and not attached to the passive layer, the less eventual curvature is achievable.

These closed environmental chambers do not have to be build from scratch. Old drying kilns could be repurposed to a new function. As these drying kilns are already made for the timber production sector, logistically it works well. As for energy usage of these chambers, the salt solutions causes the RH to rise, so no additional energy consumption is needed. However, the heat needs to be regulated at room temperature, which might cause some extra energy cost, but not significant enough to be mentioned.

Construction assembly

One of the challenges with designing and manufacturing self-shaping timber elements with moisture is keeping or achieving the correct curvature when a specific building has been build. As the element is a semi-moving object, assembly is difficult. Furthermore, transportation will be a challenge as well.

There are two options during the assembly and mounting of the element at the building site. One option is to passively curve the element on site, the other option is the make pre-fab curved elements. The problem with on site curving is that the curving takes time to settle. Also, the products will probably be curving in an outdoor environment, resulting in more curvature of the element when in the indoor situation. The curve height would therefore be unpredictable.

By making the curved elements pre-fab, the only thing that need to happen at the construction site is mounting. It should be noted that the self-shaped elements need to be protected from the elements, especially from relative humidities. By covering them with plastic bags, could be an option.

As the size of the elements are not greater than 3.6 meter, which is a conventional grid size, transportation with trucks or trains should not be an issue. Standard trucks can ship construction materials and elements over 10 meters.

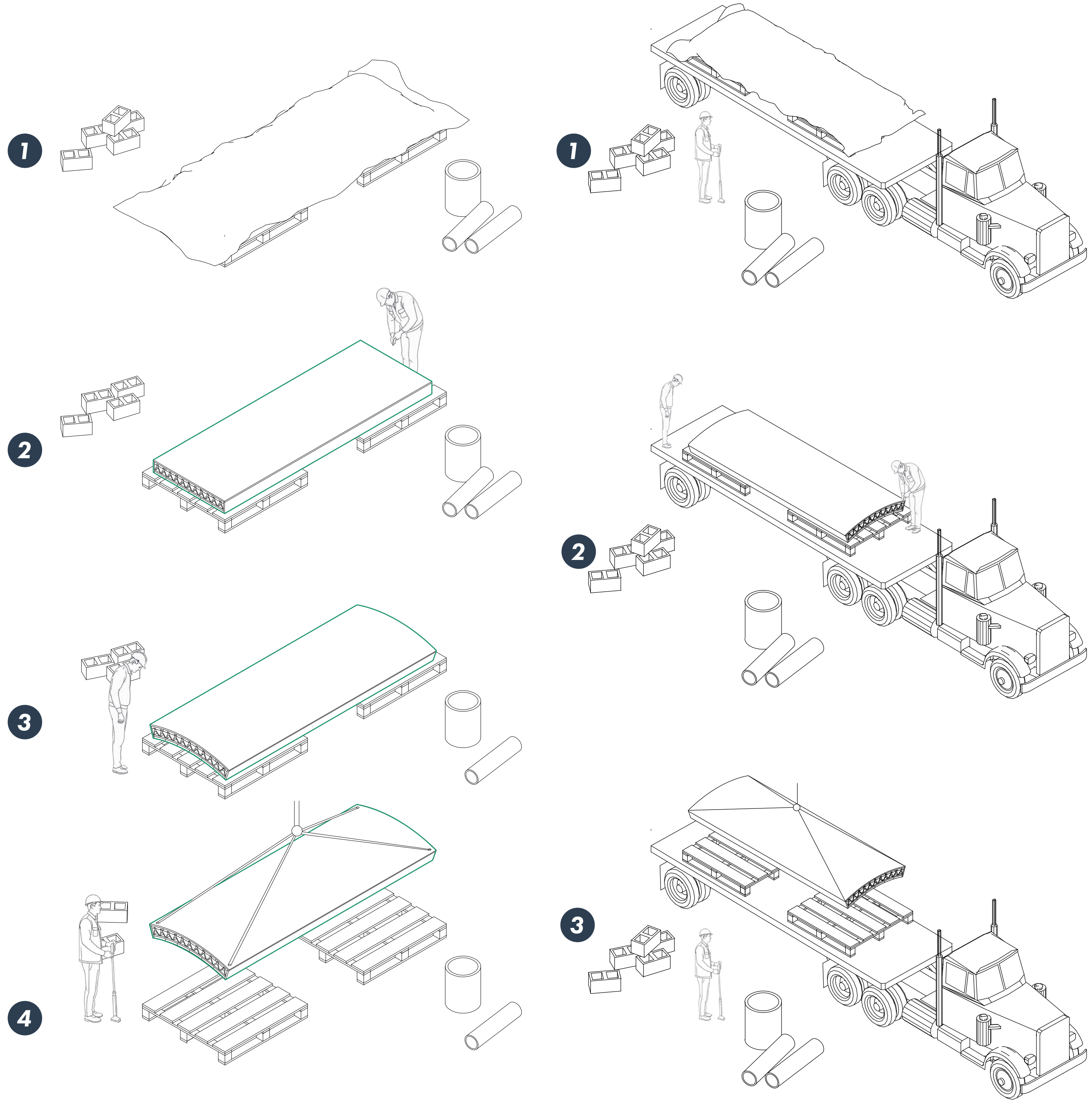


Figure 85: On-site curving vs Pre-fab curving

8.3 Regulations

Timber, as an organic material, presents unique challenges when used in construction compared to steel or concrete. Some typical challenges that need to be addressed when building with timber include: Creep, loss of strength capacity, joint connections and organic degradation. Addressing these challenges requires careful consideration in design, construction, and maintenance practices to ensure the durability, safety, and longevity of timber-based constructions.

Creep and strength

Creep is a phenomenon where an material will show increased deformation over a longer period of time under a certain permanent load (Granello & Palermo, 2019). As the self-shaping objects will be used as structural elements, permanent loads and thus creep will become an issue. According to the EN 1995-1-1; Eurocode 5: Design of timber structures, creep must be taken into account when designing sturctural elements by correct creep medication factor K_{def}. This factor is influenced by multiple components like type of timber material and service class.

Due to the nature of the self-shaping elements, multiple different types of timber are used, however the element will still fall under the solid timber, glulam and LVL category. The service class on the other hand is related to the changes in mechanical properties with moisture. There are 3 different service classes:

SC1: Timber in a heated building (MC ≈ 12%)
SC2: Timber in a covered building (MC ≈ 15-18%)
SC3: Timber in an outdoor situation (MC > 20%)

There are even reports from Switzerland suggesting that the indoor MC of timber can get below 6%.

Also, the duration of a load has effect on the strength of timber. During the initial ultimate limit state (ULS) calculations, K_{mod} is the factor which accounts for this loss of strength over time. K_{mod} is influenced by the service classes and by the load duration. From instantaneous loads like wind, to medium term imposed floor loads (up to 6 months) and permanent self weight loads (> 10 years). The higher the load duration, the lower the K_{mod} factor.

Organic degradation

Timber can also lose its structural strength by deferred maintenance. Maintenance is an imported factor in reducing or preventing mold or fungi forming. These organisms weaken the overall strength and develop in moist and warm climates. Due to the high moisture content treatment in the moisture chambers, the risk for mold or fungi forming is increased. It can be mitigated by preventing the wood moisture content to rise above 22%. Regular check-ups and treatments are therefore needed to prevent this phenomenon. Furthermore, termites pose a growing concern in the Netherlands. These insects are notorious for damaging timber elements by consuming material and creating holes and tunnels. While termites present a significant issue, it is not directly relevant to the scope of this research.

Joint connection

Maybe the most important part of a mass timber element is the joint connection. Joint connections can be the most fragile position of a structural element and should therefore be designed well. Wetting should be prevented and unnecessary moisture contact is undesirable. As the newly developed mass timber self-shaping elements interact with moisture this could form a problem. However, when the elements are assembled at the construction site, the moist timber is not going to be an issue. They are already dried and self-curved, resulting in 'normal' wood moisture content.

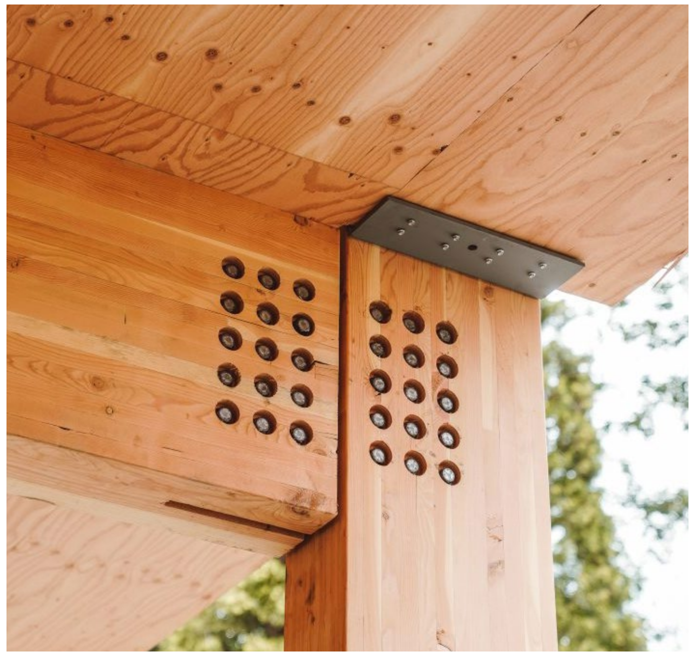


Figure 86: Steel moment connection (Timberlab, 2024)

8.4 Fire safety

Fire safety is arguably the most important safety regulation there is, especially for timber. The EN 1995-1-2 elaborates on general fire design rules. Section 2.1.1 note 3 states that deformation of the load-bearing structure must be taken into account unless during a nominal fire exposure, the separating elements can comply to the requirements. Furthermore, Solid timber and Glulam, LVL mass timber elements are graded higher than elements with small elements to create a greater whole. This is especially an issue for the spacer typology.

Moreover, timber elements are over dimensioned to deal with fire weakening the element. The outer layer of timber chars, but the core remains relatively intact over a longer period of time as wood is a great insulator. Charring rates are different for softwoods and hardwoods. Solid hardwoods are known for being more resistant to charring and have an charring rate of approximately 0.55mm per minute (P_k > 290 kg/m³) whereas softwoods only have 0.7mm per minute rate. Due to the many small elements in the spacer typology, this creates more surface area and less overall volume. This means that the element may not be fire proof, as the charring effects the core of the small elements to much. The required hours it needs to be structurally stable can not be provided. Therefore a coating or some kind of box-element is needed to protect the smaller element from direct fire contact.

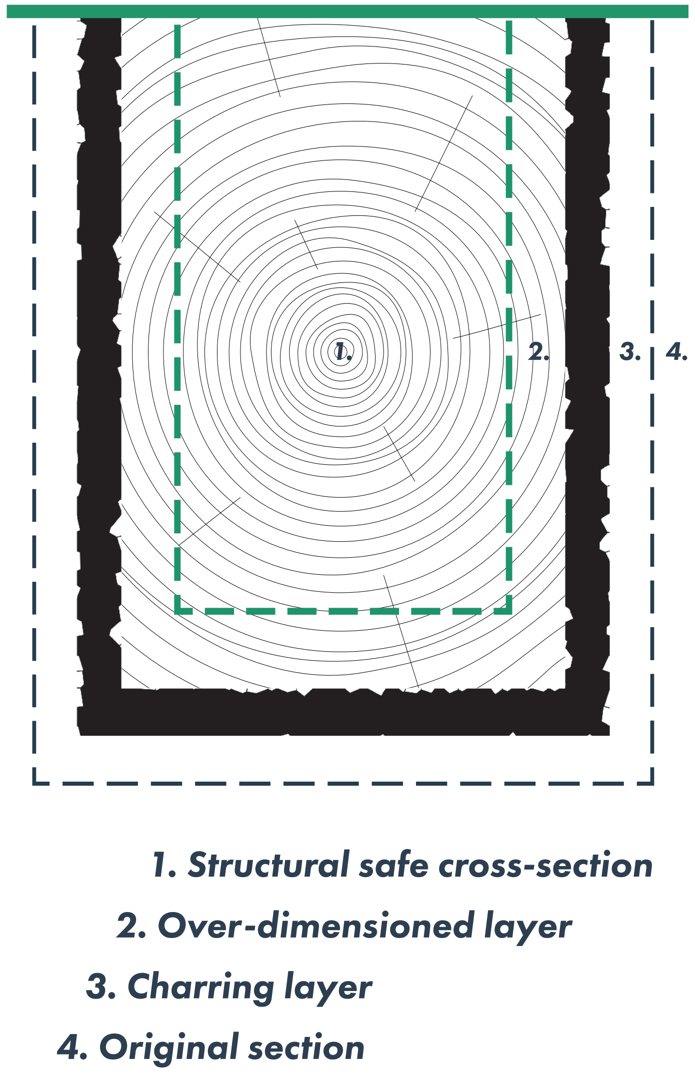


Figure 87: Over-dimension for fire safety

Figure 88: Burned timber log

8.5 Bottle necks

The whole geometry of the new boxfloor element has some bottlenecks, specifically some problematic spots which should be pointed out, and be developed further to prevent unwanted phenomenons. One of these problems is punching shear. This phenomenon occurs when a substantial and concentrated force punches through a material, causing a shear failure cone. Although this challenge is most relevant for concrete elements, it is not unheard of to happen with mass timber product. As seen in figure 89, a schematic overview is displayed where the punching shear occurs in the context of the self-shaping boxfloor element.

Another relevant challenge is the connection and assembly under an angle. When forces are applied on an element which is fixed on a slanted base, there is a realistic chance for the element to shift, slide or brake. Therefore the joint of the lower bi-layer and the spacer element (most importantly the elements on the sides with the largest incline) must be design properly. However, as shown during the testing phase, it is recommended to assemble the whole element in phases. This means that it is hard to make a perfect fit, as the exact curvature can not be predicted. Still, a general estimation can be made, and the joint be designed on this basis.

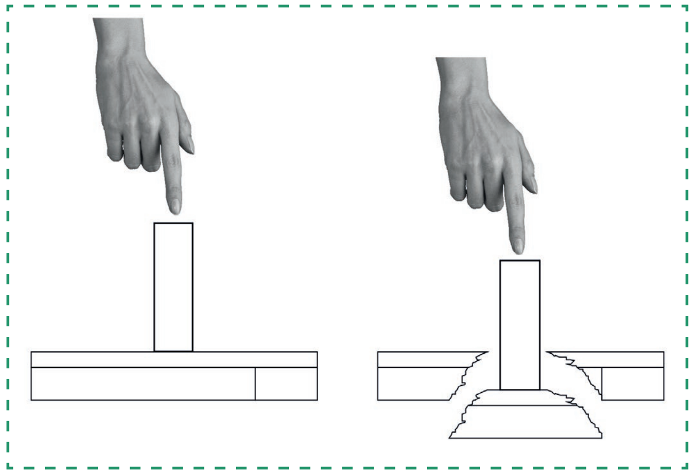


Figure 89: Punching shear

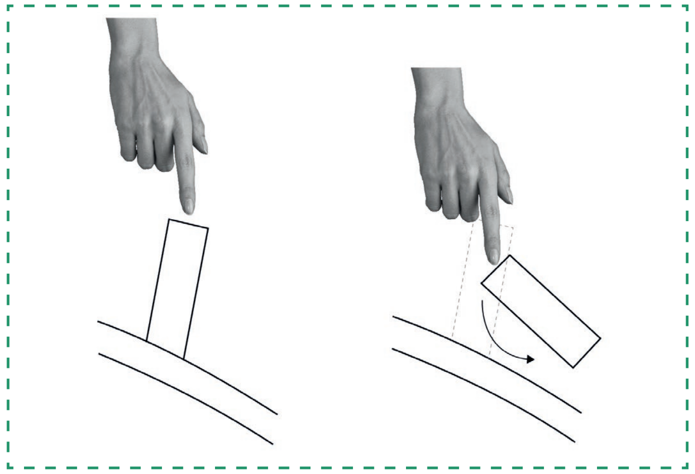


Figure 91: Shifting problem

Due to the fact that the loads will be transferred towards the beams by the lower bi-layer (compression and tension), the spacer elements will have a concentrated load which will be placed on a relatively thin bi-layer slab. Therefore its dimension of both the spacer element (area) and bi-layer thickness should be complementary to each other.

As this challenge is only theoretically mentioned and not been physically tested, no hard conclusions or data can be presented. It is therefore advised to conduct further research on these topic to understand the structural limits of such a timber element and perhaps even compare the data to already existing mass timber floor typologies.

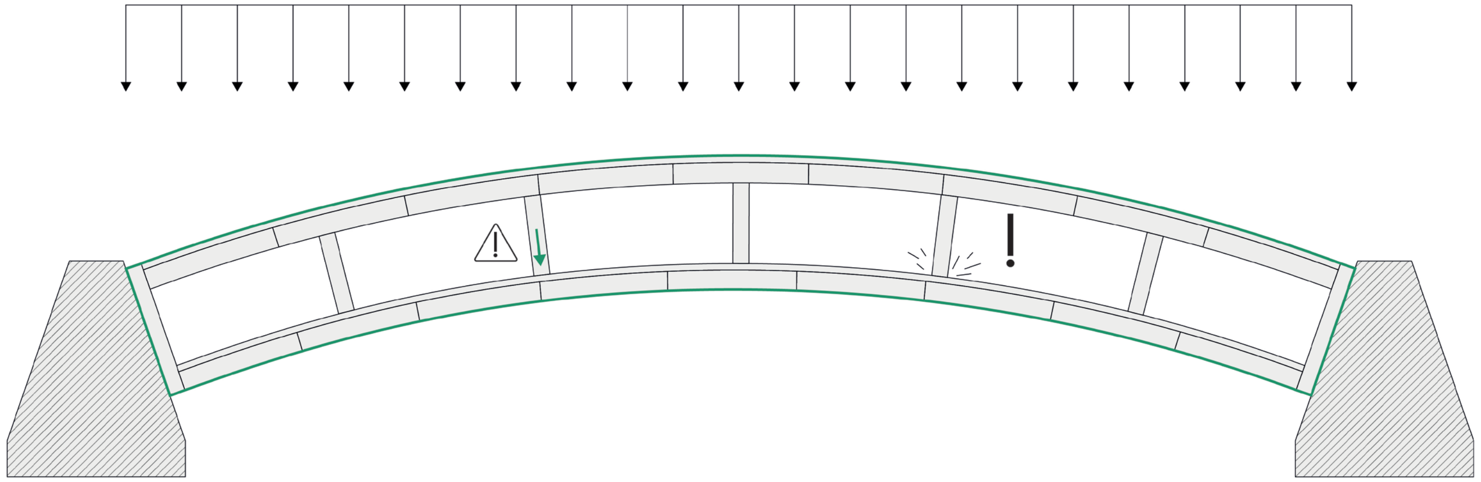


Figure 90: Structural working spacer element

8.6 Structural orientation

A relevant challenge with the geometry and orientation of the passive and active layers is the fiber direction and thus the span direction. As mentioned in chapter 4, timber is an anisotropic material meaning that the expansion and shrinkage ratios are different in the different axis. As the tangential swelling is approx. 10%, this axis shows significantly more hygro-expansion than the other two. Therefore the tangential axis is exploited in the passive self-shaping structural element assembly.

The challenge however is the span orientation. As the active layer is the thickest and most structural robust part in the whole element, it is responsible of load transference. Nevertheless, as seen in figure 92, the orientation of the active layer slats are perpendicular of the most optimal direction. As stated by Grönquist et al. (2019c), The dominant wood grain direction is equal to the load-bearing direction. This challenge is one of the reasons for designing interconnections between the slats, creating a rigid and stable curved element.

There is also a possibility to keep the original span direction, however this may undermine the soul purpose of the curved typology system. Due to the fixed fiber direction, the elements can also be implemented as curved wall units. However, the same argumentation can be used that the efficient curved geometry is not used properly.

Furthermore, as hardwood is more robust and relatively stronger compared to softwoods, it is the main contributor to a structural stable boxfloor element. Still, only about 50% of the design contains hardwood. Increasing this percentage is hard. As the passive layers must be more flexible and twice as thin as the active layer, a hardwood passive layer is difficult to construct due to its proneness to shatter or brake. Therefore it is undesirable to conduct further research on these possibilities.

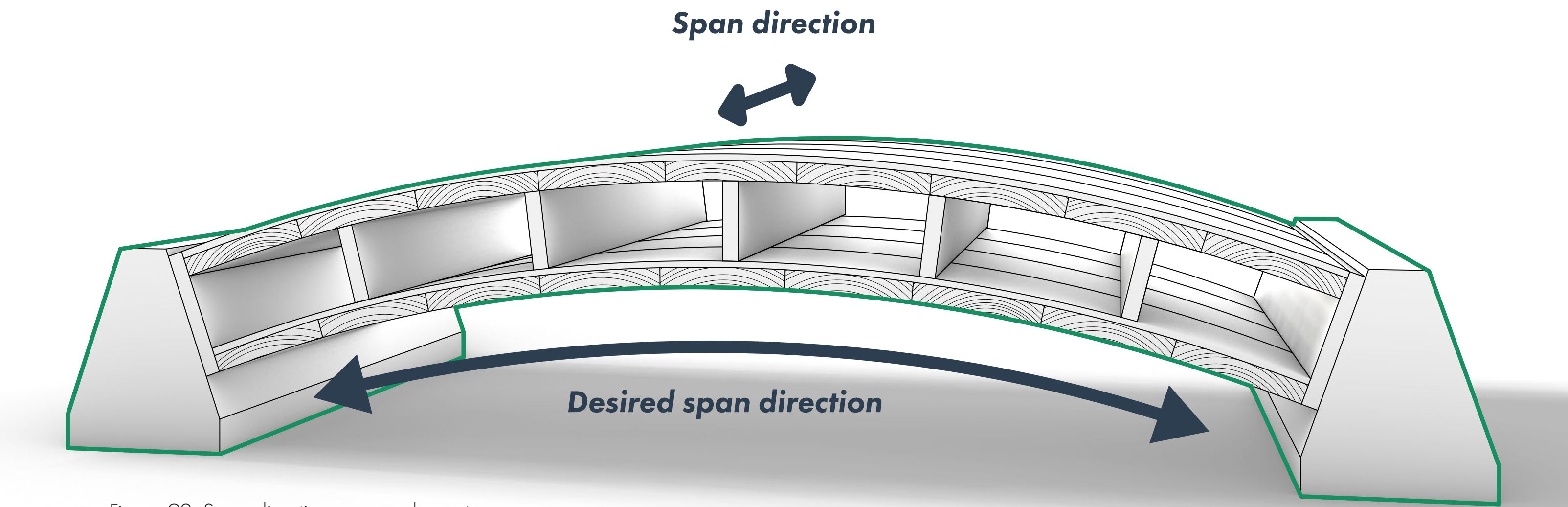


Figure 92: Span direction spacer element

8.7 Position

This new structural timber element, which can be used in the build environment needs to compete with already existing structural timber floor elements. However, there are some specific parameters for the designed and developed prototype which limit its position compared to well established mass timber element. As stated before, the width of 1200mm was taken as a benchmark for the capped ceiling 1/12 curve height ratio. The length of the element however. For the specific design option developed, it should be noted that the specially designed beams are essential for the curved floor elements. These special secondary beams are not necessary with conventional boxfloor elements. This could mean that overall the material saving is minimal or even non-existing.

Compared to CLT, the newly designed boxfloor element only spans in one direction instead of two. Conventional CLT floor elements use on average 3 to 7 wooden layers, which are glued together in a perpendicular pattern. Usually these CLT elements are no more than 1.2 to 3.6 meters in width. Still, currently these CLT element can a structural stable length of over 15 meters, depending on the amount of timber layers is used.

A different yet well renowned timber floor element is the Kerto-ripa boxfloor. Kerto-ripa is a collective name for a specific timber construction type. By using ribs (planks), and panels a box can be manufactured. There are different typologies, like an open bottom, a closed box or flanges on the ribs. This relatively simple yet efficient and effective element is a conventional timber floor typology and regularly used in the construction sector. As this element is so efficient, competing with standardised Kerto-ripa floor elements is hard. A span of over 10 meters is not unheard of.

Due to the fact that the timber floor industry is already an well established sector, introducing an innovative yet complex and relatively expansive new product is not advisable. Only with the right economical prospects or by introducing something fresh into the sector, there is a change of competing with the already known and existing boxfloor typologies.

As the claim that the newly developed and tested passively-curved element is more efficient in term of load distribution and thus uses less material can not be verified, a comparison with the other systems is unfounded. Moreover, as mentioned before the special beams which are used to connect the curves elements together add lots of extra material. Therefore the claim of less material usage can be questioned.

Nevertheless, due to the unique and interesting shape of the new elements, it adds a new form and geometry in the timber boxfloor sector. It adds to the aesthetic value of boxfloor elements which are static and linear.

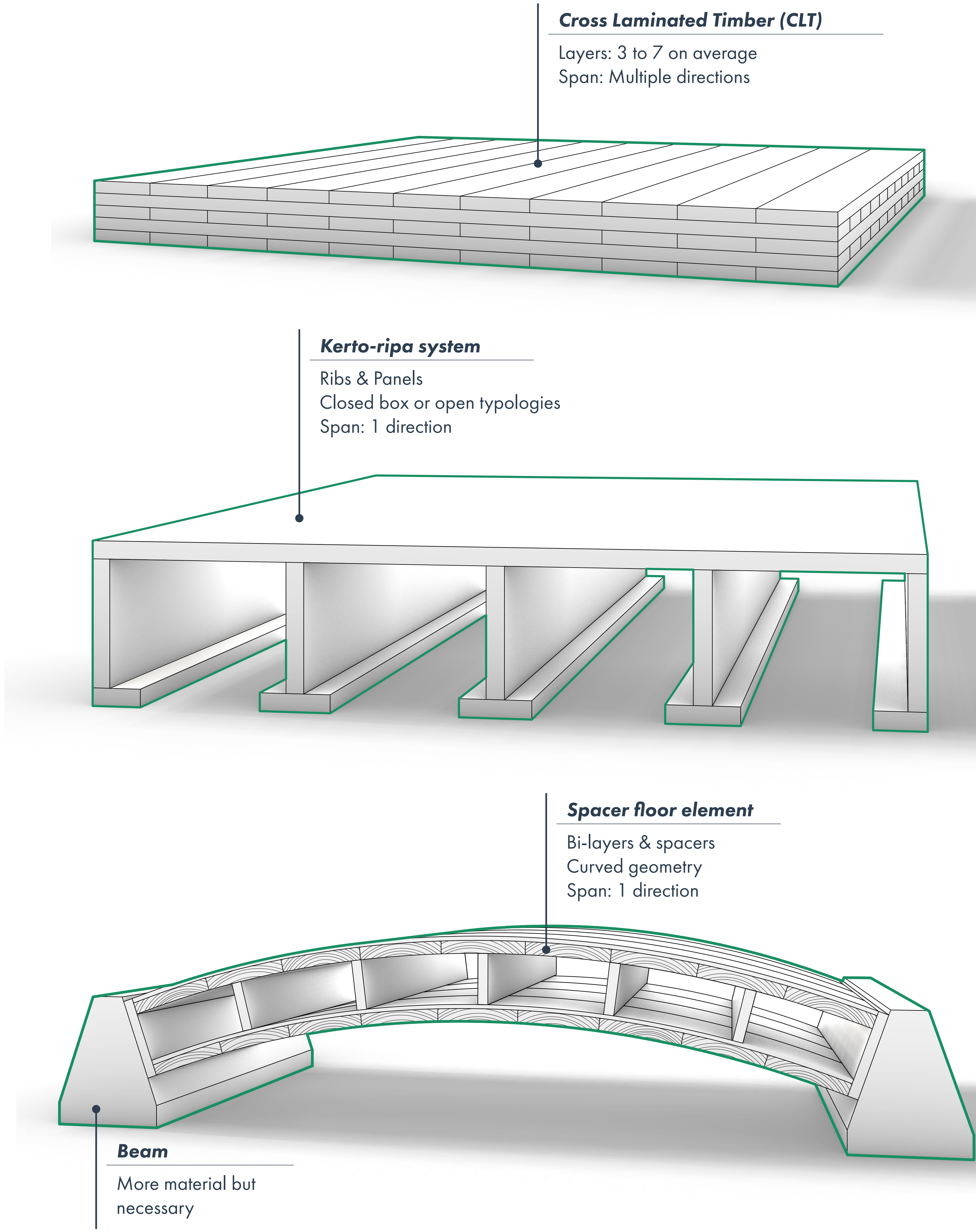


Figure 93:Different floor typologies

Conclusion

Discuss the results

9

9.1 Structure

This research thesis delves into the material properties of timber and explores their potential application in the creation of an innovative and efficient structural element. This element is intended to address the challenges faced by the construction sector, which is often reluctant to adopt sustainable practices and is associated with high carbon emissions.

The development process of this product is punctually documented, following a step-by-step academic approach. The study aims to determine how curved structural floor elements can be designed and created by carefully selecting materials, designing prototypes, conducting tests, and examining various multi-layer typologies. Drawing from methodologies used in other studies on hygromorphic bi-layer curving, which have successfully resulted in self-shaping curvature, this research seeks to adapt and apply these principles to the context of timber structural elements in the Netherlands.

This structured phased approach can be divided into three main steps:

Material properties - The first phase focuses on the study of material science and sample properties. This involves investigating cell working and the environmental effects on the material, aiming to understand how these factors influence its behaviour.

Product designing - In the second phase, the insights gained from the material properties phase are integrated into the design process. The focus shifts towards designing a product that incorporates and embodies the physical properties of the material, aiming to create innovative and functional structural elements.

Physical testing - The third and final phase involves transitioning from academic research to practical experimentation. Real-life scaled models are subjected to physical testing to examine the self-shaping phenomenon. This phase aims to validate the theoretical concepts and assess the practical feasibility of implementing self-shaping characteristics in structural elements.

9.2 Materials

In the Dutch construction sector, a variety of timber species are available and utilized. However, each subspecies possesses distinct material properties, making that not every species is suitable for hygroscopic curving. Additionally, it is recommended to incorporate both softwoods and hardwoods to broaden the scope of potential applications.

Several timber species, including spruce, red pine, douglas fir (softwoods), and beech, ash, maple, and oak (hardwoods), have been reviewed based on criteria such as swelling, growth rate, etc. Among the reviewed timber species, spruce and beech demonstrated the highest suitability for implementation during the testing phase compared to others.

Figure 95: T-group compared with A- and B-group

Based on the literature selection, conventional spruce timber was procured from the local hardware store. During the initial test conducted at 85% relative humidity, there was a significant increase in moisture content and weight observed. However, the volumetric change was not measurable, indicating its absence or non-existence.

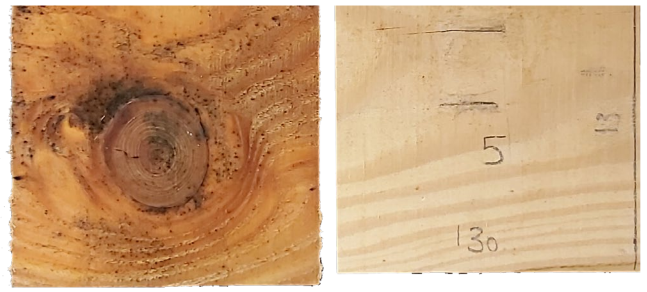


Figure 96: Water vs. Mooisture treatment

Treatment periods

The time to reach the equilibrium moisture content (EMC) can take over a month (Moya et al., 2009). Due to the fact that many different typologies had to be tested, this 30 day period has not been achieved once. This means that the materials used in this research thesis never reached the full property potential. The longest period for a test specimen, used in the experiments, to be in the climate chamber was no longer than 7 days.

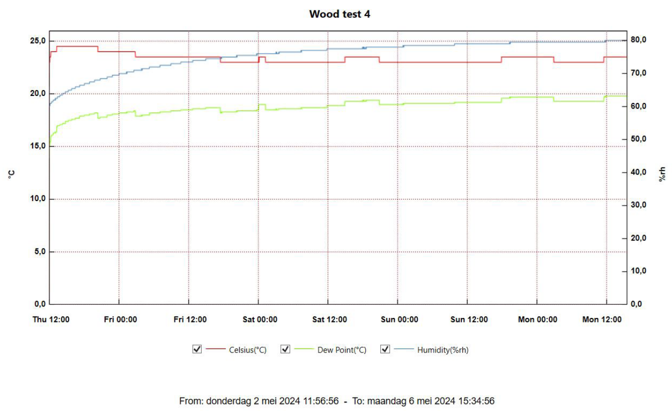


Figure 97: Moisture treatment period

Specimen condition

The hardwood elements, sourced from Amsterdam, were found to be in suboptimal conditions. As primarily scrapwood material, they exhibited numerous cracks, knots, and other imperfections, which were observed to have an influence on the end results of the tests. These irregularities made the hardwood blocks brittle when cut into smaller sizes. During machining with the saw table in the maquettehall at the Faculty of Architecture in Delft, test block 3 broke into 2 pieces. Additionally, during the weighting procedure, block 7 broke when a small force was applied to the element. Moreover, some pieces used in the second test had a paint layer and kit attached to them, posing challenges during water testing.

In contrast, the spruce wood pieces were in a decent state. There were no major issues encountered during the processing of the wooden blocks. These blocks responded well to the relative humidity test, although no significant swelling was observed. It should be noted that due to the small thickness of the original spruce boards, some exhibited curvature already; however, this curvature was deemed insignificant.

Dimensions

There were some boundary conditions used to stay within the scope of the structural building element. These boundaries were depicted from the conventional 3.6 meter grid. As a benchmark, a scaled1:3 element was taken. Later on, the 1:3 scaled size which is 1.2 meter, became the new standard for a capped ceiling boxfloor element. As the closed environment chamber had a size of 300 x, 400 x 450mm, this limited the size of the active layer piece. However, the depth of the passive layer was the dominant size limiter. The depth of the passive layer is equal to the length of the active layer. For the passive layer a 55 x 7 x 2100mm spruce slat was sawn in half, to get 2 passive layers. The active layer pieces are originally a 91 x 12 x 2100mm.

Figure 98: Fridge dimensions

Tools
As stated, the humidity chamber had impact on the dimensions of the timber pieces. However, other tools used during the experiments had an impact on the overall results.

Bosch meter - To measure and observe the increased wood moisture content (WMC) of the wooden blocks the weight was determined and a Bosch UniversalHumid meter was use. This devise has 2 pins which have to be stuck into the blocks to measure a WMC percentage. The UniversalHumid measurer can scan both softwoods and hardwoods, by changing the settings. With a measuring accuracy of ±1%, claimed by Bosch, the devise should be reliable. However during moisture testing, the percentages differed sometimes more than ±1%, which made me sceptical of the devises accuracy. Therefore each block was tested twice, and an average of the 2 measurements was taken.
The weight increase was measured with a Mettler Toledo scale, available in the laboratory at the Architecture faculty.

Figure 99: Bosch moisture content tools

Adhesive and clamps - For the assembly of the overall element, adhesives and clamps are necessary components. While the detailed usage of these products will be further elaborated upon in the testing phase, it's important to note that the type of adhesives can also impact the results. Initially, a standard Bison water-resistant adhesive with a 2-methyl-2H-isothiazol-3-on basis was used. However, later on, a stronger effervescent glue was employed. It's worth mentioning that due to the time sensitivity of the drying period, strong construction adhesives could not be utilized. These adhesives typically require pressure for over 8 hours, which may not be optimal for the element to self-shape effectively.
Two types of clamps were utilized to apply pressure on the timber blocks: one-handed clamps and screw clamps. The one-handed clamp offered quick usage and had suitable clamp dimensions. However, their weight posed a risk of bending the overall element if handled carelessly. On the other hand, the screw clamp, being smaller in size, was well-suited for the small dimensions of the timber blocks. However, their usage proved to be time-consuming and impractical due to the circular motion required to apply pressure. During clamping, the timber blocks tended to shift and move along with the circular motion of the screw clamps, resulting in gaps between the blocks.

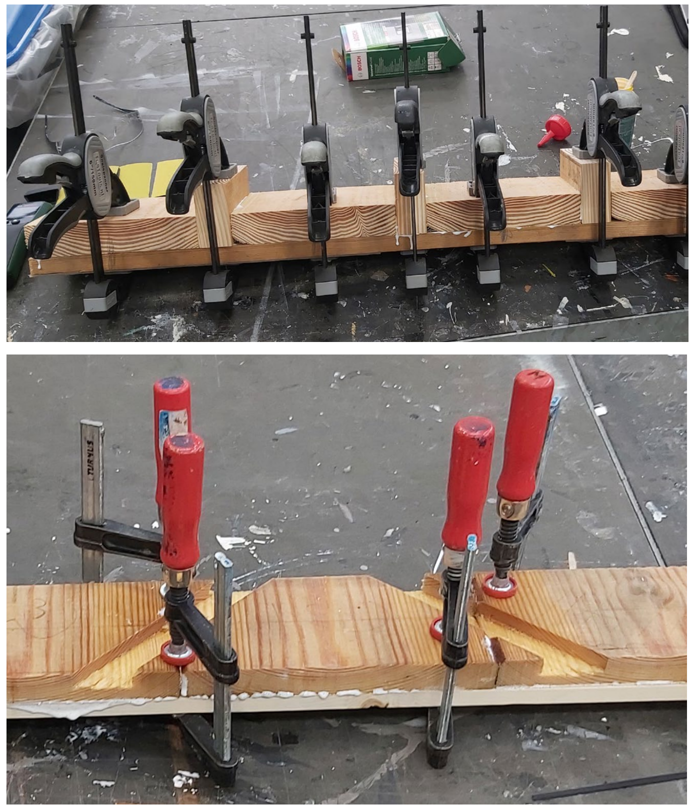


Figure 100: Clamps used during assembly

Salt - To artificially create a high relative humidity (RH) in an environmentally closed chamber, salt concentrations were used. Three different salt concentrations were available in the laboratory, each corresponding to different RH percentages: 75%, 85%, and 95%. According to Thybring and Fredriksson (2023), the hygroscopic range of wood spans from 0% to approximately 97%-98% relative humidity, with hygroexpansion increasing as the RH rises. Initially, the 85% salt concentration was used, followed by the utilization of the 95% salt batch. However, a relative humidity higher than 85% was never achieved during the testing process.

Available woodworking tools - The available woodworking tools was limited. Therefore the more complex typologies took significant time to make manually. The saw table could only be used by a employee. The smaller wood adjustments could be done with a saw machine and sander. Overall, the lack of available woodworking tools, limited the making of complex typologies.

Despite facing various challenges such as suboptimal materials, incorrect adhesives and clamps, challenging timber quality, limited woodworking tools, and relatively low relative humidity, the experiment phase still managed to achieve self-shaping curvature. This outcome, albeit achieved under less than ideal conditions, should be viewed as a positive indication. It suggests that even with these limitations, the potential for self-shaping curvature exists.

Moving forward, professionalizing the manufacturing process and addressing the suboptimal factors identified during the experiment phase can lead to significant improvements in self-shaping curvature. By optimizing material selection, using appropriate adhesives and clamps, ensuring high-quality timber, providing adequate woodworking tools, and maintaining optimal environmental conditions, the self-shaping curvature can be further enhanced. Therefore, these challenges encountered during the material and experiment phase serve as valuable lessons and opportunities for improvement in future endeavours.

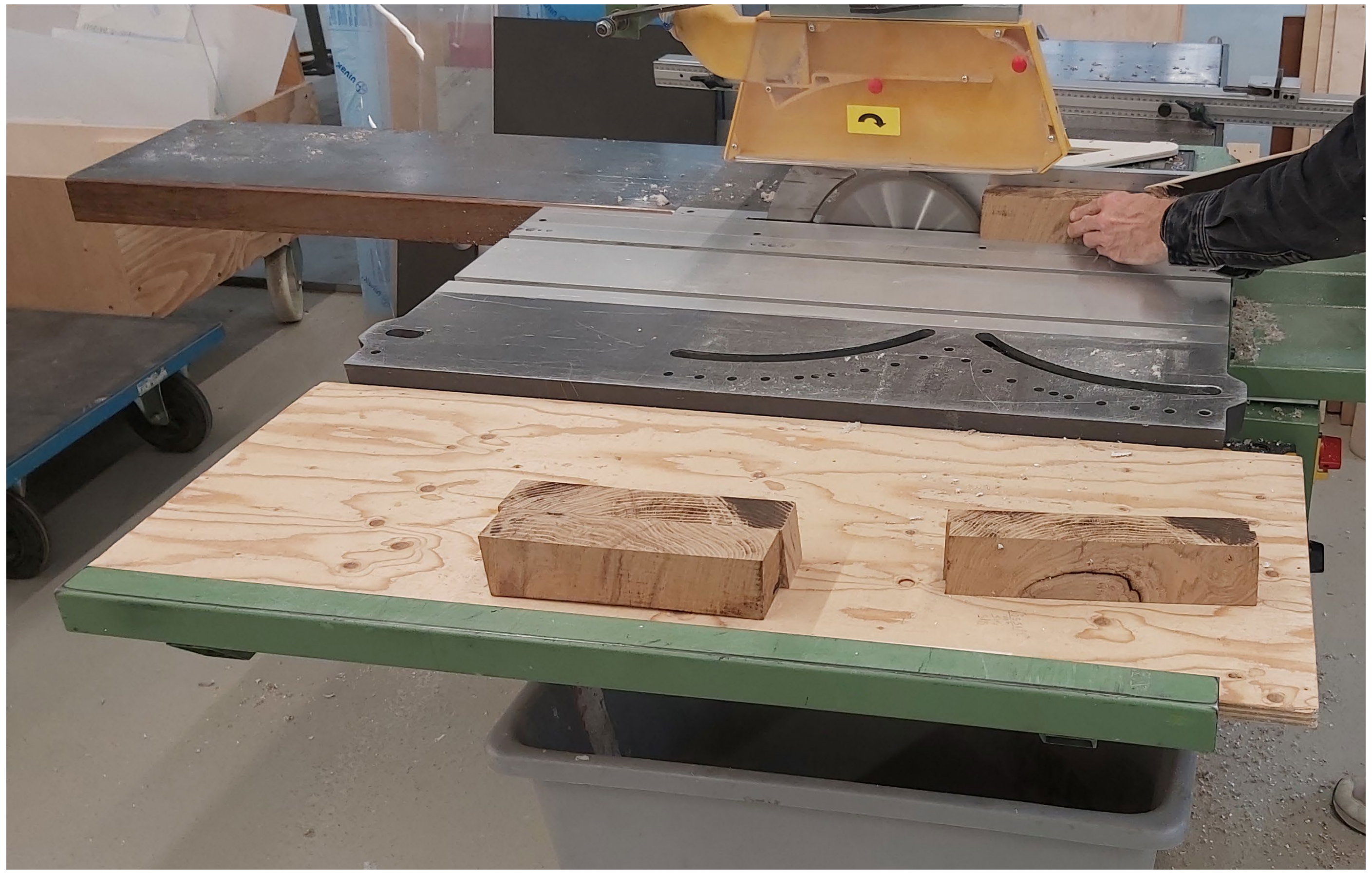


Figure 101: Sawing hardwood at the Architecture faculty

9.3 *Product design*

The journey toward developing a new typology and product is inherently non-linear and often deviates from initial expectations. The primary goal of this thesis is to investigate the feasibility of creating a structural element capable of hygromorphically self-shaping. This specific objective represents a research gap, indicating that it has not been explored previously. While there exists a study by Grönquist et al. (2019b) on self-shaping CLT-barrel ceilings, it focused on the same structural basis and assembly method compared with the Urbach tower. The integration of boxfloor elements or multi-layer typologies, as pursued in this thesis, has not been previously attempted.

Embracing the uncertainty of not knowing what to expect or what will be discovered presents a significant challenge. Initially, the main focus was on creating curved beams and columns, but as research and testing progressed, it shifted toward exploring boxfloor elements. While this versatility fosters open-mindedness, it also introduces challenges as goals evolve throughout the process. Despite these challenges, the dynamic nature of the research keeps the investigation engaging and allows for unexpected discoveries along the way.

Alteration

'From bi-layer to multi-layer to shift from slabs to beams and columns.', this quote from the p2 presentation shows the initial route this thesis was suppose to follow, looking at mass timber beams and columns. However, along the way the aim to look at beams and columns shifted towards boxfloor elements. This shift is caused by the geometry of the researched typology. The mass timber beam/column was the centre of the research, with almost half a dozen sub-typologies extracted. One of those typologies is the spacer geometry.

To ensure the reliability and validity of the thesis research, it was recommended to limit the total number of typologies to be researched and experimented with to a maximum of three. By philosophizing the chances of success of the five typologies based on literature and existing examples, two types were eliminated. However, due to time constraints, the remaining three typologies were ultimately reduced to essentially one. The spacer typology emerged as the sole geometry that was thoroughly researched and tested. While this narrowed focus may have been necessitated by time limitations, it allowed for a more in-depth exploration and understanding of the chosen typology.

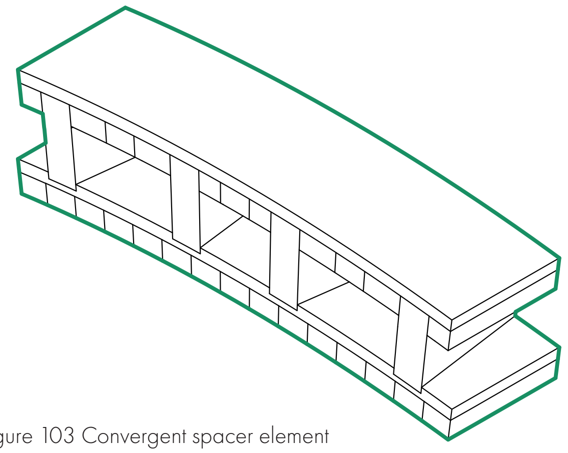


Figure 103 Convergent spacer element

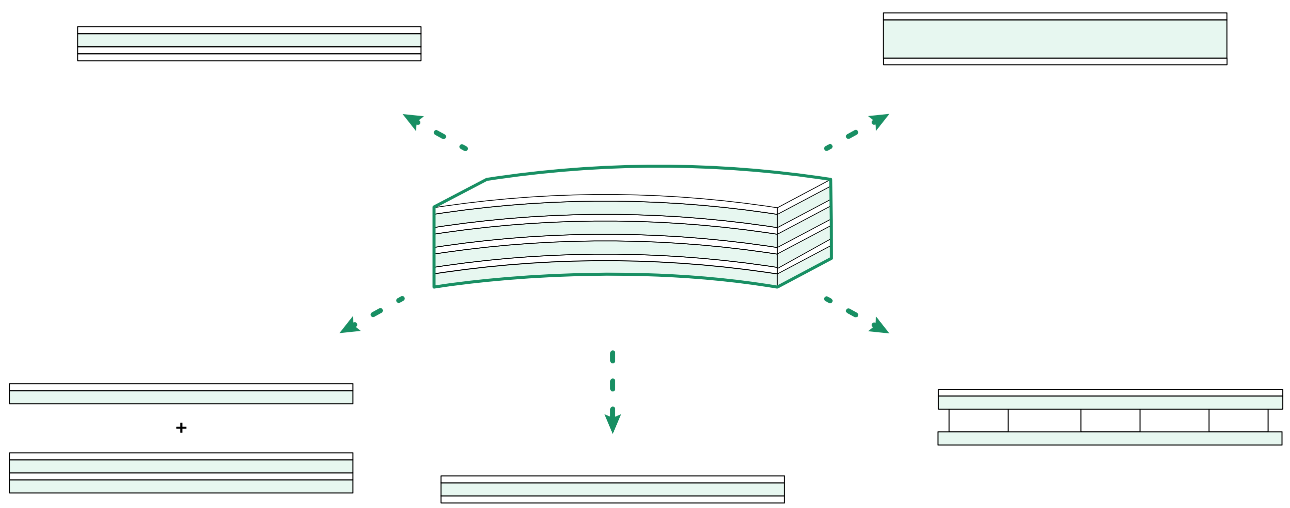


Figure 102: Different typologies from multi-layer concept

Before delving into the specifics of the spacer typology, it's important to define what a spacer is. In this context, a spacer refers to an element or geometry that connects an upper and lower part while maintaining a space between them. Through a sketching and exploration phase, numerous typologies were conceived, all based from the spacer principle.

The selection process for determining the most promising typologies revolved around four main factors: Manufacturing, Structurality, Circularity, and Curvature. Each of these factors was explained to clarify its significance and ensure repeatability of the selection process by individuals lacking the same level of knowledge or expertise. Assigning a 5-point system to each sketch design per factor facilitated the identification of the most viable typologies for further exploration. Among these, the Y-shape and convergent geometries emerged as the most promising candidates. While the rod geometry also scored highly, personal preference led to the decision to focus on the Y-shape typology due to its intriguing interlink system of blocks. This eventually led to the philosophical approach of using extreme relative humidities to make an interlocking system and thus excluding the need for an additional locking layer. Consequently, the Rods typology was excluded from further consideration, and efforts were directed towards refining the Y-shape typology.

9.4 Testing

Once the materials were acquired and the appropriate typologies selected, the testing phase began. This phase involved systematically assessing whether the typologies exhibited any self-shaping characteristics, progressing step-by-step. Given the novel nature of the research, it was important to begin with a conventional bi-layer. This bi-layer, which has been extensively studied and validated in previous research, served as a benchmark from which further development could proceed.
Following the completion of the bi-layer, experimentation with the new typologies commenced. By gradually incorporating spacer elements into the test element, insights were gained into the mechanisms underlying the occurrence or absence of curvature. It's important to note that this process was non-linear, allowing for iterative refinement and redesign. Embracing this iterative approach, characterized by re-development and occasional steps backward, was crucial for the advancement of the research. This development process is illustrated in Figure 105.

Challenges

The testing phase encountered several unexpected challenges that may have influenced the results. One such incident occurred when the fire alarm at the Architecture faculty disrupted an assembly phase, causing the moist timber blocks to undergo hygroshrinkage without being properly attached to the passive layer. This unexpected interruption likely affected the accuracy of the testing outcomes.

Additionally, effective time management proved to be crucial during the testing phase. Unfortunately, the research schedule was further impeded by an international study trip, which inevitably slowed down the development process. These external factors necessitated careful consideration and adaptation of the research timeline to ensure that testing procedures were conducted as effectively as possible despite the challenges encountered.

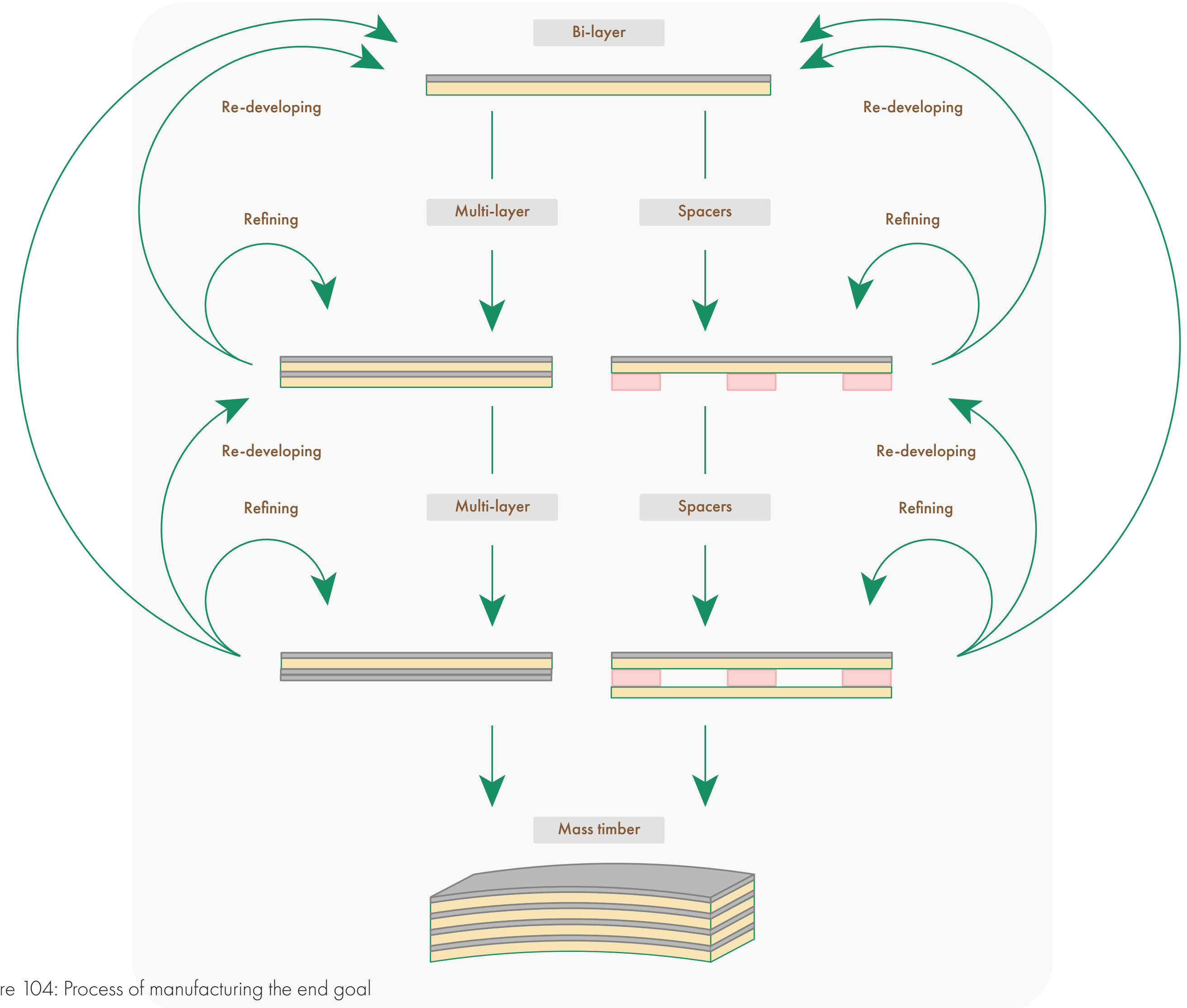


Figure 104: Process of manufacturing the end goal

The results indicated varying curvature rates between specimens treated with humidity and those treated with water. While the initial assumption might suggest that water treatment would be more promising in creating self-shaping curvature, the findings from the experiments suggest otherwise. In fact, humidity treatment demonstrated more promise in generating self-shaping curvature based on the observed results.

The results did and did not meet expectations, which may sound paradoxical yet it is true. After the first moisture treatment period, no hygroexpansion was observed. Both visual observation and measurements showed no dilation, therefore when the first test resulted in significant self-shaping curvature the expectations were, surprisingly, met. Still, not every test showed self-shaping curvature, or significant curvature.

The active layer pieces curved themselves and not the overall element due to bonding problems. As a result of weak adhesives the pieces detached from the passive layer during the drying period. These test results provided new insight on the relation between self-shaping and the treatment method, as well as the importance of the bonding process. These new insights were implemented in the test conducted hereafter.

Due to the failure in the second test, the third test had to be brought back to the basics. Only by going back, steps forward can be made. The third test had the same methodology as the first test, yet also the water method of the second test was added, this to understand and conclude why the failure of no curvature happened. The more complex designed typologies were simplified. The outcome of this decision was two more complex elements with varying curvature. The humidity element showed 150% more curvature height as the water treated element.

As it is proven that a more complex bi-layer is capably of self-shaping, a boxfloor element is created in the fourth test. This element, which was humidity treated, showed self-shaping. The curvature height is less, compared to earlier test. This could be explained by the increase of material, thus the increase of self-weight. The self-weight could impact the achievable curvature during the drying time of the element. The orientation of the element when drying is therefore of importance. The elements have been drying on an axis which would not change compared to the surface.

Furthermore, the assembly order was investigated. The first few test were all assembled in one go before self-shaping. However, the possibility of restricted curvature due to this decision was not acknowledged previously, the separate self-shaping and assembling afterwards may impact the curve height positively. According to the results showed by the last test, assembling an element after self-shaping does indeed improve the overall curve height, as the highest curve height was achieved.

However, the generalizability of the results is limited by several factors, including the sample size which only exist of 9 elements, the specific characteristics of the materials used, which is dominated by conventional spruce wood. Additionally, variations in manufacturing processes, testing methodologies, and measurement techniques may also impact the applicability of the findings to broader contexts. Therefore, caution should be exercised when extrapolating the results to other scenario. Further research with larger sample sizes or dimensions and diverse conditions is needed to enhance the generalizability of the findings.

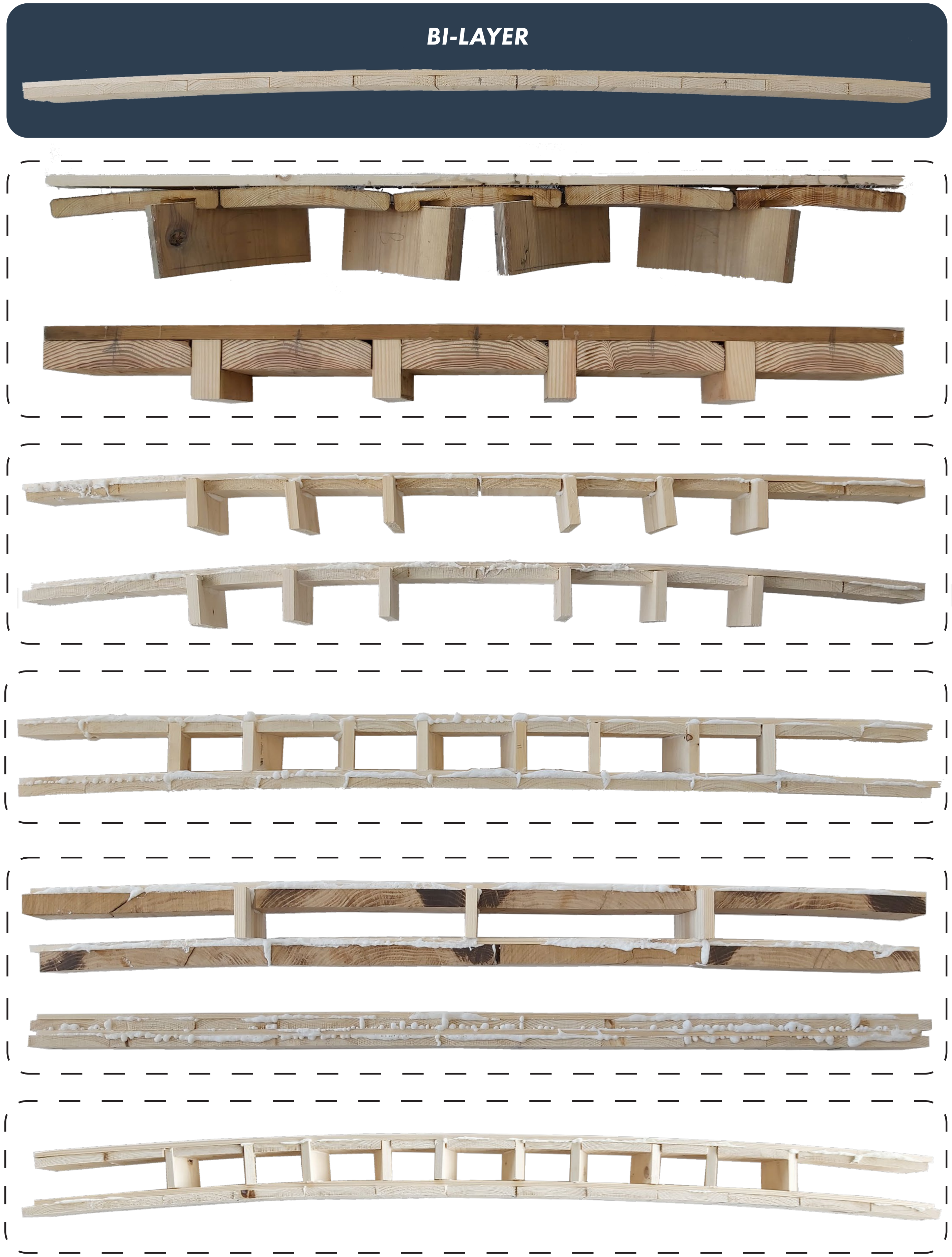


Figure 105: Physical elements tested in chronological order

9.5 Future

Timber species

As this research thesis comes to a closure, there are still some significant unfinished factors which can be researched further. The types of timber used during testing were mainly softwoods. Although the last test used hardwood, this pool of just 1 hardwood test is to small to draw accurate conclusions. Therefore it is recommended to use different hardwoods, with the right quality and not scrap wood, in future physical tests.

Interlocking system

Additionally, a new study can be started which focusses on the possibility to create a interlocking mechanism with the extreme relative humidities. This promising concept is only philosophically mentioned. A few ideas were already sketched, however that is it. Due to the interlocking possibility the need for a locking layer is gone, resulting in an even more sustainable structural element.

Long-term effects

The short-term effects are measured and investigated, however the long term effect of the moisture self-shaping is still unknown. If a real-life product want to hit the market, the safety of the product needs to be guaranteed. There is a possibility where over time, due to creep or other phenomenons, the curvature losses its curve height of strength. This should therefore also be investigated.

Mechanical testing

Although it was not the main goal of this thesis, a structural test would provide new insights and information which can perhaps be compared to other existing boxfloor elements. It can be done by a professional tool or low-tech with weights to see the deflection or even its limit state to failure.

Multi-layer

The multi-layer has not been developed or tested enough to draw conclusions. This is because the main focus was at the spacer typology. It could still be very interesting to see if multi-layered elements can self-shape with moisture. By changing the assembly, adding curved bi-layers or curving the multi-layers in one bunch can give valuable information for the creation of a new timber construction element.

Timber orientation

The position and orientation of the timber in the spacer element influences the span direction. Due to the expansion direction of timber, the active layer is bound to a certain axis. It is possible to change this axis, but this will influence the overall curving. Still, it is interesting to investigate if the hardwood can be rotated to increase the curving and thus also the span direction.

Interconnection

On of the challenges faces during the testing phase was the detachment of the active layers between themselves. By solving this problem, the eventual curve height may be increased significantly. A solution for this problem in the form of dovetails has been given, however this theoretical idea has not been tested. It shows great promise, but it needs to be proven. A downside of using dovetails is it will increase the complexity of the overall simple design.

9.6 Improvements

While this research has yielded valuable information and insights into the self-shaping of timber elements, it is important to acknowledge that there is room for improvement to transition from hypothetical studies to real-life applications in the mass timber industry. Several areas for enhancement have been identified:

Water research - In the water research, two tests involving timber blocks treated with water yielded insignificant to no self-shaping effects. Despite this, these tests demonstrated the largest hygroexpansion among all trials, rendering the results inconclusive. Efforts were made to identify potential causes for the lack of self-shaping, but with only two tests conducted with water treatment, definitive conclusions could not be reached. Consequently, further refinement and enhancements in the water testing methodology are necessary to achieve more reliable results.

Element connection - Regarding the element connection aspect, this thesis primarily focused on the mechanical aspects of self-shaping. However, in practical applications where real-life boxfloor elements are manufactured, attention must also be given to the connections and details. While a hypothetical detail was conceptualized, additional work and improvements are required to develop manufacturing-ready elements. Enhancing the design and engineering of these connections will be essential for ensuring the structural integrity and performance of the self-shaping timber elements in real-world applications.

Integration with building systems - Integrating self-shaping timber elements into existing building systems and construction practices necessitates collaboration with architects, engineers, and industry stakeholders to address compatibility, code compliance, and practical implementation challenges.

Scale-Up and Manufacturing Considerations - Scaling up from laboratory prototypes to full-scale mass timber elements requires careful consideration of manufacturing processes, cost-effectiveness, and structural performance at larger dimensions.

9.7 Conclusion

In conclusion, this master thesis has explored the feasibility of utilizing hygromorphic self-shaping principles to curve structural timber floor elements. Through the development and testing of a novel spacer typology, it has been demonstrated that self-shaping is achievable for more complex geometries beyond a simple bi-layer configuration.

One of the primary challenges in curving structural timber elements lies in addressing mass and area limitations, which impact bending strength. By integrating bi-layers and introducing the new spacer typology between them, this thesis has made strides in mitigating these challenges. The resulting element exhibits enhanced flexibility, and through the natural hygroexpansion and shrinkage properties of timber, it is capable of curving up to 27 millimetres.

Furthermore, the type of treatment for the active layer seems to impact the curvature height. Although the sample pool consist of 2 test-elements, they showed significant to no self-shaping whereas the humidity test-elements all showed curvature, except of the largest element.

Overall, this research not only contributes to the understanding of self-shaping principles in timber construction but also offers practical insights into the development of innovative structural elements with improved performance characteristics. The findings presented herein pave the way for further advancements in the field of hygromorphic timber engineering, with potential applications ranging from architectural design to sustainable construction practices.

Figure 106: Context render

Reflection

Thesis process

10

1. What is the relation between your graduation project topic, your master track (A, U, BT, LA, MBE), and your master programme (MSc AUBS)?
The official TU Delft website describes the Building Technology (BT) track as a programme where students learn to design sustainable and innovative building elements. As the topic of this graduation project focused on the possibility for structural multi-layered timber floor elements to hygromorphically self-shape and curve, it embodies both sustainable material use with timber and innovative design aspects like the self-shaping phenomenon. Due to the fact that a structural product needs to be designed, the Structural and Product design sub-master programmes seamlessly intertwine with the project topic.

2. How did your research influence your design/ recommendations and how did the design/ recommendations influence your research?
Before any (literature) research was conducted, the goal was to passively curve mass timber elements like beams and columns. Curving these mass timber elements is possible, however doing it passively has not been done before. During both the literature review and physical testing it became clear that due to the stiffness of these mass timber elements it is nearly impossible to self-shape them. Therefore the design changed into a boxfloor like geometry. By keeping the strength, yet removing material to allow for possible self-shaping, a new typology was created. However, as the design changed, so did the testing methodology and thus the research. Some designs showed more curvature than others. To understand why this happened, different testing methods were used, for example treating the specimen with humidity or water. Essentially it was an equal conterplay between research influencing design and vice versa.

3. How do you assess the value of your way of working (your approach, your used methods, used methodology)?
There is no straight answer to this question, as it is more nuanced. The methodology was based on previous relevant research based on hygromorphic shaping, which set a well-founded benchmark to conduct research. By changing the approach from focussing on the curvature to focussing on the shape and interaction between the elements themselves, this research methodology distinguishes itself as it is a new approach.

The measurements are a key factor during the testing phase, as they confirm different phenomenon and the overall hygroexpansion. Initially, a comprehensive set of measurements including dimensions, volume, moisture content, and weight was recorded during the first test. However, the time-intensive nature of this approach posed challenges in managing the project timeline effectively. As time management was a challenge, the mentors advised to reduce the complexity and focus on the essentials (Moisture content and Weight). While this adjustment reduced the academic standard of data collection, it proved to be a strategic choice. By spending more time to designing and constructing the models, the research was able to progress more efficiently. It is therefore plausible that by reducing the academic data collection approach benefitted the overall research.

Furthermore, as time management was a challenge during the research project, taking initiative is important. However, I have been too naïve and too dependent in getting timber to start the testing phase. In total, over 1,5 months were semi-wasted due to no reaction from different stakeholders which could or would have provided material. By maintaining this reluctance, precious time was lost. Due to this reason, fewer testing models were created than expected. Eventually I took matters into my own hand and bought timber at the local hardware store, however this was perhaps too late. Taking more initiative is the main change I would make, looking back at the project process.

4. How do you assess the academic and societal value, scope and implication of your graduation project, including ethical aspects?
The whole goal of the thesis is to combat excessive steel and concrete usage in the build environment by creating a new sustainable curved timber structural element. By creating such an element, the thrive to still use pollutant construction materials should be reduced. This goal is still dominant in the research thesis, working with wood and creating ways to passively self-shape them. The production of a simple boxfloor element is cheaper than a complex hygromorphic typology. As the boxfloor market is already well established, competing with well-known and perhaps less expensive rival products is hard. Still, the drive to make innovative and sustainable building elements, by research, can lead to a better world. On an academic level this research gives great insights in the possibility to passively self-shape complex multi-layered wooden elements. This could mean that further research can start investigating the possibility of mass timber elements or façade blocks.
The structural engineering aspect is a cornerstone of the master's program, typically involving extensive calculations related to strength and loads. However, the nature of this project and its central question meant that detailed calculations were not a primary focus. This departure from the norm left me feeling uncertain at times, questioning whether the project was sufficient. Engaging in discussions with mentors provided invaluable reassurance. They emphasized that the essence of the structural engineering program extends beyond calculations alone. Instead, it encompasses a holistic approach to problem-solving, innovation, and research. This perspective alleviated my concerns and allowed me to refocus on the project's objectives without undue anxiety about adhering to traditional standards.

As the modern day continues to develop, why should we not use it. During the writing of the report, chat-gpt was used, but not in the conventional way. Chat-gpt was not used to just write paragraphs and chapters. However it was used as a rewriter. Every bit of text was already written, chat-gpt rewrites the paragraph into a more formal style. Due to my dyslexia, it also helped as a spelling controller. Did the use of chat-gpt impacted the academic scientific integrity? That is up for debate, but personally I do not think so, as it was just a rewriting machine. All statements have references, the text has been written by me, etc.

5. How do you assess the value of the transferability of your project results?
The research project is implementation specific, it is a boxfloor element used in the build environment. Although it may be unwise to say that the project results can be transferred into a new context, without researching this new context, its implementation can possibly be utilised other than a boxfloor element. The findings of passively curving multi-layered elements can perhaps be used in carpentry, however the need and the value of implementing this new design and manufacturing method can be called in question due to the many shaping techniques already used in carpentry. Also, timber is not the only hygroscopic material. The principle of hygroexpension and shrinkage where the self-shaping phenomenon is based on, is not only bound to timber elements but can theoretically also be used with other materials like paper or cotton. Still, this change of context or transferability is hard and needs thorough research before it can be used. Therefore limiting the value of transferability.

6. How did the mentor relationship influence the research project?
During the initial stages leading up to the P2 presentation, communication with the second mentor proved to be challenging. At one point, I even considered seeking a replacement mentor due to the difficulties encountered. While I acknowledge that mentors often have busy schedules, and responding to emails may take time, the lack of communication was less than ideal. However, following the P2 presentation, there was a noticeable improvement in communication. By being more straight forward the mentor's personal contact information was obtaining and direct channels of communication was established, interactions became more effective and timely.

7. How did the results influence the conclusion and perception?
This research project is a high-risk research, meaning that outcomes are uncertain which makes it challenging to predict results. Consequently, when results emerge, there is a tendency to overemphasize these positive results. The outcomes indicated that only 6.1% of the desired curvature height was achieved. Despite this relatively low percentage, the results physical results seemed overly optimistic. This difference between expectations and reality highlighted the need to temper optimism with a healthy dose of scepticism. It served as a reminder of the challenges and complexities involved in pushing the boundaries of knowledge and innovation.

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Figure 1: AI generated Background (Adobe, 2024)

Figure 2: Dispenza, K. (2011). Heydar Aliyev structure. Buildipedia. https://buildipedia.com/aec-pros/from-the-job-site/zaha-hadids-heydar-aliyev-cultural-centre-turning-a-vision-into-reality

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Figure 5: Methdology comparison (own work)

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Figure 11: Strategies for sustainability design (Own work)

Figure 12: AI generated Background (Adobe, 2024)

Figure 13: Different typologies (Own work)

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Figure 27: Species overview (Own work)

Figure 28: https://www.familyhandyman.com/article/tips-for-drying-wood-for-woodworking-projects/

Figure 29: Moisture lab (Own work)

Figure 30: Sandwich (Own work)

Appendix

Testing data (Test 1)

Measurement 1

				Dry weigth	382 [Kg/m3]			Calc.	Bosch
	Measurements							T0	T0
Blocks	Length	Width	Height	Volume	Weigth	Weight	Wet weight	MC	MC
	[mm]	[mm]	[mm]	[m3]	[g]	[Kg]	[kg/m3]	[%]	[%]
1	93	55	12	6,14E-05	24,64	0,02464	401,43	5,087354	8
2	92,5	55,5	12	6,16E-05	24,63	0,02463	399,81	4,66105	8,2
3	92,5	55	12	6,11E-05	24,36	0,02436	399,02	4,454764	8,2
4	93	55	12	6,14E-05	24,41	0,02441	397,69	4,106425	8,4
5	92,5	55	12	6,11E-05	25,37	0,02537	415,56	8,785606	8,5
6	93	54	12	6,03E-05	24,53	0,02453	407,04	6,555588	8,8
7	93	54,5	12	6,08E-05	24,63	0,02463	404,95	6,008418	8,7
8	93	55	12	6,14E-05	24,85	0,02485	404,86	5,982985	8,6
9	92,5	55	12	6,11E-05	26,36	0,02636	431,78	13,03069	8,6
10	92,5	55	12	6,11E-05	25,16	0,02516	412,12	7,885134	8,7
11	92,5	55	12	6,11E-05	25,98	0,02598	425,55	11,40126	8,8
12	92	54,5	12	6,02E-05	24,88	0,02488	413,51	8,248388	8,7
13	92,5	55	12	6,11E-05	24,85	0,02485	407,04	6,555866	8,1
14	92,5	55	12	6,11E-05	24,83	0,02483	406,72	6,470106	7,8
15	92,5	55	12	6,11E-05	24,42	0,02442	400,00	4,712042	7,6
16	93	55	12	6,14E-05	24,74	0,02474	403,06	5,513845	7,3
17	92,5	55	12	6,11E-05	23,97	0,02397	392,63	2,782459	7,7
18	92	54,5	12	6,02E-05	23,31	0,02331	387,42	1,417601	7,8
					24,77333		406,12	6,31	8,25

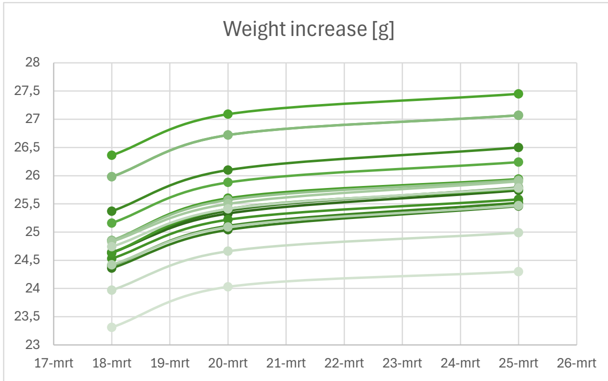
Measurement 2

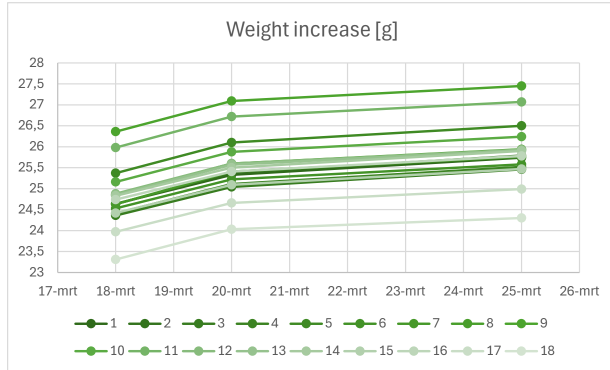
		Bosch			
		T0			
Length	Length increase	MC	Mc change	Weight	Weight change
[mm]	[%]	[%]		[g]	[%]
94	1,08	10,4	2,4	25,33	2,80
93,5	1,08	11,1	2,9	25,38	3,05
94	1,62	11,2	3	25,04	2,79
93,5	0,54	11,4	3	25,11	2,87
94	1,62	11,5	3	26,1	2,88
93,5	0,54	11,2	2,4	25,22	2,81
94	1,08	11,7	3	25,41	3,17
93	0,00	11,1	2,5	25,6	3,02
94	1,62	10,8	2,2	27,09	2,77
94	1,62	11	2,3	25,88	2,86
93,5	1,08	11,1	2,3	26,72	2,85
94	2,17	11	2,3	25,6	2,89
93	0,54	11,2	3,1	25,57	2,90
93,5	1,08	11	3,2	25,5	2,70
93	0,54	10,4	2,8	25,09	2,74
93	0,00	10,4	3,1	25,41	2,71
93	0,54	10,9	3,2	24,66	2,88
92,5	0,54	11,1	3,3	24,03	3,09
93,50	0,96	11,03	2,78	25,49	2,88

Measurement 3

		Bosch		
		T0		
Length	Length increase	MC	Mc change	Weight
[mm]	[%]	[%]		[g]
94	0,00	13,1	5,1	25,74
93,5	0,00	12,8	4,6	25,79
94	0,00	12,9	4,7	25,46
93,5	0,00	13,1	4,7	25,52
94	0,00	13,5	5	26,5
94	0,53	13,5	4,7	25,58
94	0,00	14,1	5,4	25,76
93,5	0,54	13,2	4,6	25,94
94	0,00	12,7	4,1	27,45
94	0,00	12,3	3,6	26,24
93,5	0,00	13,6	4,8	27,07
94	0,00	13,2	4,5	25,93
93	0,00	12,7	4,6	25,92
93,5	0,00	12,4	4,6	25,9
93	0,00	11,7	4,1	25,47
93	0,00	12,1	4,8	25,78
93	0,00	11,8	4,1	24,99
92,5	0,00	12,2	4,4	24,3
93,56	0,06	12,83	4,58	25,85

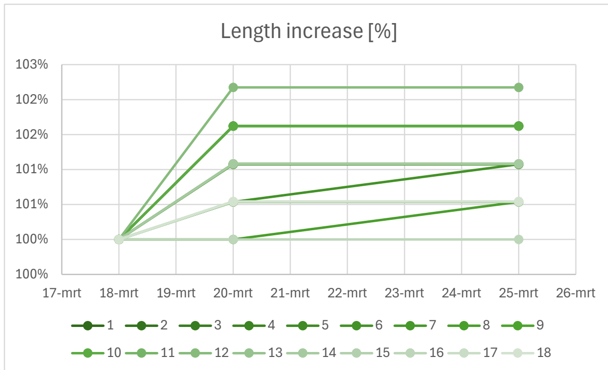
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
18-mrt	24,64	24,63	24,36	24,41	25,37	24,53	24,63	24,85	26,36	25,16	25,98	24,88	24,85	24,83	24,42	24,74	23,97	23,31
20-mrt	25,33	25,38	25,04	25,11	26,1	25,22	25,41	25,6	27,09	25,88	26,72	25,6	25,57	25,5	25,09	25,41	24,66	24,03
25-mrt	25,74	25,79	25,46	25,52	26,5	25,58	25,76	25,94	27,45	26,24	27,07	25,93	25,92	25,9	25,47	25,78	24,99	24,3

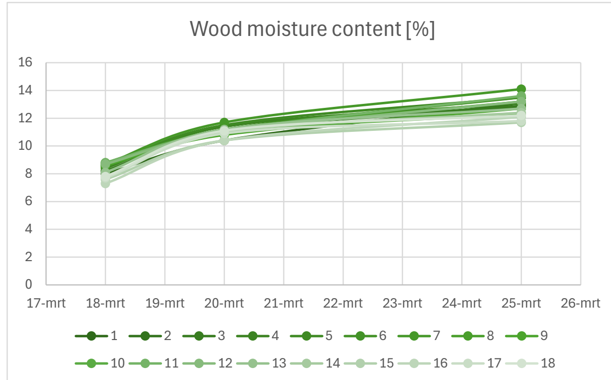




18-mrt	93	92,5	92,5	93	92,5	93	93	93	92,5	92,5	92,5	92	92,5	92,5	92,5	93	92,5	92
20-mrt	94	93,5	94	93,5	94	93,5	94	93	94	94	93,5	94	93	93,5	93	93	93	92,5
25-mrt	94	93,5	94	93,5	94	94	94	93,5	94	94	93,5	94	93	93,5	93	93	93	92,5

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
18-mrt	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
20-mrt	101,08%	101,08%	101,62%	100,54%	101,62%	100,54%	101,08%	100,00%	101,62%	101,62%	101,08%	102,17%	100,54%	101,08%	100,54%	100,00%	100,54%	100,54%
25-mrt	101,08%	101,08%	101,62%	100,54%	101,62%	101,08%	101,08%	100,54%	101,62%	101,62%	101,08%	102,17%	100,54%	101,08%	100,54%	100,00%	100,54%	100,54%





	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
18-mrt	8	8,2	8,2	8,4	8,5	8,8	8,7	8,6	8,6	8,7	8,8	8,7	8,1	7,8	7,6	7,3	7,7	7,8
20-mrt	10,4	11,1	11,2	11,4	11,5	11,2	11,7	11,1	10,8	11	11,1	11	11,2	11	10,4	10,4	10,9	11,1
25-mrt	13,1	12,8	12,9	13,1	13,5	13,5	14,1	13,2	12,7	12,3	13,6	13,2	12,7	12,4	11,7	12,1	11,8	12,2

Testing data (Test 2)

Measurement 1

Test 1				Dry weigth	600 [Kg/m3]			Calc.	Bosch
Measurements								T0	T0
Blocks	Length	Width	Height	Volume	Weigth	Weight	Wet weight	MC	MC
BIG	[mm]	[mm]	[mm]	[m3]	[g]	[Kg]	[kg/m3]	[%]	[%]
1	200	130	40	1,04E-03	640,25	0,64025	615,63	2,604167	10,8
2	200	130	40	1,04E-03	678,23	0,67823	652,14	8,690705	10,4
3	200	130	40	1,04E-03	685,53	0,68553	659,16	9,860577	10,4
4	200	130	40	1,04E-03	691,2	0,6912	664,62	10,76923	10,6
5	200	130	40	1,04E-03	696,43	0,69643	669,64	11,60737	10,7
A	130	80	40	4,16E-04	258,37	0,25837	621,08	3,513622	11,4
B	130	80	40	4,16E-04	260,26	0,26026	625,63	4,270833	10,9
C	130	80	40	4,16E-04	269,52	0,26952	647,88	7,980769	10,5
D	130	80	40	4,16E-04	268,61	0,26861	645,70	7,616186	9,9
W	200	130	40	1,04E-03	732,09	0,73209	703,93		11,2

				Dry weigth	420 [Kg/m3]			Calc.	Bosch
								T0	T0
	Length	Width	Height	Volume	Weigth	Weight	Wet weight	MC	MC
SMALL	[mm]	[mm]	[mm]	[m3]	[g]	[Kg]	[kg/m3]	[%]	[%]
1	186	93	23	3,98E-04	183,6	0,1836	461,48	9,875195	9,9
2	186	93	23	3,98E-04	172,7	0,1727	434,08	3,352103	10,2
3	186	93	23	3,98E-04	172,63	0,17263	433,90	3,310212	10
4	186	93	23	3,98E-04	174,42	0,17442	438,40	4,381435	9,9
5	186	93	23	3,98E-04	184,1	0,1841	462,73	10,17442	9,7
A	186	81	23	3,47E-04	165,57	0,16557	477,81	13,76445	10,4
B	186	81	23	3,47E-04	165,59	0,16559	477,87	13,77819	10,1
C	186	81	23	3,47E-04	164,96	0,16496	476,05	13,34531	10,2
D	186	81	23	3,47E-04	173,6	0,1736	500,98	19,28192	9,8

Measurement 2

			Dry weigth	600 [Kg/m3]			Calc.	Bosch
ents							T0	T0
Length	Width	Height	Volume	Weigth	Weight	Wet weight	MC	MC
[mm]	[mm]	[mm]	[m3]	[g]	[Kg]	[kg/m3]	[%]	[%]
200	130	40	1,04E-03	645,15	0,64515	620,34	3,389423	11,8
200	130	40	1,04E-03	683,23	0,68323	656,95	9,491987	12,4
200	130	40	1,04E-03	691	0,691	664,42	10,73718	12,6
200	130	40	1,04E-03	695,84	0,69584	669,08	11,51282	13,3
200	130	40	1,04E-03	701,46	0,70146	674,48	12,41346	13,4
130	80	40	4,16E-04	260,71	0,26071	626,71	4,451122	12,8
130	80	40	4,16E-04	262,53	0,26253	631,08	5,180288	11,9
130	80	40	4,16E-04	271,71	0,27171	653,15	8,858173	12,7
130	80	40	4,16E-04	271,11	0,27111	651,71	8,617788	12,9
205	130	40	1,07E-03	848,8	0,8488	796,25		26,6

			Dry weigth	420 [Kg/m3]			Calc.	Bosch
							T0	T0
Length	Width	Height	Volume	Weigth	Weight	Wet weight	MC	MC
[mm]	[mm]	[mm]	[m3]	[g]	[Kg]	[kg/m3]	[%]	[%]
186	93	23	3,98E-04	186,53	0,18653	468,84	11,62865	12,1
186	93	23	3,98E-04	175,24	0,17524	440,46	4,872163	11,7
186	93	23	3,98E-04	175,19	0,17519	440,34	4,842241	11,7
186	93	23	3,98E-04	177,01	0,17701	444,91	5,931417	12,1
186	93	23	3,98E-04	186,91	0,18691	469,80	11,85606	12,1
186	81	23	3,47E-04	167,93	0,16793	484,62	15,38602	11,9
186	81	23	3,47E-04	168	0,168	484,82	15,43412	11,8
186	81	23	3,47E-04	167,36	0,16736	482,98	14,99437	11,9
186	81	23	3,47E-04	175,99	0,17599	507,88	20,92411	11,2

Measurement 3

Test 3				Dry weigth	600 [Kg/m3]			Calc.	Bosch
Measurements								T0	T0
Blocks	Length	Width	Height	Volume	Weigth	Weight	Wet weight	MC	MC
BIG	[mm]	[mm]	[mm]	[m3]	[g]	[Kg]	[kg/m3]	[%]	[%]
1	200	130	40	1,04E-03	651,65	0,65165	626,59	4,43109	12,9
2	200	130	40	1,04E-03	689,93	0,68993	663,39	10,56571	13
3	200	130	40	1,04E-03	697,95	0,69795	671,11	11,85096	12,1
4	200	130	40	1,04E-03	702,5	0,7025	675,48	12,58013	12,9
5	200	130	40	1,04E-03	708,3	0,7083	681,06	13,50962	13,4
A	130	80	40	4,16E-04	263,55	0,26355	633,53	5,588942	14,4
B	130	80	40	4,16E-04	265,31	0,26531	637,76	6,294071	14,3
C	130	80	40	4,16E-04	274,63	0,27463	660,17	10,02804	14,2
D	130	80	40	4,16E-04	274,15	0,27415	659,01	9,835737	13,7
W	205	130	40	1,07E-03	848,8	0,8488	796,25		26,6

				Dry weigth	420 [Kg/m3]			Calc.	Bosch
								T0	T0
	Length	Width	Height	Volume	Weigth	Weight	Wet weight	MC	MC
SMALL	[mm]	[mm]	[mm]	[m3]	[g]	[Kg]	[kg/m3]	[%]	[%]
1	186	93	23	3,98E-04	252,37	0,25237	634,33	51,03052	27,1
2	186	93	23	3,98E-04	238,54	0,23854	599,57	42,75397	26,4
3	186	93	23	3,98E-04	243,98	0,24398	613,24	46,00953	27,5
4	186	93	23	3,98E-04	244,34	0,24434	614,14	46,22497	27,7
5	186	93	23	3,98E-04	254,32	0,25432	639,23	52,19749	27,7
A	186	81	23	3,47E-04	228,32	0,22832	658,90	56,88046	26,9
B	186	81	23	3,47E-04	227,34	0,22734	656,07	56,2071	26,2
C	186	81	23	3,47E-04	232,71	0,23271	671,57	59,89687	27,1
D	186	81	23	3,47E-04	235,11	0,23511	678,49	61,54593	29,4

Testing data (Test 3)

Test 1	Measurements					
	1	2	3	1	2	3
Blocks	Weigth	24h		Bosch	24h	
	[g]			MC [%]		
T1	20,78	20,66	20,74	7,1	7,6	7,30
T2	23,1	22,96	23,04	7,2	7,9	7,10
T3	20,69	20,51	20,57	7,2	7,1	7,20
T4	18,05	17,86	17,92	8,2	7,6	7,60
A1	27,01	35,24	41,41	7,3	24,5	28,40
A2	24,57	34,81	41,71	8,3	26,6	27,40
A3	26,84	35,16	41,47	7,5	24,1	28,20
A4	23,51	34,5	41,15	8,5	26,8	28,50
B1	24,42	24,99	25,25	8,4	11,1	12
B2	28,17	28,78	29,19	7,5	10,1	12,1
B3	25,47	25,98	26,31	7,6	10,6	11,7
B4	26,89	27,45	27,84	7,4	10,1	11,8

Testing data (Test 4)

Test 4	Measurements					
	1	2	3	1	2	3
Blocks	Weigth	4 days		Bosch	4 days	
	[g]			MC [%]		
T1	25,34	26,13		8,4	12,2	
T2	23,43	24,18		8,2	11,6	
T3	23,56	24,27		8,3	11,8	
T4	26,5	27,29		8,5	13,7	
T5	28,27	29,15		7,9	11,5	
T6	28,39	29,31		8,2	12,3	
T7	24,23	25,02		9,4	12,2	
T8	26,65	27,49		8,2	11,8	

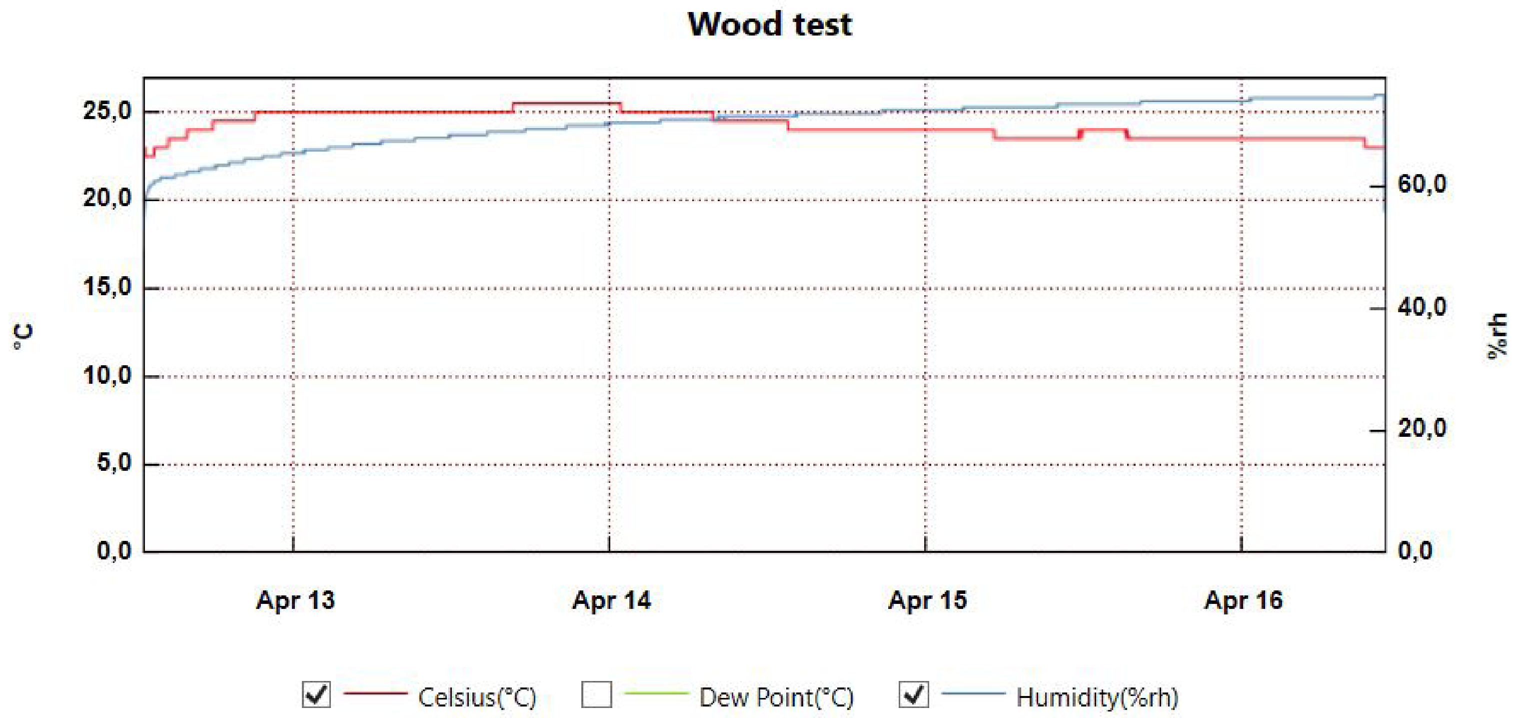
Testing data (Test 5)

Test 5	Measurements					
	1	2	3	1	2	3
Blocks	Weigth	4 days		Bosch	4 days	
Eiken	[g]			MC [%]		
T1	209,57	212,18		11,4	14	
T2	184,94	188,13		9,8	14,2	
T3	191,92	195,14		10	14,1	
T4	196,04	199,4		10,2	14,4	
T5	231,25	234,27		10,5	15,1	
T6	210,11	212,75		11,6	14,8	
T7	195,9	199,13		10,2	13,6	
T8	172,72	176,14		9,8	14	
Zacht						
T1	27,41	28,2		8,8	12,2	
T2	27,13	27,89		9,6	12,8	
T3	26,8	27,54		9,6	12,2	
T4	26,38	27,12		9,8	12,9	
T5	26,63	27,36		9,4	12,2	
T6	23,64	24,16		8,4	11,3	
T7	26,58	27,37		8,7	12,3	
T8	26,34	27,06		9	12,6	

Testing data (Test 6)

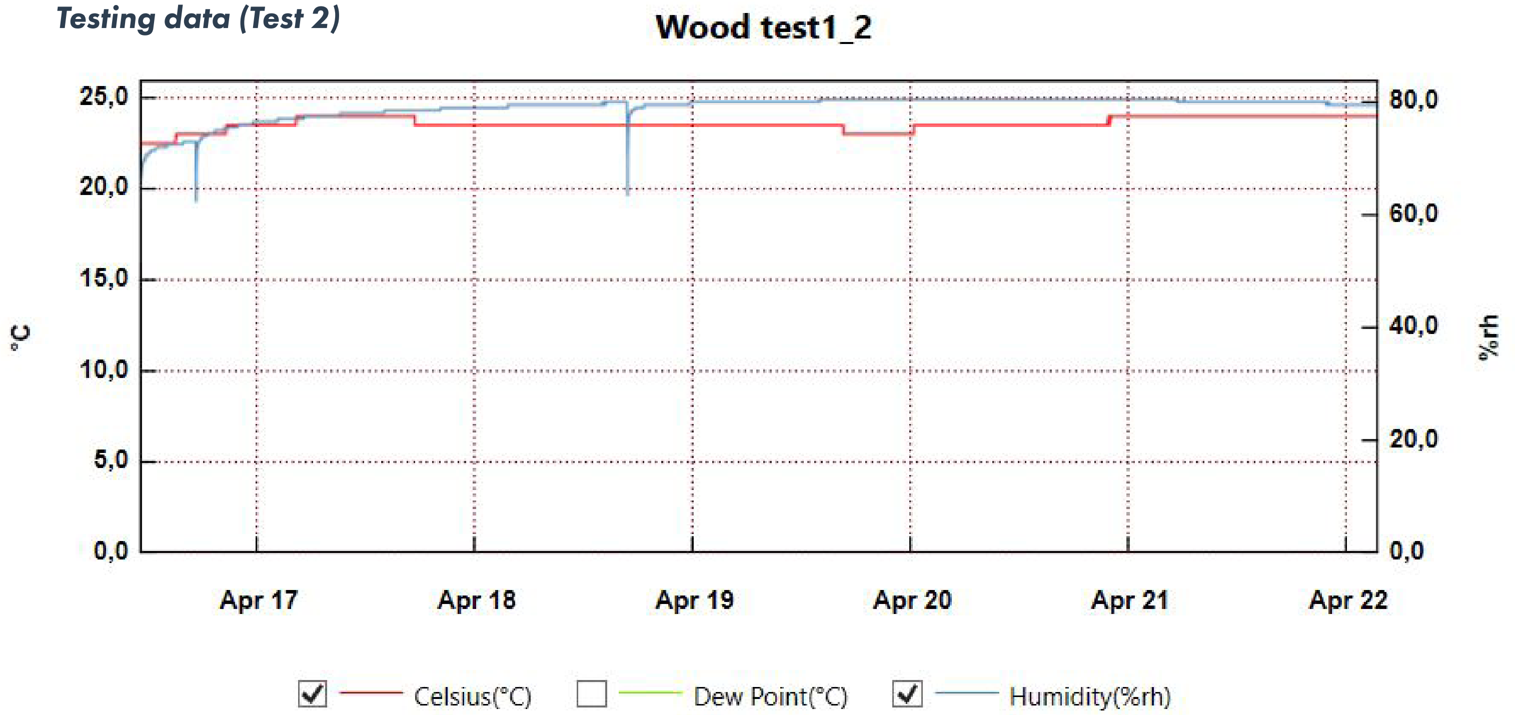
Test 5	Measurements					
	1	2	3	1	2	3
Blocks	Weigth	4 days	11 days	Bosch	4 days	11 days
vuren	[g]			MC [%]		
Aw	24,96	24,98	26,82	9,2	9,7	17,70
Ax	24,54	24,57	26,3	9,8	10	17,60
Ay	18,61	18,58	19,81	10,4	10,4	17,00
Az	22,81	22,87	24,52	9,2	9,8	17,50
Bw	30,91	30,97	33,15	9,2	9,8	17,70
Bx	23,71	23,65	25,23	10,4	10,5	17,40
By	30,71	30,75	33,03	9,4	9,8	17,80
Bz	26,29	26,32	28,22	9,3	9,9	18

Testing data (Test 1)



From: vrijdag 12 april 2024 12:33:08 - To: dinsdag 16 april 2024 11:03:08

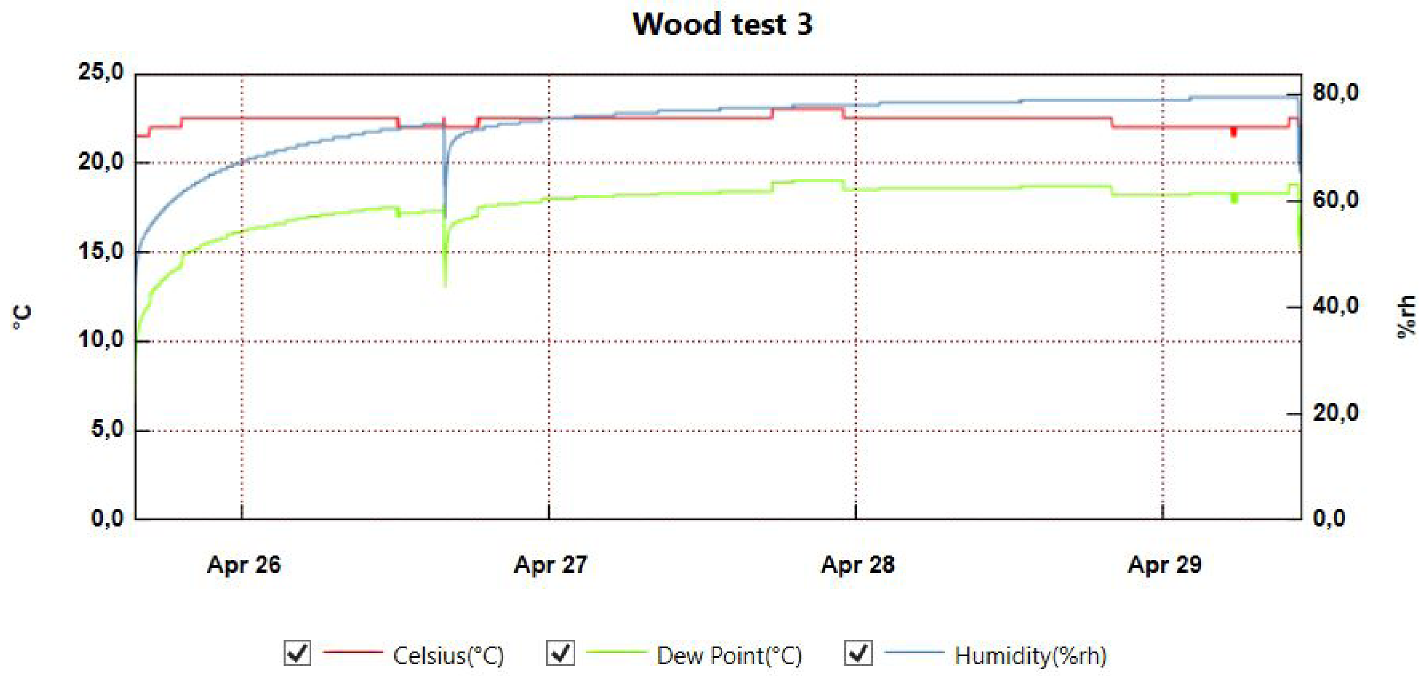
Testing data (Test 2)



woensdag 17 april 2024 01:33:56 [23,5 76,5]

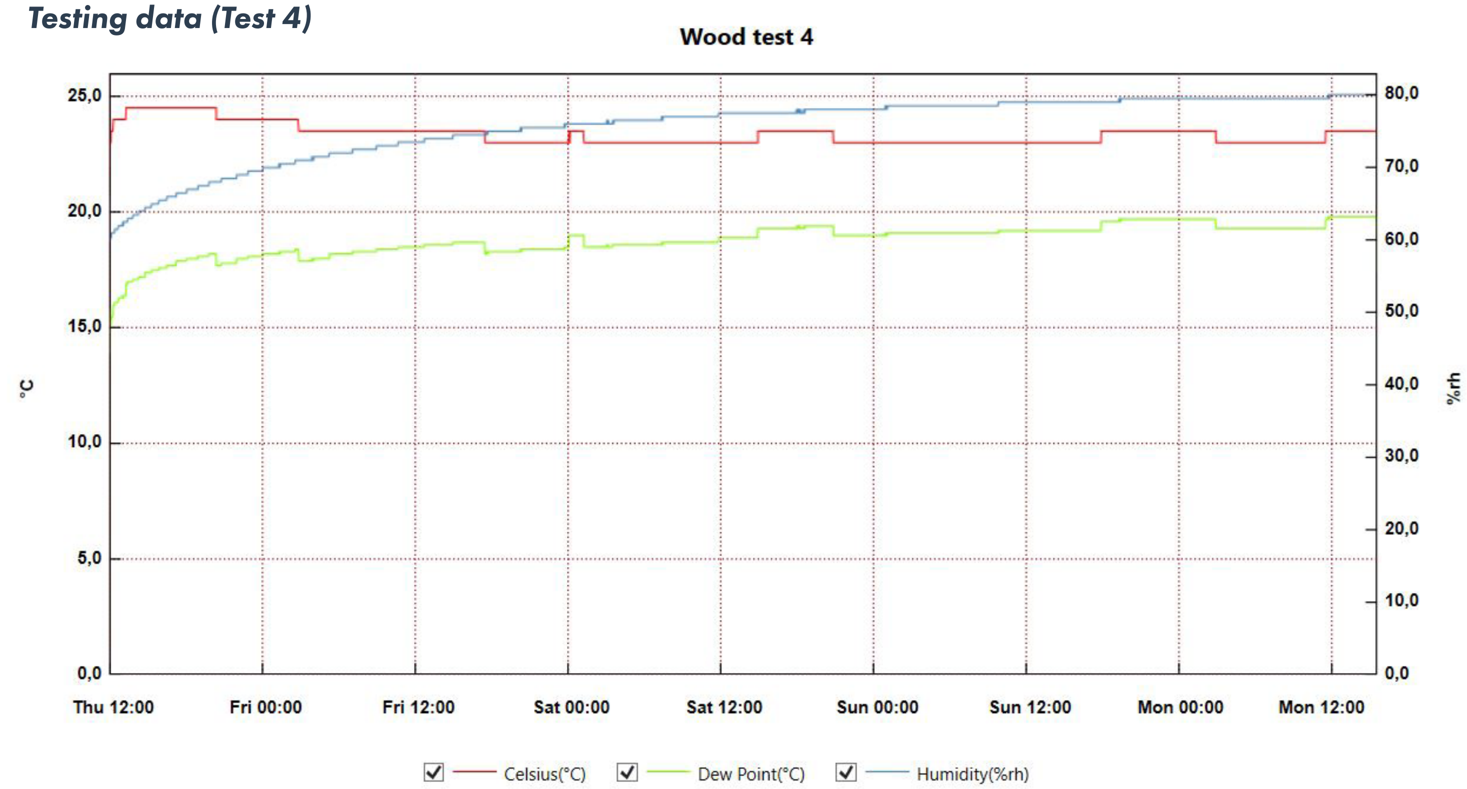
From: dinsdag 16 april 2024 11:04:31 - To: maandag 22 april 2024 03:35:01

Testing data (Test 3)



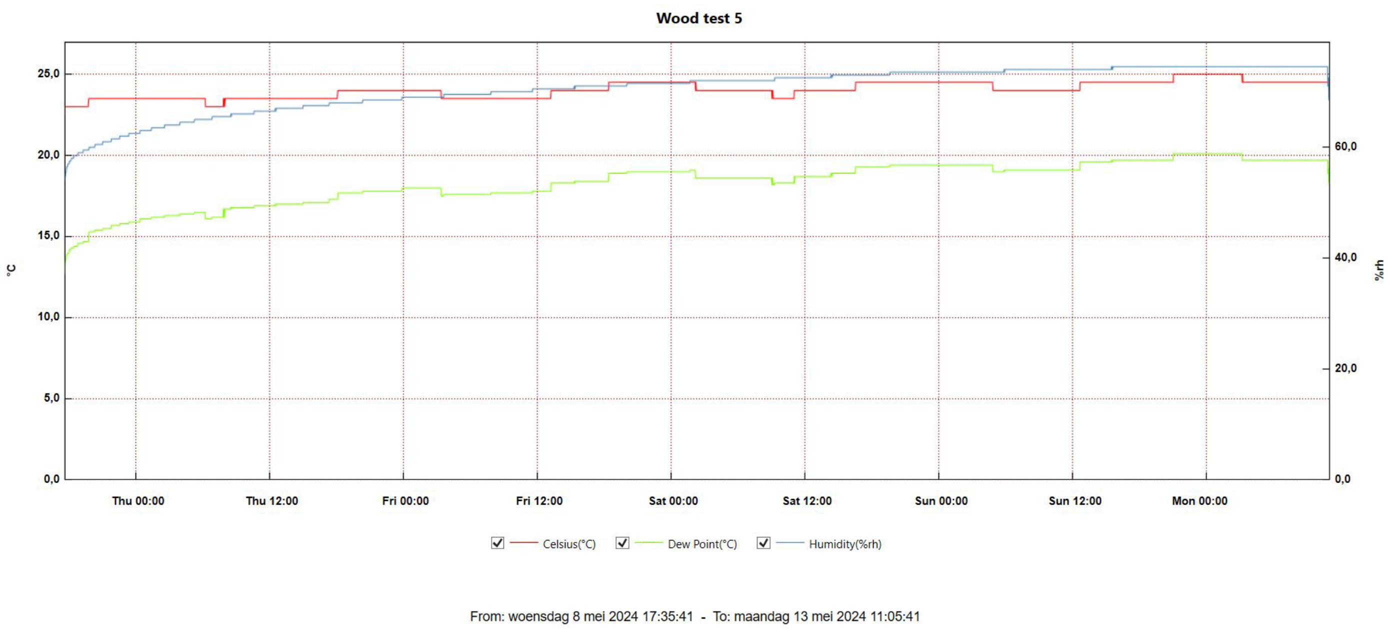
From: donderdag 25 april 2024 15:34:49 - To: maandag 29 april 2024 10:56:19

Testing data (Test 4)

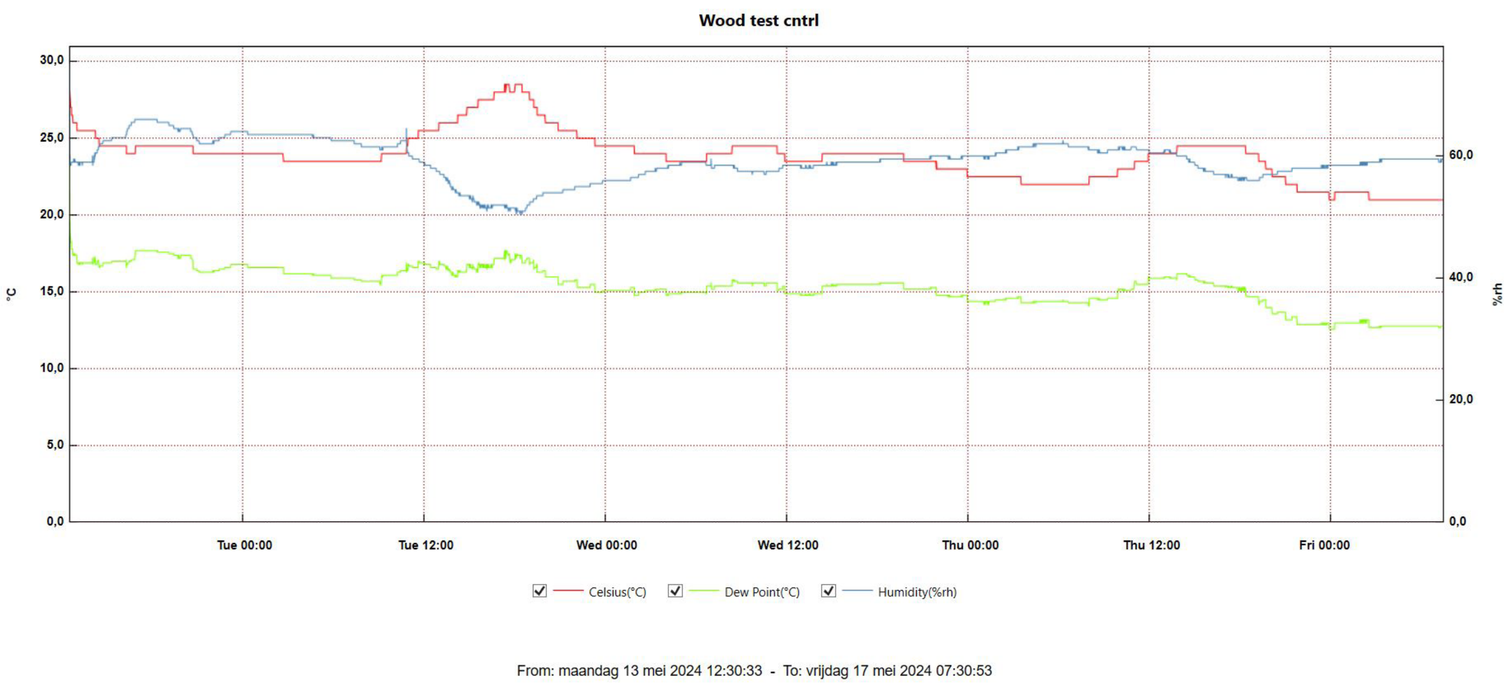


From: donderdag 2 mei 2024 11:56:56 - To: maandag 6 mei 2024 15:34:56

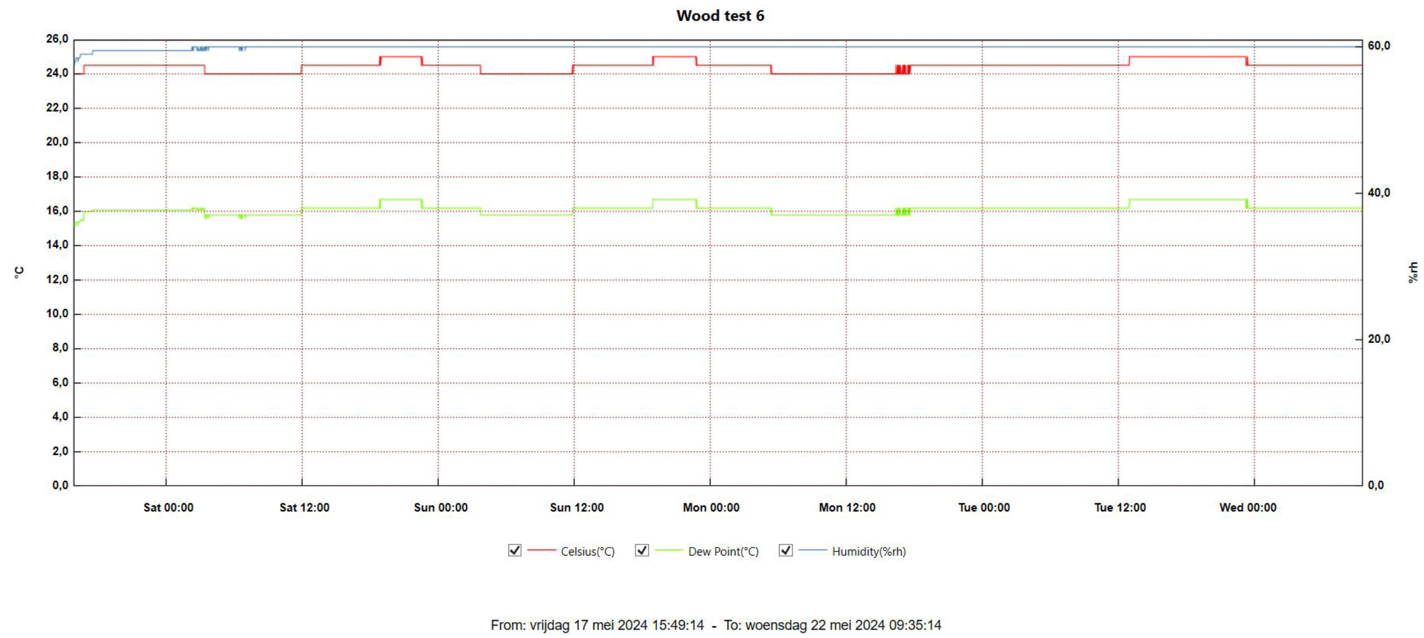
Testing data (Test 5)



Testing data (Control test)



Testing data (Test 6)



Testing data (Test 6_2)

Timoshenko python code

```
import numpy as np
import matplotlib.pyplot as plt
from scipy.integrate import simps

# Function to calculate total work, axial stress, and curvature
def calculate_total_properties(h1, h2, Q1_x, Q2_x, alpha1_x, alpha2_x, phi2, omega_range, length):
   I1 = h1**3 / 12
   I2 = h2**3 / 12

   Q2_11 = Q2_x * np.cos(phi2)**4 + Q2_x * np.sin(phi2)**4 + 2 * (Q2_x / 4) * np.sin(2 * phi2)**2
   K = (h1 + h2) / 2 + 2 * (Q1_x * I1 + Q2_11 * I2) / (h1 + h2) * ((1 / (Q1_x * h1)) + (1 / (Q2_11 * h2)))**(-1) * (alpha2_x - alpha1_x)

   # Integrate to find total work
   total_work_integral = 0.5 * K**2
   total_work_integral *= omega_range
   total_work_integral = simps(total_work_integral, omega_range)
   total_work = total_work_integral * length

   # Integrate to find axial stress
   sigma_integral = K * np.sqrt(2 * (Q1_x * I1 + Q2_11 * I2) / (h1 + h2))
   sigma_integral *= omega_range
   sigma_integral = simps(sigma_integral, omega_range)
   sigma_0 = 0  # Assume initial stress is zero
   sigma = sigma_integral * length



   return total_work, sigma

def calculate_stiffnesses(E1, E2, nu12, nu21, alpha_L, alpha_R, alpha_T):
   Q1_x = E1 / (1 - nu12 * nu21)
   Q2_x = (E1 - nu12 * nu21 * E2) / (1 - nu12 * nu21)
   return Q1_x, Q2_x


# Placeholder for moisture content array - replace it with your actual values
omega_range = np.linspace(8, 18, 100)


nu12 = 0.38  # Example value for Poisson’s ratio for aluminum
nu21 = nu12  # Assuming isotropy

alpha_L = 0.0001
alpha_R = 0.0019
alpha_T = 0.0040

# Your other parameters
h1 = 0.04
h2 = 0.02
E1 = 1.0
E2 = 0.9
alpha1_x = alpha_L
alpha2_x = alpha_R
phi2 = np.radians(30)
length = 3.6

Q1_x, Q2_x = calculate_stiffnesses(E1, E2, nu12, nu21, alpha_L, alpha_R, alpha_T)

# Initialize lists to store total work and axial stress values
total_work_list = []
sigma_list = []

# Calculate total work and axial stress
for i in range(len(omega_range) - 1):
   domega = np.diff(omega_range)[i]
   total_work, sigma = calculate_total_properties(h1, h2, Q1_x, Q2_x, alpha1_x, alpha2_x, phi2, omega_range[:i+2], length)
   total_work_list.append(total_work)
   sigma_list.append(sigma)

# Plotting the results
plt.figure(figsize=(10, 6))

# Plot axial stress
plt.subplot(2, 1, 2)
plt.plot(omega_range[:-1], sigma_list)
plt.title(‘Axial Stress vs Moisture Content’)
plt.xlabel(‘Moisture Content’)
plt.ylabel(‘Axial Stress’)

plt.tight_layout()
plt.show()
```



```
import matplotlib.pyplot as plt
from datetime import datetime

def read_data_from_file(filename):
   “””
   Reads data from a text file.

   Args:
   - filename: Name of the text file.

   Returns:
   - timestamps: List of timestamps.
   - celsius_values: List of Celsius temperatures.
   - humidity_values: List of humidity values.
   “””
   timestamps = []
   celsius_values = []
   humidity_values = []
   with open(filename, ‘r’) as file:
      next(file)  # Skip the header line
      for line in file:
         parts = line.strip().split(‘,’)
         timestamp = parts[1]  # Timestamp
         celsius = float(parts[2])  # Celsius value
         humidity = float(parts[3])  # Humidity value
         timestamps.append(timestamp)
         celsius_values.append(celsius)
         humidity_values.append(humidity)
   return timestamps, celsius_values, humidity_values

def plot_data(timestamps, celsius_values, humidity_values):
   “””
   Plots Celsius and Humidity values against time.

   Args:
   - timestamps: List of timestamps.
   - celsius_values: List of Celsius values.
   - humidity_values: List of humidity values.
   “””
   plt.figure(figsize=(10, 5))

   # Plot Celsius values
   plt.plot(timestamps[::10], celsius_values[::10], label=’Celsius(Â°C)’, color=’blue’)  # Plot every 10th timestamp

   # Plot Humidity values
   plt.plot(timestamps[::10], humidity_values[::10], label=’Humidity(%rh)’, color=’green’)  # Plot every 10th timestamp

   plt.xlabel(‘Time’)
   plt.ylabel(‘Values’)
   plt.title(‘Celsius and Humidity Over Time’)
   plt.legend()
   plt.grid(True)
   plt.xticks([])  # Remove x-axis ticks
   plt.tight_layout()
   plt.show()

# Example usage:
if __name__ == “__main__”:
   filename = r’C:\Users\Raymen\Documents\Master opleiding\Afstudeer\test1 easylog.txt’  # Change this to your text file’s full path
   timestamps, celsius_values, humidity_values = read_data_from_file(filename)
   plot_data(timestamps, celsius_values, humidity_values)
```

Timoshenko Grasshopper code