SLIM SKINS

BUILDING A NEW GLAZED FACADE SYSTEM

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A search for the most transparent unitized and sustainable facade system

Master of Science thesis

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ABSTRACT

Glass has been around for four thousand years and its demand to be used in facades has been increasing ever since. The appeal of a glazed facade is the transparency factor which can connect inside and outside environments without losing the protection a facade provides against the elements. Nowadays the glazed facades that have high transparency tend to be inefficient due to it being time-consuming to design, as it needs a lot of customization, and to produce and assemble on site. Other glazed options deal with the same issues, however, they do not provide the same amount of transparency. To address this gap in the market, this research will look into possibilities to achieve higher transparency in a unitized facade system.

The first thing to establish in this research is the requirements with which the facade panel must comply. These can be arranged into five categories, transparency, unitized system, maintenance, sustainability, and design for practice, which includes structure, movement, tolerances, safety, thermal, and water- and air-tightness. Next, a provisional detail was created by using two projects as inspiration for its structural concept as they were examples of a two-sided support system and of how to use composite action to achieve a slimmer profile. With this detail, a reliable structural finite element model could be built to facilitate further analyses. The last steps of this research focused on investigative design. This uses variations of the provisional detail design to get an understanding of what aspects influence each other and how each performance compares against the set requirements.

From these analyses, it was concluded that to achieve a highly transparent, unitized facade system the composite action between the glass panels and the mullion is crucial. Furthermore, having the mullion sandwiched between the glass not only provides a better composite action but is also the visually most pleasing option as it has little variety of materials shown on the surface. Even though the final design settled on, is considered the best option in this study, it nevertheless has some challenges. One of these challenges is the use of adhesives, as it can have a negative effect on the sustainability aspect regarding the end-of-life. Another complication can appear when looking at the proportions between the glass panels and the mullion. The mullion is quite small compared to the glass and thus making it an intricate process when assembling.

ACKNOWLEDGEMENTS
I would like to thank Mauro Overend, my main research supervisor, for always finding the time to help me with the project, even with such a full agenda. I would also like to thank Arie Bergsma for asking the sometimes difficult but surely crucial questions. These helped me look at the design from a new perfective allowing me to keep improving it even further.

Furthermore, I would like to express my gratitude to Octatube for the support and guidance on understanding the more practical aspects that come with designing a facade system. A special thanks go to Rebecca Hartwell for guiding me through the sustainability of a facade panel at its end-of-life, as this topic can easily be overwhelming due to the extensive aspects that can be considered.

Lastly, I want to thank my room-mates for all the food, drinks, snacks and care during the most stressful times, my boyfriend for the moral support and my friends and family for always listening to my stories, whether it was an exciting new thing I learned or a much-needed rant.

PREFACE
A facade is where many parts of the building come together. It needs to account for climate issues, structural elements, weatherproofing while also being aesthetically pleasing. And al these fundamental components need to come together harmoniously in a small facade detail. Finding this balance in an intricate detail has been my fascination since the beginning of my studies. This chosen topic, of exploring a unitized facade system, is thus the perfect match to continue the dive in the process of optimising such detail and finding the balance between all the elements.

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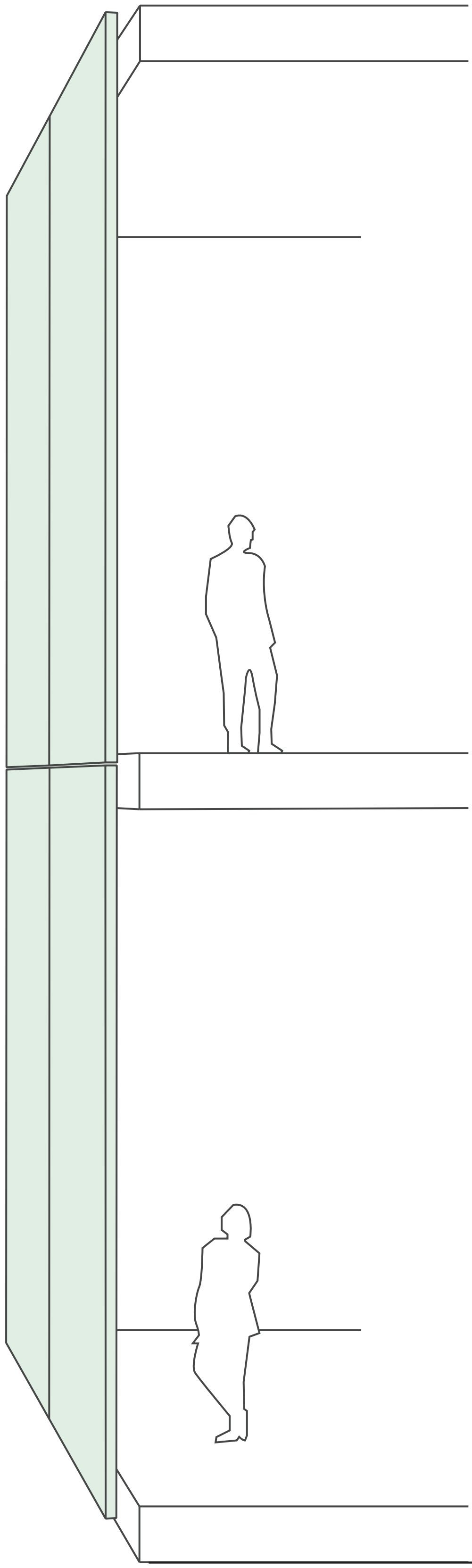


1. PROJECT CONTEXT

1. Maison La Roche lack, Paris
Small description

2. Nykredit Headquarters, Copenhagen
Building under study *Stender (2006)*

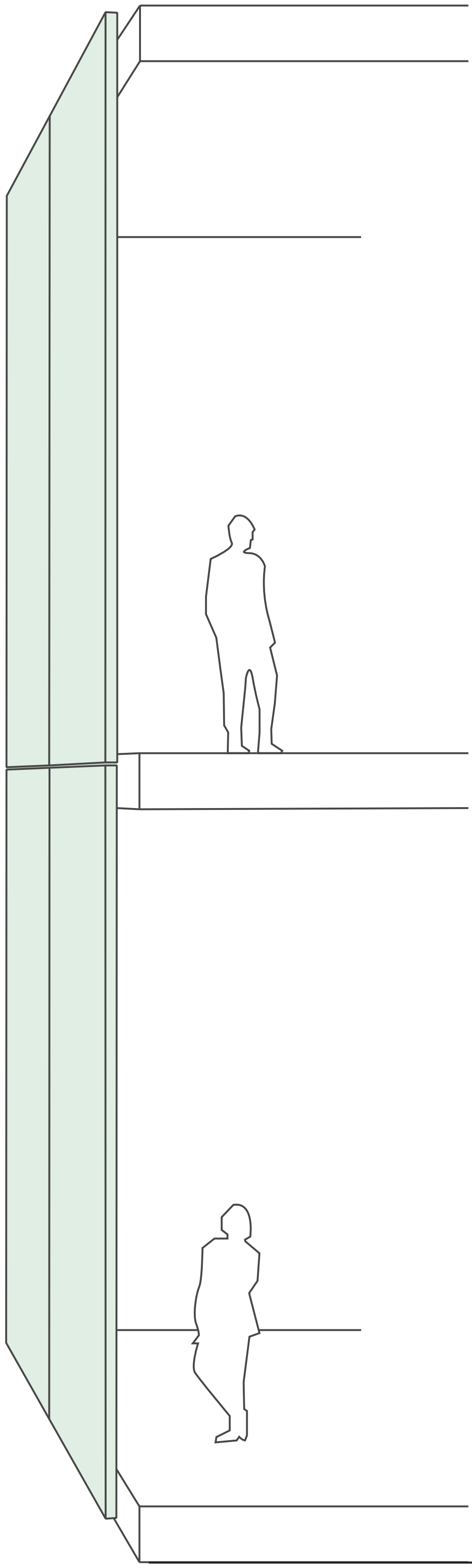
Glass is estimated to have been discovered around four thousand years ago. But it was not until the 1st century AD that it was used in architecture, like window glass *(Patterson, 2011)*. Throughout the years' glass had been used mainly for natural lighting whilst protecting from weather elements. This meant that the topic of the transparency of the windows had not yet been important *(Wigginton & Harris, 2002)*.

Improvements in glass production and application gave way for a shift from an artisanal process to mass production *(Eskilson, 2018)*. Due to these changes, glass windows became more popular and available around the 18th century. At the beginning of the industrial revolution, the density increase in cities was creating the need to build upwards. This set the perfect stage for new technological advancements of materials such as iron, steel, concrete and glass to be widely implemented *(Patterson, 2011)*.

With the rise of Modernism transparency turned into a symbol of modernity, not only on a technological level but also in terms of its artistic meaning *(Whiteley, 2003)*. During this time light played an important role in architecture, as Le Courbusier states "architecture is the [...] play of masses brought together in light" *(Corbusier, 1986)*. Furthermore, there was a great interest in creating a continuous space, connecting the interior with the exterior. These aspects made glass widely popular for architectural use *(Ascher-Barnstone, 2003)*.

A different reason for the use of glass facades came up in the anthropological study of *Stender (2006)*. It concluded that living in a very transparent building it provided a sense of community. Exposing the interior of the building would ease the sense of isolation. For office buildings in specific, the use of transparent facades would not only benefit the workers but also the portrayed image of the company. People would perceive these companies as open, accessible and without anything to hide *(Steiner & Veel, 2011)*.

This demand for glass seems to continue to increase evermore. The expected growth of the flat glass market is around 1.3% of its current value (in 2020) by 2026 *(Mordor Intelligence, 2020)*.



2. RESEARCH DEFINITION

2.1 PROBLEM STATEMENT

Throughout the years' improvements were made to the glass facades to achieve full transparency. Nowadays the most commonly used system is the curtain walls. However, due to its protruding frame, it does not meet the wishes, in terms of transparency, of many users.

On some occasions the desired level of transparency can be achieved through a frame-less system, using structural glass. Nonetheless, this is not an ideal solution as it is an inefficient use of materials and time consuming to design, produce and assemble. Which leads to a higher environmental impact.

As can be seen from the growth of the curtain wall market, there is a demand for a more unitized facade system *(Reports and Data, 2019)*. Together with the demand for a fully transparent facade, it can be said that there is a gap in the market for fully transparent unitized facade systems.

2.2 RESEARCH QUESTION

The main research question this paper will explore is:
How can a unitized facade system achieve an higher transparency?

2.3 SUB-QUESTIONS

To help answer the main research question the following sub-questions will be addressed:

- *What characteristics of a unitized facade system are desired to adopt?*
- *What defines an higher transparency?*
- *What are further design requirements a facade panel needs to meet to be a credible system?*
- *How can the design concepts be evaluated and optimised to achieve set goals?*
- *How can the designed facade element be evaluated in terms of sustainability?*

2.4 OBJECTIVE

The main objective of this research is to fill in the gap in the current market by designing a facade system with a high percentage of transparency which at the same time is efficient on various aspects through being a unitized system.

With this, there are also a few sub-objective that should be achieved.

- Develop an understanding of the existing glazed facades.
- Define the characteristics which will be adopted from existing unitized facade systems.
- Define what makes a facade more transparent than others.
- Determine the design requirements the facade element needs to meet to be a valid system to use in practice.
- Develop a method for assessing designs against the set requirements.
- Design and evaluate different system options through the set method.
- Establish an assessment method for the sustainability aspect and carry it out.

2.5 RELEVANCE

As we spend more and more time inside our buildings the demand for transparent facades continues to increase. While fully transparent facades are already in use, they are not a standard system utilised by many. This can be attributed to higher costs in custom designing and testing these facades. By designing a type of facade that is very transparent and at the same time a more unitized system it can be implemented more regularly. Reducing the exclusivity of a fully transparent facade.

Furthermore, this design would be an addition to the existing facade types architects and engineers can choose from. Besides that, it also offers a more resource-efficient way of creating as much transparency as possible.

2.6 METHODOLOGY

Firstly the research framework needs to be set. To do this a background study is conducted to get more insight into the history of glass facades and why glass is so popular. Afterwards, the problem statement is made together with the objectives and research question.

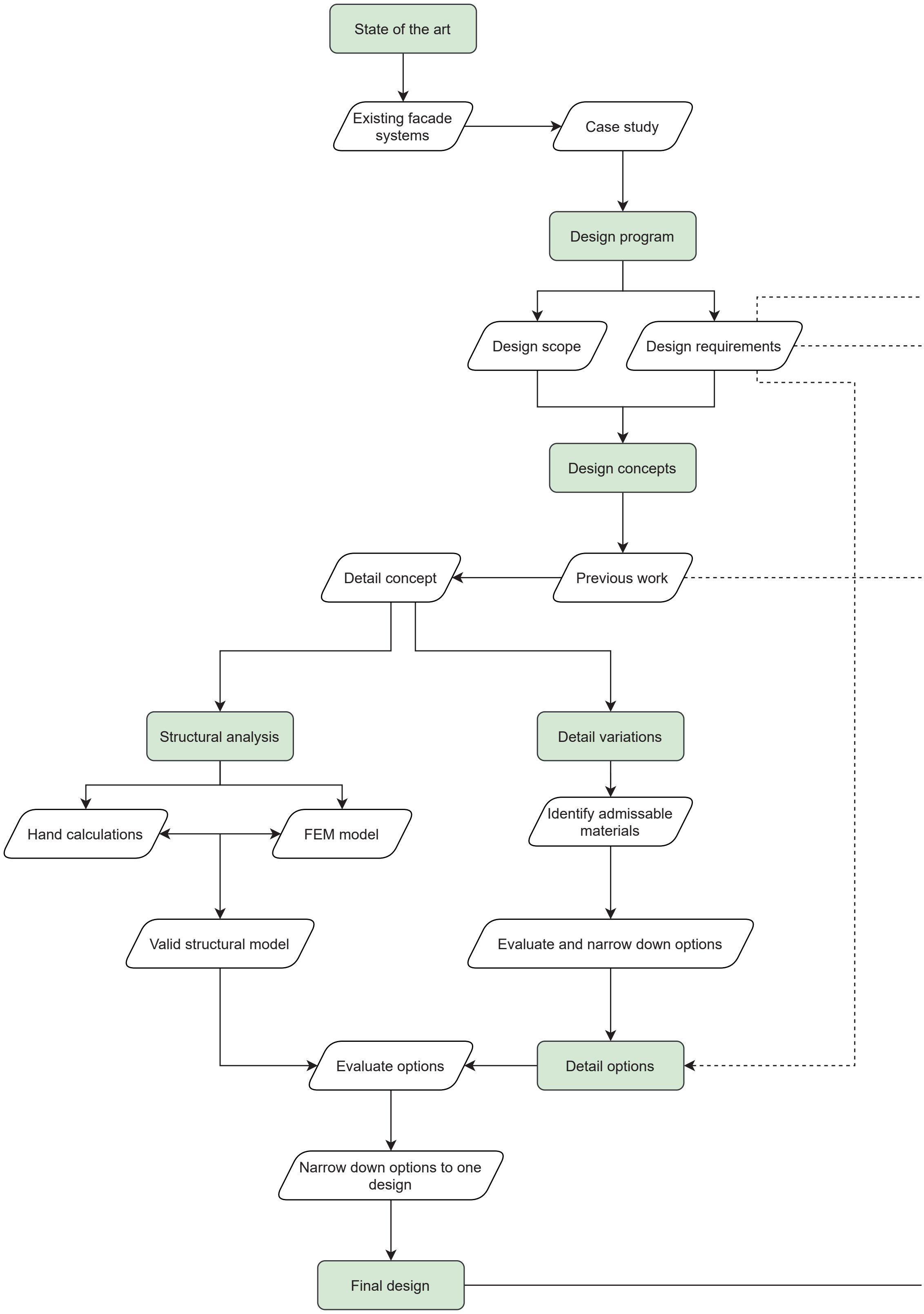
With a literature review into the state of art, an evaluation can be made on the existing transparency of facade systems through the use of case studies. This will move the design in a good direction. From here a design scope and requirements to which the design needs to satisfy will be proposed.

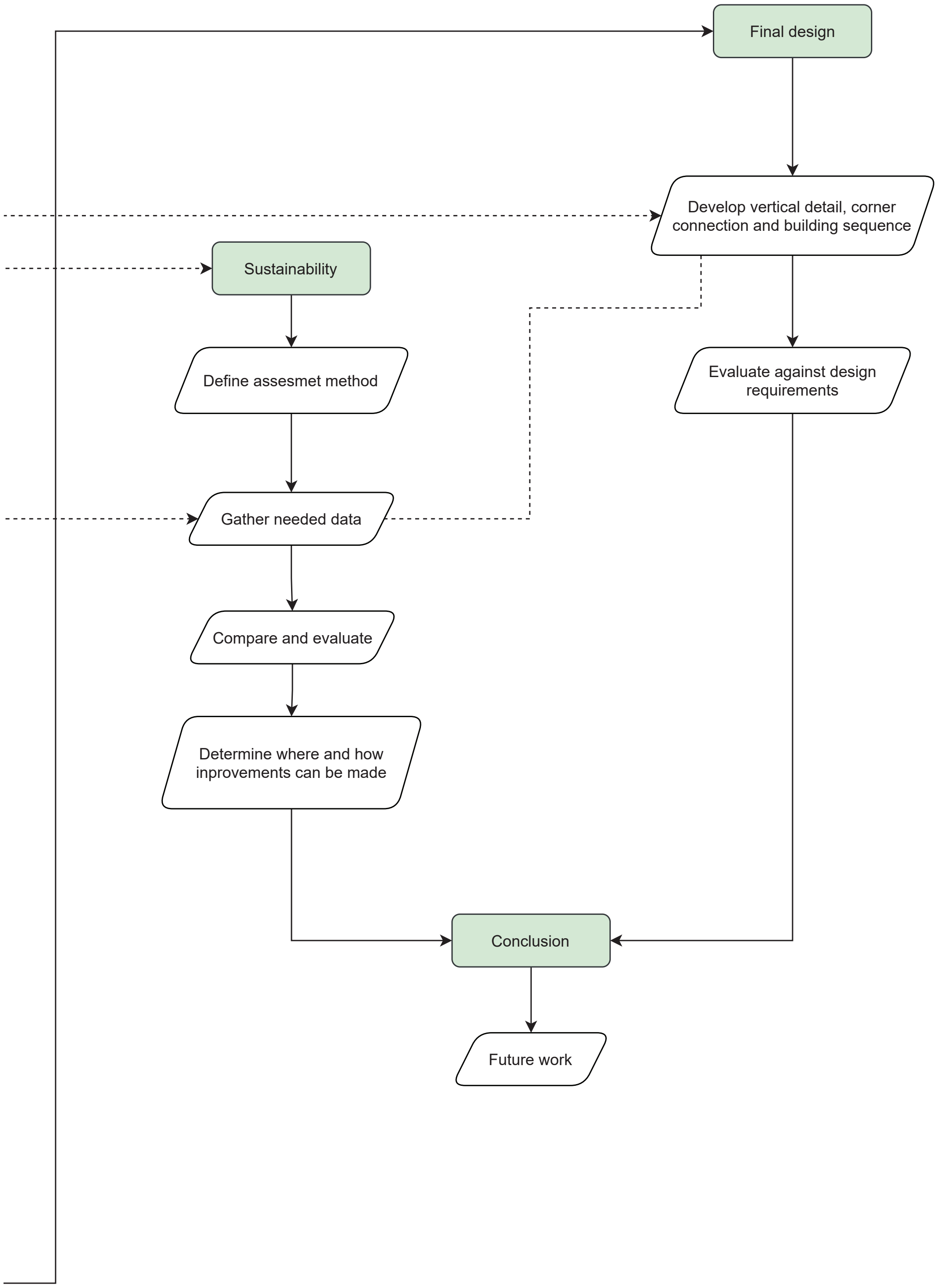
The first set up of design concepts will be done by looking at previous work. Afterwards, the structural analysis needs to be set up besides the design variations. With the structural analysis, it is the goal to set up a valid structural model that will be used later on for analysis. In the meantime a better understanding of the admissible materials is formed and the choices for a profile are narrowed down.

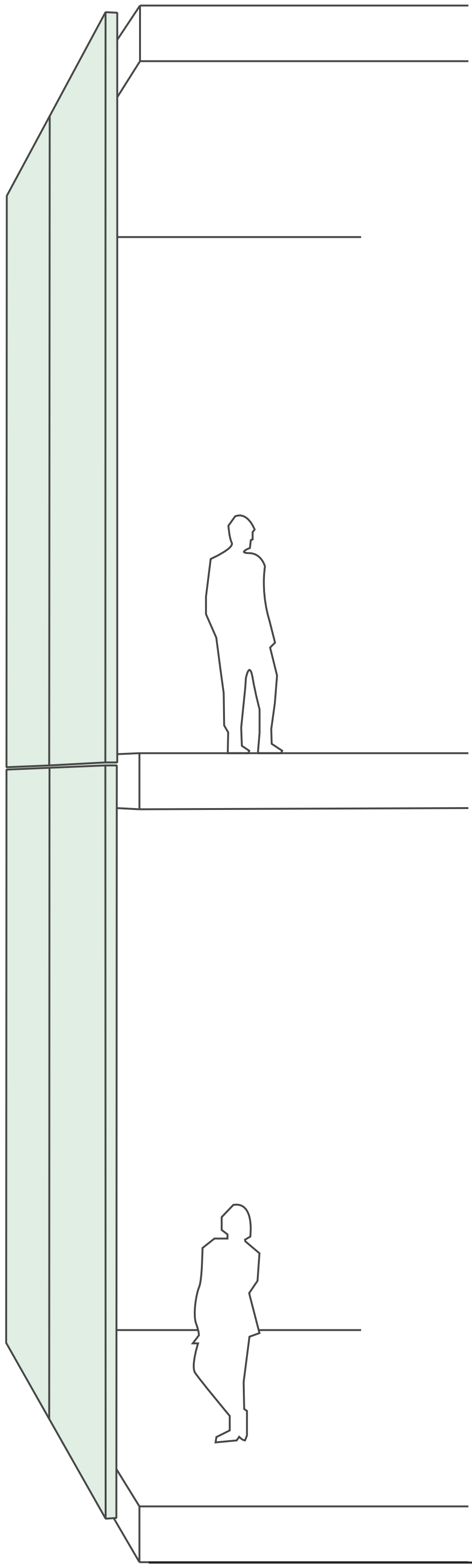
In the design options phase, the different design variations are now further developed into specified details. With the help of the structural model and the set requirements, these options are evaluated and the best one is chosen.

Following these steps, the horizontal profile that was chosen will be developed further into a vertical profile, corner detail and building sequence. Meanwhile, the sustainability aspect is started. Here the assessment method will be defined and the gathering of required data can be started. When the assessment is done the improvement needed will be determined.

Lastly, together with the final evaluation of the final design against the set requirements, the conclusion and recommendations for future work can be determined. The overview of this approach can be seen in figures 3 and 4.


State of the art
Existing facade systems
Case study
Design program
Design scope
Design requirements
Design concepts
Detail concept
Previous work
Structural analysis
Detail variations
Hand calculations
FEM model
Identify admissable materials
Valid structural model
Evaluate and narrow down options
Evaluate options
Detail options
Narrow down options to one design
Final design


Final design
Develop vertical detail, corner connection and building sequence
Sustainability
Define assesmet method
Evaluate against design requirements
Gather needed data
Compare and evaluate
Determine where and how inprovements can be made
Conclusion
Future work



3. STATE OF THE ART

3.1 EXISTING TYPES OF FACADES

After having made clear which specifications the final design should meet, a better assessment of the existing systems is needed. The systems looked at will be the curtain wall, the closed cavity, and the structural glazing. First, a quick review of the system is made to which afterwards is assessed through a case study.

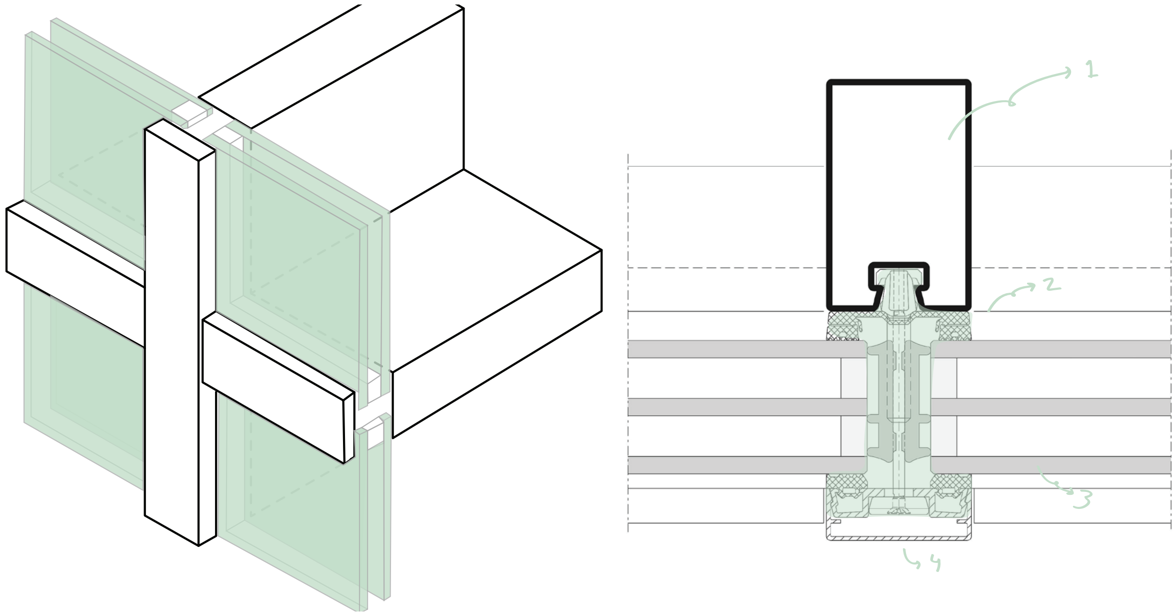
3.2 CURTAIN WALL

With the development of new construction materials, the load -bearing structure moved from the outside of the building to the inside. Since the facade did not need to bear the floor load anymore, this gave more room to new facade compositions. As *Mills Friba (1957)* described, a curtain wall is in its essence a none load bearing wall. Later on it was added that on top of that, a curtain wall system can also be characterised as a framework where different materials, functions and shapes can be implemented *(Murray, 2009)*.

As mentioned above within the curtain wall system many options can be explored. All these options can be mainly categorised in a stick or unitized system. The difference between these two systems lay in their fabrication and installation method. For the stick system curtain wall, the assembly is done on-site, piece by piece. Whilst a unitized system is assembled at the factory and then brought to the building site for installation *(Murray, 2009)*.

This paper will only further examine the unitized system as research has shown that this is in high demand *(Reports and Data, 2019)*. This type of system is often chosen because it can assure very high-quality control since it is pre-fabricated in the factory under controlled conditions. Furthermore, the pre-fabrication allows for an easy assembly on-site with a reduced labour force. A downside of this system is its high shipping costs *(Murray, 2009)*.

As can be seen in figure 5, a unitized curtain wall system consisting of four main elements: the structural mullion on the inside (1), the fixation system (2), the insulated glazing (3) and the finishing on the outside (3).



5. Unitized Curtain Wall

3D & Horizontal detail

3.3 CLOSED CAVITY

The closed cavity system could also fit the descriptions *Mills Friba (1957)* and *Murray (2009)* gave on the curtain wall system as it is also a none load-bearing framework with infill materials. However, the closed cavity system has an additional layer on the outside to improve thermal isolation and low energy consumption. This was nothing new as it had already been done previously with the double-skin facades. But due to high maintenance costs a new system emerged, the closed cavity facade *(Balog, 2019)*.

Between the double-skin facade and the closed cavity system, the main difference is the double-skin facade uses natural ventilation in its cavity whilst the closed cavity facade regulates its airflow very strictly *(Balog, 2019)*.

For this paper, only the closed cavity facade system is considered. The reasoning behind it was the improvement on the double-skinned facade, therefore making it more interesting to look at the most recent implemented system. As already has been pointed out, this type of system creates the opportunity to increase thermal isolation whilst lowering the energy demand. Yet it comes with a few challenges regarding the replacement of the sun shading elements within the cavity *(Balog, 2019)*.

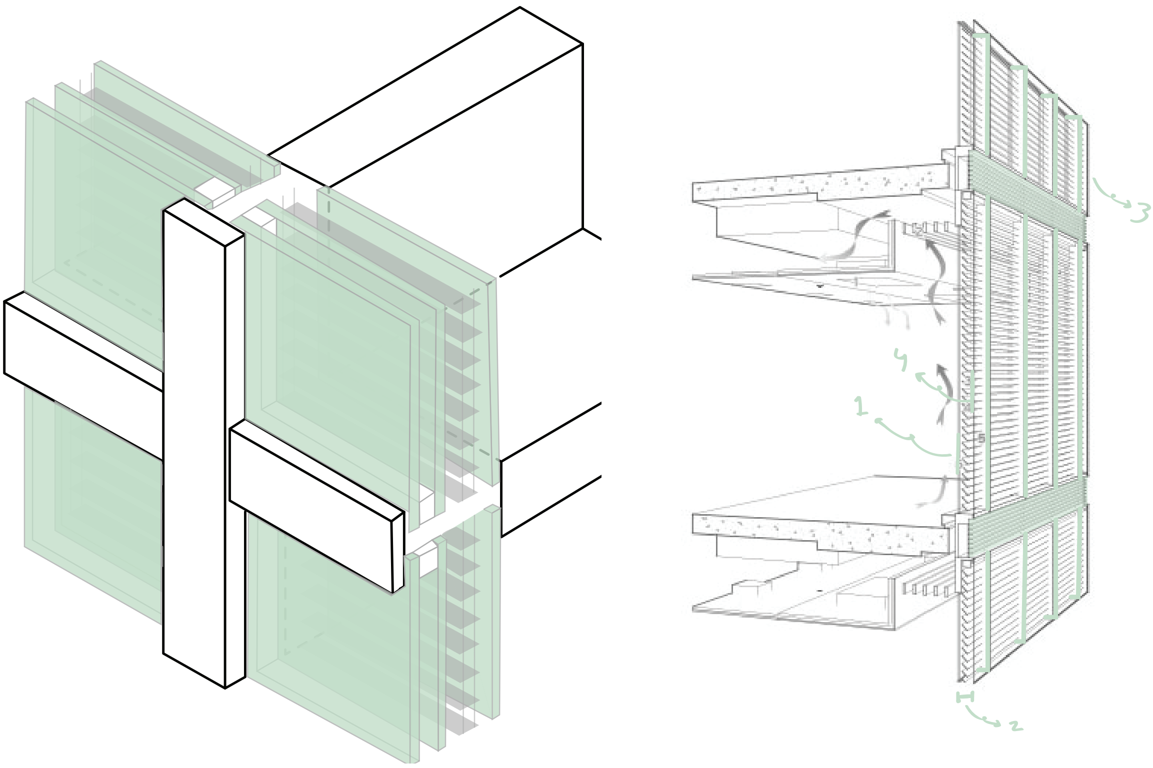
This system is composed of four parts, see figure 6. From the inside out, the first one is the insulated glazing (1), after that there is the cavity (2) with sun shading and the structural mullions inside (3) and lastly, to close the cavity, another layer of glass is used (4).

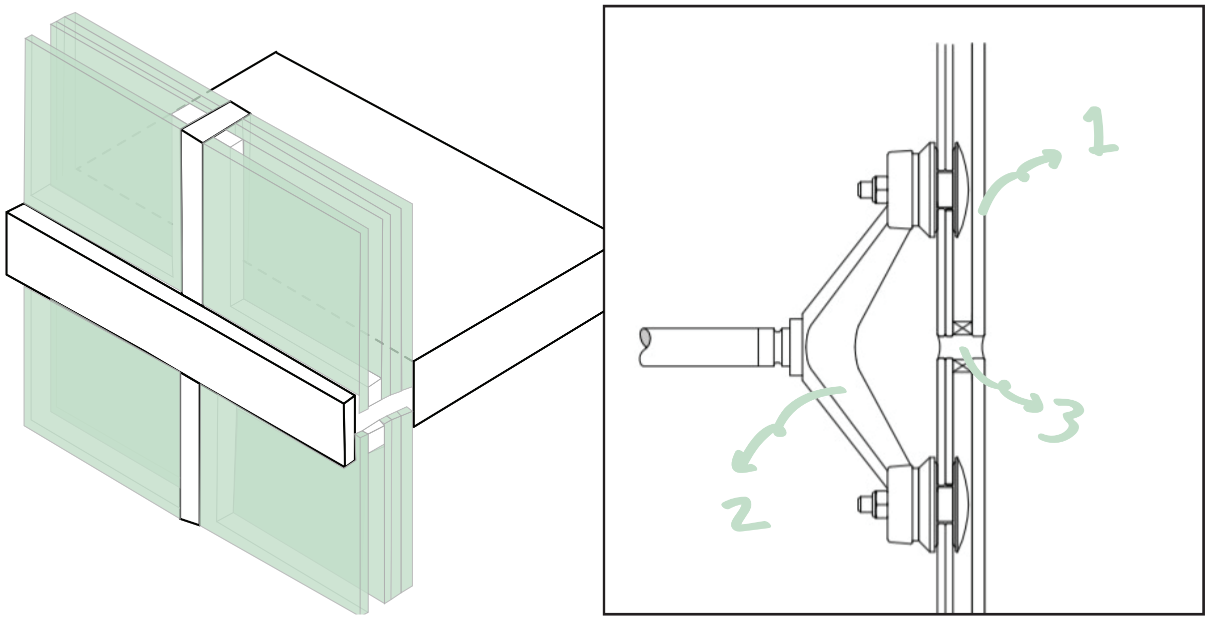
3.4 STRUCTURAL GLAZING

As mentioned before there has been a continuous demand for transparent facades. This system was designed to address that and so it differs quite a bit from the previous systems. The structural glazing does not have a framework to take the loads on the facade but instead, the glass takes over this task. Some facade designs require a stabilising support structure. For this, there are two different options, glass fins and point fixtures *(Afghani Khoraskani, 2015)*.

6. Closed Cavity

3D & Vertical section





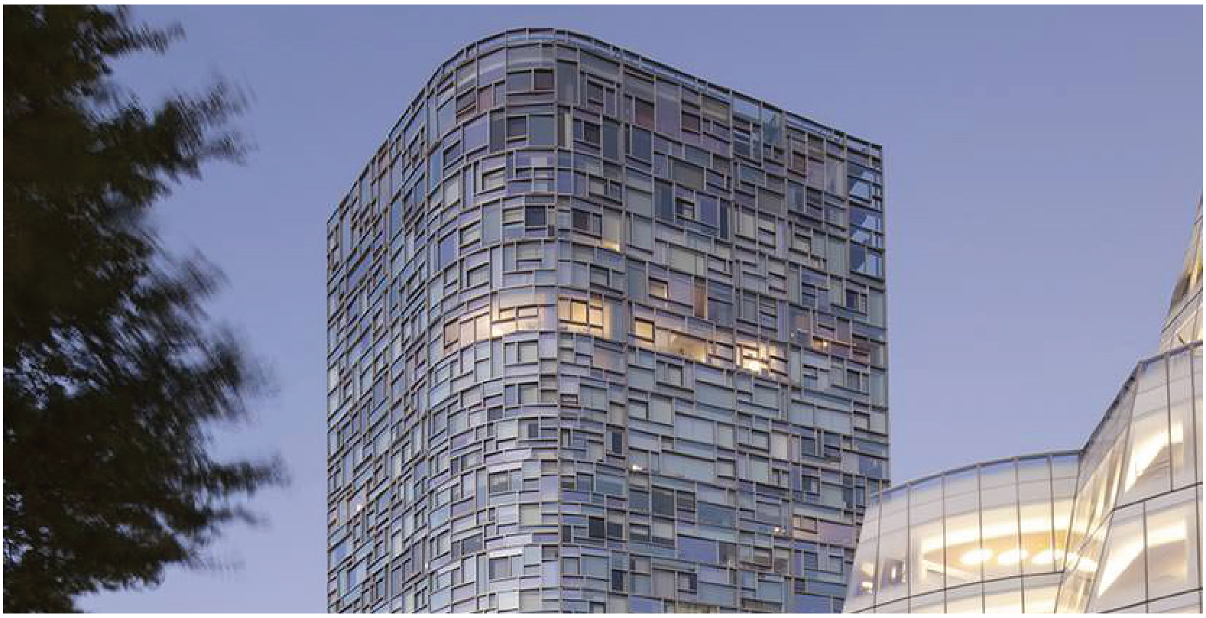
7. Structural Glazing
3D & Horizontal detail

An example of a structural glazing system with a four-point fixture can be seen in figure 7. Here the structural glass (1) takes the majority of the load which is subsequently transferred through the point fixture (2) into the main structure. In between the individual glass panels, the weatherproofing is realised with a sealant (3).

3.5 CASE STUDY

From the research question and sub-questions it can be concluded that four general aspects are fundamental during the design process. These are aesthetics - high transparency of the facade; building sequence - a unitized system which can be built in the factory and installed quickly on-site; sustainability; and well-rounded design - as it should be valid to be used in practice.

In order to get a better understanding of how these systems compare to the four main aspects a case study was done using different examples of each system. Note that the criteria of a well-rounded design were not evaluated as all case studies have



8. 100 Eleventh Avenue
NY, USA

been realised, thus confirming this has been achieved.

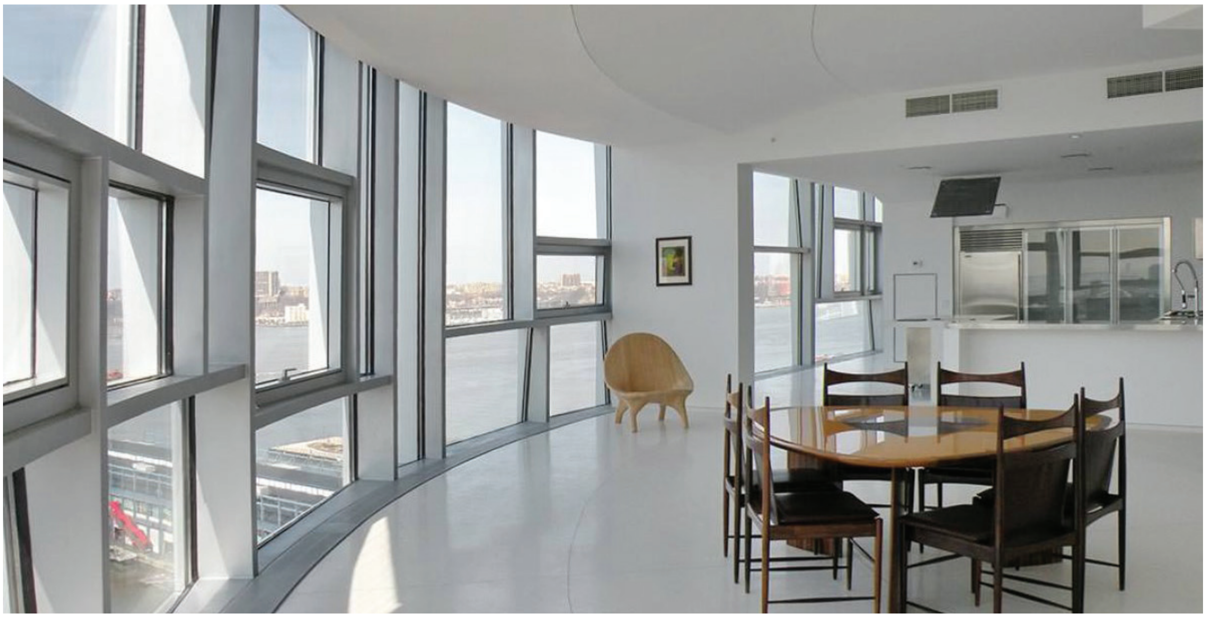
Curtain Wall: 100 Eleventh Avenue
This case study is a residential building situated in New York, United States of America. The project was completed in 2009.

Aesthetics: In terms of transparency the curtain wall achieves great views, however when standing at an angle from the facade the oversized framework obstructs the view. This difference can be seen in figures 9 and 10.

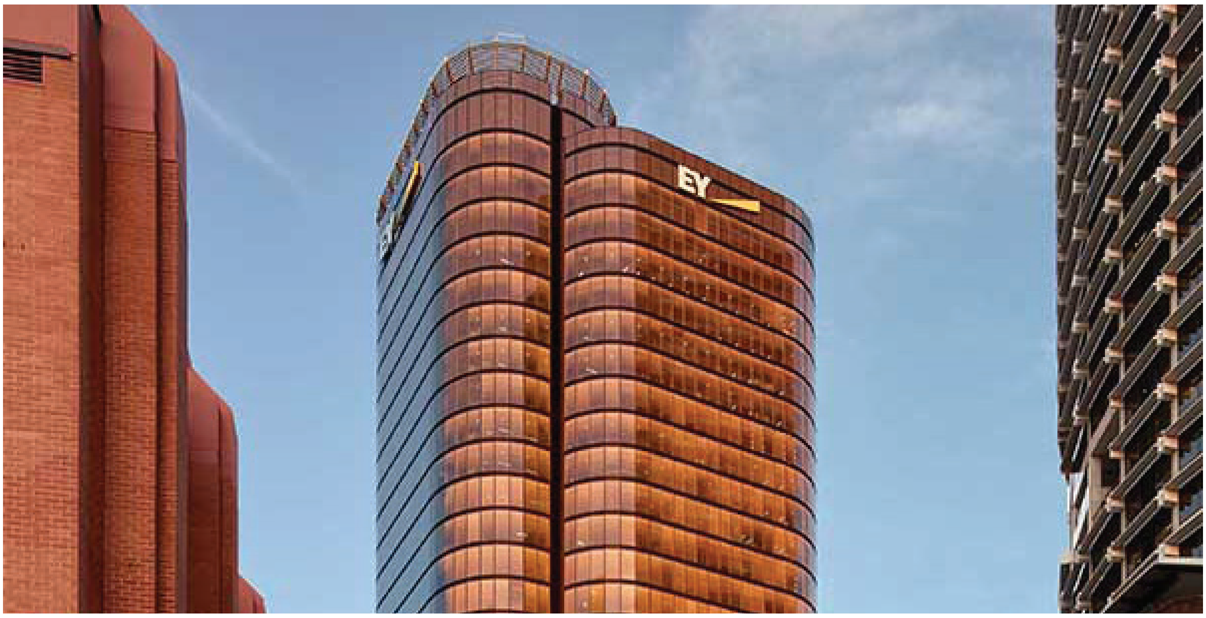
Building sequences: The assembly of the facade made use of a unitized system. Two types of units are used to create a dynamic composition. For assembly this works well, yet for its disassembly at end-of-life it can be a challenge considering one panel holds many glass panes.

Sustainability: When it comes to material efficiency it seems quite efficient because it uses strong material for the structure. However, in terms of energy efficiency, it only uses double glazing. When it comes to embodied carbon it will be quite

9. View inside
View standing
directly in front of
the facade



10. View inside
View standing at
an angle from the
facade



11. EY
Sydney, Australia

high as it uses quite a lot of steel.

Closed Cavity: EY Centre
For this case study, a better look has been taken into the EY Centre in Sydney, Australia. It is an office building completed in 2016.

Aesthetics: When it comes to transparency the same problems arise as with the curtain wall case study. Because of its large framework, the view can be impeded. Furthermore, the blinds also act as an obstruction to the view in the same way the framework does.

Building sequences: Considering the facade uses unitized systems with a reasonable size it can easily be assembled and presumably disassemble for end-of-life purposes.

Sustainability: Material efficiency is quite good since it has better energy efficiency even though it uses a lot. For the embodied carbon of the facade, it is assumed that the main structural elements are made of steel which is quite high in embodied

12. View inside
View standing in
front of the facade

13. View inside
View standing at
an angle from the
facade

14. Triodos Bank
The Netherlands

carbon. When also accounting for the extra use of material this scores rather low.

Structural Glazing: Triodos Bank
In this case study, an office building was analysed. This project is situated in Driebergen-Rijsenburg in The Netherlands.

Aesthetics: This type of facade achieves a high level of transparency. Even when looking at it from an angle its 'framework' does not stand in the way of the view.

Building sequences: This is a none unitized system, meaning that its assembly would have taken a bit longer as more needs to be done on-site in unhandy positions. The same problem arises when looking into the end-of-life disassembly. Because there are some strong adhesives in play it can be an issue to do this.

Sustainability: As mentioned before the glass carries the load in this case, to do so it needs to be increased in size and thus not very material-efficient. Although insulated glazing is used there is still a lot of glazing which is not ideal for energy efficiency.

15. View inside
View standing at an angle from the facade

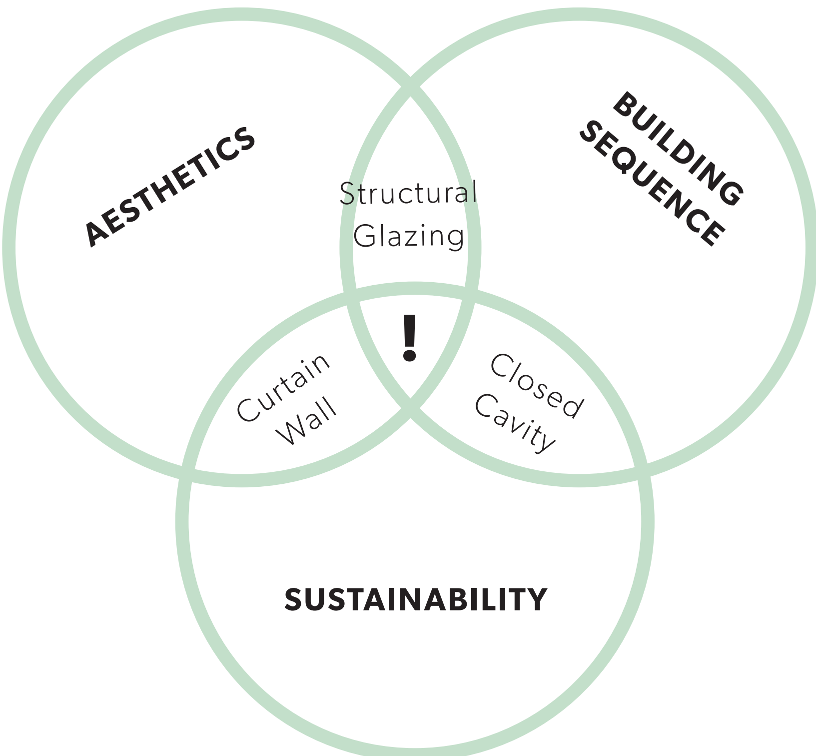
		Aesthetics	Building sequence		Sustainability		
		Transparency	Assembly	Disassembly	Material efficiency	Energy efficiency	Embodied Energy
Curtain Wall	100 Eleventh Avenue	Fair	Good	Fair	Good	Fair	Fair
Closed Cavity	EY Centre	Poor	Good	Good	Fair	Good	Poor
Structural Glazing	Triodos Bank	Good	Fair	Poor	Poor	Poor	Fair

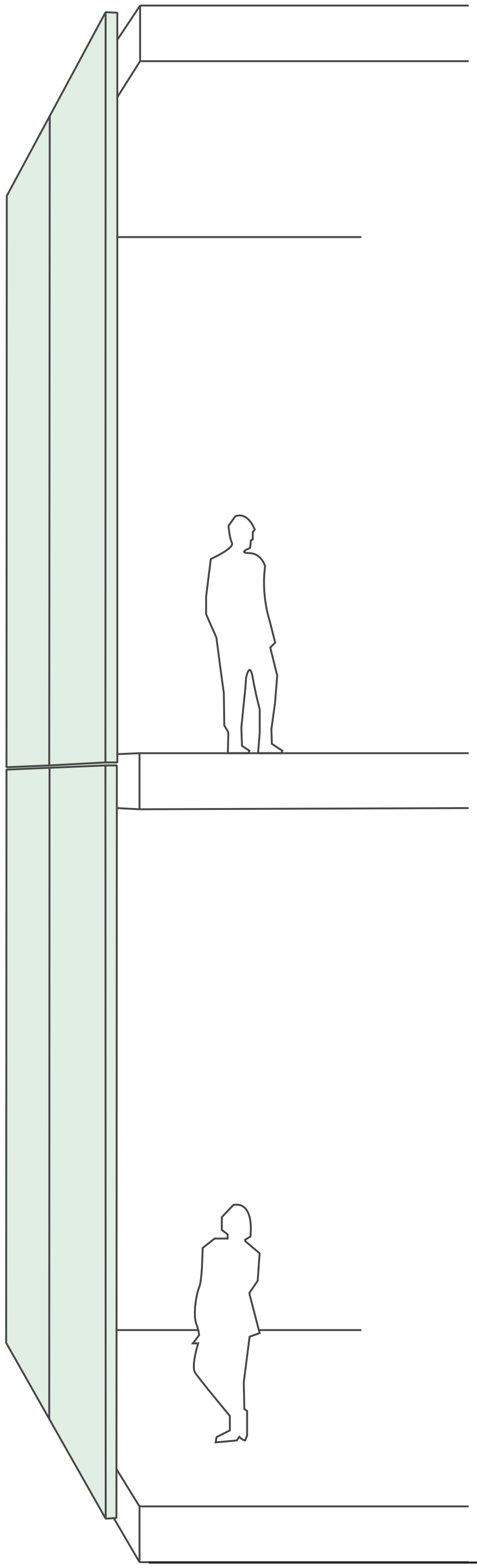
16. Performance assessment
Of the case studies

In terms of embodied carbon, it has less steel than the other systems but it makes up for it in terms of glass usage.

A summary of the results can be found in figure 16. There the case studies have been rated good, fair or poor, based on the findings mentioned before. From this, a better understanding was achieved of the current situation and where the proposed design needs to fit, see figure below.

17. The missing gap
Compared to state of the art





4. DESIGN PROGRAM

4.1 ASSESSMENT METHOD

In the process of designing the desired panel, there will be a need to assess the resulting options to be able to make the right choices for the set goals. These goals which have been identified in chapter 2.4 are still formulated in broad terms and cannot be assessed quantitatively. In order to do this, a literature research was done on the minimum requirements in the building code. With these in mind, the set goals will be translated into the design requirements specified for this project. Thereafter it will also be determined how these will be evaluated during the design development.

4.2 DESIGN SCOPE

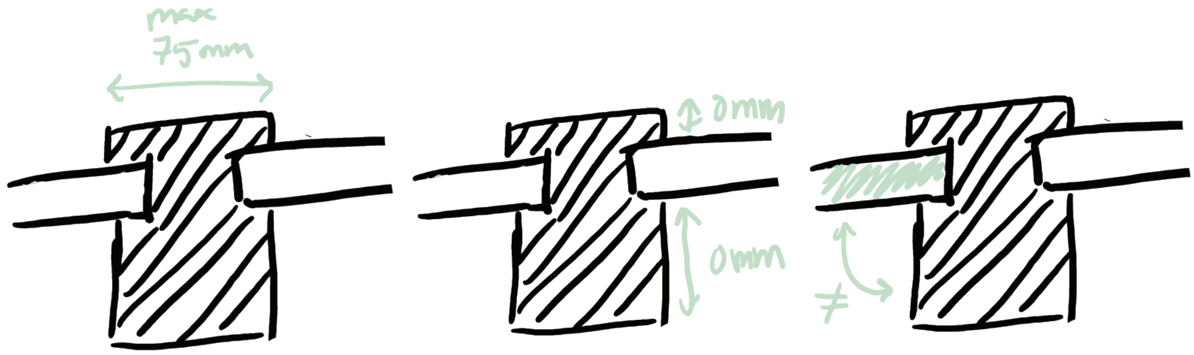
To narrow down the scope of the research a few boundary conditions were applied. This research will focus on facade panels that span from floor to floor with a size of 4x2 meters. It will be a system that does not allow for moving parts, this in order to not add extra to the project.

The typology of the building on which the panel is situated will not be applicable for residential use as there is a lack of a demand for such a width of interrupted glassed facades within a living space. The reason behind this is the amount of room separation walls that are needed in a residence. As those will intersect with the facade at various points, interrupting the seamless glass facade that is being accomplished here.

Furthermore, it was chosen to design a facade element that can be used in a 10 stories high building situated in the Netherlands. This country was chosen to facilitate searching the building code and other site information to which familiarity has been obtained from previous projects.

4.3 DESIGN REQUIREMENTS

As mentioned before the design requirements will be based on the minimum required by the building code and by *VMRG (2021)* whilst considering what is important to achieve the set goals. A few of these aspects are objectives that are being researched and optimized in this paper whilst others are requirements that the



18. Transparency objectives

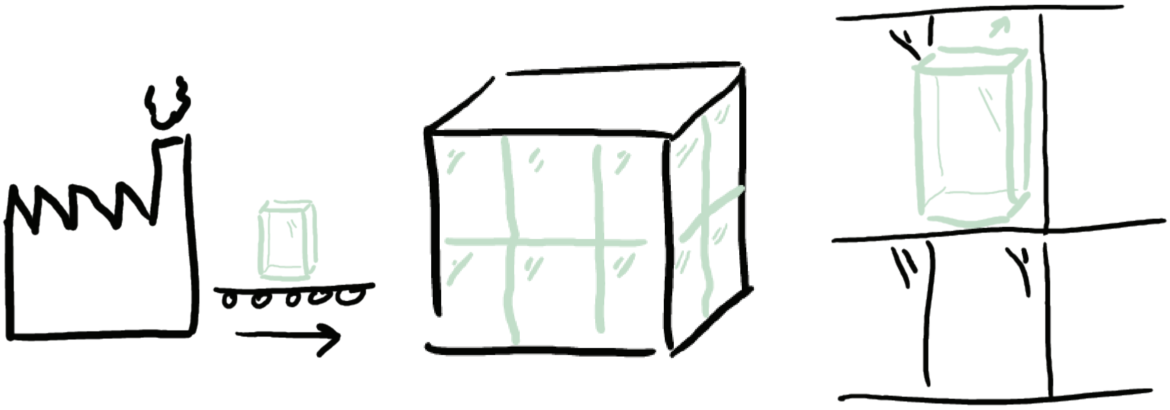
Width, depth, and materialization

facade panel needs to have in order to be a valid design to use in practice. This will be indicated in the following explanations.

Transparency (objective)

One of the main goals is to achieve a facade element with a high transparency value from both the inside and outside. This transparency is translated into three aspects.

First is the amount of visibility through the element when standing right in front of it. The panel should have more percentage of its total area being a see-through element than a standardized curtain wall system. The curtain wall system looked at in the case study had a lot of mullions as part of the design. This makes it unrealistic to use for comparison and, is why a more standard system from Reynaers was used. The chosen system is their Element Facade 7-SG as it provides a "continuous glazed facade appearance" *Reynaers (n.d.)*, which is similar to what is trying to be achieved here. In this system the visible width of the interior is 75mm thus the new design should not surpass this *(Reynaers, 2021)*.



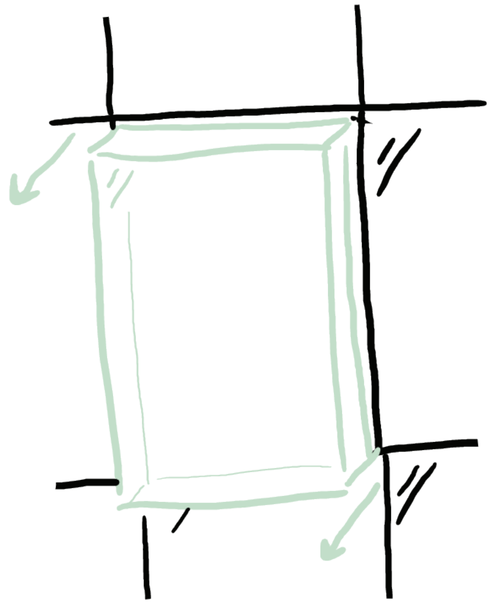
19. Unitized system objectives
Factory assembly, repetition, and individual attachment

The second aspect that affects the transparency of the panel is an irregular depth on the surface. As has been concluded from the case studies protruding elements out of the facade can obstruct the view when standing at an angle. To avoid this the element should have a continuous depth. This means that all elements should be flush to the inside and outside glass panes.

Full transparency has been achieved when at first it is not noticeable the window element is there at all. An aspect that can disturb this goal is the different types of materials used and showing next to the glass. Thus it should be avoided having different materials shown through the glass so that their reflection, texture and colour stay unnoticeable.

Unitized system (objective)
Another main goal is to have the facade element be a unitized system. This means it has to satisfy different aspects.

The first aspect is that the panel needs to be assembled entirely in the factory so that it can be transported as one element.



20. Maintenance objective
Individual removal

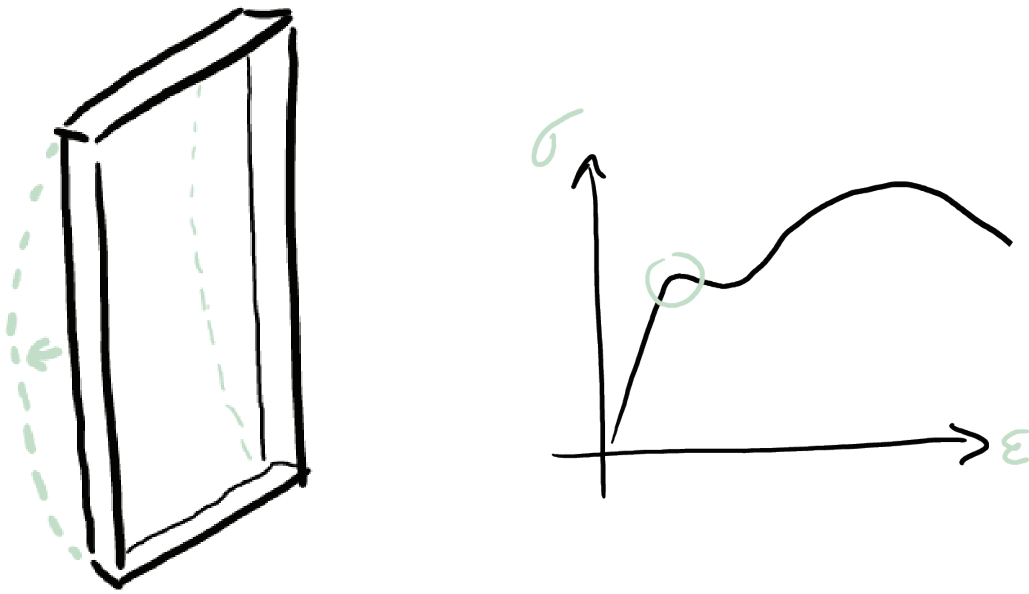
Another aspect it must meet, is the ability for repetition of the element. This means that the facade needs to be built op trough repeating this facade panel along the height and width of the building.

Lastly the facade element also needs to be able to be attached individually to the building. Thus not needing its size panels for structural support.

Maintenance (objective)
The third goal with this facade element is allowing for the possibility to easily replace an element for repair. Hence it is required to be able to remove a single facade unit without moving the adjacent panels.

Structural (requirement)
In order to design a panel that is valid for use, it should be certain that it is structurally stable. For these requirements it will be looked at through two aspects the panel needs to meet.

Due to the wind load on the building, the facade panels will



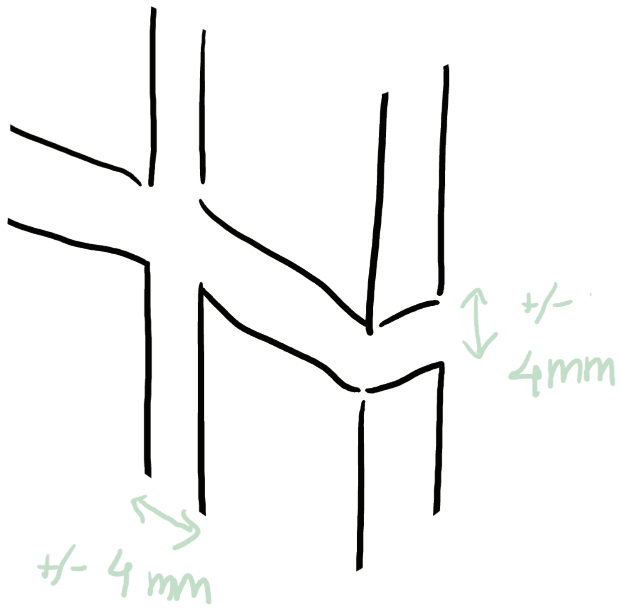
21. Structural requirements

Deformation and stress

deflect. This deflection will be measured and assessed at two points on the panel. For the edge of the panel, the deflection cannot be higher than the length of the mullion divided by 200 as it is said by *Het Nederlands Normalisatie-instituut (2014).* Considering a length of 4 meters this maximum allowable deflection is 20 mm. For the deflection at the centre of the glass it is required to be a maximum of the diagonal divide by 65, thus 68.8 mm.

The second aspect that the panel needs to meet to achieve a structurally sound design, is the stresses caused by the wind and its own weight. All of the materials chosen for the element need to be able to take the imposed stresses on it. This will be assessed by comparing the maximum strength of the material and the occurring stresses.

Movement (requirement)
When the building is finished its structure will be subjected to different temporary loads which will make the structure skew. This inevitably will also make the individual panel move. There are two ways the building moves.



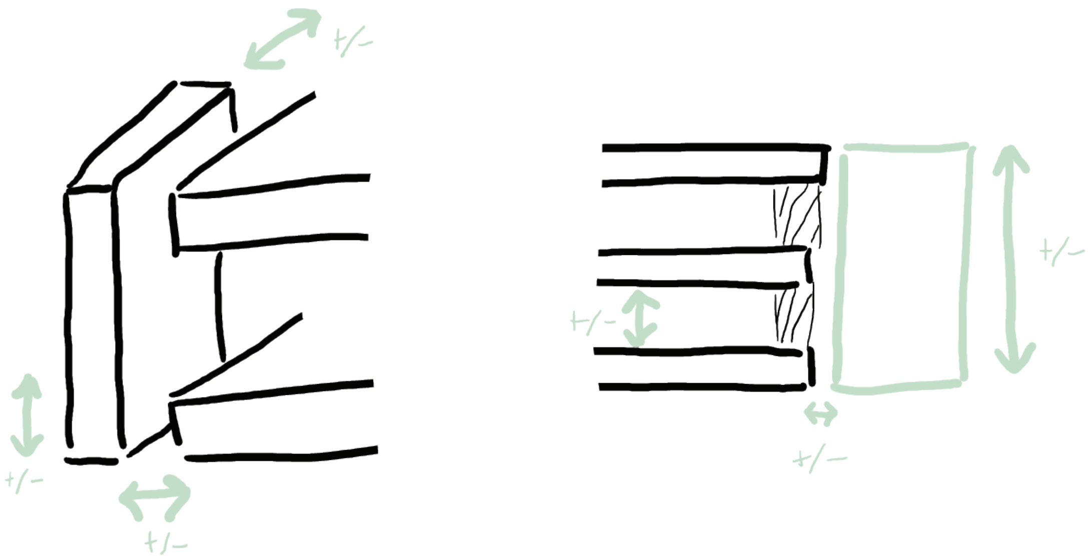
22. Movement requirement
Horizontal & Vertical joints

One of the movements is due to the live load on the floor creating a movement downward. This means that the vertical joint between the panels will be smaller at the top and bigger at the bottom. Furthermore, it will also change the horizontal joint as it gets bigger at the top and smaller at the bottom.

The second way the building moves is by swaying due to wind loads. This sway causes the panels to displace horizontally between levels. This means that the horizontal joint also needs to allow for this displacement.

In order to take both these movements into account, the vertical and the horizontal joint should be able to move at least +/- 4mm in each direction according to *VMRG (2021).*

Tolerances (requirement)
When attaching the panel to the main structure, there is a need to adjust the location of the panel on-site. This is because two different types of tolerances are need to be accounted for in the facade.



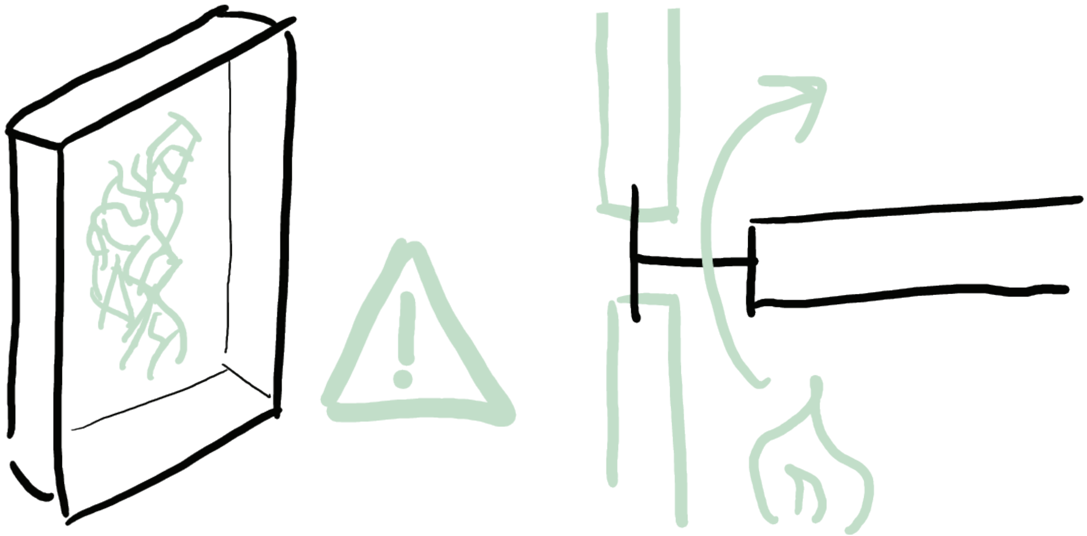
23. Tolerances requirements

External & internal

The first one is the building tolerances. Whilst the floor of the building is being laid it can vary slightly in height and span. This means that it is not aligned with the other levels and thus the panel will not be flushed with the ones below or above. In order to account for these tolerances, the connection point to the building structure should be able to move up and down and back and forth.

The second tolerance to take into account is related to fabrication. When a panel is manufactured it will be slightly different in size compared to the design, this can be +/- 2mm *(VMRG, 2021)*. Consequently, when on the building site, the panels will not match perfectly during installing. This means the designed connection should allow moving the panel into the correct place either by moving up and down or side to side.

Additional to these tolerances, which need to be accounted for in the connection with building, the manufacturing tolerances also are of importance. As mentioned before the panels can vary in total size. This is due to the tolerances imposed on



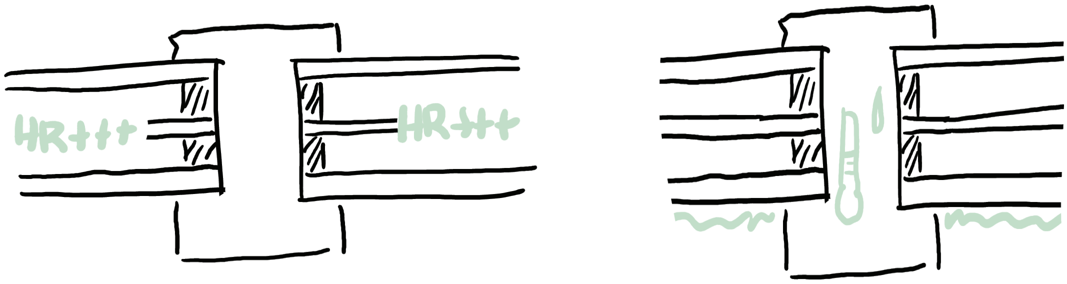
24. Safety requirements
Breakage and fire

manufacturing of each element and assembling it. Thus when creating the design it should be regarded that all the elements can vary in size which needs to be accounted for in the methods of connecting these elements.

Safety (requirement)
As in all elements of the building, safety plays a role. For the facade, two aspects can be identified that should be considered while designing.

The first would be regarding the risk of breakage of the glass element. Next to the above mentioned normal forces, it also needs to be able to manage exceptional loads. This means a soft load, someone bumping into the glass as a hard load, like a tool smashing the glass. To avoid complete failure of the panel the glass should stay in place even if there is a crack in it.

A second aspect regarding safety is the spread of fire. At the edge where a panel meets the facade could be a possible way for the fire to spread to the next floor. Thus it is required to block this with a barrier that will not allow fire to pass through.

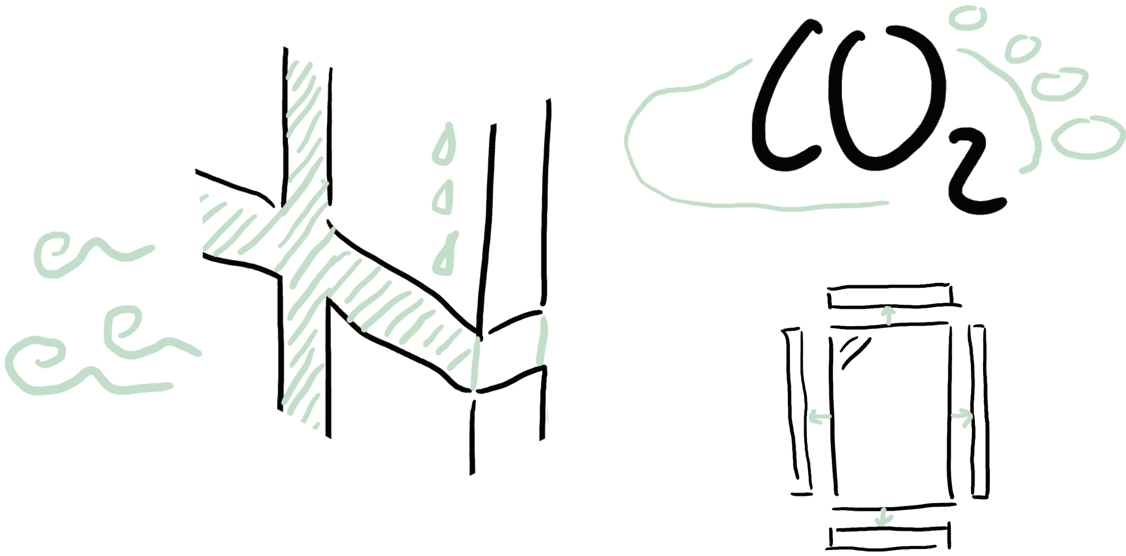


25. Thermal requirements
Heat-transfer and condensation

Thermal (requirement)
One of the functions of the facade is keeping the environmental elements out. Regarding the heat aspect, it is important to keep the inside environment at a comfortable temperature. The maximum allowable according to *Rijksoverheid (2012)* is a heat transder coefficient (U) of 2.2 W/m²K. However, this is quite a high value compared to what is mostly used in the market. Considering the panel will be mostly made of glass the requirement is to use HR+++ glass with a U value of 0.6 W/m²K *(Glaskoning, n.d.)*.

Furthermore, the heat difference between inside and outside should not cause any condensation. In order to assess this, the thermal bridging can be looked at and comparing the inside surface temperature with the due point.

Air & Water *(requirement)*
Another environmental element are air and water. For the comfort of the user, the facade should impermeable. This means that no air or water should leak through cracks within the unitized panel or at the joint between the two. The aforementioned should not



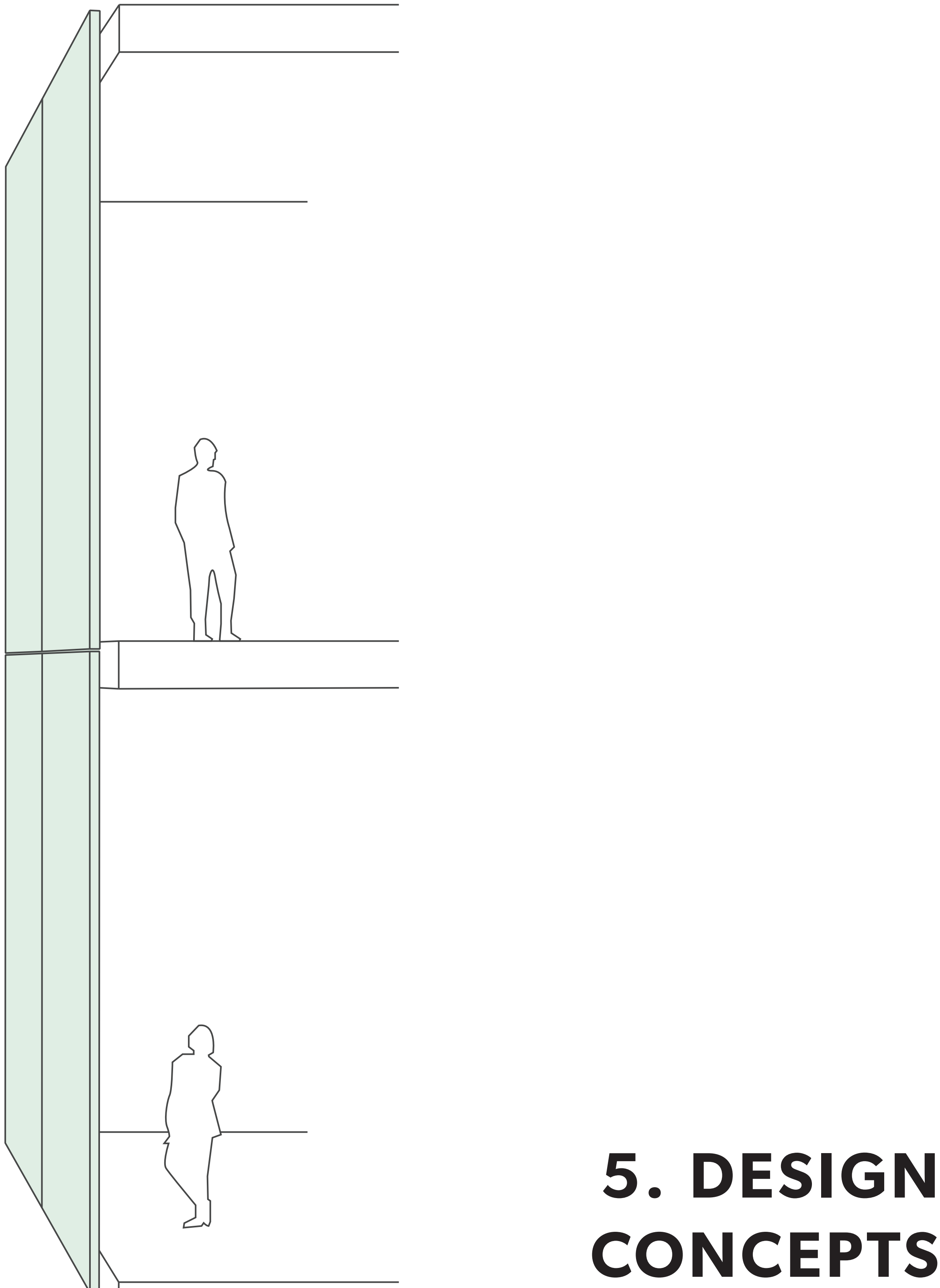
26. Air & Water and Sustainability requirements
Impermeability, $CO_{2\text{-equivilant}}$, and, disassembly

only be the case for the panels when in the correct place but also when they move along the building movements, as described before.

Sustainability (objective)
When looking at the sustainability for the created design it would add great value if it takes into account the end-of-life environmental impact through two aspects: embodied carbon and the embodied energy of an entire panel.

These two aspects can be reviewed through an end-of-life assessment method developed by *Hartwell & Overend (2019).* The results of this analysis can then be compared to the results of an existing facade element to show which points it has improved and where it can still be revised further.

Aspects not considered
A few aspects were not looked at while designing as they either are not necessary to achieve the set goals or are not a key element to design an integral facade element. These are the sound insulation and the transportation boundaries.



5. DESIGN CONCEPTS

5.1 PANEL CONCEPTS INSPIRATION

To start the development of the design, previous work was looked into. Here the main focus was on the system's structure as, to realize the panel design, it should be able to withstand the forces applied. There were two projects that were looked at for inspiration.

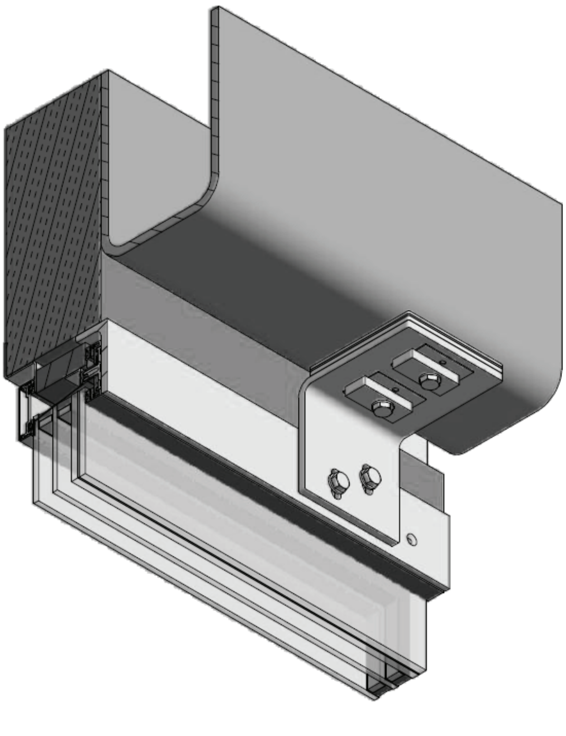
The first one is a relied project previously evaluated in chapter 3.5, namely the Triodos Bank building where Octatube designed the facade. In figure 27 on the left, a detail of this system can be seen. This facade system has a two-point support, top and bottom, instead of four like a standardized curtain wall. By using this support system the vertical structure that is normally seen becomes redundant. Thus achieving a very transparent facade. However, this system heavily relies on structural glazing to endure the applied loads.

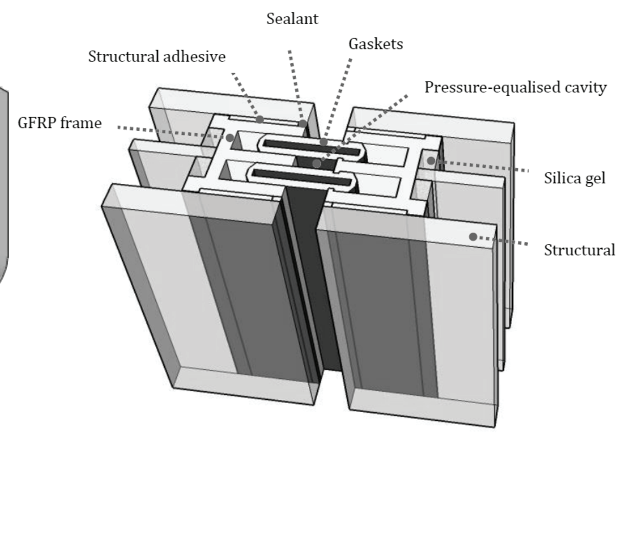
Along with this project, the research work of *Cordero (2015)* was also considered. This research focused on improving the thermal transmittance of a curtain wall system. As can be seen in figure 27 on the right, *Cordero (2015)* proposes a frame integrated

27. Previous work details

Left: Triodos Bank

Right: Cordero (2015)





system where the mullion is sandwiched in between the glazing. This will not only allow for a lower thermal transmittance but also create a far slimmer facade element. In order to achieve this system, the advantages of composite action were used. As *Cordero (2015)* describes, composite action is a phenomenon that occurs when two building elements are working together due to being structurally interconnected with each other. In the design proposed in the study, this composite action is achieved, by using structural adhesives, allowing for a slimmer structure.

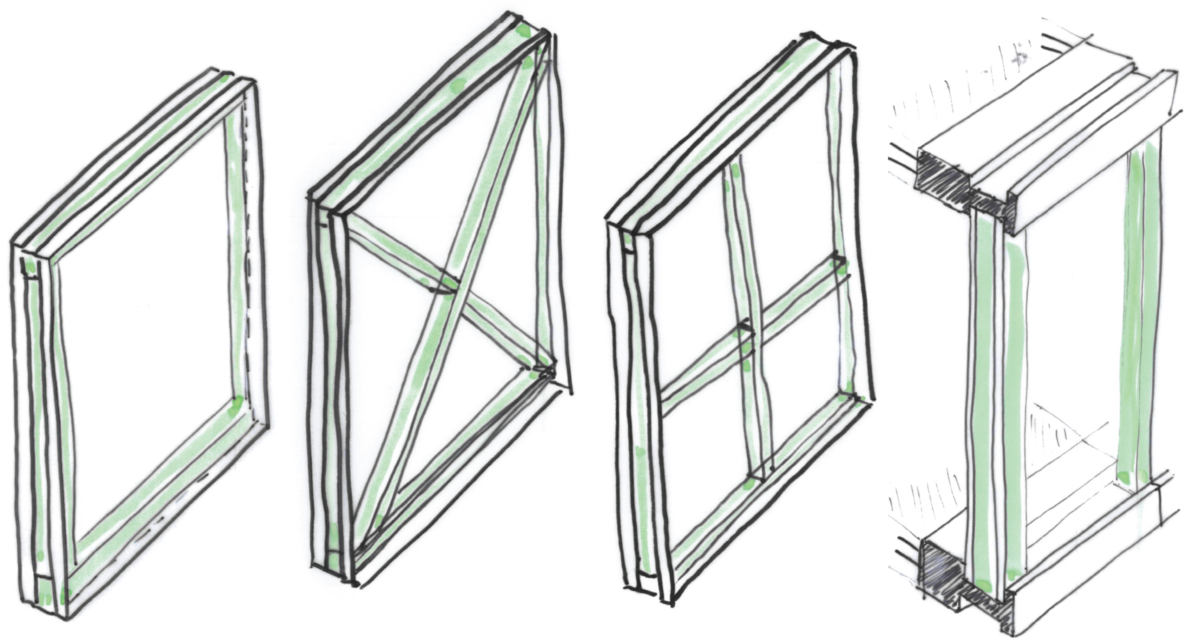
By taking inspiration from the structural concepts of these two projects, four structural design concepts were made for the Slim Skins (figure 28). As the forces that the panel needs to be able to endure are yet unknown, these concepts provide a variety in the expected structural performance.

5.2 STRUCTURAL CONCEPTS

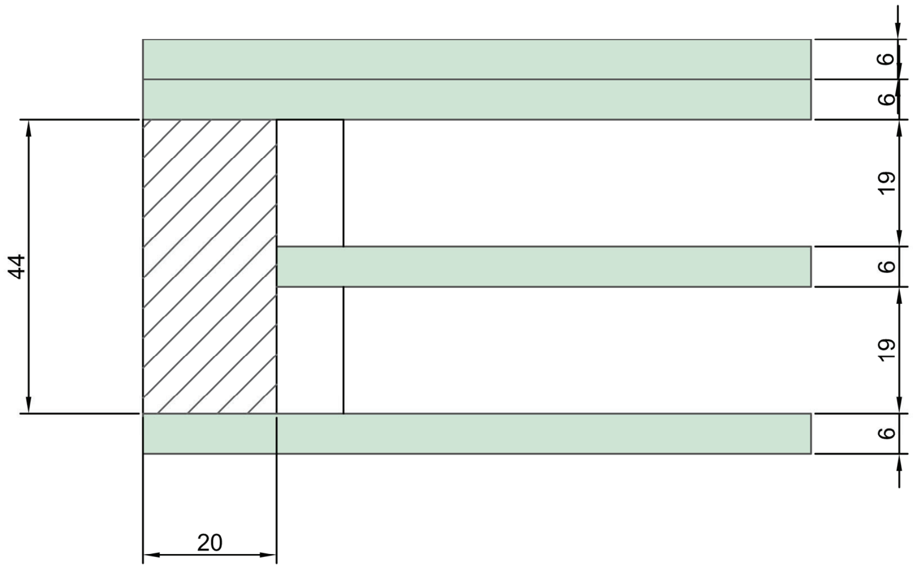
The first three of the structural concepts are based solely on the frame integrated system as *Cordero (2015)* uses. Designs numbers 2 and 3 are the same as one only they have an additional

28. Structural concepts

Inspired by previous work



1 2 3 4



29. Provisional detail

Simplified

element crossing the panel to add reinforcement. The 4th design combines this frame integrated system on the vertical side with the clamped support at the top and bottom as seen in the Triodos Bank. In this concept, it is expected that there is less of a need to use structural glazing as it has support on all sides.

In order to compare these concepts, the most important design requirements, transparency and unitized system were taken into account. Concept number 4 uses a clamping system which can often be bulky and non unitized. Compared to the other three it performs the lowest. For concepts 2 and 3, the extra reinforcement elements take away from the transparency aspect of the facade panel. Thus it can be concluded that option number 1 would be the best.

This structural concept was chosen, however the other options were taken into account as a fall-back system if the chosen one would be proven structurally not feasible.

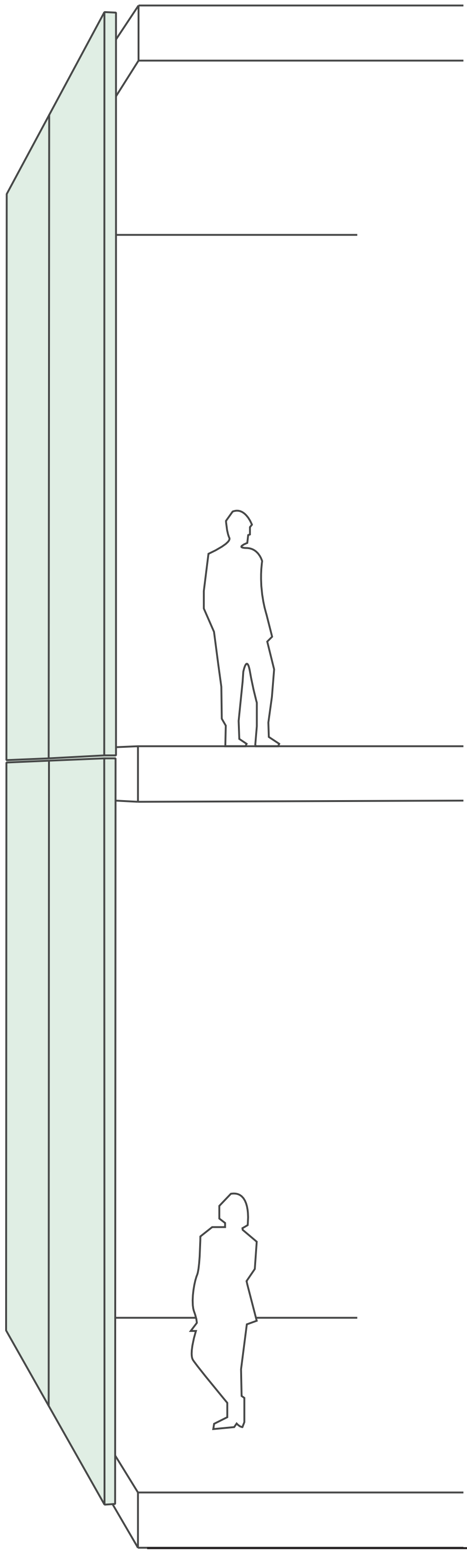
5.3 CHOSEN CONCEPT

The chosen concept has mullions that are slender but which are also able to function as a unitized system. This system would then span over two sides (top and bottom) so that the connection can be hidden at the floor level.

With the concept decided on, a first draft of the horizontal detail (figure 29) was made according to the structural concepts used in previous work.

In this detail the dimensions were based on commonly used insulated glass units (IGU). The triple glazing was chosen to satisfy the thermal requirements to its best. Furthermore, an extra glass layer was added to the inside of the panel to prevent accidents in case of a glass breakage as required for safety.

The materials used in this first detail are glass for the windowpanes and aluminium for the mullion and spacer elements. This composition will be used further for structural calculations in the next chapter.



6. STRUCTURAL ANALYSIS

6.1 APPROACH

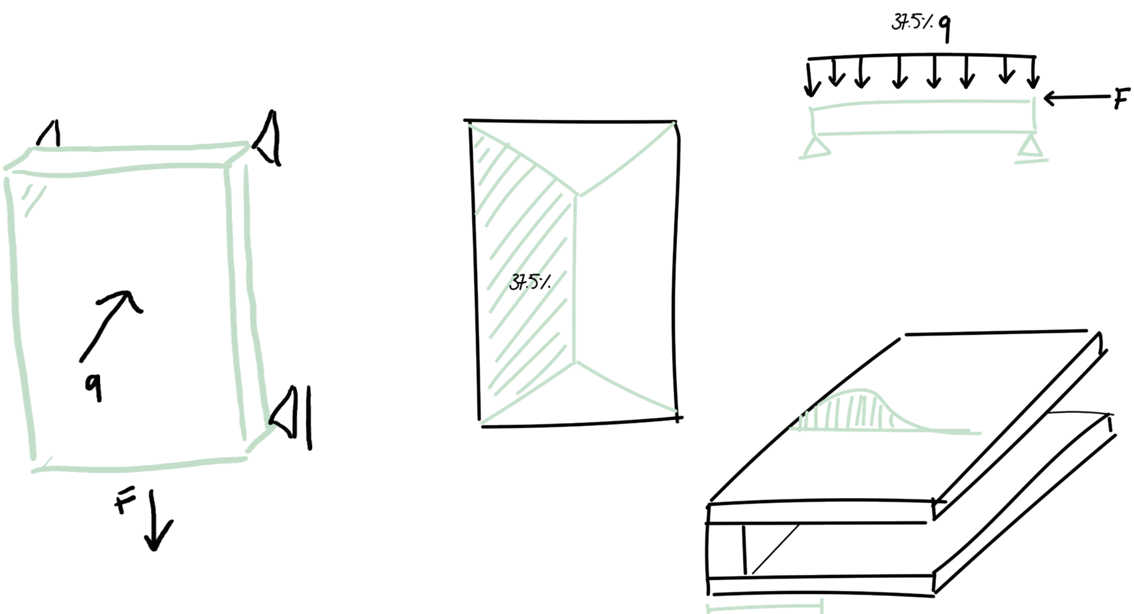
In order to calculate the chosen structural concept correctly, the following step was taken. First, the deflection and stresses of the vertical mullion were calculated by hand. Next, the panel is modelled in ANSYS, a finite element modelling software. The results of both are compared to find dependencies between them. Both the calculations by hand as well as those in the model are adjusted accordingly until the results are similar and can be assumed as realistic.

6.2 APPLIED LOAD

On the facade panel, two loads are applied. There is an axial load consistent of its own weight and a pressure load caused by wind as can be seen in figure 30 on the left.

The force caused by the panels own weight (F) was calculated by accounting for only the glass panes. This was done because the panel consists of 97% glass and thus the weight of the mullion will not contribute enough to be significant. The axial force produced is 4.7 kN.

30. Applied Loads
Left: On the facade panel
Right: For the hand calculations



The wind pressure (q) on a facade is susceptible to its environment. Because the location of the facade application is unknown, the worst possible situation was taken into account. Thus in this case the basic site wind velocity used was retrieved from the average of the worst storms in the Netherlands from the past 20 years *(KNMI, n.d.)*. This has a value of 28.46 m/s corresponding to an 11 in the Beaufort wind scale. With this, the calculated net wind pressure and suction was 2.33 kN/m^2.

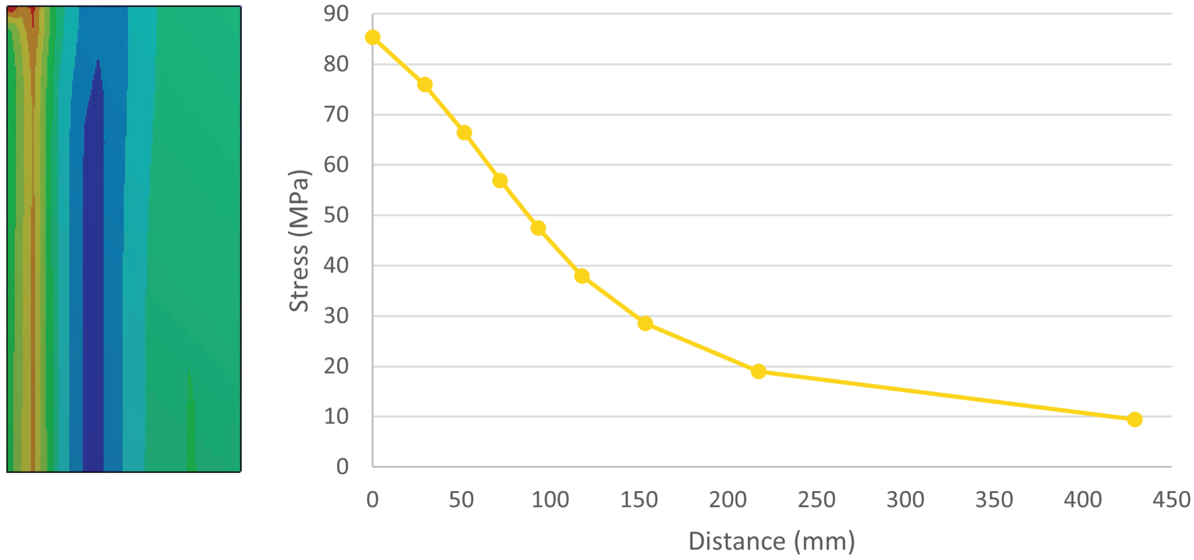
6.3 HAND CALCULATIONS

When looking at the behaviour of the mullion in the panel it acts similarly as a simply supported beam with the wind load as distributed load plus an axial load (figure 30, top right).

The load on the panel will not be transferred uniformly to the four sides but will be distributed higher to the longer sides. The panel is 2x4 meters and thus the load applied on the vertical side will be 37.5% of the whole load (figure 30, middle right). This means the distributed load on the simply supported beam calculations would be 1.75 kN/m.

During the process of comparing the hand calculations with the FEM, it was clear that there was one component not taken into account while calculating the second moment of inertia, namely the shear lag. In the FEM this is autocratically taken into consideration.

The panel consist of three main elements. The mullion and the two glass panels. Because they are bonded to each other with an adhesive it is expected to work together for the stiffness of the panel. When taking half of the panel this mullion has 1 meter long flanges. Because these flanges are so proportional large they won't be able to, at some point, take any stress. This can be translated to a length of the flanges on which they are not contributing anymore (figure 30 bottom right). The area of the profile (mullion + glass panels) that does take stress is the effective area. This effective area is the profile area to use to calculate the second moment of area (I).

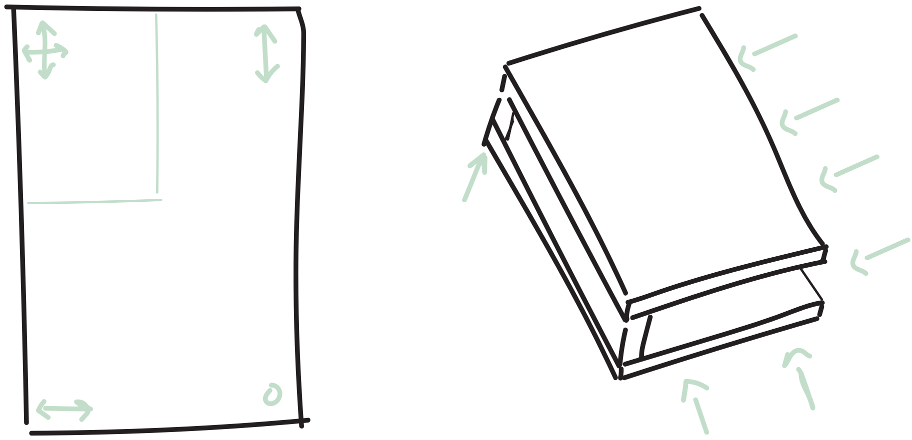


31. Shear lag
Left: Stress on the panel
Right: Shear lag at the top of the panel

The effective area can be calculated by hand calculation however, this can be quite complex. Another way to calculate it is by using a FEM. This needs to be the same as the existing FEM. However, the transom should not be present as to be able to see the stress occurring clearly. From the model, the stresses are taken into a shear lag graphic. As can be seen in figure 31, the shear lag was taken at the top of the panel as the maximum stress is higher (red areas) there. However at this point, the minimum stress does not go as low as in the middle (dark blue) so the stress will not go until 0 MPa. Nonetheless, the width of the flanges that contribute to the profiles' structural abilities can still be calculated. This can be done by using the area below the curve to calculate the effective area and thus the width of the glass flanges. In this case, it is 288.59mm.

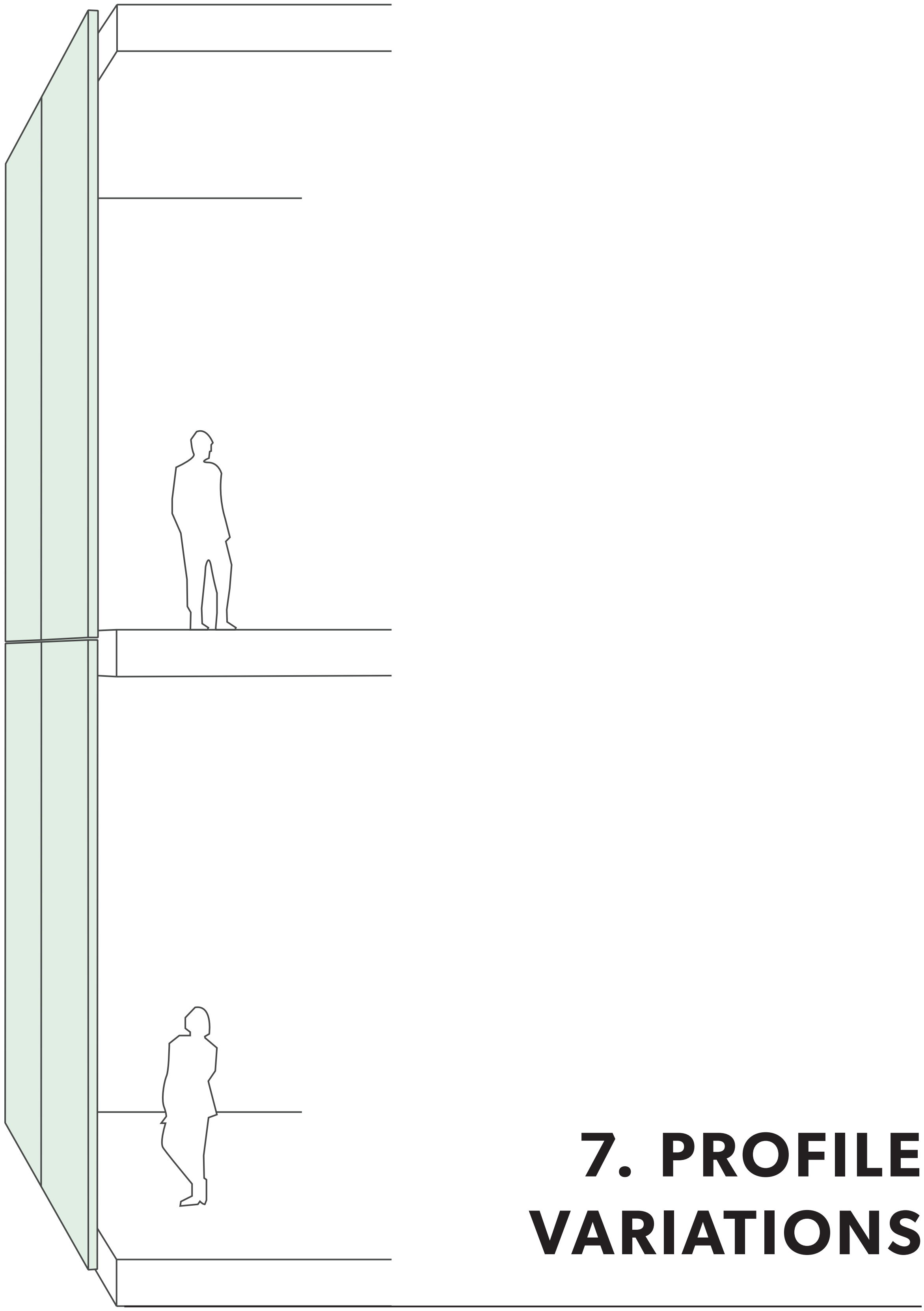
6.4 FEM MODEL

For the FEM model, it was chosen to model only 1/4 of the panel as it can run faster. This will help further along the way when the model is used for many iterations. The model needed



32. Inputs FEM
Small description

to act in the same way a whole panel would. So it should take into account that a panel is at one corner completely restrained from movement, whilst at the opposite corner it should be able to move freely (figure 32). The remaining corners each take one of the two restrained directions. All of them are inhibited when it comes to the movement towards or away from the main construction.



7. PROFILE VARIATIONS

7.1 PROFILE RESEARCH

After having established a first draft of the detail (chapter 5.3), a study was done on a variety of profiles with different sizes and shapes. The goal of this study is to explore various options to determine which mullion designs can be used in the facade system according to the set requirements. Furthermore, this study will look into the materials that can be used for the mullion and the adhesive.

In order to know whether these different profiles are valid to use in the panel design, they need to be structurally feasible. This means that each design needs to satisfy the deflection and stress requirements set. Additionally, the basis of the thermal requirements played a role in the study.

7.2 RESEARCH METHOD

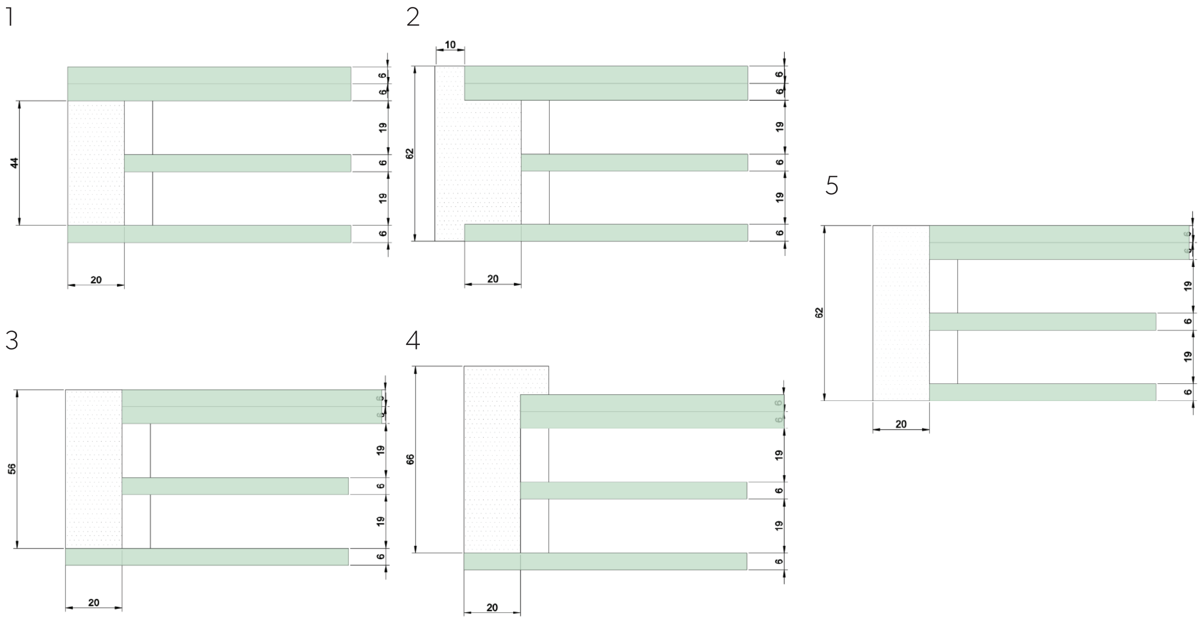
The first step in this research is creating variations of the first detail draft. These different profiles can be seen in figure 33. Profile 2 is based on profile 1, also known as the first detail draft. However, in profile 2, it can be seen that there is an added set of wings. This was done to facilitate the building sequence besides also allowing for more contact surface between the mullion and glass. Profile 3 and 4 are similar to profiles 1 and 2, respectively. However, the difference is that in these profiles the mullion is not sandwiched between glass. This means that there is less contact surface with the glass. Lastly, profile 5 has a mullion only connected on one side to the glass.

With these profile variations defined, the calculations regarding the structural feasibility of each profile can be determined. As stated in chapter 4.3, the structural requirement takes two aspects into account: stiffness and strength.

The allowable stiffness of the profile depends on the allowable deflection, caused by an applied wind load. The deflection of the profile can be calculated as followed *(StructX, 2021)*:

$$\text{deflection} = \frac{5wL^4}{384EI}$$

w - wind load
L - length mullion
E - young's modulus
I - second moment of area



33. Different profiles
Different profiles used
to research possibilities

In this case, the allowable deflection, the length of the mullion, and the wind load are known values. With that, we can calculate the minimum EI needed as:

$$\mathrm{EI} = \frac{5wL^4}{384 \times \text{allowable deflection}}$$

w - wind load
L - length mullion
E - young's modulus
I - second moment of area

The section needs an EI of a minimum of 5.81×10^5 Nm^2. For each profile, the second moment of area (I) can be calculated by using the parallel-axis theorem as the centroid is slightly displaced. Now that the minimum required EI and I of each profile are known, the minimum stiffness (E=Young's Modulus) can be calculated.

The second structural aspect to consider is the strength required to withstand the applied forces. This is done by looking at the maximum stress occurring in the beam. On this panel, the profile will need to withstand the wind load and the load of the panel itself. This creates three stresses: bending stress, axial stress, and shear stress.

The normal stress can be calculated by the flexure formula as seen in the equation below *(Goodno & Gere, 2018)*.

$$\sigma_x = \frac{My}{I}$$

M - bending moment
y - distantance from neutral axis
I - second moment of area

The profile was calculated as a simple supported beam. Therefore, to find the bending moment, the following equation was used *(StructX, 2021)*.

$$M = \frac{wL^2}{8}$$

w - wind load
L - length profile

For the calculation of the axial stress the force used was the dead load of the panel itself. In the calculation of this load, the profiles were not taken into consideration as their contribution to the total dead load is negligible compared to that of the glass panels. This dead load divided by the area of the profile is equal to the axial stress.

The third stress acting on this beam is the shear stress. This shear stress is influenced by the shear force that can be calculated as followed *(StructX, 2021)*:

$$V_x = w(\frac{L}{2} - x)$$

w - wind load
L - length profile
x - distance from reaction point

It is known that the highest shear force is situated at the edges of the beam, where the distance from the reaction point (x) equals 0m. The shear stress can then be calculated with the following formula *(StructX, 2021)*:

$$\tau = \frac{V}{th}$$

V - shear force
t - thickness web
h - hight profile

These three stresses combined are the minimum strength needed. This, together with the minimum required stiffness, concludes the calculations for the structural feasibility of each profile variation.

Following this, the thermal feasibility will be looked at through two aspects. First, the allowable thermal expansion coefficient of the mullions material will be calculated. This is needed since two different materials are being bonded and each material reacts differently to the changes in temperature. With this, the adhesive is put under shear stress which it needs to be able to withstand in order not to fail.

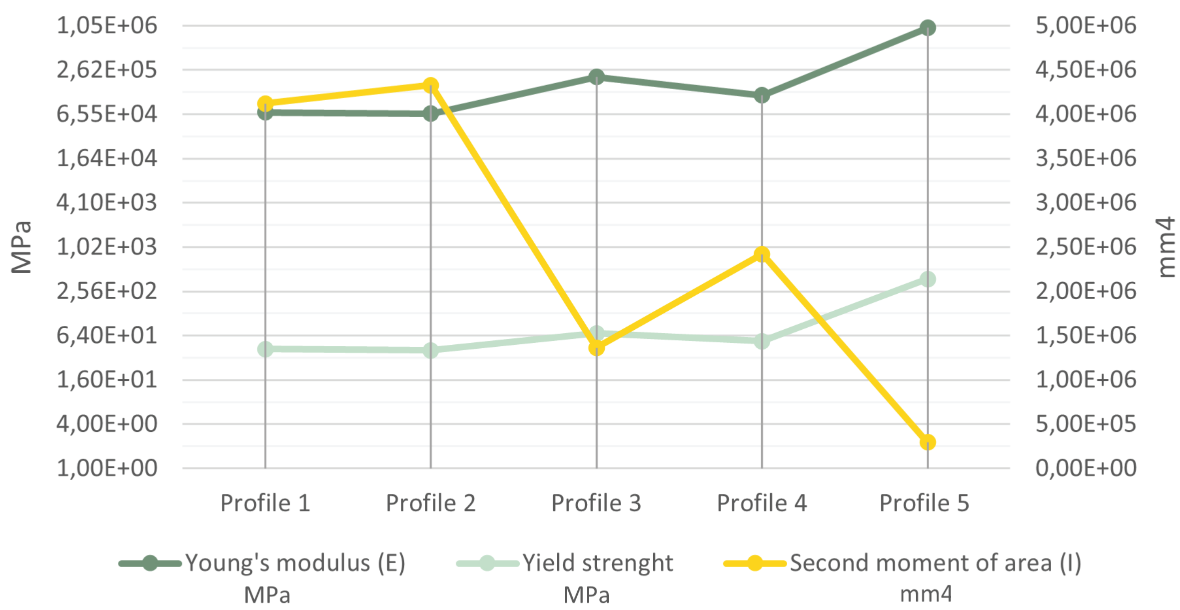
There is a variety of adhesives in the market. These range from very rigid to flexible. As the name suggests, a flexible adhesive allows for more movement and consequently it is able to handle a greater thermal expansion difference between materials. The rigidity depends on the shear modulus of the adhesive. In general, the higher it is the less flexible.

The allowable thermal expansion coefficient of the second material can be calculated, as the thermal expansion coefficient for glass in addition to the temperature difference, the adhesive shear modulus, the adhesives tensile strength, and its thickness are known.

In addition, a maximum allowable thermal conductivity should be defined. This is to prevent thermal bridging by using materials for the mullion that have a relatively higher thermal conductivity value. The thermal conductivity of soda-lime glass (used for facades) ranges between 0.7 and 1.3 W/m·°C *(CES EduPack software, 2021)*. Therefore, the thermal conductivity of the mullion material should not exceed 1.3 W/m·°C.

Now that all these structural and thermal properties, to which the materials and profiles must comply are known, the evaluations of the profiles can be executed. Important here is to identify whether the materials used in the profiles are structurally or thermally feasible. If they are not, the profiles need to change, either in the material choice or the size.

At last, the profiles, with possible changes, will be discussed and a selection of profiles and materials is made to continue to explore further.



34. Minimum required structural values

Per profile

7.3 RESULTS

The results of the structural calculations can be seen in figure 34. In the graph, it is quite clear how the second moment of area influences the minimum required stiffness (E) and yield strength. The bigger the profile, the less is required in terms of structure. Here the amount of composite action also has an influence, as the more contact the mullion has with the glass the less it needs to be strong and stiff. This can be observed in the increase in I and decrease of stiffness and strength between profiles 1 and 2 and 3 and 4.

When calculating the allowable thermal expansion coefficient, 7 different adhesives were considered. The application thickness equals 2 mm for each. This value is retrieved from the same research of where the adhesive properties were retrieved from. The results can be found in figure 35. Here it can be seen that with a decrease in the shear modulus there is an increase in the range of allowable thermal expansion coefficients of the mullion's material. This is expected, as a lower shear modulus means a more flexible adhesive. However, the adhesives calculations also showed that the more flexible they are the less strength they have (appendix A). This is relevant as the adhesives' shear strength needs to be equal to or higher than the shear stress in the profile as to not fail under the expected loads.

Between the 5 different profiles, there is a maximum shear stress of 13.07 MPa. This value should be compared to the shear strength of the adhesives. However, this is an unknown value. To get an approximation, the shear stress can be compared to 60% of the tensile strength *(Porreco, 2017)*. This means that the Sikaflex265, Dow Corning 993, and SikaForce-7550 L15 will not be suitable for use as they only have a tensile strength of a maximum of 7.2 MPa and thus a maximum shear strength of 4.32 MPa.

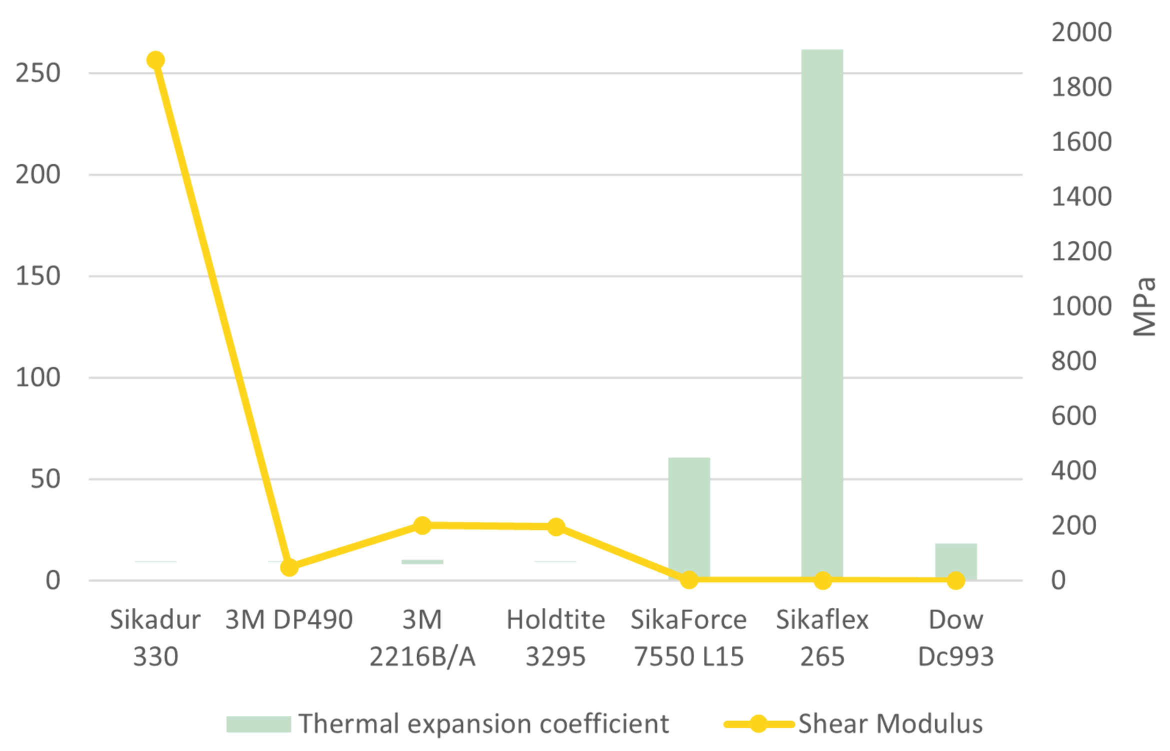
With the 4 remaining adhesives, the materials for all the different mullions can have a thermal expansion coefficient between 3.54 and 14.78.

7.4 EVALUATION PROFILES

To assess if the properties of the used materials are within the

35. Adhesive properties

Range of the allowable thermal expansion coefficient and shear modulus



allowable ranges, to make the profile structurally and thermally feasible, a look will be taken at the composition of the profiles.

When looking at the profiles, it can be seen that it is mostly made out of glass. In four of the five profiles, the glass contributes at least 60% to the second moment of area. The young's modulus of glass is known to be 69 GPa. Thus, to achieve a deflection that is within the allowable, the minimum stiffness needed (young's modulus) should not exceed that value of 69 GPa. As the second moment of area (I) differs per profile, the minimum needed young's modulus (E) will also vary. Note that for these calculations the modular ratio was not used as the influence on the results are negligible because, the profile is quite a small part of the section.

As can be seen in figure 34, all of the values for the young's modulus (E) exceed 69 GPa. To improve this value the second moment of area needs to be adjusted considering the other values (length panel, wind load, and young's modulus) are fixed variables.

In the first four profiles, the most efficient way to improve this is by using thicker glass panels. For profile number 2, changing the single glazing to 8 mm instead of 6 mm is enough to improve the section so it does not exceed 69GPa. In profile number 1, an increase in the thickness is required so not only the single glazing of 8 mm but, also the laminated glazing should be 6mm-8mm instead of 6mm-6mm.

When looking at the composition of profiles 3 and 4, they miss the composite interaction with one of the glass panels, this is also shown in the results as the improvement needed is much bigger. Here there is a need for a glass thickness of a minimum of 28mm and 16mm accordingly.

The last profile, number 5, does not have much composite action with the glass panel. This means that the minimum needed young's modulus can be a bit higher if the mullion is of a certain material. With the initial measurements, the needed young's modulus is 982 GPa. When taking the aspect of the thermal conductivity and thermal expansion coefficient into account, there are no materials that have a young's modulus of a minimum of 982 GPa. The highest young's modulus material is carbon fibre reinforced polymer (CFRP), with a value between 69 and 150 GPa. To achieve an allowable value for the young's modulus this profile needs to be almost 100mm in width instead of 20mm.

These improvements in the profiles to meet structural and thermal allowable values are represented in figure 36.

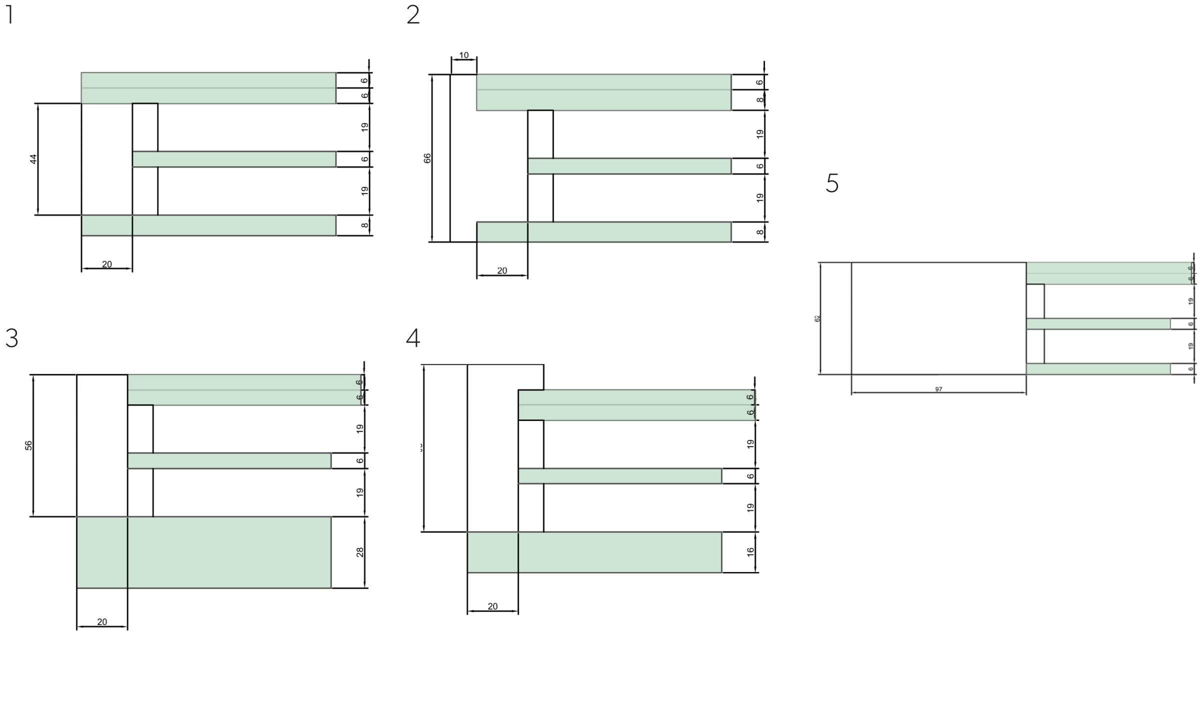
7.5 EVALUATION MATERIALS

With all improvements made and the parameters gathered, the material selection for each profile can begin. The first two parameters are valid for all the profiles; the thermal conductivity (maximum 1.3 W/m·°C) and the thermal expansion coefficient (between 3.54-14.78MPa).

These inputs are introduced into the *CES EduPack software (2021)* as a filter to the 100 different materials. From this selection, 13 materials met the above-mentioned criteria. The

36. Improved profiles

In order to achieve structural and thermal feasibility



stiffness influence has already been taken into consideration, whilst improving the profiles. The following part of the selection is done per type of profile design as the required strength differs depending on the shape.

For the profile numbers 1, 2, and 4 the materials that can be used for the mullion are the same, two composites; glass fibre reinforced polymer (GFRP), and CFRP and four types of wood; bamboo, hardwood (oak, along the grain), plywood, and softwood (pine, along the grain).

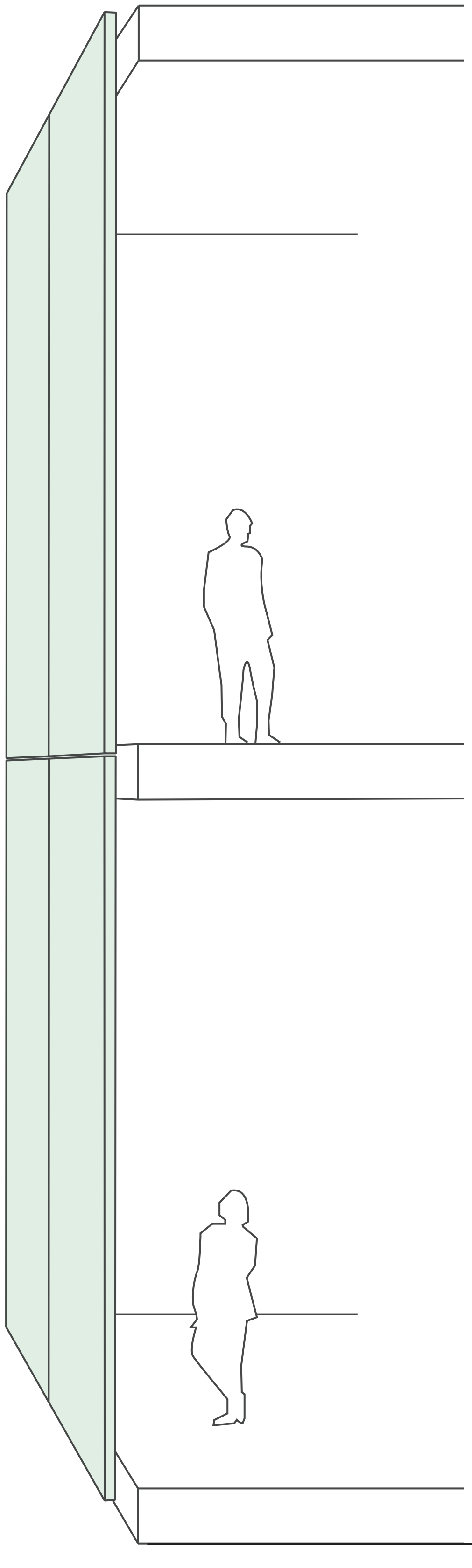
Profile number 3 has a larger help of a thick glazing and thus has a lower needed yield strength. This allowed for two more suitable materials than for the profiles above. Specifically paper and cardboard and soda-lime glass.

The last profile (number 5) needs a material with a higher yield strength. This means that there is only one suitable material namely CFRP.

When taking all of these aspects into consideration there are a few profiles that seem to be less suitable for this panel design. Profile numbers 3 and 4 need to have a thickness of 16 mm and 28 accordingly. The maximum thickness produced at the moment is 25mm. Thus it is not possible to realize profile number 4. For profile number 3 this also poses a problem, since above 12mm thickness (15mm, 19mm, and 25mm) is uncommon to produce due to the need for longer cooling times and the difficulty when cutting the edges. Whilst some companies are producing these thick glasses it becomes very expensive. Thus profile number 3 is also not suitable for the panel design.

7.6 CONCLUSION

According to the aspects discussed before profiles 1, 2, and 5 seem to fit the panel design. In the following chapter, these preliminary profiles will be designed further according to the material possibilities. This means that for profiles 1 and 2 there will be a design for each with wood and a fibre reinforced polymer as material. For profile 5 only a composite material is taken into account.



8. DESIGN VARIATIONS

8.1 DESIGN RESEARCH

Now that the mullion design alternatives have been narrowed down to three, they will be elaborated on further. This will be done to get a better understanding of each design options dimensioning. Furthermore, through a series of evaluations, this study explores the influence of the different sizes, shapes, and materials on the structural, thermal, visual, and other performance aspects.

With all of the analysis completed a conclusion can be made on the best option to meet all the set requirements and goals.

8.2 RESEARCH METHOD

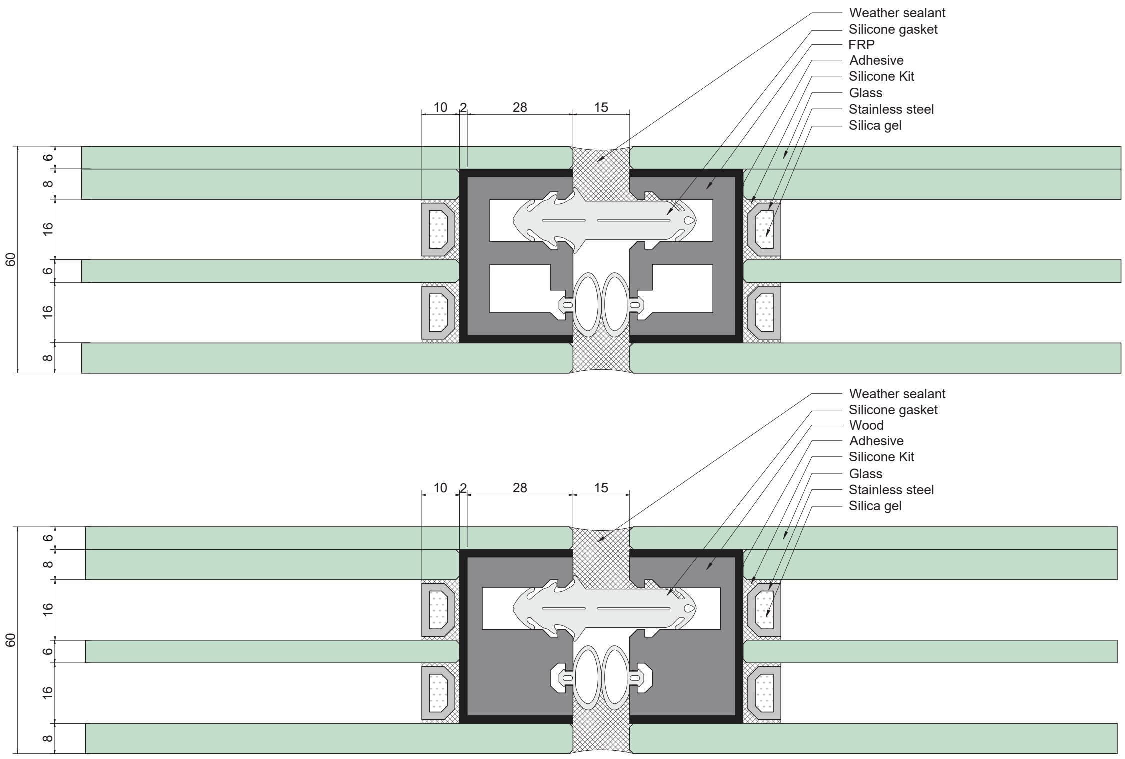
The method used in this design study is based on a series of analyses. Before being able to do these, the design options need to be developed further to reach a higher level of detail. This can be done by looking at the materials used in terms of sizing and the limitations that the set requirements create.

The first analysis will be validating the structural feasibility of the design options. This will be done by using the finite element model (FEM) optimized in chapter 6.4.

Secondly, the designs will be analysed in terms of thermal bridging and condense possibilities due to the temperature difference between inside and outside. These will be observed and calculated through the use of the software THERM. This software will give an estimate of the building's heat-transfer flow.

Next, the assessment of the visual impact needs to be executed. This will be an analysis that relies on the observation of certain requirements. To facilitate this, a 3D model of the profiles is needed. Then the images shot from the same perspective can be placed next to each other to compare the results.

Furthermore, other performance requirements will be discussed together with the results of the analysis so a conclusion on the best design option for this panel design can be made.



37. Design A 1:2

Top: composite

Bottom: wood

8.3 RESULTS

To further develop the three profiles, the materials used needed to be taken into consideration. From the previous chapter, a variety of materials was found to be suitable for the mullions within the profile. In order to facilitate the design of the different mullions the materials were categorized into two types: wood and fibre reinforced polymer (composite).

Each material has its own restrictions that need to be respected when designing. A material from within each of the material types was chosen to use as a base for the design. This choice was made based on the amount of data available about the fabrication and sizing of the material into a mullion.

For the composite types, the material chosen was glass fibre reinforced polymer (GFRP). A GFRP profile is made via a pultrusion process. This uses a die that cannot be wider than 1050mm and higher than 300mm. The minimum allowable thickness is 2mm *(Fibraworld, n.d.).* A variation of thickness along the section is allowed as long as it does not surpass the maximum thickness of

60mm *(Fibrolux, n.d.).*

The designs that have a wooden profile were created by using plywood as a reference for the measurements. This was done as it comes in standard sizing of 4mm for a 5-ply. The profile would be produced with a combination of sewing different pieces together and gluing. For this research, the strength of the bond between these different pieces was not taken into consideration. Furthermore, it was assumed that the adhesive would adhere between the wood and glass in the same way as it does with the GFRP and glass.

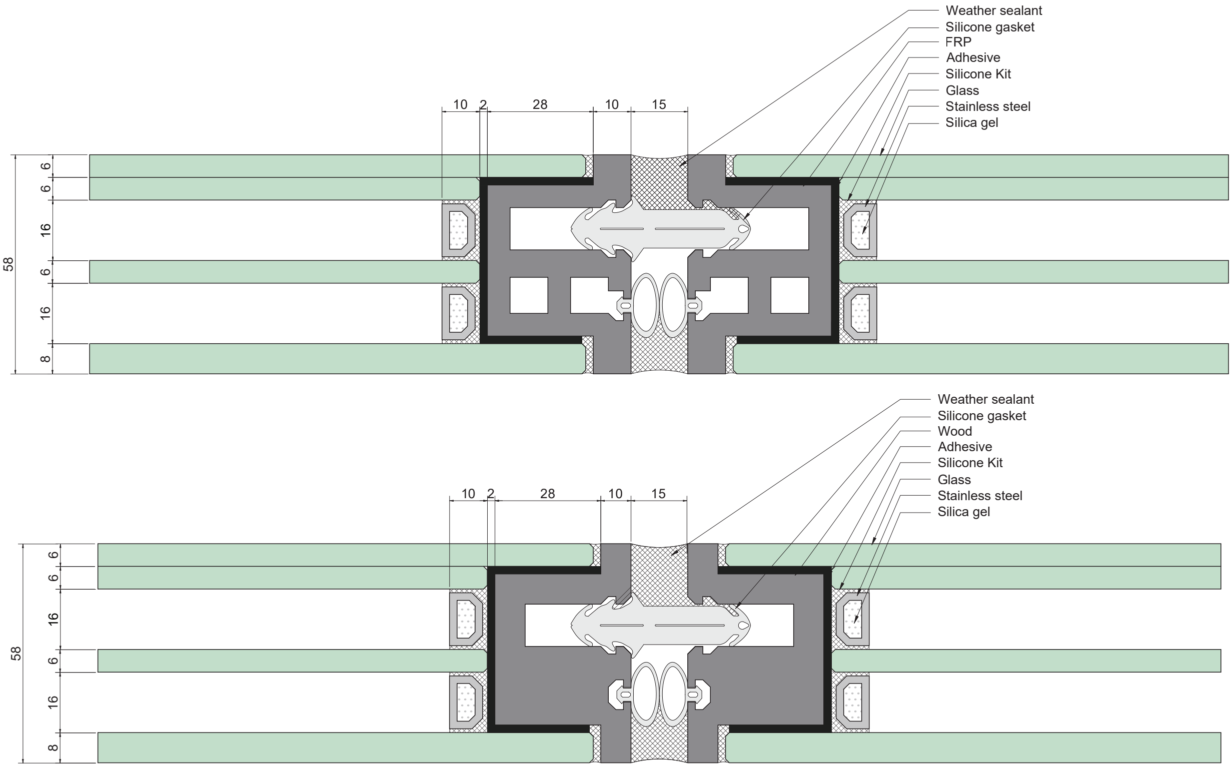
In addition to these material properties that have been taken into account, the type of gaskets and sealants needed also played a role in further designing the profiles.

As mentioned before (chapter 4.3), the facade needs to be impermeable. For this, there are a few barriers needed. On the outside, the first barrier will be to keep the water out. Next, a cavity will be needed to equalise the pressure in the profile and drain any water that managed to get in between the panels. If for the first barrier a kit sealant is used instead of a gasket, there is a need for a second element, which prevents the sealant from filling the cavity fully when applying. Following the cavity, a toggle needs to be used to join the adjacent panels and allow them to move together. Lastly, a barrier is applied to make the element airtight. If this barrier is a kit sealant there is no need for an extra element, unlike with the first barrier. This is due to the toggle element also being able to function as a kit blocker.

The chosen joint measurement is 15mm with an allowable movement of +/- 5mm. This together with the measurements of a standard size toggle was taken into consideration when looking at the needed width of the profile *(Schüco, 2020).*

Lastly, the cavity size was also reduced in all the design options from 19mm to 16mm. This was done to optimize the thermal insulation properties of the glazing.

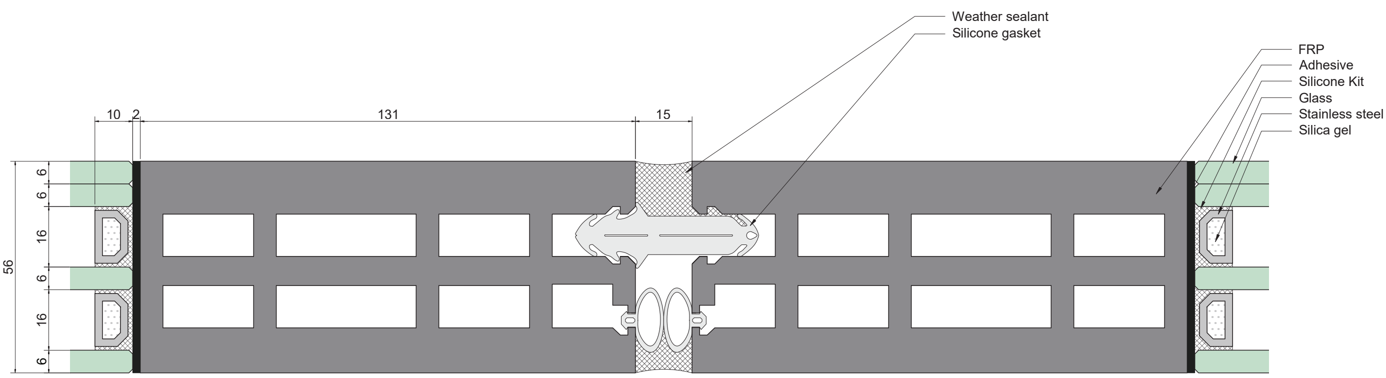
All these constraints together were used when designing the five different options. The final designs can be seen in figures



38. Design B 1:2

Top: composite

Bottom: wood



39. Design C 1:2

Composite

37 and 38, and 39. These are based on profiles 1, 2, and 5 accordingly.

These designs were then used in further structural, thermal and visual analysis. The results can be seen in figures 40 and 42 accordingly. The designs were simplified for the analysis (see appendix E) and the material properties used can be seen in appendix F.

8.4 STRUCTURE EVALUATION

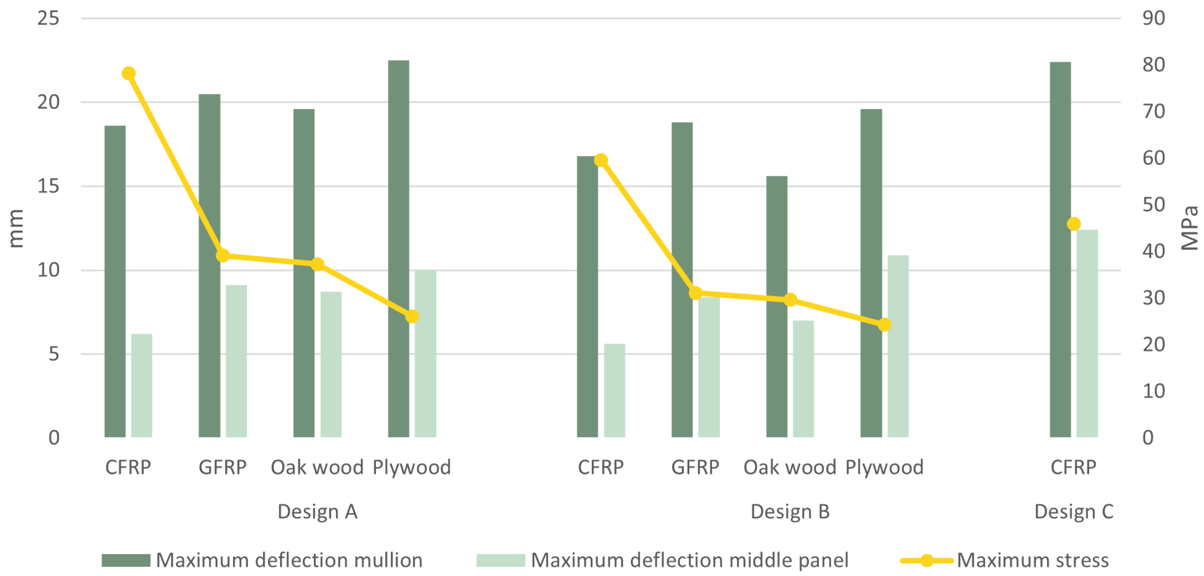
For the structural analysis, the different profiles were simplified (see appendix E) and used as geometry in the FEM model optimised in chapter 6.4. When looking at the composite Designs A and B, both CFRP and GFRP were used as inputs for the analysis, so a good comparison of the materials could be made. For the wood Designs A and B the choice was made to use the extremes of the range of types of wood. Oak is the strongest and stiffest, whilst plywood is the weakest of the four wood types (appendix D).

The maximum stress and deformation results of these analyses can be found in figure 40. For the complete analysis see appendix G.

The allowable deformation in the middle of the glass is 68.8mm, whilst at the edges, where the profile is situated, it is 20mm. All the design and material combinations are within these allowable deflections. This is expected as in chapter 7.4 it was calculated which materials could be used without exceeding the allowable limit, and those were used here.

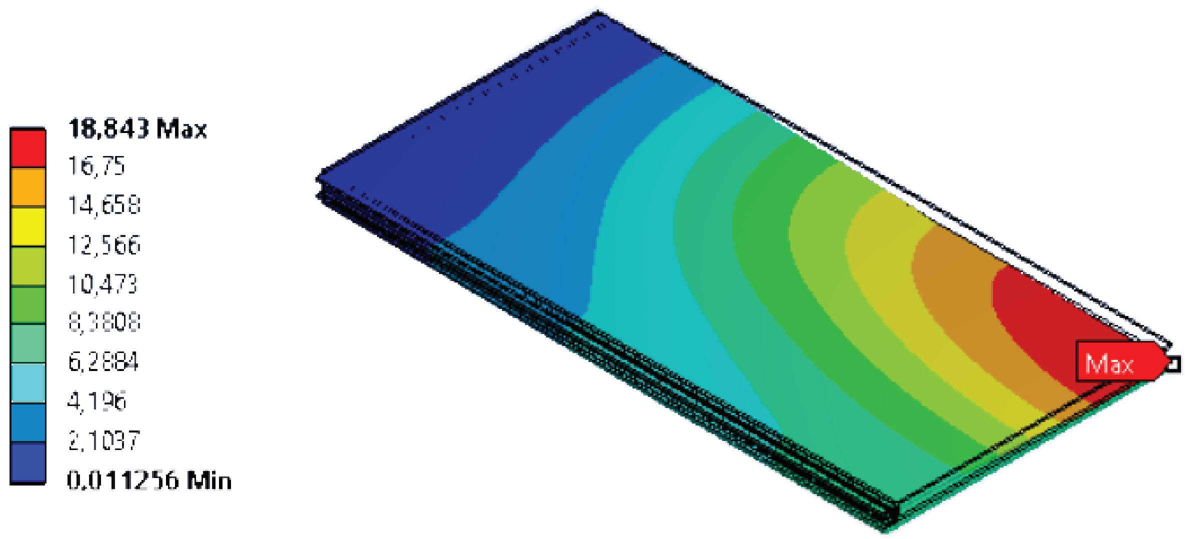
Regarding the stresses, for most of the design combinations, the maximum stress is situated on the mullion. This stress was then compared with the yield stress of the mullions' material. For all of the combinations it was within allowable limit, thus the panel would be able to take the applied forces.

Furthermore, when looking at the results in figure 40 once more, the effect of different profiles on the contribution to the composite action is clear. The overall best performance



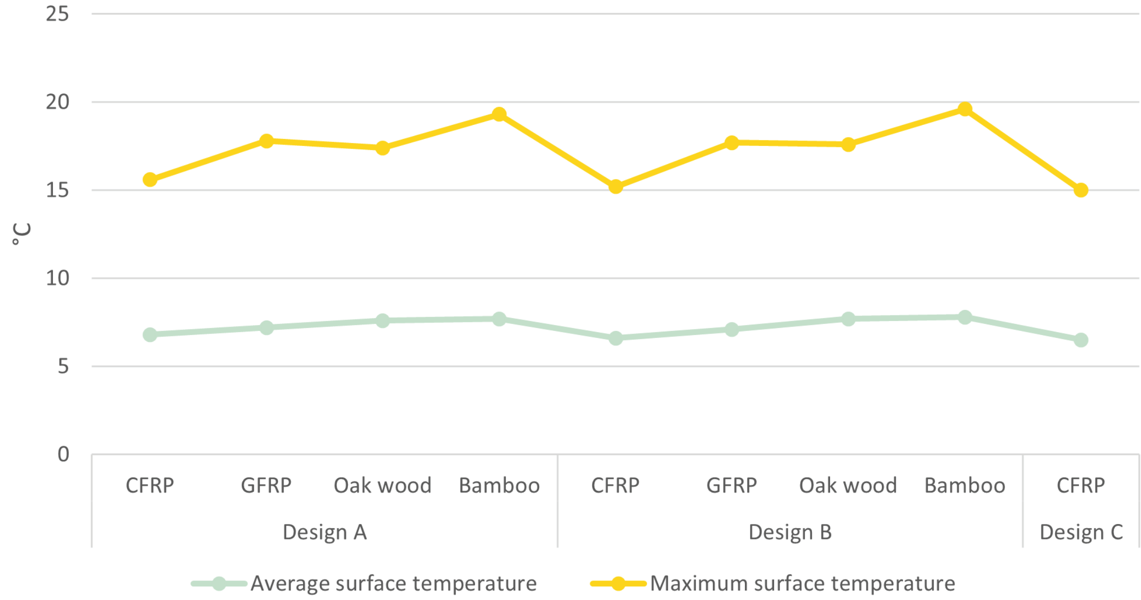
40. Structural analysis

Deflection and stress

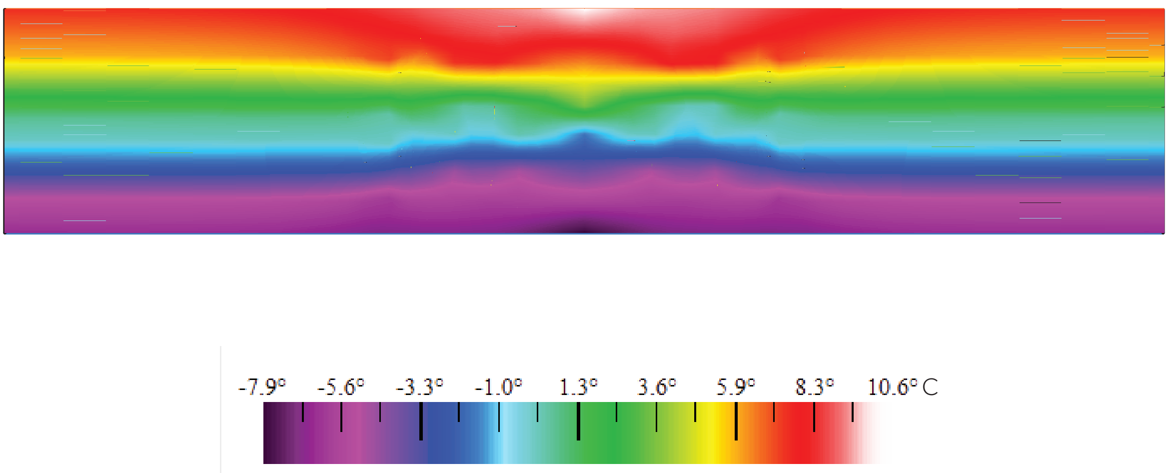


41. Example FEM analysis

Design B GFRP - Deflection



42. Thermal analysis
Surface temperature



43. Example THERM analysis
Design B GFRP

structurally is achieved by Design B as the average stress and deflection results between the different materials are the lowest. This was according to the expectations because, as mentioned before, it has the most contact area where adhesive is placed and thus can achieve more composite action between the mullion and glass. This creates an overall stiffer and stronger design. Next in performance comes Design A and followed by it Design C. Additionally to this the stiffness of the material also plays a role as it can be seen that how stiffer the mullion material is the less the occurring deflection is. However, it also creates more stress between elements thus finding a material that achieves a balance between these aspects is important.

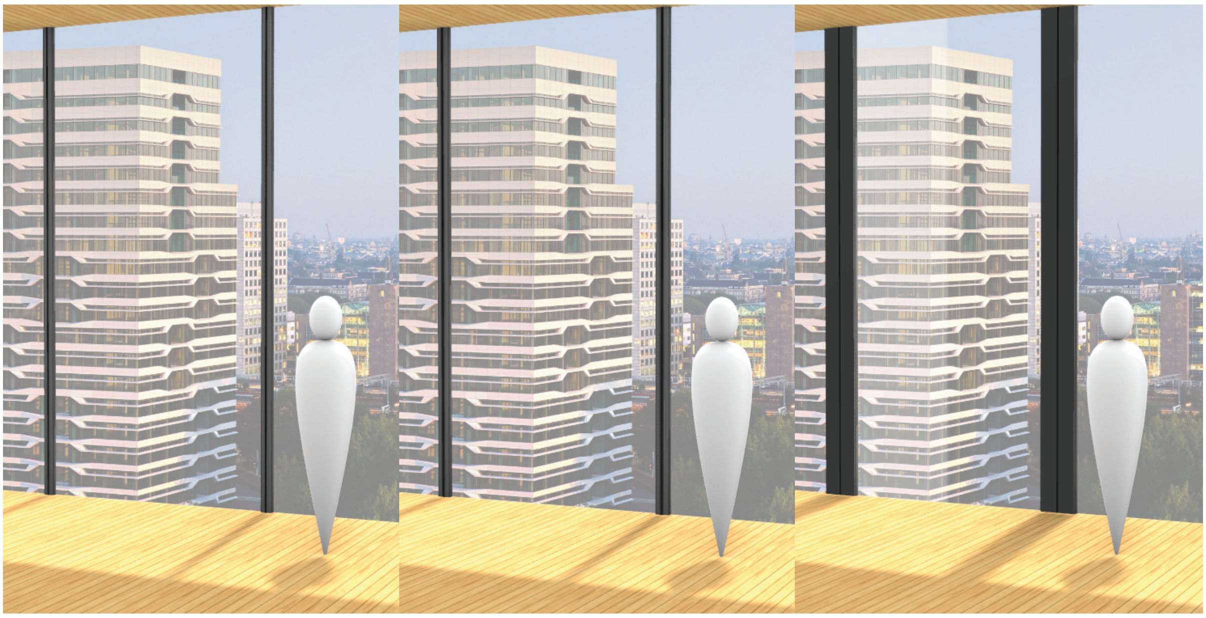
8.5 THERMAL EVALUATION

When looking at the thermal performance two things were taken into consideration: thermal conductivity and thermal bridging.

For all the options the U-value remains the same, as that was defined in the design requirements (chapter 4.3). Where they differ is in the thermal conductivity of the profile used. Most of the materials analysed are better insulators than glass. There is only one exception: CFRP. Furthermore, it can be established that within the wood category bamboo scores best and oak worst.

Even though most of the used materials score fairly well in terms of thermal conductivity a heat transfer analysis is still required to see where possible thermal bridging and thus condensation could occur. This analysis was done by importing the simplified versions of the design combinations (appendix E) into THERM and subsequently attributing the right thermal properties for the analysis. Once more both of the composite materials were used in the analysis and for the woods the extreme ones were chosen (oak and bamboo). The used material properties can be found in appendix F. For the boundary conditions, the following were used: outside -10°C and 25 W/m²K; inside 20°C and 7 W/m²K.

With a relative humidity of 40% and an inside temperature of 20°C the dew point is 6.0°C. None of the analysed design combinations had a surface temperature lower than 6.0°C.

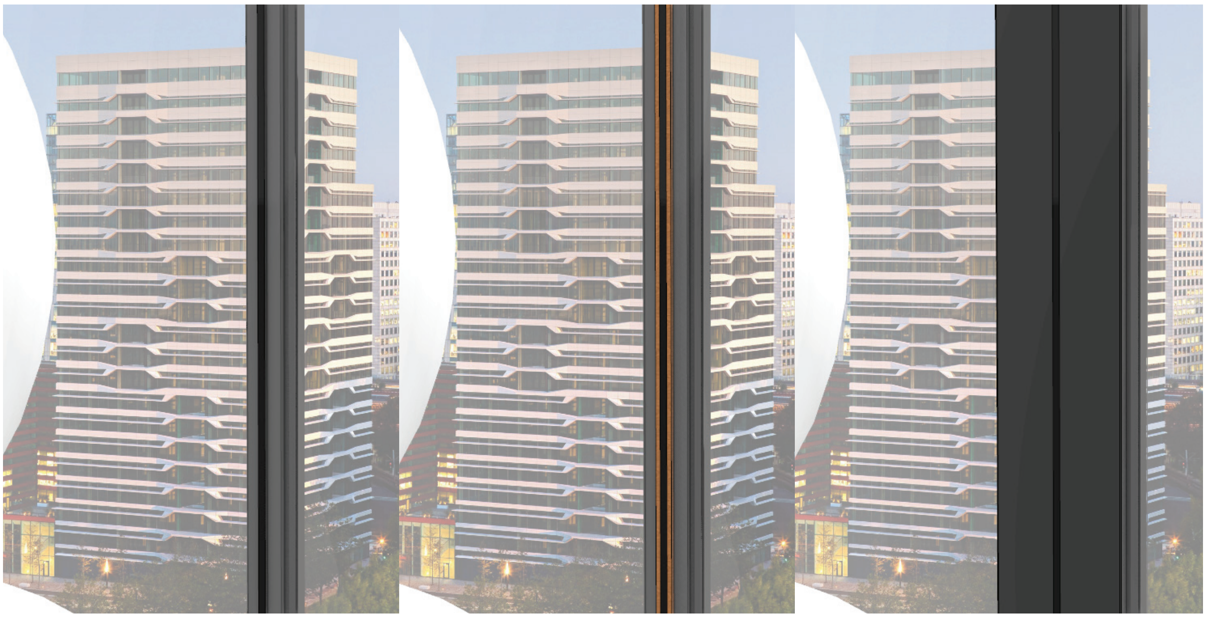


44. Width visual

Left: Design A

Middle: Design B

Right: Design C



45. Materials visual

Left: Design A - Wood

Middle: Design B - Wood

Right: Design C - CFRP

Thus no condensation is expected to happen. Even though the same material is used in different design options they behave differently. The composite materials behave the best in Design A whilst the woods are at their best in Design B. This can be related to the fact that there is more profile in Design B and because wood is a better insulator it will enhance its total thermal performance. Furthermore, CFRP does behave as expected quite poorly compared to the other materials.

8.6 VISUAL EVALUATION

Another aspect that is relevant to look at is the visual aesthetic of the design. This is an important part as the main goal is to achieve a transparent facade. The first way to compare the designs is by the width of the profile. The bigger the width, the more it obstructs the view. The design requirements call for a maximum width of 75mm. This was however not achieved in any of the profiles as they focused on meeting the second requirement: not having any protrusion. Nonetheless, the design options still have a variety of widths for comparison. As can be seen in appendix E and also in figure 44, Design C has a very large width and thus the panel is less transparent. The last way that the designs are compared on the visual impact is by the materials shown (figure 45). For Design A there is only the small joint showing. In Design B there is a bit of a different material showing next to the joint. This can be seen as an extra interruption in the even flow of material properties (reflection, colour, and texture). Design C has an even bigger interruption as a large part of a different material than glass is shown.

8.7 EVALUATION OTHER REQUIREMENTS

When evaluating a facade system it is important to also look at the other requirements to choose a design option that is feasible in a variety of aspects. The first aspect examined is the building process.

For each of the profile types and materials used there are different pros and cons to the building process. As mentioned before creating the profile out of a composite or wood involves two very distinct processes. A composite profile is created through pultrusion allowing it to be intricate in detail. To create the wood profile shape the wood is milled down. The amount of intricate details possible is dependent on the available sizes of milling saws.

When the profile is created the way it is assembled with the glass depends on the design. Design A can pose a difficulty as the profile needs to fit perfectly in between the glass panels. This can be a problem when the tolerances that are taken into account are quite high. In Design B this problem is addressed as it has flanges that stop the profile from going further than it should. However, this means that the adhesive in between the panel and the glass needs to fill in the gap if, because of the tolerances, the profile back is not touching the glass panel. All these troubles are avoided in Design C as the profile simply adheres to the size of the glazing.

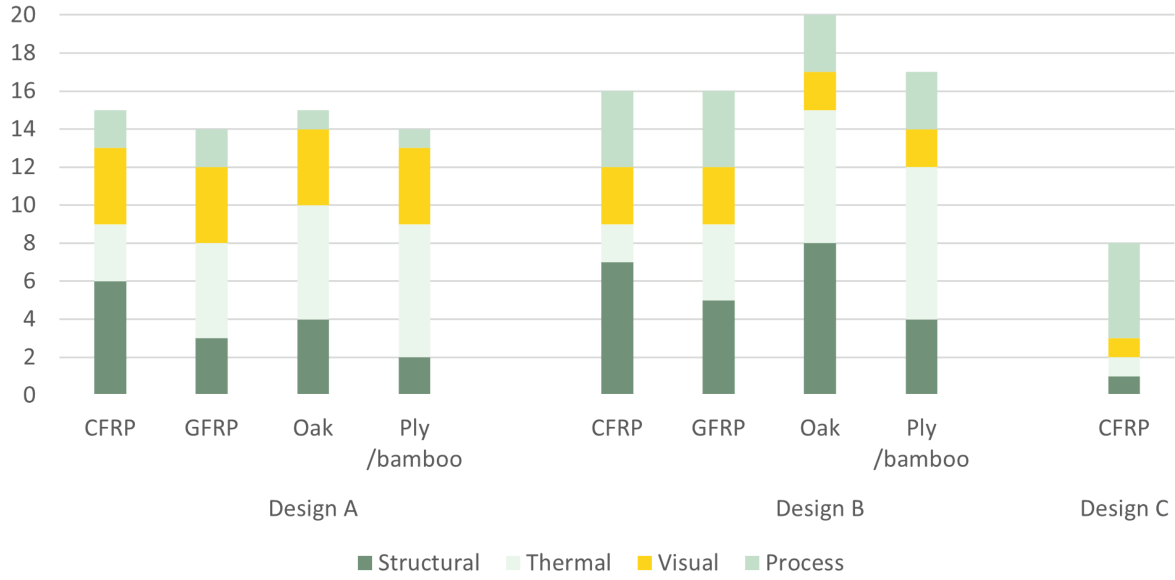
Next, the water-tightness of the design will be looked into. In all profiles, no water or air gets through inside as gaskets and sealants were used. However, in Design C the adhesive between the glass and the profile is exposed to the outside. This can allow water to damage the adhered properties of adhesive which can cause delamination.

The following aspect is the same or similar for each design and thus does not require further analysis and comparison. This regards the safety requirement that the glass should stay in place when breakage occurs. This has been prevented by having a laminated layer of glass on the inside of the panel. This will allow the broken panel to stay attached to the one that is still intact.

All of the remaining design requirements are regarding the vertical detail of the facade which will be discussed in chapter 9.1.

8.8 COMPARISON DESIGNS

In order to better evaluate the design combinations, they were given a ranking depending on the results from the previous analysis with 1 as the lowest value. The ranking can be seen in



46. Design options comparison

Overview of the analysis results

figure 46. For the structural ranking, the deflection results were taken into account because that is what will factor in the most when looking at the structure. For the thermal analysis, the average surface temperature was compared for the ranking.

The first way to access these design options is by looking at the visual ranking. This is done because the visual aspect weighs the most when trying to achieve the proposed goal. There are three design combinations that score quite badly: Design C and both wood options of Design B. For Design C the cause is the width of the mullion and for the wood options of Design B, it has to do with the interruption of the glass material with a dominant colour and texture, which disregards the design requirement to avoid different materials showing. This is unlike the composite which blends better with the kit that is already there.

Looking at the remaining options two materials stand out because they score quite badly in the structural and thermal analysis. These are Designs A plywood and Design B CFRP, respectively.

After this only four options remain: Design A - CFRP, Design A - GFRP, Design A - Oak, and Design B - GFRP. Of these four options, it was chosen not to use wood as a material as more actions are required while producing it compared to a composite material. Another reason not to use wood in this design is the uncertainty of the workings of the composite action between the wood element and the glass.

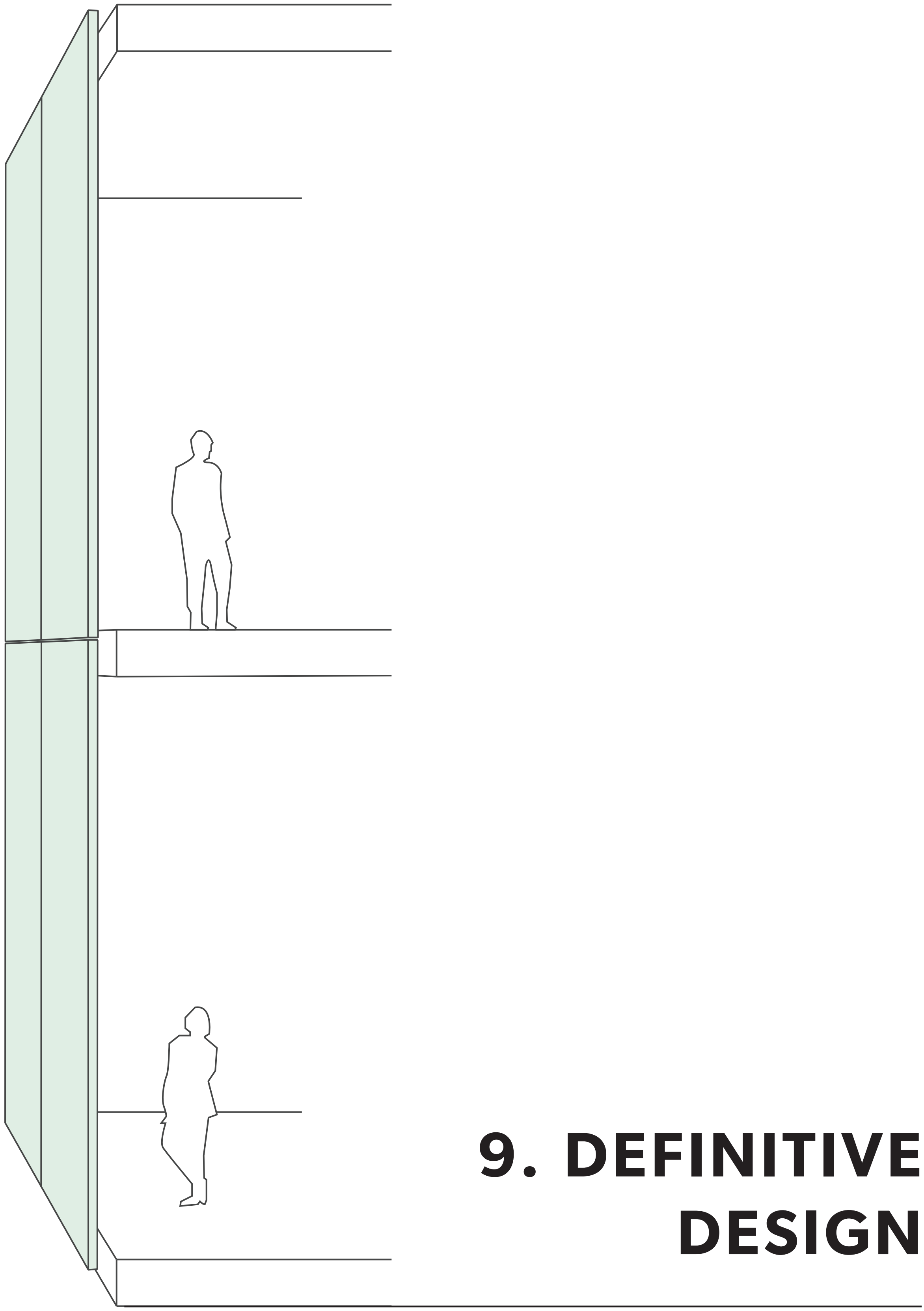
The other three options are overall similar with each having its pros and cons emerging from the analysis. These three design options use two materials: GFRP and CFRP. The latest has great properties however it is high in cost. Not only compared to the most common construction materials used like concrete, steel and aluminium, but also to other materials within the same composite category GFRP *(CES EduPack software, 2021).* This can be attributed to the process of making carbon fibre being more complex than glass fibre *(Sheppard, n.d.)*. It needs a wider variety of raw materials including gases and liquids *(Cavette, n.d.)*. For this reason, the Design A - CFRP option will not be used further.

This leaves Design A - GFRP and Design B - GFRP. When looking at the ranking across all the different aspects of Design B it performs slightly better than design A. However, when looking at the visual aspect only, Design A achieves a higher score. As mentioned before this aspect weighs more when deciding on a design option and thus Design A - GFRP was chosen to be use in this facade panel design.

8.9 CONCLUSION

Design A with the material GFRP has been chosen as the one to use in the design of the facade system. This was chosen regarding many of the set requirements and by a process of elimination of the other options. As mentioned before, this option does not necessarily score better than all other options but when prioritising some requirements over others this is the best choice. The prioritising had to do with the main goal that is trying to be achieved with the design, namely a highly transparent unitized facade system.

The chosen design option is satisfactory in almost every design requirement that applies to the horizontal detail. The only aspect where improvement is necessary is the building process. This has been improved in the final design (chapter 9).



9. DEFINITIVE DESIGN

9.1 FINAL DESIGN

The chosen design option was further developed and improved. This was done by first looking at the horizontal detail and making the small improvements needed from the design assessed in the previous chapter.

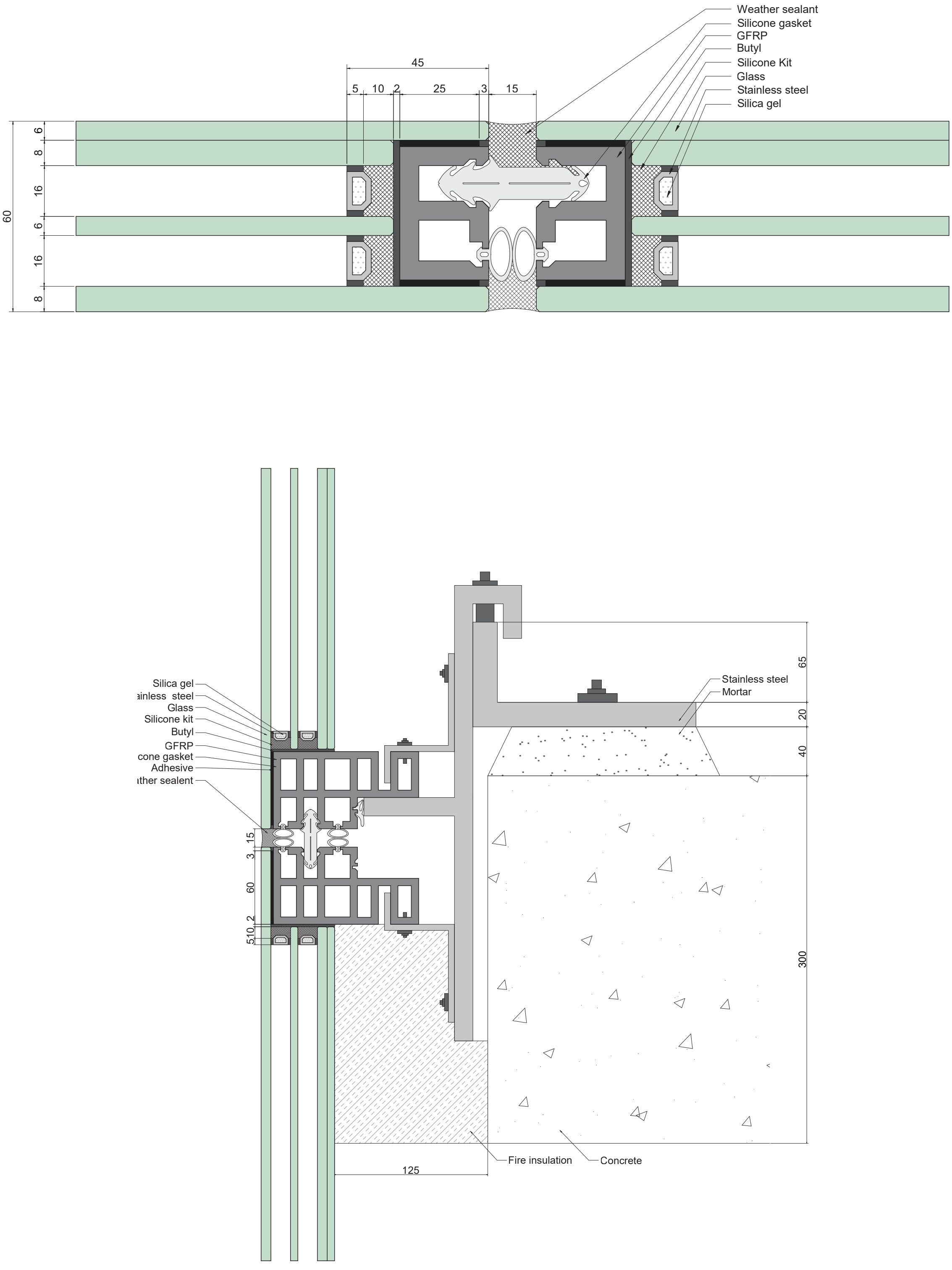
Secondly, the vertical design was translated from the horizontal detail. In this process existing facade systems were used as inspiration as then it could be assured that it would work. Furthermore, the vertical design was changed during the design process in order to accommodate the requirements regarding the assembly and building methods.

The final design details can be seen in figure 47.

9.2 HORIZONTAL DETAIL

To finalise the horizontal detail, three aspects needed to be looked at. First, a decision on which adhesive to use needs to be made regarding the structural, sustainable, and visual requirements.

The adhesive needs to be able to take the shear stress occurring in the profile whilst also not breaking due to different thermal expansion coefficients. In chapter 7.4, it was already determined that only four out of 7 investigated adhesives would be suitable for use in this design: DP490, Sikadur-330, EC-2216 B/A and HA M3295. In the previous design, the adhesive used was DP490. This had a low shear modulus and a high tensile strength. However, newer research has shown a higher shear modulus for the same adhesive. In the research, the shear modulus of DP490 was found to be 400 MPa instead of 49 MPa *(Overend et al., 2011)*. With this new finding, the adhesive is established as very rigid, which can be a problem when looking at the sustainability requirement. To get a better chance of separating materials at the end-of-life the adhesive with the lowest shear modulus should be chosen. This is the acrylic adhesive HA M3295. However when looking further into the properties of the adhesive there were two reasons why this adhesive would not be the right one to use. The first reason is the colour, being pink or green, which will be showing through the windowpane, interrupting the



47. Details final panel design

Top: Horizontal detail; scale 1:2

Bottom: Vertical detail; scale 1:5

visual uniformity of the facade. Secondly, it had a fixture time of 2-3 minutes. This can pose a problem when assembling the panel as it does not allow for some time to move the profile into the correct place. The next best option would be EC-2216 B/A which in colour is grey and has a handling time of 90 minutes. Overall this is the best adhesive to use for this design.

The second aspect is regarding the amount of adhesive used. Because even though the chosen adhesive has the lowest rigidity possible without failing it should be used as minimally as possible to regard the end-of-life and the ability to separate materials. With this in mind, it was decided to look for areas where adhesive would not be required. This was done by changing the geometry in the FEM model. From this short analysis, it could be concluded that there was no need for adhesive on the short side of the glass, only on the glass panes sticking out.

The third and last aspect to consider when finalising the horizontal detail design is the delamination risk. It is known that the silicone kit when in contact with a laminated glass layer can cause delamination. This same issue could occur when adhesive and silicone come in contact causing the GFRP profile to detach from the glass and cause critical failure of the panel. The void created by the second aspect's improvements gives a perfect opportunity for the solution to this delamination risk. With the adhesive only being situated at the sides of the profile, contact with the silicone kit is avoided through a layer of butyl rubber in between. These are situated at the ends of the profile sides and at the back of the profile where it meets the short side of the glass.

9.3 VERTICAL DETAIL

With the changes made in the horizontal detail, the design can be adapted to the vertical detail. With this translation, four aspects made the design full-fill the set requirements (chapter 4).

The first aspect has to do with an improvement point mentioned earlier in chapter 8, namely the assembly of the glass panel. The main issue was the needed precision to create the insulated glass unit with a few parts of the glass extruding on all sides. When looking at the vertical connection there was a need for a protruding element to connect to the building structure. This protrusion on the top and bottom of the panel also allowed for easier assembly. As a majority of the glass panels could be aligned to the profile.

Another aspect that was taken into consideration was limiting the number of custom pieces. In this way, there are only two types of gaskets used and two types of profiles. The horizontal profile needed to be different to accommodate the connection with the building structure.

The third aspect influencing the design is the way the panel is attached to the building's main structure. It was chosen to have the panel supported at the bottom instead of hung from the top. It is most common to hang the unitized systems as they have profiles made of metal which are more prone to buckling if being supported at the bottom. As the profile in this design is made of GFRP this does not pose such a problem. Furthermore, having the panel supported at the bottom allows for easier removal for repairs as the weight is already being supported whilst removing the connection points. This is in line with the maintenance requirements.

Lastly, the elements that create the attachment to the main structure were designed considering the many movements they need to make to allow for adjustments in the building order.

Three elements secure the panel to the facade. The first one is the corner profile that is secured to the edge of the floor slab. This element will allow for movement back and forth towards the slab and also from side to side. Next, the T-shaped element is there to allow for movement up and down and to support the weight of the panel. The thickness of this element was determined via a FEM model to be sure it would be able to support the panel. Lastly, there is a click system designed to secure the panel to the building. This element is applied at four points on the top and bottom of the panel.

An earlier design of this system, seen in figure 48, had two flaws.

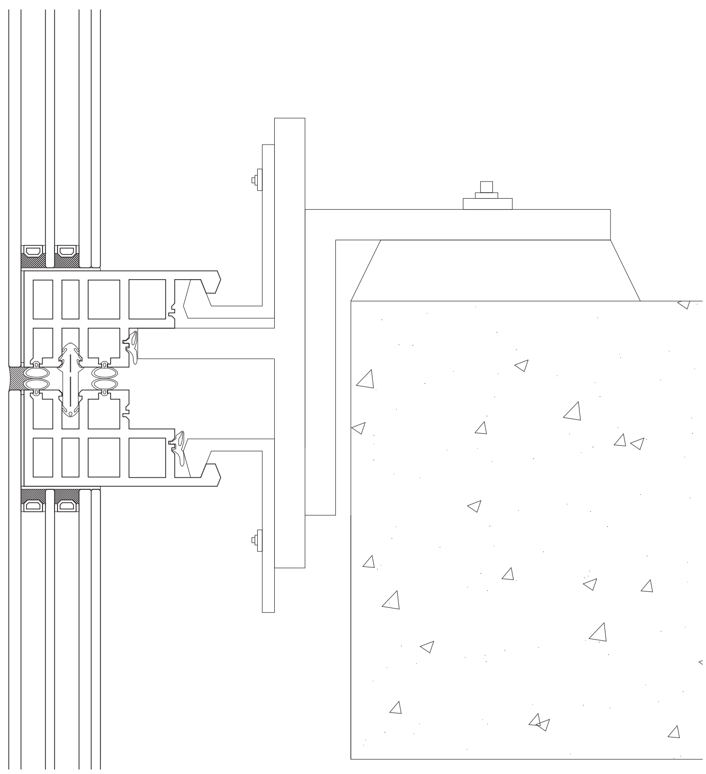
The first issue was the connection between the T-profile and the corner profile. Here it is needs to be adjusted up and down thus having slots for the bolts in that direction. However, this is also the direction in which the forces are situated increasing the risk of failure. Furthermore, the design relied solely on a hook system to ensure the panels' placement. This also had a high risk of failure as it could not be ensured that, when there was thermal expansion or contraction, the hook would hold the panel in its place. These issues were addressed in the final design by using a different hanging technique with another T-profile and by adding bolts to the hooking system.

9.4 ASSEMBLY & BUILDING ORDER

In figure 49 the assembly process of the panel can be seen. It starts with the correct size glass panels and the preferred film coatings (1). These are then laminated and hermetically sealed with the choice of gas inserted (2). A layer of butyl rubber is placed on the sides of the glass where no adhesive will be added (3). In between these, the adhesive is applied (4). Now the mullion, which already has it's corner connection elements

48. Vertical detail

Earlier version



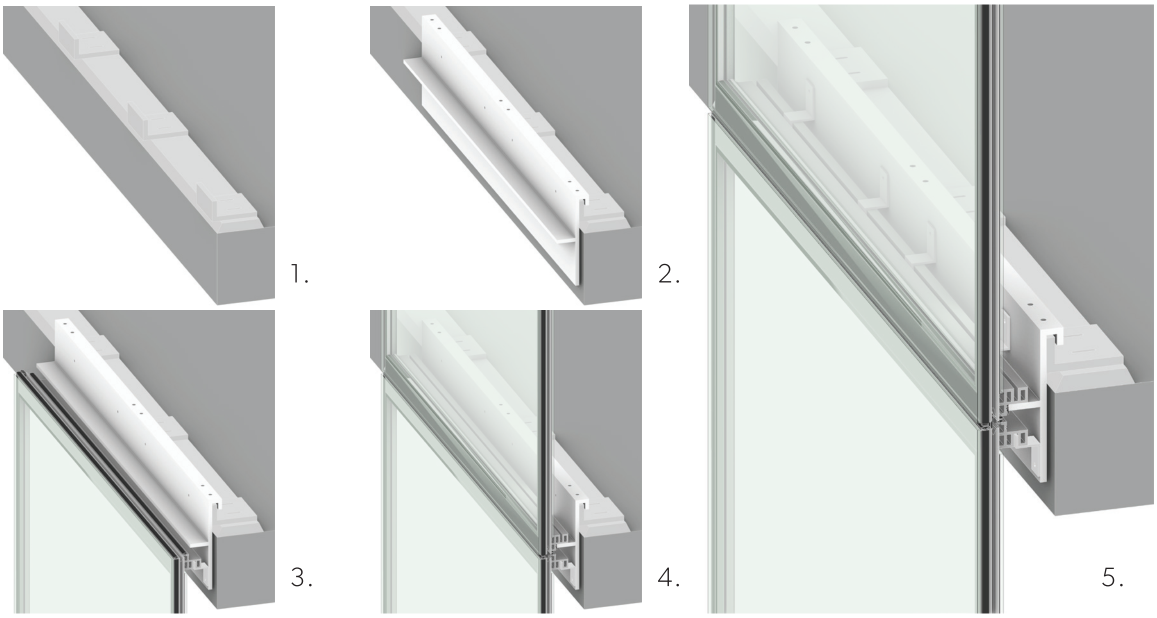
attached, is pushed into the gap between the glass (5). Next, the adhesive is applied on the corner connection element and the windowpane on the top or bottom of the panel (6). Then the profile is added to the panel (7). These last two steps are repeated on the other transom and following this on the remaining mullion to finish the whole frame. To finish the panel, the gaskets are added all around (8).

This panel will then be transported to the building site and attached to the main structure. The building order of this process can be found in figure 50. On-site first the floor needs to be prepared with mortar and an anchoring system. On top of that, the L shaped brackets are installed and adjusted to the right position (1). Then the T profile attaches to it after being adjusted for height (2). When the panel below is installed (3) the top panel can be placed on the T profile (4). With the weight of the panel supported it only needs to be secured in place. For this, the click elements are placed at the top and bottom and secured to the T profile (5).

To complete the building of the facade the weather seal needs

49. Panel assembly

Done in factory



50. Building order

Done on building site

to be applied on the outside and the inside. Afterwards, the fire barrier and the wanted isolation can be placed on the top or bottom part of the profile.

9.5 EVALUATION

At the beginning of the design process a set of design requirements were set out. Throughout the process, these where kept in mind when designing. The choices were made to meet these requirements, however they were not always achieved. To finalise the design process the design will be evaluated regarding the previous set requirements.

Transparency

For the transparency aspect, there were 3 requirements. The vertical mullion should have a maximum width of 75 mm next to being flush with the window pane and avoiding different materials showing through the window.

With the final design, the first requirement was not met. This had to do with the fact that along the process the second requirement weighted more in the decision making. In order to get the flush window, the mullion needed to be inserted into the glass panel thus having a width of 100mm.

As mentioned above the second requirement was met. Regarding the last requirement, the design met as only the texture and reflection of the silicone kit are visible. The other elements are also visible however because they are behind the glass they are less noticeable and thus achieve the wanted goal.

Unitised system
This aspect was one of the first to be met as it was decided on from the beginning. The panel can be assembled completely in the factory and afterwards be attached to the facade individually next to the same type of panel that fills the whole building. Thus it meets the requirement.

Maintenance
Regarding this requirement, it was solved by making the way the panel attaches to the facade a removable system with the help of a few elements which keep it in place.

Structural
As discussed thoroughly the deformation and stresses were within the allowable set by the building code.

Movement
In order to take into account the movements of the building the horizontal and vertical joints, which are identical, can move +/- 5 mm. Additionally, the chosen silicone kit is a weather sealant that can stretch and shrink 50% of its original width *(Dow, 2020)*.

Tolerances
To meet the tolerance requirements the facade element can move all the needed ways as explained in the previous chapter.

Regarding the tolerances within the panel itself, these were not looked into in-depth. The expectation is that the adhesive and butyl layer being a bit flexible will account for the discrepancies.

Safety
The panel first met the safety requirements by using laminated glass to prevent complete failure when breakage occurs. Secondly, it made use of a fire barrier so a fire would not spread through the connection point between the panel and the facade.

Thermal
For the thermal aspect, the required glazing was used and a check on the possibility of condensation was done. It could be concluded that no condensation would form and thus satisfying the requirement.

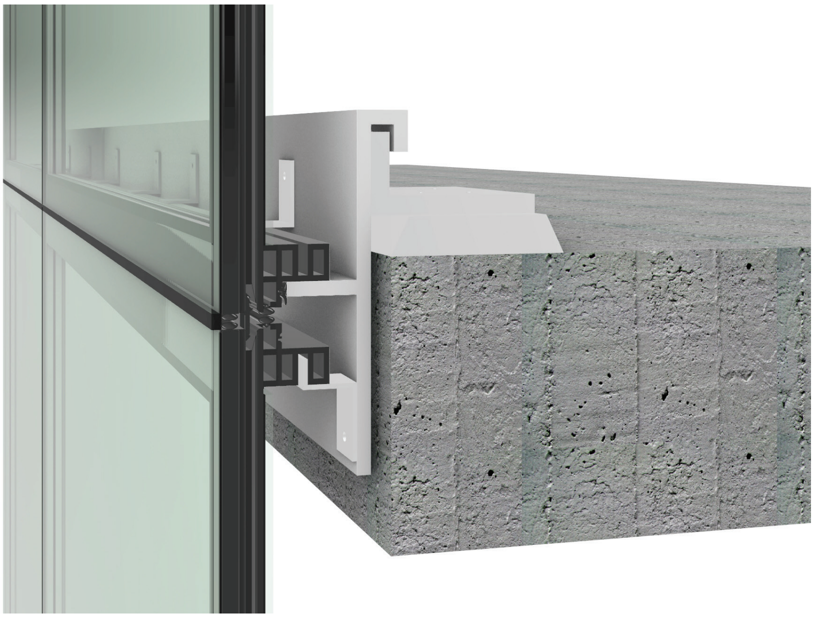
Air & Water
The gaskets used allow for the panel to move without there being a gap. This means that it can be assured that no air or water will get through. And even if it would get through the first barrier it could be drained through the panel cavity.

Sustainability
To already account for this before the end-of-life assessment would be completed the amount of adhesive on the mullion connection has been reduced to the minimum possible. This aspect will be dealt with further in the next chapter.

9.6 LIMITATIONS
The unitized panel design achieves great transparency however it has its limitations. Because the profile is very slender it deals with smaller tolerances than a normal unitized curtain wall panel would. This means that while building the panel it should be done with precision.

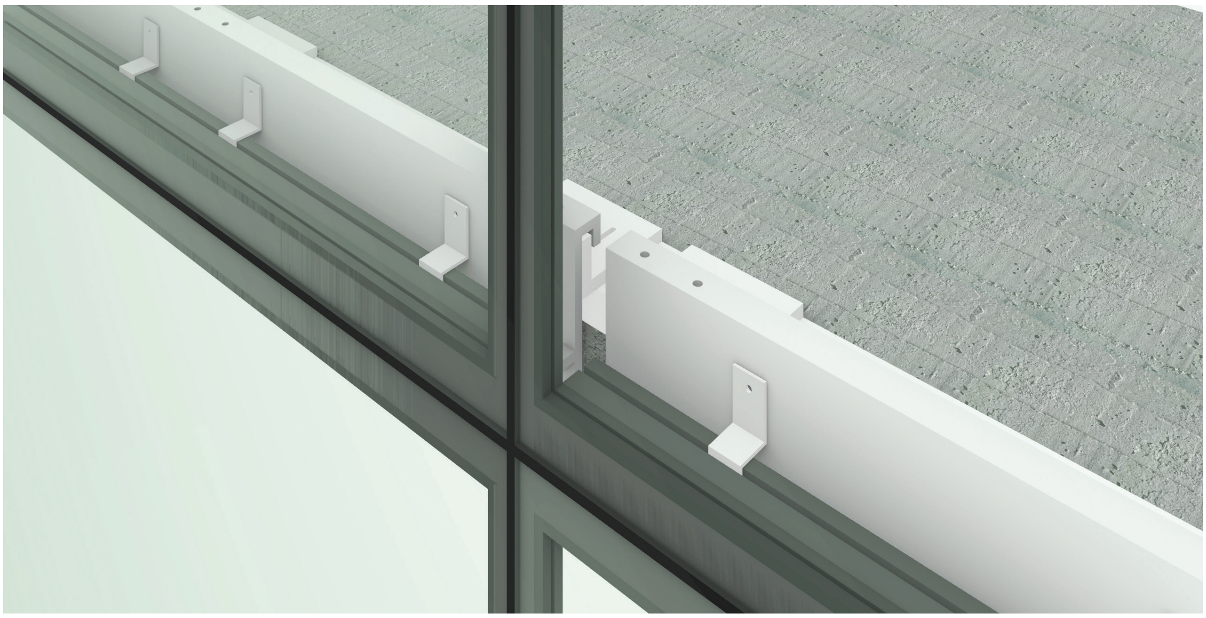
51. Entire facade front

The lowered ceiling and
floor are not included



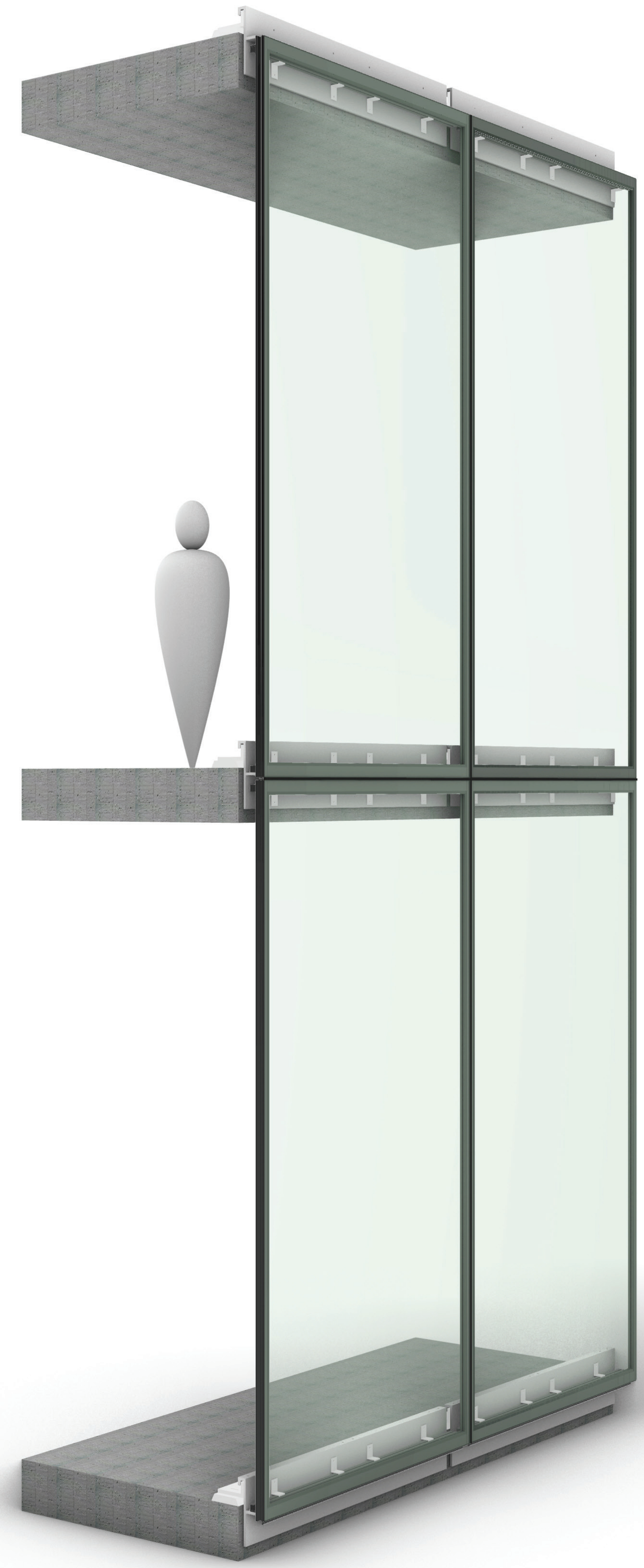
52. 3D Section

Focus on the detail



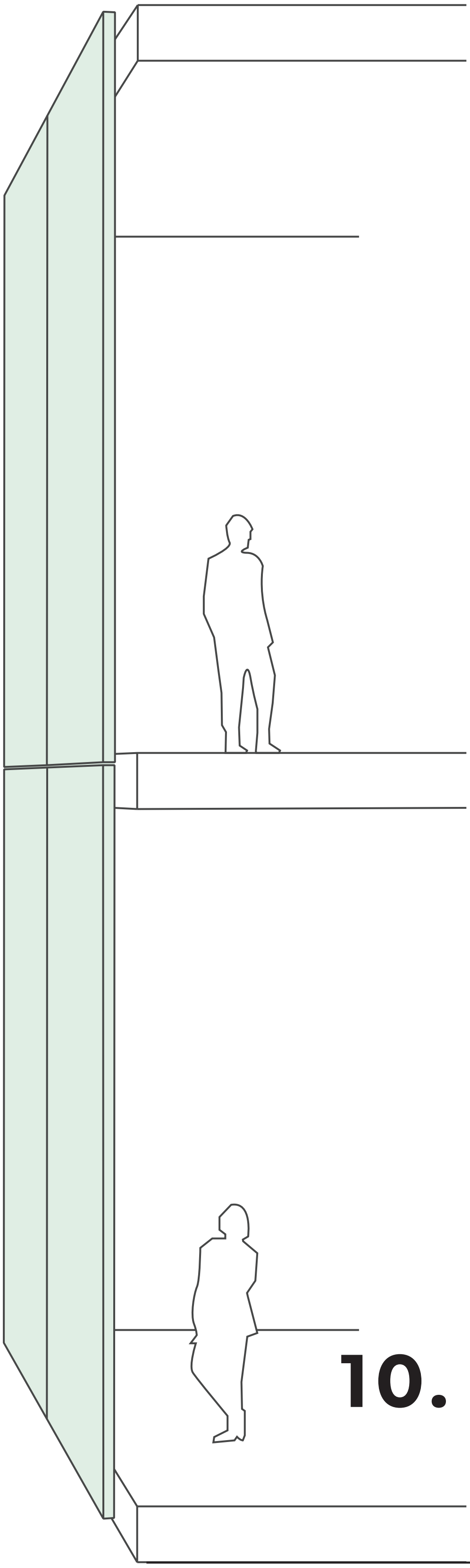
53. 3D facade front

Focus on the outside finish



54. Entire facade side

The lowered ceiling and
floor are not included



10. SUSTAINABILITY ASSESSMENT

10.1 INTRO

Nowadays sustainability is an aspect that is crucial to consider when designing any building component. Along the process, this was moderately considered but it was not the main goal. However, it is still interesting to define how the designed facade system impacts the environment at its end-of-life. This will give a greater understanding on how this facade panel performs in terms of sustainability compared to the existing market. Furthermore, the assessment can highlight where improvements could be made to better its impact on the environment.

10.2 METHOD

Within the building sector, the focus lays on improving the operational energy (OE) of the building. From previous research, it has been established that due to this focus the balance between embodied energy (EE) and OE has been shifted *(Chastas et al., 2017)*. This means that the EE has been dismissed when looking at sustainability, however, it has a great impact when looking at the whole life cycle of the facade. This is because the EE is influenced by the choice of materials and connection methods used in terms of manufacturing energy intensity, recycle potential and reuse potential at its end-of-life (EoL).

By using the method created by *Hartwell & Overend (2019)* not only can the sustainability performance of the different facades be compared to each other but also in terms of the different EoL scenarios possible.

The method provides a process-based life-cycle impact assessment which demonstrates the impact that different new or existing facade systems and EoL routes have on the environment in terms of embodied energy (EE) and carbon emissions also called global warming potential (GWP).

The first steps in this method are to gain expertise on what the facade panel is made of and how it is made. Firstly, an inventory of all the materials used in the panel and their mass is needed. This will give a better overview of the ratios of the materials used. Secondly, a diagram is made to show what the existing connections are in the facade and what type they are. By creating the diagram it can become clear what the challenges are when looking at the disassembly process.

As mentioned before this method looks at different EoL scenarios to compare them. The first two scenarios are most commonly used nowadays. Scenario 1 is based on the demolition of the facade and the disposal of all the materials through landfill. Scenario 2 is focused on recycling by either recycling to achieve the same product, down-cycling when recycling to the same material is not possible or energy recovery through incineration when both recycling and down-cycling are not an option. The remaining two scenarios focus on a EoL route that is placed higher on the waste hierarchy, namely reuse. In scenario 3 the facade components are all de-attached from one another and reused separately. Whilst in scenario 4 there is no need for disassembly as the whole facade system is reused at another building site.

With these four scenarios in place, the environmental impact can be calculated for each material per different facade system and per EoL route. The equation used for this is the following.

$$\sum_{i=1}^{n} Environmental\ Impact = \sum_{i=1}^{n} E_{Transport} + E_{Endlife} - E_{Recovery}$$

The first aspect that is accounted for is the environmental impact of the transport ($E_{Transport}$) to the correct destination which is, either a recycling facility, landfill or new building site. Secondly, it accounts for all the energy needed and $CO_{2\text{-equivilant}}$ produced during the recycling processes ($E_{Endlife}$). Lastly, all the energy and $CO_{2\text{-equivilant}}$ that is recovered by incineration and saved through recycling and reusing ($E_{Recovery}$) is subtracted to show the complete impact that the facade system in that scenario has on the environment.

10.3 SCOPE

The two facade systems that will be assessed are the Slim Skins, the novel glazing system developed in this paper and the recently build Triodos Bank in The Netherlands, also analysed in chapter 3.5.

Two of the aspects that impact the environment, $E_{Transport}$ and $E_{Endlife}$, have a negative impact whilst $E_{Recovery}$ will always have a positive impact as it produces or saves energy. For this study, only $E_{Recovery}$ will be taken into account. $E_{Transport}$ was not considered as the project location where the Slim Skins facade system will be placed is unknown and thus cannot be compared to that of the Triodos Bank. Furthermore, the $E_{Endlife}$ was not studied as some of the data was unavailable making the inventory incomplete for this aspect.

Additionally to these two aspects, the service life and performance degradation of the facade due to aeging was also not studied as it goes beyond the scope of the study.

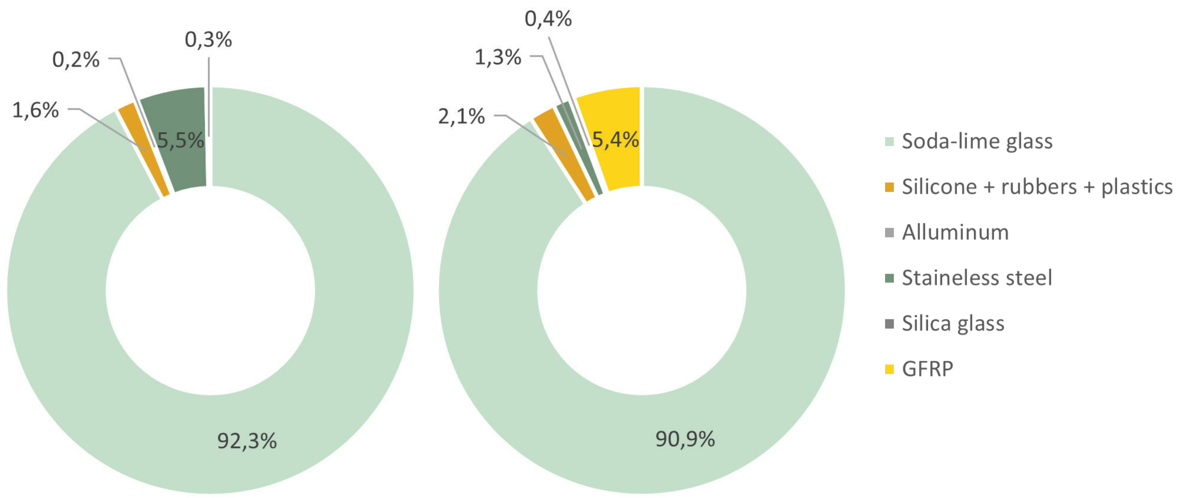
10.4 DATA

For the evaluation of the Slim Skins facade system, one panel of 2x4 meters was used. Here the connection elements to the floor and the fire insulation were not taken into consideration to simplify the assessment. Regarding the facade system of the Triodos Bank estimates were made by looking at the horizontal and vertical detail. It is known that a facade panel on this building is 3.2x1.9 meters. However to facilitate the comparison of the results of both panels it was assumed that the panel of the Triodos Bank was also 2x4 meters.

As previously stated an inventory of the components materials (figure 55) and type of connections is needed. Apart from gathering the mass of each material used in one panel, there is also a need to define if the material can be reused, recycled, incinerated, or ends up in the landfill.

Furthermore, the embodied energy and embodied $CO_{2\text{-equivilant}}$ at the recycling phase needs to be established. For the materials that cannot be recycled but can be incinerated for energy, it is important to know the energy and $CO_{2\text{-equivilant}}$ generated through combustion.

For the reuse scenario, it is necessary to know how much there



55. % Mass of facade panel in kg

Left: Triodos Bank

Right: Slim Skins

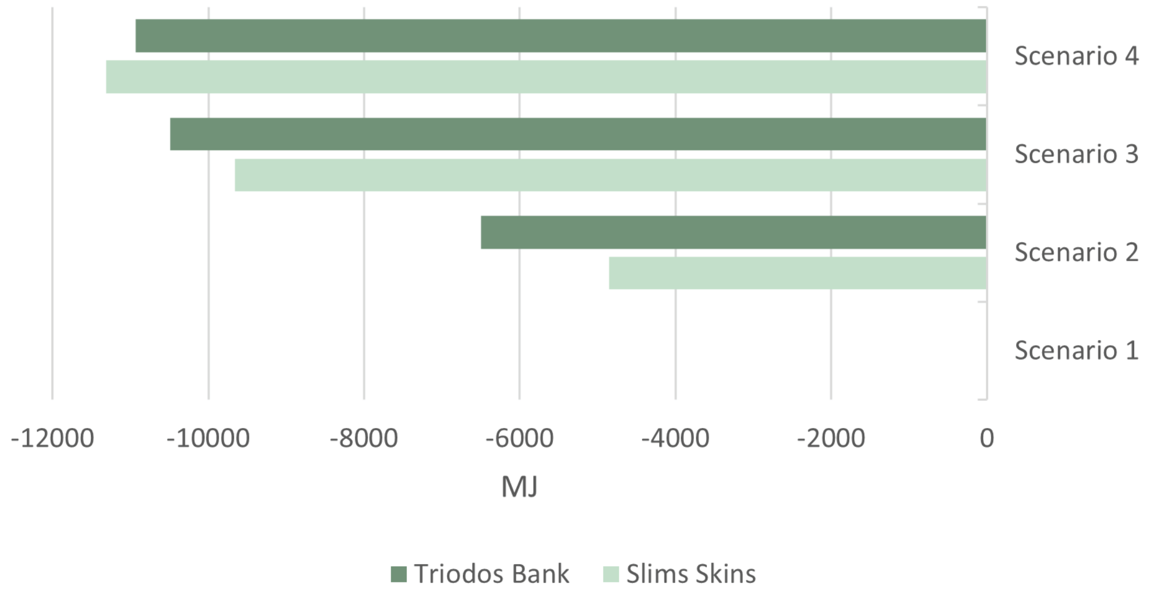
will be saved by preventing the re-production of that material as a whole. This value can be retrieved by making an inventory of the primary production embodied energy and $CO_{2\text{-equivilant}}$.

The materials embodied energy and $CO_{2\text{-equivilant}}$ data was gathered by using *CES EduPack software (2021)* where the average of the value range was used.

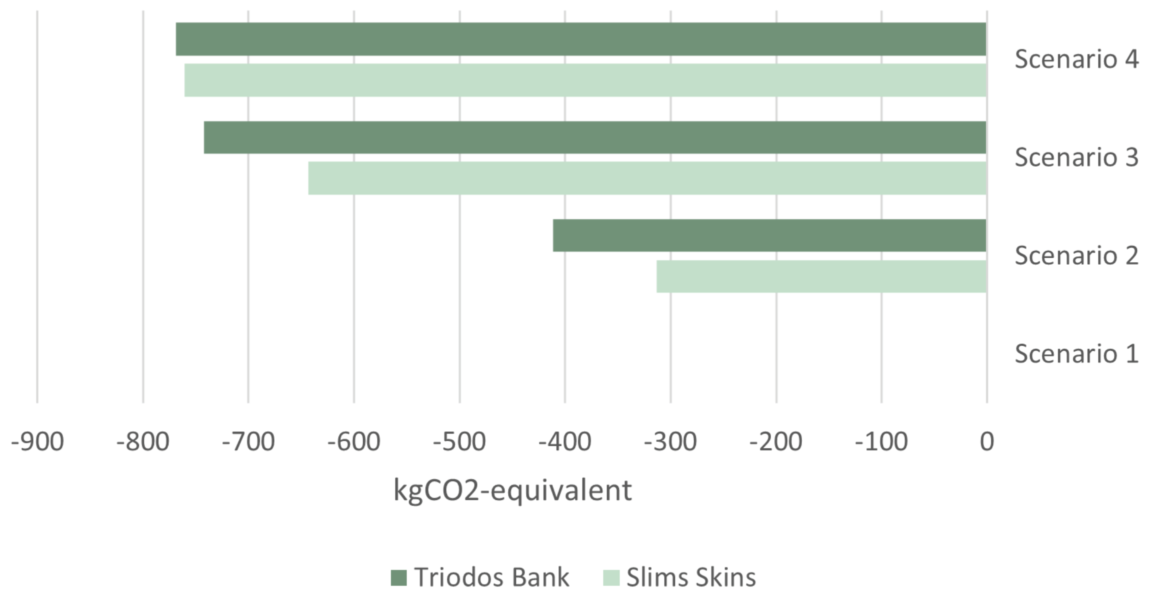
10.5 RESULTS

The results showed in figures 56 and 57 are on the negative side of the spectrum as it represents the energy and $CO_{2\text{-equivilant}}$ recovered at each EoL scenario which means that it has a positive environmental impact.

In these results al the polymer based materials, like rubbers, silicone gaskets, GFRP, and adhesives were incinerated for energy recovery. However, it is important to note that even though the plastics can be incinerated for energy recovery it has been shown that this is only a better option than landfill in terms of environmental impact in specific cases *(Eriksson & Finnveden,*



56. Environmental Impact EE
In terms of Embodied Energy



57. Environmental Impact GWP
In terms of global warming
potential (carbon emissions)

2009). For it to be a better alternative than incineration, the plant needs to have a high efficiency, a high electricity-to-heat ratio and can only be used to replace energy generated by fossil fuels. This means that in many cases landfill is a better option as there will be less energy recovered and $CO_{2\text{-equivilant}}$ saved than the amount of energy needed and $CO_{2\text{-equivilant}}$ produced during the process of incineration.

If the polymer based materials would not be incinerated but rather end up in the landfill $E_{Recovery}$ would decrease by at least 13% in terms of EE and 17% in terms of GWP for the Slim Skins system. For the Triodos Bank facade system, it would decrease by at least 5% in terms of EE and 6% in terms of GWP.

10.6 DISCUSSION & CONCLUSION SCENARIOS

When looking at the different EoL scenarios it can be concluded that scenario 4 has the most environmental savings, regardless of which of the two facade panels is looked at. This scenario is thus considered the baseline to which other scenarios can be compared. This means that scenario 4 can be assumed being 100% fully re-use potential (FRP).

The approach of scenario 3 scores the best with an average FRP of 90.7% in terms of EE and 90.6% in terms of GWP. The next best EoL route is scenario 2 which exploits the FRP to an average of 51.2% in terms of EE and 47.5% in terms of GWP. Last comes scenario 1 which does not have any environmental savings as all the material goes directly to the landfill.

The results in this study only look at the energy saved disregarding the energy it needs to accomplish this, as previously mentioned in chapter 10.3. From the study done by *Hartwell & Overend (2019),* it can be observed that even with the $E_{Transport}$ and $E_{Endlife}$ accounted for the order of best to worst scenario remains the same. However, the value is significantly lower for scenario 2 due to the impact of the recycling processes.

From these results, it can be concluded that scenarios 3 and 4 are the best option as it has an increased environmental savings of at least 1.8 times higher in terms of EE and 1.9 in terms of

GWP compared to scenario 2. When taking the environmetal impact of transport and end-of-life process into account, it is expected that the benefit of re-use will be even higher.

Nowadays the most common EoL route is scenario 2: recycling. However, with this assessment, it can be determined that re-use is more beneficial and thus new designs should allow for such EoL scenario.

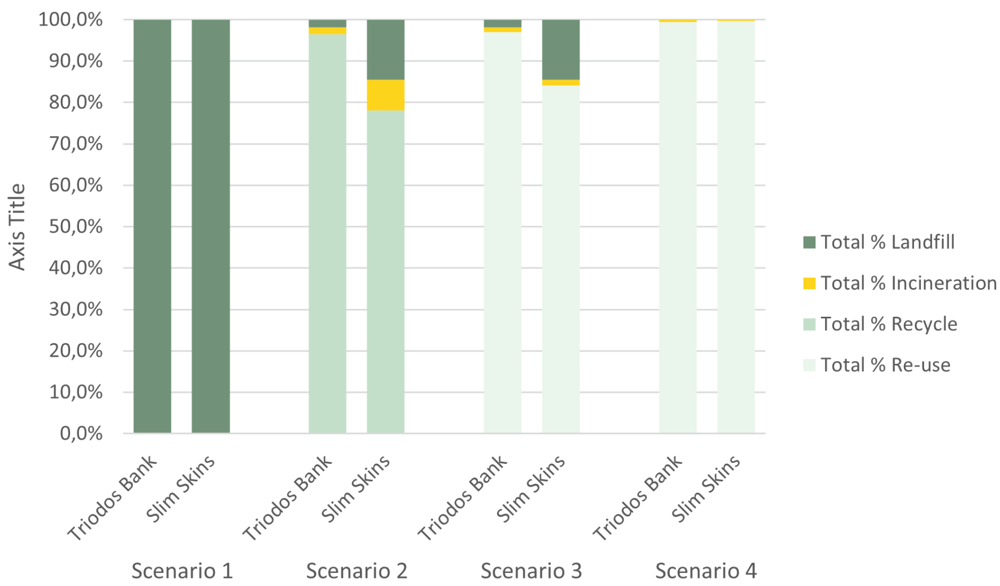
10.7 DISCUSSION & CONCLUSION SYSTEMS

As mentioned above re-use of components or the whole system are the best scenarios in terms of environmental impact when it comes to EoL routes. Thus, when comparing the different facade types scenarios 2 and 1 are not discussed further.

When looking at scenario 3: components reuse it can be seen in figure 58 EoL that the Triodos Bank facade system has the highest percentage of the weight of its materials that can be reused (97%) whilst for the Slim Skins system only 84% of the weight of its materials can be reused. This difference is also seen in the environmental impact regarding EE and GWP. This is mainly due to the amount of glass that needs to be cut away because of the adhesive residue left behind. In the connection diagram from the Slim Skins system (figure 59), it can be seen that the adhesive connections play a great role and thus more glass will be unable to be re-used.

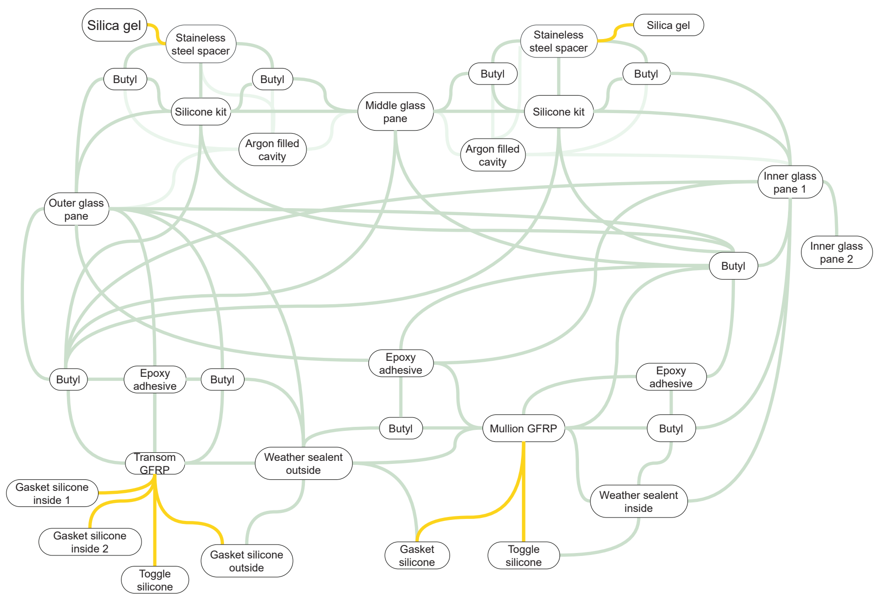
For scenario 4, where the whole system is reused elsewhere, the Slim Skins system has 0.3% more material weight that can be re-used than the facade system of Triodos Bank (figure 58). This small difference is a bit more present when looking at the environmental impact regarding the EE (figure 56). This can be attributed to not having to cut the glass like in scenario 3, as it does not need to be separated from the other elements. Al in all it can be said that both facade systems perform similarly when looking at the end-of-life environmental impact.

However, in scenario 4, it should be considered that dismantling all the elements and building it up again at another site can come with issues such as damage or loss of parts. So in that case Slims



58. Material EoL by weight %

Per each scenario and facade system



59. Connection diagram

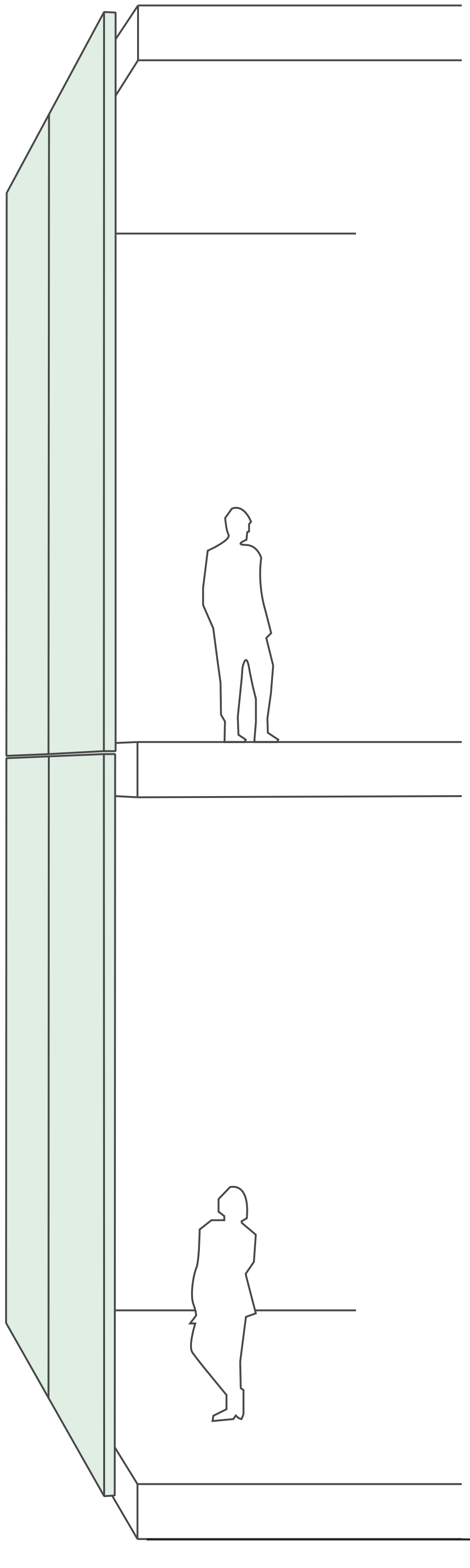
Slim Skins facade system

Skins has a small advantage of being a unitized system and thus ensuring an easy relocation.

10.8 IMPROVEMENTS & FUTURE RESEARCH

From the assessment, it became clear that the future of EoL routes is reuse, preferably as a whole. This can not always be the case and thus reusing the components separately should also be an option. Because the Slim Skins system has such a large amount of adhesive connections it can be difficult to disconnect all elements for reuse. To improve this system in terms of EoL sustainability future research should focus on three aspects.

First, new methods are needed to break the adhesive connection between materials to allow for disassembly. Secondly, more research is needed in the process to remove adhesive residue from certain materials to be able to reuse the component in many ways. Lastly, the way of connecting certain materials could be explored further staying away from adhesives by looking at interlocking systems. This would allow for easier disassembly of individual components, however, it should not jeopardise the unitized nature of the facade system or the amount of transparency it provides.



11. FINAL CONCLUSION

11.1 RESEARCH QUESTION

At the beginning of the study, the main research question was defined. To help answer this question and help conclude on the study, the sub-questions will be addressed first. The sub-questions and the corresponding answers can be found below.

- *What characteristics of a unitized facade system are desired to adopt?*

As was discussed in chapter 4.3 the desired characteristics of a unitized facade system are the ability to assemble the panel at the factory, the possibility of repeating the panel along the building. And lastly, the panel can be individually attached onto the buildings main structure. This will allow for an easy process when removing the panel due to needed maintenance.

- *What defines a higher transparency?*

A high transparency of the facade panel is defined by a small width of the mullion, having all the structural elements flush to the windowpane, and using as few different materials as possible too avoid many textures, colours, and reflections (chapter 4.3).

- *What are further design requirements a facade panel needs to meet in order to be a credible system?*

Based on the information gathered in chapter 4.3 it can be concluded that to have a credible system it needs to take into account the structural feasibility, the movement restriction, the tolerances allowed, the safety need, the thermal performance, and the air- and water-tightness.

- *How can the design concepts be evaluated and optimised to achieve set goals?*

To evaluate and optimise the design concepts, hand calculations using known formulas, analyses with a finite element and a heat-transfer software and visual observation can be used. This study illustrates the validity of these methods in chapter 7, 8, 9, and 10.

- *How can the designed facade element be evaluated in terms of sustainability?*

In this research the sustainability evaluation was regarding the end-of-life of the design. This was done by using four possible scenarios and comparing the embodied energy and $CO_{2\text{-equivilant}}$ emissions from each. Furthermore, these results were compared to a facade system already on the market to place the results in context.

Now that the sub-questions have been answered, the main research question can be answered. The research question explored in this thesis was: *How can a unitized facade system achieve a higher transparency?*

To achieve such high transparency in a unitized system, the concept of composite action was used. This allowed the panel to require a minimum amount of profile dimensions, as it uses the glass as the main stiffness element. The design was evaluated to determine if it would be viable to use it in practice. In theory, it satisfies all of the objectives and most of the requirements.

With the final design proposed to answer the research question, there were some challenges. The design is quite intricate in terms of its profile. Considering this together with the size of the panel itself, complications can be expected while building as a high precision is required even if the tolerances are taken into account.

Another challenge is the amount of adhesive used. This has a negative effect on the end-of-life of the panel as it can be hard to remove and disassemble all the elements for recycling or reuse. However, for the reuse of the complete system, it does provide an easier transfer process from and to the new building site.

11.2 FURTHER RESEARCH

Along the process of answering the set research question some points were found that can be investigated in future work.

- A further insight into the tolerances whilst assembling the panel.

- Testing the design physically to see if there are aspects that need further redesign.

- Calculate the influence of the profile within the panel on the overall U value according to *EN ISO 10077-2 (2017)*. This can be of influence when designing the detail and choosing the appropriate profile.

- Elaborate on the adhesive study to better compare the properties and try and see if there could be a design using silicone-based adhesive.

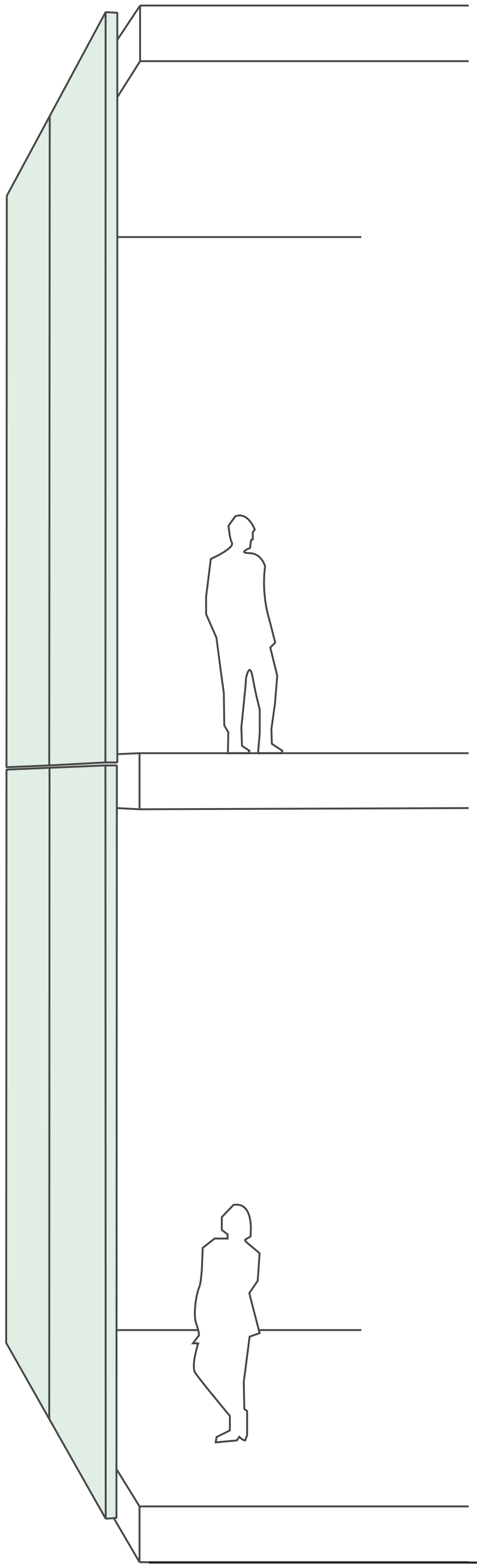
- Research about the chemical reaction and possible deterioration, even delamination of the adhesive chosen when coming in contact with the silicone kit.

- Determining to which extend there is composite action possible between wood and glass. Furthermore researching the adhesives comparability with the material.

- Explore new methods to break the adhesive bond of rigid adhesives to separate materials from each other.

- Research further on possibilities to remove adhesive residue from certain materials to allow for better recycling and reuse of the component.

- Explore other designs which use an interlocking system to connect different material components, without jeopardizing the unitized and transparency aspect of the panel.



APPENDIX

A. ADHESIVE PROPERTIES

	SIKADUR 330	3M DP490	3M 2216B/A	HOLDTITE 3295	SIKAFORCE 7550 L15	SIKAFLEX 265	DOW DC993
shear modulus (MPA)	a. 1900	a. 49	b. 201.88	b. 195.89	b. 1.5	a. 0.5	a. 0.03
Yield strength (MPa)	d. 33.8	e. 30.3	f. 24	g. 25	h. 5	i. 7.2	j. 0.95
Thermal expansion coefficient	9.09 - 9.23	9.09 - 9.23	8.08 - 10.24	9.04 - 9.28	-21.14 - 39.46	-121.75 - 140.07	-278.72 - 297.04

60. Adhesive properties & sources

a. *Pascual et al. (2017)*
b. *Overend et al. (2011)*
d. *Sika Corporation (2018)*
e. *3M (1996)*
f. *3M (2009)*
g. *Holdit Australia (n.d.)*
h. *Sika Nederland (2010)*
i. *Sika Corporation (2020)*
j. *Dow Corning (2011)*

B. THERMAL EXPANSION

Lenght	4	m		
Temperature difference	55	Celsius		
Adhesive				
Thickness	0,2	mm	2,00E-04	m
Shear modulus	0,19589	GPa	1,96E+08	N/m²
Yield strenght	25	MPa	2,50E+07	N/m²
Glass				
Thermal expansion coeficcient	9,16E-06	1/Celsius		

Thermal expansion glass =	total lenght * temperature difference * thermal expansion coefficient
	2,02E-03
Max shear strain of adhesive =	Yield strenght / shear modulus
	1,28E-01
Max displacement with 2mm adhesive =	Max shear strain * thickness
	2,55E-05
Max thermal expansion profile =	Max displacement + thermal expansion glass
	2,04E-03
Max thermal expansion coefficient profile =	max thermal expansion / (total lenght * temperature difference)
	9,28E-06
Min thermal expansion profile =	Thermal expansion glass - Max displacement
	1,99E-03
Min thermal expansion coefficient profile =	Min thermal expansion / (total lenght * temperature difference)
	9,04E-06

9,04E-06	<	Thermal expansion coefficient	<	9,28E-06

61. Thermal expansion coefficient calculations
Based on the adhesive Holdtite 3295

C. STRUCTURAL CALCULATIONS

Profile 1	**y (m) =**	**0,034**	**tot A (m) =**	**0,00665171**				
hA (mm)	8		hB (mm)	44		hC (mm)	12	
bA (mm)	288,586		bB (mm)	20		bC (mm)	288,586	
IA (mm4)	12313		IB (mm4)	141973		IC (mm4)	41556,3	
AA (mm2)	2308,68		AB (mm2)	880		AC (mm2)	3463,03	
dA (mm)	31		dB (mm)	6		dC (mm)	22	
Profile 2	**y (m) =**	**0,034**	**Profile 3**	**y (m) =**	**0,023**	**Profile 4**	**y (m) =**	**0,03**
tot A (m) =	**0,00727**		**tot A (m) =**	**0,00342868**		**tot A (m) =**	**0,00373**	
hD(mm)	62	200	hE(mm)	56		hI(mm)	10	
bD (mm)	10	85	bE (mm)	20		bI (mm)	30	
ID (mm4)	198607		IE (mm4)	292693		II (mm4)	2500	
AD (mm2)	620		AE (mm2)	1120		AI (mm2)	300	
dD (mm)	3		dE (mm)	11		dI (mm)	37	
			dA'(mm)	20		dA"(mm)	27	
						dE'(mm)	4	
						Profile 5	**y (m) =**	**0,031**
						tot A (m) =	**0,00112**	
						hI(mm)	56	
						bI (mm)	20	

62. Second moment of area (I)

Of each different profiles

Wind load (w)	1725,00	N/m	Deadload glass 1 mullion (F) =	p*Ag*tg*gravity*0,375		
Length profile (L)	4	m			1905,3	N
Density Glass (p)	2490	kg/m3	Shear force (Vx)=	w((L/2)-x)		
Area glass (Ag)	8	m2		3450	N	
			Allowable Deflection =	L/200		
				0,02	m	
			Minimum EI needed =	(5* w * L^4) / (384 * allowable deflection)		
				2,88E+05	N*m2	

63. Base values for structural calculations

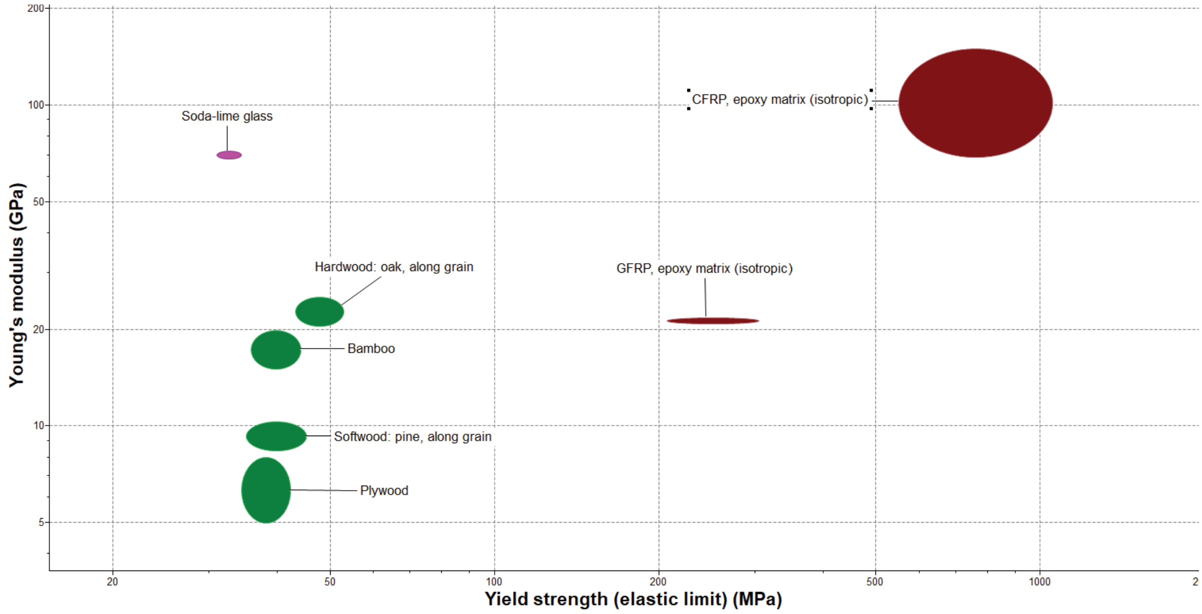
Same for all the profiles

Itot Profile 1 =	(IA+AAdA^2) + (IB+ABdB^2) + (IB+ABdB^2)				**My =**	((wL^2) / 8) * y			
	4,12E+06	mm4	4,12E-06	m4		1,17E+02	Nm2		
Minimum E scenario 1 =	Itot scenario 1 / Minimum EI needed				**Stress bending =**	My / I			
	6,97E+10	N/m2	6,97E+04	MPa		2,85E+07	N/m2		
Stress max scenario 1 =	stress bending + stress axial + stress shear				**Stress axial =**	F / total area			
	4,18E+07	N/m2	42	MPa		2,86E+05	N/m2		
					Stress shear =	(V/th)			
						1,31E+07	N/m2	13,07	MPa
Itot Profile 2 =	(IA+AAdA^2) + (IB+ABdB^2) + (IB+ABdB^2) + (ID+AD				**My =**	((wL^2) / 8) * y			
	4,33E+06	mm4	4,33E-06	m4		1,17E+02	Nm2		
Minimum E scenario 2 =	Itot scenario 1 / Minimum EI needed				**Stress bending =**	My / I			
	6,65E+10	N/m2	6,65E+04	MPa		2,71E+07	N/m2		
Stress max scenario 1 =	stress bending + stress axial + stress shear				**Stress axial =**	F / total area			
	4,04E+07	N/m2	40	MPa		2,62E+05	N/m2		
					Stress shear =	(V/th)			
						1,31E+07	N/m2	13,07	MPa
Itot Profile 3 =	(IA+AAdA'^2) + (IE+AEdE^2)				**My =**	((wL^2) / 8) * y			
	1,36E+06	mm4	1,36E-06	m4		7,94E+01	Nm2		
Minimum E scenario 3 =	Itot scenario 1 / Minimum EI needed				**Stress bending =**	My / I			
	2,11E+11	N/m2	2,11E+05	MPa		5,82E+07	N/m2		
Stress max scenario 1 =	stress bending + stress axial + stress shear				**Stress axial =**	F / total area			
	6,90E+07	N/m2	69	MPa		5,56E+05	N/m2		
					Stress shear =	(V/th)			
						1,03E+07	N/m2	10,27	MPa
Itot Profile 4 =	(IA+AAdA"^2) + (IE+AEdE'^2) + (II+AIdI^2)				**My =**	((wL^2) / 8) * y			
	2,42E+06	mm4	2,42E-06	m4		1,04E+02	Nm2		
Minimum E scenario 4 =	Itot scenario 1 / Minimum EI needed				**Stress bending =**	My / I			
	1,19E+11	N/m2	1,19E+05	MPa		4,28E+07	N/m2		
Stress max scenario 1 =	stress bending + stress axial + stress shear				**Stress axial =**	F / total area			
	5,36E+07	N/m2	54	MPa		5,11E+05	N/m2		
					Stress shear =	(V/th)			
						1,03E+07	N/m2	10,27	MPa
Itot scenario 5=	(bh^2)/12				**My =**	((wL^2) / 8) * y			
	2,93E+05	mm4	2,93E-07	m4		1,07E+02	Nm2		
Minimum E scenario 5 =	Itot scenario 1 / Minimum EI needed				**Stress bending =**	My / I			
	9,82E+11	N/m2	9,82E+05	MPa		3,65E+08	N/m2		
Stress max scenario 1 =	stress bending + stress axial + stress shear				**Stress axial =**	F / total area			
	3,77E+08	N/m2	377	MPa		1,70E+06	N/m2		
					Stress shear =	(V/th)			
						1,03E+07	N/m2	10,27	MPa

64. Structural calculations

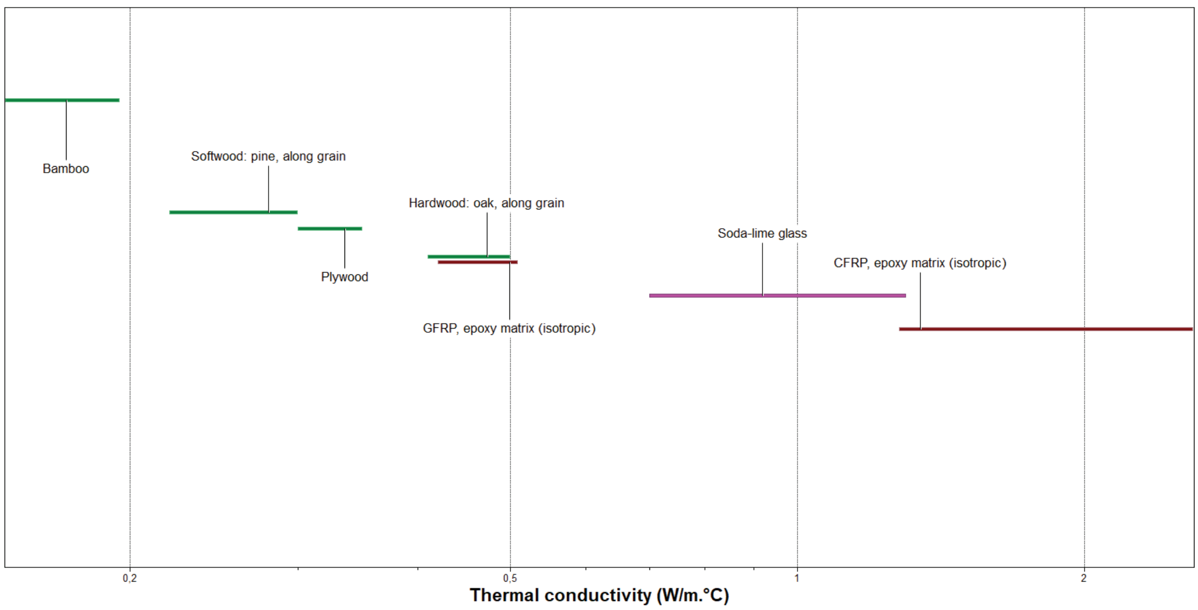
For each different profiles

D. MATERIAL CHOICE ANALYSIS



65. Young's modulus & yield strength

Suitable materials



66. Thermal conductivity

Suitable materials

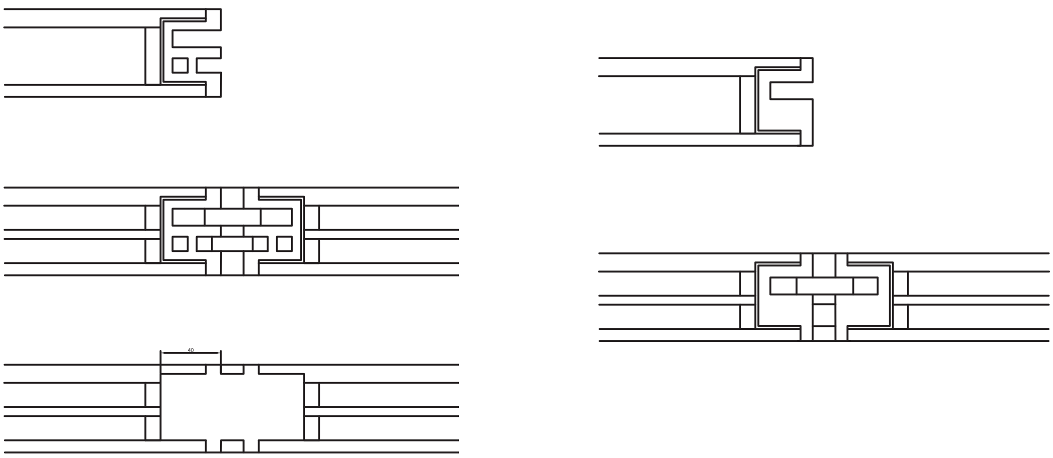
E. DESIGN OPTIONS SIMPLIFIED

Top: structural
Middle: thermal
Bottom: visual

Right: FRP
Left: Wood

Scale 1:5
Visual is the same for both FRP and Wood

67. Design A - FRP & Wood

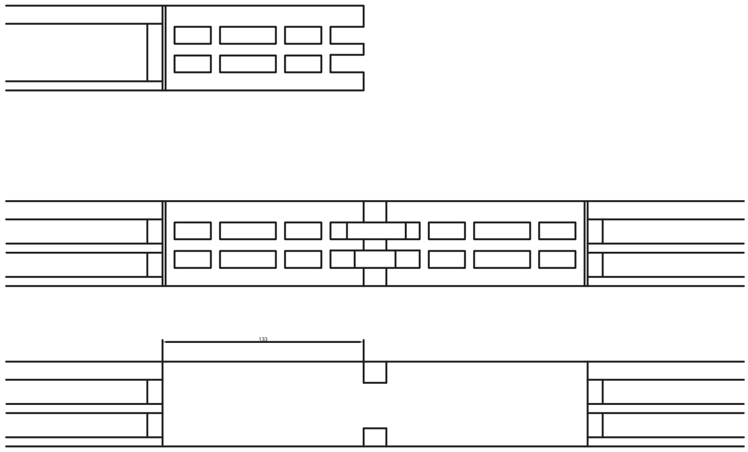


Top: structural
Middle: thermal
Bottom: visual

Right: FRP
Left: Wood

Scale 1:5
Visual is the same for both FRP and Wood

68. Design B - FRP & Wood



Top: structural
Middle: thermal
Bottom: visual

Scale 1:5

69. Design C - FRP

F. MATERIALS USED ANALYSIS

The material properties used where retrieved from *CES EduPack software (2021)*.

GFRP
Young's modulus: 21000 MPa
Yield strength: 207 MPa
Thermal conductivity: 0.42 W/m°C

CFRP
Young's modulus: 69000 MPa
Yield strength: 550 MPa
Thermal conductivity: 1.28 W/m°C

Oak
Young's modulus: 20600 MPa
Yield strength: 43.2 MPa
Thermal conductivity: 0.41 W/m°C

Plywood
Young's modulus: 5000 MPa
Yield strength: 34.4 MPa
Thermal conductivity: 1.28 W/m°C

Glass
Young's modulus: 68200 MPa
Yield strength: 31 MPa
Thermal conductivity: 0.7 W/m°C

Bamboo
Young's modulus: 15100 MPa
Yield strength: 35,8 MPa
Thermal conductivity: 0.148 W/m°C

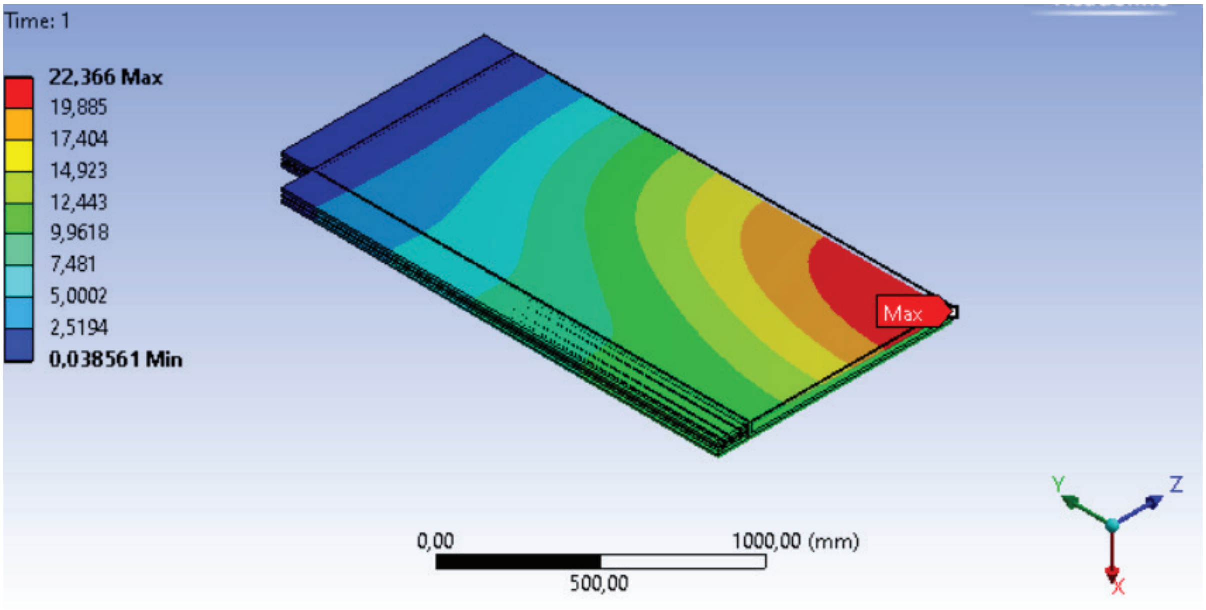
Pine
Young's modulus: 8400 MPa
Yield strength: 35 MPa
Thermal conductivity: 0.22 W/m°C

Stainless steel
Thermal conductivity: 17 W/m°C

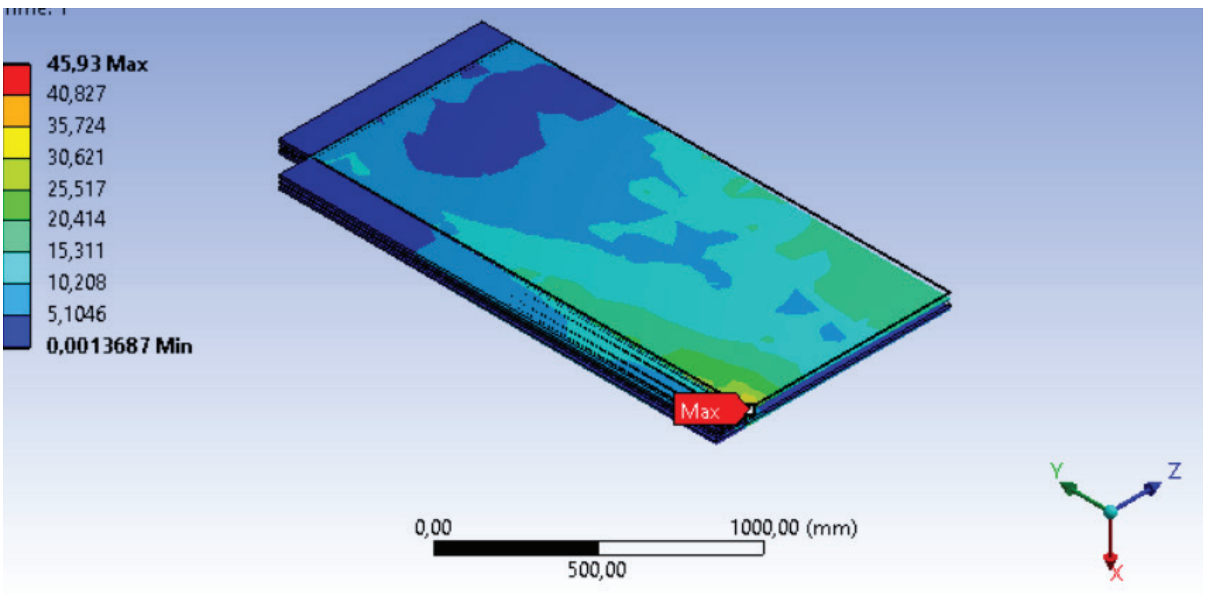
Silica gel
Thermal conductivity: 0.03 W/m°C

Silicone
Thermal conductivity: 0.2 W/m°C

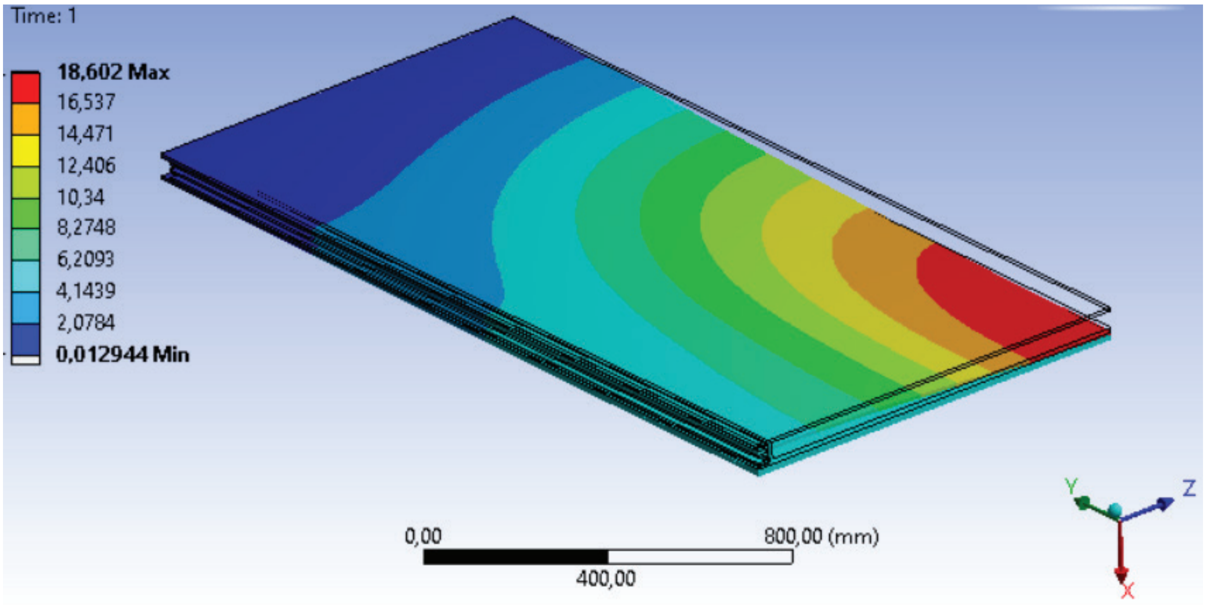
G. STRUCTURAL ANALYSIS



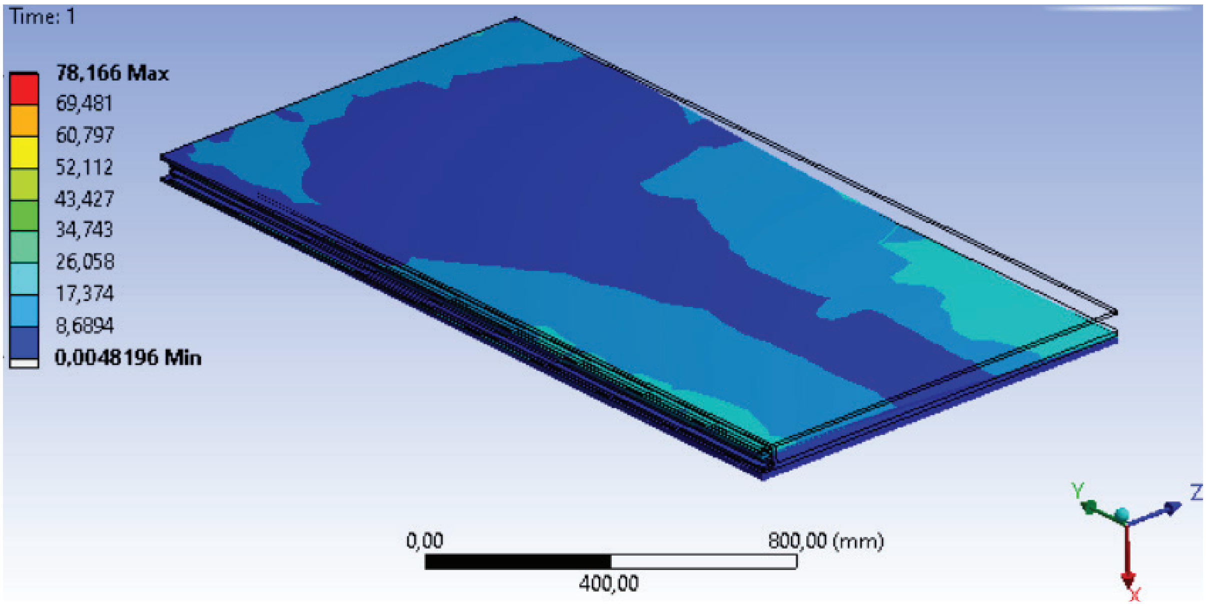
70. Design C CFRP - Deflection



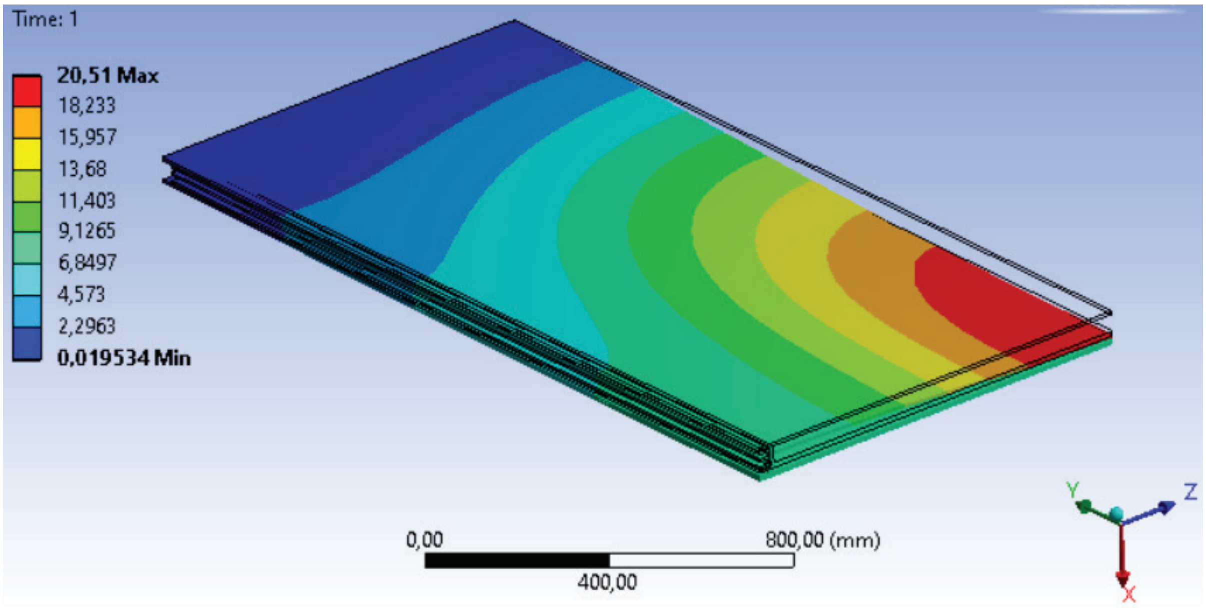
71. Design C CFRP - Stress



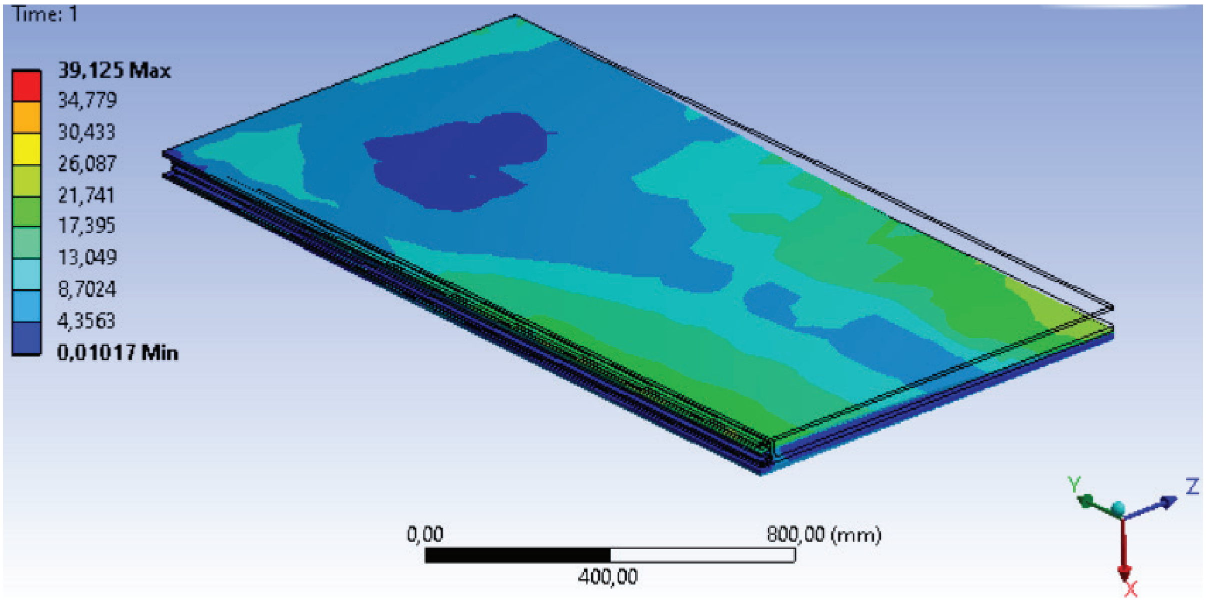
72. Design A CFRP - Deflection



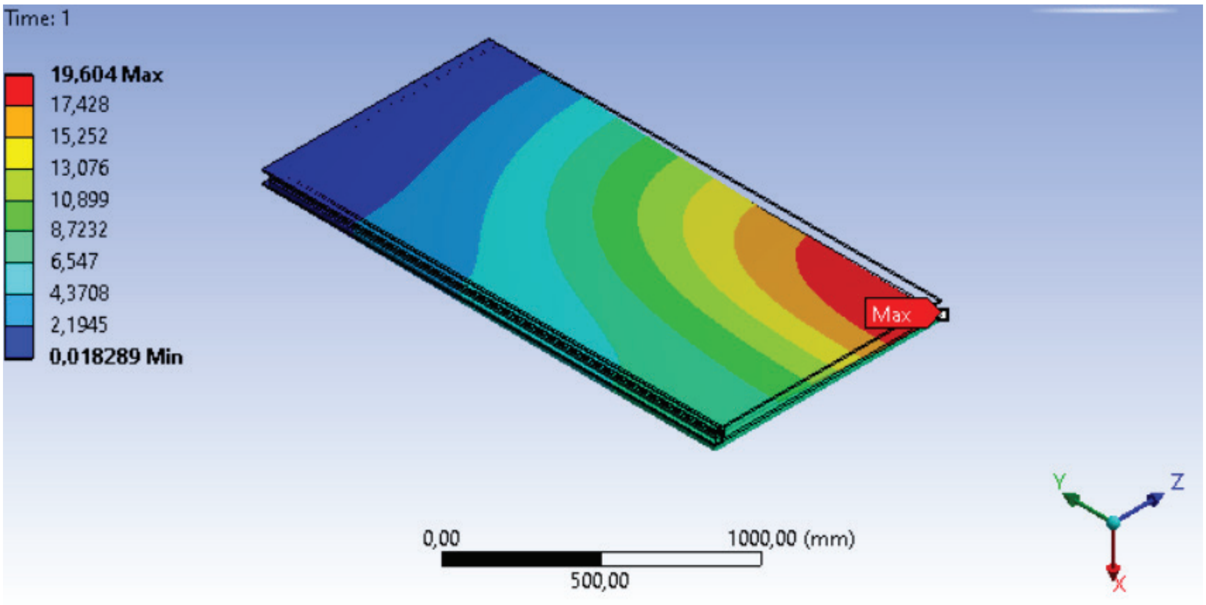
73. Design A CFRP - Stress



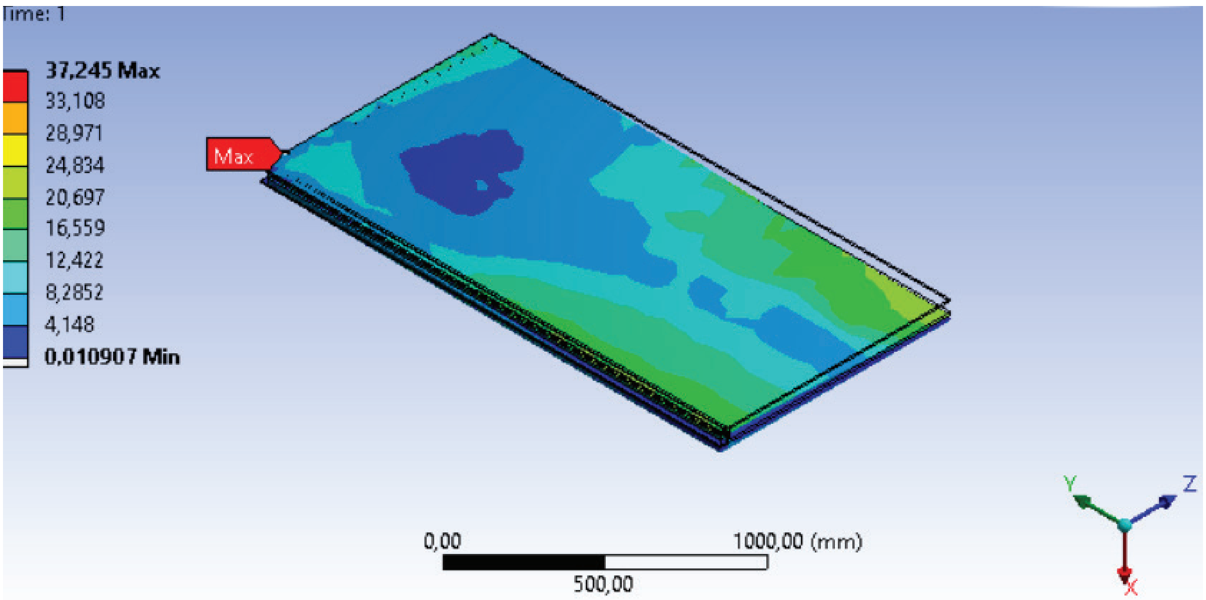
74. Design A GFRP - Deflection



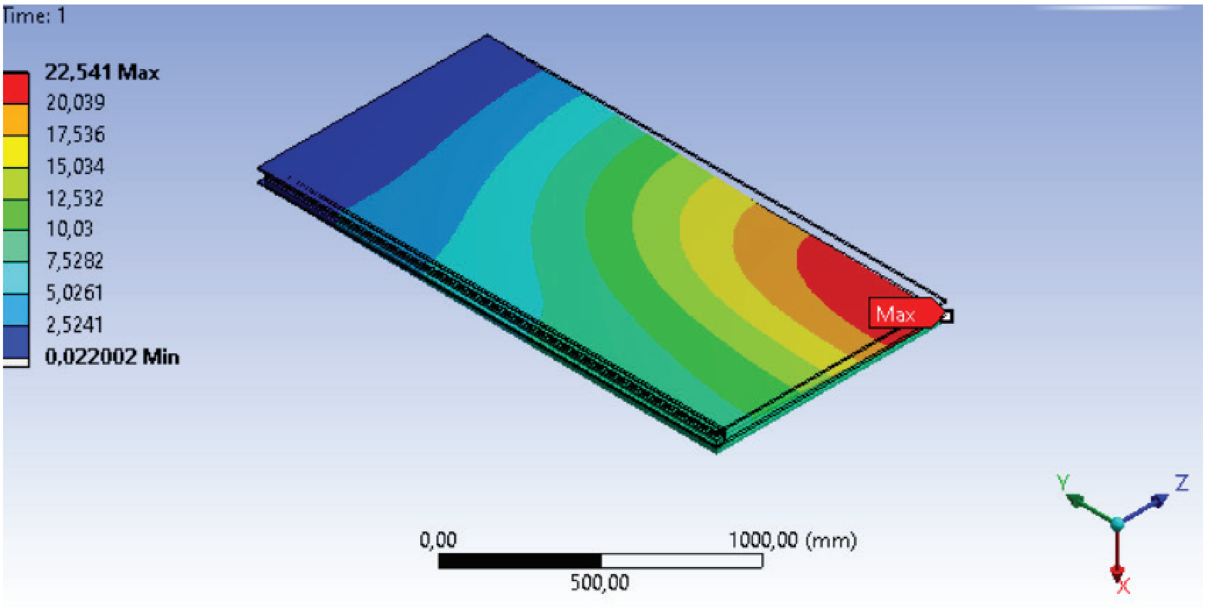
75. Design A GFRP - Stress



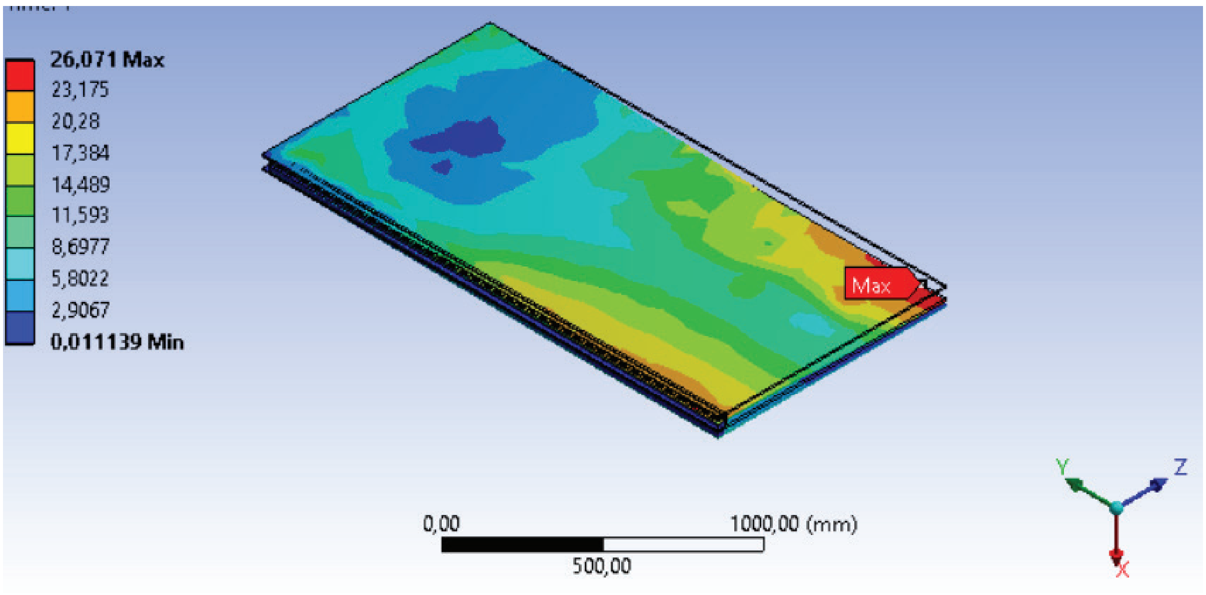
76. Design A Oak - Deflection



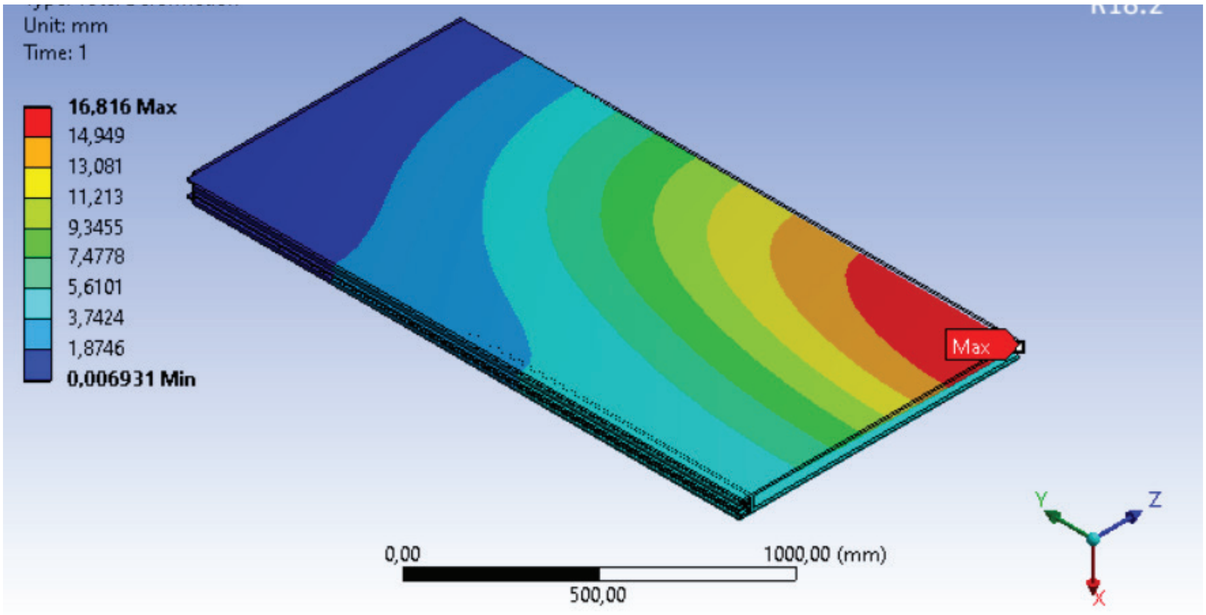
77. Design A Oak - Stress



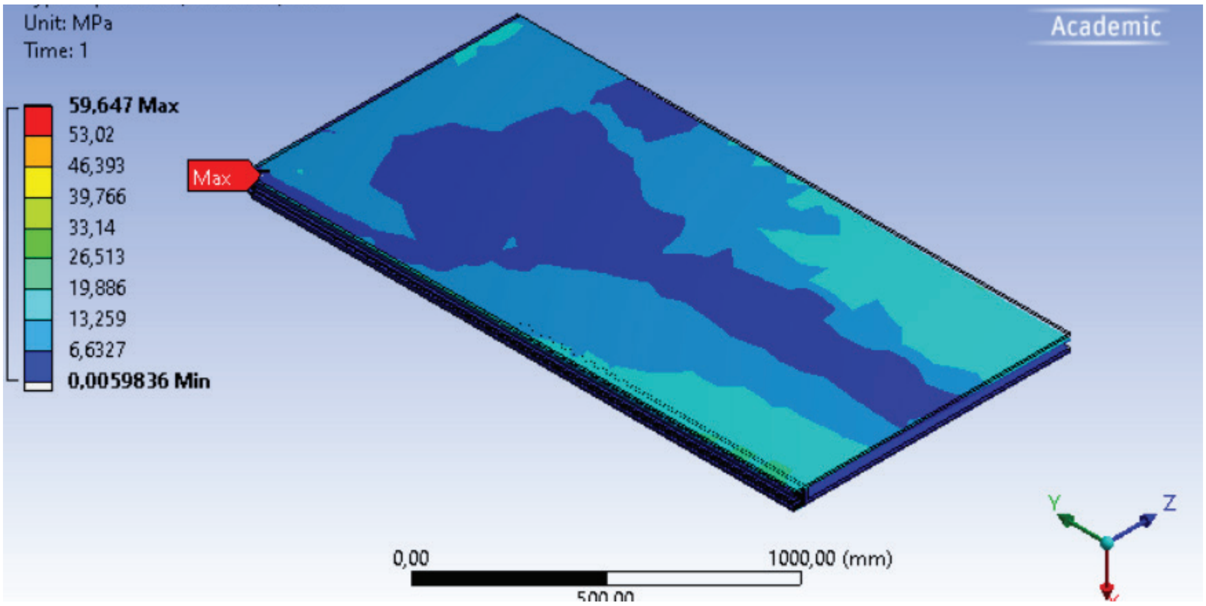
78. Design A Plywood - Deflection



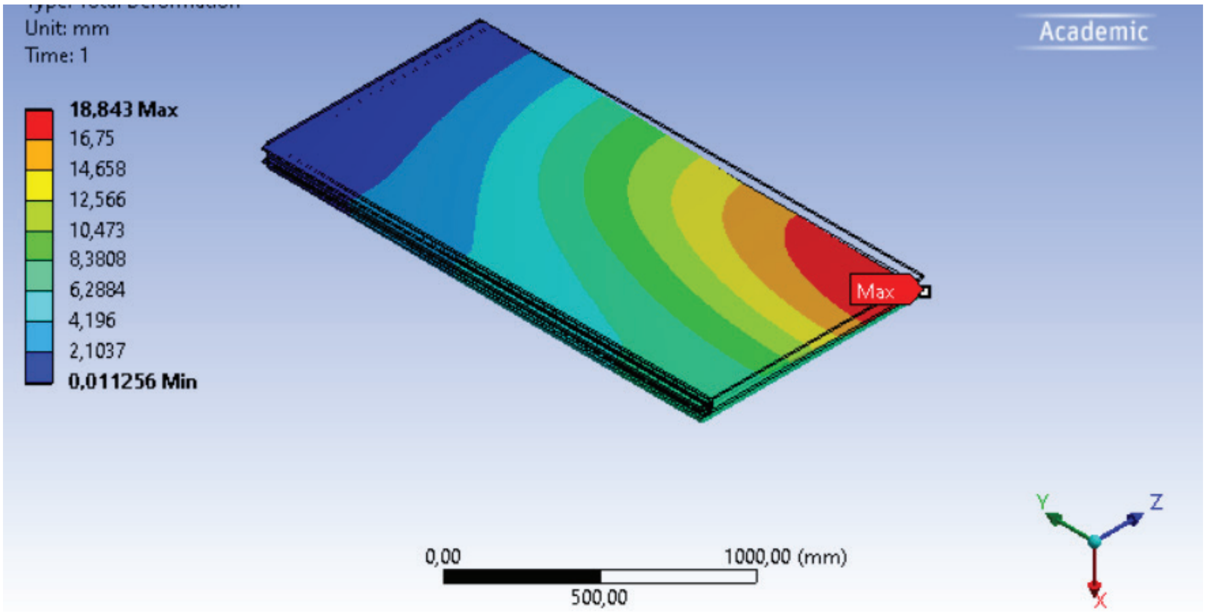
79. Design A Plywood - Stress



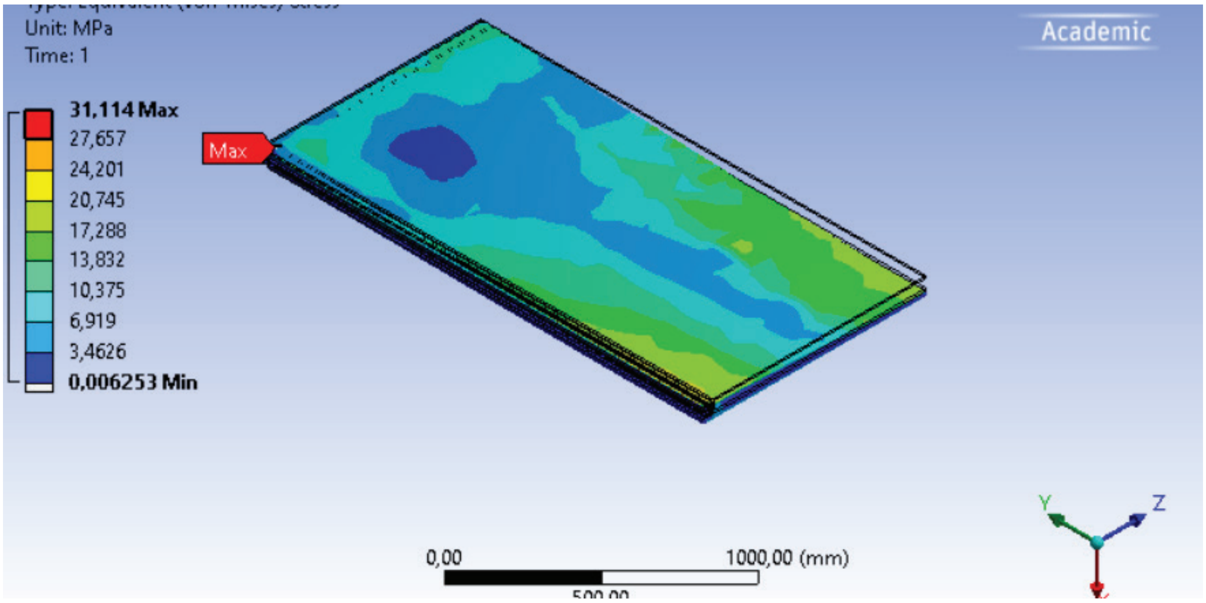
80. Design B CFRP - Deflection



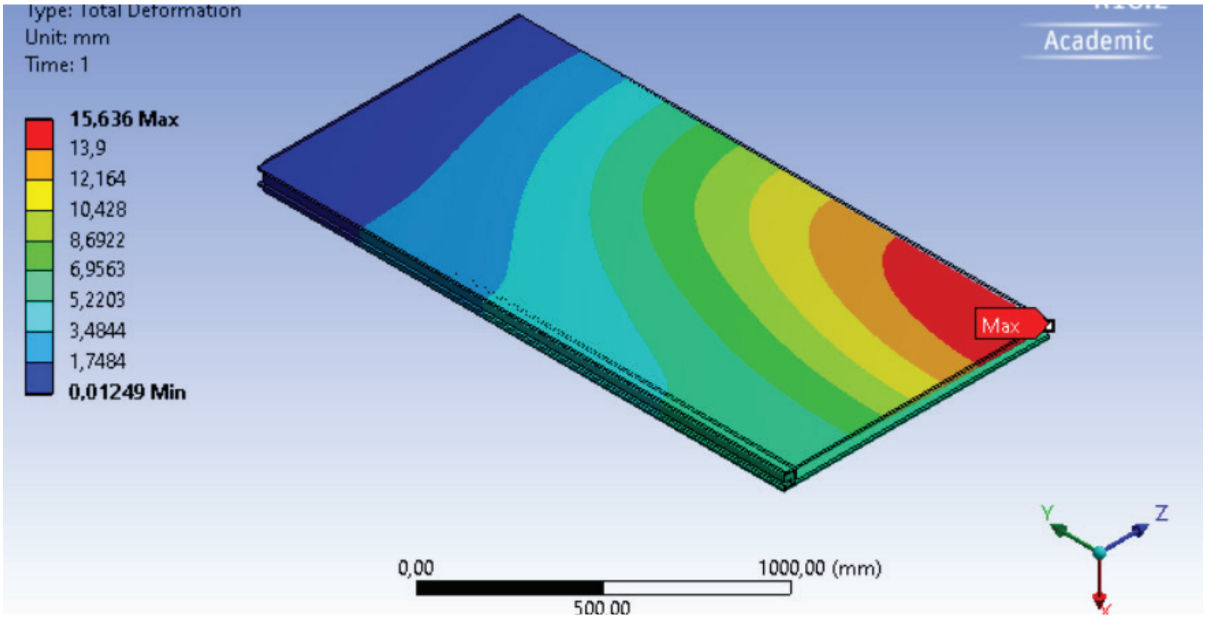
81. Design B CFRP - Stress



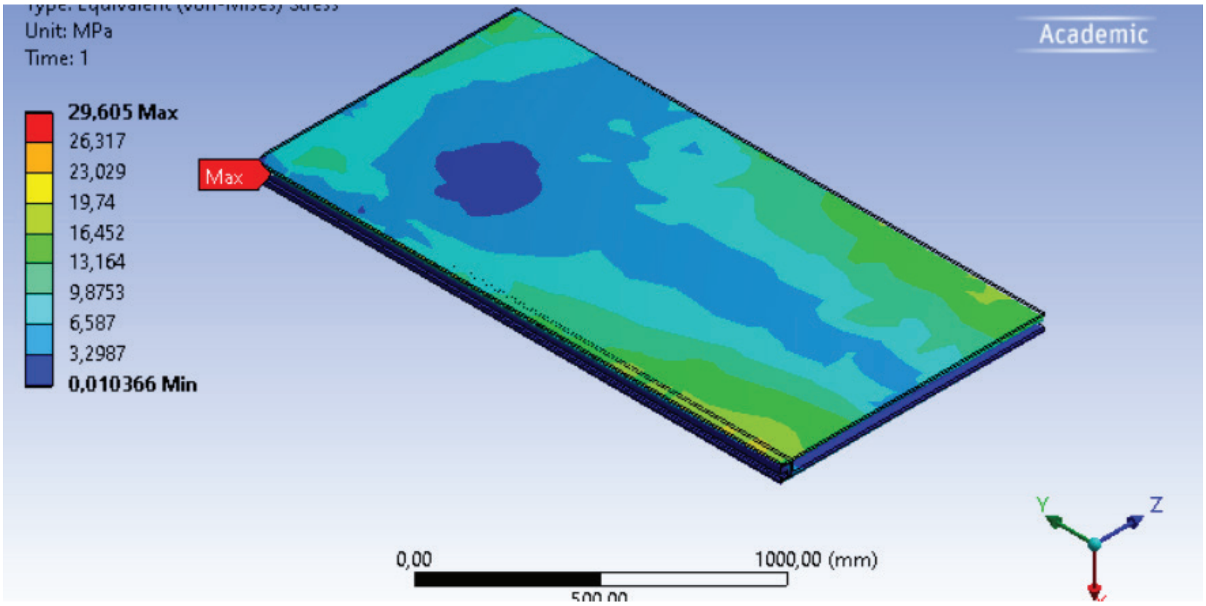
82. Design B GFRP - Deflection



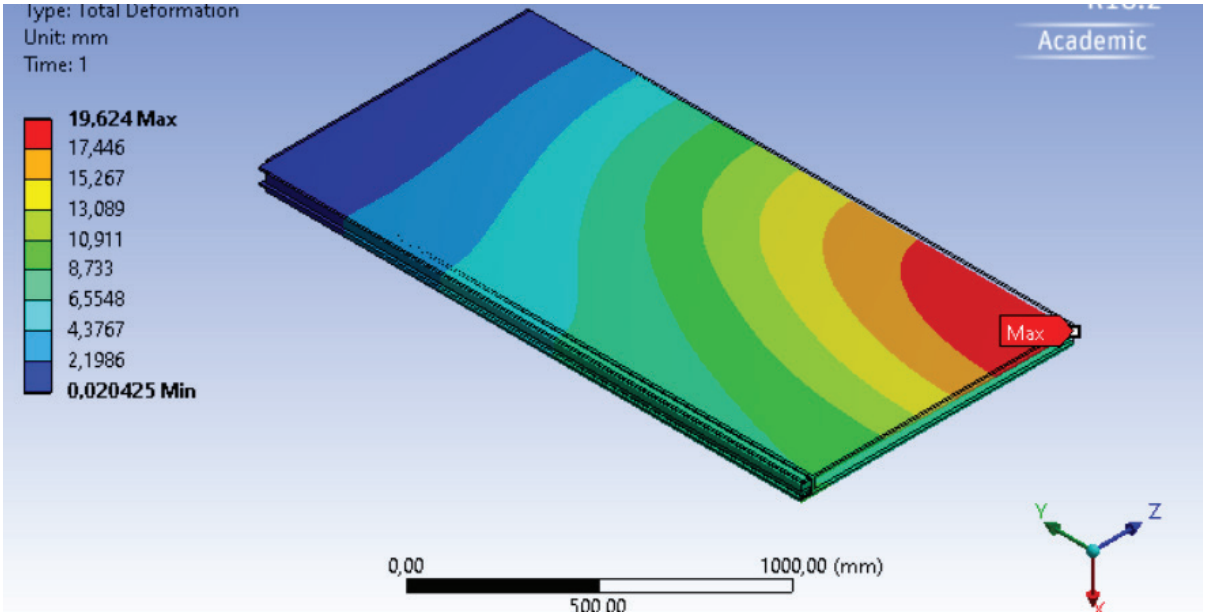
83. Design B GFRP - Stress



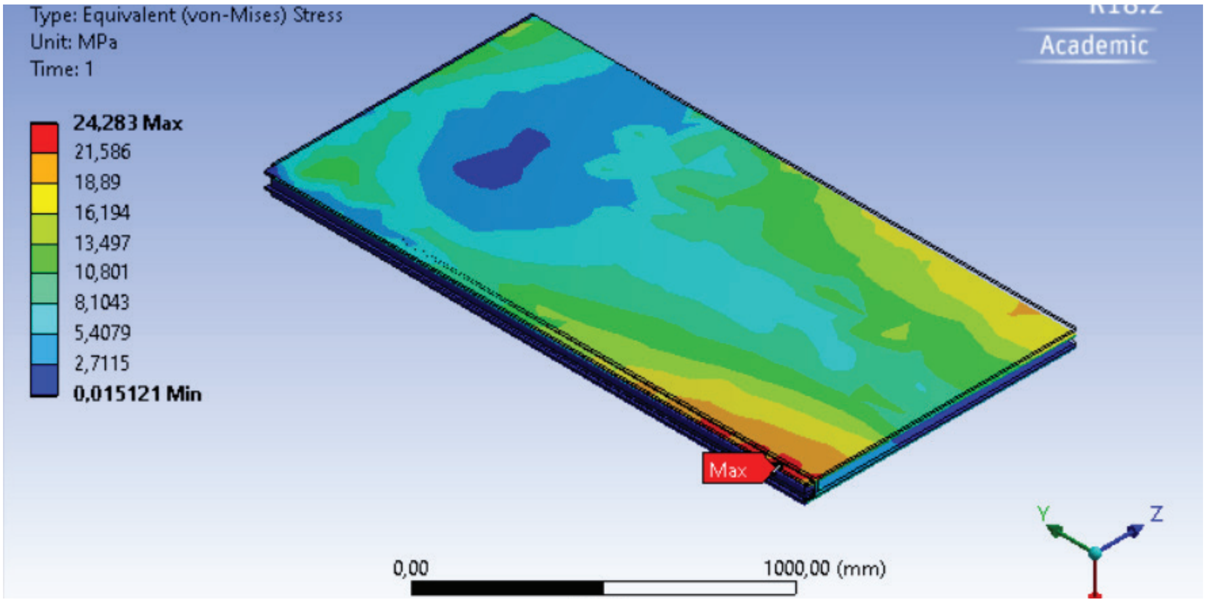
84. Design B Oak - Deflection



85. Design B Oak - Stress

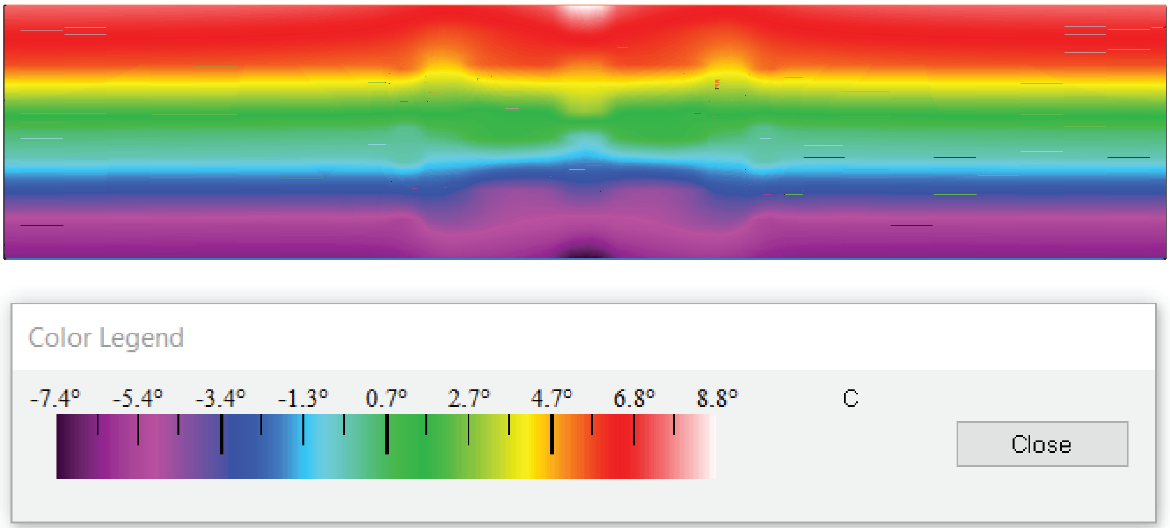


86. Design B Plywood - Deflection

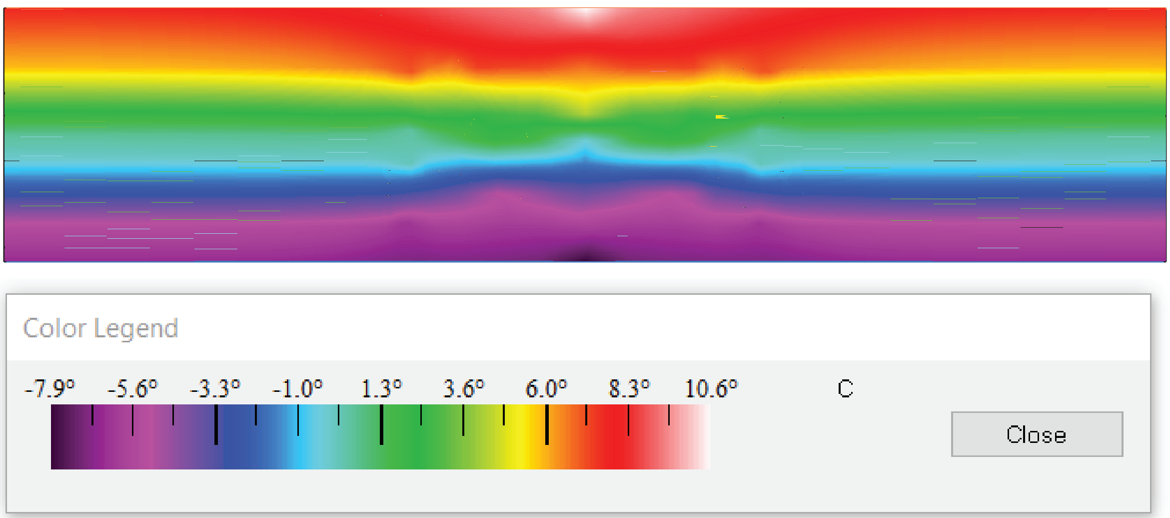


87. Design B Plywood - Stress

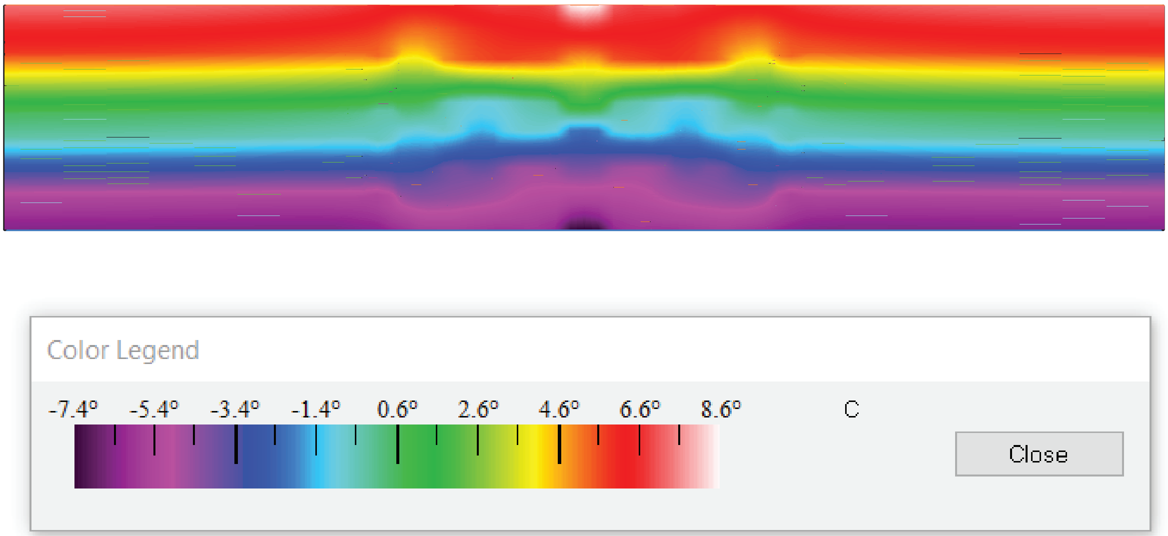
H. THERMAL ANALYSIS



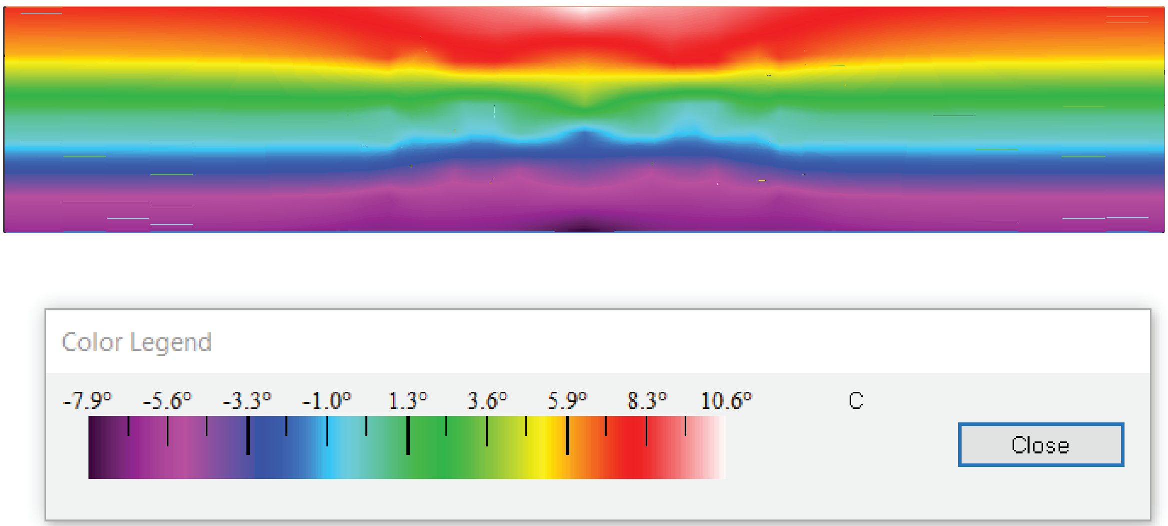
88. Design A CFRP



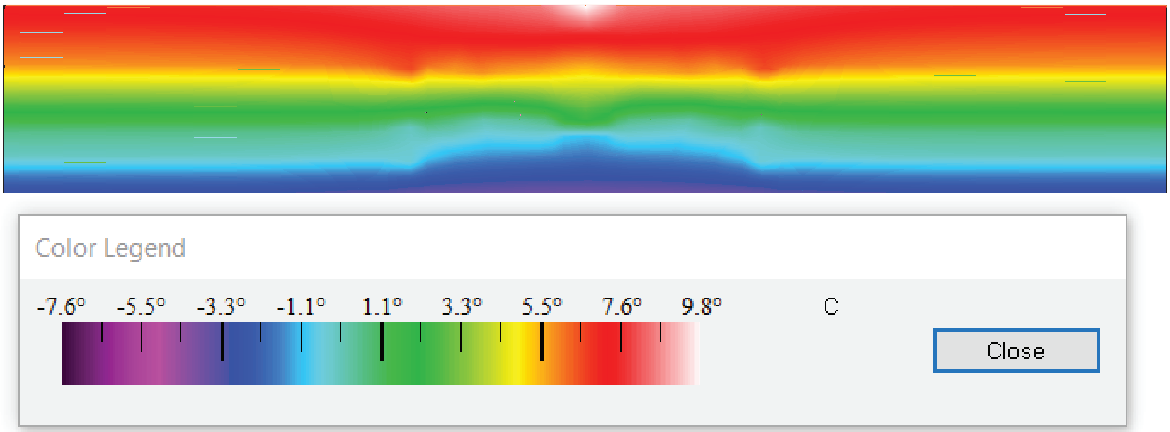
89. Design A GFRP



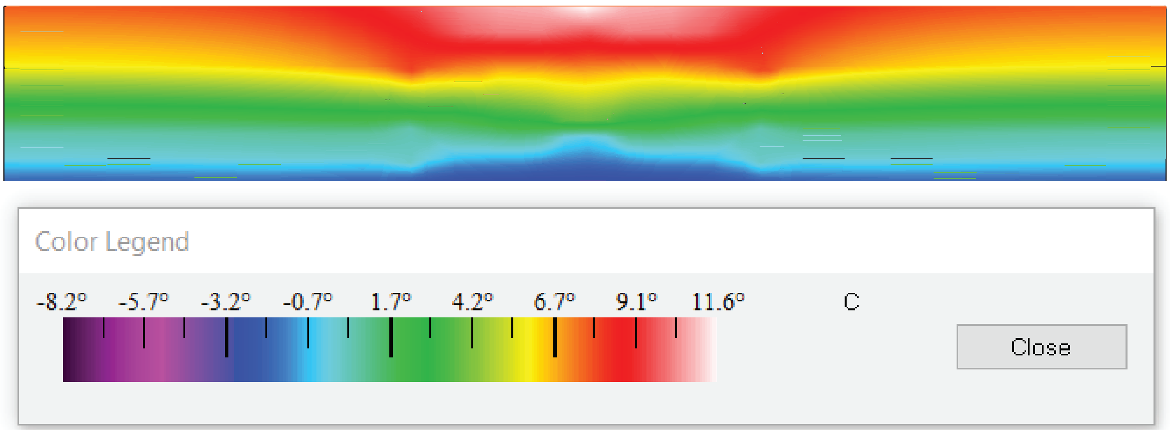
90. Design B CFRP



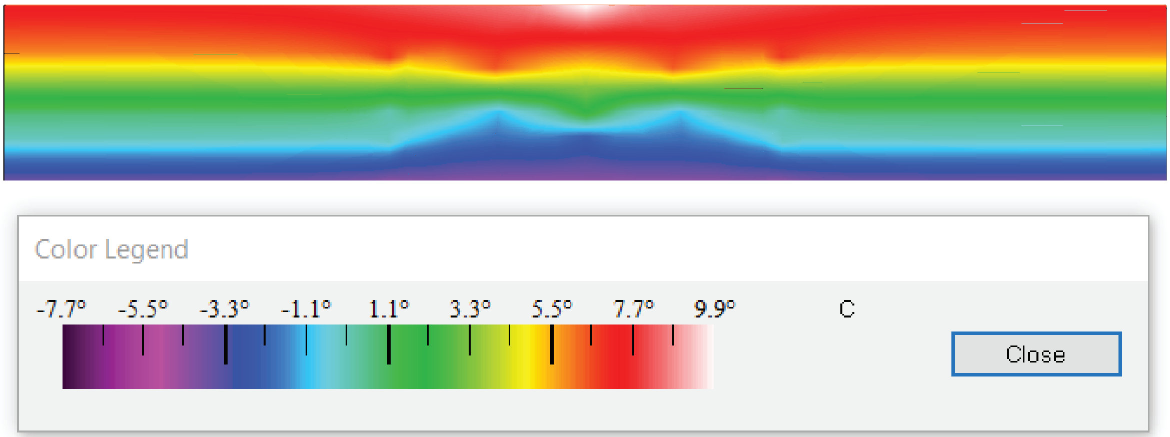
91. Design B GFRP



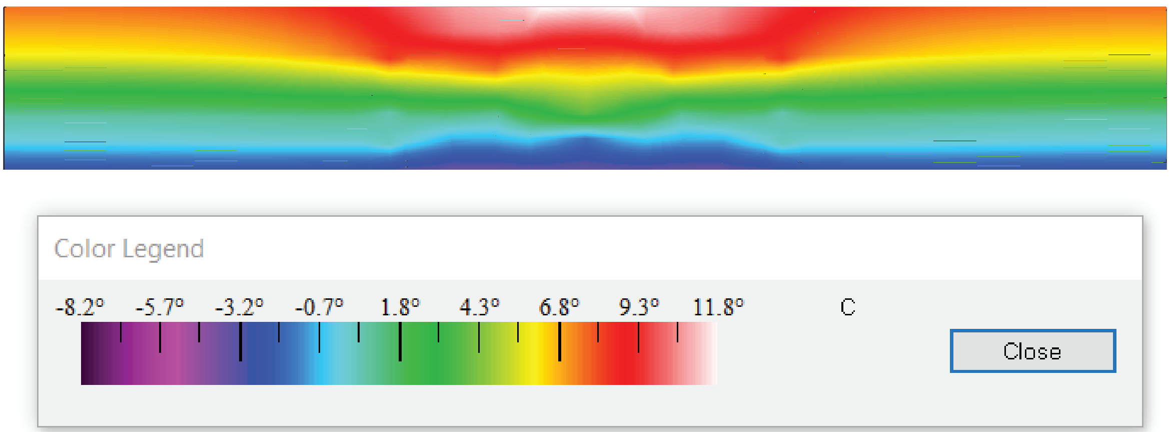
92. Design A Oak



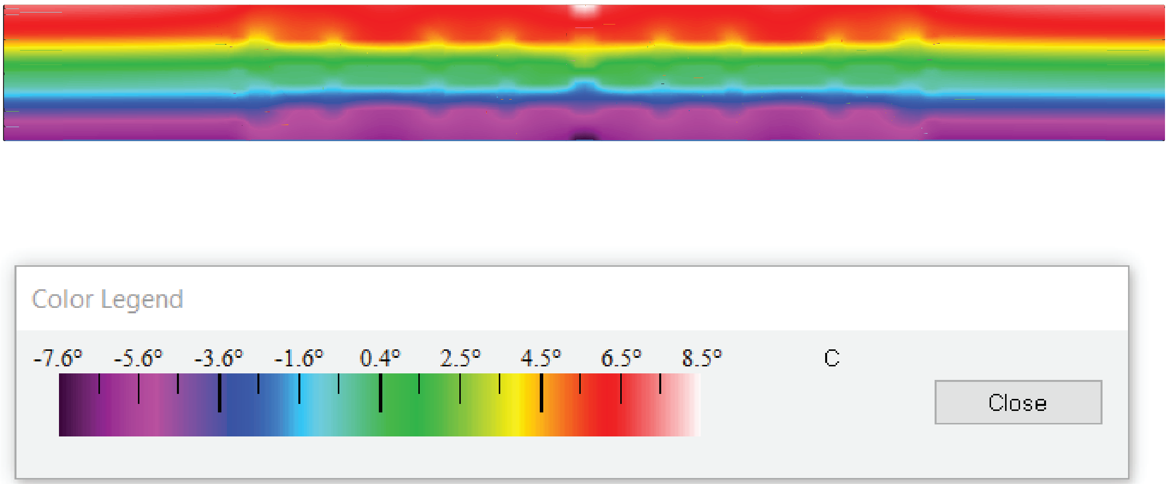
93. Design A Bamboo



94. Design B Oak



95. Design B Bamboo



96. Design C CFRP

REFERENCES

3M. (1996, March). Product Data Sheet - EPXÔ Adhesive DP490.

3M. (2009, June). Product Data Sheet -Epoxy Adhesive EC-2216 B/A.

Afghani Khoraskani, R. (2015). Advanced Connection Systems for Architectural Glazing. SpringerBriefs in Applied Sciences and Technology, PoliMI SpringerBriefs.

Ascher-Barnstone, D. (2003). Transparency. Journal of Architectural Education, 56:4, 3-5.

Balog, V. (2019, December 13). Innovative Facade Types – The Closed Cavity Façade. Glass on Web. https://www.glassonweb.com/article/innovative-facade-types-closed-cavity-facade

Cavette, C. (n.d.). How carbon fiber is made. How Products Are Made. Retrieved 15 October 2021, from http://www.madehow.com/Volume-4/Carbon-Fiber.html

CES EduPack software (2021). Cambridge, UK: Granta Design Limited.

Chastas, P., Theodosiou, T., Bikas, D., & Kontoleon, K. (2017). Embodied Energy and Nearly Zero Energy Buildings: A Review in Residential Buildings. Procedia Environmental Sciences, 38, 554–561. https://doi.org/10.1016/j.proenv.2017.03.123

Corbusier, L. (1986). Towards a New Architecture. New York: Dover Publications, 229-265.

Cordero, B. (2015). Unitised curtain wall with low thermal transmittance frame integrated within the insulating glass unit though structural adhesives. Escuela Tecnica Superior de Architectura.

Cordero, B., García-Santos, A. & Overend, M. (2015). Thermal performance of novel frame-integrated unitised curtain wall. Journal of Contruction, 14(1), 23-31.

DOW. (2020). Technical Data Sheet -DOWSIL™ 791 Silicone Weatherproofing Sealant. (62-1636-01-0920 S2D).

Dow Corning. (2011, December). Product information - 993 Structural Glazing Sealant (62-0918L-01).

EN ISO 10077-2. (2017). Thermal performance of windows, doors and shutters - Calculation of thermal transmittance - Numerical methods for frames. CEN, Brussels, Belgium

Eriksson, O., & Finnveden, G. (2009). Plastic waste as a fuel - CO2-neutral or not? Energy & Environmental Science, 2(9), 907. https://doi.org/10.1039/b908135f

Eskilson, S. J. (2018). The Age of Glass. London: Bloomsbury Academic.

Fibraworld. (n.d.). GRP profiles & gratings. GRP Profiles | Fibraworld. Retrieved 9 October 2021, from https://www.fibraworld.ba/grp-profiles/

Fibrolux. (n.d.). GRP Custom Profiles. Fibrolux GmbH. Retrieved 9 October 2021, from https://fibrolux.com/grp/grp-profiles/custom-profiles/

Glaskoning. (n.d.). Hr+++ Triple Glas. Retrieved 22 September 2021, from https://www.glaskoning.nl/dubbel-glas/tripleglas/?gclid=Cj0KCQiA7oyNBhDiARIsADtGRZayUBThCOCwPx1rzI9nBXe6ah-Op4RcR1gysHDpVEy7Fa7Oj8AUygwaAtB-EALw_wcB

Goodno, B. & Gere, J. (2018). Mechanics of Materials (Ninth Edition). USA: Cengage Learning.

Hartwell, R., & Overend, M. (2019). Unlocking the Re-use Potential of Glass Façade Systems. GPD Glass Performance Days.

Het Nederlands Normalisatie-instituut (2014). NEN 2608 (nl): Vlakglas voor gebouwen - Eisen en bepalingsmethode. Delft.

Holdit Australia. (n.d.). Structural Bonding. Retrieved 24 November 2021, from http://www.holditaustralia.com.au/products/structural-bonding

KNMI. (n.d.). Zware stormen in Nederland sinds 1910. Retrieved 30 September 2021, from https://www.knmi.nl/nederland-nu/klimatologie/lijsten/zwarestormen

Mills Friba, E.D. (1957). Curtain Walling. The Architect & Building News, 2961, 4-7. London: Iliffe & Sons Limited.

Mordor Intelligence (2020). Flat Glass Market - Growth, Trends, COVID-19 Impact, and Forecasts (2021 - 2026). Mordor Intelligence. https://www.mordorintelligence.com/industry-reports/flat-glass-market#faqs

Murray, S. (2009). Contemporary curtain wall architecture. New York: Princeton Architectural Press.

Overend, M., Jin, Q. & Watson, J. (2011). The selection and performance of adhesives for a steel–glass connection. International Journal of Adhesion and Adhesives, 31(7), 587–597. https://doi.org/10.1016/j.ijadhadh.2011.06.001

Pascual, C., Montali, J. & Overend, M. (2017). Adhesively-bonded GFRP-glass sandwich components for structurally efficient glazing applications. Composite Structures, 160, 560–573. https://doi.org/10.1016/j.compstruct.2016.10.059

Pascual, C. & Overend, M. (2021). Buckling of sandwich struts with a particular application in composite multi-layer glazing. Engineering Structures, 230, 111545. https://doi.org/10.1016/j.engstruct.2020.111545

Patterson, M. (2011). Structural Glass Façades and Enclosures: A Vocabulary of Transparency. New Jersey: John Wiley and Sons Ltd.

Porreco, A. (2017). Calculating Yield & Tensile Strength. Anchor Bolt and Construction Fastener Manufacturer. Consulted on 3 November 2021, from https://www.portlandbolt.com/technical/faqs/calculating-strength/

Reports and Data (2019). Glass Curtain Wall Market To Reach USD 89.03 Billion By 2026.

Reynaers. (2021). ElementFaçade 7-SG. Reynaers Aluminium. Retrieved 20 September 2021, from https://www.reynaers.com/en/products/curtain-walls/elementfacade-7-sg

Reynaers. (n.d.). ElementFaçade 7. Reynaers Aluminium. Retrieved 20 September 2021, from https://www.reynaers.com/en/products/curtain-walls/elementfacade-7

Rijksoverheid. (2012). Artikel 5.3. Thermische isolatie | Bouwbesluit Online. Bouwbesluit online. Retrieved 16 September 2021, from https://rijksoverheid.bouwbesluit.com/Inhoud/docs/wet/bb2012/hfd5/afd5-1/art5-3

Schüco. (2020, February). Fabrication manual 2–7: Unitized Façades (No. 98425). Schüco International KG.

Sheppard, L.M. (n.d.). How glass fiber is made. How Products Are Made. Retrieved 15 October 2021, from http://www.madehow.com/Volume-2/Fiberglass.html

Sika Corporation. (2018, August). Product Data Sheet - Sikadur®-330 (Version 03.01).

Sika Corporation. (2020, September). Product Data Sheet - Sikafloor®-265 (Version 01.05).

Sika Nederland. (2010, July). Product informatie blad - SikaForce®-7550 L15 (Version 03).

Steiner, H. & Veel, K. (2011). Living behind glass facades: Surveillance Culture and New Architecture. Surveillance & Society, 9 (1/2), 215-232.

Stender, M. (2006). En nation af vindueskiggere: Glashuse til debat. Arkfokus.

StructX. (2021, May 25). Simply Supported Beam - With UDL. Retrieved 28 September 2021, from https://structx.com/Beam_Formulas_001.html

VMRG. (2021). VMRG Kwaliteitseisen en adviezen 2022.

Watts, A. (2005). Modern construction facades. Springer.

Weller, B., & Institut für Internationale ArchitekturDokumentation. (2009). Glass in building : principles, applications,examples (Ser. Detail practice). Birkhäuser.

Whiteley, N. (2003). Intensity of Scrutiny and a Good Eyeful: Architecture and Transparency. Journal of Architectural Education, 56, 8-16.

Wigginton, M., & Harris, J. (2002). Intelligent skins. Oxford: Butterworth-Heinemann.

PICTURE CREDITS

Figures that are not listed are by the author.

1. Maison La Roche lack, Paris
Source: May, T. (2015). Le Corbusier, Maison La Roche, Paris (1923–25). Fattori Fraser. https://waltergropius-blog.tumblr.com/post/109496744139/le-corbusier-maison-la-roche-paris-1923-25

2. Nykredit Headquarters, Copenhagen
Source: Schmidt Hammer Lassen Architects. (2001). Nykredit Headquarters. SHL. https://www.shl.dk/nykredit-headquarters/

5. Unitized Curtain Wall
Source: https://www.jansenbyods.com/en/product/jansen-viss/

6. Closed Cavity
Source: https://architizer.com/blog/practice/details/glazed-facade-details/

7. Structural Glazing
Source: Brochure Octatube, February 2018

8. 100 Eleventh Avenue
Source: https://www.frontinc.com/project/100-11th-avenue/

9. View inside
Source: https://www.frontinc.com/project/100-11th-avenue/

10. View inside
Source: https://www.frontinc.com/project/100-11th-avenue/

11. EY
Source: https://www.skyscrapercenter.com/building/the-ey-centre/13290

12. View inside
Source: https://www.businessinsider.com.au/first-look-eys-new-sydney-hq-is-one-of-australias-greenest-buildings-2016-4

13. View inside
Source: https://www.skyscrapercenter.com/building/the-ey-centre/13290

14. Triodos Bank
Source: https://www.archdaily.com/926357/triodos-bank-rau-architects/5da08a063312fd498d00004e-triodos-bank-rau-architects-photo?next_project=no

15. View inside
Source: https://www.archdaily.com/926357/triodos-bank-rau-architects/5da08a063312fd498d00004e-triodos-bank-rau-architects-photo?next_project=no

27. Previous work details (left)
Source: Octatube. (2017). Detail 06 - Bovenconsole verdieping. In Triodos de Reehorst Driebergen - Zeist.

27. Previous work details (right)
Source: Cordero, B. (2015). Unitised curtain wall with low thermal transmittance frame integrated within the insulating glass unit though structural adhesives. Escuela Tecnica Superior de Architectura.

65. Young's modulus & yield strength
Source: CES EduPack software (2021). Cambridge, UK: Granta Design Limited.

66. Thermal conductivity
Source: CES EduPack software (2021). Cambridge, UK: Granta Design Limited.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