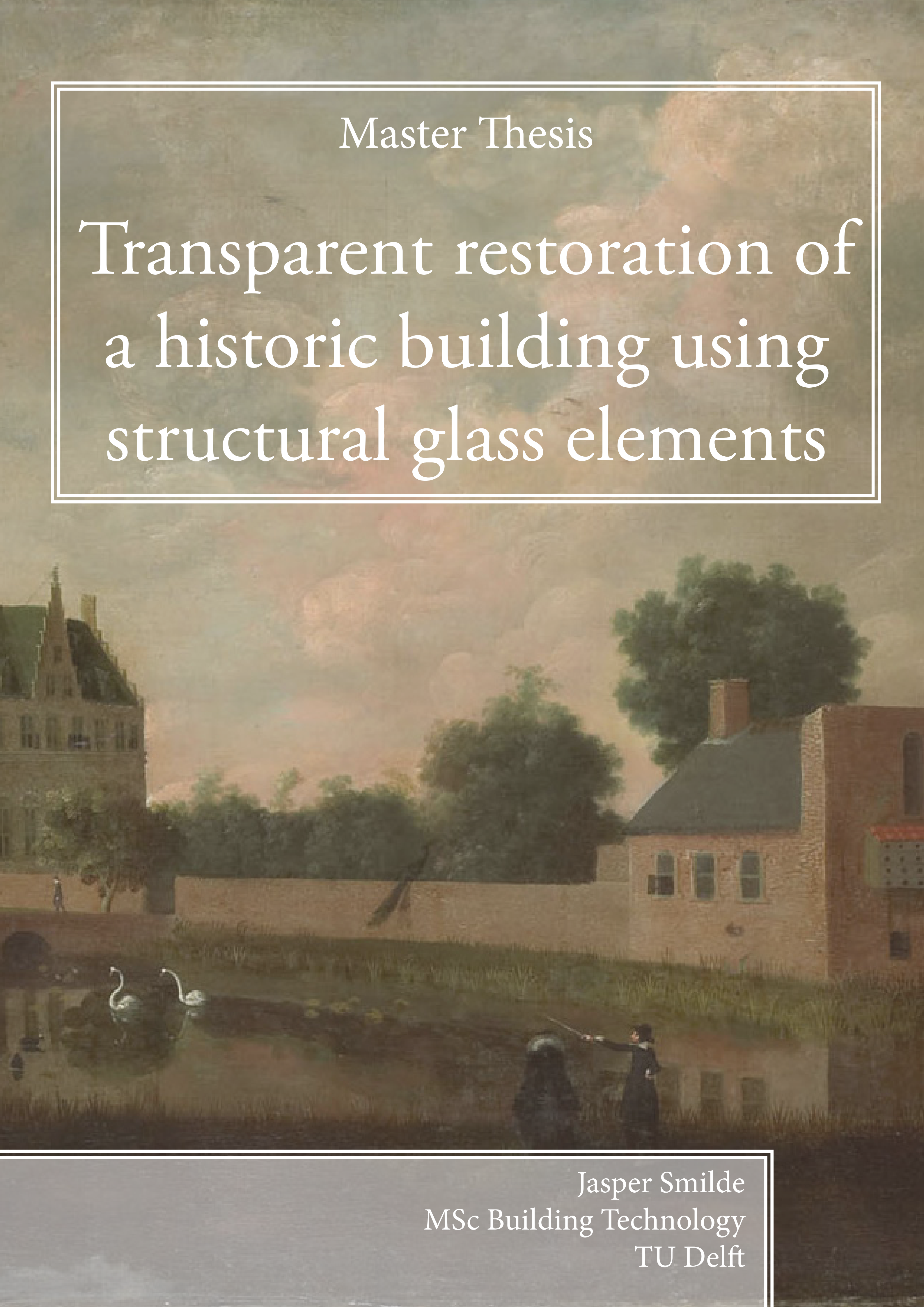

Master Thesis

Transparent restoration of a historic building using structural glass elements

Jasper Smilde
MSc Building Technology
TU Delft

Cover image:

Oil painting Slot Teylingen 1640, unkown artist.
Source: SK-A-608 (schilderij, olieverf op doek), Schilderijencollectie Rijksmuseum

Master of Science thesis

Transparent restoration of a historic building by use of structural glass elements

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This thesis is also digitally available at:

www.repository.tudelft.nl

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This master thesis is the result of the research project I have been conducting from November 2015 till June 2016. The research project is the final part of the Master of Science study which, after graduating, allows me to become an Engineer. I have enjoyed working on this challenging and multi-disciplinary project, where multiple fields of knowledge come together in one structural glass design. An interesting aspect was that this graduation research took place in an real research environment, where alongside an investigation was being conducted to search for a future appropriate function of Slot Teylingen. Hopefully this graduation research can in any way contribute to this investigation, and act as a teaser, showing the possibility of restoring an historic building using an innovative material as structural glass.

I would like to thank my mentors Faidra Oikonomopoulou and Christian Louter for their encouraging support and guidance during this project. Their input and critical feedback has helped me to stay on the right course, and to come to the right design solutions. Their experience with conducting researches and extensive technical knowledge of glass has helped me improve my project continuously. My thanks for Rob van Hees for his valuable input on how to find information and authentic documents on historic buildings.

A special thanks to Mark van den Bos, director of the Stichting Monumenten Bezit, which is part of the National Monument Organisation, the current owner of Slot Teylingen at this moment. His input has helped me to get a good understanding of the history and current state of Slot Teylingen. This proved essential to make an appropriate befitting design.

Also, I would like to thank my parents and sisters for the emotional, moral and financial support throughout my studies in Delft. Without them it would not have been possible for me to follow and finish my education. And last but not least, I would like to thank my girlfriend Sophia, for her patience, understanding, trust and support during the last years of my study.

Jasper Smilde
Rotterdam, June 2016

Summary

Vacant monumental buildings, a bad thing
Valuable monumental historical buildings often lose their function over time, which results in vacancy of the building. Once it has lost its use, this often means the building deteriorates over time due to lack of maintenance and care. This deterioration is bad for the building, but also for the environment the building is situated in. Valuable architectural and historical elements of the building could become damaged or get lost, and a vacant and damaged building is not a pleasant view for its city.

One way to prevent deterioration is by restoring the building, and by placing a new function in it. However this often means adding new elements to the building, or replacing missing elements, to allow the building to become functional again. The restoration and addition of a missing element is however a very complicated and delicate intervention. This is due to international agreements, called The Venice Charters, which is a set of high demands to any change to a monumental building. The Venice Charters state that if a missing original element is replaced, it should integrate harmoniously into the building, but the new should also be distinguishable from the original, in order to prevent falsification. The new element should also no detract from the important elements of the monumental building. For this reason the choice of material for a replacing element is often a debate.

Glass as a solution, but could it work?
In this thesis it is stated that structural glass could be the solution for this material choice debate. The reason for this are the unique properties of glass. it is transparent, has a contemporary look, and when applied right it can be used as a structural material. With these properties, a restoration with structural glass allows for a restoration that can show the shape of the original structure, but still allows to see how the current collapsed historic monument looks like. This creates a connection, a continuum between the old and the new. And because the glass can be a structural component, it is not merely a cladding or esthetic component, but also the actual structural element.

However, restorations of monumental building using structural glass have rarely been done before. As a result, this raises questions on an architectural field regarding the integration of old with new, and engineering questions of how to design and detail the glass structure.

A design research
In order to investigate how structural glass could be used in a restoration, a design research has been conducted in this graduation project. Here an appropriate monumental vacant case study has been chosen, for which an original missing element has been replaced by a glass structure. During this design research the architectural and engineering questions will be solved, and as a result general guidelines for future glass restorations are formulated. The societal relevance for this research is new knowledge on how to integrate and design a transparent restoration, and showing the building industry a new approach to restoration. The technical knowledge derived from this design research is relevant for the scientific field.

The chosen case study is Slot Teylingen in Voorhout, being the oldest castle in the Netherlands, dating back to the 13th century. This castle has lost its wooden roof in 1676 in a fire, and has since been vacant. This particular building is chosen due to its relatively good condition, great historical value and great potential for repurposing this building. In order for the building to become functional again, the roof will be repositioned on top of the donjon of the castle, materialized in structural glass. This glass roof is the focus of the design research, which will be elaborated from sketch proposal to detailed design. The structural, façade and climate facets will all be integrated into one appropriate integrating yet distinguishable glass roof for Slot Teylingen.

Literature research leading to design requirements
In order to formulate clear guidelines for design of this glass roof, a literature study has been done.
A study into the restoration philosophy theory has shown that proper research into the history of the building, documentation and old drawings is of vital importance to understand the building and its context better. The intervention to the building should above all be done with respect to its original context, history and current state. The new element should be fitting to the original building, its shape and appearance, and be reversible. In this way the addition can be later removed if wanted, without leaving permanent damage to the building.

The original shape of size of the wooden roof of the castle was researched in the chapter of the past, present and future of Slot Teylingen. The research showed that the building has a rich history, and minor restorations have taken place in the past. An interesting discovery was that the municipality of Teylingen together with the owners of the castle, the National Monuments Organisation, was also conducting a research into an appropriate new function for a refurbished Slot Teylingen. Based on the proposals given in this research, a new master plan and function was proposed, where the surrounding area around the castle would be converted into a medieval garden and events area. A glass roof would enclose the ruin, and a bar and restaurant could be located in the castle, which is the focal point in this grand master plan. The glass roof would serve as a view post to overlook the beautiful new surroundings. The current state of the castle show deteriorated and weakened masonry, which is rather fragile. The walls are damaged over time and show an uneven top surface. In order to prevent damage to the old walls by the new roof, measurements will have to be taken to prevent loading large unwanted forces on the walls which could harm the structure.

An investigation in the material glass and its structural properties learned that glass is a brittle and hard material, and that good detailing is crucial for the overall strength of the material. To minimize the probability and consequence of structural failure of the glass, heat-treated laminated glass could be used, combined with the use of embedded hybrid adhesive connections to create a strong and safe structure.

Preliminary design phase and elaboration of design
With the design requirements formulated, main design decisions could be taken. It was chosen to make the new roof in the original size and shape as the wooden roof. Next, after doing a case study research into different structural glass systems, five sketch proposals were designed. After assessing each option by its performance based on the design requirements, the decision was made for a glass beam structure, supported by a steel contour frame, cladded in glass curved panels.
Next, this proposal was elaborated into a final technical design. Following a critical research methodology, for each element of the roof variants have been created which were assessed by comparing them with the main design requirements. This method was applied from the large decisions such as the overall structural setup, down to the small scale decisions as detailing. Structural calculations were made to validate and check the structural performance of the design, allowing thorough design of the detailing of the roof. The design of the glass roof was an iterative design process where the design decisions on every scale influenced the other, which finally lead to an integrated detailed technical design.

Final technical design
The product of the design process is an plausible and elegant solution for covering the historic building with an all glass roof that respects the historical and aesthetical value of the monument. To respect the building, the roof is shaped in the original shape and size of the wooden roof. To minimize the intrusiveness off the glass roof is minimized by using large glass elements which align with the grid and appearance of the original roof. A slender steel frame allows for easier assembly and protects the walls from unwanted forces, translating the weight of the roof into bearable compressive loads which should not harm the old walls. The building is enclosed by placing new masonry on the crumbled walls which

distinguishes itself to prevent falsification and a clear division between old and new. A zinc rain girder allows for proper water draining and further water corrosion, and also houses an controllable natural ventilation system. Passive climate measures have been taken prevent overheating of the glass roof and to create a controllable comfortable indoor climate. Proper technical detailing was done for ten typical locations of the glass roof, showing how the roof is assembled, and how all the elements come together. Measurements are taken to allow for tolerances and size deviations during manufacturing and construction of the elements. The safety and strength of the roof is guaranteed by choosing the appropriate type of heat-treated glass, by laminating the glass components, and by proper choice of detailing types.
Visual renders and images are used to shows how the new refurbished Slot Teylingen might look from the in – and outside with the new structural glass roof. These make it understandable what the glass roof design would mean for a possible future of Slot Teylingen.

Conclusion
This research has shown that if designed and detailing right, structural glass can be a very appropriate solution for the restoration of monumental buildings. The glass roof refurbishes the castle into an functional, attractive and usable location. The visual language of the roof engages with its environment, reflecting the past in its transparency in material and geometry, shape, size, and overall layout, creating an integrating yet distinguishable addition to the monumental building.

For future transparent restorations it is clear that a thorough research in the original building is of vital importance in order to understand the building and treat it with respect. Good detailing in glass structures is crucial to provide a safe and strong structure, and to allow for a demountable structure. Measures should be taken to minimize the probability and consequences of failure of the glass. The force introduction of the new structure into the old structure should be done very carefully and well-considered to prevent permanent damage to the monument. Finally all the technical solutions should be integrated, so that the glass structure can become one slender and transparent whole.

Content

1. Introduction

1.1 Background information

Since old and historic monumental buildings are the living witness of generations of people and their age-old traditions, they can be seen as a portal back in time, imbued with a message from the past. Since people are becoming more conscious of the unity of human values, these ancient monuments are often regarded as common heritage. Ancient monuments are often unique, and of great cultural-historical value. Next to that the monument is often a harmonic part of the surroundings it sits in, and therefore has a visual-emotional relation to the local residents. Because of these reasons it is our duty and of paramount importance to safeguard these monuments, and to retain them with as much authenticity as possible. This so that we can pass these buildings on, so that they may educate and inspire future generations.

Some buildings however have lost their function over time and have become vacant. This can be a concern for all involved agencies, since this usually means the buildings are not so well maintained anymore. Thereby the buildings are exposed to the elements, vandalism, theft or destruction. This can cause serious decay of the monument, and also have a negative influence to its surroundings. In some cases it could eventually even lead to the demolition of a building which should be avoided for obvious reasons of among others, great loss of valuable cultural-historical heritage.

Once monumental buildings have become vacant, there are a few different options. One of these options is the repurposing of the monument. This would mean the loss of the original function of the building, because repurposing implies making interventions to the building to make it suitable for a new function. The big advantage of this option is that the atmosphere and character of the building must be kept, maintaining its iconic value, while it still allows for a new use of the building, thereby giving a positive boost to the building and its surroundings. This is also backed up by the Venice Charter(1964), the leading charter of international agreements regarding the conservation and restoration of historic monuments. It states in article 5: ''The conservation of monuments is always facilitated by making use of them for some socially useful purpose. Such use is therefore desirable but it must not change the lay-out or decoration of the building. It is within these limits only that modifications demanded by a change of function should be envisaged and may be permitted.''

As can be seen, the Venice charters allows repurposing of vacant historical buildings, however because restoration is often such an intrusive operation in a monument, the Charters demand this is done in respect to the history and cultural values of the building. Summarized, in terms of restoration, the Charters state that the aim should be to preserve and reveal the aesthetic and historic value of the monument. Restoration should be based on respect for the original material and authentic documents. In order to allow the building to become functional again via restoration, it is often required to replace a collapsed or destroyed element of a building. The Charters also has set requirements for this, where it states that replacement of missing original parts of a building must integrate harmoniously with the whole, but at the same time be distinguishable from the original so that restoration does not falsify the artistic or historic evidence. Also, additions cannot be allowed except in so far that they do not detract from the interesting parts of the building, its traditional setting, the balance of its composition and its relation with its surroundings (International Council on Monuments and Sites, 1964).
Because of these strict regulations, the choice of material when in restoration original elements are replacement, is an ongoing debate. One of the worst results of a restoration process could be that the cultural-historical value of a building is faded, because it is unclear after restoration what part of the building is authentic and what part is new.

If you look at these restrictions and demands in restoration, it is a logical step to choose for structural glass as a material. This because the material has unique characteristics: it has a contemporary look, it is transparent, and due to the high amount of current innovative research in the material properties and applications possibilities, glass can also be applied as a structural material. This allows for a glass replacing structure that can show the shape of the original structure, but still allows to see how the current collapsed historic monument looks like. Because the glass can be a structural component, it is not merely a cladding or esthetic component, but also the actual structural element. When it is designed to be subtle and simple, the glass will blend in, and the actual monument will receive all attention. This is why structural glass is a very suitable material for restoration of buildings.

1.2 Problem statement

It can be concluded that in theory glass can be a very suitable material for restoration. However the main problem is that restorations where original elements of a building are replaced by glass structures, have not often been done before. This means there are a lot of questions that need to be solved.

The first sub problem is one the architectural aspect and the restoration philosophy: It should be determined in what way an old element should be replaced with a glass replacement. It can be discussed what should be done and what not in terms of copying the old elements of the original structure and the building. Achieving an harmonic integration with a glass structure in an old historic monument can be difficult while using such a modern material as glass. Also falsification should be prevented in order to make the restoration an architectural success.

The second sub problem is on an technical/engineering aspect. It is unclear how to apply current knowledge in glass order to engineer an replacing glass structure of an original element. Also the question exists on how specific shapes or geometry could be made in glass. The detailing at the connection between glass and old building is critical, just as the point of how forces should be transferred through the supports in the old building.

1.3 Research objectives

The main objective is to research how structural glass can be used in the restoration of a monumental building, by doing a design by research for a replacing glass structure for a selected case study building. Based on this design by research, general guidelines can eventually be formulated. Perhaps it could also lead to an innovation in the application of a new glass technique or element.

The first sub-objective is researching how a replacing glass element can integrate architecturally harmoniously with the existing monument, in respect to the history of the building.

The second sub-objective is researching how an original element can be designed and engineered out of glass. This will involve researching how the required shape of element can be made out of glass, looking at detailing in the structure itself as to the connections to the old building. The forces of the replacing elements should be transferred properly to the monumental building.

1.4 Constraints of the research

A major part of this research is to design a restoration of a monumental building, by designing a glass structure which allows the building to become functional again. Before this can be done, a case study needs to be chosen. However not just any monumental building is suitable for this research. First should be determined that the monumental building is of any relevance at all, so that the building is worth keeping and restoring. This has led to the decision that the design by research will be done on **Slot Teylingen** in Voorhout, just north of Leiden(The Netherlands). The arguments and criteria for choosing this building is explained in chapter 3.1.1. and 3.1.2.

Since the castle has great potential for repurposing, the proposal is to make this building functional again by putting a roof on and floors in the castle. The focus among the proposed interventions shall lie on the roof because this is the biggest contributor to making the building functional again. The roof shall be made out of glass. The design of such a structure is also most challenging and interesting for the glass science. A roof is complex because it is part of the building façade, therefore it has to perform well in terms of climate and façade technical.

The main focus on the design by research shall be the general design of the roof structure as a whole, detailing this glass structure, and a general structural focus of checking the design on structural performance. Another option is to check the design on climate performance.

1.5 Research Questions

1.5.1 Main research questions

Based on the previous objectives, the following main research question is formulated:

''How can structural glass be used in order to make a transparent roof restoration for Slot Teylingen?''

1.5.2 Sub-research questions:

1. What is the general philosophy and ideology behind restoration of monuments?
2. What are general restoration design requirements based on this philosophy?
3. How to achieve an integration of the glass replacing element in the monument?
4. What is the pathology/history of Slot Teylingen?
5. What could be the new use of Slot Teylingen?
6. What was the shape of the original roof and structural system?
7. What is glass and what are its properties? How could its properties be improved?
8. What should be the shape of the new roof?
9. How could this shape be made using structural glass?
10. How to detail the connections to itself as to the monument?
11. How to model the structure in order to make calculations to check its structural performance?
12. What measurements should be taken to prevent overheating of the glass roof?
13. What is the impact does the new roof have on the building, and how does it change the use of the building?
14. Based on the findings in the design process, what general guidelines can be formulated for the future design of glass roof restorations?

1.6 Relevance of research project

1.6.1 Societal relevance

By doing this research, new knowledge is created about how to execute restorations on monumental buildings in a very transparent and non-intrusive way. By doing this, monuments that have become vacant can now become functional again, while not losing their authenticity or atmosphere. By repurposing vacant monuments, these buildings become available for public again, increasing the cultural value of the area.
Also, succeeding in making a feasible architecturally and technically working glass roof design for a monument can be convincing teaser for the building industry in showing a new approach to restoration. Glass could be the answer to avoiding ''falsified'' monument restorations, because due to wrong choice of material it becomes unclear after restoration what part of the building is old and part is new.

1.6.2 Scientific relevance

By making a glass roof design for a monument, a new theoretical approach is developed for applying glass structures in monuments. First of all from an architectural point of view this could be a refreshing approach, which fits nicely in the restoration philosophy. The research would provide arguments for the strong relation between glass and the restoration science.
Next, from an engineering point of view it is a technical engineering challenge to construct an original element of a monumental building, in glass. The original element may have an complex shape, which has been made using a material that works completely different then glass. This requires proper translation into the structural build up that works for glass. The resulting design research may lead to new types of elements or geometry made. Another special engineering challenge is the combination of a structure made of a modern material, and an old structure, which poses challenges. The way forces are transferred will require good engineering solutions and detailing. This may lead to interesting new glass details. This research is related to ongoing research of the Glass and Transparency group of the TU Delft. Here new ways of constructing with glass are developed, which opens a new market and application field for applying the knowledge of glass and glass structures: historic building and monuments.

1.7 Approach to the research and chapter division

The research can be subdivided in different phases. This is illustrated by Fig. 1.1 on the next page. The different phases are described in the chapters. Next, each phase and it's corresponding chapter is described.

1.7.1 Literature study

In this phase, information is retrieved mainly from literature. Chapter two about monuments will involve a research into the general philosophy behind restoration, and could be a good way to restore an original element from a monument in glass. Also this chapter will elaborate more deeply why glass is an suitable material for restoration.
In the third chapter, necessary information about Slot Teylingen gathered in the next part, regarding it's past, it's current state and the future of the building. First of all the pathology and history of the building will be researched, and specifically the shape and build-up of the original roof. Based on information gathered by a site visit and literature, the current state of the building is researched. Next, the future of the castle is discussed by determining a new use for the building, proposing interventions to the Donjon in order to make it functional again. This will be based on literature, but also in discussion with the NMo organization who owns the castle. This way the sub-research questions 4-6 can be

answered. This information is needed in order to formulate a clear context and firm arguments for the direction of the glass roof design.
In chapter four a literature study is done about glass. Here general and detailed technical information is gathered about the material properties, mechanical properties and production techniques.
These three topics together can be used to formulate design requirements based on the restoration philosophy, the past & current & future of Slot Teylingen, and the material properties of glass.

1.7.2 Preliminary design

Information from the literature study allows proceeding to the second phase of the research, where the first design steps are made. These steps are discussed in chapter five. First the major design decisions have to be made, like the shape of the roof and what the general structural build up should be. The question regarding the roof shape is done based on the design requirements that flow out the three topics from the literature study. Once the shape is determined, a case study review is done in order to research ways of constructing the chosen specific roof shape in glass. The case study review will retrieve information from literature and from websites from companies that have design, and built glass structures. The projects will be clustered and categorized by structural type.
Drawing inspiration from the case study review, different conceptual designs are proposed. These designs are different in that they each represent a different way of constructing with glass. Out of these proposals, one has to be chosen. This selection is based on the design requirements that flow out of the literature study phase. The choice for one type will be a strong converging step, where this specific structural type will be elaborated.

1.7.3 Design research

In chapter six the chosen conceptual proposal will be elaborated and designed to detail. First the main structural build-up will be elaborated and further developed, following by the design on a gradually smaller scale. Eventually the design will be validated by structural calculations done by hand and calculation software like Diana and Matrixframe. 3D software like Rhinoceros will be used to design in 3d, and to make models. Finally, after this iterative process, the design will be finalized. The final design results are explained in chapter seven. Here the design is shown in renderings, 3d, 2d sections and details, combined with scheme's which explain the working of the façade and climatic system.

1.7.4 Feedback

At the end of the design stage, once the design has been finalized, the process and design results can be evaluated. This part is explained in chapter eight. First an evaluation is made of the design results, reflecting on the impact of the new roof for Slot Teylingen and its new use. Next, based on the findings in the research, general design guidelines can be formulated for glass roof restorations of historic monuments and buildings. These guidelines can be used by future designers and engineers when another monumental building has to be restored, using structural glass.

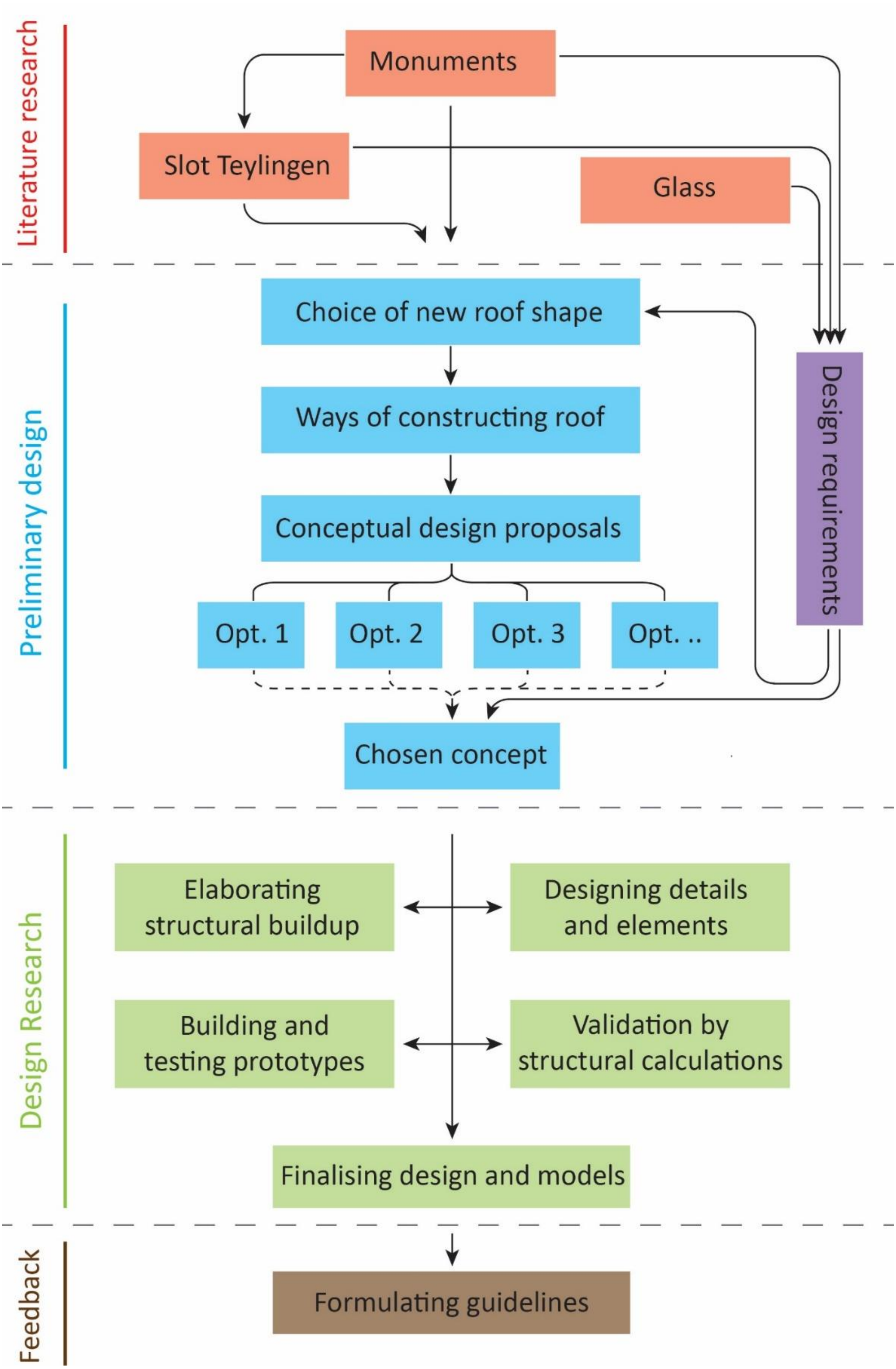


Figure 1.1. The research approach. Source: own ill.

2. Monumental buildings and restoring with glass

In this graduation research the main design question is how to use structural glass for the restoration of a historic building. Although it has already been mentioned short in the problem statement of the research framework, this chapter will elaborate on the literature background of monuments and restoration. Since restoration is a very delicate and complex process where an old building will be restored using new techniques or elements, the question rises about what should and should not be done in the restoration. For this reason it is necessary to look into literature and legislation. Based on these guidelines different definitions will be given for a monument, the restoration process, and ultimately trying to come up with a set of guidelines. These guidelines should guarantee the quality and authenticity of the historic building when it is restored using glass. The final design of the glass structure should therefore fit these guidelines.

2.1 Safeguarding our heritage

2.1.1 Monumental buildings

The original Latin meaning of the word monument is ‘’remembrance’’(Van Hees, 2004). In that sense its name also describes the core value of a monument: it allows us humans to learn from our past. According to the Dutch Monument Act of 1988, the following can be labeled as a ‘’monument’’: any crafted immovable property older than 50 years, that is of general importance because of its beauty, its scientific value or its cultural-historical value. ("Monumentenwet ", 1988)
Buildings that meet this criteria are labeled as protected monuments, which is done to protect that building from being damaged, demolished or altered in an incorrect way. The majority of the roughly 44.000 monuments in the Netherlands date back to before 1850 (Nelissen, 1999). Some of these monument have lost their function over time and have become vacant. These buildings could be reused. That is however only possible when the building is in a proper state, that enables it to be used. If the building is vacant this can be a concern for all agencies that are involved with historic preservation. Especially if the building is rather large, because they often have a big influence on the silhouette and appearance of the neighboring town or city. If the building has become vacant, this can have a bad influence on its surroundings. A second large issue with vacant monuments is that it often means that they are not so well maintained anymore, and are exposed to the elements, vandalism, theft or destruction. This can cause serious decay of the monument, and also influence its surroundings in a negative way.

If a building is vacant for too long, the chance that the building will be demolished increases. According to Nelissen(1999), this is because it often lacks the owners of the building of insight in the opportunities the building still has. There are various reasons why demolishing of the building should be avoided(Hoogenberk, 1983):

- Demolishing the building would mean a great loss of valuable cultural-historical heritage, which should therefore often be avoided.
- The building could be a harmonic part of the surroundings and be part of visual-emotional connection.
- The building is for some reason unique: e.g.: oldest building in its type etc.
- Because the building still has an excellent structure and therefore there is no logic reason to demolish it
- The building still has excellent opportunities for repurposing

It is therefore in many cases, but not all (Van der A, 2012), better to preserve a building, and find some use for it.

2.1.2 Why restore?

Once monumental buildings have become vacant, there are a few different options. One of these options is the repurposing of the monument. This would mean the loss of the original function of the building, because repurposing implies making interventions to the building to make it suitable for a new function. The big advantage of this option is that the atmosphere and character of the building must be kept, maintaining its iconic value, while it still allows for a new use of the building, thereby giving a positive boost to the building and its surroundings. This is also backed up by the Venice Charter(1964), where it states in article 5: ''The conservation of monuments is always facilitated by making use of them for some socially useful purpose. Such use is therefore desirable but it must not change the lay-out or decoration of the building. It is within these limits only that modifications demanded by a change of function should be envisaged and may be permitted.''

In many cases it is necessary to restore the building in order to repurpose it. This because the building is damaged or decayed over time, not enabling use of it. However, as stated above, the restoration of a building should take place in between certain limits of intervention. The limits of intervention should be determined properly, which will be explained in the next part of this chapter.

2.2 Restoration philosophy

Because restoration is such an intrusive operation in a monument, it is important this is done right. To handle these and to guarantee a certain quality in the restoration process, international agreements have been made upon the philosophy of restoration: the Venice charters.

The Venice charters (1964) state that the aim of restoration process should be to preserve and reveal the aesthetic and historic value of the monument. The restoration process should be based on respect for the original material and authentic documents. That means that the restoration process is a highly specialized operation, where great care must be taken in order to treat the monument properly. Changes to parts of the building are only allowed when removing that part of the building will reveal a underlying layer of the building of a different period, where the removed material is of little interest, and the revealed material is in a good enough state to justify the action and of great historical, archaeological and aesthetic value. However valid contributions of all periods to the building of a monument must be respected, since unity of style is not the aim of the restoration.
All these action are done to preserve the building in the state it is in, and to treat the history of the building with respect.

In article 12 the charter states that replacement of missing parts must integrate harmoniously with the whole, but at the same time be distinguishable from the original so that restoration does not falsify the artistic or historic evidence. This is a very important aspect of restoration: since restoration means restoring the building to a state the building once has been in, this has an aspect of mimicking the old. However a very dangerous outcome for the monument could be if this is done wrong, and in the end result it is difficult to determine which parts of the building are old and which are new. This would be a threat to the historical *authenticity* of the monument. This is also backed up by article 10 of the Venice charters where it is noted that restoration should stop at the point where conjecture begins, and in this case moreover any work which is indispensable must be distinct from the architectural composition and must bear a contemporary stamp. This aspect of authenticity has been much discussed, and resulted eventually in the development of another international agreement: the Nara document(1994). This document is developed by ICOMOS in 1994, at the Conference on Authenticity in Relation to the World Heritage Convention in Nara, Japan.

The Nara document speaks about authenticity as being a multifaceted concept of values, where it can be subdivided in different aspects. These aspects would be form and design, materials and substance, use and function, traditions and techniques, workmanship, location and setting, and spirit and feeling, and other internal and external factors. Each of these aspects should be distinguished as being an artistic, historic, social or scientific value (International Council on Monuments and Sites, 1994). In this way a better understanding can be obtained of the monument.

It is clear an inter-disciplinary methodology is needed in the restoration process of a monument. Using this methodology it is guaranteed that the authenticity and the historical, archaeological and aesthetic values of the monument are not compromised. Based on gathered information and knowledge about the monument and its separate values, design requirements and boundary conditions can be formulated for the restoration design and process. These boundary conditions cannot just be based on the designers preference, but should be clearly determined within the knowledge of the monument and its history, otherwise this would again threaten the authenticity.
An scheme is shown below which illustrates the approach to restoration, for in this case the mortar mix design for restoring an monumental masonry building.

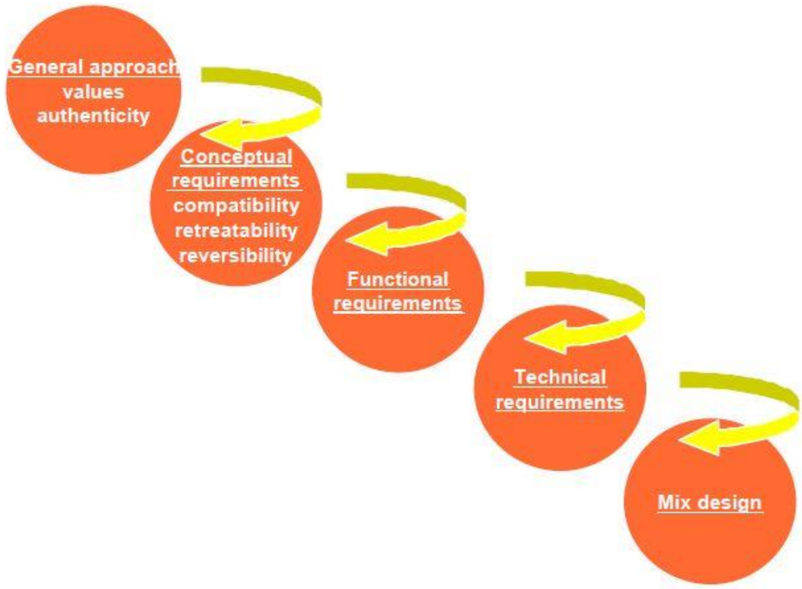


Figure 2.1 Approach to restoration. Source: (van Balen, Papayianni, van Hees, Binda, & Waldum, 2004)

To be able to form the design requirements and boundary conditions, and to achieve a successful restoration process, knowledge of various types about the monument is crucial (Nelissen, 1999). Relevant knowledge and information should be known about historical background of the building, but also the structural condition, the architectural qualities, the cultural-historical values, which adjustments are allowed to be made to the structure and also which new function the building could get. Based on all this information the boundary conditions and design requirements can be formulated, which will eventually all congregate in the architectural concept of the repurposing.
The debate around authenticity brings up the question of which material to use for the restoration process. Since now have been shown this is a critical aspect in the restoration process, and that the choice of material should be a well thought decision, it is no wonder this question is an ongoing-debate.

2.3 Glass as a solution

I want to state in this graduation thesis that there is a material which would be a really suitable answer to the question of the restoration material. When looking closely at the articles in the Venice charters (International Council on Monuments and Sites, 1964) one could see that this material suits the requirements. For example in article 9: ''..(the restoration process) must stop at the point where conjecture begins, and in this case moreover any extra work which is indispensable must be distinct from the architectural composition and must bear a contemporary stamp.'' In article 12: ''Replacements of missing parts must integrate harmoniously with the whole, but at the same time must be distinguishable from the original so that restoration does not falsify the artistic or historic evidence.'' And in article 13: ''Also, additions cannot be allowed except in so far that they do not detract from the interesting parts of the building, its traditional setting, the balance of its composition and its relation with its surroundings.''

When summarizing these requirements in own words, any addition or replacement of an original part of the building must:

- Be distinguishable from the original structure and bear a contemporary stamp.
- integrate harmoniously in the original structure
- not detract from the interesting parts of the buildings, the setting, balance in composition and relation to its surrounding.

A transparent material could be an answer to all the above prerequisites, as it would be able to show the monument at its existing and at the same time at its previous condition. What material could suffice in all these requirements: <u>***structural glass***</u>

Glass fits these criteria so well because of its unique characteristics: it is transparent, has a contemporary look, and when applied right it can be used as a structural material. With these properties, a restoration with structural glass allows for a restoration that can show the shape of the original structure, but still allows to see how the current collapsed historic monument looks like. This creates a connection, a continuum between the old and the new. And because the glass can be a structural component, it is not merely a cladding or esthetic component, but also the actual structural element. For example, structural glass can be used make a roof structure, allowing for the closing of the partially collapsed monument, which could protect it against the elements and at the same time make it functional. It is not only that the ''transparency'' requirement is met in the material itself, but also in the shape of the structure. It is necessary to design a subtle minimalistic type of structure, which make the replacement part blend in with the monument, become 'transparent', and the actual monument will receive all attention.
Another good characteristic of glass is that it is a sustainable material. This because glass can be recycled indefinitely, and is made of materials that are abundantly available.

A downside to glass structures are that they are most likely more expensive than when a structure would be made of conventional materials like wood or steel. But in restoration projects money will usually not be an issue, because the cost is often not the main decisive factor. This because the meanings of the architectural heritage are of such a great value, that the goals and targets of design are often set very high, and they must usually be reached by all means (Lefaki, 2005).

2.4 Design criteria based on restoration philosophy

As have been said before, based on the knowledge of the monument one could formulate design criteria and boundary conditions. These all congregate in the architectural concept of the restoration design. Since this is not an architectural research, this will not elaborated too deeply, and a full architectural analysis of the building will not be made. However some design criteria are formulated which will later be used to formulate an architectural concept for the restoration of the case study.

- A new added glass structure need to be reversible. This not only refers to the level of construction, but also to a conceptual level, as transparency offers ways of simultaneous seeing. If the future demands the newly added structure to be removed in order to purify the structure to its historical core, this new element should me removable.

- The restoration should be befitting to the original building, and integrate nicely. It should have a conveyance of history and time scale as glass structures explicitly state the time elapsed between the historic and the contemporary, without causing confusion regarding time or meaning. It is therefore also very important that the new structure should be distinguishable from the old.

- Authenticity of architectural language, as glass is not able to ‘pretend’. The material defines the form and vice versa. The glass should be used in a way it functions best, without trying to copy and old structure shape exactly, since the original structure is likely made out of a different material than glass.

- The glass structure should have an balanced esthetical quality. New glass constructions have drawn many monuments out of obscurity and decline, enhancing their features, without imposing strict and nonnegotiable ways of interpretation. The old building should be enhanced by the newly added structure.

3. Case study: Slot Teylingen

The aim of this research is as having said two fold. The first aim is to formulate a general methodology for restoring monuments with glass. The second aim is to actually make a glass restoration design for a case study, which will show the concept as well as help develop the methodology.
Where in the previous chapter the theoretical background has been discussed of the restoration with glass of a monument, this chapter will discuss the chosen case study. First the relevance of a case study research will be discussed, which will be followed by an explanation of the case study and possible future of the castle.

3.1 Case study research

A major part of this research is to design a restoration of a monumental building, by designing a glass structure which allows the building to become functional again. Before this can be done, a case study needs to be chosen. However not just any monumental building is suitable for this research. The next part describes what requirements the building should fit to be suitable.

3.1.1 Choosing a suitable case study

First of all, the monumental building needs to be of relevance, so that the building is worth keeping and restoring. As has also been mentioned in paragraph 2.1.1 of the previous chapter, there could be various reasons why an building is of relevance, and why it should be maintained and renovated. These, with some personal additions made up the criteria for choosing a suitable case study:

The first criteria would be that the monument has an iconic value, and is harmoniously integrated in its surroundings. It therefore plays an important visual role in the surroundings and neighboring towns or villages. The building has a visual-emotional connection for its neighboring residents.
Another criteria would be that the building is of a monumental, cultural-historical or architectural value. This would mean that building has had a part in an important historical event, or that it has had historically known inhabitants.
It could also be that the building is for some reason unique. This would for example because it is the oldest in its kind, or has a beautiful or unique architecture.
An important practical criteria is that the building has a usable structure. The structure should have enough integrity to be used, and should be enough intact. Together with the mentors we came to the conclusion that the structure should at least be 70 % intact. This because this project would otherwise would be too much of a new-construction project, and not so much a restoration project.
The building should also have a suitable structure for a glass restoration. This means that a certain part of the building is missing or damaged, which can be replaced by a glass structure.
The last important criteria is that the building still has excellent opportunities for repurposing. After repurposing the building should be able to become functional and attractive again. An important part of this, is that the building is well located, meaning it is easily accessible. Preferably near a (large) city. When the building would get functional again, this would allow easy access for those with interest living in the city.

3.1.2 Why Slot Teylingen?

Within the scope of monumental buildings that would fit all the criteria's mentioned above, there are still a large amount of possibilities. There are different kind of building types that would be interesting. This leaves room for a personal preference.

A personal preference of myself was that of the building type of castles. I have always had a preference for the medieval style and cultural-historical context. I like the materials used, the craftsmanship that went into making these structures, and the whole atmosphere of these old wooden stone structures. When visiting old castles I never have much trouble imagining how it would be to live in such a place. A nice fact is that there are still a lot of castles in the Netherlands, and most of these castles are well documented. This speeded up the selection procedure by quickly going through the lists of Dutch castles. Finding a suitable and attractive castle was the goal, which was achieved by applying the selection criteria mentioned earlier.

This had eventually lead to the choice of **Slot Teylingen** in Voorhout, just north of Leiden(The Netherlands)

This castle was chosen because it fits all the criteria mentioned. Slot Teylingen is of great historical value. The building is very old, and unique in its kind and condition. The location of Slot Teylingen is perfect, located near a large city in a populated area of the Netherlands. The direct surrounding is spacious and offers room for potential new functions. The structure of the castle is very usable, because it is mostly intact. It has a very strong shape, and I personally find the castle to have a certain beauty. According to research the castle is popular among residents (Gemeente Teylingen, 2015), and people feel connection to castle. Because of all these properties the castle has excellent opportunities for repurposing. The castle will be further explained in image and text in part 3.2, to elaborate on this summarized short list of properties.

3.1.3 Current ongoing study into future possibilities of Slot Teylingen

Another interesting aspect of Slot Teylingen is that there is a current ongoing research project initiated by the municipality of Teylingen. In this research a exploration for a future prospect for the castle is started. The interesting part is that this research coincides greatly with my own research. It is therefore relevant to review this research and see if there a possibilities to connect the outcome of my research to the research of the municipality.

The municipality initiated the research to an exploration of future possibilities of the castle, because of several reasons. These reasons are the problems which the municipality recognized with the castle(Gemeente Teylingen, 2015).

- The castle has a unique history and special meaning for the municipality, the province and even for the Netherlands as a whole. This national monument thus deserves a surrounding which appreciates and respects the monumental value of the castle better. The landscape around the ruin is increasingly being dominated by buildings for residential and business purposes, and infrastructure. This deteriorates the visibility of the castle, and an investment in the surrounding which would increase the experience of the castle is desirable.
- The castle is important for many of the residents of Teylingen. After all, the municipality of Teylingen was chosen to be named after the castle after merging the former municipalities of Voorhout, Sassenheim and Warmond.
- The current entrance to Slot Teylingen is very unclear. Because of this, the castle is hard to find and also has a low accessibility.
- The castle, and in specific the ring wall and the Donjon (the tower), are in rather poor structural condition. An intervention is urgently needed in order to prevent further deterioration of the structure. This intervention may likely be drastic. Placing a roof on the donjon is a serious option which is being researched on. This would allow a new function in the donjon, and would protect the exposed top surface of the walls from further deterioration.

- The maintenance and management of the castle is expensive. Partially because of this the swap of ownership is taking place in 2015(Teylingen, 2015) from the Dutch ''Rijksvastgoed'' to the NMO, the National Monuments Organisation. The NMO will have more funding for proper, efficient and consequent maintenance, but this also pushes for a reconsideration of the current financial exploitation of the castle which may results in more funding.

Because of these reasons the municipality want to formulate a vision of the future prospect of the castle. This will however be done by close involvement of the local residents and other involved parties such as the Province of Zuid-Holland, the Dutch government, historical unions and the union that currently manages the castle in name of the Dutch government: ''Stichting Beheer Kasteel Teylingen''. This advice will then be handed over the owner of the castle, the NMO. This advice will not consist of a finished design, but of several directions of development which are widely supported by all involved parties and local residents.

In order to give the research project a more practical and real life applied relevance, the outcomes of this research will later be used as input. This will be elaborated on in chapter 3.3.1

3.2 Slot Teylingen history

Slot Teylingen is an special object, with a rich history. The earliest parts of the castle date back to 13th century. Even on an international scale the castle is a striking example of medieval castle architecture(den Hartog, van Immerseel, & Coops, 2005). While today only a moated round encircled fortress remains with a donjon and a gate, the castle used to be much larger.

Figure 3.1. Birds-eye view of Slot Teylingen. Source: (Ministerie van BZK - Rijksoverheid.nl)

It originally consisted of two parts: the still existing main stronghold, and the former outer bailey. The main stronghold was located on an island with a moat and consisted of a circular masonry wall, a donjon and a gatehouse. On the terrain of the outer bailey there was a large residential building and a large gatehouse with surrounding buildings. There also used to be a moat around the outer bailey, but this has, just like all buildings of the outer bailey area, disappeared(den Hartog et al., 2005).

Slot Teylingen is located Voorhout, in the Netherlands.

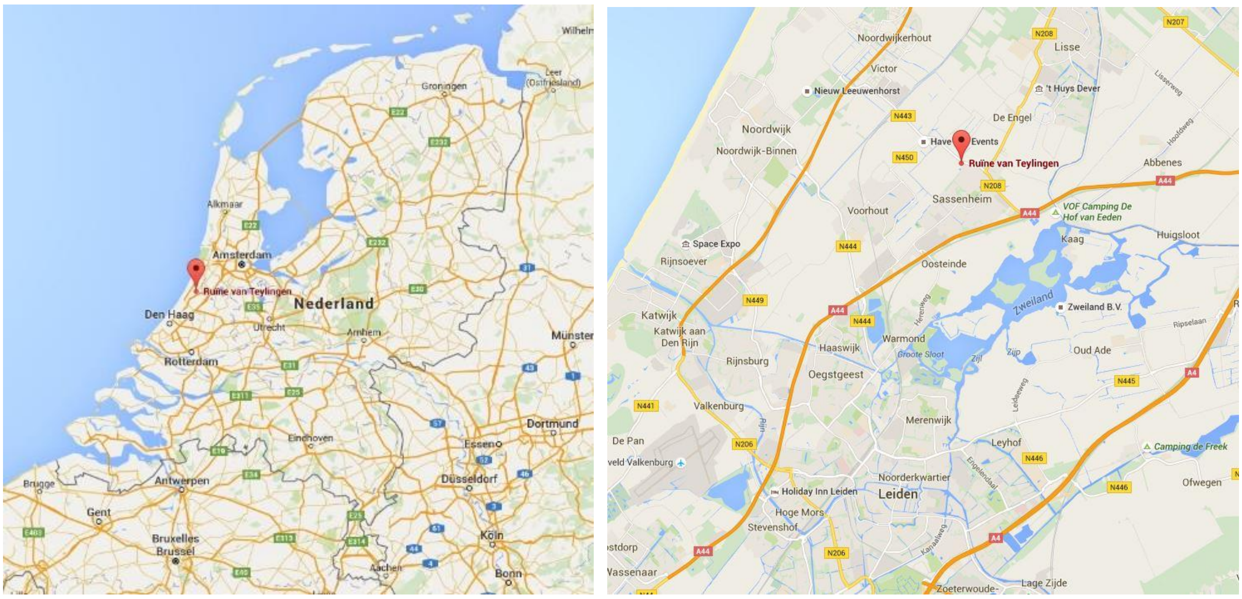


Figure 3.2 The location of Slot Teylingen. Source: googlemaps.com

Voorhout is a small village near Sassenheim, 10 km north of Leiden. Leiden is one of the larger cities in the province of Zuid-Holland.

3.2.1 Historical development – pathology of building

Slot Teylingen has a rich history with many time layers. There is a lot to tell about the history, but since this is not all relevant for this research, only a brief overview will be given.

3.2.1.1 Building phase 1

In the 12th and 13th century the round encircled castle with the donjon and gatehouse played a central role in the castle complex. At the beginning of the 13th century the round stone wall was built with a small tower(fig 3.3), where half a century later the current donjon was build, as a replacement of the small tower. In this way the defensive value of the castle was increased. The lords of Teylingen are first named in 1143. The castle then functioned as a hunting castle and a forestry. The most famous resident was de Dutch Countess Jacoba van Beieren (Gemeente Teylingen, 2015).

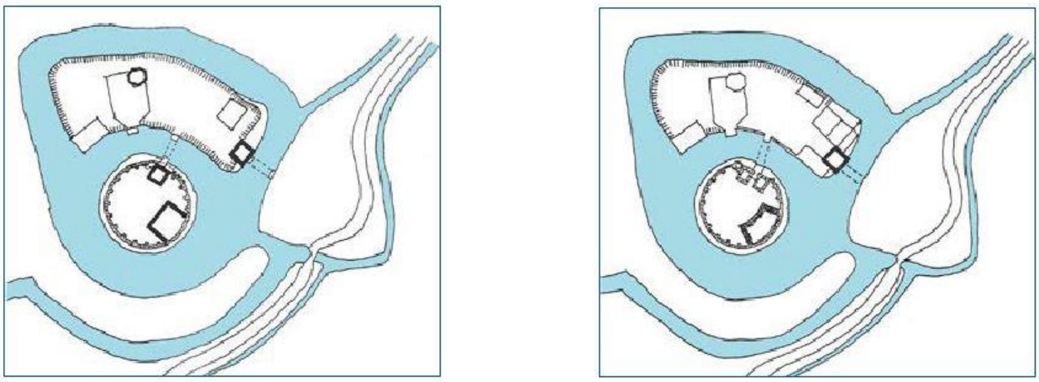


Figure 3.3: on the (left) the stone wall with a smaller tower, and on the (right) a drawing of the renewed donjon. Source: (Annema, Rijksgebouwendienst Bureau Rijksbouwmeester Adviesgroep Monumenten in Rijksbezit, Ministerie van Volkshuisvesting Ruimtelijke Ordening en Milieubeheer, & Kamphuis, 1994a)

3.2.1.2 Building phase 2

In the 14th, 15th and 16th century the outer bailey became more important. In 1405 the first stone buildings were built here. In 1477 the residential function shifted from the donjon to the main house in the outer bailey(Nationale Monumenten Organisatie, 2015).

During the 80 Year's War the castle was heavily damaged. Slot Teylingen was attacked in 1572 by the Spanish, during the siege on Haarlem and Leiden, destroying the castle to a state of a ruin.

Figure 3.4. The oldest depiction of Slot Teylingen, dating back to 1596. Here the battered castle is shown after being damaged in the 80 year's war, showing a badly damage gatehouse and burned out donjon. Source:(Annema et al., 1994b)

In 1605 drastic repairs were initiated. The Donjon, front gate and outer bailey were restored. After 1614 the outer bailey became the central part of the complex, and a garden area slowly arose around the castle. In that time the Donjon was mostly used as a prison. Because the complex served as control Centre and residence for the chairman for the forestry of Holland, a large house was built in the outer bailey.

Figure 3.5 A old painting of Slot Teylingen. On the left the main fortress, with on the right the outer bailey with gatehouse and residential building just behind Slot Teylingen. Source: http://www.geheugenvannederland.nl/?/en/items/RIJK01:SK-A-608

3.2.1.3 Building phase 3

In 1676 the Donjon burned out, destroying all the wooden floors, roof and interior of the building. The donjon was not restored after this, and this started the deterioration of the castle. At the same time, the buildings on the outer bailey flourish, with a large park and garden around the residential house, where the lieutenant-forester (chairman of forestry) lived(Annema et al., 1994a).

Figure 3.6. An old painting of the luxurious residential building, with in the back the deteriorated castle. Source:(Gemeente Teylingen, 2015)

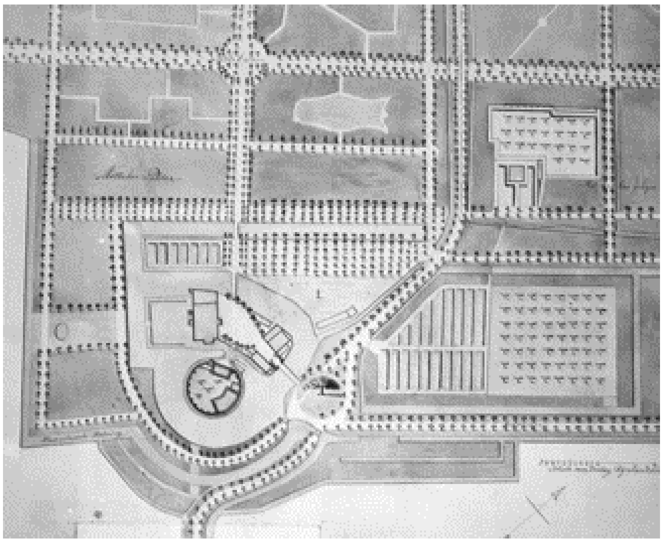


Figure 3.7 An old drawing from 1801 with the large garden area around the Castle. Source: (Gemeente Teylingen, 2015)

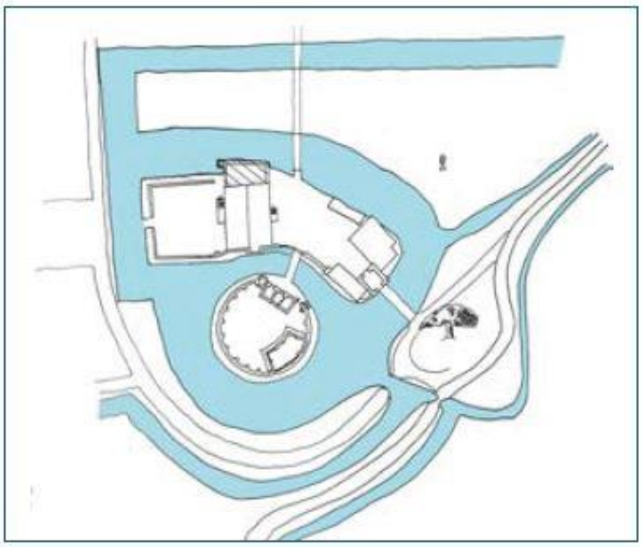


Figure 3.8 This image shows the buildings in the complex. The outer bailey has evolved greatly. Source:(Annema et al., 1994b)

3.2.1.4 Building phase 4

In the period after 1800 the institute of the forestry was dismantled. This caused the buildings to become vacant and new renters were not found for these houses. Eventually this led to a total demise of the complex. The complex was sold, under the condition the main fortress should remain standing. After that, the complex was split up, and the buildings in the outer bailey were eventually demolished. The moat around the castle was removed (Annema et al., 1994b).

Figure 3.9. Image of the badly deteriorated castle. Source: (Annema, Rijksgebouwendienst Bureau Rijksbouwmeester Adviesgroep Monumenten in Rijksbezit, Ministerie van Volkshuisvesting Ruimtelijke Ordening en Milieubeheer, & Kamphuis, 1994b)

3.2.1.5 Building phase 5

In the period after 1888 the castle was bought by the Dutch government to stop any further demise of the castle tower. Minor repairs took place, of which little documentation is available.

Figure 3.10. An image at around time of repairs. It is clear the castle was in bad shape. Source:(Annema et al., 1994b)

3.2.1.6 Building phase 6

In the period after 1900 a lot has happened in the surroundings of the castle which meant a derogation of the context of the landscape for the castle and its complex. More and more buildings of horticulture industry arose around the castle. In 1933 historical research was done on the site to gain a more scientific insight in the development of the castle over time. This has revealed foundations of a large gatehouse at the castle and a cesspool. Next to this diggings, the building was partially restored(Annema et al., 1994a).

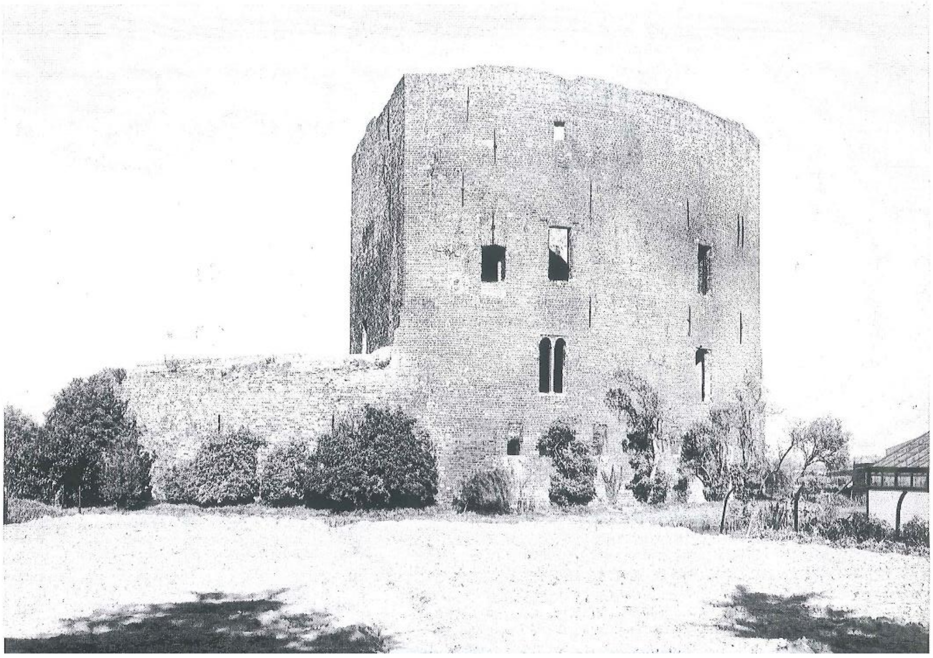


Figure 3.11 The castle after a partial renovation, somewhere between 1933-1977. Source:(Annema et al., 1994b)

3.2.1.7 Building phase 7

Around 1977 the last big intervention took place when an organization was founded with had the target to restore the context of the landscape to an original state, and to increase the integration of the castle in the cultural activities of the area. This had led to the partially re-digging of the moat around the castle, and a re-purchase of a piece of land around the castle (Annema et al., 1994a).

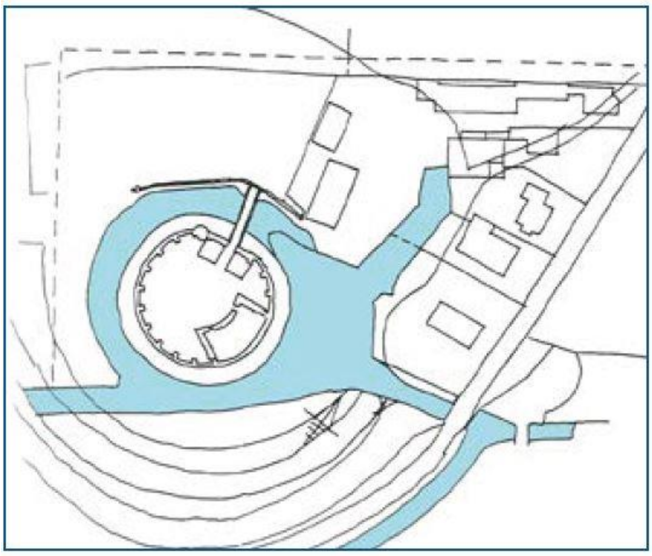


Figure 3.12 The current setting of the castle. Source: (Gemeente Teylingen, 2015)

3.2.1.8 Conclusion

It is clear that the building itself has experienced many different time phases of damage, restoration and repairs. This is why different parts of the castle date back to different time frames, which is illustrated below in the floorplan of the castle.

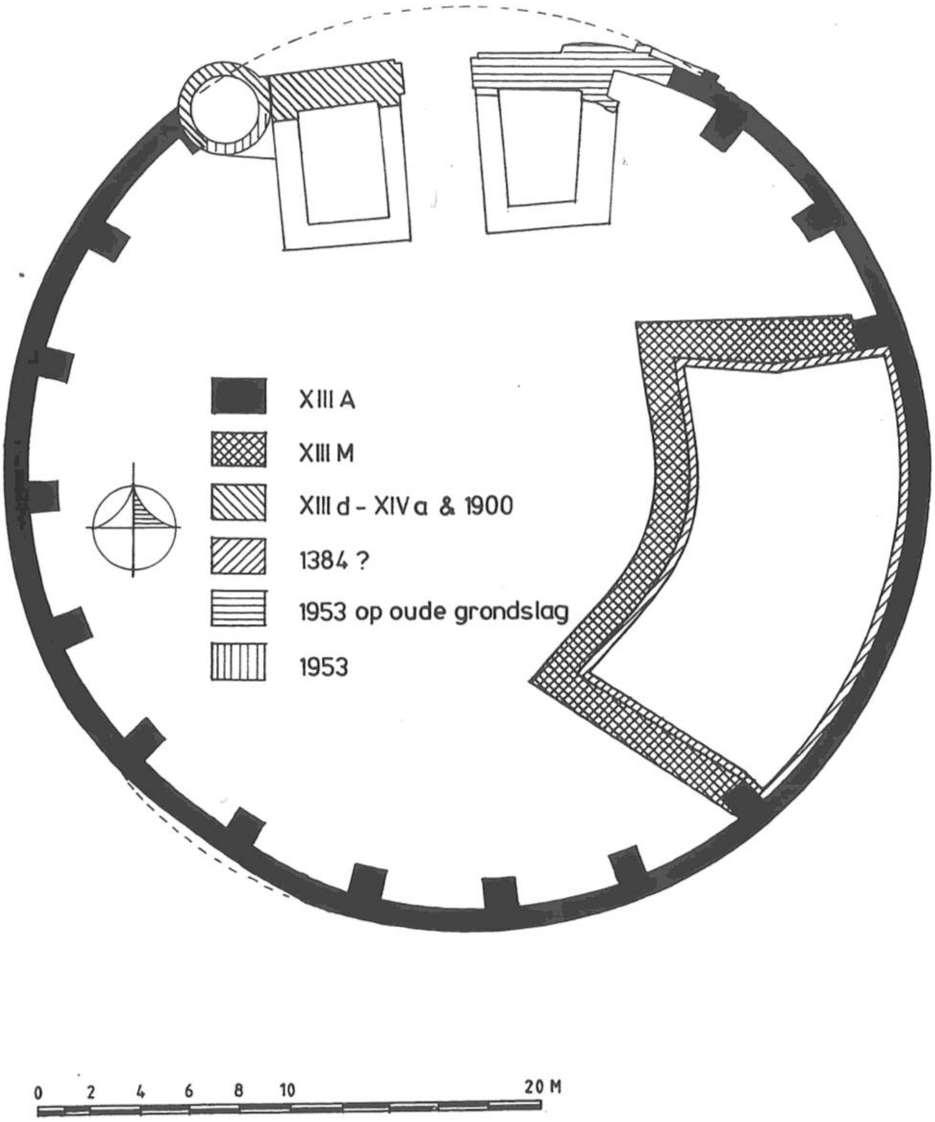


Figure 3.13 Floorplan is the castle, showing the different time frames where the structure part originate from. Source: (Annema et al., 1994b)

3.2.2 Cultural-historical value

Slot Teylingen is of great cultural historical value for the Dutch kingdom, the province and the municipality. The history of the castle is related to the formation of the Dutch states. Within all the time phases mentioned above there have occurred so many different historical events. The story telling about Slot Teylingen can be focused on dozens of residents, foresters, stewards and owners that have been part of the history of the castle. With this interesting history the castle can play a bigger role in the identity of the region.

A partial or complete restoration of the castle, together with a thorough redevelopment of its surroundings is a way to firmly integrate the castle back in its region, and prevent further deterioration. This should however be done carefully, with great respect to the history of the building.

3.3 Restoring Slot Teylingen

It is now clear Slot Teylingen fits the criteria of being an interesting and valuable castle, and that it deserves to be restored. By restoring the Donjon, the goal is to make the castle functional again. As described in chapter two, by putting a function in the castle again this will help conserve the tower. It will place the castle ‘’back on the map’’.

Restoring is however quite a broad term and it could be done in many different ways. In this part a focus is determined. A first question would be: what function could the castle get? And what kind of restoration is needed in order to make this possible in the building?

3.3.1 What new function?

For determining which function the castle should get, I would like to refer back to current ongoing research by the municipality. This question is also asked in that research, and four possibilities are named in the report. By evaluating the proposals for the function in this report, and using one of these functions as input for research, the two separate researches can be connected. This will make that the result of this research will have enough support in reality by the municipality and local residents.

The four proposals in the report of the research into possibilities from Municipality of Teylingen (2015), are drawn from a great amount of involvement from the local residents. In several meetings these locals were allowed to share their ideas on the future of Slot Teylingen. All these ideas finally were refined and joined into 4 models. These models are projected onto the current situation, which means that it has been made clear what changes need to made to the current context of the castle. These four models will be addressed now.

3.3.1.1 Model 1: Glorious Teylingen

In the first model the goal is to emphasize the interesting history of the ruin. This is done by an inconspicuous consolidating of the current castle. In this way the current state and look will be maintained. The walls of the donjon are protected from further erosion, but is not covered by a roof. An small new building next to the castle will act as entrance building with a small museum showing information about the castle, and with a small attractive catering function. The area around the castle and at the former location of the outer bailey will get a recreational function where visitors can have walks and enjoy the historical atmosphere.

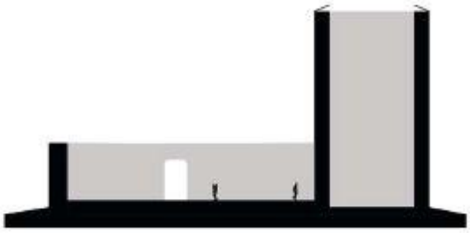


Figure 3.14 A section of the castle in model 1. Source:(Gemeente Teylingen, 2015)

Figure 3.15 A example of this model. Source:(Gemeente Teylingen, 2015)

3.3.1.2 Model 2: Ruin-garden Teylingen

Het goal of is this model is to restore the surrounding of the ruin into that of a higher quality and to make it more friendly for public. The ruin will be the focal point in this.
It will be consolidated by placing a roof on it that appears to be separate and floating on the donjon, to minimalize effect on the silhouette of the donjon. A staircase will be placed in the castle, and on the top floor of the tower a viewpoint is located. The walk on the stairs will give an view up close of the many details in the walls of the donjon, creating a ‘’promenade architecturale’’, telling the story of the castle. From the top floor the visitor will have an amazing view on the castle garden. This attractive garden houses a small museum, information center and a café, combining educational and recreational functions. In this model the historical value of the donjon will be untouched, while the context is enriched.

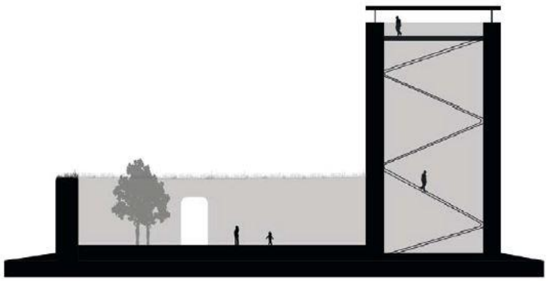


Figure 3.16. A cross section of the castle, showing the staircase and roof. Source(Gemeente Teylingen, 2015)

Figure 3.17. An example of this model. Source:(Gemeente Teylingen, 2015)

3.3.1.3 Model 3: Medieval construction spectacle

In this model the castle will be reconstructed using traditional medieval construction techniques. This revives the special history of the ruin, bringing it back by showing the historical techniques. This attractive construction process will use traditional materials take 20-30 years, and will attract many visitors. A roof and floors will be placed inside the Donjon, and the gatehouse and walls will be completely restored. The garden around the castle will be made to complement the building process, placing the castle in full view. On the building area a small educational and recreational building will be placed, in medieval style.

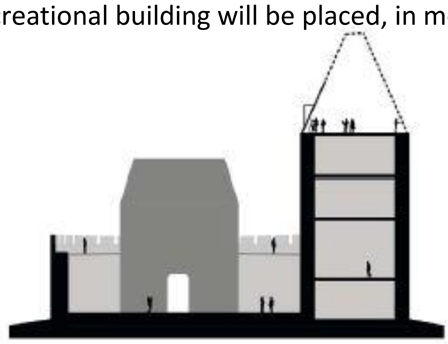


Figure 3.18. Crossection of castle. Source:(Gemeente Teylingen, 2015)

Figure 3.19. An overview of the area around Slot Teylingen. Source: (Gemeente Teylingen, 2015)

3.3.1.4 Model 4: Castle and congress park Teylingen

in this model the castle will be reconstructed to a complete historical encircled castle but with a modern function. The medieval history is combined with the history from the 17th and 18th century where there was a large garden around the castle. This involves making a large public forest for touristic and business purposes. The castle will be the prime focus in this model, because after restoring this will house a modern function which a high financial feasibility. This business approach makes the redevelopment of the castle also interesting for entrepreneurs. The garden around the castle will house a teahouse, music pavilion and a chapel.

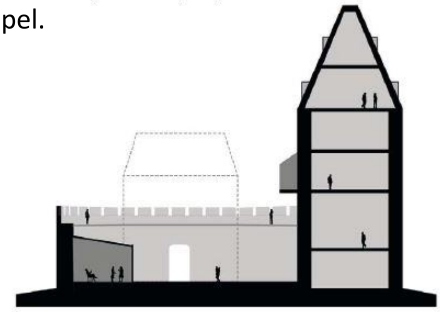


Figure 3.20. A cross section of the castle. Source:(Gemeente Teylingen, 2015)

Figure 3.21 An overview of the restored castle with forest and new functions. Source:(Gemeente Teylingen, 2015)

3.3.1.5 New proposal: a combination of previous proposals

In this model I would combine several proposals to come up with a new function. A combination is made between model 2 and 4, where the context of the castle is restored back into garden state it was once in. The castle will play a central role, and will be restored by placing a glass roof on it, closing the castle and making it functional(fig. 3.23). Under this roof a view point can made to look out over the beautiful landscape. A glass staircase is made inside the castle to reach the top floor. This transparent staircase will be a promenade architectural, where it tells the story of the castle. Potentially also floors can be placed added, which houses a café where visitors can have drinks, and a floor level with a small museum. These floors could be made of the traditional wooden structure, combining a new with an old structure. The glass roof and staircase will bring light back into the building, by being transparent. The glass roof should fit the building in respect to its history. The staircase and roof are made of glass to minimalize impact on the atmosphere and to respect the old structure. The functions in the castle should make the tower attractive not just for one-time visitors, but also for local residents who should be drawn to the castle for a cozy cup of coffee or a meal. The functions should be made to fit the medieval atmosphere of the castle. These functions would also increase the financial feasibility of the restoration of the castle. It can attract entrepreneurs to exploit the castle.

The area around the castle will also be a mixture of the proposed models. As in model 2, a castle garden will be made in part of the surrounding of Slot Teylingen (see fig 3.22). Another part of the land will be made suitable for events, which are currently happening already(Teylingen, 2015). This way medieval reenactments can be held next to the castle, increasing the experience of the area. A new clear entrance will be made, with enough room for parking. Some buildings near the entrance will need to be demolished to increase view and space.

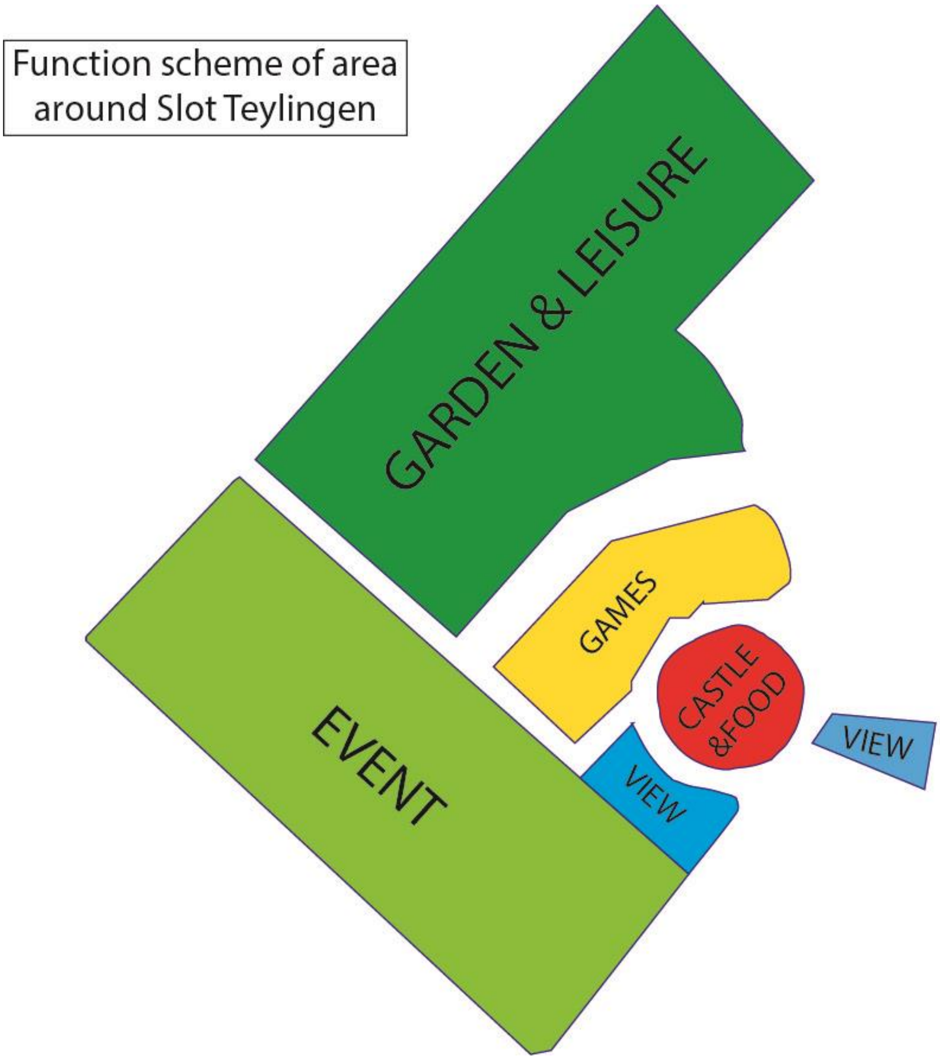


Figure 3.22. Function scheme area of Teylingen. Source: own ill.

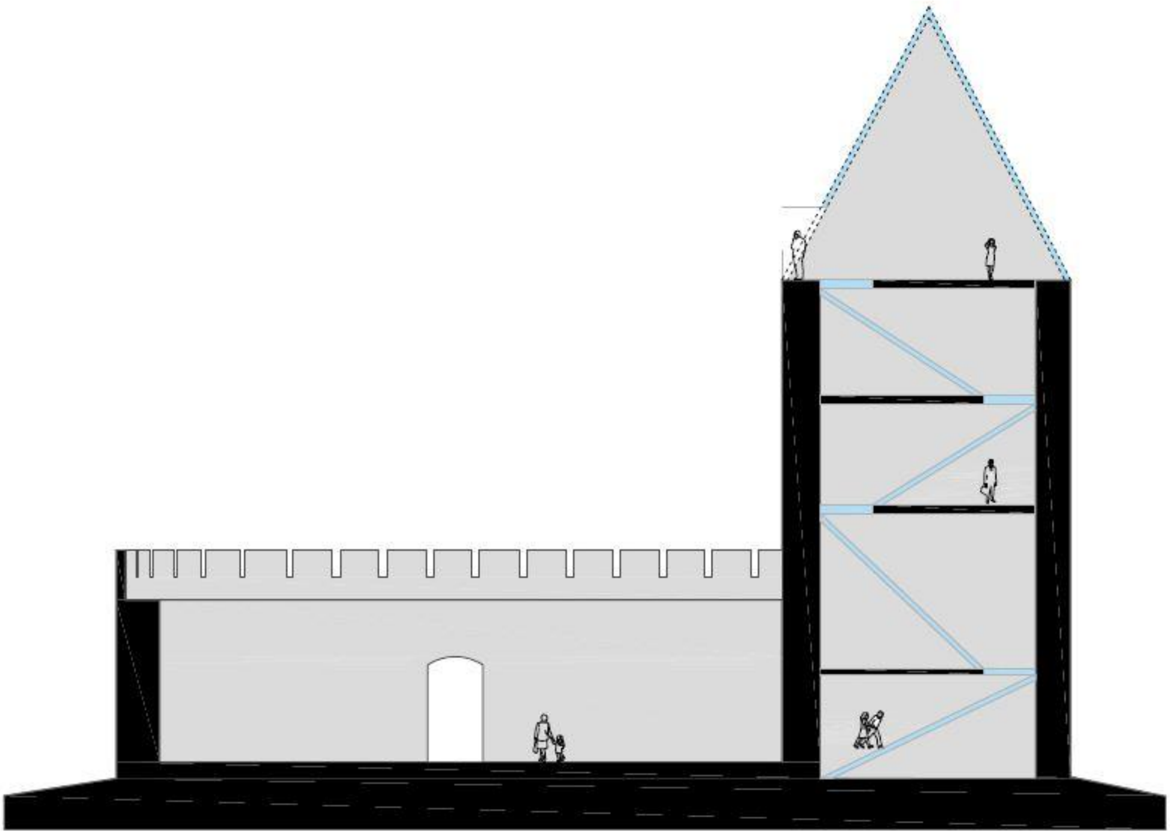


Figure 3.23 Cross section of the castle with glass roofs, glass stairs and new floors. Source: own ill.

3.3.2 Restoration focus: the roof

In order to make the castle functional again, there are a few interventions that have to be done. As can be seen in figure 3.23, the proposal involves a glass roof, a glass staircase, and floors in the donjon. Because designing all three of these elements is too broad for this research, it is necessary to define a focus.

This focus will go to designing the glass roof. This focus was determined in conjunction with the mentors. The roof is the most fundamental element in the intervention, since without the roof a new functionality is not possible. Also, the glass roof is the most interesting element looking from an engineering perspective. Even just making a roof in these dimensions will give challenging engineering problems. These challenges will lie in the connection between glass and the old masonry, but also in the connections in between the glass elements. There are several ways to make such large glass structures, therefore this is also an design question. The roof should eventually fit the old monument, and integrate harmoniously.

This structure will be elaborated and designed in different phases. After determining the original shape and size of the roof and the structure, different concepts are shown to make this shape. These concepts will have different structural systems. After that, one of the concepts is chosen to elaborate on, and will be designed up to detail.

3.3.3 Determining shape and structure of original roof

The first step in designing a new glass roof, is determining the shape this new roof has to have. As has been covered in the chapter about restoration, it is very important that a new roof on the building will integrate harmoniously with the old structure. It would be very strong if the new roof can somehow relate to the shape and structure of the old roof. That is why in the next part the original shape of the old roof is discussed. Another requirement is that the new roof is distinguishable from the old structure. As has also been discussed previously, glass as a material is good way to reach these goals. The ''transparency'' is however not merely lying in the material itself, but also in the overall structural set up. To achieve this transparency, the structure should be designed minimalistic and simple.

3.3.3.1 The original shape

A mockup can be seen inside the encircled walls of Slot Teylingen, where it is placed in an information center. This mockup shows the shape of the original roof, since it is to be expected it has been made according to historical research. This particular shape can also be seen in historic drawings and paintings(Annema et al., 1994b), making the assumption that this is roughly the right shape, more plausible.

In this mockup can be seen that the long edges of the roof are both curved, following the curvature of the walls below. The other sides are triangular and flat.

Figure 3.24 Photos of mockup of the original castle. Source: own photos.

In (Annema et al., 1994b) old drawings of the ruin are shown which include measurements, made in 1933 at the time of historical research as start of a first renovation. These technical drawings included a scale, which allowed a distillation the rough size of ruin and the old roof.

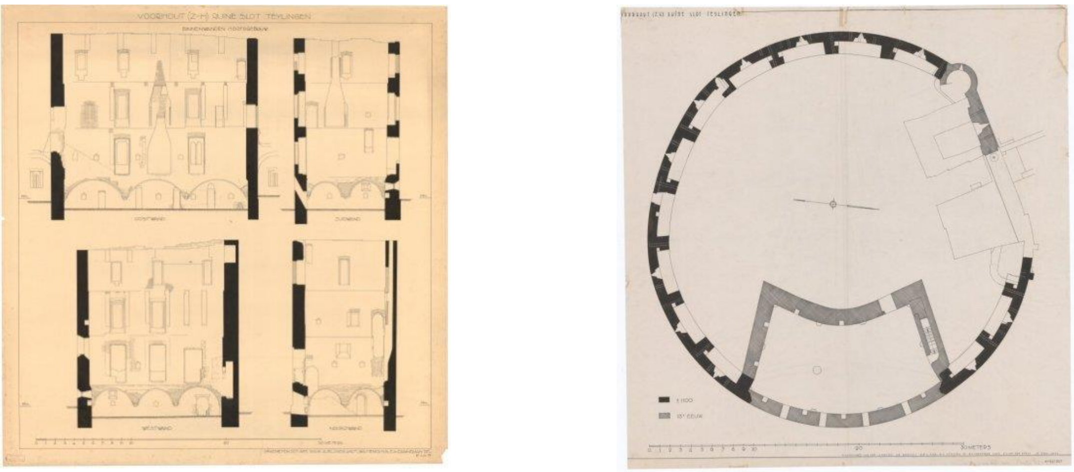


Figure 3.25 Old drawings with measurements. Source: (Annema et al., 1994b)

With these sizes drawings could made roughly to scale. This has leads to a section and plan drawing of the donjon, with the shape and size of the original roof, and the remaining wall structure. Here can be seen that the roof used to be rather large, with a total height roughly just over 9 meters. The horizontal span of the roof is roughly 11 by 19,5 meters. The length of the roof panels used to be around max. 11,5 meters. On the right a 3d model can be seen of the rough shape. This rough model is made based on the dimensions found an based on old drawings and the mockup.

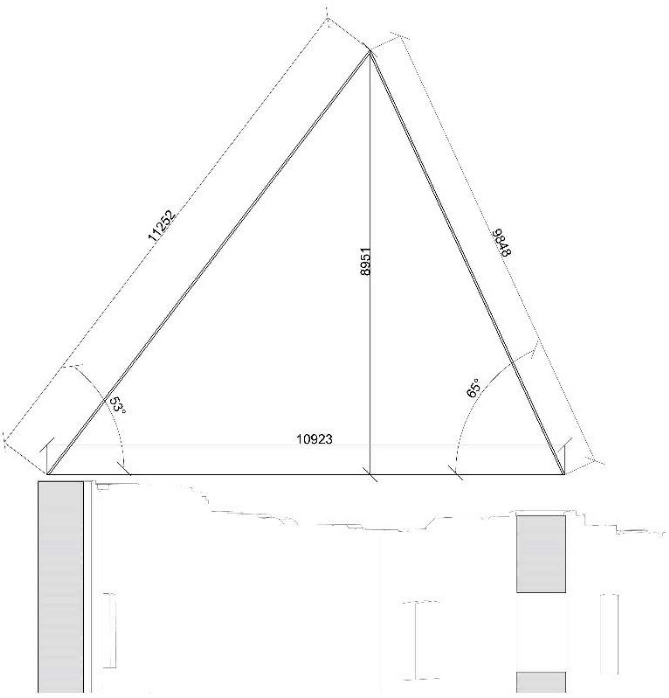


Figure 3.26 Scheme of original roof structure. Source: own ill.

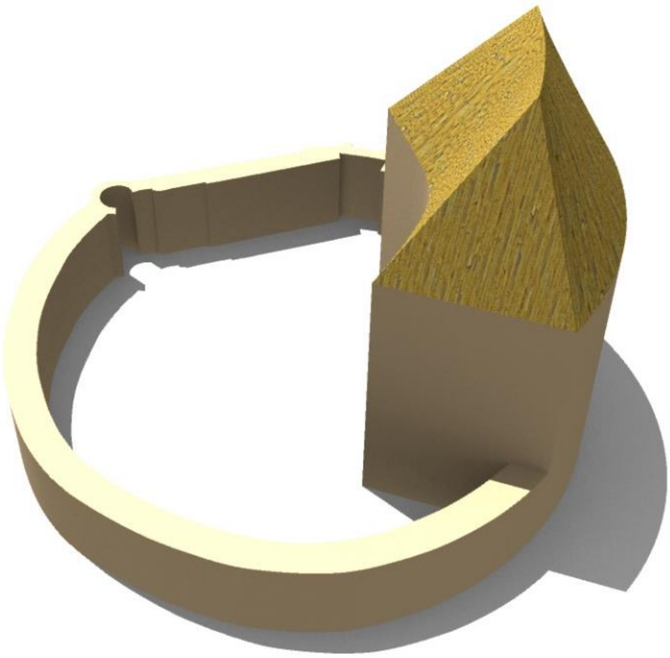


Figure 3.27 rough 3d model of the roof shape. Source: own ill.

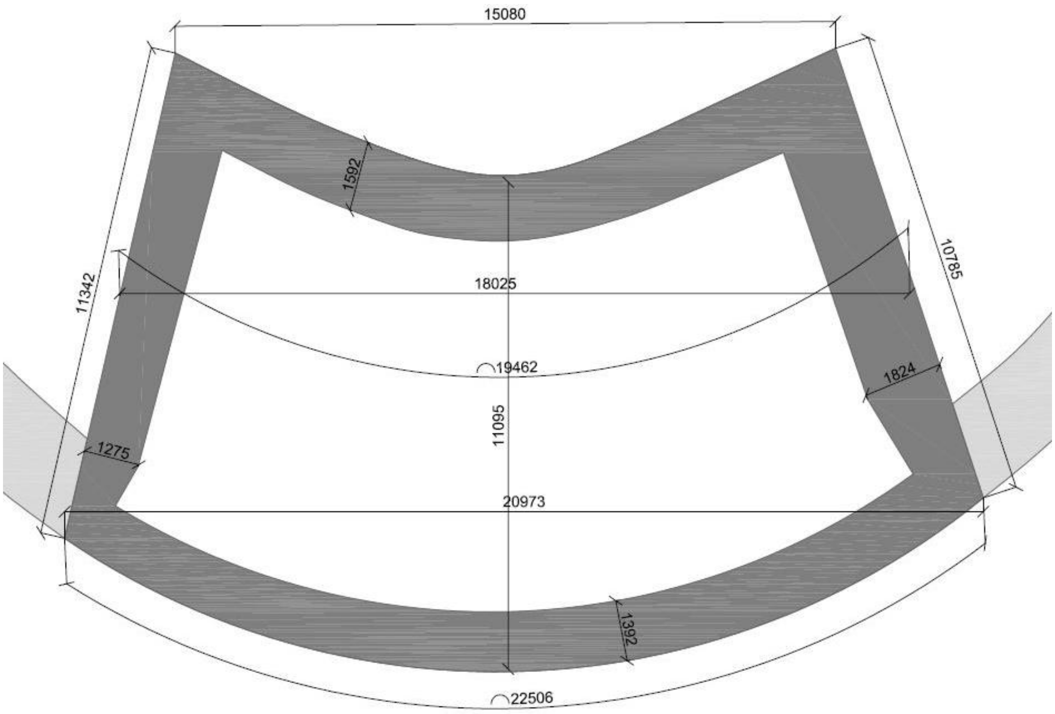


Figure 3.28 A floorplan based on traced old drawings. Dimensions are current sizes. Source: own ill.

The new glass roof structure will, in order the follow the restoration philosophy, need to relate to the old structure. This is either done by having the shape of the roof, but it could also by relating to the old structural build-up. For example if glass beams are used, the glass structure could have roughly the same frame buildup, or grid. In order to do this, first knowledge of the original structural build up is needed.

3.3.3.2 The original structure

Since the original roof structure has burned down in the late 17th century, and has not been rebuild ever since, it is difficult to find drawings or images of the original underlying structure. Therefore a historical building is sought which is standing nearby and is built in the same era as Slot Teylingen. In this way this can act as an example of the old roof structure.

There is an donjon which is located nearby Slot Teylingen, which is built in roughly the same era and style. This donjon is called ‘t Huys Dever.

Figure 3.29 ‘t Huys Dever. Source: http://www.dazzlingphotos.nl/kasteel-huys-dever.html

This castle is located in Lisse, 4 kilometers north of Slot Teylingen. The donjon dates back to the 14th century, being built in 1375. Over time the tower has been part of a larger complex with several residential buildings and a square. A wide moat encircled the complex. Until 1750 the complex was lived in, after which it got vacant. This started deterioration of the complex which caused the collapse of the building surrounding the donjon. In 1862 the roof the donjon collapsed after a heavy storm, which also destroyed the interior. From 1973 till 1978 the donjon was restored and opened for public. The roof and floors of the building are restored to their original state, based on historical research. and can therefore be a very valuable precedent, giving a good insight how the roof and floor structure of Slot Teylingen probably have looked.

Images below of this reconstructed roof give an impression of the original structure that supported the roof.

Figure 3.30 Restored roof structure of ‘t Huys Dever. Source: https://goo.gl/maps/SohZsBspQwM2

Figure 3.31 Restored roof structure of ‘t Huys Dever. Source: https://goo.gl/maps/SohZsBspQwM2

As can be seen the roof structure is a wooden beam structure, applied in the typical frame shape. Frames are placed on top of the stone structure, with then smaller corbels placed in between, finished by wooden planks and roof tiles on top of that. Visually the network of beams draw attention and determines the atmosphere of this type of roof.

3.3.3.3 The original floor structure

In case the wooden floors also need to be restored on the lowers floors, these can also be based on the old structure. In the image below the floor can be seen of ‘t Huys Dever.

Figure 3.32 The restored floor structure of ‘t Huys Dever. Source: https://goo.gl/maps/SohZsBspQwM2

Figure 3.33 The old structural floor system

In the image on the right an clear scheme can be seen of how the original floor system used to work. There used to be vertical wooden beams which slotted in shallow grooves in the masonry wall. A wood support frame then supported the main beam onto which secondary beams are placed. Onto these secondary beams the wooden floors planks are placed. These shallow grooves are still visible in the original wall structure.

3.3.4 Structural condition present

The old structure is as mentioned in a relatively poor condition. An image below shows the current situation.

Figure 3.34 The interior of the donjon in its current state. Source: (Annema et al., 1994b)

There a loose bricks in the walls of the donjon, which is also why thorough restoration was preferred. It is nice to see that the walls still tell a lot about the original structure, because the old grooves are still visible in the masonry. The old building had four floors, with the 4th floor at roof level. Before a new function can be put in the building, the donjon will have to be well consolidated in order to restore the majority of the masonry in a good state. As can be seen in figure 3.28, the thickness of the walls vary from roughly 1824mm to 1275mm.

Another important characteristic of the donjon walls is that the surface of the walls are not flat. Since the walls are not protected from the elements due to the lacking roof since 1677, corrosion has damaged the mortar and bricks over the past 400 years. In the 1970's during restoration a concrete beam has been inserted in the top of the walls(Rijksgebouwendienst | Advies & Architecten | Afdeling Monumenten, 2014), as a replacement of the steel tensile rods holding the walls the together. This has however damaged the walls even further, due to the different expansions coefficients. The current state of the walls show a height difference of roughly 1,3 meters.

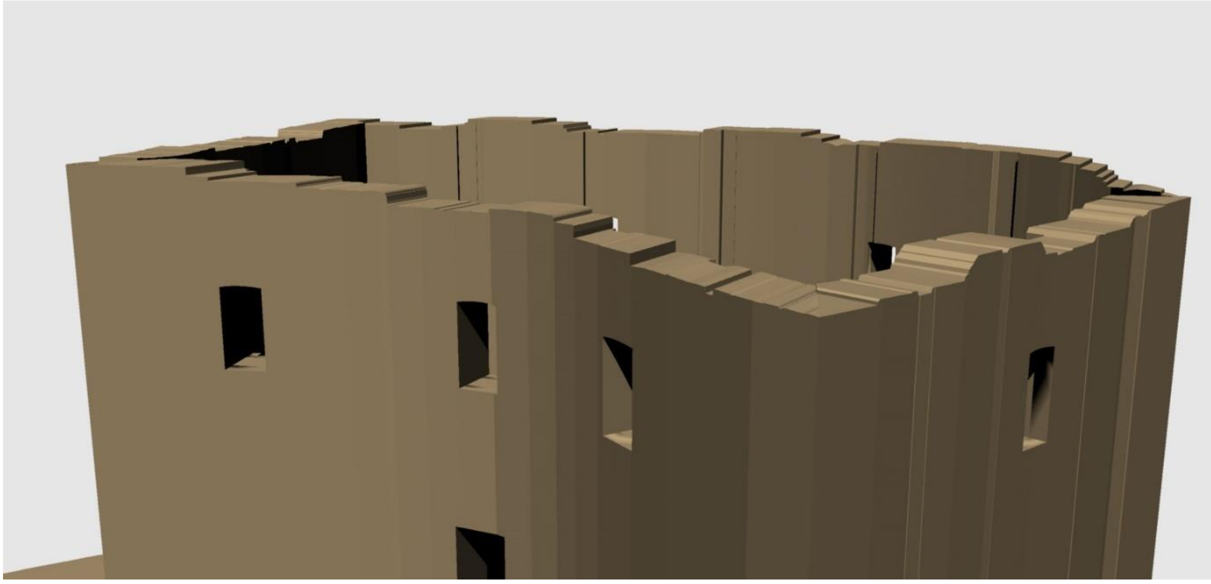


Figure 3.35. A 3d model of the Donjon with its current wall state

Because these bricks are old and weakened over time, this requires special treatment. The structural performance of these brick walls are weakened, which means that the new glass roof should not exert too much force on it and near its connections. Otherwise the wall can be damaged by the roof, or in worst case, even fail.

The structural properties of masonry brick walls are depending on a lot of factors. But very roughly it can be said that the properties are ranging as following:

Type of allowable stress	Value	Unit
Compression stress	2-10	N/mm2
Tensile stress	0.25-0.8	N/mm2

Figure 3.36 Global properties of masonry. Source:(TGB Steenconstructies NEN, 1996)

This shows that masonry is much stronger in compression than in tension, where it is rather weak. This means that the connections of the glass roof on the masonry should not exert tensile forces or bending moments. This would otherwise cause damage to the walls. This should be a boundary condition of the final design. Also, the compression stresses of the new roof will have to be divided well across the supports to prevent compression damage of the walls. Since the walls are very thick, the risk of buckling is not present.

3.3.5 What degree of intervention is allowed?

Installing a new roof on the donjon will mean making a large intervention to the castle. The new roof has to be joined to the old walls, which not only means adding a large new volume to the old building, but means making connections to the old masonry. The questions rises how this should be done? Since the building is historical, not just any adjustment or addition can be made to the monument. The Venice Charters are used as guidelines for formulate the possibilities in intervention in the monument.

Regarding the replacement of a missing element, this has already been largely addressed in chapter two. Adding any large new element to a monument requires very careful and well-thought measures. An interdisciplinary approach is needed to respect the history of the building on every level. It could be argued that the best way to respect the historical value of the building, is to leave it untouched. However, this would mean the building would often further deteriorate, and it would be left vacant. This is why an intervention or addition of a new element is often inevitable.

Regarding the connection level, the Venice Chapters state that the roof should be built in such a way, that it could be removed without leaving permanent changes to the monument. However, it seems making no changes at all the monument is inevitable. This because there is always need for some type of fastening of a new element to the old structure.

When looking at the point mentioned in chapter two regarding the restoration guidelines regarding the degree of intervention that is allowed in a monument, it can be said that the restrictions are not very strict or clear. It will be a gray area where good argumentation is the basis for the proposed actions. Once this is done, the best solution must be chosen.

To reduce visual impact and prevent falsification of the old building, glass has been chosen as the material for the replacing element. In this way both states of the monument, the old and the new, will remain visible after restoration. Even though the roof will be made of a transparent material, it is still a large intervention. This is however necessary to allow the building to become functional again.

For the intervention regarding the installation of the new glass roof onto the monuments walls, different systems are possible. If going for a damaging method, the connections would be drilled into the masonry. This will create a very small connections, hardly visible, doing little harm to the architectural overview. But it is doing permanent damage to the castle. Another option would be making sort of sleeves which slide over the top the walls, consequently being able to resist bending moment. This system will no harm to the walls, but will likely be very bulky and ugly, which harms the historical and architectural feel. This shows the discussion on this topic.

Eventually it was chosen that the best option would be making bolted connections to the donjon walls. This has been chosen due to the relatively subtle connections that can be made to the old building, and the minor bolt holes that will be left in the donjon walls.

4. Glass

Glass is a unique material. It is very transparent with 95 % transparency with a 10mm thick glass plate, while at the same not allowing water to pass through (Nijsse, 2015). Another important aspect is that the material is very strong. Due to these properties the material has been used for a very long time in architecture. Especially the property of transparency seems to be very important. This property allows the architect to make a separation between the inside comfort and the outside environment, where it can be cold, wet and windy. This is done without making visual separation, allowing the architect to ''connect'' the building and its inhabitants to its surroundings.
Another important aspect of glass is its sustainable nature. It is a material made from natural sources which are all abundantly available on earth, and the material can be recycled indefinitely.

Thus far glass has mostly been used as a cladding material, where it would be connected to a loadbearing structure usually of aluminum or steel. Although glass is very strong, it is also very brittle, often breaking without notice. For this reason engineers and architects have not often tried, dared or thought of using glass in a structural way. New insights in the structural applicability of glass by research from for example the Glass & Transparency group at TU Delft, have proofed glass can actually be used as an innovative and exciting structural material.

However, since glass is a relatively new structural material, there is still a lot of innovation and development going on. There is a lot of research needed to develop good details and connections is glass, as well as finding new types of manufacturing of new glass elements. With a focus on a new application field of monuments and historic buildings, these topics arise again. Before designs or new research can be done or made, a literature study is needed to orientate on what has already been researched and done. In this chapter first the material glass will be described, before showing what structural solutions have already been found for current structural components.

4.1 Material properties of glass

Glass as a material is quite difficult to define. It is a solid material without a crystalline structure. Since most solids do have a crystalline structure, and fluids by principle do not, glass is often described as a ''super cooled liquid''(Navratil, 2009). It is a material that has been heated to a melt, and shows glass transformation behavior when cooled down fast enough. Glasses are characterized by having short periodic atomic arrangements, meaning they have an irregular geometric network of crystals. This is in contrast with most of the solid materials, which do have a regular geometric pattern of atoms.

There are many kinds of glass, with all slightly different compositions of raw materials, and therefore different material properties. Of the many types of glass used in the building industry, soda-lime glass is the most commonly used type of glass (Wurm & Peat, 2007). Other glass types are for example borosilicate, known for its good fire resisting properties due to its low thermal expansion coefficient. Lead glass or low-iron glass are other types.
Since soda-lima glass is the most common glass type in the building industry, the production process and the properties of this type of glass will be described. However, in order to understand the material properties of soda-lime glass, it is necessary to first look at material on a small scale, zooming into the composition of the material, into the chemistry of glass.

4.1.1 Chemical composition

Soda-lime glass is primarily made out of 3 raw materials: Silica (SIO2), limestone(CaO) and soda(Na_2O)(Van der Velde, 2015). Almost three-quarters of glass is composed of sand (see figure 4.1). Sand's most common form is quartz, which primarily consist of silicon dioxide (SIO_2). Quartz can be found in all sorts of sands and rocks on planet Earth and is abundantly available, being the second most abundant mineral in the Earth's continental crust. ("Quartz,") Silica has a melting point of 1723 degrees. Differences in color of different kinds of sand are caused by coloring oxides. It is important to notice that for making glass, silica with very few impurities is needed. That is why only white pure silica sand is used for making glass. There are however always a few impurities left in the material, like iron oxides, which give soda lime glass its characteristic greenish color. (Haldimann, Luible, Overend, International Association for, & Structural, 2008)
The soda is added in order to reduce the melting temperature of silica and lowering the viscosity once melted, so this allows for easier production. Lime is added in the mix to toughen the material and to improve the chemical resistance of glass. The rest of mix consists of a variety of materials to enhance certain properties of the glass, like for example dolomite. Additives can be used to color the glass, these will usually be no more than 1% of the total mix. The exact composition of the mix can be changed to enhance certain properties of the final material.

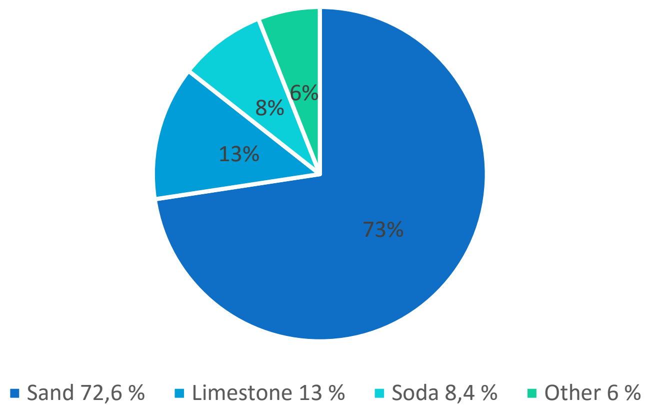


Figure 4.1. Composition of glass. Source: own ill.

4.1.2 Chemistry of glass production

In order to make a clear glass panel the raw materials need to be melted. The composition is made and mixed according to the required specifications. It happens often that next to the raw materials also recycled glass shards are added to the furnace. This makes the melting process easier.
When melting the materials, a chemical reaction takes place. The molecules of the raw materials break apart, allowing the atoms to form new bonds.

The following chemical reaction takes place when melting:

$$SiO_2 \quad + \quad Na_2CO_2 \quad + \quad CaCO_2 \ \rightarrow \quad SiO_4 \quad + \quad CO_2 \quad + \quad Na \quad + Ca$$

Or written in words:

$$Sand + Soda + Lime + heat -> SIO_4 + Carbon\ dioxide + Sodium + Calcium$$

After melting, the atoms bond together as SiO_4, and also forming carbon dioxide gas, and separate sodium and calcium atoms.
As (Le Bourhis, 2008) explains in his book, The SiO_4 molecules have a particular shape: a tetrahedron (see figure 4.2)

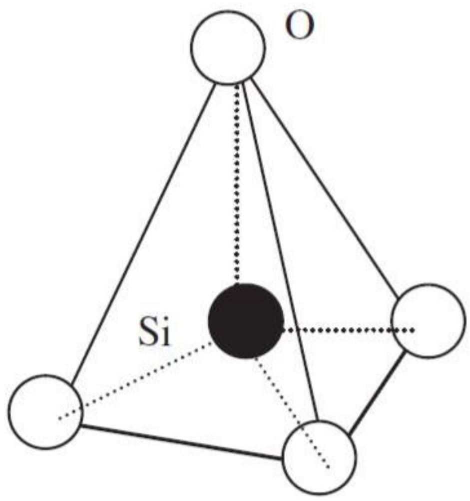


Figure 4.2. A silica tetrahedron. Source: (Le Bourhis, 2008)

What is clear is that the positive Si^{4+} is centered in the middle, connecting to four negatively charged O^- atoms. In the molecular structure, O^- atoms are shared between different Si atoms. At the same time, the negative charged oxygen atoms repel other negative oxygen atoms. The positive charged sodium and calcium atoms are called modifiers, because they alter the silicon structure. This creates an irregular network of silicon and oxygen atoms, with alkaline parts in between. (figure 4.3)

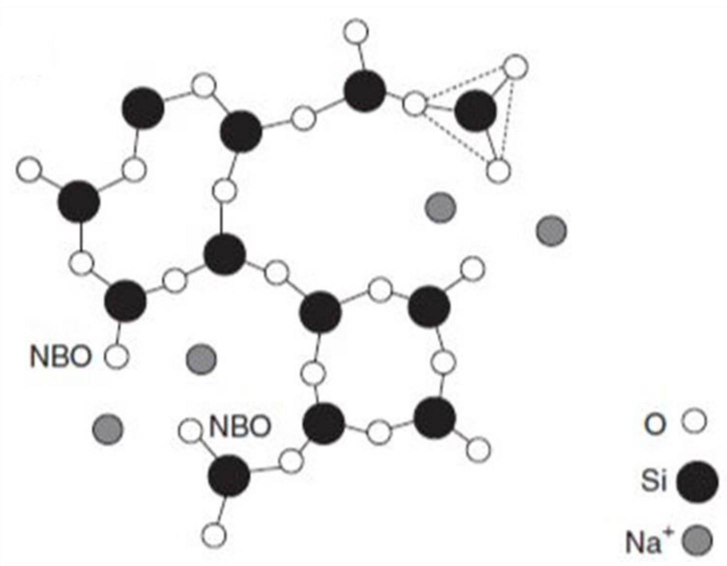


Figure 4.3 The molecular structure of glass. Source: (Le Bourhis, 2008)

This non crystalline structure explains the material properties of glass. Because of the relatively large gaps in the molecule structure, light waves can pass through, making the material transparent. These gaps also explain why glass can break very easily when damaged or scratched.

4.2 Production techniques of flat glass

4.2.1 The ancient techniques

The production is glass dates back far in history. Civilizations as old as Mesopotamia and the Romans mastered the knowledge of producing clear glass (Nijsse, 2002). The Romans used the technique of glassblowing. A hollow metal pipe was used to manually blow air into a blob of molten glass, creating a hollow glass shape. Later wooden molds were used to blow the glass into, allowing the production of standardized glass products.
A later invention enable the first glass products suitable for the building industry. This involved blowing cylinder-shaped glass elements, which can then be cut open when still hot to create a flat sheet of glass. This technique allowed for making flat sheets of glass of 1000 X 800 millimeters.(Nijsse, 2002)

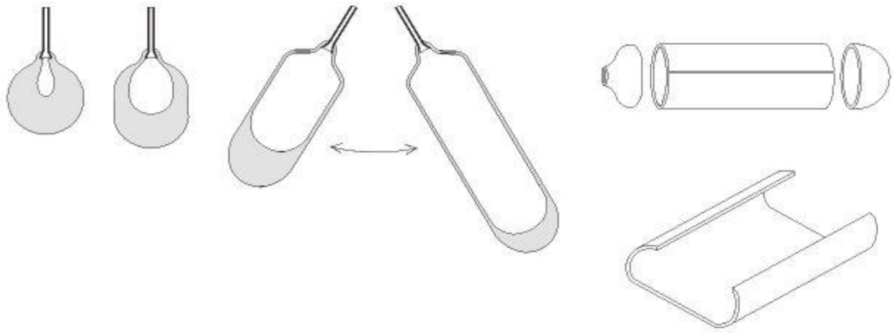


Figure 4.4. The production of flat glass pane out of a blown cylinder. Source: (Schittich et al., 2007)

With the industrial revolution the demands for flat glass rose rapidly. New techniques were developed, which increased the total production of glass worldwide between 1845-1885 by ten-fold.
This resulted in an enormous drop of price, making the application of glass in the building industry much more approachable.

4.2.2. Industrialized pulling and drawing techniques

The first of industrial production techniques was called the Fourcault system (figure 4.5). This technique was developed by Emille Gobbe in 1901 (Schittich et al., 2007). An iron bar would place down into a narrow opening. The molten glass would stick to the bar, after which the bar was being pulled up. While being pulled up, the glass is cooled so it would harden. A similar technique was used in the Pittsburgh system, which was developed in 1921 (fig 4.6). Here glass is pulled through a series of rollers, which flatten the glass. The distance between the rollers together with the pulling speed could determine the thickness of the glass pane. This could allow for more precise controlling of the thickness and flatness of the glass. In 1915 the Libbey Owens system allowed for making very thin glass panes. Here glass was pulled vertically through a set of bars, and then pulled horizontally over a cooled steel roller into a cooling furnace. This allowed for glass panes varying from 0.4 to 20mm (Leung, 2010).

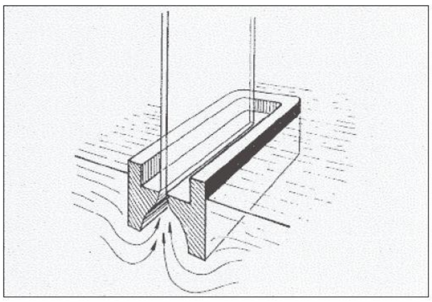


Figure 4.5: The Fourcalt system
Source: (Leung, 2010)

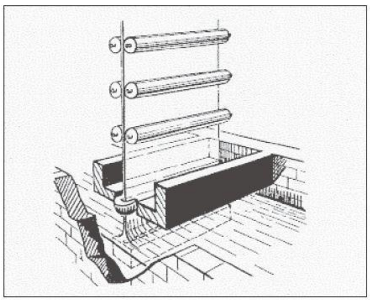


Figure 4.6: Pittsburgh system

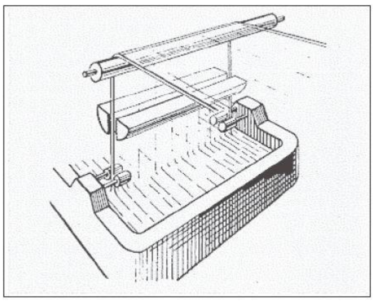


Figure 4.7: Libbey Owens system.

4.2.3 Float glass

In 1959 the Pilkington Brothers commercially introduced a new technique of producing flat glass: the float glass technique. This technique nowadays accounts for 90% of today's flat glass production worldwide (Haldimann et al., 2008). This techniques has major advantages over older production techniques. Using this method it is possible to reliably produce large size glass panes at a low cost, with a superior optical quality. Also because the technique was widely available, this completely reshaped the glass production industry. This allowed glass to become one of the most important materials in architecture.

Float is produced in large manufacturing plant in a continuous process: meaning the plants operate 24 hours a day, 365 days a year. The production process is shown in fig 4.8.
As the start of the process the raw materials are weighed and mixed to produce a mix according to the required specifications for the glass product. These materials are melted in a furnace at around 1550 ˚C. Once the glass has become liquid, it is poured continuously onto a shallow pool of molten tin, at a temperature of about 1000 ˚C. Because tin has a higher specific weight then glass, the glass floats on top of the pool of tin, where it reaches an equilibrium thickens creating a very smooth and flat surface. The molten glass is slowly pushed forward by small rollers at either side of the molten glass pane. By adjusting the speed of the rollers, the thickness of the glass pane can be adjusted from 2 to 25mm (Haldimann et al., 2008). Next, at a temperature of around 600 ˚C, the glass enters a long oven called a ''lehr''. In the annealing lehr the glass is gradually cooled down to prevent residual stress inducing in the glass by the temperature differences. After leaving the Lehr, the glass is cooled down and cut to a standardized size of 3.21m X 6.00m. Any broken glass or waste glass parts are being fed back to the start of the process for reuse. Glass produced using this method is the standard ''annealed'' glass.

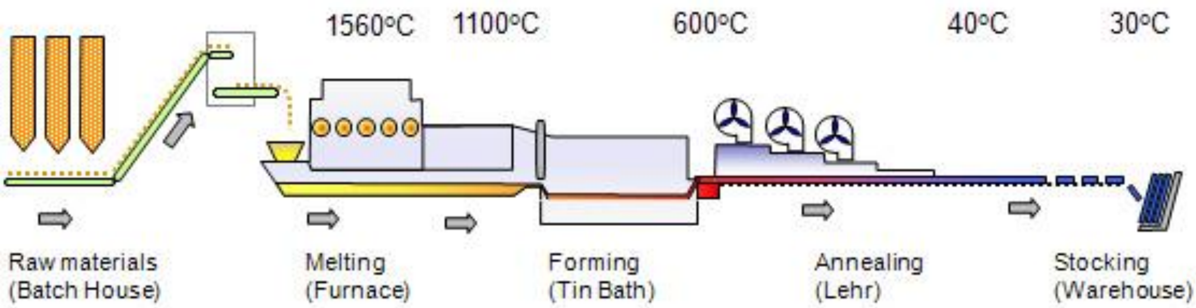


Figure 4.8 The float glass production process. Source: (Russia)

4.2.4 Cast glass production

An older production technique is the cast process for making flat glass. Here molten glass is poured on a table and then rolled between metal rollers to form a flat sheet of glass (Sedlbauer, 2010). Using this method, larger thicknesses of glass can be achieved compared to the float glass production process. The rollers may be engraved so the glass can be given a surface design or texture (Haldimann et al., 2008). Important to known is that cast glass is often not transparent, but translucent. By polishing the flat surfaces, clear glass can be obtained. Using the cast technique, it is also possible to produce wired glass. Here, a steel wire mesh is sandwiched between two separate panes of glass. Previously wired glass was

Figure 4.9 The process of casting glass. Source:(F Oikonomopoulou, Veer, Nijsse, & Baardolf, 2014)

formerly known as ''safety glass'', because the mesh was supposed to keep the shards together after breaking. However this would still create dangerous sharp shards of glass. Nowadays a new alternative has been developed for that, in the form of laminated glass. This type of glass will be explained later in this chapter.
Next to flat glass panes it is also possible to produce glass profiles using the cast process. This is however limited to U-shaped and circular hollow sections. (Haldimann et al., 2008). Also very different shapes can produced, like glass bricks.(F Oikonomopoulou et al., 2014), illustrated in figure 4.9.

4.3 Mechanical properties of glass

Glass is brittle and hard material. Glass is a material that shows linear-elastic, isotropic behavior. Upon breaking it shows brittle failure. Due to the molecular structure of glass, glass is not able to distribute stresses by means of plastic deformation (this will be explained later). That is why glass can show some elastic deformation, but no plastic deformation at all. Glass is therefore very sensitive to stress concentrations. (Louter, 2011)

The following table shows some (mechanical) properties of (annealed) Soda-lime glass, based on EN 572-1:2004.

Property	Symbol	Value	Unit
Density	ρ	2500	kg/m^3
Hardness (Knoop)	$HK_{0,1/20}$	6	GPa
Young's modulus	E	70000	MPa
Poisson's ratio	ν	0.23	-
Tensile bending strength	F_t	45	MPa
Specific thermal capacity	c	720	$J\ kg^{-1} K^{-1}$
Thermal expansion coefficient (between 20 and 300 ˚C)	α	9	$10^{-6} K^{-1}$
Thermal conductivity	λ	1	$W\ m^{-1} K^{-1}$
Average refractive index to visible radiation (380 to 780 nm)	N	1.52	-

Figure 4.10. (Mechanical) properties of annealed soda-lime glass

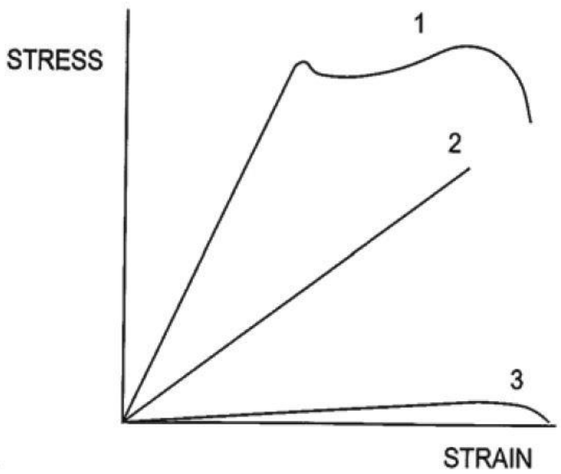


Figure 4.11. Material behavior of glass (2) compared to steel (1) or timber (3). Source: (Ouwerkerk, 2011)

In table 2.1 the tensile bending strength of annealed glass is given. This value is however not a material constant, but this value is dependent on a large variety of variables.

4.3.1. The strength of glass

The strength of any material is determined by the bonds the molecules have in the molecular structure of the material. Based on the molecular forces, the theoretical tensile strength of glass is extremely high with 6000 MPa - 10000 MPa, with an even higher compressive strength (Haldimann et al., 2008). However, because of the irregular crystalline structure of glass, no plastic deformation can occur. This because when an bonding is broken, no new bonding between atoms can easily be formed. In consequence, when local stresses in the material exceed the chemical bond strength, the bond will fail causing the material to fracture. This will subsequently cause an increase in local stresses, causing the crack to grown until the entire element has fractured (Veer, 2007).

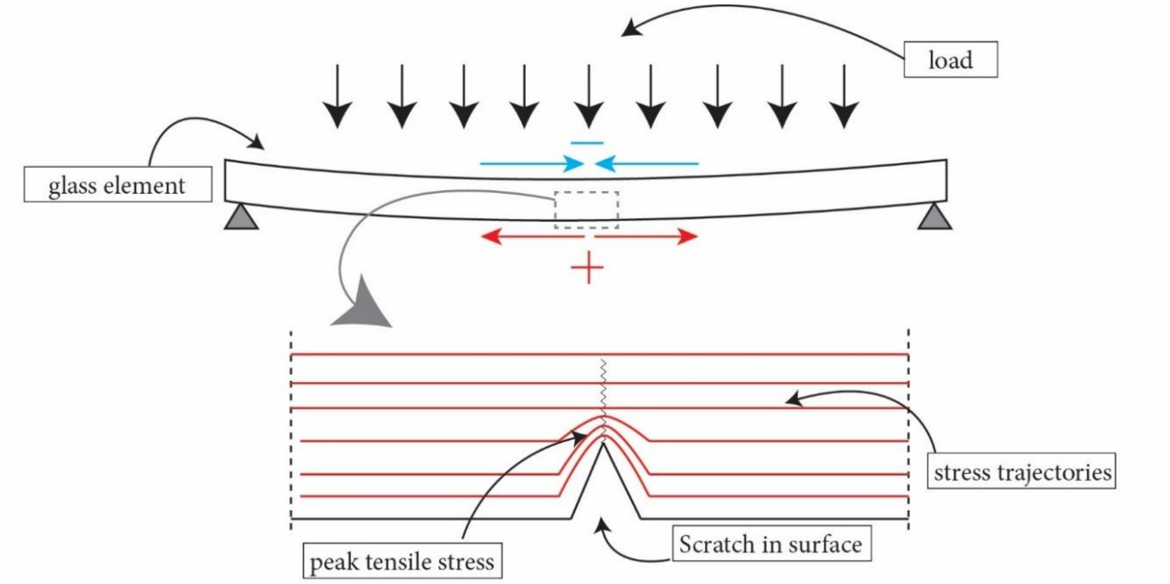


Figure 4.12. The buildup of peak stresses by surface scratches in glass. Source: own ill.

Therefore, as for any brittle material, the tensile strength of glass depends very much on mechanical flaws on the surface. The flaws are usually not visible to the naked eye, but play a vital role in the structural strength of glass. These flaws occur from the processing of the material.
In the factory the continuous sheet of glass that comes out of the ''lehr'', is cut into parts using a glazier's diamond or a tungsten carbide roller that scratches the surface, as shown in figure 4.13. By bending the plate slightly, tension is generated in the cut causing the material to crack in two parts. This cutting action however also induces an edge damage alongside the crack, as shown in fig 4.14.

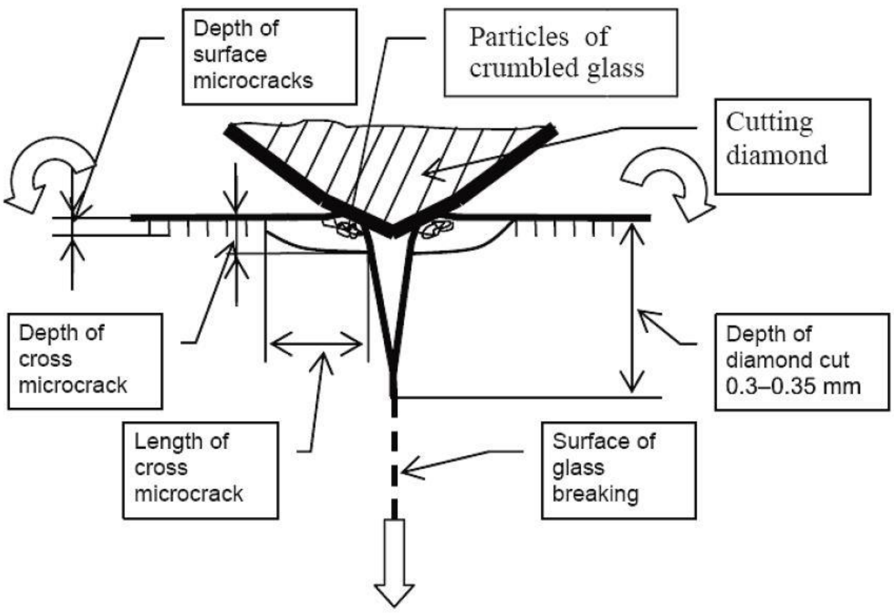


Figure 4.13 The cutting of a glass sheet. Source: (Rodichev & Veer, 2011)

This damage forms a weak spot where local stress peaks can occur, causing the material to likely break at that location when loaded.

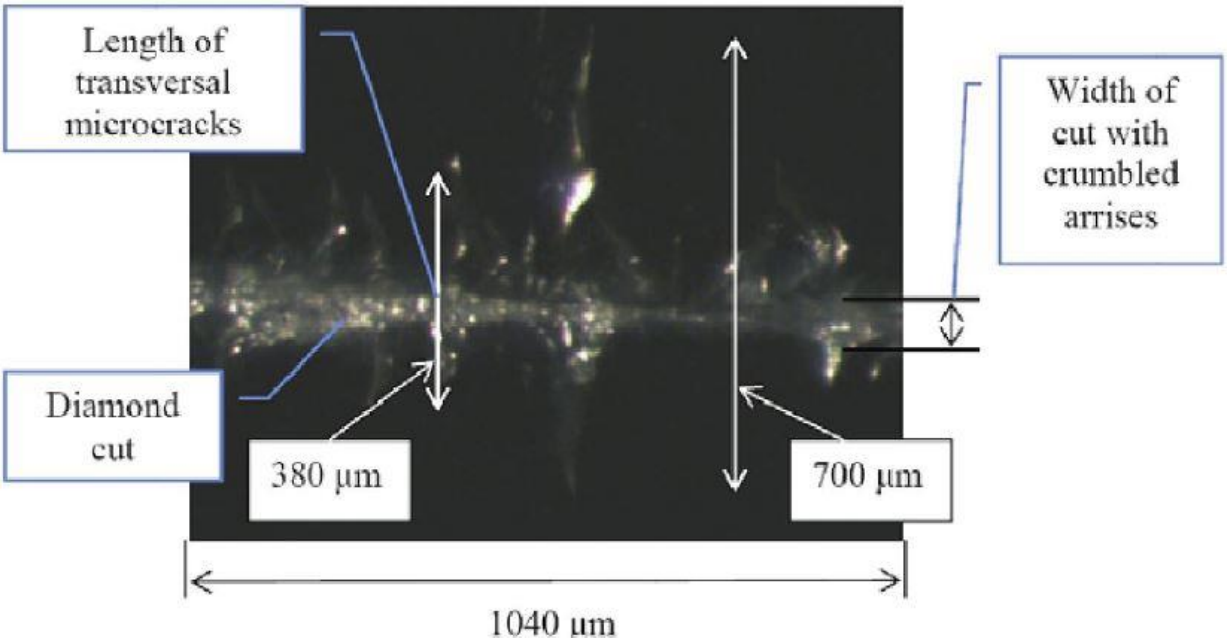


Figure 4.14 Close up of glass cut groove. Source: (Veer, 2014)

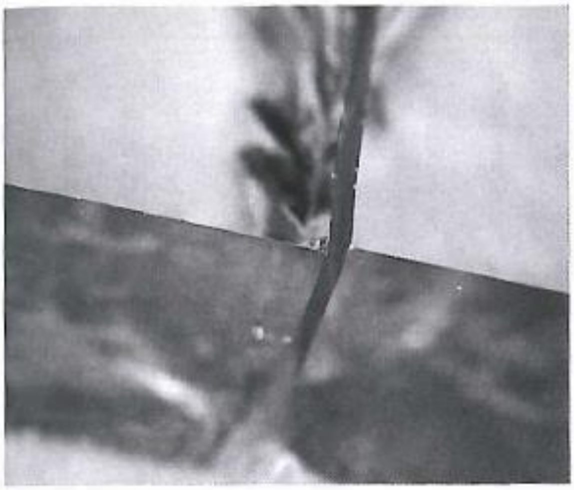


Figure 4.15 Defect and crack in glass edge. Source: (Veer, 2014)

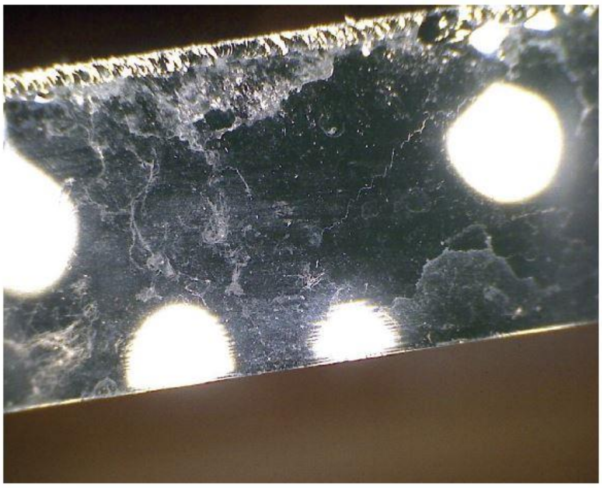


Figure 4.16 Flaws in glass edge after cutting. Source: (Veer, 2014)

This means that the strength of a glass pane is lower near the edge of the panel. The center of the panel will likely have a higher strength. It can thus be concluded that the strength of glass is not a constant value, but it is very dependent on surface quality and stress distribution. (Veer, 2007)

Based on experimental research a bending strength of 20 MPa for annealed glass has been found that proves reliable and safe to use in practice when using annealed glass in structures (Veer, 2007).

4.4 Mechanical processing of glass

Because of the brittle nature of glass, and it sensitivity to peak stresses, several methods have been found to make the material stronger and more reliable. These measures will be discussed here.

4.4.1. How to increase strength?

4.4.1.1 Edge quality

As said before, glass can be cut in a variety of shape into smaller pieces using a glazier's diamond or a tungsten carbide roller. It is also possible to drill holes in glass. These holes can be used to create connections. However, often during drilling these holes the glass is damaged at its edge. Both drilling and cutting therefore weakens the glass.

To give the glass more strength the edges of glass panels are often grinded and polished, which involves locally cracking the glass into very small fragments which are then washed away. The surface is hereby flattened, and the edges are often ground to an angle of 45 degrees to further improve the strength. Although these techniques in principle increase the strength of a glass pane by removing many scratches, it is very important that the machines used for this are well maintained. Otherwise they can cause damage that is invisible to the human eye, but has a significant effect on the strength of the panel (Veer, 2007).
Another possibility is to use water jets to cut the glass. This uses high pressure jets, cutting with water in which abrasive particles are mixed. The accuracy when cutting with this technique is higher, and it produces cleaner edges with less damage. This technique is however not often used but it is time and cost consuming(Van der Velde, 2015).

After the glass has been cut and polished according to requirements, it can undergo a heat treatment, that will strengthen the glass.

4.4.1.2 Heat treated glass

Glass that is used for structural applications is very often tempered, to increase the strength of the glass. While with annealed glass the material is cooled very slowly to prevent residual stresses, the goal of heat treating is exactly the opposite. The glass is cooled rapidly to create a favorable residual tensile stress in the core of the panel and compressive stresses on and near the surfaces (fig 4.17). Because the core contains very little flaws this can sustain the tensile stresses much better than the surfaces. The unavoidable flaws in the glass surface will only grow if a high enough tensile stress is exhibited on them. Since with tempering an residual compressive stress is induced on the surface, this will compensate for tensile stresses that occur. As long the tensile stress due to actions is smaller than the residual compressive stress, the total stress will still be compressive. Since cracks will only close due to compressive stresses, this means the panel can sustain much higher loads and bending stresses. This is why heat treatment makes glass panes stronger (Haldimann et al., 2008). There are two ways to heat treat glass. Glass can be so called *fully-tempered* or be *heat-strengthened.*

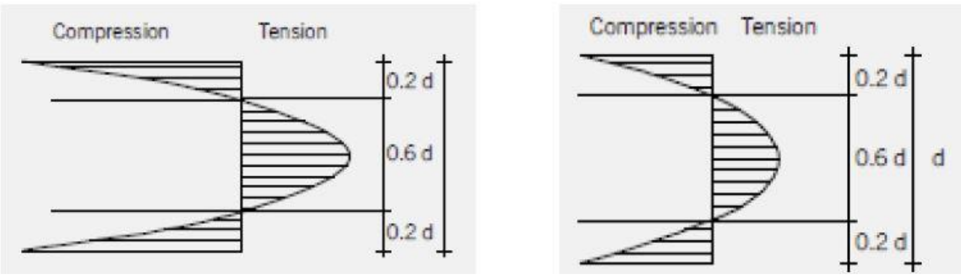


Figure 4.17. On the left compression in the surface of fully-tempered glass. On the right the less intense effect in heat-strengthened glass. Source: (Wurm & Peat, 2007)

Fully tempered glass has the highest residual stresses and is made by heating up a float glass just above its glass-temperature (approx. 650 ˚C), after which it is quenched by jets of cool air. This causes the outside surface to cool rapidly and to solidify, before the core is cooled. This will eventually lead to a residual compressive stress in the outside surface, and tensile stress in the core. This type of glass is also called *safety glass* because this glass has the property to break in small relatively harmless dice of glass.

Heat strengthened glass is made in the same method as fully-tempered glass, but the glass is cooled less rapidly after heating. As a results, the residual stress in heat-strengthened is less intense as in fully-tempered glass (fig. 4.17)

Annealed, heat-strengthened and fully tempered glass all have a distinguishable way of shattering upon failure, as a consequence of the different heat-treatment procedures. This is shown in figure 4.18.

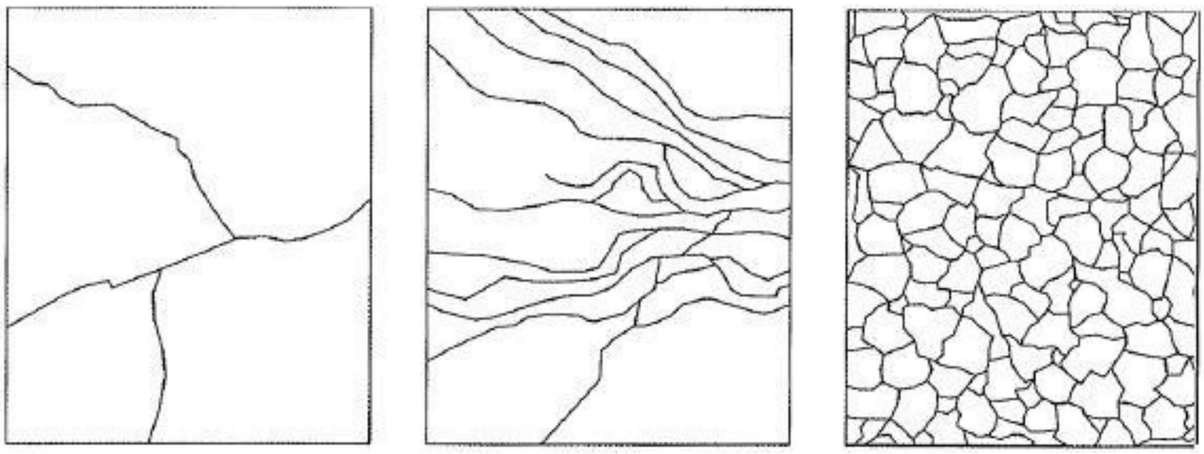


Figure 4.18. The breaking patterns of annealed (left), heat-strengthened (middle) and fully tempered glass (right). Source:(Ouwerkerk, 2011)

Based on experimental research, Fred Veer (2014) came up with reliable practical values for the different types of glass. These values are shown in fig. 4.19.

Type of glass	**Value of Tensile stress**	**Unit**
Annealed glass	20	MPa
Heat-strengthened glass	40	MPa
Fully tempered glass	80	MPa

Figure 4.19 Reliable safe values used for designing with glass structures

Although fully-tempered glass has the highest strength values, it has very bad performance after breaking because it fractures into small pieces. Heat-strengthened glass is there for an interesting compromise between structural performance and sufficiently large breaking pattern for good post-break performance(Haldimann et al., 2008).

4.4.2. How to increase safety?

4.4.2.1 Laminating with foils

Because glass breaks in small, potentially harmful shards, using glass in structures can be hazardous. In order to prevent glass panels or elements from falling down upon breaking, glass panels can be *laminated*. Here, at least two panes of glass are held together by a layer of clear polyvinyl butyral (PVB) or Sentryglass foil. This holds the shards of broken glass panes together when the panel breaks. The nominal thickness of a single foil is 0.38mm, but sometimes several layers of foils are used to make one interlayer in a laminated panel (Navratil, 2009). Thus a glass element can also be build up out of several smaller elements, a process called spliced lamination.

4.4.2.2 Sacrificing layers

Other techniques used to make the use of glass panels safer, is by using laminated glass panels consisting of more than two layers. The outer layers of glass can then serve as sacrificing layers, which are designed to be non-necessary for reaching the load bearing capacity of the element(Navratil, 2009).

4.4.2.3 Fire protection glass

Fire protection glass is laminated glass with a special transparent intumescent interlayer. The pane that faces the flames will fracture, but remain in place and foam up to form an opaque insulating shield that blocks the heat transfer and radiance(Navratil, 2009).

4.4.2.4 Blast proof glass

Blast-resistant glasses are laminated panels using special energy absorbing interlayers. These panels can absorb the energy of a potential blast or impact, keeping the broken glass panes together(Navratil, 2009).

4.4.2.5 Steel reinforced glass elements

Another option to increase the safety of glass is by ''reinforcing'' the glass element with steel. This has been the topic of the PhD research ''Fragile yet Ductile'' of dr. ir. Christian Louter (2011). The basic idea behind the system Louter came up with is simple: if the glass fails, the steel must take up the stresses. For this, Louter constructed a variety of multi-layered beams with an internal laminated steel tube or stripe glued along the underside. This steel is not necessarily added to increase the strength of the element, but acts mainly as a safety technique. When the glass would fail under a high stress, the element would not completely collapse but could still bear stresses. Another benefit of having a steel element laminated in between the glass panes, is that it creates the possibility to make good connections. This is explained in the next part.

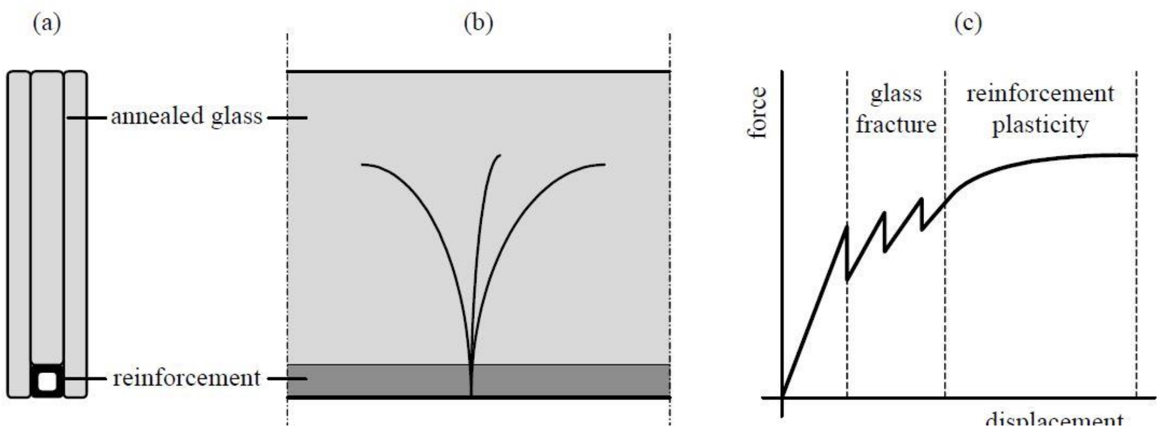


Figure 4.20. Schematic representation of the functioning of the reinforced glass beam concept (a) cross-section of reinforced glass beam; (b) side-view of a cracked reinforced glass beam; (c) force-displacement diagram of reinforced glass beam loaded in displacement controlled bending. Source:(Louter, 2011)

4.4.3 Connections in glass

Because of the specific properties of glass, the connections and detailing are often crucial in the final strength in a load-bearing glass structure. Glass has to be treated differently in connections than other conventional materials like steel, wood or concrete. This is because of the hard brittle nature of glass, which does not allow for stress distribution, causing peak stresses. Great attention must be paid to the proper designing of the details.

The most common type of connections used in glass are explained below. This is just a very brief overview of the different techniques, with their corresponding qualities and shortcomings. Generally a distinction can be made into three different types of connections: mechanical, glued and physical connections.

4.4.3.1 Mechanical connections

Almost all mechanical connections in glass are bolted or clamped connections. One way of connecting is a linear support, which is mainly applied for (protruding) glazing that is loaded perpendicular in its plane. Here the glass is either clamped, or is bolted onto a structure. A less visually intrusive way of connecting is a local edge support. A local point support is a typical bolted connection, as can be seen below. These connections require holes to be drilled in the glass, which as is explained in part 4.4.4.1 causes small scratches in the surface of the glass. If structural members are joined by a bolted connection, high stresses can occur at these locations which are induced around the drilled hole in the glass. Although Fokke van Gijn (2007) developed a new and much stronger version of this connection, that Z-shaped connection is only usable in specific cases. For this reason it can be said that in general these type of connections are typically not very strong and should therefore be avoided where possible.

Figure 4.21. A bolted glass connection, requiring a drilled hole. Source: http://www.stellaglasshardware.com/

Figure 4.22 A clamped glass stair tread.

Source: (Nijsse, 2013)

4.4.3.2 Adhesive connections

In glued connections, compressive forces are transferred by shear stresses. The strength of a glued connection depends not only on the strength of the bond material itself, but also on the design the joint and several aspects relating to build and curing quality(Nijsse, 2007). Glued connections have some typical properties: they can withstand high shear and tensile stresses, but are very weak to peeling forces(Veer, 2013). Proper designing of a glued connections is therefore critical, preventing unwanted forces on the joint. It is also important the two glass surfaces should be flat and be cleanable before gluing. An equal and exactly right thickness of the glue is also important. A glue layer that is too thick or too thin will result in a weak connection. When these factors are done right, glue connections can be very strong. Glass, just as stainless steel are materials that are very suitable for gluing because of their stiffness and high surface energy (Veer, 2013). It is also a good way to induce forces into the glass, because usually larger surfaces are needed for proper bonding, with that spreading the stresses.

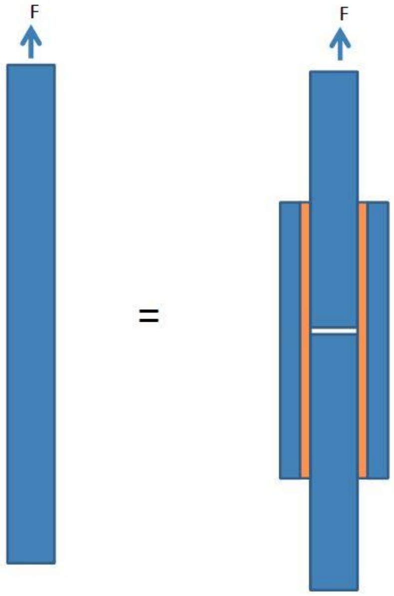


Figure 4.23. The principle of a glued glass connection. Source: (Veer, 2013)

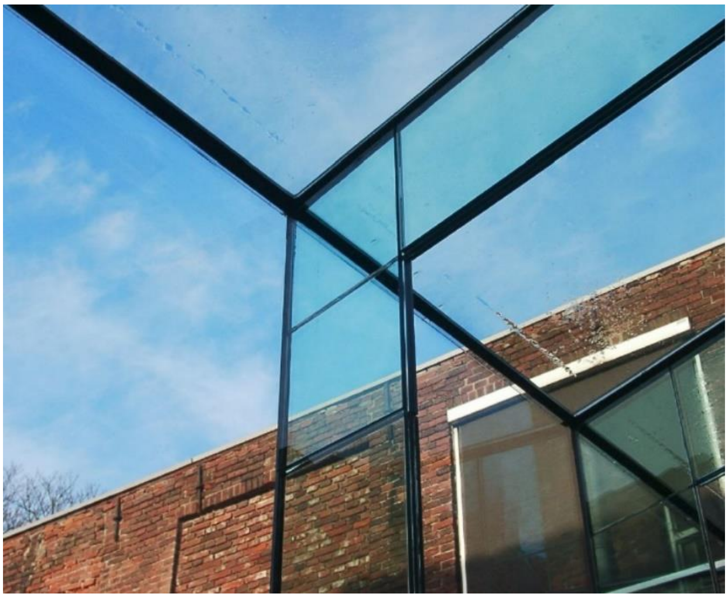


Figure 4.24. A glued glass connection in practice. Source: (Nijsse, 2013)

4.4.3.3 Embedded adhesive hybrid connections

What is also a possibility, that instead of gluing glass to glass, steel embedded inserts are glued to the glass. The large forces and stresses are then transferred through the steel inserts, which allows for a stronger connection because steel can bear stresses the glass is not capable of. The steel inserts can then be bolted together, which allows for more freedom in connecting. One variant is to glue in local stainless steel inserts in between laminated glass panes. This creates very minimalistic subtle connections. Another variant is the system of Louter. Here the stainless steel element that is laminated in between the glass panes, that functions as a safety mechanism, is also used to make connections. This is a slightly more visually intrusive method, but allows for a large variety of connections. The steel insert becomes multifunctional in this variant.

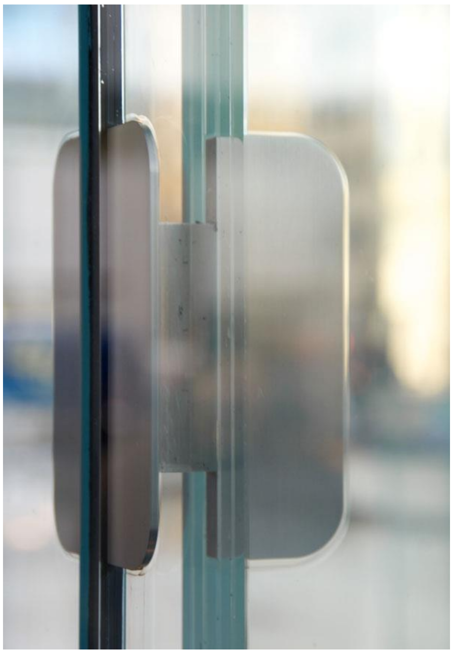


Figure 4.25. A glued in stainless steel insert used to make connections from steel to steel. Source: http://www.eocengineers.com/img/image_tall/305/APPLE5TH_MK2_MEDIUM_D.jpg

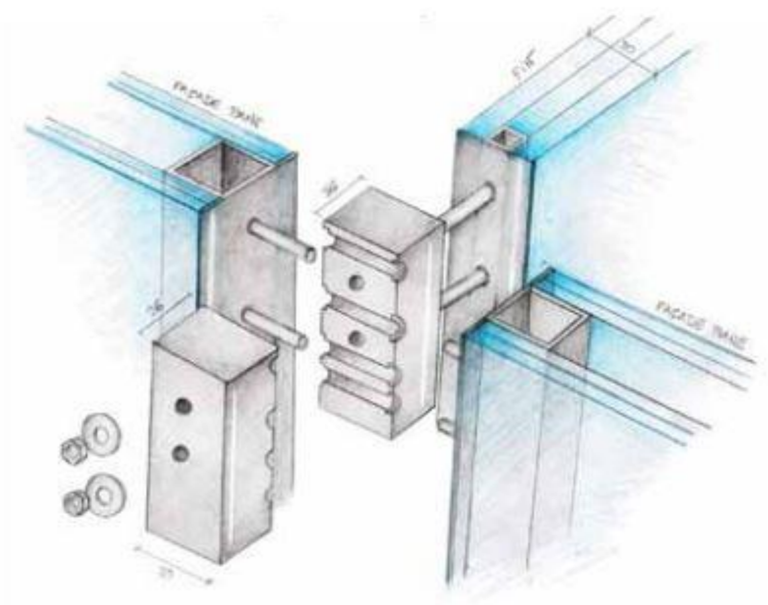


Figure 4.26. A way of connecting using the steel linear inserts from the system of Louter. Source:(Faidra Oikonomopoulou, 2012)

4.4.3.4 Physical connections

A physical connection could be described as a connection in which either the two to-join elements are shaped so that they fit each other, or that a third element is added that by its shape closes the joint. The first way could either by means of interlocking geometry, or by welding two elements together, which is often done by glass blowers. However if the cooling rate is too fast, the glass will crack. Accordingly, a very slow cooling process is needed to prevent residual stresses. Next to that residual stresses are inevitable in soda-lime glass due to its large thermal expansion coefficient, good temperature control is almost impossible with large joints, therefore welding is almost never done (Veer, 2013).

Figure 4.27. Interlocking geometry of bricks. Source: http://marshield.com/wp-content/uploads/2014/05/Thin_Lead_Bricks.jpg

If in a connection a third element like an aluminum element is used to for example hold a glass panel in place, it is important that contact between the metal and glass is avoided. This is to prevent excessive stress peaks between the two hard materials (Ouwerkerk, 2011).

4.4.3.5 Preferred type of connecting

	Mechanical connection	Adhesive connection	Embedded adhesive hybrid connection	Physical connection
Reversibility	+	-	+	+/-
Force distribution	-	+	+	+/-
Visual result	-	+	+	+/-
Assembly	+	-	+	+/-
Structural strength	+/-	+	+	+/-

Figure 4.28 Comparison between the connection types. Source: own ill.

A table (figure 4.28) has been made to compare the different connection types and to score these. Mechanical connections are not suitable because they result in the undesired visual impact of the mechanical fixations and the stress concentrations that occur due to the local force introduction at specific locations in the structure (drilled holes for example). The adhesive connection is strong however complex to do on site and results in an irreversible connection. The physical connection type such as welding of glass or using interlocking geometrical glass bricks are (up till now) uncommon techniques, and therefore rarely used in load-bearing glass structures.

When looking at the table, regarding reversibility, force introduction into the element, easy of assembly, strength and visual quality, the embedded adhesive hybrid connection type may be the best option. This because it combines the strong characteristics of the mechanical and adhesive connection, resulting in a transparent, reversible strong and safe joint, which can be easily assembled on site.

4.4.4 Curved glass

In order to create more free-form shapes with glass, lately more research is done in the bending of glass. In this way you are not bound to flat pieces of glass, but create more complex curvatures. This greatly increases the applicability of glass in creating organic shapes. The glass can be bend in two ways (Cilento, 2011).

4.4.4.1 Hot bending of glass

In the hot bending process the glass is placed upon a mold that has the desired shape, and is evenly heated to 650 C. At this temperature the glass changes to a visco-plastic state where it loses its stiffness and brittleness, and can therefore be shaped by gravity or mechanical pressure, obtaining the aimed geometry by cooling it. Cylinders, s-curves and double curved shapes can for example be made using this technique, also with very small radius up to 100mm. Warm bending can be rather expensive mainly due to the need of a unique mold for every panel that is used. In case a geometry can be made by 1 panel type which is repeated this is very efficient, however in case many differently shaped panels are needed, many unique molds will have to be produced. This makes this technique undesirable in some cases. Another downside is that surface of the glass tends to slightly deform, which causes visual deformations in the glass face.

Figure 4.29. Hot bend glass. Source: http://www.glgroup.com.tr/userfiles/editor/Hot%20bending%20Glass.jpg

4.4.4.2 Cold bending of glass

In the cold bending process, flat glass panes are brought to the desired shape by means of external contact pressure, which demands holding the curved glass unit in its desired form. The glass can be curved at the construction site, where it is held in place by clamping strips, or it can be curved in the factory before laminating. This allows for very innovative designs, however research on this technology is taken place. A benefit to cold bending is that just regular glass sheets can be used, and they can be bend in place at the construction site. This is beneficial if many different unique panels are required to make a certain geometry, reducing cost significantly. The better visual quality, and lower costs are the main advantages of cold bending over hot bending of the glass.
A complexity in this technique that the glass can only be bend up to a certain point before it breaks. It also requires good detailing so that the forces required to bend and hold the glass panel in place, are induced properly in the main structure. This also means that the main structure should be able to take up these forces due to cold bending.

The amount of deformation that is possible through cold bending is a very complex topic. At Octatube extensive research has been done, in practice by mockups but also in theory by researcher and engineer Dries Staak (Crisinel, 2007). With the results of this theory, Octatube has developed models which can be used to design and engineer cold bend glass structures. These results will be briefly summarized now.

The amounts of deformation allowable is dependent on various factors, including the length-width ratio of the panel, the thickness of the glass, and the type of deformation(Crisinel, 2007). A brief distinction can be made in cylindrical bending and torsional bending (twisting).

The first type of deformation is cylindrical deformation, as shown in fig 4.30. In this method, a glass pane is bent along its symmetrical axis, which is parallel to the edge of the panel, to form an curved shape, which is part of a half circle. When this method used, the glass is bent according to a specific radius.

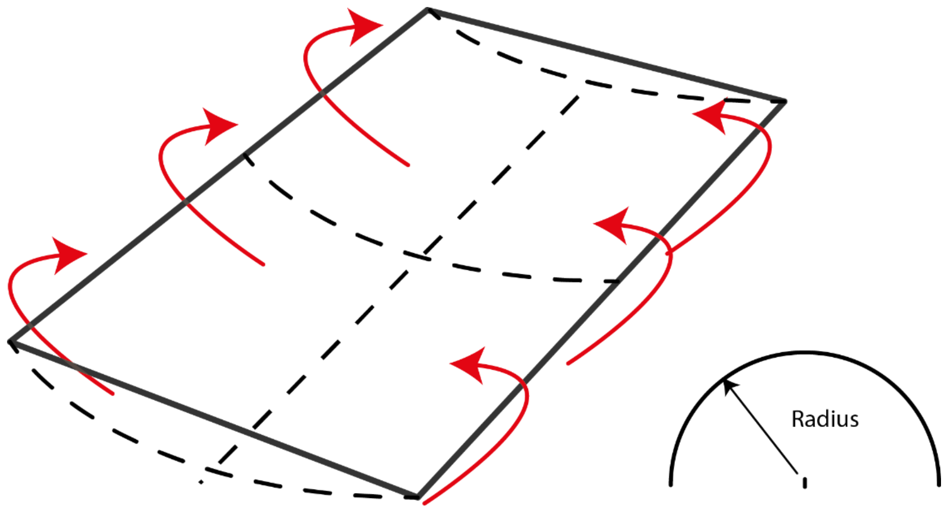


Figure 4.30. Cylindrical bending of a glass panel. Source: own ill.

Based on research, Seele Sedak(2016) shows on its site that for a general rule of thumb it can be said that the minimal bending radius of glass panel is 1500 x thickness of the glass panel. For example a 10mm glass panel, has a minimal bending radius of 15m.

The second type of bending is torsional bending, which is essentially the twisting of a panel, as shown in figure 4.31. In this way one or two corners are lifted out of plane, creating a twist. Various options are possible here, but one often applied deformation is the twisting of one corner out of plane. The deformation is then described as the distance of which that corner is twisted out of plane.

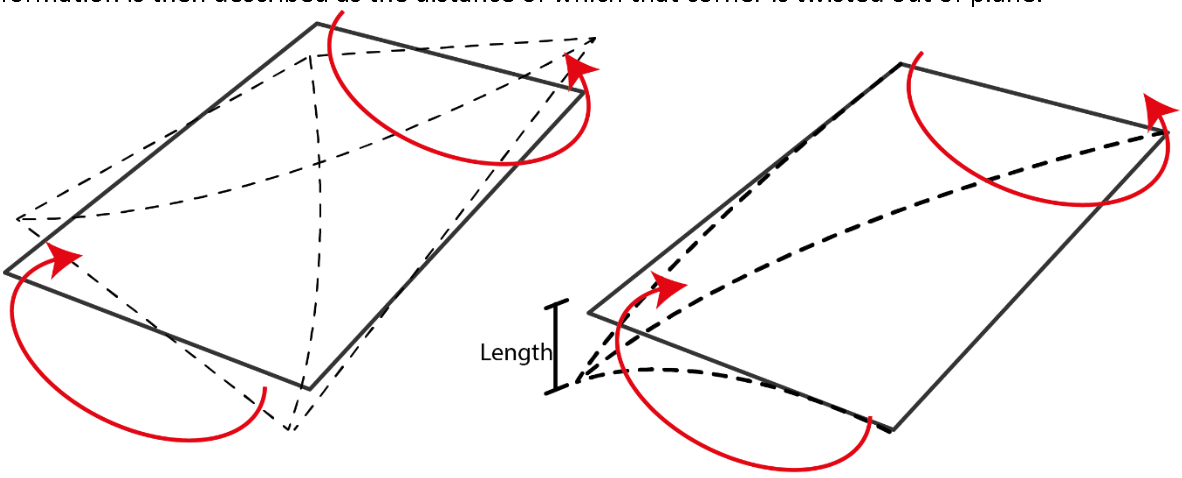


Figure 4.31. Torsional bending of the glass. Source: own ill.

In his research, Dries Staaks(2007) researched the effect of cold twisting glass on its stresses and deformation. He discovered that glass panels can be cold twisted elastically, deforming in a symmetrical way into a hypar surface as long as the enforced deformation is less than 16 times the panels' thickness. More twisting will evoke a change of deformation pattern due to a instability phenomenon. The double curvature of a twisted plate causes membrane forces: pressure in the middle, and tension along the edges. Staaks discovered that for increase of twisting the membrane forces increase exponentially until the pressure causes the plate to buckle, resulting in the change of deformation. The amount of twisting at which instability occurs proved to be linear related to the panels' thickness, independent of material and size except for the length/width ratio of the glass panel. For small amounts of twisting (plates thickness) stresses are uniformly distributed. This stress is linear related to the plates' thickness. A thinner plate will cause equally lower stress. For increasing twisting the stress will increase more than linear due to the growing influence of the membrane forces.

As a general rule of thumb, twisted geometries with a deformation up to 10% of the panels' width are possible using pre-stressed glass (Crisinel, 2007).
In an consultancy meeting with Barbara van Gelder(Octatube, 2016), she mentioned an experiment where sheet of glass of 1x3 m was cold bend. In this experiment one corner was deformed 60mm out of plane.

4.4.4.2.1 Projects with cold bend glass

Octatube has applied the theory of cold bent glass in several projects. For example for the façade of the town hall of Alphen aan den Rijn, in the Netherlands(Crisinel, 2007).Here insulated glass panels with a maximum size of 900x2000mm, consisting of 8mm fully tempered glass panels was twisted out of plane at a maximum of 40mm.

Figure 4.32. The façade for the townhall in Alpen aan den rijn. Source: http://www.octatube.nl/projecten/34/stadhuis-alphen-aan-den-rijn/

In another project, Octatube designed and built the glass roof structure at the bus stop Zuidpoort in Delft(figure 4.33). Using the theory Dries Staaks developed about calculating deformations and stresses in cold bent glass, Octatube went to the limits of what possible in cold bending of glass. The glass panels are laminated and prestressed here, and had a size of 1500x3000 mm. The maximum deviation out of plane was 100mm.

Figure 4.33. The glass roof at bus stop Zuidpoort in Delft. Source: http://www.octatube.nl/projecten/20/zuidpoort-luifel/

These projects show that cold bending has been researched and also put into practice. This research is however still ongoing, since there is a continued demand for more free-formed shaped buildings and facades. This would also mean that perhaps in the future larger deformations are possible by altering the glass properties, which is for example what can be seen in thin chemical strengthened aluminosilicate glass.

5. Preliminary design of the roof

In the previous chapters has been argued that in order to restore Slot Teylingen, a glass roof will be designed on top of the donjon. By placing a roof on the castle, this will enclose it and allow a new function to be put in the castle. The roof should according to the restoration philosophy integrate harmoniously while also be distinct from the original structure. This is why it is made of a transparent material, glass, which allows a subtle and minimalistic design.

5.1 Possible shapes of the roof

The new glass roof could however be made of in various shapes. The primary shape should first be chosen, before this can be further elaborated on.

5.1.1 Flat square roof

The first shape could be a very abstract shape. A flat square roof. Because this roof is so simple it would not distract from the original structure, therefore it would fit the building.

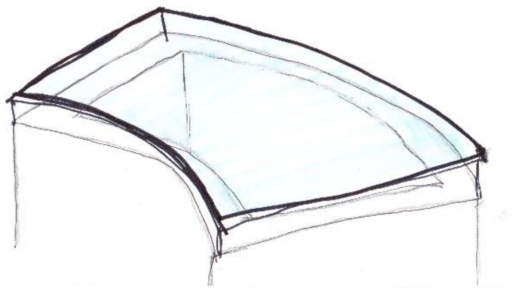


Figure 5.1 Flat square roof shape. Source: own ill.

5.1.2 Round curved roof

The second could be a round curved roof structure. This could either be a curved roof system, or a dome-like structure.

Figure 5.2 Round roof shape. Source: own ill.

5.1.3 Free form tent shaped roof

This shape would be a more free-formed shape. It could be tent-cable like structure, something like the Olympia stadium from Frei Otto. This would allow for very free and abstract shapes.

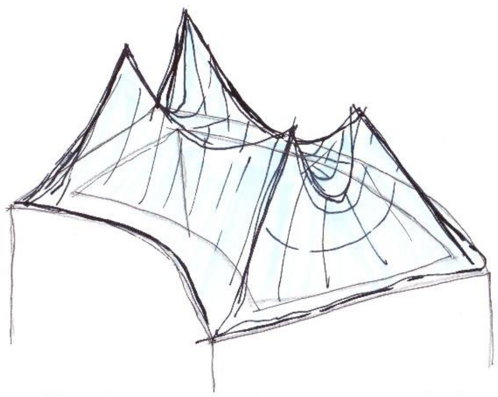


Figure 5.3 Free form roof shape. Source: own ill.

5.1.4. Pitched roof – As original roof

In this option the roof would be shaped as the original roof. This means the roof is pitched, and has two single-curved surfaces, following the contour of the donjon's wall.

Figure 5.4 Pitched roof shape. Source: own ill.

5.1.5 Choice of shape

Figure 5.5 is a table which shows a scoring of the different roof shapes. Here can be seen that although the pitched roof does not score best on every criteria, it does score best at the visual integration. Since this is the most important criteria, the pitched roof is chosen. This means roof will be made in the same shape and size as the original roof of Slot Teylingen. The criteria is visual integration is chosen based on the restoration philosophy that is explained in chapter two. Here it is stated that the any replaced part of the structure should integrate harmoniously with the old, but also is distinct from the old because of its modern appearance. With the original shape of the roof explained in part 3.3.3.1, it would seem most befitting to the historical and aesthetical value of the building to make a roof that matches this original shape. Because of the transparency of glass, this would allow for a simultaneous view of the old and new structure: the ruin can be seen in the shape it was originally in, while at the same time an impression can be given of the original roof the building once had. Because of the modern appearance of the material and the way it will be constructed, a sense of falsification is not likely to arise.

	Flat square roof	Round curved roof	Free form tent roof	Pitched roof
Visual integration	-	-	-	+
Complexity	+	+/-	-	-
Cost	+	-	-	-
Effectiveness	-	-	-	+/-

Figure 5.5 Comparison of the different roof shapes. Source: own ill.

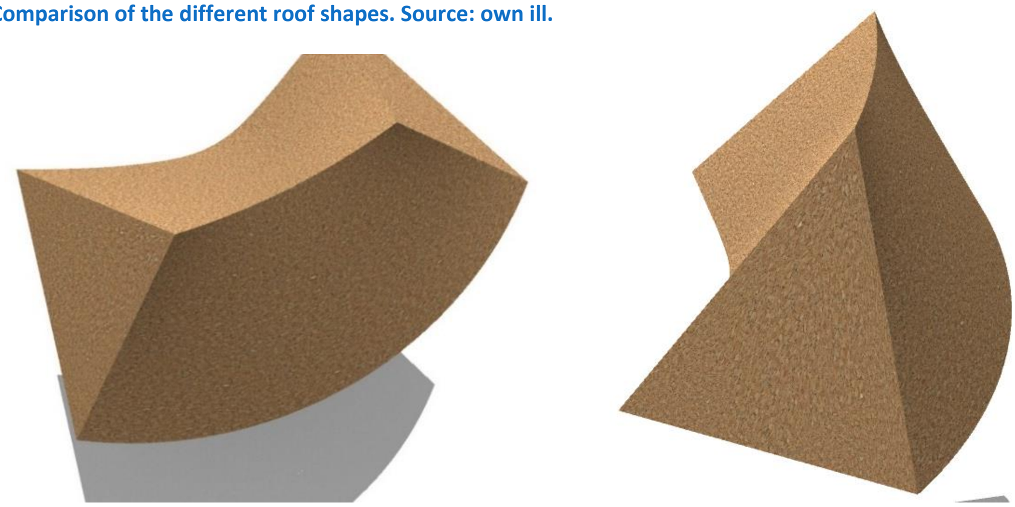


Figure 5.6 The chosen shape for the design of the new glass roof. Source: own ill.

5.2 Overview of applicable systems of glass roof structures

The goal is to design a structural glass roof. The definition of structural glass is however not entirely clear. One could say that structural glass means that the glass plays a part in the structural system, but this description is not clear enough. Because using this definition every glass pane or window would be structural glazing, because also a window panel has to conduct wind forces back to the main loadbearing structure. Also many glass structure types still use metal elements in for example the connections, or tensile elements. Therefore a structural glass roof should rather be defined as a self-supporting glass structure in which is aimed for maximum transparency by using as much glass as possible.

Next an overview is given of possible ways to construct the chosen roof shape in glass. According to the book *Structure System*s of Heino Engel (1999), a clear distinction can be made between the different types of structural systems. In his book he elaborates on all these types and their sub-types. This book has helped to categorize the structural types which can otherwise be a quite difficult task. The structure types that are used for glass structures are elaborated on. Since the roof shape does not have horizontal surfaces but rather sloped surfaces, façade structures will also be shown. The façade principles could act as inspiration, which could later be translated into a roof application, just as all the projects will act as inspiration which will later need to be translated into an application for this specific roof of Slot Teylingen.
It is not the point of this chapter to make a very clear analysis and strict categorization of the glass systems, trying to fit every project into one of the boxes. In his book, Engel used many subcategories which fit under the five main categories in his book. A clear positioning of each system into one of the categories would require also the distinction of a specific subcategory. Instead of that, only the main category and first main subcategory is named in each title. This is followed by an general description of each type, followed by example projects in which these glass structures have been used. Every part discussing a structure type is concluded with a basic analysis, discussing the general properties of each type. The categorization is kept more broad, so that the structure type is analyzed and discussed on its basic properties. For example the mechanical workings of one structural type is very distinctive, and will have technical or architectural implications for a design if such a system is used. This can help to make a clear choice of a structural type in the conceptual design proposals.

5.2.1 Beams – section active

5.2.1.1 General description

A beam structure according to Engel(1999) consists of straight-line, bending-resistant structural elements that not only resist forces that act in the direction of their axis, but by means of sectional stresses can receive also forces perpendicular to their axis and transport them laterally along their axis to the ends.

5.2.1.2 Example projects

5.2.1.2.1 Leiden glass conservatory

Location	Leiden, The Netherlands
Span	4 m
Type of glass used	Laminated insulating panels, laminated beams
Thickness of glass	3x10mm beams, 10-12-5,5-5,5 mm for panels
Type of connection	Adhesive connection

In this project of ABT and Rob Nijsse, a complete glass conservatory has been built in Leiden in 2001. The roof is held up by glass laminated beams, which is on one side supported by a glass beam, and on the other side by a connection in the masonry. On top of these beams and in front of the columns insulated glass panels are placed, enclosing the structure. Because of the maximum use of glass, it gives the structure a subtle simple appearance. The beams and columns are both made up of 3x10mm glass panels, and the connection between the beam and columns is a glued connection.

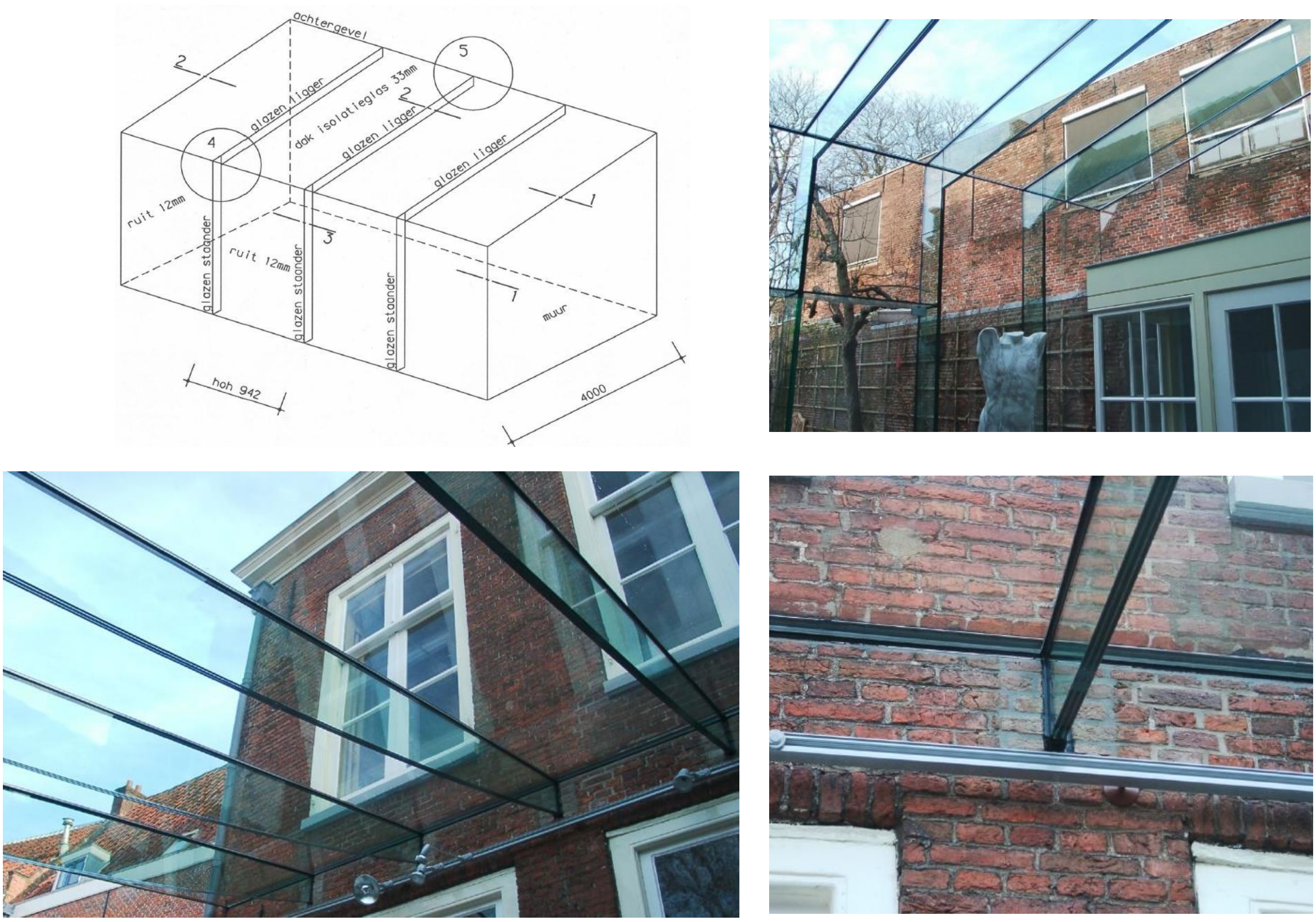


Figure 5.7. Leiden glass conservatory by ABT. Source:(Nijsse, 2013)

5.2.1.2.2 Apple store cube NY

Location	New York, USA
Span	10x3,6 meters
Type of glass used	Laminated fully tempered glass panels, laminated beams
Thickness of glass	-
Type of connection	Embedded adhesive hybrid connection

This well-known example of structural glass is the Apple store cube in New York. This is a design by the international engineering firm of Eckersley O'Callaghan. There has been two versions of this cube, the first version originating in 2006. After research and developing new techniques, the second structurally simplified and much more transparent version was built in 2011. The side panels of the second version has been made of tempered glass panels of 10x3.6m. Most of the connections consist of steel embedded adhesive components, which are bolted together.

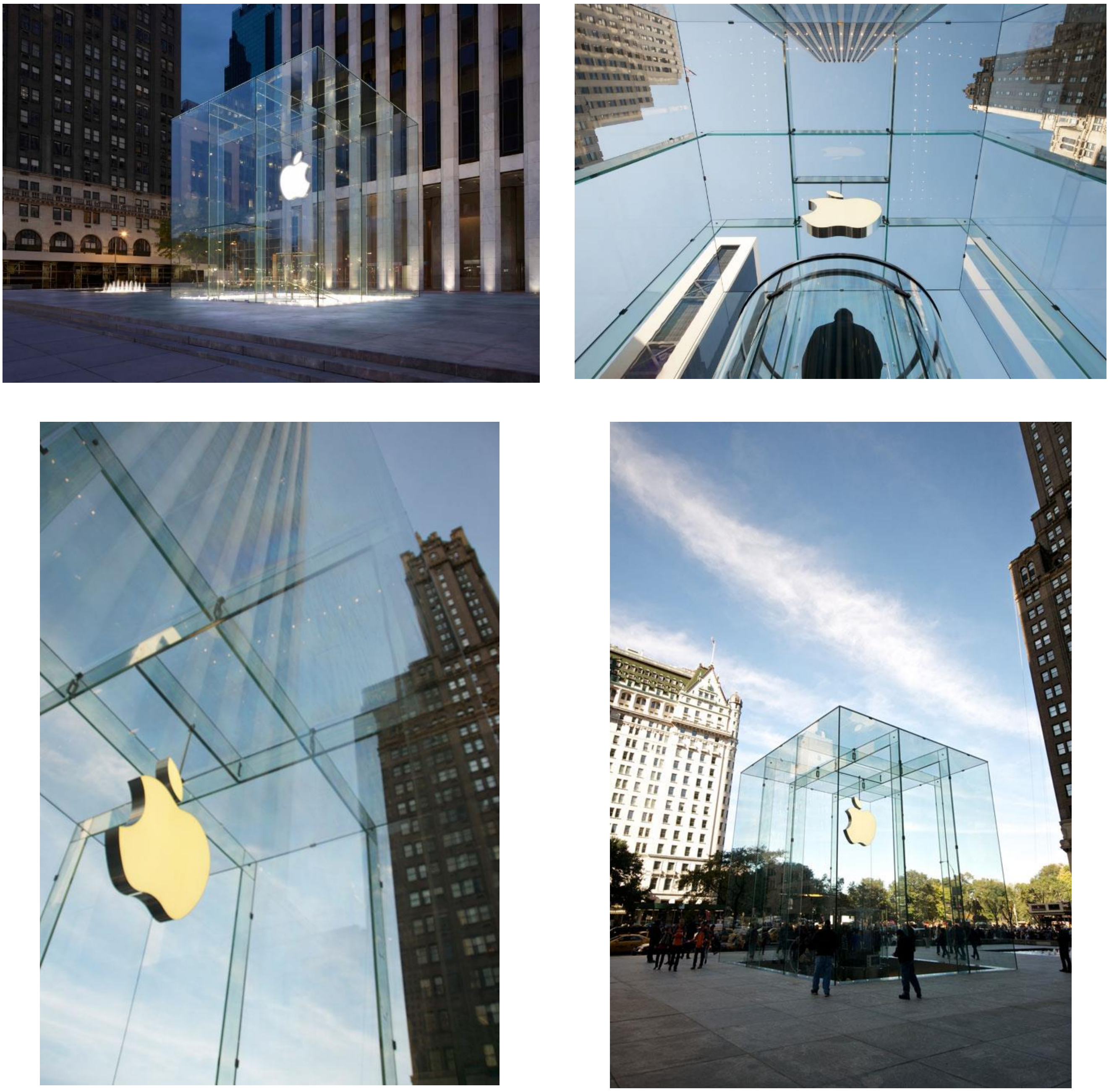


Figure 5.8. The Apple store glass cube. Source: http://www.eocengineers.com/project/apple-5th-avenue-mark-2-100

5.2.1.2.3 Victoria & Albert Museum Daylit Gallery

Location	London, UK
Span	11 meters
Type of glass used	Laminated fully tempered glass beams, cold bend laminated heat treated panels
Thickness of glass	3x12mm for beams
Type of connection	Embedded adhesive hybrid connection

This glass roof structure is a design by Octatube. The roof spans a new Medieval and Renaissance gallery of the Victoria & Albert Museum in the UK. This gallery is mainly lit by daylight, hence the name. In order to realize this, structural glass beams of tempered glass are used that span 11 meters. The unusual curved roof has been realized using these linear elements. The covering roofpanels are insulated glass panels, which are connected to the beams using small mounting clamps in the joint of the glass, which on its turn are connected to the a steel profile laminated in the glass beams. The roofpanels are cold-bend into shape. The beams are 450mm high, laminated glass panels of 3x12mm thick.

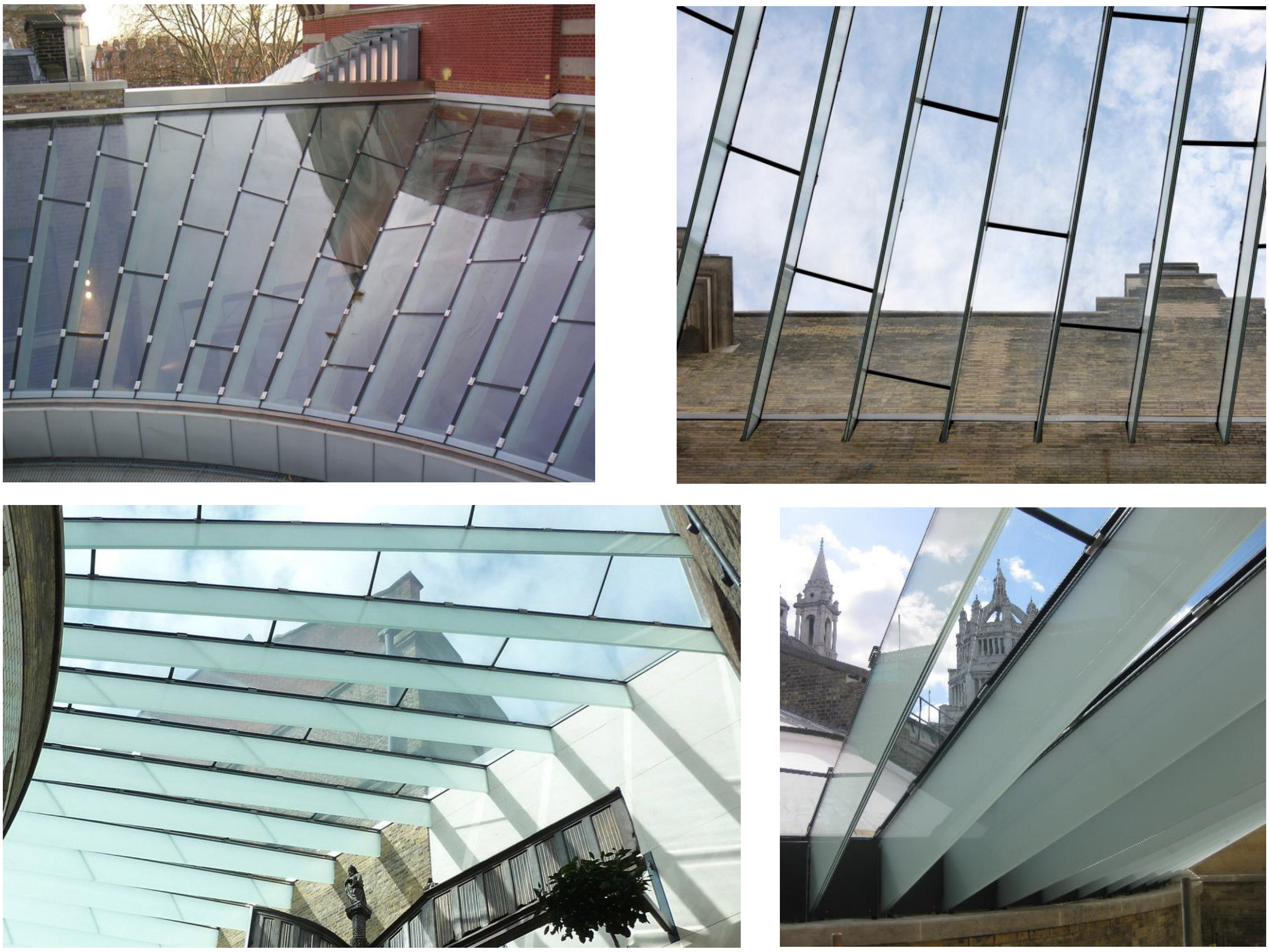


Figure 5.9. The structural glass roof structure of the Victoria & Albert Museum. Source: http://www.octatube.nl/projecten/4/victoria-albert-museum-daylit-gallery/

5.2.1.2.4 Van Gogh museum Amsterdam

Location	Amsterdam, The Netherlands
Span	12 meters
Type of glass used	Low iron, triple laminated SG beams and cold bend triple laminated SG IGU panels
Thickness of glass	-
Type of connection	Embedded adhesive hybrid connection

In the new entrance of the Van Gogh museum a radical glass structure is designed and engineered by Octatube. The structure is a glass curved roof, supported by glass beams with a span of 12 meter. The beams are laminated with Sentryglass layers, and are 700mm high. The main steel structure which runs along the perimeter of the roof, has steel brackets welded onto them, in which the beams are connected. The façade panels are cold bend, and help to stabilize the entire structure.

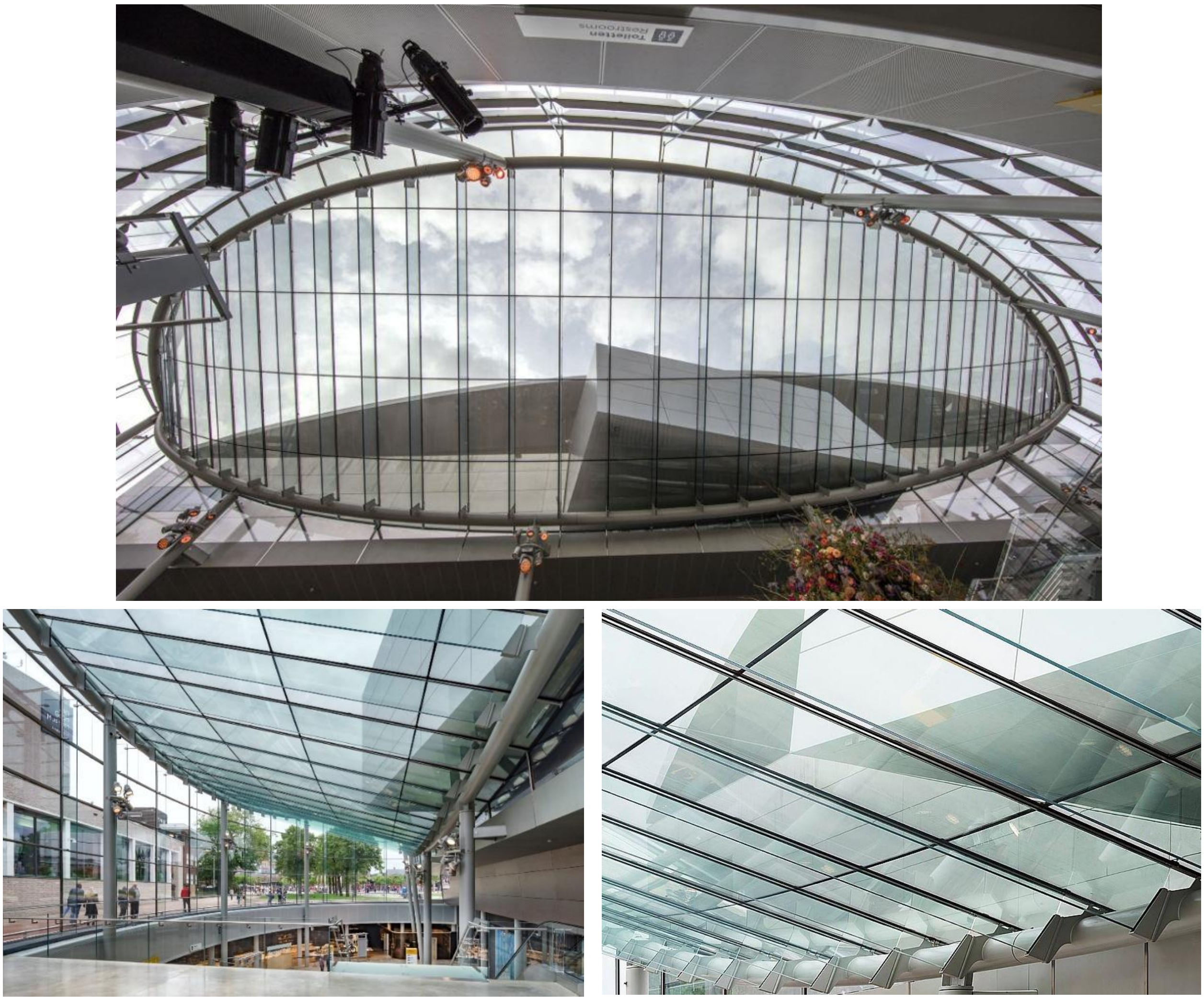


Figure 5.10 The new entrance of the van Gogh museum with a curved glass roof. Source: http://www.octatube.nl/nieuws/148/grensverleggende-glasconstructie-van-gogh-museum/

5.3.1.3 Concluding

Beams are a straight-forward way to make spans. Lengths of 12 meters can be reached, with beams of roughly 700mm high. The glass is often heat-tempered or heat-treated and executed in several laminated layers. It is possible to make curved and rounded roofs with a beam structure, although this will require either hot-bending or cold-bending of the roof panels in order to follow the shape.
Another aspect is that the beams tend to get quite high at larger spans. This has an impact on the overall look and architecture of the structure.

5.2.2 Truss – vector active

5.2.2.1 General description

The description in the book of Heino Engel states that a truss structure consists of solid straight line elements (bars or rods) in which the redirection of forces is effected through multi-directional splitting of forces. The structure members are subjected to compression and tension. Truss structures are very efficient structures, being able to withstand large forces while consisting of small-scale straight line elements. This makes the self-weight/span ratio of trusses high compared to solid beam structures. Also because trusses are very open structures, they are more transparent than solid beam structures. Since there is a clear division in the truss of compression and tension members, often suitable materials are chosen for both member types to make them more efficient. In glass trusses often the compression members consist of the glass, while the tension members are made of steel.

5.2.2.2 Example projects

5.2.2.2.1 Glass roof Juval Castle

Location	Ciardes, Italy
Span	-
Type of glass used	Laminated PVB heat treated glass
Thickness of glass	2x8mm
Type of connection	Mechanical connection

The Juval castle is restored by replacing the original collapsed roof with a modern version. Although this roof is not the cleanest glass structure, since the main loadbearing structure is a very slender steel structure, this is however a very transparent roof, fitting the monumental building. The shape of the roof resembles to a large extent the former structure. The tensile members of the trusses are made out of steel cable, with the compression part a I-beam. The glass panels are double layered laminated glass sheets, which are also supported by a small truss-like structure in order to prevent stresses at the fixture points. The drilled holes for the fixture points are filled with epoxy resin in order to bond the metal to the glass, preventing direct contact and therefore critical stresses.

Figure 5.11 The roof structure of the renovated Juval Castle. Source:(Schittich et al., 2007)

5.2.2.2.2 Zwitserleven office roof

Location	Amstelveen, The Netherlands
Span	-
Type of glass used	Glass compression rods
Thickness of glass	-
Type of connection	Physical connection

In this roof structure the glass plays a fundamental role in the truss structure. Although the upper bar is a steel beam, the compression members in the triangular structure are massive glass rods. The tensile elements are on the other hand steel members. Much attention has been paid to the connection of the glass rod into the connection, making it a hinged connection while also preventing local stress due to contact from the glass and steel. This was eventually solved by gluing on metal caps on the rods, separated with neoprene rings from the glass. The final design is a transparent structural glass system.

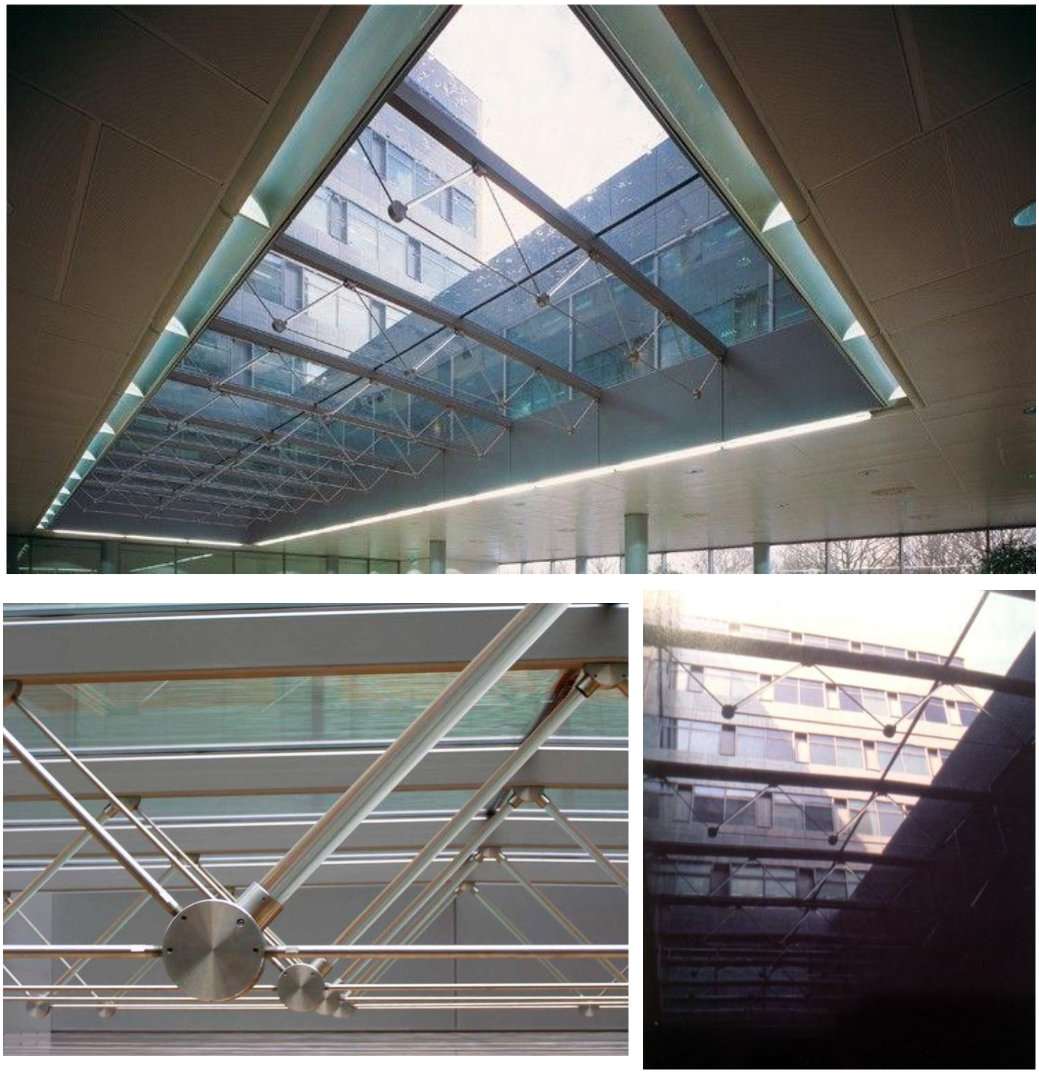


Figure 5.12 The glass roof structure of the Zwitserleven office building. Source:(Nijsse, 2002)

5.2.2.3 Concluding

As can be seen, truss structures can be elegant structures to cover larger spans. This can lead to very transparent roofs. What however often is also done is that steel is used in the tension elements, which is not always an option that improves the transparency of the structure. The glass then is not the main structural material, making it basically a more hybrid structure.

5.2.3 Cables – form active

5.2.3.1 General description

Form-active structure, of which cable structures are part of are description by Heino Engel as structure systems of flexible, non-rigid matter in which the redirection of forces is effected through particular form design and characteristic form stabilization. Its basic components are primarily subjected to but one kind of normal stresses, either compression or to tension. Typical for form-active structures is that they redirect external forces by simple normal stresses. This is also why these systems develop horizontal stress at their ends, which is a difficult property when designing such structures. Cable structures, because there are only stresses by simple tensions are the most economical systems for large spans looking at their self-weight-span ratio. These structures often result in very transparent thin structures.

5.2.3.2 Example projects

5.2.3.2.1 Markthal Rotterdam

Location	Rotterdam, The Netherlands
Span	1,5 x 1,5 m panels
Type of glass used	Laminated heat strengthened panels
Thickness of glass	2x12mm
Type of connection	Mechanical connection

The spectacular design of the Markthal has on both ends of the building, with 42 by 34 meter one of the largest cable-net structures in Europe. Both facades have 26 vertical and 22 horizontal steel cables which are installed with a high pretension in order to become a stiff net. Special joints hold together the vertical and horizontal cables on their crossings. Onto these joints laminated glass panels are connected. With extreme wind loads the facades are flexible, and can move back and forth 70 centimeters. Coping with the high tension loads on the contour structure are however a challenge.

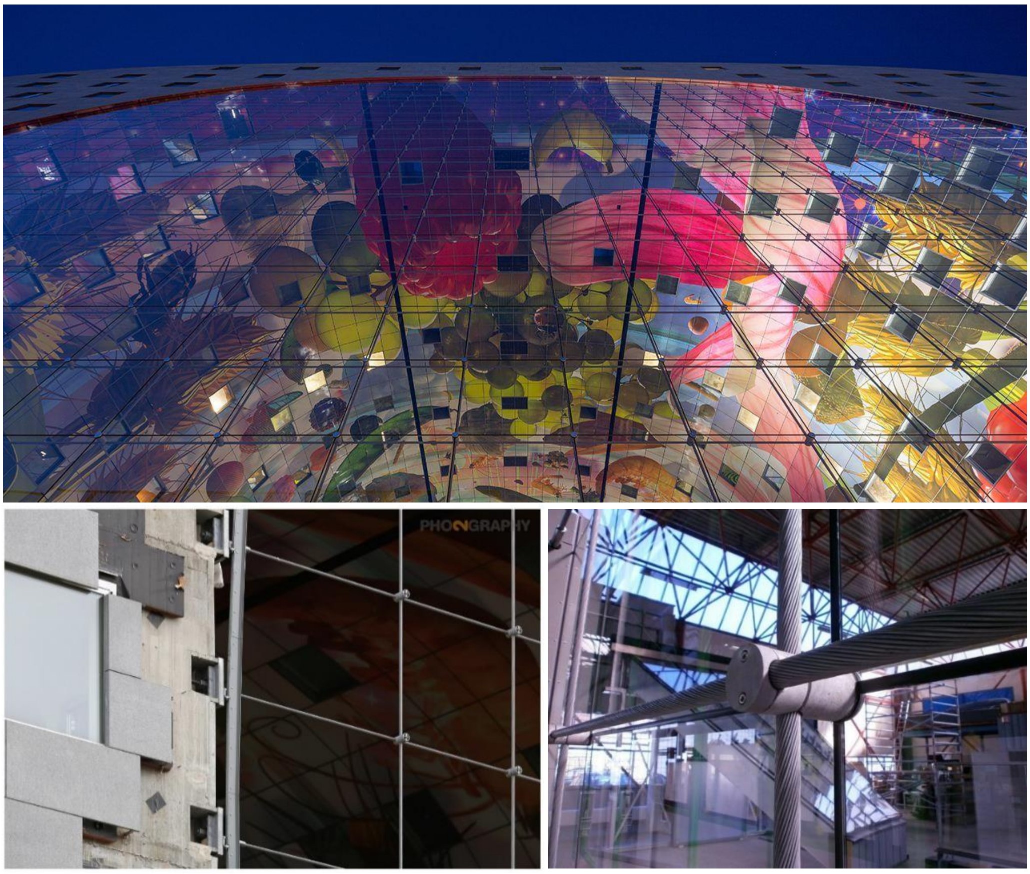


Figure 5.13 The cable glass structure of the Markthal Rotterdam. Source: http://www.octatube.nl/projecten/148/markthal/

5.2.3.2.2 OZ-Building

Location	Tel-Aviv, Israel
Span	1,8 x 1,8 m panels
Type of glass used	Laminated heat strengthened panels
Thickness of glass	-
Type of connection	Mechanical connection

In this façade design by Octatube in Tel-Aviv an enormous surface is covered, with 52m height and 16m width. An steel cable structure is used in order to efficiently span these lengths. The horizontal wind load on the façade is taken up by horizontal tension frames in the shape of ‘’fish-bellies’’. These horizontal tension forces are redirected to the concrete building structure. The laminated pretensioned glass panels of 1,8 by 1,8 meters are held in place by spiders, which are part of vertical rods just behind the glass panels. The vertical loads are taken up by vertical cables.
Although this system is applied in a façade structure, just as the Markthal façade, it might also be translated in principal to a roof structure.

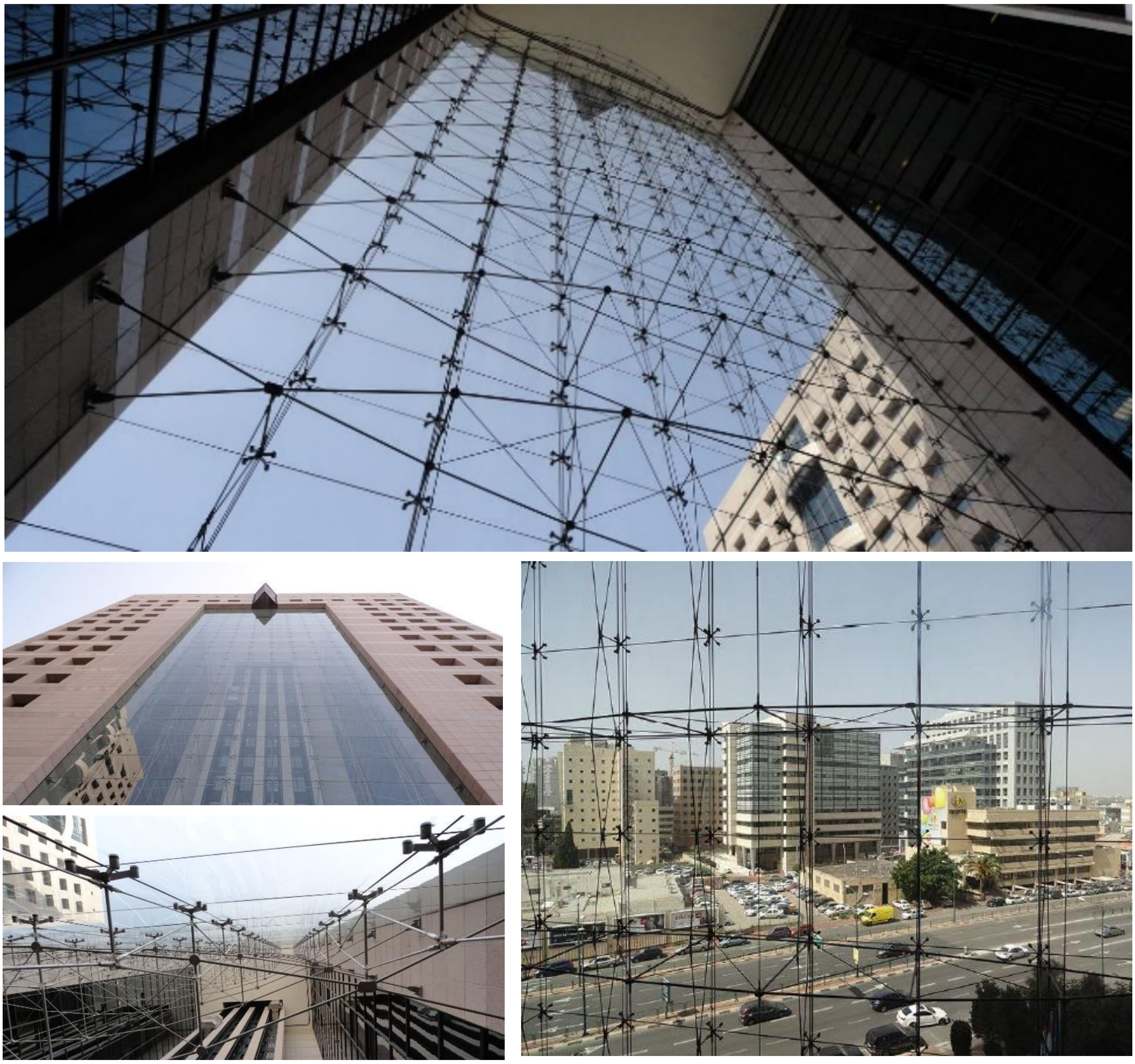


Figure 5.14 The glass facade supported with by steel cable structure. Source: http://www.octatube.nl/projecten/32/oz-building/

5.2.3.2.3 Rotunda reception building

Location	Paris, France
Span	1 x 1 m
Type of glass used	-
Thickness of glass	-
Type of connection	Mechanical connection

This small reception building is covered by a glass 14m diameter disc. The glass plates are supported on the four corner points by small steel fixtures which rest on steel cables. The pretensioned steel cables are connected to a round steel ring which is part of a steel structure. The cables form a grid, in order to function together similar as the wires in a tennis racket. The clever part of this specific structure however is that the cable structure is combined with a truss structure in order to increase stiffness of the glass roof. This results in a transparent and efficient structure.

Figure 5.15 The cable/truss roof structure of Rotunda reception building. Source:(Schittich et al., 2007)

5.2.3.2.4 Rhön-Klinikum Bad Neustadt

Location	Bad Neustadt, Germany
Span	-
Type of glass used	Laminated heat strengthened glass
Thickness of glass	2x4mm
Type of connection	Mechanical connection

This tent-like glass structure is the entrance of the Rhön-Klinikum, a leading hospital in Germany. A fine cable structure is help up by columns, giving it its particular shape. The cables are all under tension. Onto these cables, glass overlapping panels are placed. The particular textured ‘’tiled’’ look of the structure is achieved by a special designed frame which fixes the laminated safety glass panels onto the cable joint. This tiled look is something that is not often seen in others structures, making this an interesting project.

Figure 5.16 The cablenet structure of the Rhön-Clinic in Bad Neustadt. Pay attention to the ‘’texture’’ in the glass panels. Source:(Schittich et al., 2007)

5.2.3.2.5 Museum History of Hamburg – arch structure

Location	Hamburg, Germany
Span	-
Type of glass used	Laminated heat treated glass
Thickness of glass	11mm
Type of connection	Mechanical connection

For this building the inner courtyard had to be covered by a transparent and lightweight roof structure. The forces on the existing building had to be as low as possible, since it was an older structure. This led to the design of the steel-glass gridshell system, which was innovative in 1989. The majority of the roof consists of steel arches, interconnected by straight longitudinal beams to distribute loads. The resulting horizontal forces of the arches are very low due to the low weight of these arches. Local steel ties work just like spokes of a bicycle wheel in order to stiffen the structure. The resulting surfaces between these structural members are quadrangular, which are cross-braced to provide necessary rigidity. Another benefit of the cross-bracing is that it allows the use of much more slender profiles. The resulting structure is a very transparent, lightweight structure which redirects forces into normal stress in the cross-bracings as opposed to bending moments in the edge beam. Therefore resulting forces on the existing structure are very low.

Figure 5.17 The roof structure of Musuem für Hamburgische Geschichte. Source:(Schittich, Staib, Balkow, Schuler, & Sobek, 2007)

5.2.3.3 Concluding

Form-active structures like cable or arch structures prove to be very efficient and transparent structures for spanning large spans. As the description however describes is that the resulting tensile forces in the cables are however high, and they should be redirected to a strong load-bearing structure. Cable-net structures allow curved shapes to be used, detailing is however more complex and critical in these structures.

5.2.4 Plates and shells – surface active

5.2.4.1 General description

According to (Engel, 1999), surface active structures of which plate structure and shell structures are part of, are systems of flexible or rigid planes able to resist tension, compression or shear, in which the redirection of forces is effected by mobilization of sectional forces. The system members are primarily subjected to membrane stresses, meaning stresses acting parallel to the surface.

5.2.4.2 Example projects

5.2.4.2.1 MAS & Casa da Musica

Location	Porto, Portugal
Span	5x1,2mm
Type of glass used	Hot bend glass
Thickness of glass	12mm
Type of connection	Mechanical connection

In 1997 OMA won the design competition for the Cultural Centre of Porto in Portugal. In this design the architect wanted to have a large transparent glass façade of 25 by 12 meter of two layers. A first layer to provide weather tightness and bear wind loads, another layer is added to separate the auditorium from the foyer. ABT consulting firm was asked to come up with a solution to make this façade, and proposed various slender cable-structures. The architect was however not pleased with this ‘’steel spaghetti’’ look, and wanted a different solution(Nijsse & Wenting, 2014). The following search eventually led to the finding of a glass manufacturing company in Spain which had the ability to produce large corrugated glass panels of 5 x1,2m high(Nijsse, 2002). The principle behind the corrugated glass panel is simple: by folding a flat sheet of glass, the bearing capacity for loads applied out of plane in the glass is increased by more than 1000%, and for loads in-plane, the buckling and plying resistances increase also dramatically (Nijsse & Wenting, 2014). The principle is proven by a simple test of folding a piece of paper a couple of times to act like a wall. An enormous increase of bearing capacity is achieved in this way, compared to a flat piece of paper.

These glass panels were chosen to construct the glass façade with. Three panels were stacked on top of each other to create the 12m high façade. Although these panels were only 12mm thick, because of their shape they could easily bear the wind loads. Therefore a minimum of support structure is needed, resulting in a maximum transparency. At the bottom and top and the intersection between the glass panels, a steel beam used placed in order to connect the glass panels together. In these connections there is also a facilitation of adjusting for tolerances.

Figure 5.18. The facade structure of Casa da Musica. Source: https://www.abt.eu/projecten/casa-da-musica-porto.aspx

Figure 5.19. An overview and close-up of the corrugated glass façade in Casa da Musica.

In another project ABT has also applied the corrugated glass facades. This was in the MAS, in Antwerp, starting in 2003. The building consisted out of spiraling concrete structure. In between these spirals, the architect wanted a large glass façade. ABT choose to use the corrugated system, based on their experience from Casa da Musica. These facades are 11m high, meaning two 5,5m high panels are stacked upon each other. Because of this height, a slender steel profile is placed at the height of the joint between two panels. This profile acts to bear horizontal wind loads, and is suspended from the roof hanging on chains. The connections allow for the absorption of production inaccuracies, which are happening because of high complexity of manufacturing.

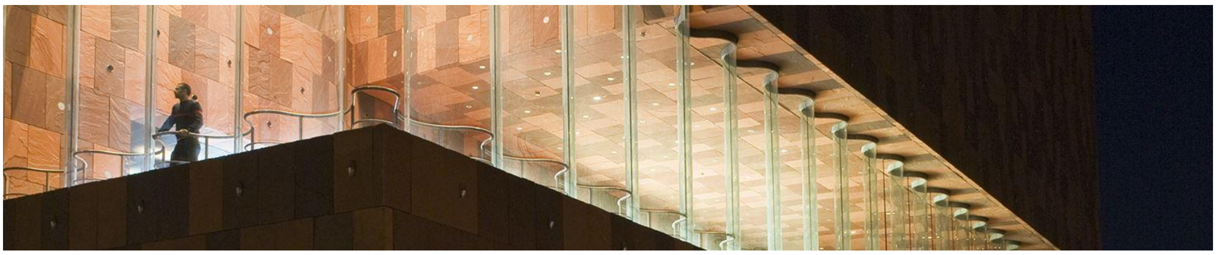


Figure 5.20. A night view of the corrugated glass façade. Source: https://www.abt.eu/projecten/museum-aan-de-stroom-mas-antwerpen.aspx

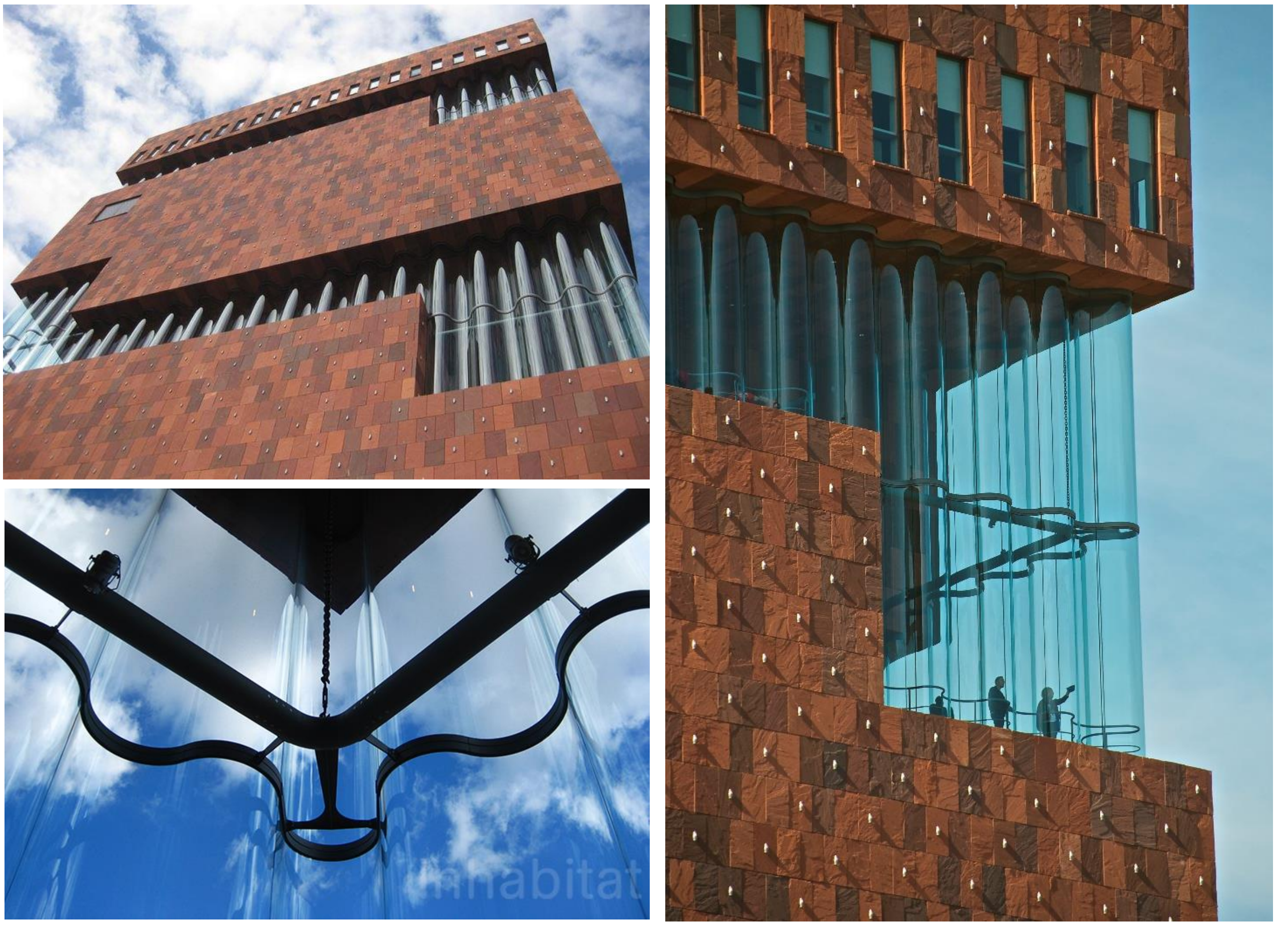


Figure 5.21 Close up view from the corrugated glass façade. Source: https://www.abt.eu/projecten/museum-aan-de-stroom-mas-antwerpen.aspx

As Nijsse and Wenting(2014) write in their journal article, the question now rises if this system could also be used as a roof structure. Since corrugating the flat glass sheet improves the stiffness so much, this does not only improve the bearing capacity of wind loads, but also of dead loads and snow loads.

5.2.4.2.2 Broerekerk Bolsward Octatube

Location	Bolsward, The Netherlands
Span	-
Type of glass used	Hot bend glass
Thickness of glass	-
Type of connection	Mechanical connection

The next project by Octatube, is a glass roof renovation. This is done for the Broerekerk, located in Bolsward, Friesland, the northern province of Holland. The building is an old church, dating from the 13th century. After the roof has burned down in 1980, the building was renovated and restored and fitted with a new glass roof.
This new roof is shaped after the original roof/barrel vault, which creates an subtle impression of how the original roof looked like. The actual curved glass panels are suspended on the steel frame structure, which represent the outer contour of the old roof. Therefore this project can really be seen as a restoration of the monument, bringing back the building in the city landscape.

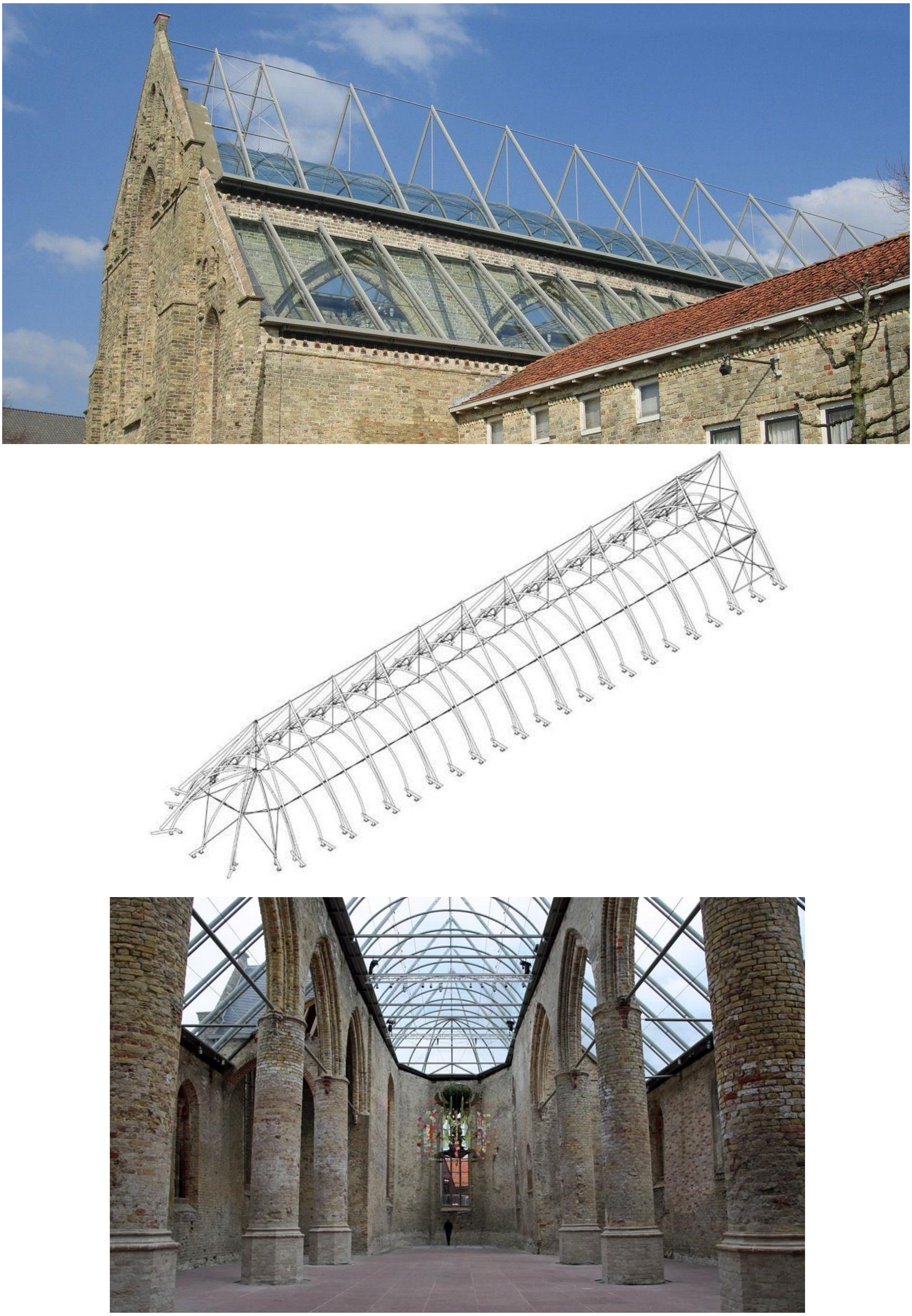


Figure 5.22 The Broerekerk glass roof. Architecturally a nice solution to create impression of outer-contours, while the actual glass is an arched structure. This creates a strong impression of the old building. Source: http://www.octatube.nl/projecten/43/broerekerk/

5.3 Design requirements & boundary conditions based on previous chapters

All the previous chapters regarding the philosophy behind restoration, the history and former and possible future use of the building, and the material properties of glass have led to a set of boundary conditions. The boundary conditions are determining what the design of the roof should fulfill. Therefore these could also be called design requirements. The roof design should follow these rules in order to be a success.

The (installation of the) new roof should be:

- Reversible. It should be able to be removed without permanently changing the building.
- Fitting in the original building, with respect to its history by means of using the original roof shape and similar structure grid
- Preventing large tensile and bending forces on the old masonry
- Using embedded adhesive hybrid connections as much as possible – preventing high tensile stress peaks
- Using metal elements where needed – preventing high tensile stress peaks
- Have an increased safety by using laminated sacrificial layers to prevent collapse
- Using heat-treated glass as a good balance between strength and safety
- From an architectural point of view be a roof with maximum transparency
- From a structural point of view should be a glass self-supporting structure with maximum application of glass

5.4 Conceptual design proposals

In the next part conceptual designs are proposed. Each proposal is based on one of the structural types explained in the previous chapter, or a combination of multiple types. They are meant to show how each type could be applied in this situation for this shape of roof. Since each type of structure has its specific properties, it also has specific pros and cons. The specific proposed designs are therefore not meant to be looked at with too much detail, they are meant to help making a rough first selection in which type of structure could be most applicable or suitable for this situation and roof shape.

Subsequently, a selection must be made. This is done based on a analysis which will score the different designs on several criteria. The highest scoring proposal will be further elaborated on.

5.4.1 Glass beam structure

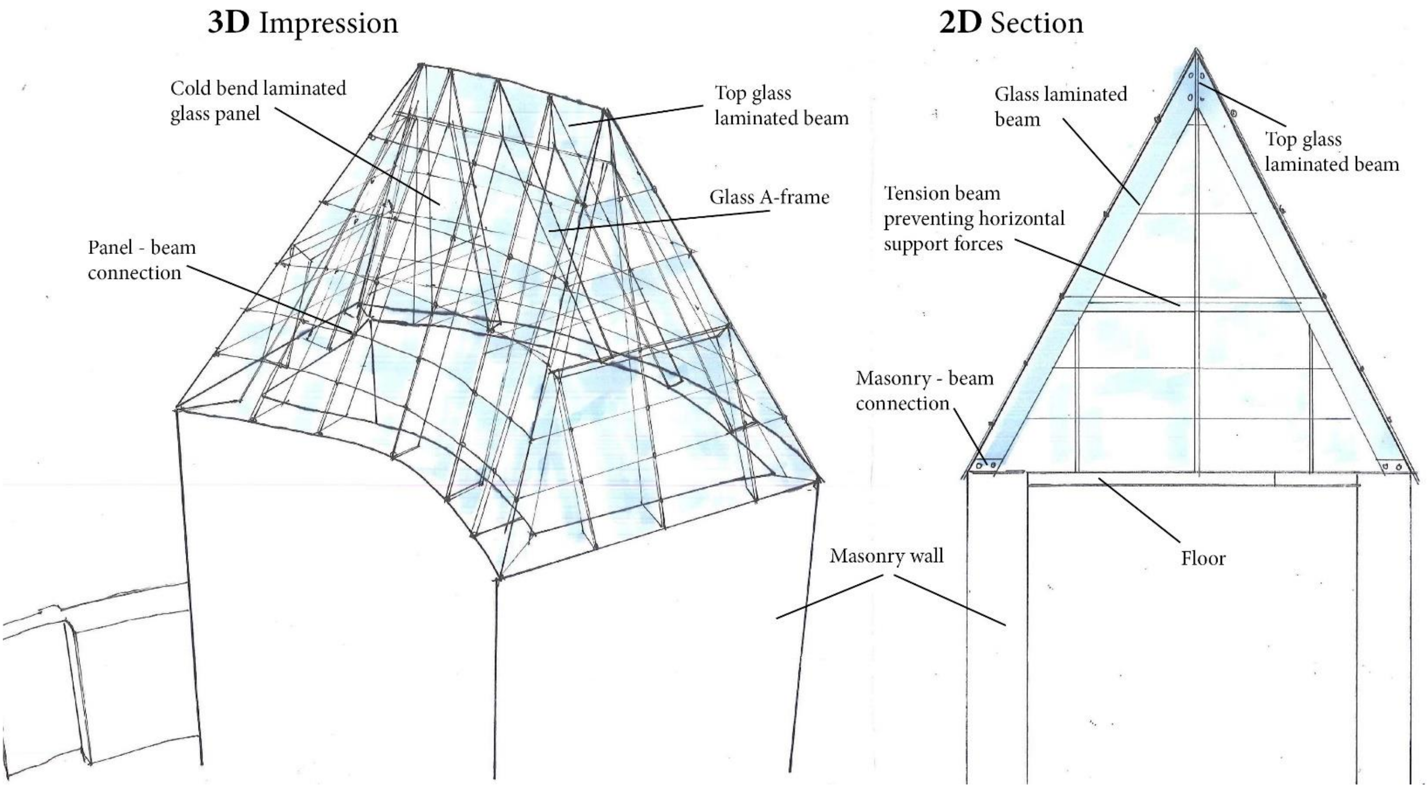


Figure 5.23 Conceptual design proposal of an glass beam structure. Source: own ill.

5.4.1.1 General description

The first proposal is based on a beam structure type. The basic setup of the roof will be a set of A-frame structures, which are placed in the length of the roof. The frames have a glued steel insert at the bottom which bolts to a joint connected to the masonry wall. The horizontal beam in the a-frame is designed to take up the horizontal forces, resulting in a tension beam. In this way the horizontal forces at the supports are minimalized. The beams will be made in one piece, out of laminated safety glass . At the top of the a-frames a horizontal beam is located, connected the different a-frames together. Subsequently, laminated glass panels are placed on top of the glass beams. They are bolted into place using glued-in metal inserts in the top of the glass beams and sides of the glass panels. In order to follow the curvature of the roof, these panels will need to be bend in shape. This is done by cold-bending them into position. The beams are placed in a grid in order to represent the old wooden structure that likely would have supported the original roof of the building. Hereby, next to the shape, also the structure build-up is a reminder of the original roof.

5.4.1.2 Advantages

- This type of structural is a similar type of structure the original roof would have had. Therefore it is a good representation of the old, using a modern material.
- Rather simple set up. Clean way to make the required shape.

5.4.1.3 Disadvantages

- The roof shape is rather complex. Making this using rather large one piece elements could be difficult.
- Cold bending the glass panels is a technical challenge. The curvature might be too large.
- Since the beams will be rather high, they could make up for a rather unsophisticated structure, where the high beams could draw a lot of attention
- The connections to the masonry could prove difficult. No large tensions forces are wanted.

5.4.2 Cable net structure with steel contour frame

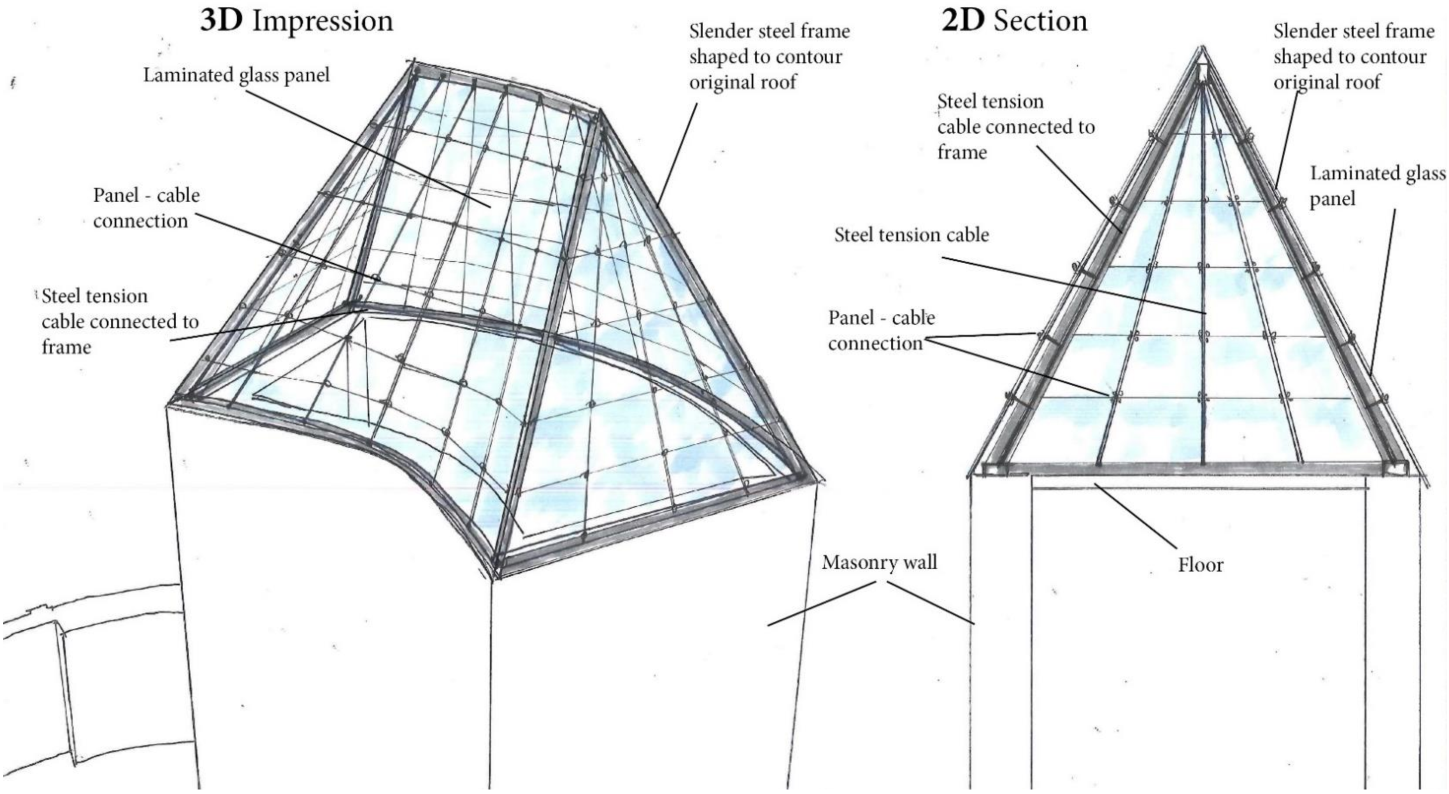


Figure 5.24 Conceptual design proposal of an steel cable glass structure. Source: own ill.

5.4.2.1 General description

The second proposal is based on a cable-net structure. Since cable structures are structures that work by tension in its elements, and masonry is not capable of bearing (high) tension forces, an additional structure is needed to bear these tensile forces. Therefore it is chosen to place a slender steel structure on top of the masonry walls. This frame is shaped in the contours of the original roof, thereby giving a clear impression of the old structure. Cables are subsequently connected vertically and horizontally in between this steel frame. The steel structures is bolted onto connections in the old masonry, internally bearing tensile stresses but externally only placing static compression forces on the structure.
Laminated glass panels are connected to the steel cables using special connections that also connect the intersecting vertical and horizontal cables. Since cable structures make up for such efficient structures, the resulting steel could very thin and minimal, thereby being very transparent.

5.4.2.2 Advantages

- An efficient and transparent structure
- The steel frame prevents unwanted stresses on the old masonry.
- The steel frame strengthens the architectural expression of the original roof.

5.4.2.3 Disadvantages

- The concave shape may be impossible to make using just steel tensile cables. Also the convex shape will require additional elements.
- The primary loadbearing material in this structure is steel. The glass just transfer wind loads and dead loads onto the steel. Architecturally it gives the impression of a glass roof, but in structural essence it is a steel structure.
- Challenging connections with difficult tolerances.

5.4.3 Steel trusses glass structure

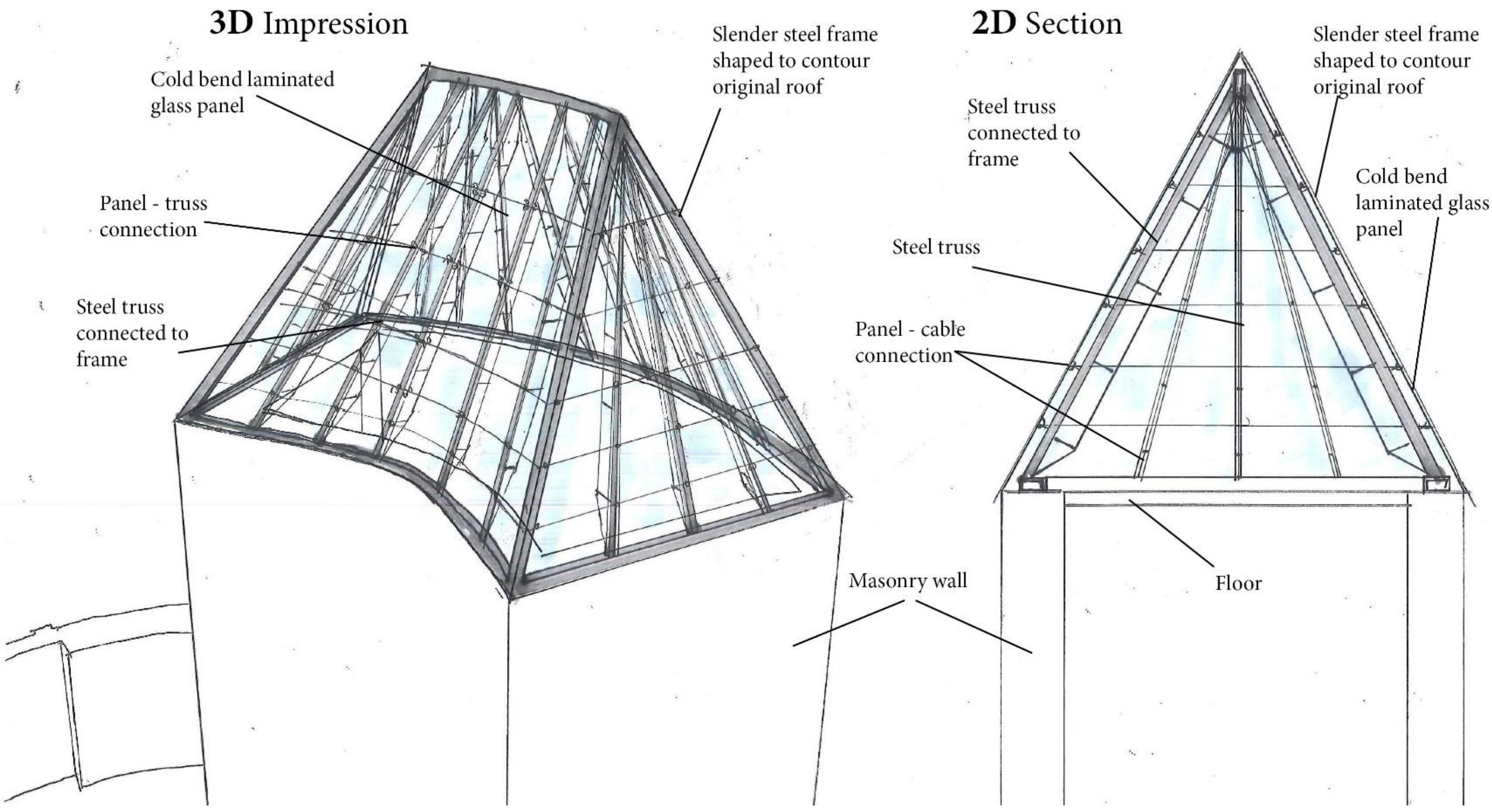


Figure 5.25 Conceptual design proposal of an steel truss glass structure. Source: own ill.

5.4.3.1 General description

The third proposal again is buildup from stiff elements, but instead of using solid glass beams, using thin steel trusses. These steel trusses can also be seen in the Juval Castle project. Just as in the second proposal, a slender steel contour frame is placed on top of the walls of the castle. Between the bottom and top beam of the steel frame, a slender steel truss is positioned. The tensile part of the truss consists of a thin steel cable, the compression part is a slender steel profile. On top of these trusses, cold bend laminated glass panels are placed. Special steel connections welded on top of the trusses allow for an angled fixation of the glass panel, to be able to make the desired curvature of the roof.

5.4.3.2 Advantages

- Fairly straight forward of setting up the main structure.
- Use of primarily steel elements gives a lot of freedom in connections
- Using the steel, the forces are stressed can easily be distributed.

5.4.3.3 Disadvantages

- The steel can become dominantly visible, losing the idea of transparency
- In a structural sense this proposal involves a primary steel structure
- Due to a relatively large amount of steel, this is the heaviest proposal

5.4.4 Hybrid system cable - glass beam structure

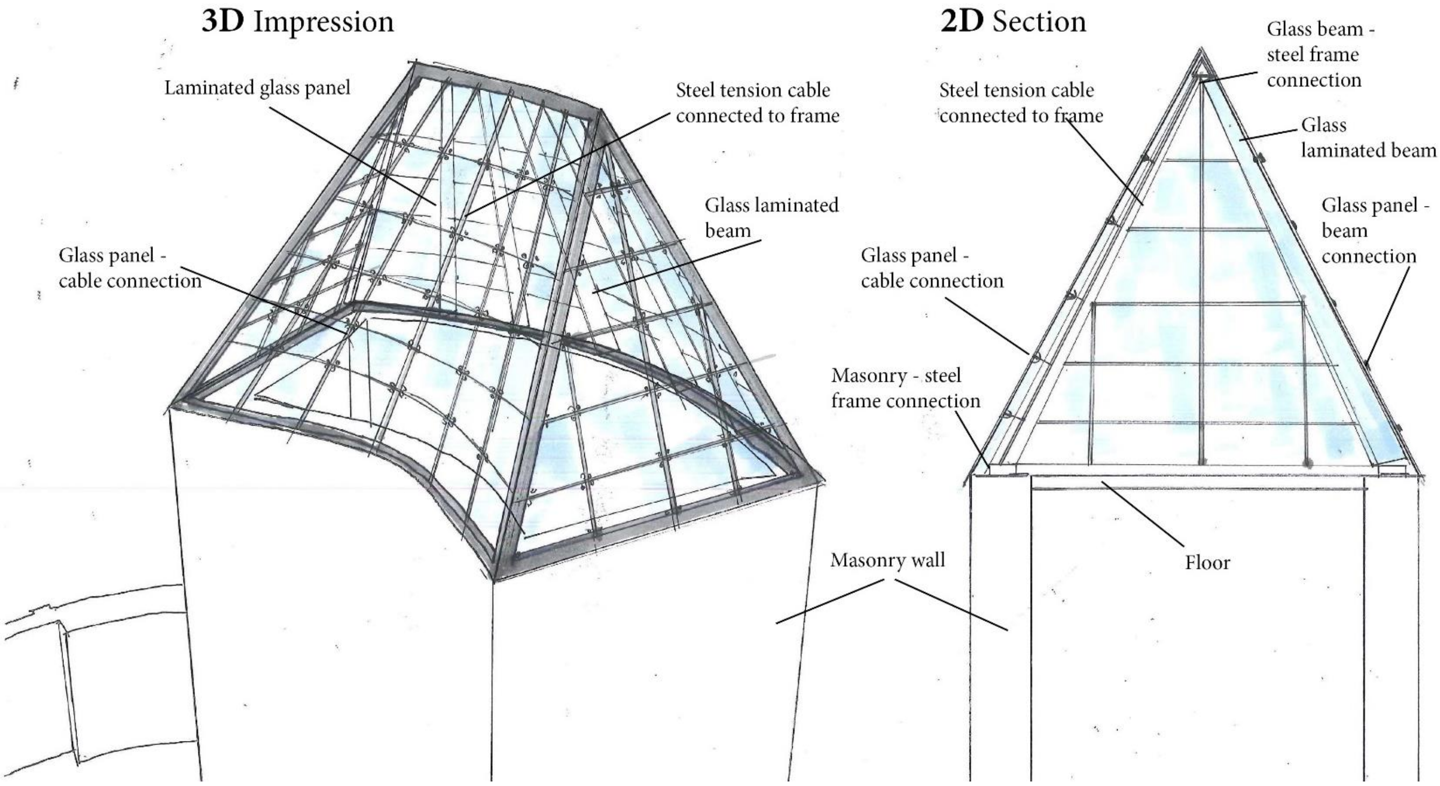


Figure 5.26 Conceptual design proposal of an hybrid steel cable -glass beam structure. Source: own ill.

5.4.4.1 General description

In this proposal a combination is used between two structural systems to create the shape. This is done to utilize the specific good properties of each structural system in its best application. A steel contour frame is used to bear stresses. In the example of fig 5.26, a cable net structure is used on the concave surface of the roof, since this is a beneficial shape for a cable structure. Wind forces will directly be translated into tensile forces in the cables. Since the sides of the roof consist of triangles, then can withstand the tensile forces of the cables well, because this force is translated into a compression forces, which triangles can bear well. Therefore cables are used on three sides of the roof.
For the convex part of the roof, glass beams are used. This because this shape is easily made using linear elements. Wind loads can easily be transferred through to the beams to the steel contour frame. Using a hybrid system you optimize the design so that it is most efficient in creating the shape.

5.4.4.2 Advantages

- Efficient structural system, optimizing the system to shape
- Transparent system by optimized slender structure
- Showcase of different glass type structures

5.4.4.3 Disadvantages

- Complex because two different types of connections
- Both systems should be matched in appearance to create cohesive look

5.4.5 Corrugated glass structure

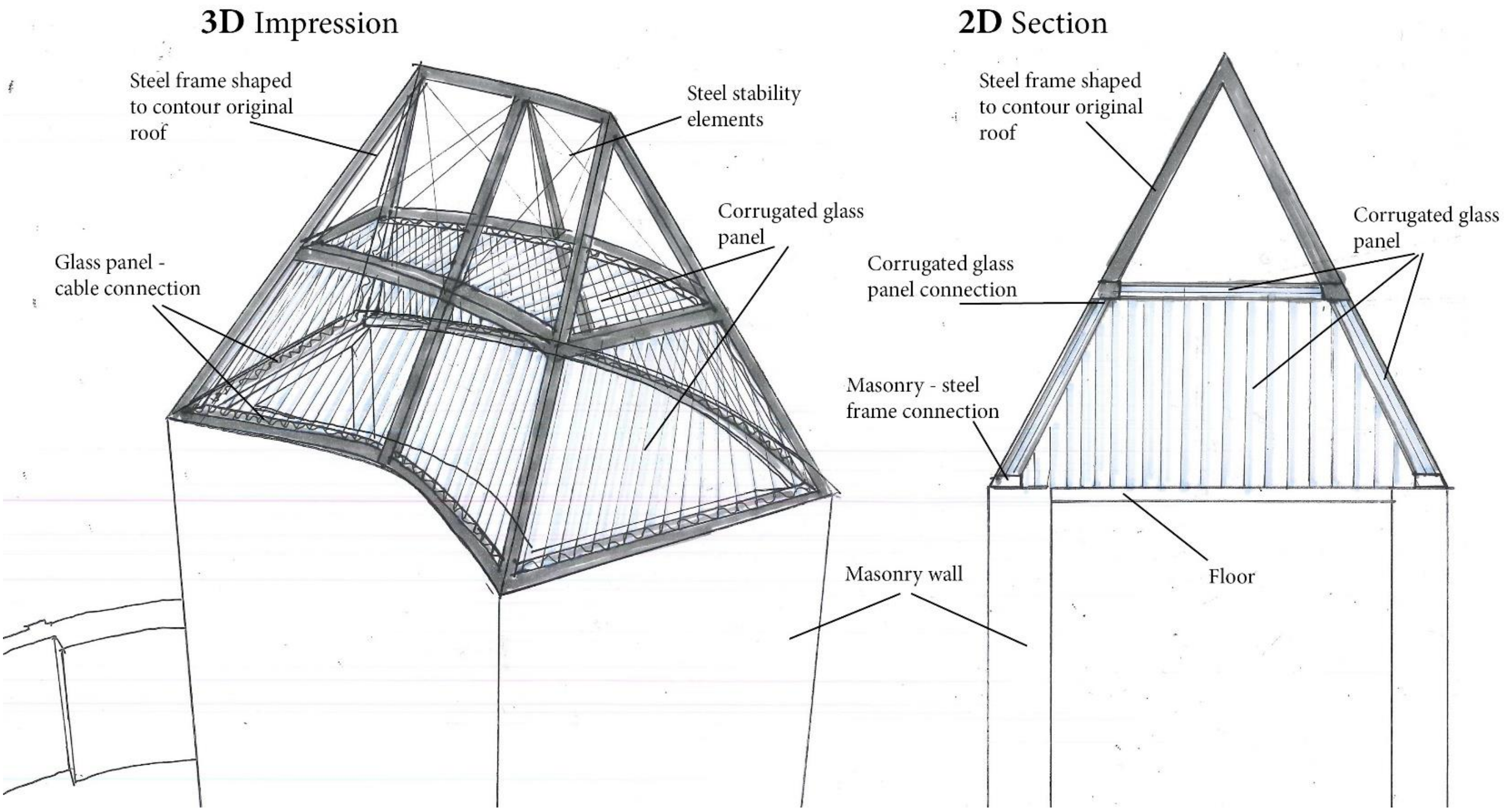


Figure 5.27 Conceptual design proposal of an corrugated glass structure. Source: own ill.

5.4.5.1 General description

The fifth proposal utilizes a very different approach from the previous proposals. Where in the previous proposals slender linear or cable elements are used to conducts forces, in this proposal plate elements are used. Corrugated glass panels are used to span half of the roof. The principal is based on the system of the Broerekerk. Here a steel contour frame is used to emphasize the original shape of the roof, where the actual closing roof surface is only a part of this shape. Where for the Broerekerk the glass follows the shape of the original barrel vault roof, here the glass follows the shape of the original wooden a-frame. Since the corrugated panels are curved, their stiffness is high enough to span 5,5 meters, which is the maximum production size of these panels. The steel contour frame should have appropriate size to be able to connect the corrugated panels.

5.4.5.2 Pro's

- A transparent roof system, with minimal amount of components
- A strong emphasize of shape due to the steel frame
- The glass plays a big role in the structure, spanning large lengths

5.4.5.3 Cons

- A roof made with corrugated glass panels has never been done before
- The steel frame is complex with difficult connections
- Architecturally a different approach to not make the entire roof surface an enclosure

5.4.6 General design options

General ideas

- Due to the shape it seems that the glass plates need to be bend into shape, or otherwise the curvature cannot be made so fluidly.
- The steel contour frame seems be a promising idea. It fits the architectural idea where the contour of the original roof is subtly emphasized, while it also functions as an important structural element. The frame allows internal forces to be taken up internally, giving a stable structure. This is then mounted on the old wall, just giving compression forces on the masonry.
- An interesting idea is create an impression of roof tiles, by applying a system as in the Rhon-Klinikum project described in part 5.2.3.2.4. This tile texture is created by using small sheets of glass that are placed upon each other, using a special mounting system. This is possibly from the point of architecture an interesting approach, creating not only in shape but also in texture a relation to the original roof.

Difficulties

- The roof has a complex shape. Each surface of the roof is different, and it is a-symmetric.. The roof has is shaped convex ánd concave and has two sloped surfaces. These curved surfaces are luckily single curved, which allows the use linear elements like beams.
- In order to achieve a fluid curved surface, the glass panels will need to be bend. Otherwise the roof will be cut up in several flat surfaces. The glass pieces will also not be shaped square, otherwise the surfaces can't be made. The bending of glass panels is however difficult. Hot bending panels is expensive and requires very precise measurements and low fabrication tolerances. Cold bending is difficult, but has been done before, and seems to be the most fitting solution. Since the curvature and shape of the roof is so complex, many unique molds would have to be made in order fabricate all the panels, which would be very expensive. Also hot bending the glass would not result in a high visual quality, since there would be a lot of distortion in the panels. For this cold bending is chosen instead of hot bending.
- If straights elements like beams or trusses are use, torsion is induced in these beams to create the connection between the curved bottom and straight top line. This could also be solved by using special connections which allow for an angled fixation of a panel.
- The connection of the new roof to the masonry is crucial. Since the top of the wall is not in a good shape, this is not a straight top surface. As consequence, measurements have to be taken in order to connect to this surface.
- The strength of the connection to the masonry is important. Since the masonry is old and therefore weakened, tensile and bending forces should avoided in the masonry, since the material has a very low strength in these forces.. Hence measurements have to be taken to redirect forces into the masonry.

5.4.7 Selection criteria for choosing a proposal

The next step is to choose one of the proposals for further elaboration. An attempt has been made to make this decision somewhat rational and structured. Therefore a technique has been used called the decision matrix, which is used to score the different proposals in order to come up with the best scoring proposal.

The selection criteria are the reformulated criteria stated in chapter 5.3, which followed out of the literature study. They have been reformulated in order to function as clear criteria for scoring the proposals. Specifically some points have been formulated clearer in order to define what a low or high score would be. For each of the proposals, for every criteria a score is given between 1 and 5. Since there can be a difference in relevance between the criteria, each criteria score is multiplied by a so called ''weigh factor''. The most important criteria has the highest weigh factor and visa-versa.

These weigh factors are determined using the table below in fig. 5.28. Each criteria on the left column has been compared to other criteria in the top row. If the left criteria is more important than the criteria in the top row, a score of ''1'' is given, otherwise a ''0''. When all the comparisons have been made, the total score is an addition of the separate scores. The criteria of the highest importance is has highest score, which in this case was the criteria of the 'fitting in the original building'.

	Fitting in the original building	Maximum transparency	Maximum structural application glass	Lightweight	Amount of unwanted forces on walls	Low complexity in element and detail	Inventiveness - amount of precedents	Low construction complexity	Total
Fitting in the original building		1	1	1	1	1	1	1	7
Maximum transparency	0		0	1	1	1	1	1	5
Maximum structural application glass	0	1		1	1	1	1	1	6
Lightweight	0	0	0		0	0	1	0	1
Amount of unwanted forces on walls	0	1	1	1		1	1	1	6
Low complexity in element and detail	0	0	0	1	0		1	1	3
Inventiveness - amount of precedents	0	0	0	0	0	0		1	1
Low construction complexity	0	0	0	1	0	0	0		1

Figure 5.28 The weigh factors of each criteria. The left column is compared to the top row. Source: own ill.

Once the weigh factors are determined, the proposals can be scored. This can be seen in fig 5.29.

	Fitting in the original building	Maximum transparency	Maximum structural application glass	Lightweight	Amount of unwanted forces on walls	Low complexity in element and detail	Inventiveness - amount of precedents	Low construction complexity	**Total**
Weegfactor	7	5	6	1	6	3	1	1	
Proposal 1 glass beams structure	5	5	5	2	2	3	3	3	**28**
Proposal 1+ glass beams+ steel frame	4	4	4	2	4	5	4	4	**31**
Proposal 2 Cable net glass structure	2	3	3	3	3	2	4	2	**22**
Proposal 3 Steel truss structure	3	2	2	2	3	3	3	3	**21**
Proposal 4 Hybrid structure	3	3	3	3	3	2	3	2	**22**
Proposal 5 Corrugated glass structure	3	4	3	2	3	1	4	2	**22**

Figure 5.29 The final selection matrix. Source: own ill.

5.4.8 The chosen proposal

Based on the matrix, proposal 1+ with the glass beam and steel contour frame came out as best scoring proposal with 31 points, closely followed by proposal 1, the glass beams structure proposal without steel contour frame. Therefore the chosen proposal for a structural buildup of the roof is a glass beam structure with a steel contour frame on top of the walls and possibly on the sides beam of the roof.

Although the calculation already implies that proposal 1+ is the most appropriate proposal for the castle, a small explanation is given.

The proposal scores high on integration in the building because the glass beam setup relates to the old wood roof structure which would have been in place. Since all the major structural elements are made of glass the roof is also very transparent, and scores high on structural glass application. The beams are solid elements, which are thus quite heavy, but this might be beneficial in a structural function to compensate for tensile forces induced by wind loads. Because a steel contour frame is placed on top of the roof, this frame can be used to connect the glass beams to. The frame also functions by taking up the bending moments and lateral forces of the roof. Because relatively little amount of elements are needed, the complexity of the design is relatively low.

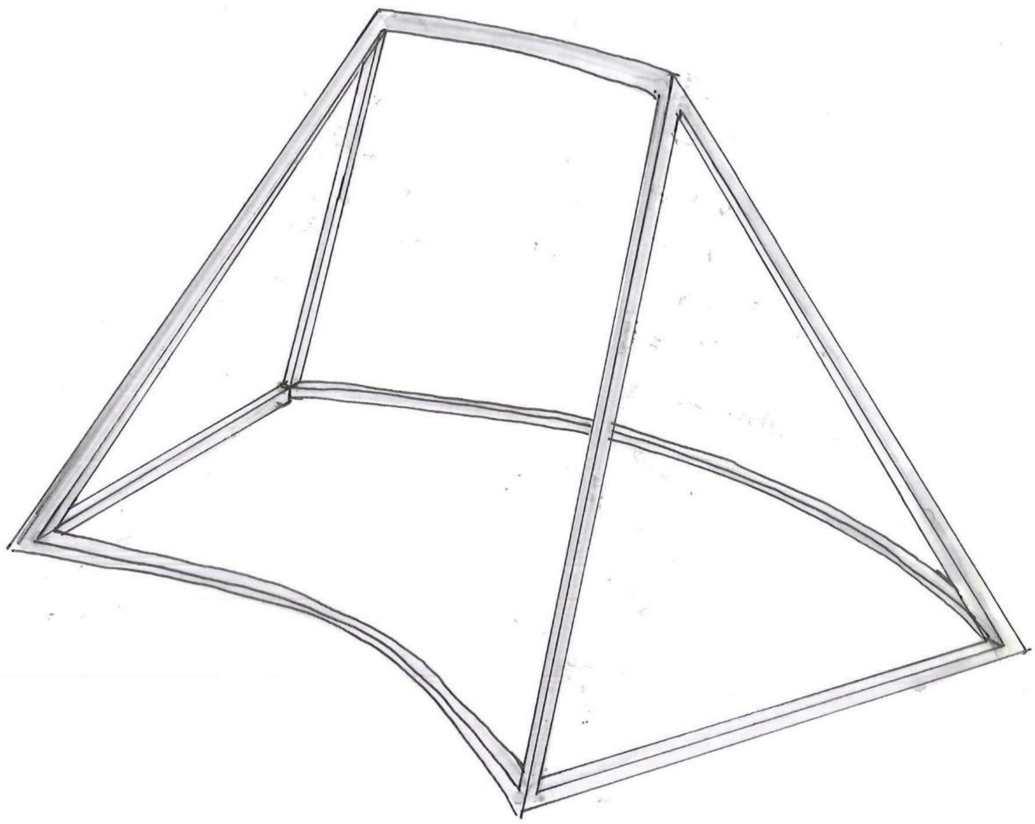


Figure 5.30 The schematic steel contour frame. Source: own ill.

In the next part of the research this proposal type will be further elaborated into a final design.

6. Elaboration of the chosen proposal

In the next chapter the proposal, chosen in chapter five, is elaborated. This is done is subsequent phases, where first the overall structural build-up is elaborated. Different options are discussed of this setup, where the elements are positioned in an integral structure. Once a beam grid has been chosen, the glass panel layout on top of these beams have to be chosen. Many different possibilities are researched and discussed, and finally selected based on several criteria. Once this setup is determined, the design can move on to the next phase of detailing, of which the design process is described in the subsequent chapter.

6.1 Elaborating on the different elements of the sketch design

6.1.1 Translating contour walls into symmetric shape

Since the goal is to make the new glass roof in the same shape as the old roof, the starting point of the design process is determining the exact shape of the new roof. The rough shaped is determined earlier as shown in chapter four and five, but the exact shape is refined now.

Looking at the contour of the donjon wall, it is clear this shape is far from symmetrical. Each side of the wall has a different length, and there is no clear horizontal or vertical symmetry-axis. If the new roof would follow the exact wall contour, this would mean the whole roof would also be asymmetrical. This would give great difficulties in production and installation of the roof, since every glass panel and beam would be unique.

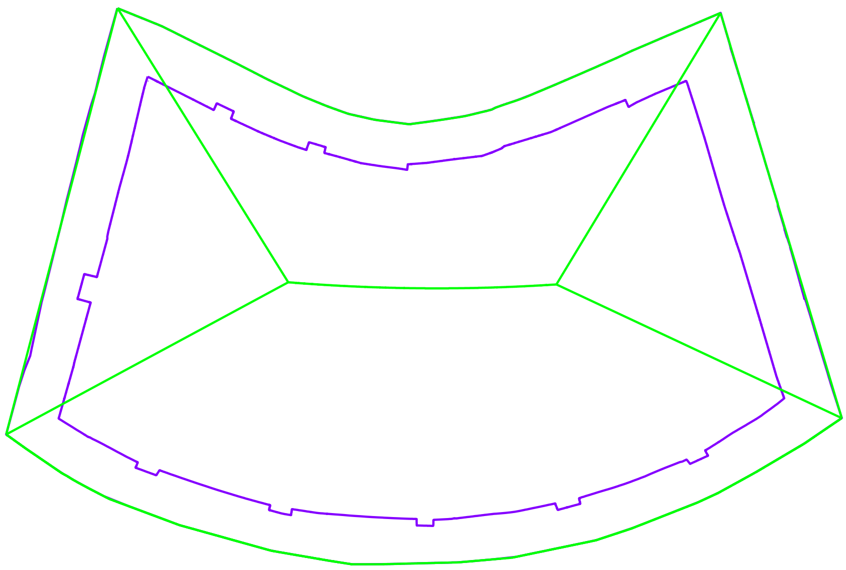


Figure 6.1. The purple contour of the donjon wall and the green matching roof contour. Source: own ill.

Consequently it has been tried to create a new contour shape which would fit the original shape as good as possible, while at the same time being symmetrical and therefore much easier to build and make.

This however required some puzzling in order to come up with a good shape which would have one clear center. In fig. 6.2 all the help lines can be seen that were needed in order to find a good symmetrical center.

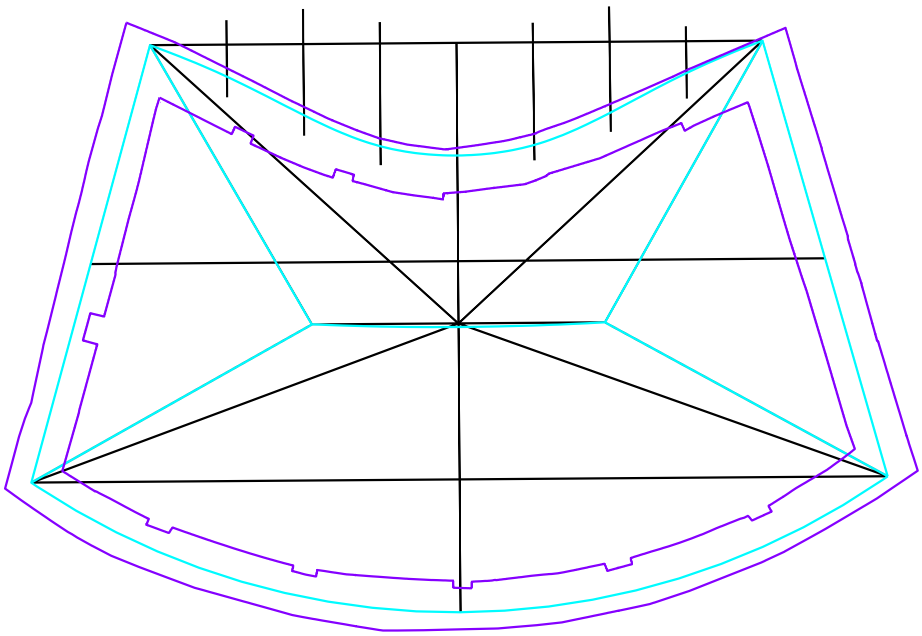


Figure 6.2 The work drawings with all the help lines (black) and the final contour shape (cyan). Source: own ill.

Once the contour was formed to the final shape, as shown in cyan color in fig 6.2, it has been scaled larger so it would fit the outer contour of the donjon wall. As can be seen in the figure below, it fits the donjon contour rather well, with a maximum deviation of around 350mm. These tolerances will have to be accounted for in the detailing of the structure. The shape is symmetrical along the axis, so basically only half the structure has to be designed.

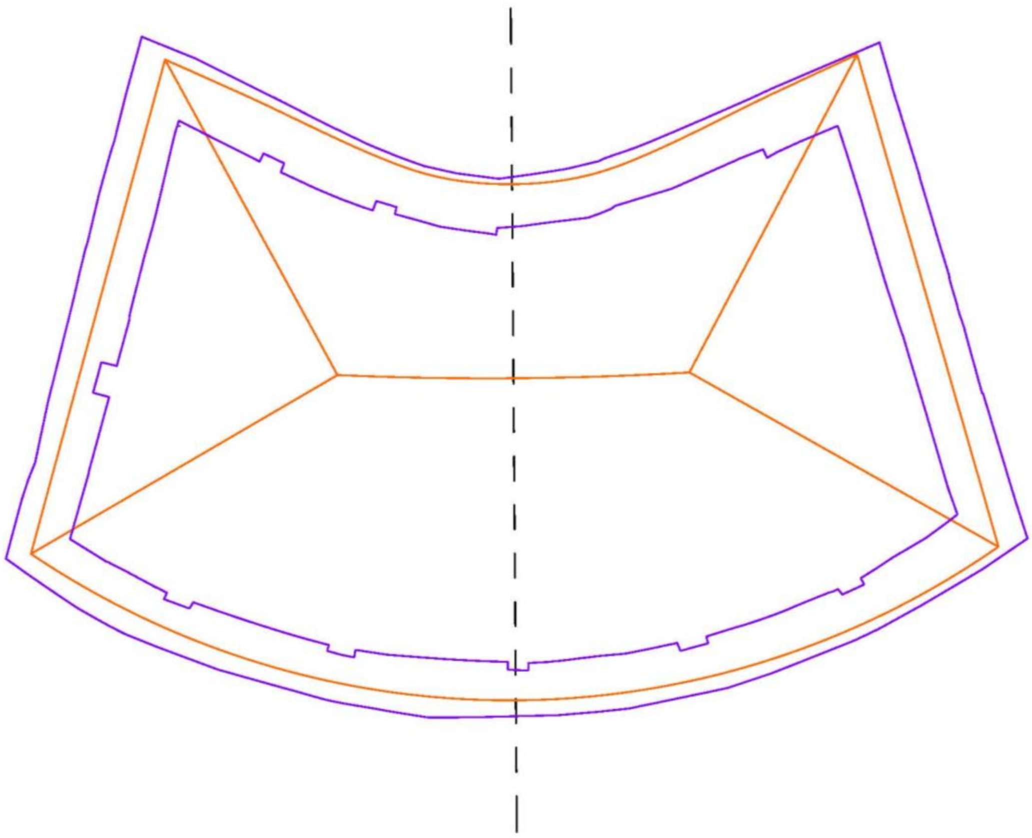


Figure 6.3 The final new symmetrical roof contour. Source: own ill.

6.1.2 The steel contour frame

As been described about the chosen proposal, a steel contour frame is used in the design. The wall in its current state is quite uneven and has eroded away over the years. Therefore, this uneven surface is difficult to use for a new structure. The frame levels out the uneven surface and allows for a straight and symmetric foundation for the glass structure.

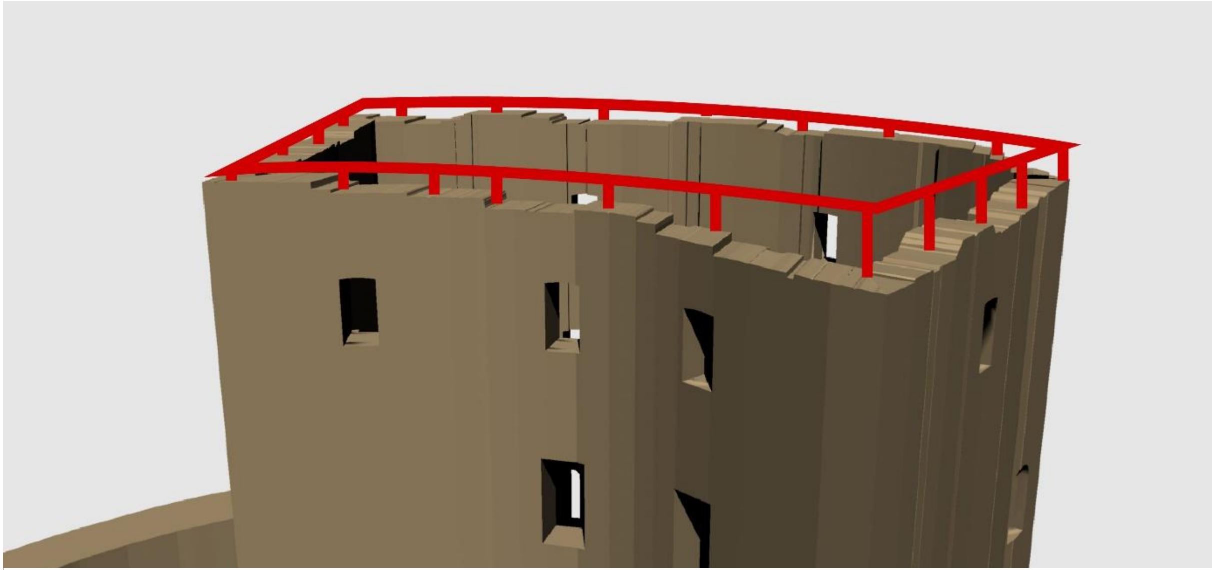


Figure 6.4 Sketch steel contour frame on top of the wall. Source: own ill.

This frame plays a very important double role, in an architectural point as in a structural way. The frame emphasizes the original shape of the roof, and therefore act as a reference for the new roof to the old structure. From a structural point of view the structure takes up the forces directly induced by the roof structure. Meaning any bending moments, points loads or tensile forces caused by elements of the roof are now induced into the steel frame, which would otherwise flow straight into the masonry wall. Since masonry is very weak against tensile forces, this would likely cause failure of the old wall. The pitched roof will cause horizontal forces at the end of the beams, which will need to be taken up by the steel frame. In order to do this properly, horizontal tie beams are added to allow the steel frame to become one stiff plate. It has been chosen to use a square steel profile, since this would make connections more easy to the supporting legs as well as glass beams. The required dimensions are determined by making structural calculations which will follow later.

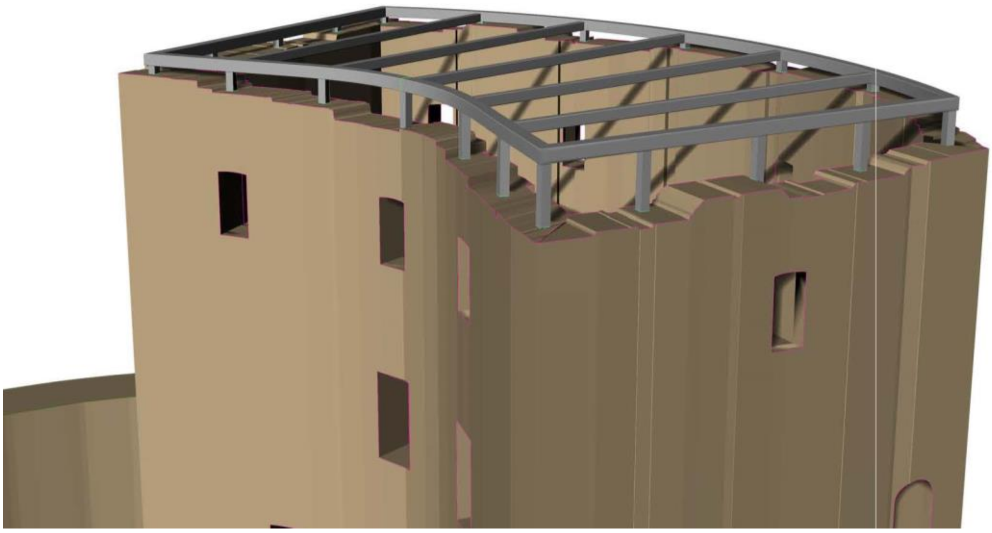


Figure 6.5 The chosen steel contour frame. Source: own ill.

6.1.3 The glass beam grid

The primary structural elements of the glass roof will be glass beams spanning from the bottom to the top of the structure. As earlier described, the top and bottom will be a steel structure, allowing for better and easier connections and better force introduction. The glass beams could be placed in several configurations in the roof shape. These configurations are discussed in the next paragraph.

6.1.3.1 Different grid options

In figure 6.6 several options are shown.

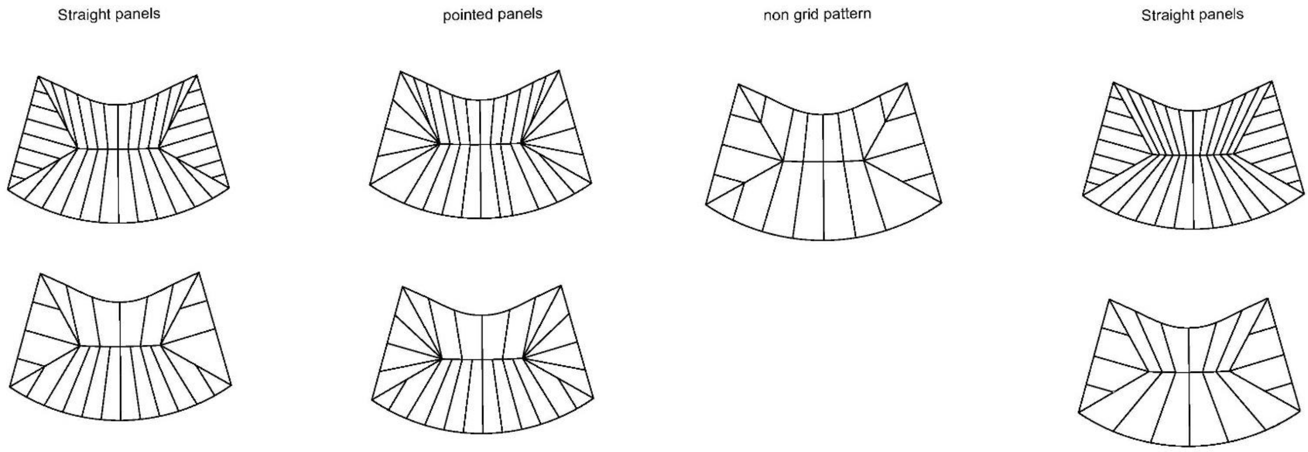


Figure 6.6 Different beam grid configurations. Source: own ill.

The left two options show more straight panels, meaning the side panels flow vertically up. The bottom and top profile have an unequal amount of subdivisions, which is why the side beams on the long sides of the roof stop halfway. Also a more course version is made. Another variant is made where the side beams all flow towards the same point, as a research of how this would look, both in fine and course versions. Next an completely different option is tried where the uniform grid has not been followed, creating a grid that flows more nicely from one side to the other.
Finally an alternative is made of the first variant, with a straight side panels. However now on the long sides of the roof, the top and bottom profile have equal amounts of subdivisions. This allow for a nicer flow of beams, without halfway interruptions. The side panels however do still meet the side beam halfway.

To get a better grasp of the curvature and complex geometry of the roof, an curvature 1:60 scale mockup was made. This concluded that the corners points of 5 meeting beams were not ideal, just as the glass beams that need to be connected to halfway to the corner beam.

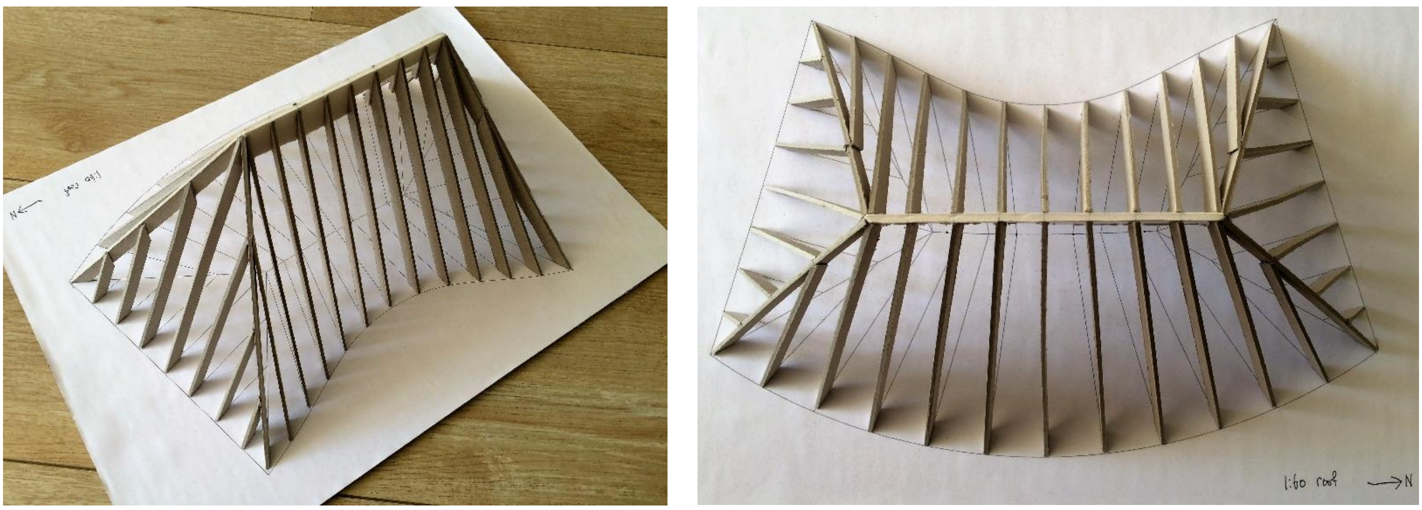


Figure 6.7 A small scale mockup of one of the beam grids. Source: own ill.

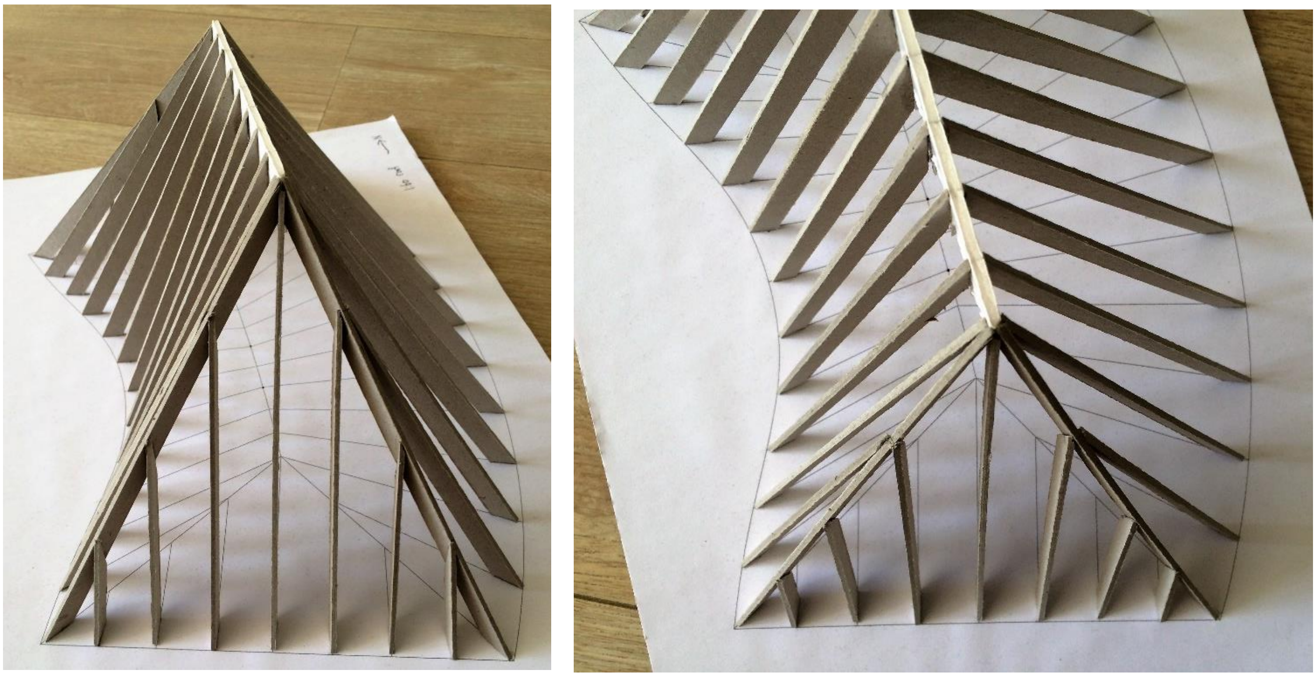


Figure 6.8. The side view of the roof grid. And a close up of the corner joint where 5 beams meet. Source: own ill.

6.1.3.2 Choice of beam setup

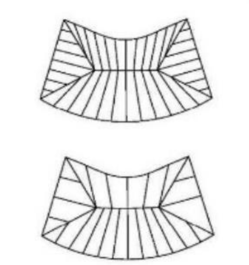
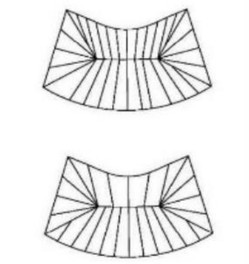
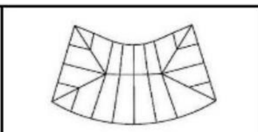
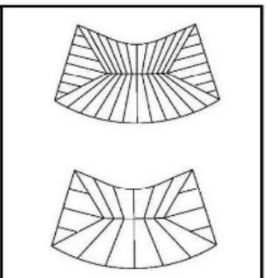
				
Aligning with grid	+/-	+/-	-	+
Complexity	+/-	-	+	+
Panel size	+/-	+/-	-	+
Transparency	+/-	+/-	+	+

Figure 6.9 Table with scoring of the different grids. Source: own ill.

From an architectural point of view, the grid of the beams had an important impact on the overall appearance of the roof, and the argument for choosing any option would have to follow out of restoration criteria. This eventually came out of the restoration criteria of integration of the old with the new. The old castle wall still have indentations in the inside of the wall where the old support structure would have been for the floors. The finally chosen beam grid is the grid which aligns the best with this old grid. In this way you create a visual harmonious integration of the new roof with the grid of the old structure. Next to that there are also practical arguments in the sense that now not many beams come together in one joint. This allows for less complex detailing. This choice results in beam that are 9595-11200 mm's long, depending on where they are located in the roof. The scoring can also be seen in figure 6.9.

Also, it has been decided to not use glass beams as main structural elements in the sides of the roof. This because this would still cause complicated detailing at the side beams. Next to that using glass beams along all four sides did not have the desired visual effect. Along these sides there are also no indentations in the walls, therefore there was more freedom to choose a different element there. Which structural element will be used there, is a matter which will be elaborated on chapter 6.1.5.

See figure 6.10 for the chosen beam grid.

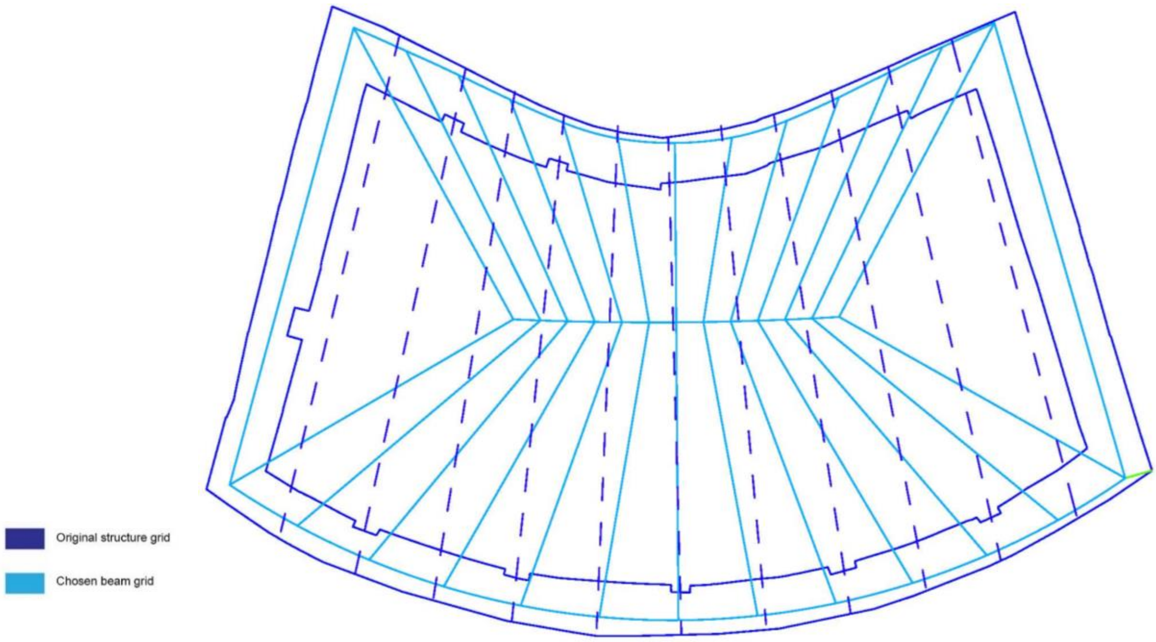


Figure 6.10 The chosen beam grid. Source: own ill.

6.1.4 The glass panel layout

Now that the grid for the beams has been chosen, the next primary structural component would be the glass panels that form the surface of the roof. Just as the beams they form an important visual element of the roof appearance.

6.1.4.1 The complexity of geometry

The panels are however also one of the most complex elements in the roof. This is because of the complex shape of the roof. In order for the panels to smoothly follow the curvature of the roof, they would have to be bend. Due to the relatively straight top beam, and curved bottom beam, the panels are twisted along their length. This bending although complex, is possible within a certain reach. The choice of panel layout would determine how much the panels would have to bend, or perhaps not at all. Also, the panel layouts would have to take into account the maximum production size of glass panels, with 6x3,6m for standard panels, and 10 or 18 x 3,6m as maximum production size for the jumbo panels, which also have a much higher cost.

6.1.4.2 The different layout options

A large variety of options are elaborated on, which are shown in 2d in fig. 6.11. Starting on the left, there are the panels with a diagonal division. This division is made in order to create an interesting combination between an old structure and a modern appearance. These triangles were also used in order to be able to make the curvature using flat panels.
The next main variant is by making very large panels with a vertical division. This is done in order to create maximum transparency, and to emphasize the verticality of the roof. Again a course and fine division of each version is made. When panels were used with a vertical division this would result in quite large panels, which would be expensive. This could be solved by adding one horizontal subdivision, which is also shown.
In the next variant squarer panels are used, with horizontal subdivision. The panels here are smaller and therefore cheaper, but it is also a relatively straight forward approach. To achieve a more interesting appearance, in the next variant the horizontal and vertical division are combined to create an offset look of the glass panels. Although this is slightly more interesting to see, the seams are all very visible.

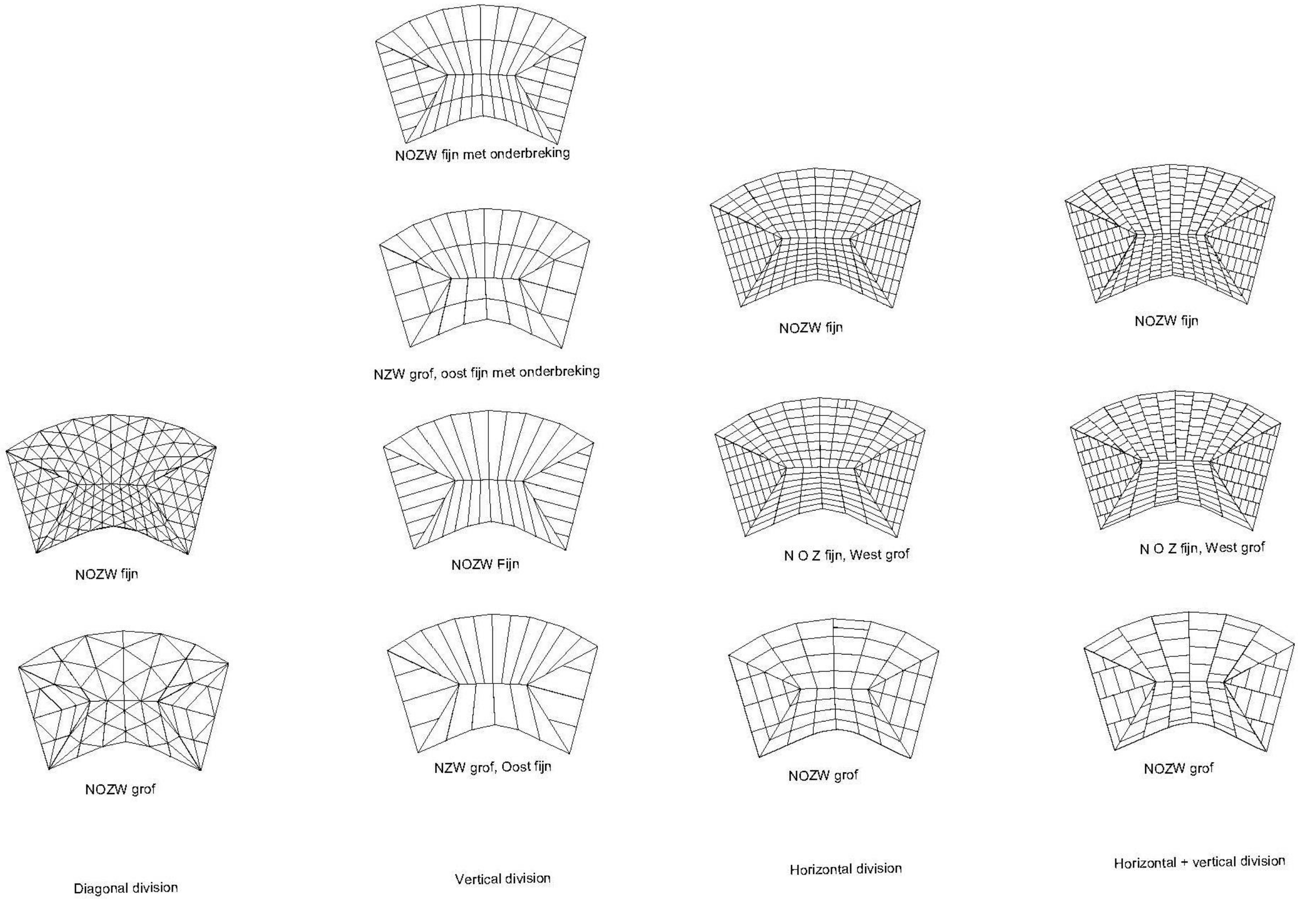


Figure 6.11 The different panel layouts in 2d From left to right: diagonal subdivision, vertical subdivision, horizontal division, horizontal + vertical division. Source: own ill.

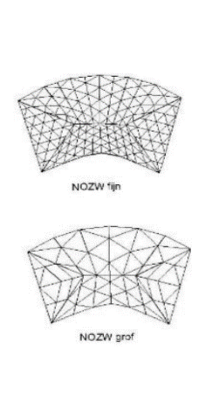
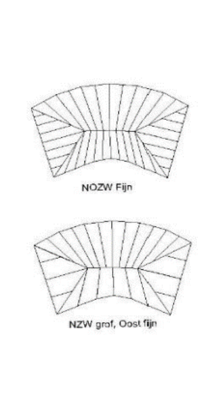
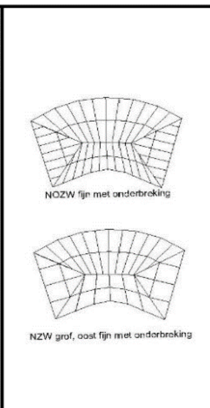
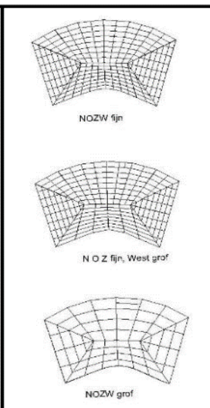
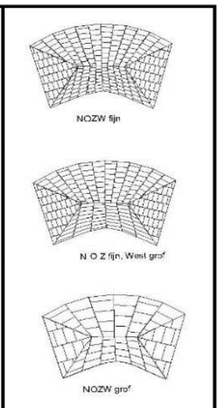
					
Transparency	-	+	+	+/-	+/-
Complexity	+	+/-	+/-	+	+
Amount of panels	-	+	+	+/-	+/-
Cost	-	+/-	+	+	+

Figure 6.12 Summary of scores for the different options From left to right: diagonal subdivision, vertical subdivision, horizontal division, horizontal + vertical division. Source: own ill.

6.1.4.3 Choice of panel layout

After making a score for each option as seen in figure 6.12, the choice has been made to go for the panel layout with the large panels and a vertical subdivision. The seams in between the panels align with the beams, which is there are very little joint visible. This cause this panel layout to be very transparent. The panels are roughly 1280-1766mm wide, and 9595-11200mm long. Although this requires the use of jumbo glass panels, which is expensive, simply due to the fact that the panels are large there are less unique panels required. This lowers overall costs and construction complexity. This was the main problem with the variants of diagonal or horizontal subdivision.

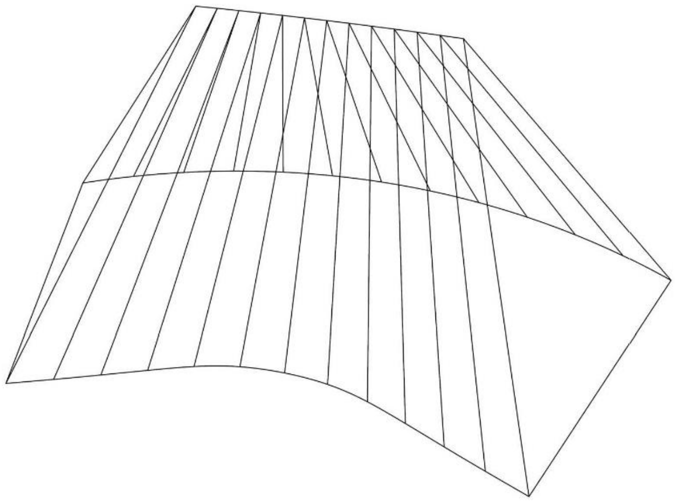


Figure 6.13 The chosen panel layout: large panels with a vertical subdivision. Source: own ill.

As can be seen in figure 6.13, the side panels are deliberately left open. Although also glass panels will be placed here, they can just be flat panels, and the grids for these panels will depend on the structure used.

For the bending of the panels there two options for doing this: warm-bending or cold bending, as described in paragraph 4.4.4.
For this project it has been chosen to use the cold bending technique. This because if the glass panels would have to be hot bend, quite a large amount of unique molds would have to be made, resulting in high costs. By cold bending the panels, flat panels can be used which are bent at the construction site. This however adds requirements to the joints which hold the glass panel into shape.

Since the topic is so complex and many variables are involved in the maximum amount of cold bending that is possible, it is therefore difficult to extrapolate the amount of cold bending which could be done with these large size panels. The amount of 40-100mm cold bending was achieved with smaller glass panels, and not with panels of these size.
In this variant, the amount of cold bending is however rather high. Figure 6.14 shows the numbering of the panels. The amount of deformation is lowest in panel 1 and 7, and increases with panel 6 and 12 the maximum.

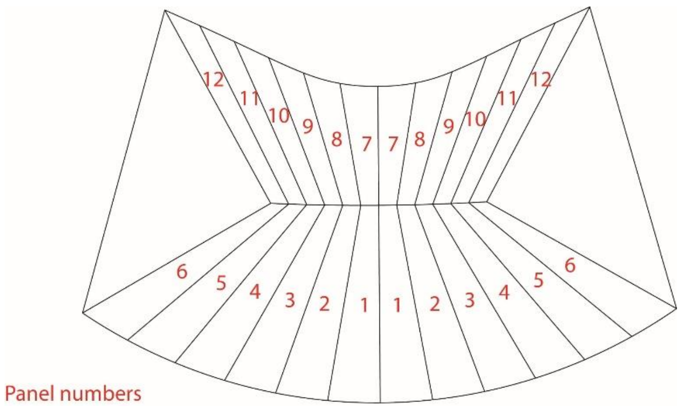


Figure 6.14 The numbering of the panels. Source: own ill.

The following table shows the deformations as done in realized projects, and the deformation in these glass panels

	Width glass panel	Length glass panel	Deformation out of plane
Town hall Alphen	900mm	2000mm	40mm
Glass roof Zuidpoort	1500mm	3000mm	100mm
Panel 7	1282 – 611 mm	9975mm	97mm
Panel 6	1949-611mm	11607 mm	885mm

Figure 6.15. Table with summary of deformations related to glass panel size. Source: own ill.

These deformations are rather large, and will likely be the biggest technical challenge in the design. The design could therefore serve as a stimulant for further research into cold bending.

6.1.5 Side surfaces roof structure

As been described in 6.1.3.2, it has been chosen not to place glass beams in the side panels of the roof. The glass beams were not necessary as a reference to the old structure here, because there are no indentations in the walls. Also, using glass beams would lead to complex detailing where the beams would meet the steel side profiles. Therefore it was chosen to go for a very different structure in the side.

6.1.5.1 The concept behind the side panels

To keep up with the important design requirements of transparency, it was chosen that the structure should be lightweight and very slender. This soon led to the use of a steel cable truss/tensegrity type structure. These structures consist out of very thin and slender components, but together can create a strong and relatively stiff structure. The steel system can also more easily be connected to the steel structure. Apart from that, this system also distinguishes itself from the glass beam system, giving an interesting combination of glass structural systems. The steel cable structure is also in a larger contrast to the old castle structure. This why the scope of options that are assessed are all steel cable trusses.

6.1.5.2 The different structure options

Several options are assessed for the side panels. The different all were cable or cable-beam trusses in different variants. Option 1 and 3 are quite alike, and are tensegrity structures. This means that all components are loaded in just in normal forces, so only in compression or tension. Since this is a very effective load transferring, as consequence members can be quite slender. The compression elements are steel rods, which at the end support a façade connection holding the glass in place. Option 2 has a steel compression profile in the top, making it a braced girder. This adds a more bulky steel profile in the top, which might be unfavorable. Option 4 uses horizontal trusses to span the sides of the roof. This however breaks up the overall grid and pattern on the roof too much. Option 5 uses more stiff steel tubular profiles as tensile element to support the truss.

In option 6 the two tensile cables of the trusses are located on the in and outside of the glass. This however makes that the structure is visible from the outside, and it disrupts the flat glass surface. Therefore option 6 may not be the most favorable option. It is however a very strong structure because the truss can be made higher, resulting in a stiffer structure with can bear higher forces.

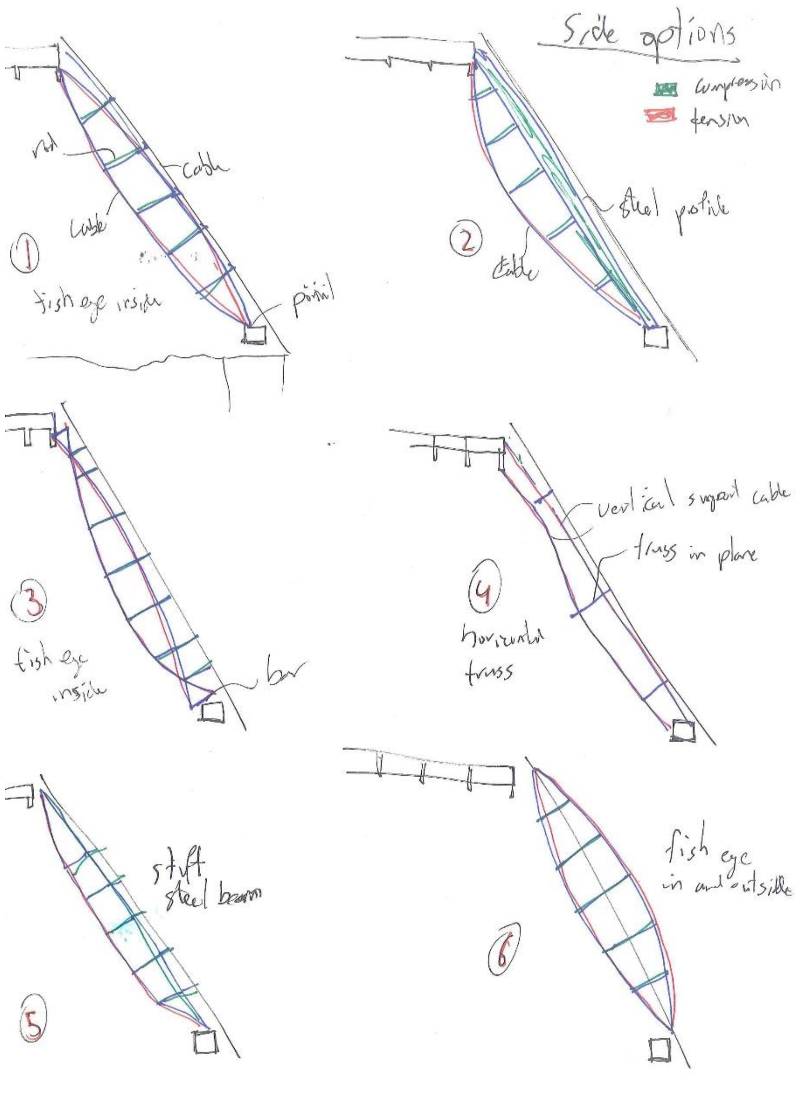


Figure 6.16 Side panel structure options. Source: own ill.

6.1.5.3 Choice of structure type

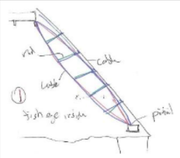
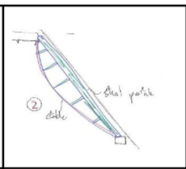
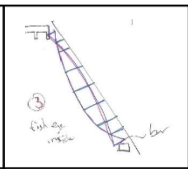
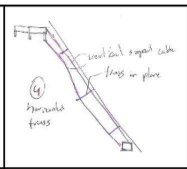
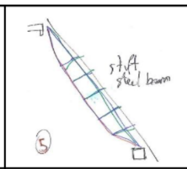
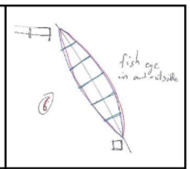
						
Transparency	+	-	+	+/-	-	+
Complexity	+	+/-	+/-	-	+	+/-
Assembly	+/-	+	+/-	-	+	+/-
Esthetical quality	+	-	+	+/-	-	-

Figure 6.17. Table of comparison of the different options. Source: own ill.

Figure 6.18 3D impression of the side trusses. Source: own ill.

Option 1 is chosen as the structure to go for. This structure seemed the most transparent and efficient structure to use. It is a steel cable truss system which acts as a tensegrity. Which means only after prestressing the cables, the structure becomes a stiff whole. The compression elements are steel solid rods, which at the end hold a joint for the supporting the glass. At the top and bottom there is a steel connection for joining the cable.
Since the total triangle surface of the roof measure 11.2 wide by 12.4 m high, the most transparent option would be to just use 3 trusses along the side. These size panels can be produced, and would be of a sensible size in terms of loading. The dimension of the trusses will later be determined in the detailing phase of the design.

6.1.6 Steel side and top profiles

The steel contour frame and the steel side and top profiles perform an important function. As explained earlier, this structure not only emphasizes the original shape and contour of the roof, but also is a key structural element of the roof. This structure gives support and acts a stabilizing element in the overall roof. The steel allows for easier connecting of the glass beams and size cable structure.

6.1.6.1 The requirements to these profiles

The profile used could however vary greatly since there are many different options in steel profiles. In the end the decision is based upon esthetical and functional requirements to these profiles.

6.1.6.2 The different profile options

6.1.6.2.1 Side profiles

For the side profiles a quick variety of options were researched. There was an interesting contradiction in the esthetical requirements of the side profiles. The profile should be big enough so that they would function as an emphasizing element of the original contour, but they should also not be too large.
An important detail was that the beam will be loaded from two different directions. This because the edge beam is supporting two different sides of the roof.
Different options have been studied, from a rectangular to a braced girder, square, triangular profile and even a glass beam. Although a rectangular profile would provide the easiest to fit profile, with a large height versus small width, this also results in a non-symmetrical stiffness. A glass beam could not be used, because a too large profile would be needed, which due to its small width would not sustain the different loading directions.

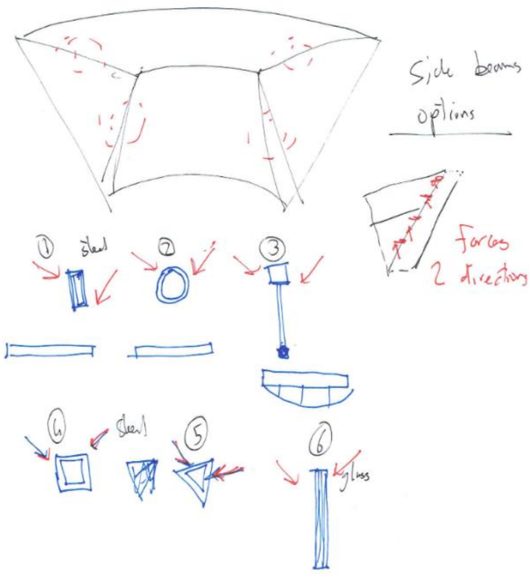


Figure 6.19 Different side profile options. Source: own ill.

6.1.6.2.2 Top profile

The decision for the steel top profile is primarily based on detailing considerations. This depended on how the beams would have been connected at the top. The beams could also have been connected directly to each other, where no need would have been for a top beam. However, further analysis showed that the steel top profile would be needed to withstand compressive forces from the two sloped triangular surfaces. Therefore, one linear element was needed. Also, the profile was needed for assembly reasons. If there would be no top profile, there would be nothing to temporarily support the beam while installing, since the opposing beam would be needed to counteract the weight. Because this would be simply too impractical, a linear element was also preferable.

Since the exact shape of the profile would follow out of the detailing design process, this would later be decided. It should however be a slender element which does not compromise the transparency of the structure.

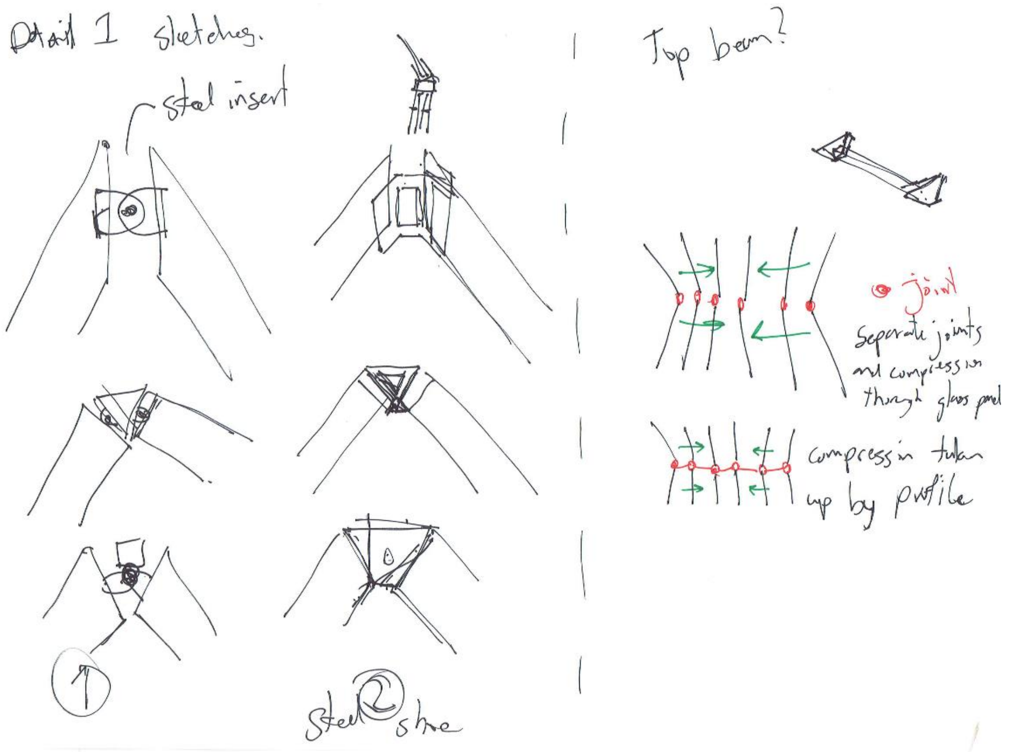


Figure 6.20 The top profile considerations. Source: own ill.

6.1.6.3 Choice of profile types

6.1.6.3.1 Side profile choice

Since these forces were not from the same direction, this eventually lead to the decision of option 2, a round tubular steel profile. This because a round section has equal strength and stiffness in all sides, in contrast to the non-symmetrical profiles. If dimensioned right, this could also lead to a rather slender profile.

6.1.6.3.2 Top profile choice

As explained, the exact shape is largely determined by the detailing, since it acts more as a linear connection element than as a mere structural beam. It should however be high but not wide, because of the sharp angles the beams come together. If the element in the top would be too large, this would lead to an bulky detail. The top profile is further elaborated on in chapter 6.3.

6.1.7 The gap between the old wall and the new structure

With the majority of the main elements discussed, one very critical element is still unexplained. With the steel contour beam placed on the wall, this leaves a rather large gap in between the old masonry wall and the steel structure. This is an interesting area and one of the more important focal points of the project: how to bring together the old with the new? The transition between the old and new should be a well-made decision, since this choice overlaps the topics of architecture, restoration philosophy, structural engineering and façade engineering.

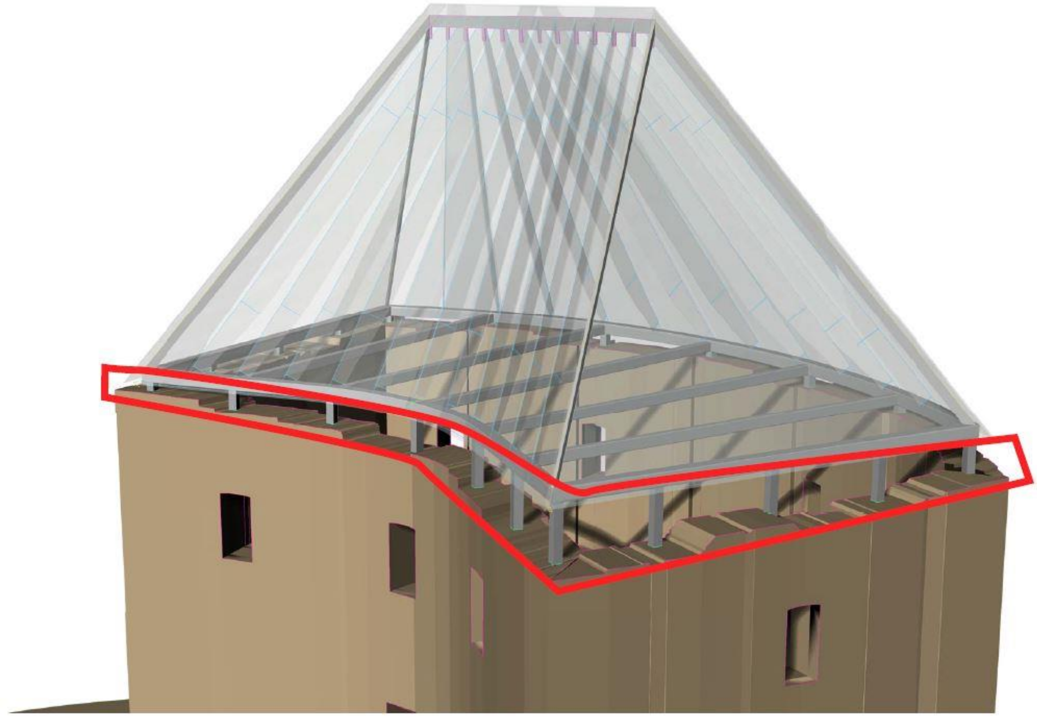


Figure 6.21 The gap in between the old and new structure. Source: own ill.

6.1.7.1 The requirements for combining old and new

Since the goal of the glass roof is to enclose and protect the ruin, so it can be refurbished, this means leaving open the gap is not an option. It would make the glass roof a very ''transparent'' intervention to the building, making it very distinguishable what is old and is new. It is however understandable if one would find the transition between old and new however rather harsh. The support legs of the contour frame are also purely functional elements, and does not have a real esthetical quality. Keeping the gap open will leave these support legs visible. Another downside to the gap is that the walls of the castle will not be protected from rainwater and wind, and is therefore not meeting the technical requirements. If the walls are not protected, the whole roof fails to achieve on of its primary practical goals.

If the gap would be closed, this addition of materials should be done carefully, since the Venice Charters are very clear about the addition of any new material to the old structure. As described previously the addition of material is however inevitable, for it to meet the technical requirements of the roof. An integral solution should then be found, combining architectural with technical requirements.

6.1.7.2 Materialization options for gap

Various options are researched into what would be a befitting way to enclose the gap. These options are illustrated in the following images.

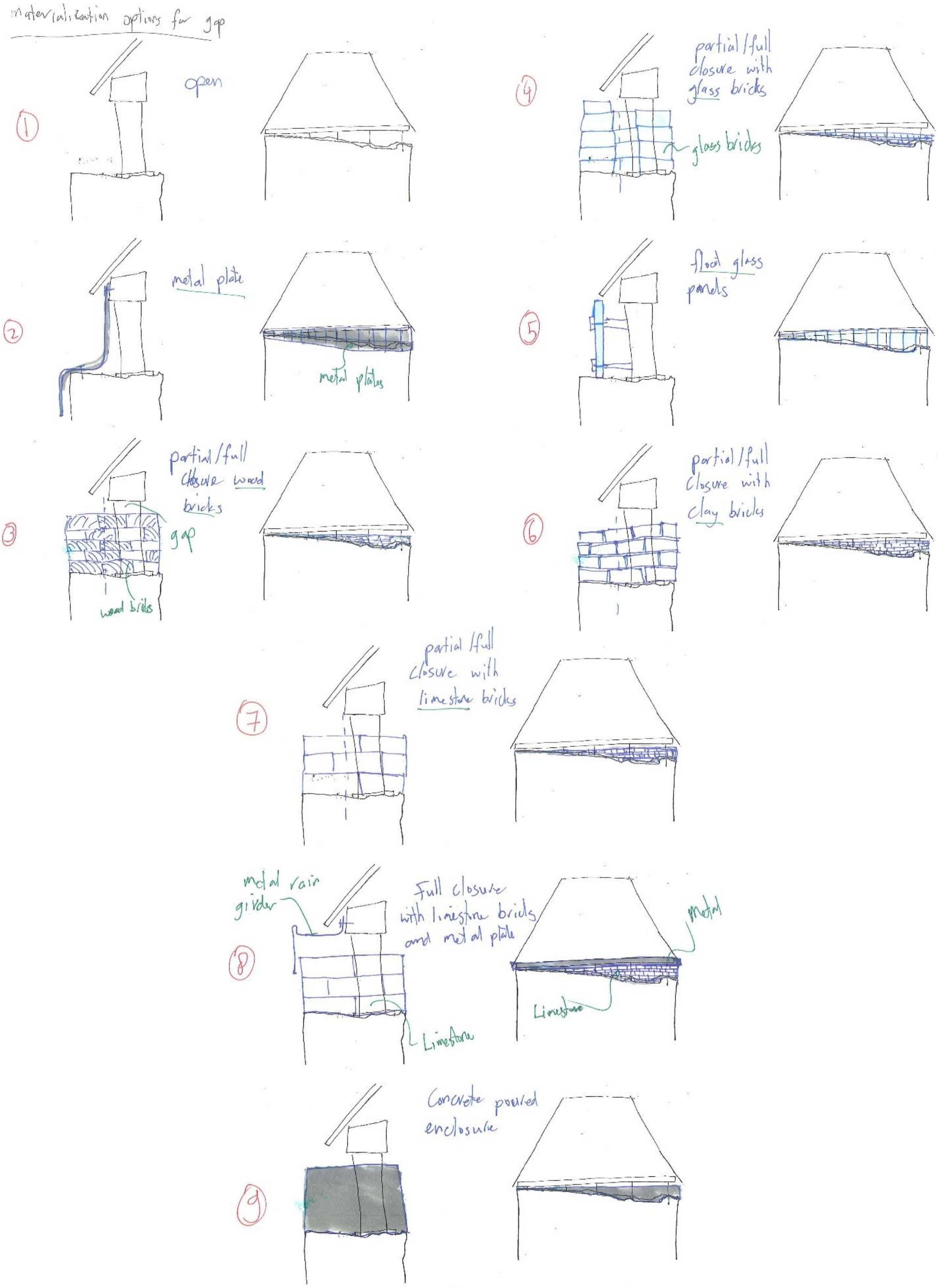


Figure 6.22 Materialization options for filling the gap. Source: own ill.

In these nine options a variety of materials, texture and component shapes are reviewed. Leaving the gap open as option 1 is already discussed. Option 2 is a metal plate which covers up the gap. Option 3 uses wood bricks to either fully or partially close the gap up, with wood being a very distinguishable material compared to the old structure. Option 4 proposes using glass bricks, staying in the mindset of adding glass as new material to the old structure. Option 5 uses flat float glass panels to close the gap. Option 6 proposes a partial/full closure with clay bricks. This option is more a material that more focusses on integration in the old instead of being very distinguishable. The right type of clay brick is however crucial for this solution to be appropriate. Option 7 uses a lime stone brick instead of clay as an slight variation on option 6, to add more distinguishability but staying in the mindset of using a more traditional building block to create more integration. In option 8 a combination is made of materials, essentially combining option 2 with the metal plate and 7 as with the limestone bricks. In option 9 the gap is closed by a concrete poured enclosure, being very distinguishable but likely less integrating.

6.1.7.3 Choice of materialization

	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6	Option 7	Option 8	Option 9
Visual integration	-	-	+/-	-	-	+	+	+	-
Assembly	-	+/-	+/-	-	+/-	+/-	+/-	+	-
Controlling climate	-	-	+/-	-	+/-	-	-	+	-
Reversibility	+	+	+	-	+/-	+/-	+/-	+/-	-

Figure 6.23 Summary of scores on each option. Source: own ill.

In figure 6.23 a list of scores was made to illustrate the decision process. Keeping in mind the combination of architectural and technical requirements, it was chosen to go for the concept of option 8. However, instead of using limestone, the clay brick is used in combination with the metal plate. This is because a clay brick would be durable than the soft limestone and more resistant against corrosion of the humid climate in the Netherlands. Choosing for a combination of the clay brick and metal (zinc or stainless steel) a gentle visual transition is created between the old and new material, while at the same time the old wall is protected by new masonry and made watertight by the metal plate. The metal plate will consist of zinc or stainless steel, and will be shaped as a traditional rain girder, being a reference to the original girder that was there.

The choice for the type of clay brick is crucial for the visual integration and distinguishability of the old and new masonry, as well as differences in material properties. Using the wrong type of mortar or brick could even do damage to the old masonry (Van Hees, 2004), which as the Venice Charter state, should be prevented at all cost. Within the scope of this research, no elaboration on the exact type of masonry will be done.

6.2 Structural validation through calculations

As part of the design process, structural calculations have been made to check the structural performance of the different components, and to obtain the required dimensions for the components of the roof design. These calculations were mostly made in Microsoft excel because for calculating the majority of these components there were no unknown variables. Some simplifications had to be made in order to able to calculate them properly by hand, which will be clarified later on.

6.2.1 Safety analysis

When designing with glass as a structural material, safety is of paramount importance. Where concrete cracks and steel yields, glass is a material that shows no warning signs when it reaches its maximum load state. It suddenly breaks, and if just a single pane is glass is used, the material loses al its structural strength. This could cause structures to collapse dramatically. Because of this, safety measures have to be taken in order to first of all minimize the probability of total failure of the structure, and secondly minimize the consequences of complete failure.

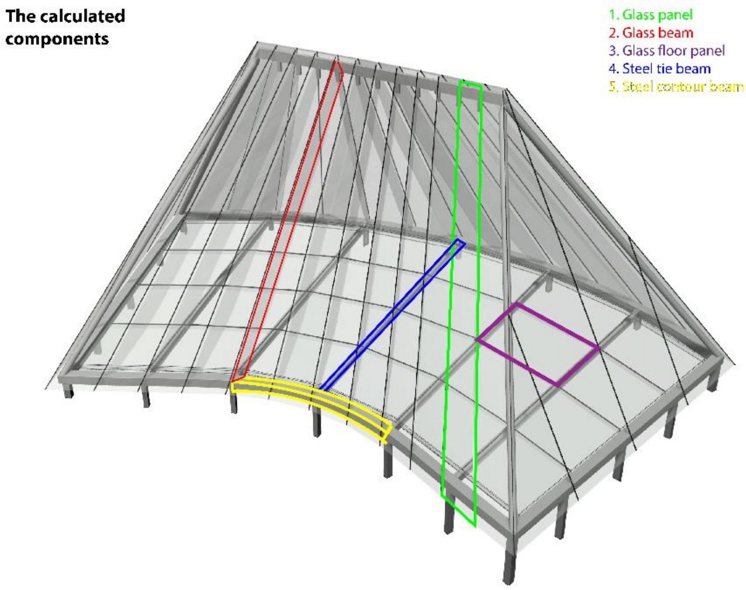


Figure 6.24 The calculated components of the roof. Source: own ill.

Minimizing the consequences of failure is done by heat treating the glass panels, and laminating several layers together with a sentry glass foil to create one solid structural member. This will be further explained in the next chapter. In order to minimize the probability of the complete failure, safety assumptions are made in the structural calculations of the components.

The risk involved in the failure of a structure can be quantified with a certain RD-value. This RD value gives a certain number, and based on the amount of risk as calculated, certain safety measures can be taken in terms of the design or ways how to calculate the structure. The RD-formula is as following(ABT, 2013):

$$RD = Probability \times Exposure \times Consequence\ at\ complete\ failure$$

The glass roof will be located on top of the castle, and once installed no heavy machines can access the roof. The roof will serve as a viewing post for pedestrians, so only persons can enter the roof. This means that the probability is very low, since persons will not likely physically be able to damage the structure in such a way that it will result in a failure of the element. It is however likely daily open and therefore exposed every day. In case a glass beam or panel would however completely fail, this would be a catastrophe and cause many deaths because of the possible high amount of visitors in the castle.

Consequently, with for the glass beams and glass panels a probability of 0,2 (practically impossible), the exposure of 6 (daily) and the consequences at complete failure 100 (catastrophe, many deaths) they both reach a RD value of 120.

Based on this calculation it was chosen to assume in the calculations that one of the laminated glass layers is always broken, and that the forces have to be taken up by the remaining panes of glass. This will be explained later.

6.2.2 Glass panel

The glass panels are one of the most complex geometrical elements of the total roof design. As described earlier, in order for the panels to follow the curvature of the roof nicely, they will need to be twisted along its length. This will induce a certain amount of shear stress in glass panel. Next to that, the panels are also loaded by wind load inducing bending stresses. These stresses combined should not the exceed the maximum amount of stress allowable in the glass in order to prevent failure. Since it was quite complex to make FEM calculations of the stress induced by cold bending the glass, it was chosen to just make a hand calculation for a rough estimation of the stresses induced. Making exact FEM calculations were not in the scope of this research, and is therefore left out.

6.2.2.1 Schematization

6.2.2.1.1 Wind loading

For the wind load the glass panel is first assumed to be a flat panel. Since panels at the other contour are larger, but all these panels are of equal width, just any panel could be taken from that side. However since also the shear stresses due to torsion will be calculated, the panel with the most axial rotation is taken. This is the panel closest to the side of the roof, which is the most heavily loaded panel. Schematizations for the roof give the following images.

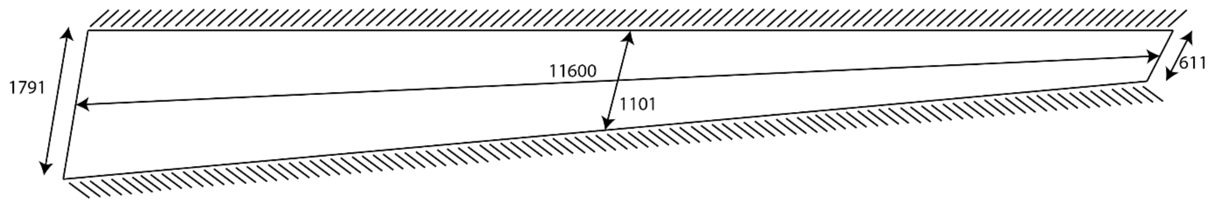


Figure 6.25. The total size of the panel. The two long edge are connected with clamped connections. Source: own ill.

Because the panel is so long, if the sand hill method is used, it is clear that forces just from one side to the other side.

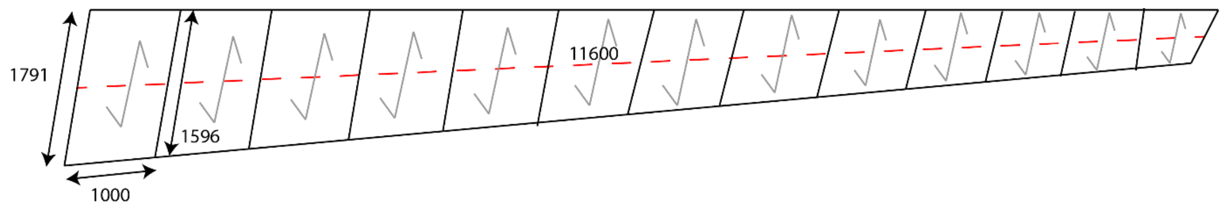


Figure 6.26. The sand hill method showing how the panel will distribute its forces to the supporting structure. Source: own ill.

Of these ''panels'' the one is chosen with the largest span, which is at the bottom. Here there average span is:

$$1791 + 1596 / 2 \ = \ 1693.5 \, mm.$$

For the width of the panel 1000mm is chosen. This results in the following panel dimensions that is used for the calculation. The panel will now start to act as a beam and can therefore also be calculated as one.

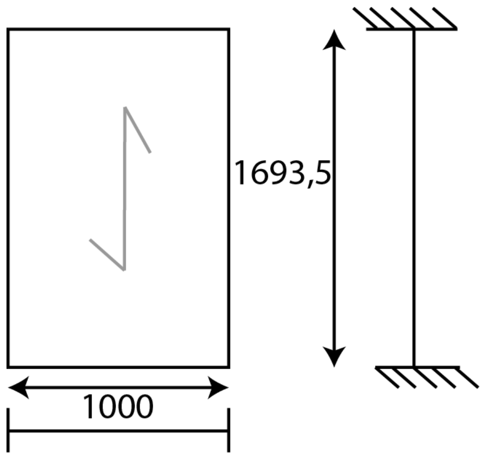


Figure 6.27 This is panel that is calculated in excel. The panel is clamped at top and bottom side. Source: own ill.

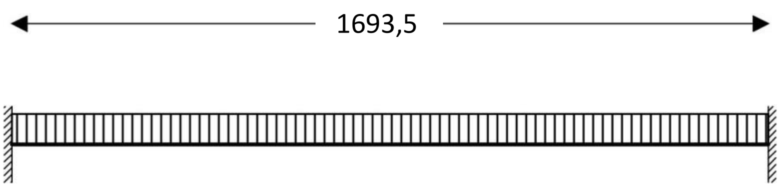


Figure 6.28 This image shows the schematization of the panel with its load, consisting of wind loads and deadweight. Source: own ill.

6.2.2.1.2 Twisting of the panel

For the calculation of the panel a few important measurements have the taken. This was done using Rhinoceros, a 3d modelling software which held a model of the entire roof design. Using this software, the relative angle between the top and bottom edge of the glass panel could be measured, together with width and length of the panel.

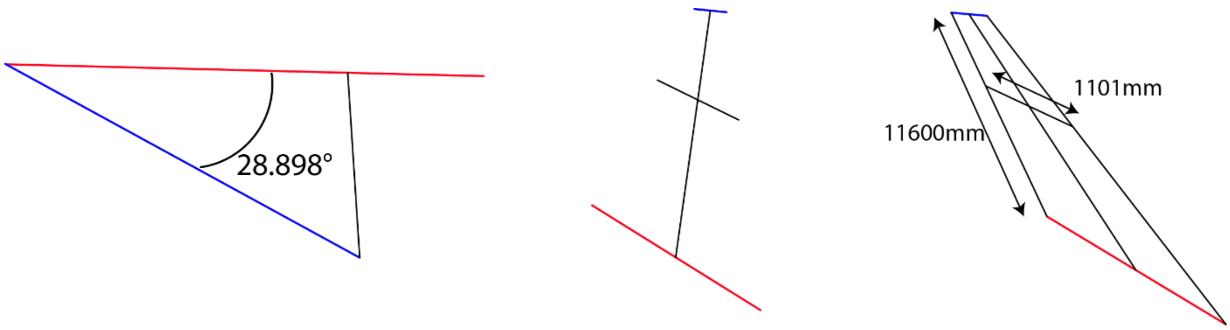


Figure 6.29 The angle of twisting along the length of the panel between the top side (blue) and the bottom side (red). Source: own ill.

6.2.2.2 Load case

Because the roof panels are under such a high pitch of 53 to 66 degrees (see fig 3.26), the roof cannot be walked on and also no snow can build up on the roof. This removes the necessity to calculate with snow loads and live loads induced by people. The permanent load case on the glass panel will consist of the deadweight. The live load of the roof consists of wind loading. The value of wind loading is calculated using values retrieved from the Civil Engineering Quick Reference(Section Structural and Building Engineering, 2014). This will result in a distributed load across the entire plate, as illustrated in figure 6.28. For the distributed load a safety factor of 1.5 is considered, for the permanent load a factor of 1.2. As a CC3 consequence class, they are both multiplied with a KFi of 1,1.

6.2.2.3 Section properties

As explained earlier, due to safety measure the panel will be calculated as if one panel will be broken. The remaining panels have to be able to carry all loads after it has been damaged. The calculation was done with a total section profile of 3 layers of 10mm glass. Due to safety measure this means that the structural section consist of 2 panes of glass instead of 3, but with the deadweight of 3 glass panes. The thickness of the glass panes is the variable parameter in this calculation.

To calculate the second moment area the following formula applies:

$$I = {}^{1}/_{12} * b * h^3$$

I= second moment area
b= width of section
h= height of section

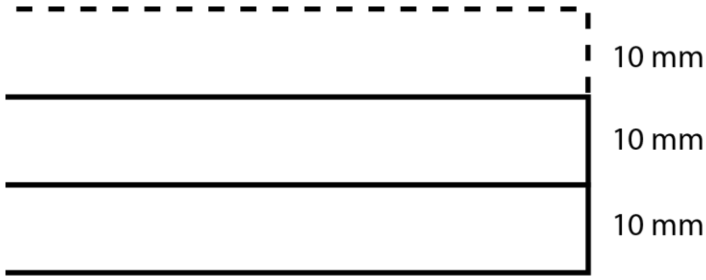


Figure 6.30 The section of the glass panel. Source: own ill.

6.2.2.4 Formulas

6.2.2.4.1 Wind loading

The maximum moment and deflection can be calculated using the formulas described in figure 6.31-6.32. With the maximum moment, the stresses can be calculated using the following formula(Hartsuijker, 2012):

$$\sigma_m = \frac{M * z}{I}$$

σ_m = bending stress
M = maximum moment
z = distance to neutral line
I = second moment of area

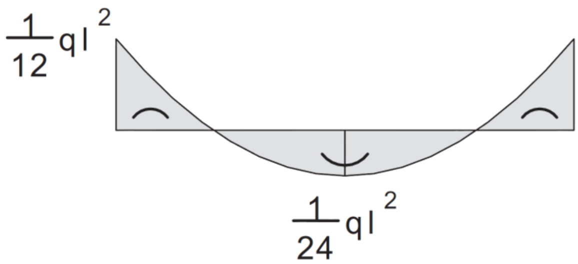


Figure 6.31 The maximum bending moment of a clamped beam

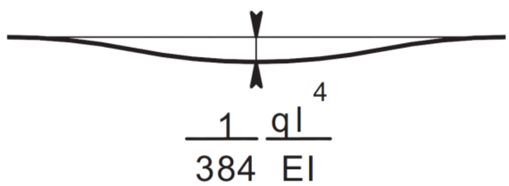


Figure 6.32. The maximum deflection of a clamped beam

6.2.2.4.2 Twisting of the panels

As explained earlier, the stresses caused by twisting the panel is more difficult to calculate. To make a rough approximation of the stresses caused by twisting the panel, the general formulas are used for torsion of noncircular prismatic shafts(Goodno & Gere, 2012).

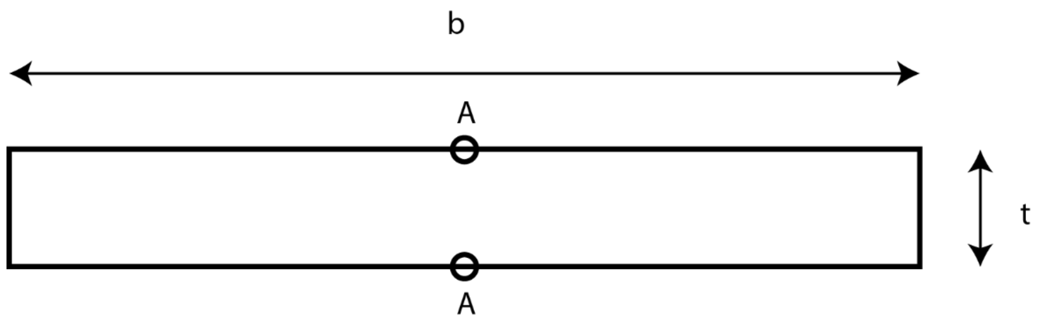


Figure 6.33 Calculation of maximum shear stress at point A in section with width b and thickness t. Source: (Goodno & Gere, 2012)

Here the maximum shear stress at point A in the surface is calculated using the following formula:

$$\tau = \frac{T}{k_1 * b * t^2}$$

Where $$T = \frac{\theta * G * J_r}{L}$$

Where $$G = \frac{E}{2(1+\epsilon)}$$

and $$J_r = k_2 * b * t^3$$

τ	= Maximum shear stress at point A in section
T	= Torsional moment
G	= Torsional rigidity
θ	= angle of twist between bottom and top part
L	= Length of panel
b	= width of section
t	= thickness of panel
ϵ	= poisson ratio
E	= Young's modulus of glass
Jr	= torsion constant
k_1	= dimensionless coefficient = 0,333
k_2	= dimensionless coefficient = 0,333

With these formulas for each panel the stresses as consequence of cold bending the panels can be calculated.

6.2.2.5 Calculation

For the calculation a excel sheet is made to calculate and optimize the design. This complete calculation can be seen in Appendix A.1. The thickness of the glass and the amount of panes are the parameter. This property has been optimized to be the thinnest possible, as this will result in the least amount of weight for the entire structure. The results of the calculation are compared to the limit state check:

Maximum deflection	W	= 0,004 * length of span = 6,2mm
Maximum bending stress	σ_m	= 40 N/mm^2
Maximum shear stress	τ	= 40 N/mm^2

6.2.2.6 Conclusions of calculation and results for design

Thickness	10mm	I	666667 mm^4	M	477779 Nmm
Length	1693,5mm	Dead load	0,72 kN/m2	σm	7,17 N/mm2
E	70000 Mpa	Live load	1,386 kN/m2	W	0,79 mm
Amount of panels	3	Total safety factors	2,34kN/m2	τ	37,58 N/mm2
Angle rotation	28,89	q-load	2,3 N/mm	Total stress	44,74 N/mm2

Figure 6.34 A summary of input and input out the calculation results. Source: own ill.

In figure 6.34 a summary can be found of the most important input and output of the calculation. An interesting conclusion can be drawn out from this. During the optimization of the thickness and interesting contradiction was discovered. Regarding the bending stresses induced by wind loads it was found that increasing the thickness of the panel, the bending stresses would lower. This is of course logical when looking at the formulas for calculating the bending stresses. Increasing the thickness increases the second moment area I, and therefore reduces the bending stresses. However it was found that when the thickness of the panel increases, also the shear stresses by torsion increases. This also makes sense, looking at the formulas for torsion. A thicker and wider section increases the torsional rigidity and thereby the torsional moment to bend that section up to the same rotational twist.

This however means there is an optimized thickness that is not too thick nor too thin where the total amount of stress in section as combination of bending and torsion is lowest.

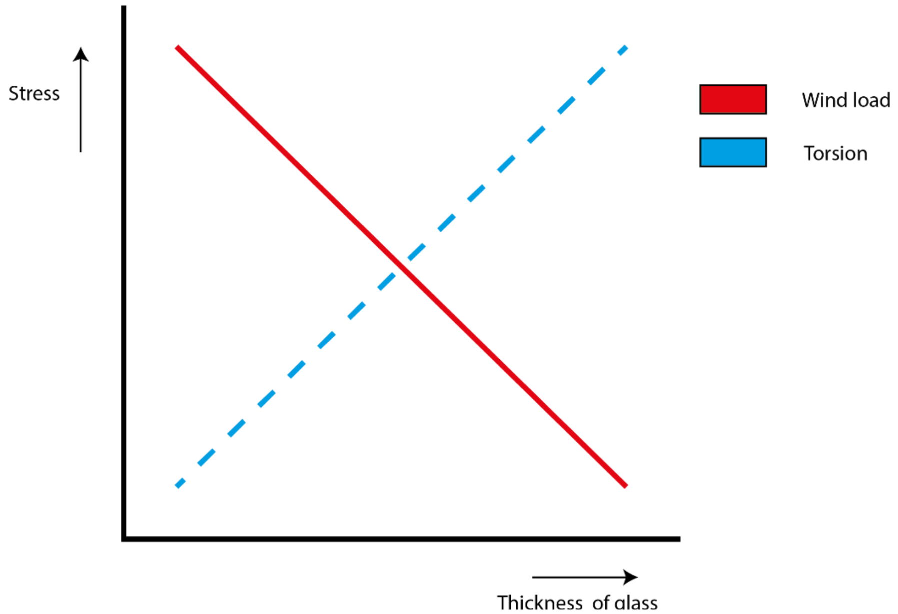


Figure 6.35 The contradiction of stresses in relation to thickness of the glass. Source: own ill.

This resulted in the choice of using 3 layers of 10mm glass. In this way the maximum total stress proved to be 45,95 N/mm2. Just slightly above the calculation values of heat-strengthened. The 2 outer layers of the panel could be executed in fully-tempered glass with the inner panel of heat-strengthened glass, to provide a good combination between high strength at the edge of the section, whilst providing a safe panel upon breaking.

It should however be noted that the calculation for the shear stress due to torsion is very rough, and assumes an even distribution of curvature along the panels length. In reality this is however not true, so that is why the calculation is just an approximation. It is chosen not to further elaborate on this, since this is not the scope of this research. The calculation shows that for the heaviest bend panel the stresses are however likely within a manageable reach. It also shows that the torsion induced the majority of the stresses on the glass panel, and wind loading is roughly only using 25 % of the stress capacity of the material. Cold bending is an intensive process for deforming the material.

6.2.2 Glass beam

One of the major structural loadbearing elements in the roof, are the 22 glass beams. These beams consist of several laminated heat-treated layers of glass. Due to the curvature of the roof, each beam is of a different length. The roof is however symmetrical which means that beams on opposite side of the symmetrical axis have the same length. The beams are all under an angle, which also changes depending on its position in the roof design. Due to the difference in length and angle, the calculation for each beam is unique. Because of the high pitch of the roof there no need to take into account snow load and variable loads by people walking on the roof. This saves a lot in the total loading on the roof, allowing for more slender beams, which is beneficial for the overall transparency of the roof.
To further increase transparency, it was chosen to make optimized calculations for each unique beam. This means every beam is only given the height it is required based on structural calculations. For the explanation of the calculation, the longest beam is chosen to show the principal of the calculation.

6.2.2.1 Schematization

In figure 6.36 a scheme can be seen of the beam. This particular beam had a length of 11238mm and is under an angle of 50,9 °.
The connections at the end are hinged connections, with the top being a roll bearing to allow for thermal expansions.
On this beam two adjacent glass panels are resting, which can be seen in figure 6.37. The two panels have a different length and taper towards the top. That is why in order to calculate the resting area in m^2 the average width and length is calculated to translate this tapered shape into a square.

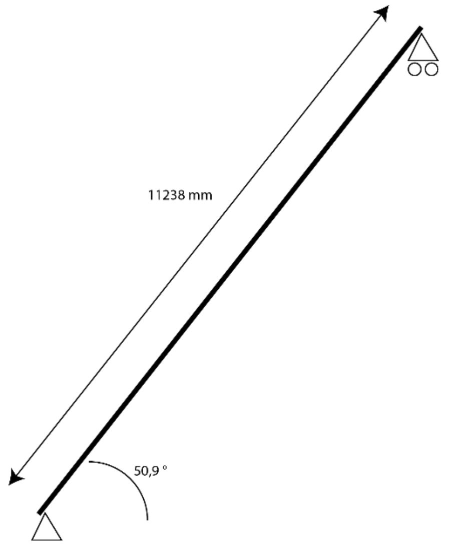


Figure 6.36 The schematization of the beam. Source: own ill.

$$A = L * B$$

$$A = \left(\frac{\left(\frac{11607 + 11525}{2}\right)}{1000}\right) * \left(\frac{\left(\frac{1791 + 611}{2}\right)}{1000}\right) = 13,89\ m^2$$

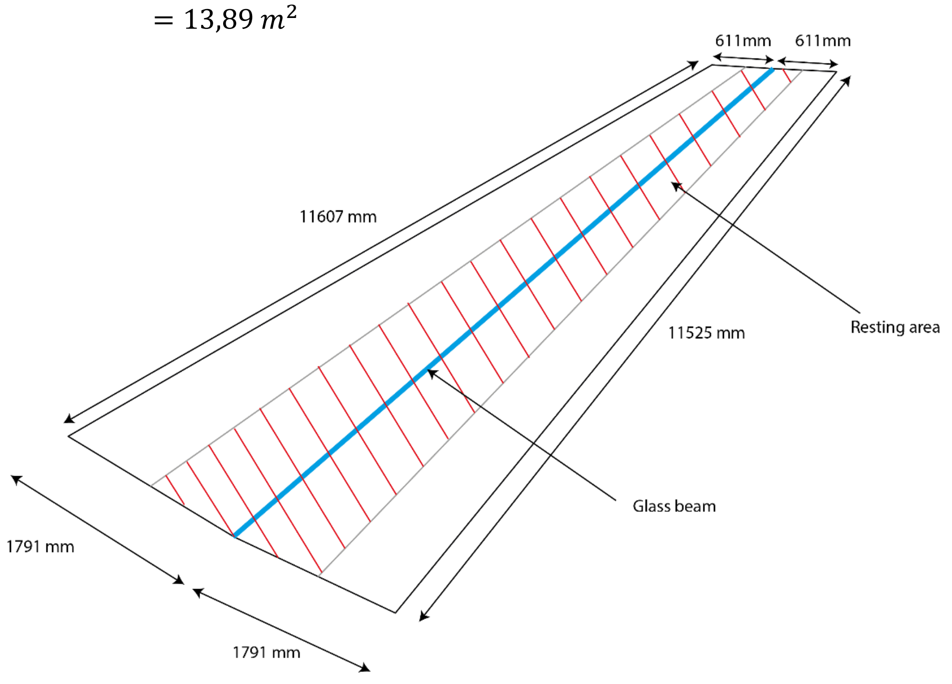


Figure 6.37 The resting area on the beam. Source: own ill.

6.2.2.2 Load case

The three loads cases on the glass beam are:
LC1 = Dead load of self-weight of glass beam
LC2 = Dead load of resting weight of glass panel
LC3 = Wind loads

The dead loads are always applied in the global Z direction, which means they are applied on the roof panel under an angle. Wind loading is applied perpendicular to the beam. This gives the following load combination on the beam.

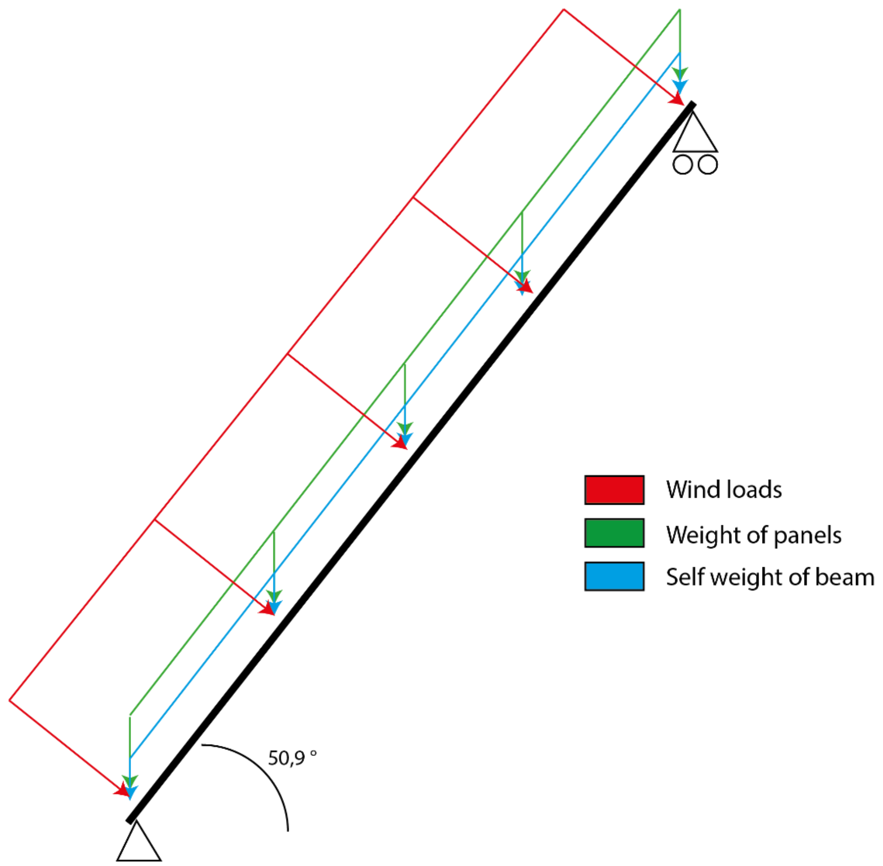


Figure 6.38 Loads on the beam. Source: own ill.

Because the hand calculation cannot directly account for loads that are applied under an angle to the beam, the dead loads have to translated into values that do apply perpendicular to the panel. Figure 6.38 shows the decomposition of the angled force on the beam, showing the components perpendicular and parallel to the beam. The force perpendicular to the beam is the value that is used in the hand calculations as loading. For the wind loads a safety factor of 1.5 is considered, for the permanent loads a factor of 1.2. As a CC3 consequence class, they are both multiplied with a KFi of 1,1.

This can be calculated as:

$$\cos \alpha = \frac{F_{perp}}{F_{resultant}}$$

$$F_{perp} = \cos^{-1} \alpha * F_{resultant}$$

As every beam has a different angle, this value changes for every beam. This is also applied in the hand calculations.

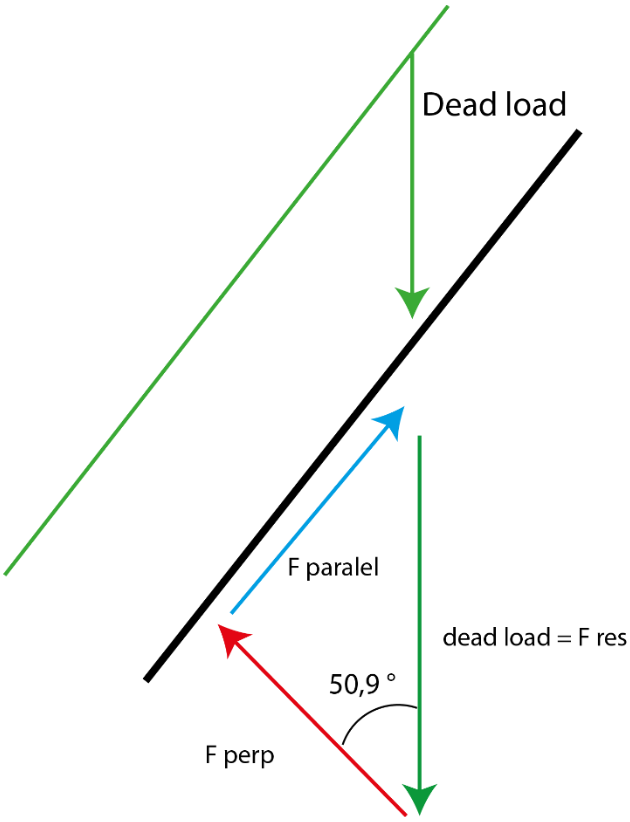


Figure 6.39 Components of angle force on the beam. Source: own ill.

6.2.2.2 Section properties

The section of the beam consists of several layers. Regarding the safety measurements to reduce failure probability, the second moment area is calculated as if one layer is always broken. As a starting point, four layers of 10mm glass are assumed to be in the section, as can be seen in figure 6.40.

$$I = {}^{1}/_{12} * b * h^3$$

I= second moment area
b= width of section
h= height of section

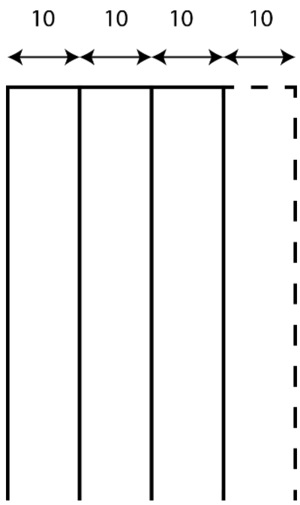


Figure 6.40. Section of the beam. Source: own ill.

6.2.2.3 Formulas

The maximum moment, shear forces and deflection can be calculated using the formulas described in figure 6.41-6.43. With the maximum moment, the stresses can be calculated using the following formula(Hartsuijker, 2012):

$$\sigma_m = \frac{M * z}{I}$$

σ_m = bending stress
M = maximum moment
z = distance to neutral line
I = second moment of area

$$\tau = \frac{V * S}{I * b}$$

τ = shear stress
V = maximum shear force
S = first moment of area
I = second moment of area
B = width of section

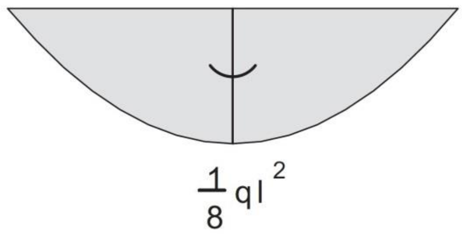


Figure 6.41 Maximum moment distributed load

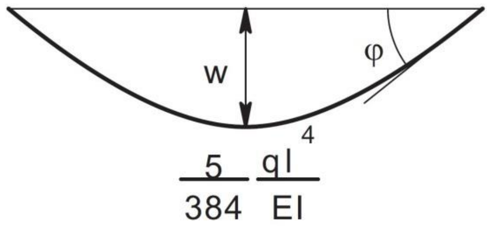


Figure 6.42 Deflection distributed load

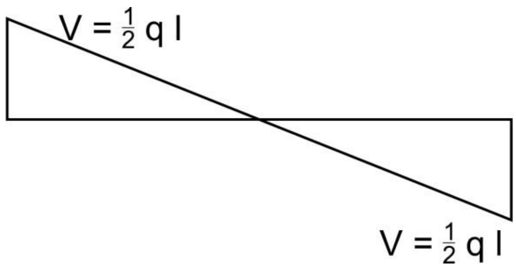


Figure 6.43 Maximum shear force distributed load

6.2.2.4 Calculation

An excel tool is made to calculate and optimize the design variables: the thickness of the glass panes and the height of the beam. The beam is optimized to use the least material possible within the design (Appendix A.2). The results of the calculation are compared to the limit states:

Deflection	W	= 0,004 * length of span = 46,3mm
Bending stress	σ_m	= 40 N/mm^2
Shear stress	τ	= 40 N/mm^2

For this particular beam this resulted in the following summarized inputs and outputs.

Thickness	10mm	I	285210312,5 mm^4	M	46353239 Nmm
Length	11566 mm	Dead load	0,29 kN/m	σm	39,41 N/mm2
E	70000 Mpa	Live load	0,54 kN/m	W	32,4 mm
Amount of panels	4	q-load safety factor	2,77 N/mm	τ	6,61 N/mm2
Angle rotation	50,9°				

Figure 6.44 Summary of most important input and output of calculation. Source: own ill.

In this case the bending stresses in the beam are the structural limiting factor. With a thickness of 4x10mm glass panes and a height of 485 mm the structure will remain safe.

As explained earlier, for every beam this calculation was done. This resulted in optimized beam heights that were not larger than they needed to be. The beams were numbered, to explain more clearly where each beam is located in the roof design. The results of these calculations are shown below.

Beam	Length	Angle	Width bottom	Width top	Avg width	**Min Beam height**	Width	Minimal manufacturing height	Rounded
1	10960	52,7	1791,0	611,0	1201,0	465	40	548,0	550
2	10970	52,6	1791,0	611,0	1201,0	470	40	548,5	550
3	11000	52,4	1791,0	611,0	1201,0	470	40	550,0	550
4	11052	52,1	1791,0	611,0	1201,0	475	40	552,6	550
5	11130	51,6	1791,0	611,0	1201,0	480	40	556,5	550
6	11238	50,9	1791,0	611,0	1201,0	485	40	561,9	560
7	9594	65,4	1277,1	611,0	944,0	330	40	479,7	480
8	9662	64,5	1276,2	611,0	943,6	335	40	483,1	480
9	9879	62,0	1277,6	611,0	944,3	350	40	494,0	490
10	10206	58,7	1278,5	611,0	944,7	365	40	510,3	510
11	10588	55,4	1278,5	611,0	944,8	390	40	529,4	530
12	11002	52,4	1278,5	611,0	944,8	410	40	550,1	550

Figure 6.45 The optimization of the beams. It shows for each beam the minimal structure height needed. Source: own ill.

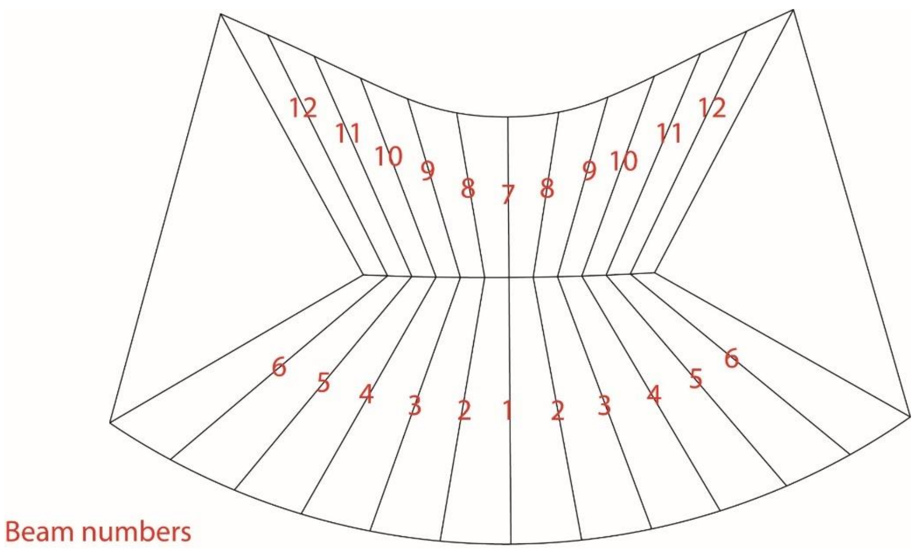


Figure 6.46. The position of each beam in the roof design. Source: own ill.

After a consultancy with an glass expert from the company Octatube(Octatube, 2016), information was given that there is a limit to the length/width ratio that is possible to manufacture glass panes in. According to the expert, this ratio should not be lower than 1/20. If the panels would be lower than that, the chance of warping during the heat-treating process is very high. With this new rule in mind, the minimum required height is calculated based on each beam's length. This result is shown in the ''minimal manufacturing height'' column.

6.6.2.6 Conclusions of calculation and results for design

The structural calculation was done for each beam to optimize the height and thickness needed. However the manufacturing limitation proved to be guiding. Therefore every beam has to be made higher than is structurally needed. Each beam still has a different height to optimize transparency and slenderness. This results in slightly higher material cost, but the upside of this is extra safety. The beams are now only loaded up to 60% of their maximum capacity. And with a length-height ratio of 1/20 the glass beam still make up for very slender transparent elements. In the end this resulted in the use of beam of 480-560mm high, with a thickness of 4x10mm glass panels, using heat-strengthened glass.

6.2.3 Glass floor panel

In between the steel tie beams of the steel structure, glass floor panels are placed. In between the steel beams there are glass support beams, to reduce the span of the glass. By using glass floors the building below will have a lot of daylight passing in. These floors also allow guests to stand inside the structure and to enjoy the view of the surrounding park, as explained in chapter 3.1.1.5. The glass floors however should be calculated for dimensions.

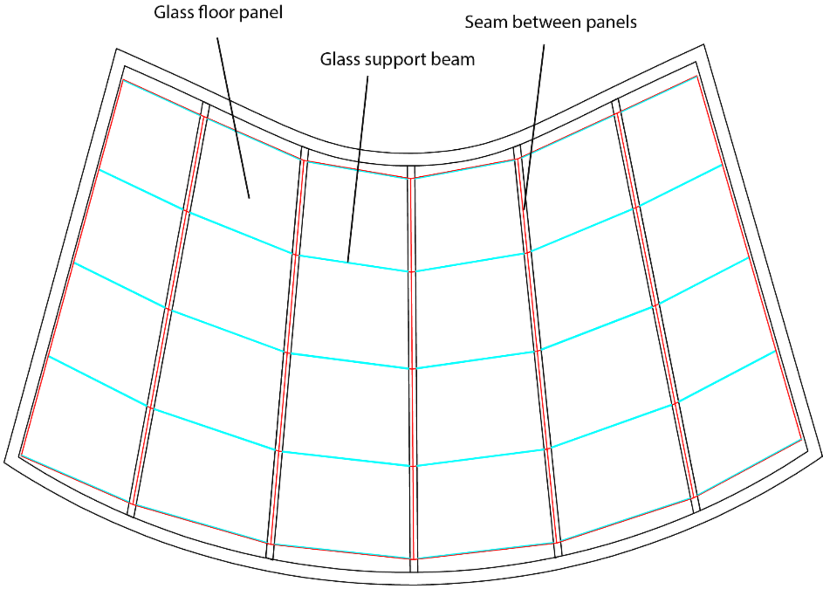


Figure. 6.47 Total view of the glass floors. Source: own ill.

6.2.3.1 Schematization

The floors are supported on four edges. Two sides rest on the steel tie beam, and two sides rest on the glass support beams. For this calculation the biggest panel is chosen, which is the panel at the outer side of the building. Due to the bigger radius this is where the panel is largest. This results in a total panel of 3380 by 2299mm. The panel will consist of several layers of laminated glass.

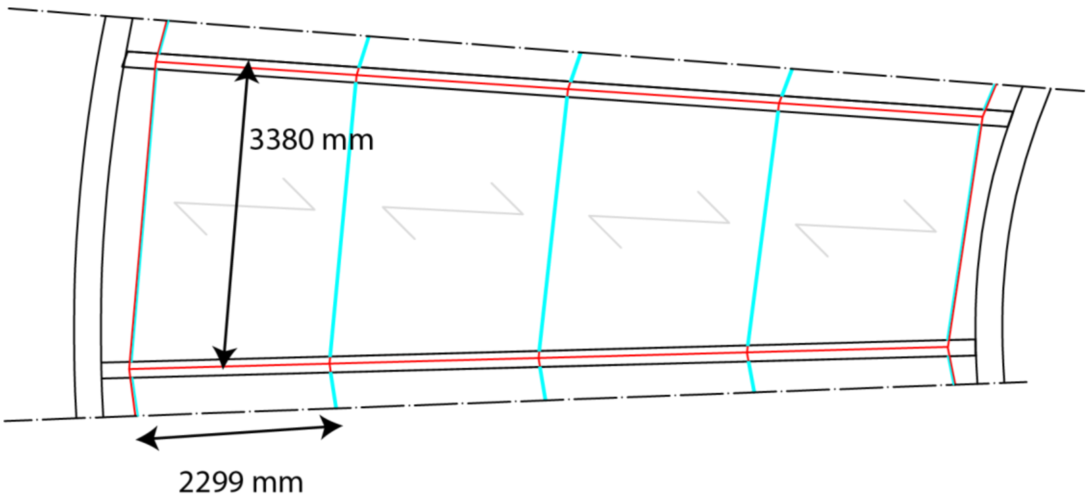


Figure 6.48 Section of the glass roof panels. The panels span from glass support beam to beam. Source: own ill.

As can be seen in in the figure 6.49 below, the sand hill method is used to determine where the forces flow to. Because the panel is supported on four edges, near the corner of the panels the forces will flow towards 3 sides. In the middle the panel however only redirects forces towards 2 sides and starts to behave like a beam. Since the biggest moments and bending occurs in this region, this part can now be calculated as if it were a beam.

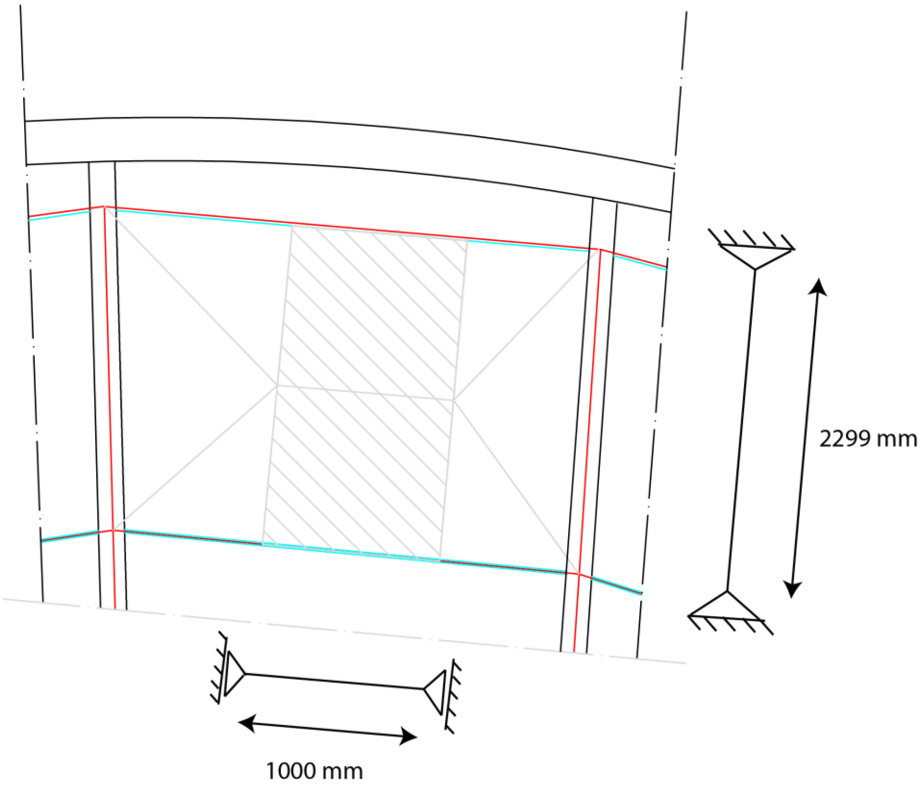


Figure 6.49 The Sandhill method for defining the transfer of loads to the sides. Source: own ill.

6.2.3.2 Load case

The two loads cases on the glass panel are dead load of self-weight of glass beam, and the live loads of people standing on the glass.
Both these load cases are applied perpendicular to the 'beam'. This results in the follow load case as seen in figure 6.50. The live loads are determined from the Quick Reference (Section Structural and Building Engineering, 2014). For the live loads a safety factor of 1.5 is considered, for the permanent load a factor of 1.2. As a CC3 consequence class, they are both multiplied with a KFi of 1,1.

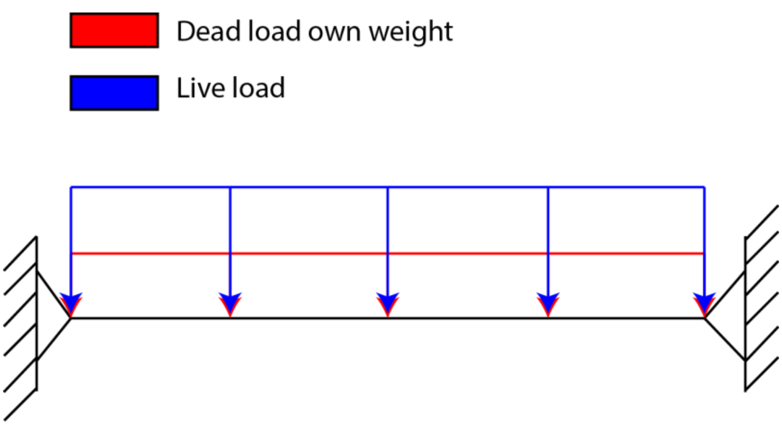


Figure 6.50 Loads on the beam. Source: own ill.

6.2.3.3 Section properties

As explained earlier, due to safety measure the panel will be calculated as if one panel will be broken. The remaining panels have to be able to carry all loads after it has been damaged. The calculation was done with a total section profile of 3 layers of 10mm glass. Due to safety measure this means that the structural section consist of 2 panes of glass instead of 3, but with the deadweight of 3 glass panes. The thickness of the glass panes is the variable parameter in this calculation.

To calculate the second moment area the following formula applies:

$$I = {}^{1}/_{12} * b * h^3$$

I= second moment area
b= width of section
h= height of section

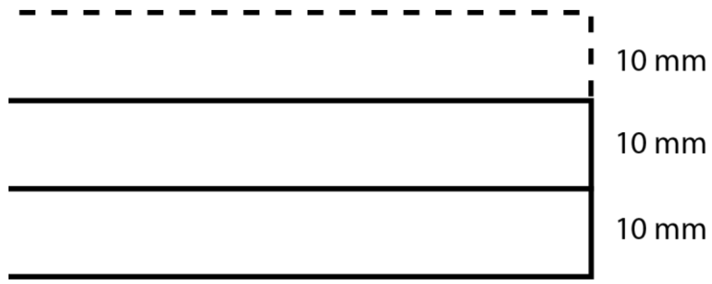


Figure 6.51 The section of the glass panel. Source: own ill.

6.2.3.4 Formulas

The maximum moment and deflection can be calculated using the formulas described in figure 6.52-6.53. With the maximum moment, the stresses can be calculated using the following formula(Hartsuijker, 2012):

$$\sigma_m = \frac{M * z}{I}$$

σ_m	= bending stress
M	= maximum moment
z	= distance to neutral line
I	= second moment of area

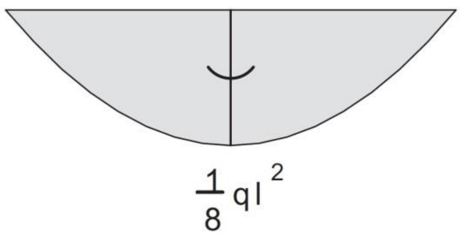


Figure 6.52 Maximum moment distributed load

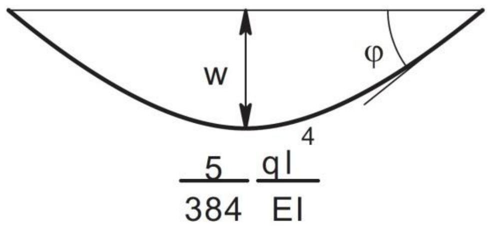


Figure 6.53 Deflection distributed load

6.2.3.5 Calculation

For the calculation a excel sheet is made to calculate and optimize the design. This complete calculation can be seen in Appendix A.3. The thickness of the glass is the parameter. This property has been optimized to be the thinnest possible, as this will result in the least amount of weight for the entire structure. The results of the calculation are compared to the limit state check:

Maximum deflection	W	= 0,004 * length of span = 9,196mm
Maximum bending stress	σ_m	= 40 N/mm^2
Maximum shear stress	τ	= 40 N/mm^2

6.2.3.6 Conclusions of calculation and results for design

Below are the most important inputs and outputs of the calculation.

Thickness	10mm	I	666667 mm^4	M	2235460 Nmm
Length	2299 mm	Dead load	0,72 kN/m2	σm	33,53 N/mm2
E	70000 Mpa	Live load	2,5 kN/m2	W	7,91 mm
Amount of panels	3	Total safety factors	5,08kN/m2		
		q-load N/mm	5,1		

Figure 6.54 Summary of in- and outputs. Source: own ill.

Based on the results, it is chosen to use a floor consisting of 3 layers of 10mm heat-strengthened glass. This will be strong enough to support the loads. The live load value now chosen is the value used for office area floors. It could be argued that instead of using that value, the CC3- congregation area value of 5 kN/m2 should be used since this is a ''high'' risk floor. It was chosen not do this because this would be unnecessary use of material to over dimension the structure that much. In case the roof does get to crowded, perhaps a limited amount of people are only allowed on the roof at one moment.

6.2.4 Matrix frame calculation of the portal

Now that the loads on and the dimensions of the glass panels, beams and floor panels are known, a complete segment of the roof can be calculated using the software Matrixframe. Using this method, a better understanding can be achieved of the overall workings of the roof structure. The output out of this calculation can then be used to make calculations for the steel tie beam and steel contour frame.

The primary goal is to check if the roof will induce tensile stresses on the ruin walls, because this would cause potential problems.

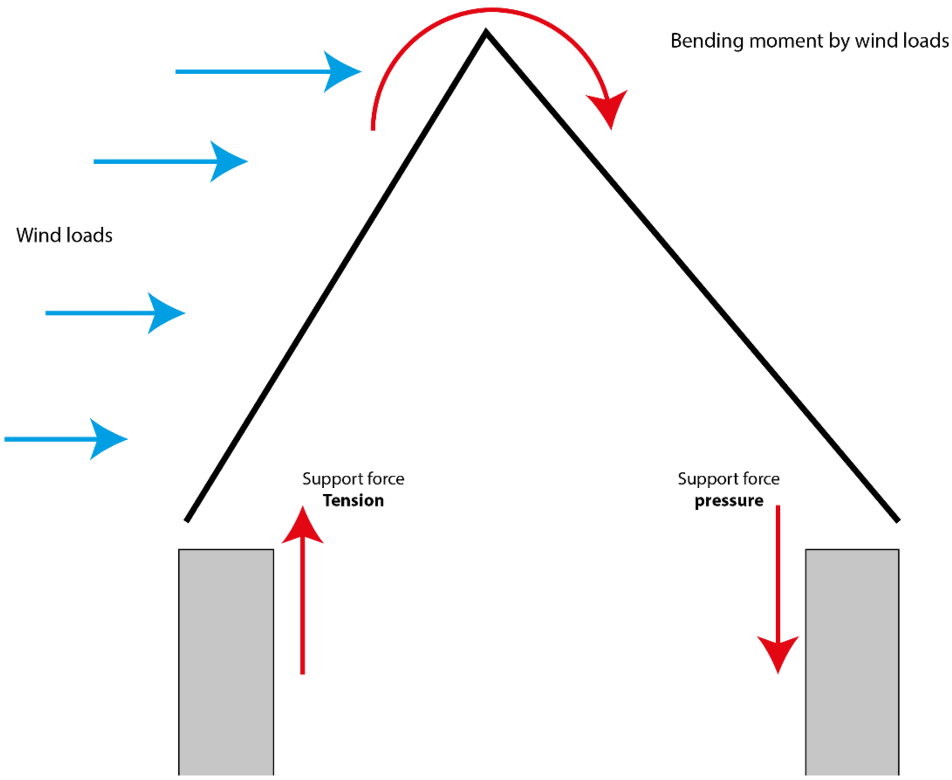


Figure 6.55 Possible tensile forces induced by windloads. Source: own ill.

6.2.4.1 Schematization

The middle beams of the roof design are taken as element to calculate. The roof is schematized without the tie steel beams in the floor. This is done to simplify the calculation, and to just focus on the reaction forces induced by the loads on the beams. Since glass as a material was not available in the library, a manual section was made. The beams are modelled as concrete beams to mimic the weight of glass, since they share the same density of 2400 kg /m3. The area and second moment area of the sections of the glass beams are entered manually.

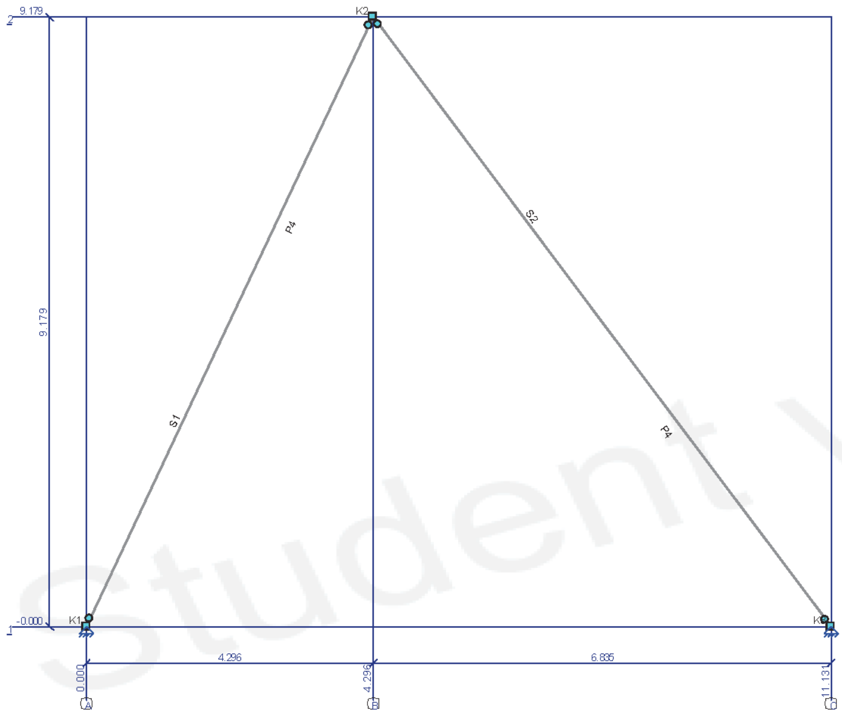


Figure 6.56 The schematization of the structure. Source: own ill.

6.2.4.2 Load case

The same loads as described in 6.2.2.2 are applied to the beams. However, since this frame consist of the two opposing beams, one beam is loaded under wind pressure, and the opposing beam is loaded under wind suction. Also, the program has automatically applied factors befitting to the total load combinations of a building of this type of monumental structures with CC3 risk factor. This is different from the hand calculations, were no factors were applied for the combination of loads other than the safety factors of 1,2 (dead load) and 1,5 (live load).

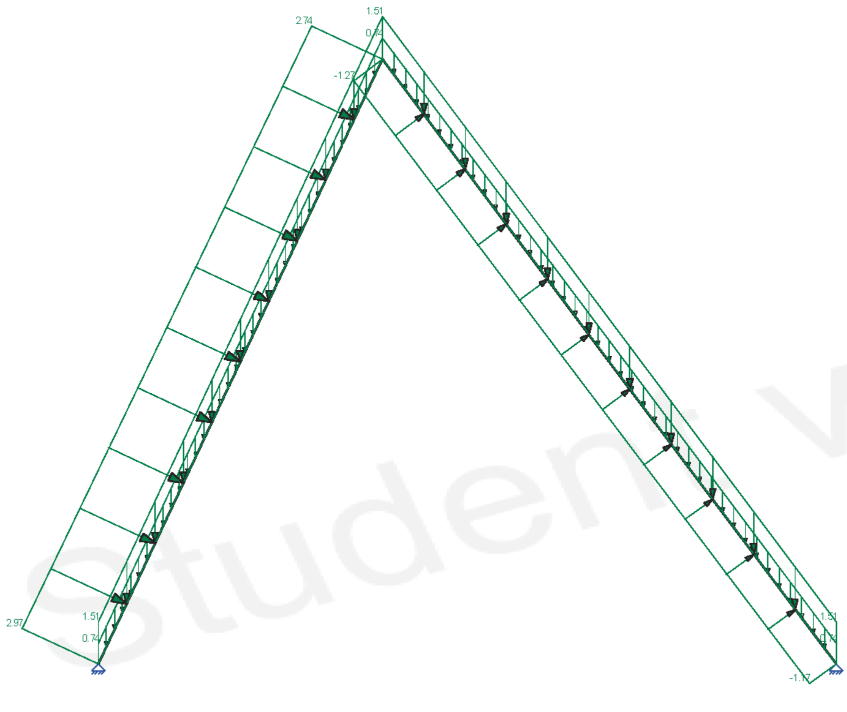


Figure 6.57 The load case on the structure. Source: own ill.

6.2.4.3 Calculation

Now that all the input is filled in, the program is given an order to make the calculations. The complete calculation report can be found in appendix A.4. The results of the calculation will be the support reactions of the supports of the beams, but also the maximum bending moments and shear forces in the elements. This data then then has to be manually recalculated to receive stress results.

6.2.4.4 Conclusions of calculation and results for design

In figure 6.58 the results of the calculation are shown for the support reactions. Here can be seen that the vertical reaction supports are all negative. This means that despite the horizontal reaction force from the bending moment of wind loads, the overall force induced on the wall support is pressure. Illustrated by the figure below, it can be seen that at the left support (where the uplift occurs) the pressure force is 18.5 kN, while at the right support the pressure force is 33.7 kN. This means uplift does occur, but the weight of the roof counteracts this uplift force, with a resultant which is pressure. While tensile forces are difficult to induce in the old masonry, pressure can more easily be taken up by the masonry. This pressure force does however need to distribute properly to avoid peak pressure forces, which can still lead to the failure of the masonry.

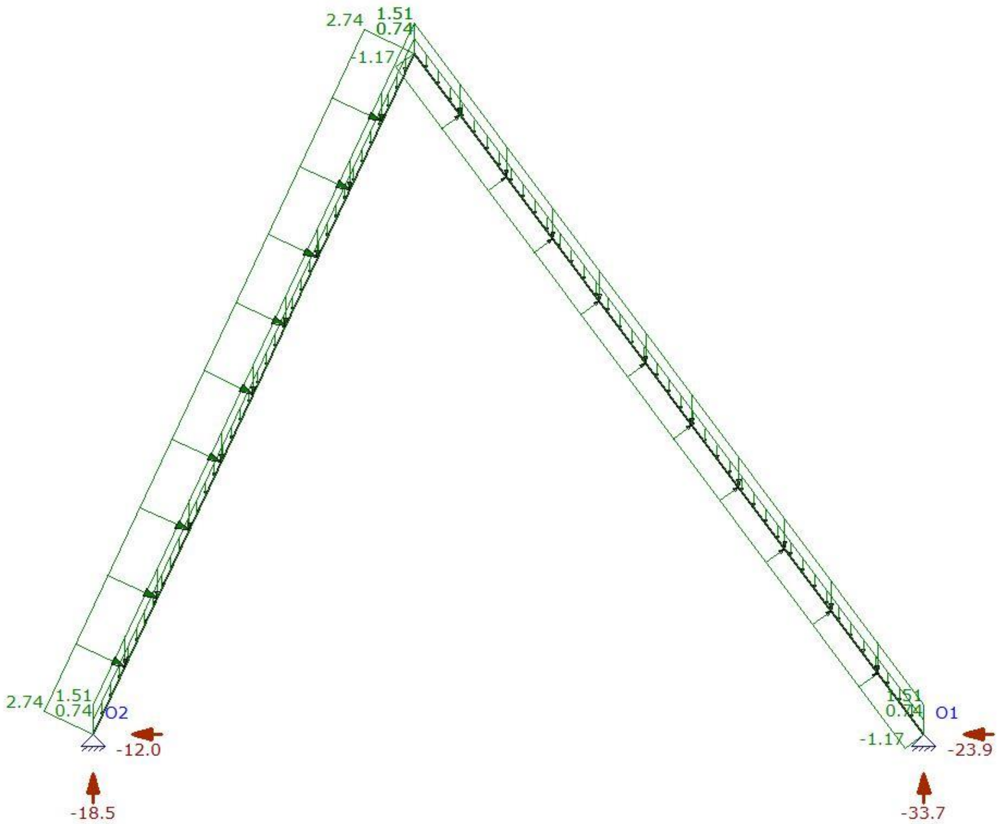


Figure 6.58 The support reactions as result of the calculations. Source: own ill.

Additionally, the bending stress and deflections on the left beam are also calculated by matrixframe. When comparing these to the hand calculations in excel, deviations can be seen. These can however be explained by the lack of using factors for the load combination in the hand calculations.

Value	Hand calculation	Matrixframe
Bending stress	23,34 N/mm2	30,2 N/mm2
Deflection	12,7 mm	27,6 mm

Figure 6.59 Comparison between matrixframe and handcalculation results. Source: own ill.

6.2.5 Calculation of the steel tie beam

The next element in the calculation is the steel tie beam, which is part of the steel contour frame. This steel beam would be a rectangular profile, which is bolted onto the steel contour frame to support the glass floor panels as well as the live loads of person on it. For this calculation the weight of the glass support beams, and the tensile force induce by the roof is left out to simplify the calculation.

6.2.5.1 Schematization

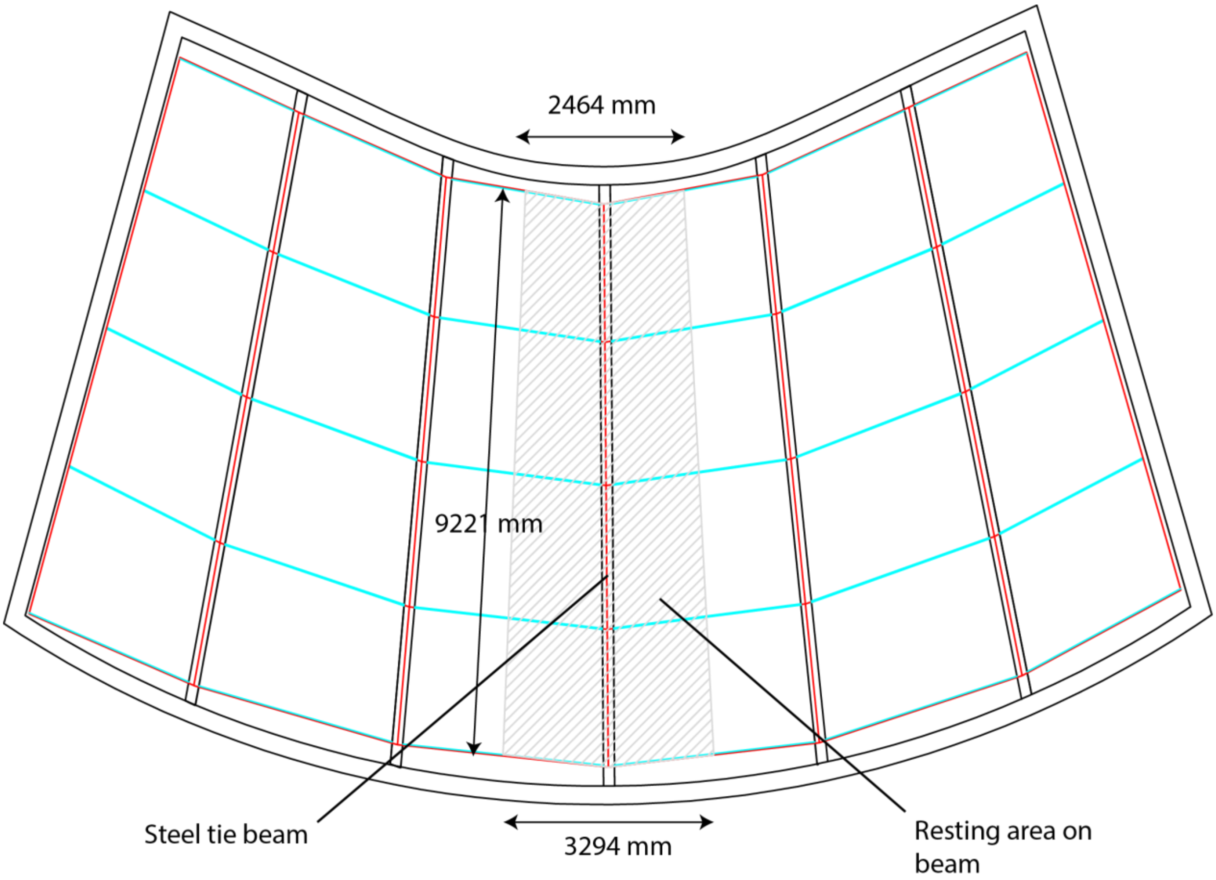


Figure 6.60. The resting area on the steel tie beam. Source: own ill.

Eight glass panels rest on the steel beam, but only half their width is supported by one tie beam. Since the area that is resting on the tie beam has a tapered shape, the total resting area can be calculated with the average width of the panels.

$$A = \left(\frac{\left(\frac{2464 + 3294}{2}\right)}{1000}\right) * \left(\frac{9221}{1000}\right) = 28{,}75\ m^2$$

The steel tie beam is supported at the two ends of the beam

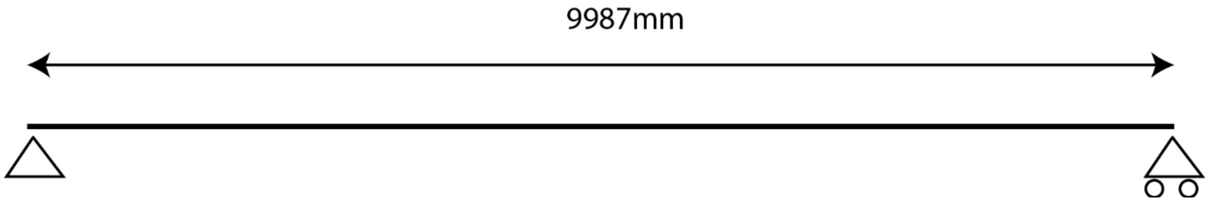


Figure 6.61 Schematic view of the beam. Source: own ill.

6.2.5.2 Load case

The three loads cases on the glass beam are:
LC1 = Dead load of self-weight of glass beam
LC2 = Dead load of resting weight of glass panel
LC3 = Live load of persons

All these load are applied perpendicular to the ‘beam’. This results in the follow load case as seen in figure 6.62. The live loads are determined from the Quick Reference (Section Structural and Building Engineering, 2014). For the live loads a safety factor of 1.5 is considered, for the permanent load a factor of 1.2. As a CC3 consequence class, they are both multiplied with a KFi of 1,1.

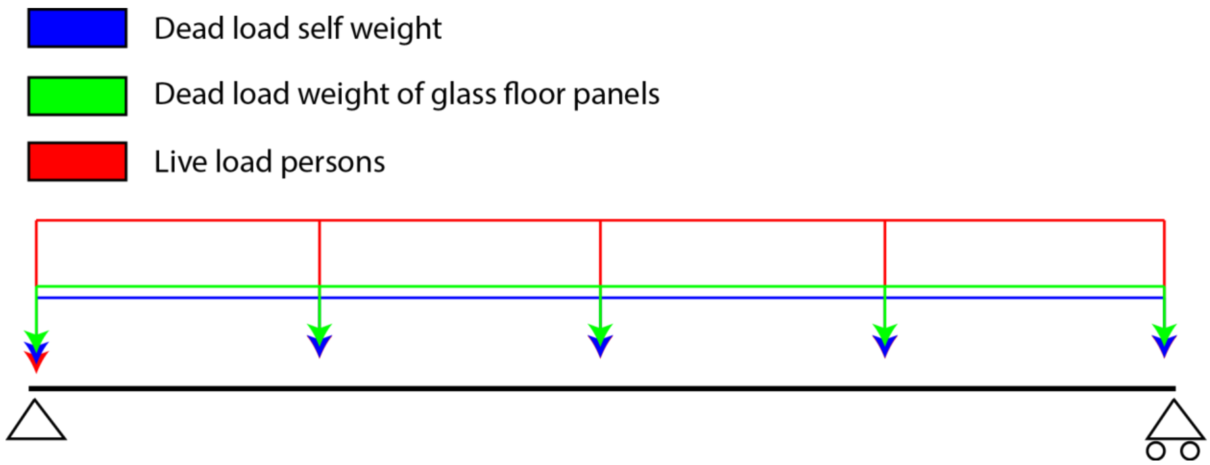


Figure 6.62 Load cases on the steel tie beam. Source: own ill.

6.2.5.3 Section properties

Different steel profiles were assessed using the information on a website with a catalogue of available steel profiles and their properties(Bouwen met Staal). Their second moment area, weight and section area are found here and applied in the calculation.

6.2.5.4 Formula

The maximum moment, shear forces and deflection can be calculated using the formulas described in figure 6.63-6.64. With the maximum moment, the stresses can be calculated using the following formula(Hartsuijker, 2012):

$$\sigma_m = \frac{M * z}{I}$$

σ_m = bending stress
M = maximum moment
z = distance to neutral line
I = second moment of area

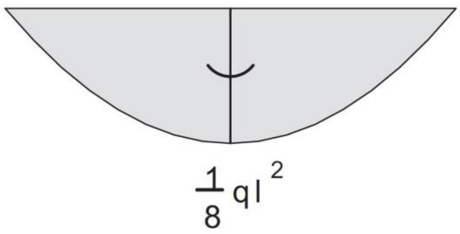


Figure 6.63 Maximum moment distributed load

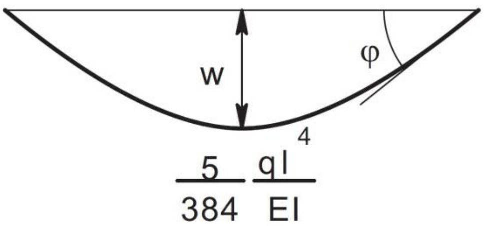


Figure 6.64 Deflection distributed load

$$\tau = \frac{V * S}{I * b}$$

τ = shear stress
V = maximum shear force
S = first moment of area
I = second moment of area
B = width of section

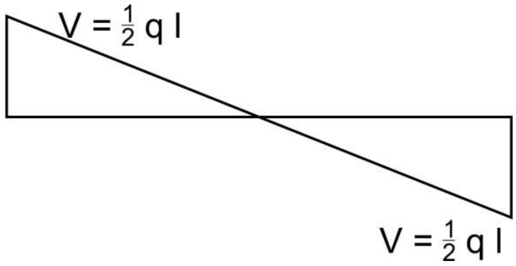


Figure 6.65 Maximum shear force distributed load

6.2.5.5 Calculation

For the calculation a excel sheet is made to calculate and optimize the steel profile. This complete calculation can be seen in Appendix A.5. The height and width of the profile, as well as the thickness of the profile are the parameters. These properties has been optimized to be the thinnest possible, as this will result in the least amount of weight for the entire structure. The results of the calculation are compared to the limit state check:

Maximum deflection W = 0,004 * length of span = 30mm
Maximum bending stress σ_m = 235 N/mm^2
Maximum shear stress τ = 235 N/mm^2

This led to the following summary of results

Thickness	16mm	Iy	97930000 mm^4	M	131748689 Nmm
Length	9987 mm	Self weight	0,94 kN/m	σm	174,89 N/mm2
E	210000 Mpa	Weight of panels	2,073 kN/m	W	20 mm
Height	260mm	Live load	2,5 kN/m2	τ	11,65 N/mm2
Width	180mm	q-load safety	15,851N/mm		

Figure 6.66 Summary of most important in – and output. Source: own ill.

6.2.5.6 Conclusion of calculation and results for design

The decision for a rectangular steel profile was partially a aesthetical choice. Because of the glass floors the steel beams would be highly visible, which is why functional but less attractive I-profile were unwanted. The height is the steel profile is also based on the detailing, and how it is connected to the steel contour beam. This will be explained later. Based on these considerations and the calculations, it was chosen to use a HFRHS 260x180x16mm steel profile, which should easily meet the requirements.

6.2.6 Calculation of the steel contour beam

The dimensions of the steel contour beam can be calculated using the output out of matrixframe. The steel contour beam is supported every 2 beams. This can be seen in figure 6.67.

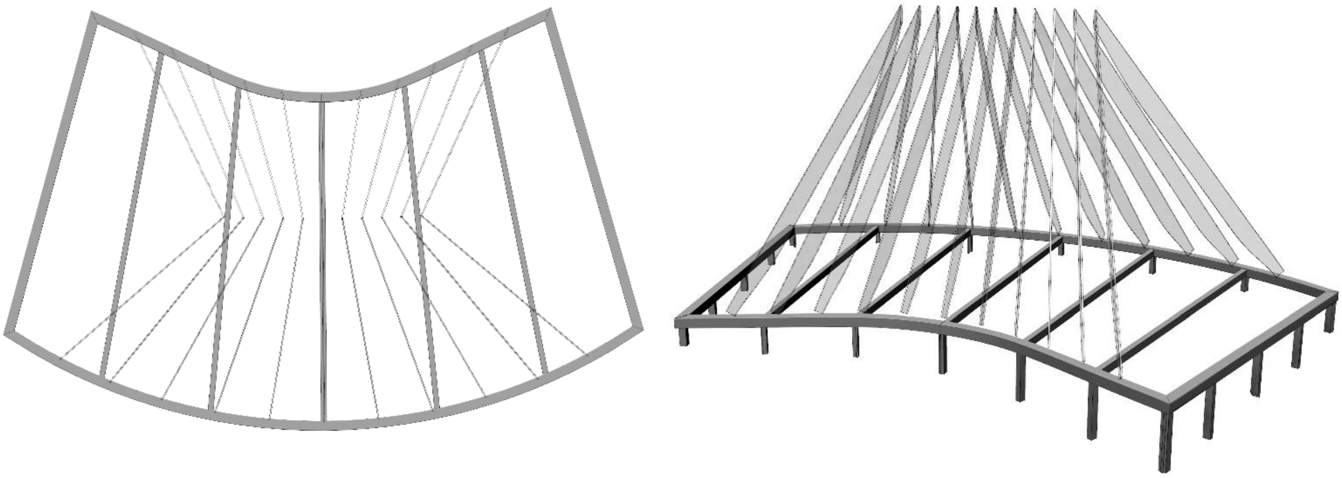


Figure 6.67 The beam grid on the steel contour beam in 2d and 3d. Source: own ill.

This means that the beam that are based at the steel tie beam and steel support will redirect their forces that way. The beam that is based in between these support however exerts a point load on the beam. The effect of this point load in terms of bending stress and deformation is calculated here.

6.2.6.1 Schematization

In the following figures the forces on the steel contour beam are assumed. The horizontal and vertical point load on the section will induce bending stresses and deflections.

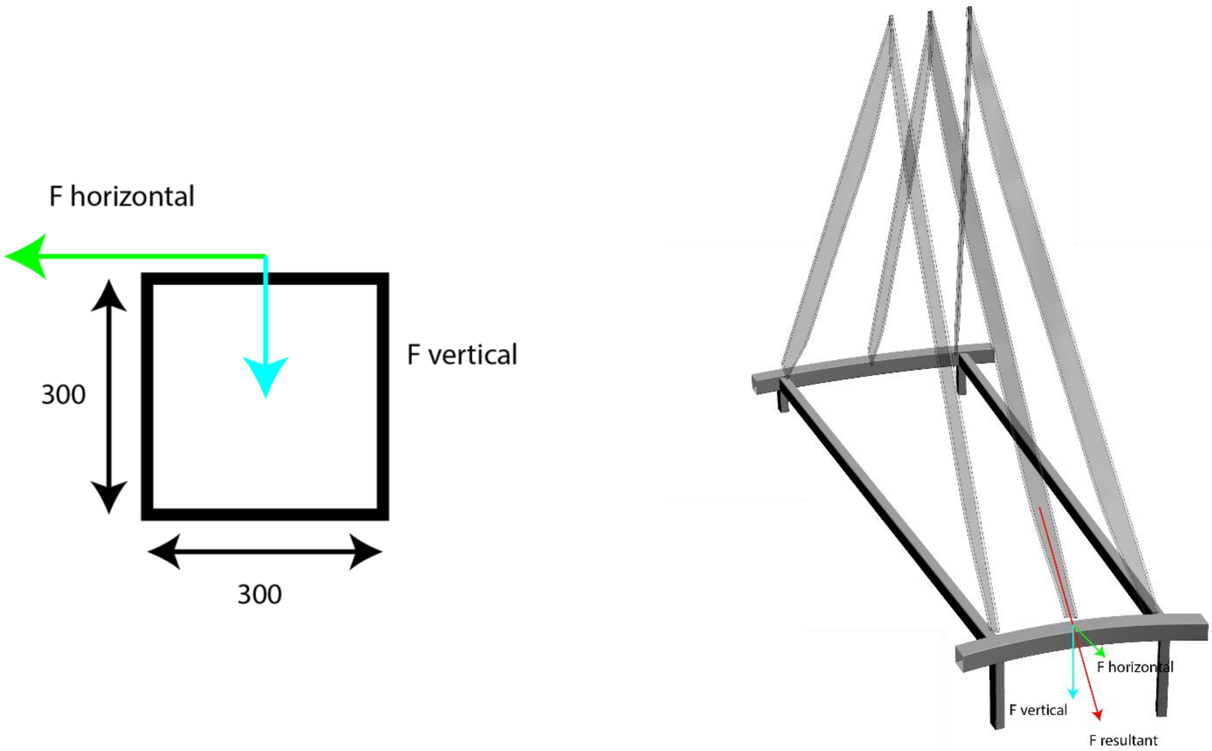


Figure 6.68 Schematization of force on section in 2d and 3d. Source: own ill

6.2.6.2 Load case

The beam is now calculated as if it would be an hinged beam. This is not an exact method, but it will give some idea of the deflections and bending moments. Since the formulas for a point load in a hinged beam result in the highest bending moments, the calculations are on the safe side. As vertical and horizontal point loads the support reactions are used which resulted out of the matrixframe calculations. These maximum forces can be found in appendix A.4. The maximum horizontal point load here was 23,9 kN and the vertical point load 34,74 kN.

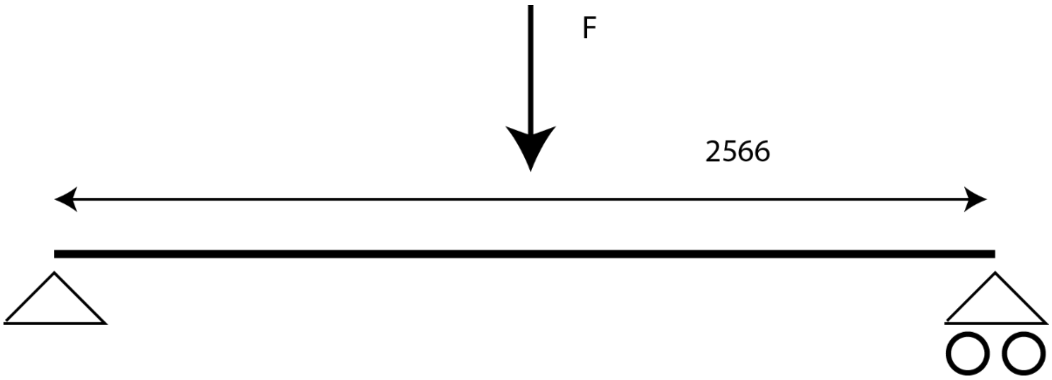


Figure 6.69 The schematization of loads on the beam. Source: own ill.

6.2.6.3 Section properties

Different steel profiles were assessed using the information on a website with a catalogue of available steel profiles and their properties(Bouwen met Staal). Their second moment area, weight and section area are found here and applied in the calculation.

6.2.6.4 Formula

The maximum moment and deflection can be calculated using the formulas described in figure 6.70-6.71. With the maximum moment, the stresses can be calculated using the following formula(Hartsuijker, 2012):

$$\sigma_m = \frac{M * z}{I}$$

σ_m = bending stress
M = maximum moment
z = distance to neutral line
I = second moment of area

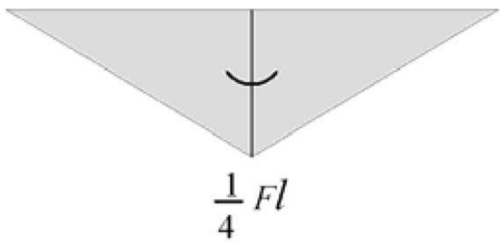


Figure 6.70 The maximum bending moment in profile.

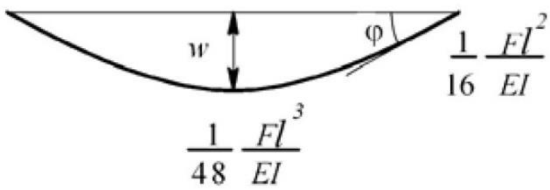


Figure 6.71 Maximum deflection in profile.

6.2.6.5 Calculation

For the calculation a excel sheet is made to calculate and optimize the steel profile. This complete calculation can be seen in Appendix A.6. The height and width of the profile, as well as the thickness of the profile are the parameters. These properties has been optimized to be the thinnest possible, as this will result in the least amount of weight for the entire structure. The results of the calculation are compared to the limit state check.

Maximum deflection	W	= 0,004 * length of span = 5,132mm
Maximum bending stress	σ_m	= 235 N/mm^2
Maximum shear stress	τ	= 235 N/mm^2

6.2.6.6 Conclusion of calculation and results for design

Thickness	10mm	Iy =Iz	160250000 mm^4	σm hor	14,35 N/mm2
Length	2566 mm	Horizontal pointload	23,9 kN	σm ver	20,86 N/mm2
E	210000 Mpa	Vertical pointload	34,74 kN	W hor	0,25 mm
Height	300mm	M vertical	15,33 kNm	W ver	0,36 mm
Width	300mm	M horizontal	22,29 kNm		

Figure 6.72 Summary of most important in - and output. Source: own ill.

The decision for the choice of steel profile was more based on detailing than on structural calculations. For the connection to the glass beam a certain width was needed to properly connect the beams. This is why eventually was chosen for a HFHRS 300x300x10mm steel profile. As can be seen in the calculations the bending stresses and deformations are very low, so the profile will easily fulfill the structural requirements. The explanation for the choice of profile based on detailing will be explained in a later chapter.

6.2.3 Summary of results

Summary of Results						
Component	**Height**	**Width**	**Thickness**	**Type of glass**	**Max stress**	**Max allow. stress**
Glass panel		30mm	3 x 10 mm	HS - FT -HS	44,74 Mpa	40 Mpa
Glass beam	480 - 560 mm	40 mm	4 x 10mm	HS	39,41 Mpa	40 Mpa
Glass floor panel		30mm	3 x 10mm	HS	33,53 Mpa	40 Mpa
Steel tie beam	260mm	180mm	16mm	S235	174,89 Mpa	235 Mpa
Steel contour beam	300mm	300mm	10mm	S235	20,86 Mpa	235 Mpa

Figure 6.73. Summary of results for the design based on the calculations. Source: own ill.

Above a table is shown with the summary of the results from the calculations. The needed heights and thicknesses and type of glass and material is shown. Here can also be seen what the occurring stresses, and maximum allowable stresses are. Now these dimensions are clear, the next phase of the design can now be entered: the detailing.

6.3 Design process of the detailing

While having no idea of the size of elements, it is more difficult to start designing the details. The dimensions often determine for a large part how the exact detailing will function. Now that in paragraph 6.2 the dimensions of the main elements are calculated, this allows for designing the details.

The overall design process of the details was a long and very iterative process of continued changes, adjustment, improvement and integration of all the different requirements for the detailing. Starting from very rough hand sketches with a wide exploration of possible design solutions, this was slowly narrowed to more elaborate and detailed designs. These design decisions root back into all the different scale levels of the roof. Therefore this is not an linear process, and not simply be illustrated by a sketch for each phase. An overview of the course development can however be given by the related design sketches.

For this glass roof design, the detailing of the structure is one of the most important design elements of all. The detailing is where all the design requirements come together and are translated into a technical design consisting of small components. As explained in chapter four, specifically when designing in glass, the detailing is crucial because this is what determines the strength of an overall glass structure.

While this paragraph describes the design process which took place, the results of this process are shown in chapter seven where the final design is shown.

6.3.1 Design requirements for the detailing

The design requirements for the detailing came partially from the overall requirements for the glass roof described in paragraph 5.3, but also from general requirements that always apply. These combined are shortly summarized below:

- The new glass roof should be reversible. The steel contour beam has to be connected to the old wall in such a way that the roof can be removed without leaving large permanent damage to the old structure.
- The details should have a certain level of esthetical quality. Since glass is transparent, almost every detail will be visible and not much is concealed.
- Keeping up with the concept of transparency, the details should also remain minimalistic, so they do not detract the attention away from the glass.
- The details should allow for forces and stresses to be induced in the glass and old masonry nicely, avoiding peak stresses which could lead to failure of either the glass or the masonry.
- Climate and façade engineering requirements should be integrated in the structure: making a wind, watertight and controllable climate inside the roof.
- Heat treated glass and laminated glass elements should be use to increase strength and safety of the structure.
- For connecting elements, use steel components and glued connections where needed, to provide for better ways of connecting glass and to avoid having to drill into the glass
- Allow for tolerances of heat-expansion, production size deviations, assembly inaccuracies and inaccuracies in the transition zone between the old and the new structure.
- Allow for overall practical assembly of the structure.

With these requirements in mind, the first design sketches were made for the detailing.

6.3.2 First sketch detailing

6.3.2.1 Determining the principal locations of details

In the roof design there is a certain repetition. Although the roof is curved, and each connection is therefore under angle different angle, the connection of the glass beam to the steel contour frame, the connection of the panels to the beam, and the top connection is quite similar all around the roof. Also due to the fact the roof is symmetrical, this means that there are a couple of principal details that can be extrapolated across the other similar details. This is illustrated by figure 6.74.

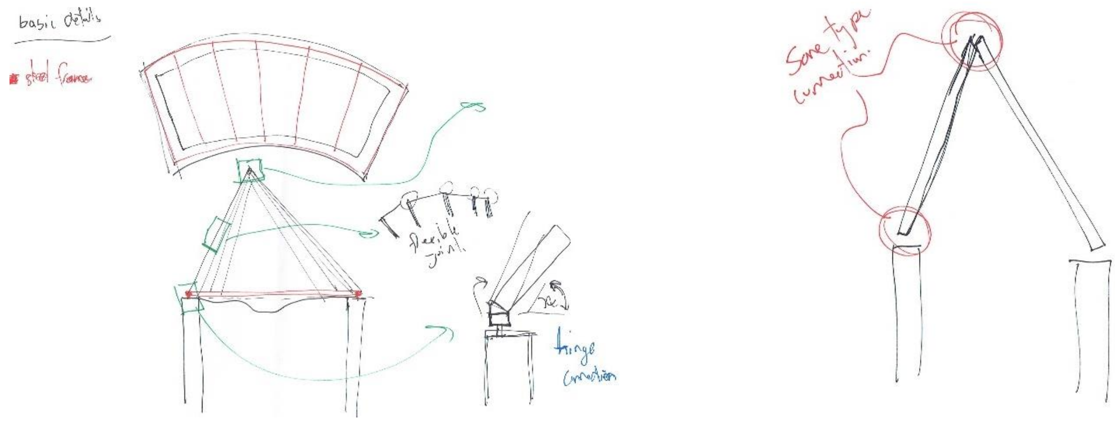


Figure 6.74 Hand sketch of location of principal details. Source: own ill.

These principal details for the 2 long curved side are the connection near the wall, the connection from the glass panel to the glass beam, and the top joint detail. The principal behind these details are then also translated into the detailing for the side panels where the steel cable trusses are located. Now for each principal detail the development is briefly discussed and illustrated with the design sketches.

6.3.2.2 The wall detail

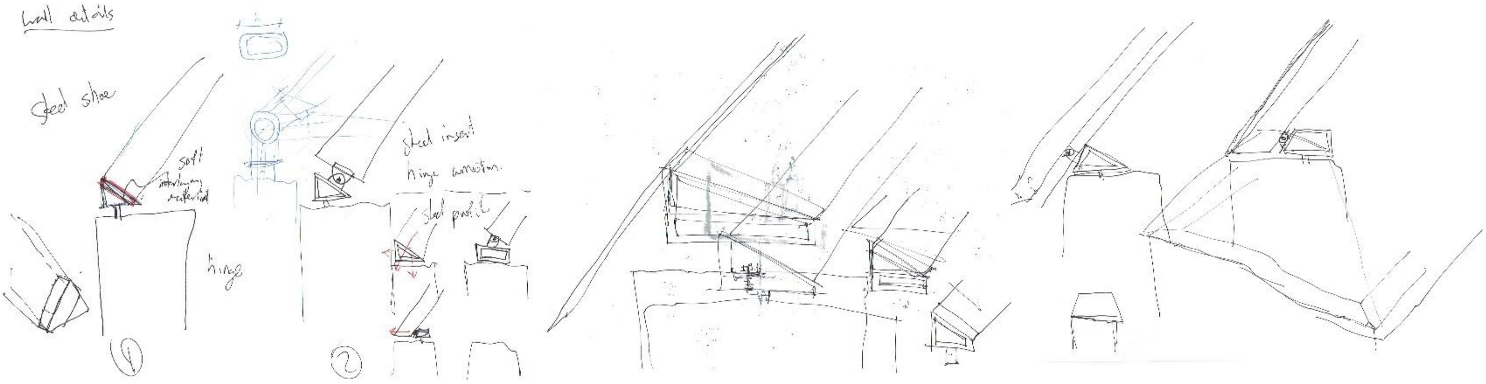


Figure 6.75. The first sketches for the wall detail. Source: own ill.

With the choice of using a steel contour beam and the glass beam, these two elements had to be somehow connected together. Different steel profiles were researched to investigate which shape would provide the best connection. The contour beam had to accommodate a connection to an old wall with an uneven surface, and somehow the gap between the old wall and new structure should also be closed in an esthetical fashion. A specific challenge was working with the width of the wall, and trying to fit the entire detail on the wall, because any protruding element wouldn’t look nicely. Next, assembly and tolerances had to be accounted for in connecting the glass beam onto steel. From early on it became clear the connection had to be a hinged connection to prevent high bending stress on the outside of the beams, but this hinge could be made in several ways. A steel shoe proved to be a reliable way of supporting the glass beam in place. Measurements had to be taken in order to prevent the beam from falling out of its shoe if the structure would deform under loads. Also, the 560mm high beam would never fit in the steel shoe, which is why the beam had to be tapered in order to nicely fit into the beam. Al these elements were taken into account in this detail.

6.3.2.3 The glass panel detail

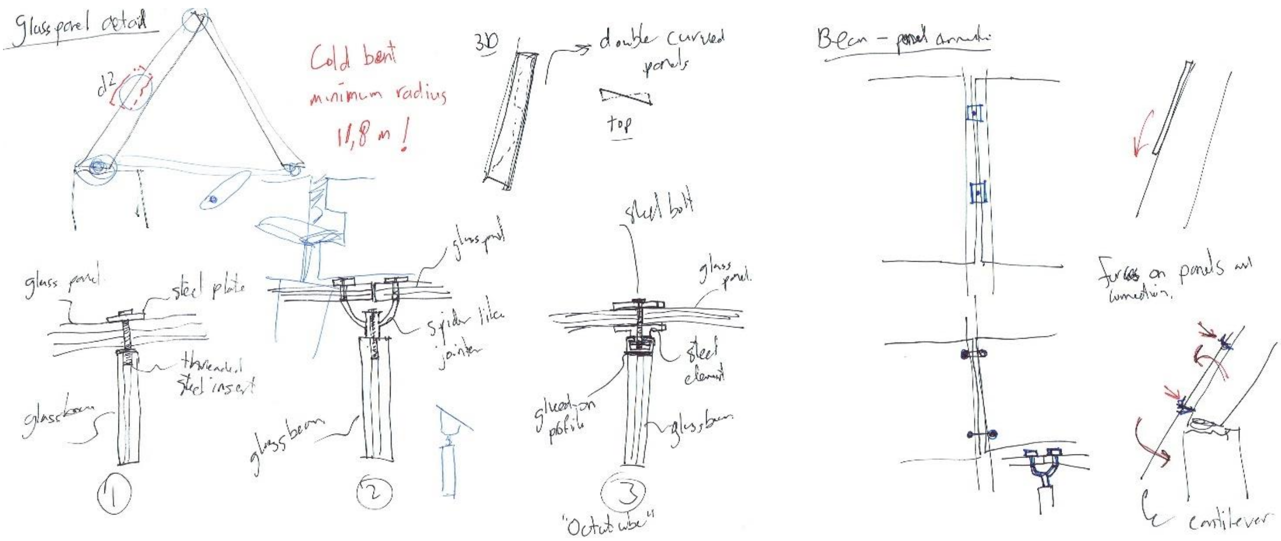


Figure 6.76 The first sketches for the panel to beam detail. Source: own ill.

For the glass panel detail the most important criteria was a slender detail, that would be strong and adjustable enough so that it could bear the forces from cold bending of the glass panels, and the changing curvature between the panels. Since the glass beam would only have a certain width, and the two panels would need to be resting on there, this does not give enough support. Also, the connection should be made in such a way that the panel could not slide off, since it is under an angle. An important question was how the steel connector holding the glass panels could be joined to the glass beam. Various options have been researched for this.

6.3.2.4 The top joint detail

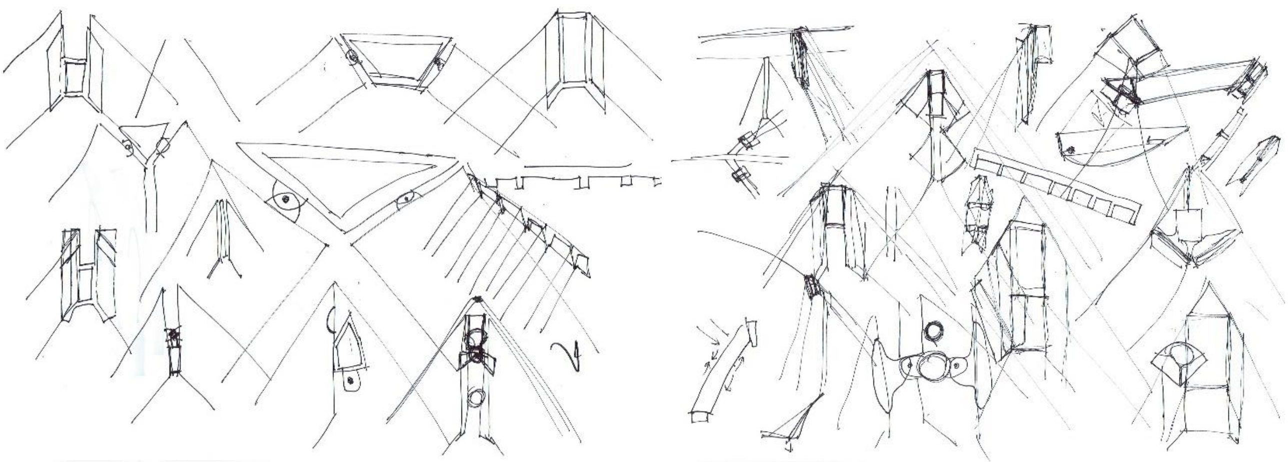


Figure 6.77 Hand sketches for the top detail. Source: own ill.

The top detail was one of the most difficult details. This because of the high slope of the roof, which caused a bulky detail if a big top element was used. There was a large variety of possibilities, from simple steel insert at both ends of the panels with a bolt connecting both (a pure hinge), or profile with flenches welded onto them into which a steel insert could be bolted. A functional but also slender and beautiful detail should be applied here, without becoming over-complicated.

6.3.2.5 First draft versions of details.

After the first phase of designing the details, an opportunity was given to present the design work to James O'Callaghan, one of the world leaders and expert on the design of structural glass structures. At the presentation, the first version of the details were presented, shown below.

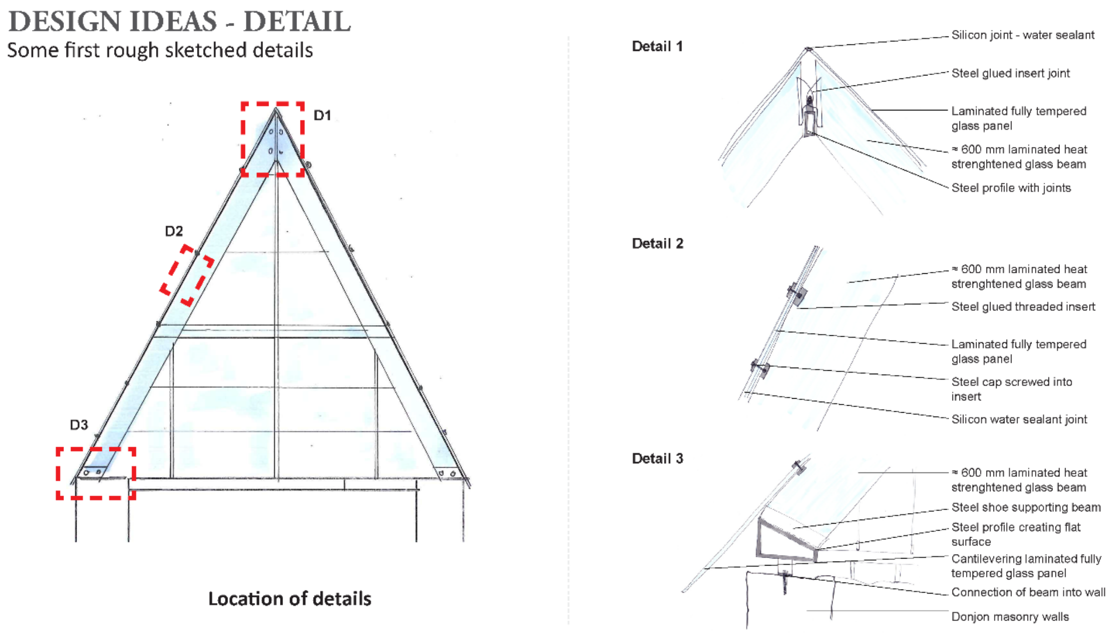


Figure 6.78 First draft version of the detailing. Source: own ill

Valuable feedback was given from him on the design, pointing the complexities and challenges in this specific design. He mentioned the forces induced by the slope of the roof and the cold bending, and the influence of that on the detailing. Also more insight was given in the combination of heat-strengthened and fully tempered glass panels combined into one sheet to combine each specific benefit. He mentioned making more unified connection types which are used throughout the structure. Also to accommodation for tolerances and thermal expansion was crucial in order for the structure to become a structural safe and sound whole.

6.3.3 Further elaboration on the detailing

6.3.3.1 Further working with hand drawings

With the feedback from given from James as well of the mentors, the details could now be further elaborated. This resulted in the following drawings.

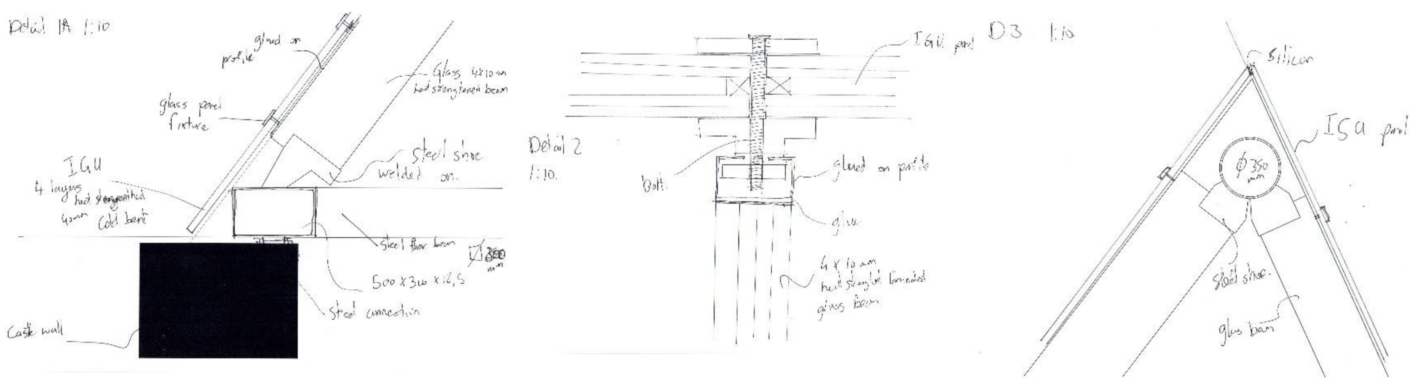


Figure 6.79. New versions of the details. Source: own ill

For the bottom detail the steel shoe was given a more refined looking, showing a more detailed way of how the beam would work, also in combination with the steel beam.

The panel to beam detail was given shape as a clamped connections, which bolted itself down into a block which was fixed in c-profile glued to the beam. This connection proved to be a good way of connecting a cold bend panel and keeping it in shape.

To give the structure a more unified appearance, it was chosen to use the same connection type at the top as at the wall position. A steel shoe was made onto the steel top profile. The top profile had to be very thin and rather high to support the steel shoes, so that it would fit nicely between the two beams.

An consult was given from Octatube to guide the design and detail process which gave some very interesting insight in the cold bending capabilities of glass, and how to detail these connections (Octatube, 2016).

6.3.3.2 From hand-drawing to digital drawing

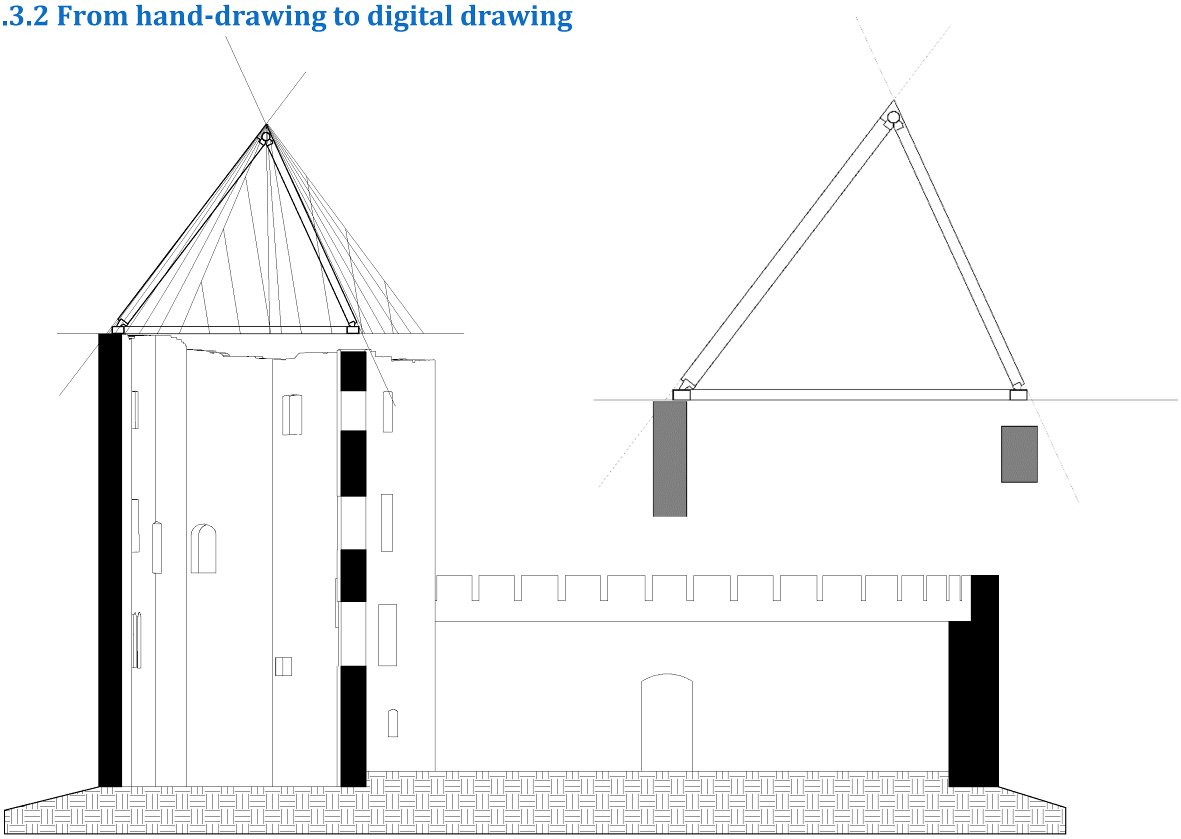


Figure 6.80 The first digital CAD drawing of the section of the roof. Source: own ill.

With this new input, the details were continuously improved and elaborated. Now that the details became more and more complex, the transfer from hand-sketching was made towards digital AutoCAD drawings to work more precise. Many more iterations were done in the subsequent weeks, integrating more and more aspects in the detailing. One important element was however still left out, which were the climatic installations. This part is described next in chapter 6.4.

6.4 Climatic performance of the glass roof

6.4.1 Problem with overheating

Until now, no attention was paid to the climatic topics of heating, cooling and ventilation. With the roof being a large glass transparent structure, placed 19 meters high on top of the walls with no shading from nearby trees whatsoever, the matter of inside climate rises quickly.

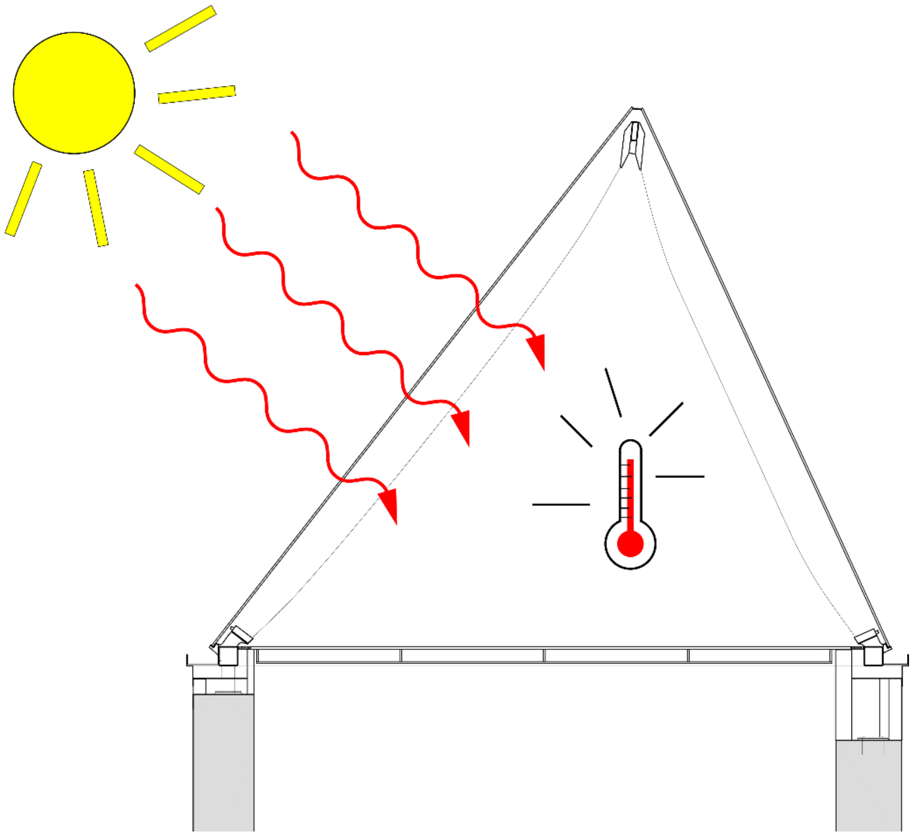


Figure 6.81. The risk of overheating of a large glass structure without ventilation. Source: own ill.

If the roof would not be ventilated, the temperatures would become very high due to sun load. A simple hand calculation(Bokel, 2015) is made to calculate the inside temperature of the roof if the sun has been shining for 5 hours on the structure on a sunny summer day with outside temperature of 15 °C, and solar load of 600 W/m². With the roof having a total surface area of 370 m², assuming use of normal glass with U=1,5 W/m2K and solar transmittance of 40%. The thermal mass (M) of the glass floor, panels and beams, and the steel contour + tie beams are taken into account.

$$T_i(t) = T_e + \frac{W}{H}\left(1 - e^{-\frac{H}{M}t}\right)$$

With

$$W = 0{,}4 * 370 * 600\ W/m^2 = 88800\ W$$
$$H = U * A = 1{,}5 * 370 = 555$$
$$M = 27238474$$
$$t = 5 * 3600\ s$$

Resulting in

$$T_i(5 * 3600) = 15 + \frac{88800}{555}\left(1 - e^{-\frac{555}{27238474}*(5*3600)}\right)$$

$$T_i(5 * 3600) = 15 + 160(1 - 0{,}69)$$

$$T_i = 64\,°C$$

6.4.2 Preventing overheating

Obviously these inside temperatures are not allowable in the structure. Therefore measures have to be taken to prevent inside temperatures from reaching this high. However, mechanical installations for cooling and ventilation are not preferred since they are often rather large and heavy. Due to the transparency of the roof, there is no place to hide the installations. That is why it was chosen to use passive measures.

These measures need to subtly integrated in the roof design. This way the installations are not clearly visible but are of critical importance for a comfortable climate inside the roof. Several options are reviewed, such as using special glass coatings which reduce sun load entering the roof, using natural ventilation, and patterns which could be printed on the glass to also reduce unloads.

A choice has been made for using natural ventilation in combination with low-e glass. These properties now had to be integrated in the design of the detailing. This was eventually done and the results can be seen in chapter seven.

7. Final technical design

This result of the design process is not an addition of the separate choices done for each element, but is rather an iterative process where each decision influences the other choices. The final design is a result of multiple iterative considerations, as also stated in the research framework.

This chapter shows the results of the design process, the final design. The design will be shown in renders, 3d, 2d sections and technical drawings. After that the façade design and climate design part will be further explained in 3d and scheme's. At the beginning of each paragraph an explanation is given of the images.

7.1 3D images of the roof

Although the 3D images speak for themselves, a few notes are placed to focus the attention to.

The first images show renderings of the roof design. In figure 7.1-7.5 impressions are shown with an eye-height and birds-eye perspective. The roof nicely follows the shape of the original glass roof. The crumbled wall has been brought to one level using a clay brick with stands out from the original brick wall. A cantilevering rain gutter reminds of the old wooden gutter that used to be there. The ventilation inlet of the roof is not clearly visible since it is integrated into the rain gutter, which will be explained later. Looking out from inside the roof, a beautiful view can be seen over the surrounding garden.

Figure 7.6 is an total overview of the 3d model that has been used to design the roof. Here also a clear distinction can be seen between the old and the new masonry.

Figure 7.7 is a close up image of the roof. Notice the curved glass panels and the glass beam, the flat sides with the steel cable trusses. The glass panels extend into the rain gutter. The underlying steel structure emphasizes the original roof shape, but is slender enough to not be dominantly present. The top profile beam ended up becoming a custom made steel profile, with an rather small main body profile, where local extensions were welded on to the main body to locally give enough height to support the steel shoes. This resulted in a top profile beam with a jagged look, that was slender enough to not intervene with the overall transparency of the roof. Ventilation grills at the bottom near long sides of the glass floor and top of the roof can also be seen, these will be explained later.

Figure 7.1 First render of the refurbished castle with the glass roof. Source: own ill.

Figure 7.2. Render from within castle walls of the new roof. Source: own ill.

Figure 7.3. Bird’s eye view render of the castle with the new roof. Source: own ill.

Figure 7.4 Render from inside the roof. Source: own ill.

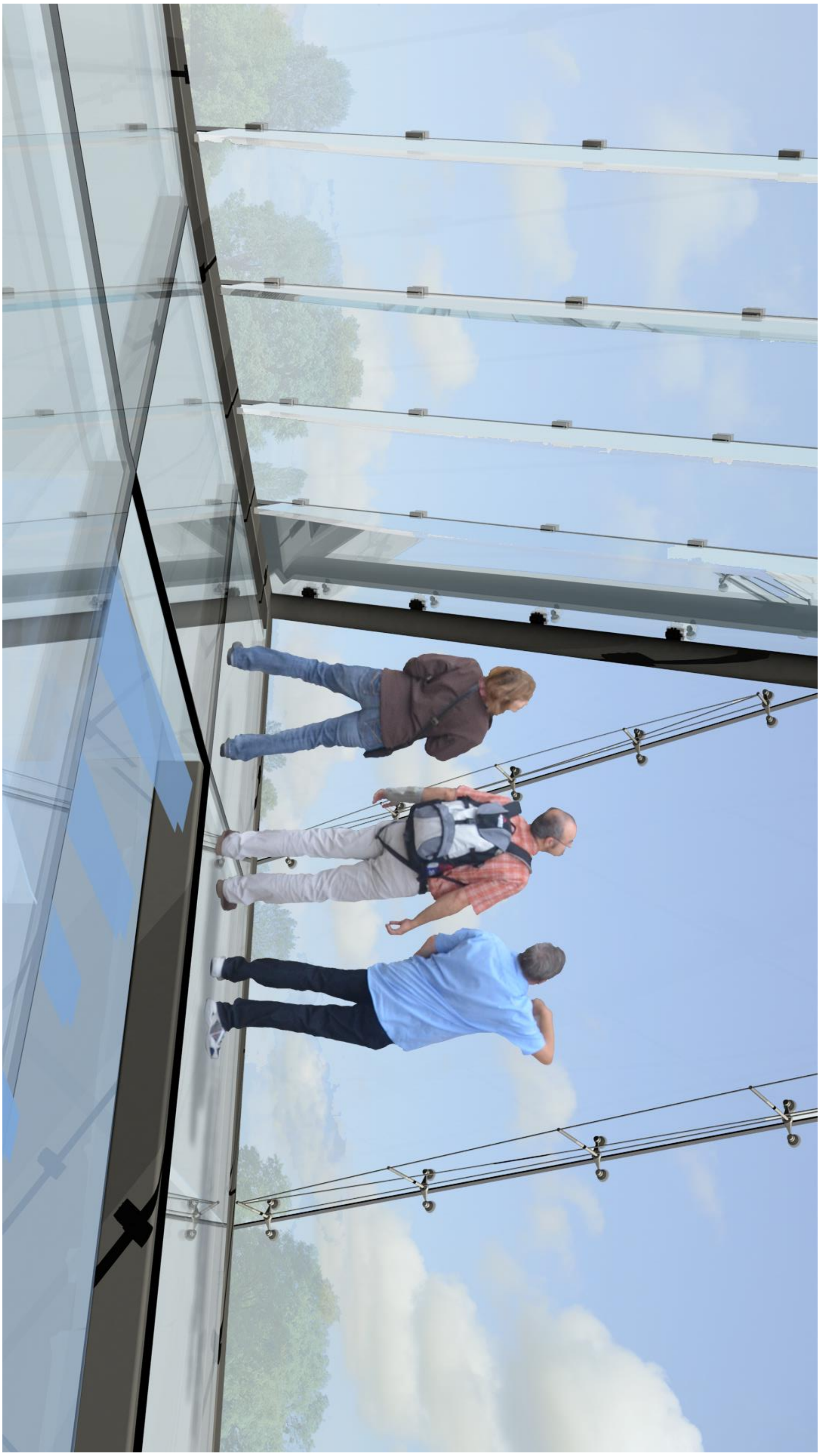


Figure 7.5. Inside render of roof, showing the cable truss and glass stairway. Source: own ill.

3D Castle with roof

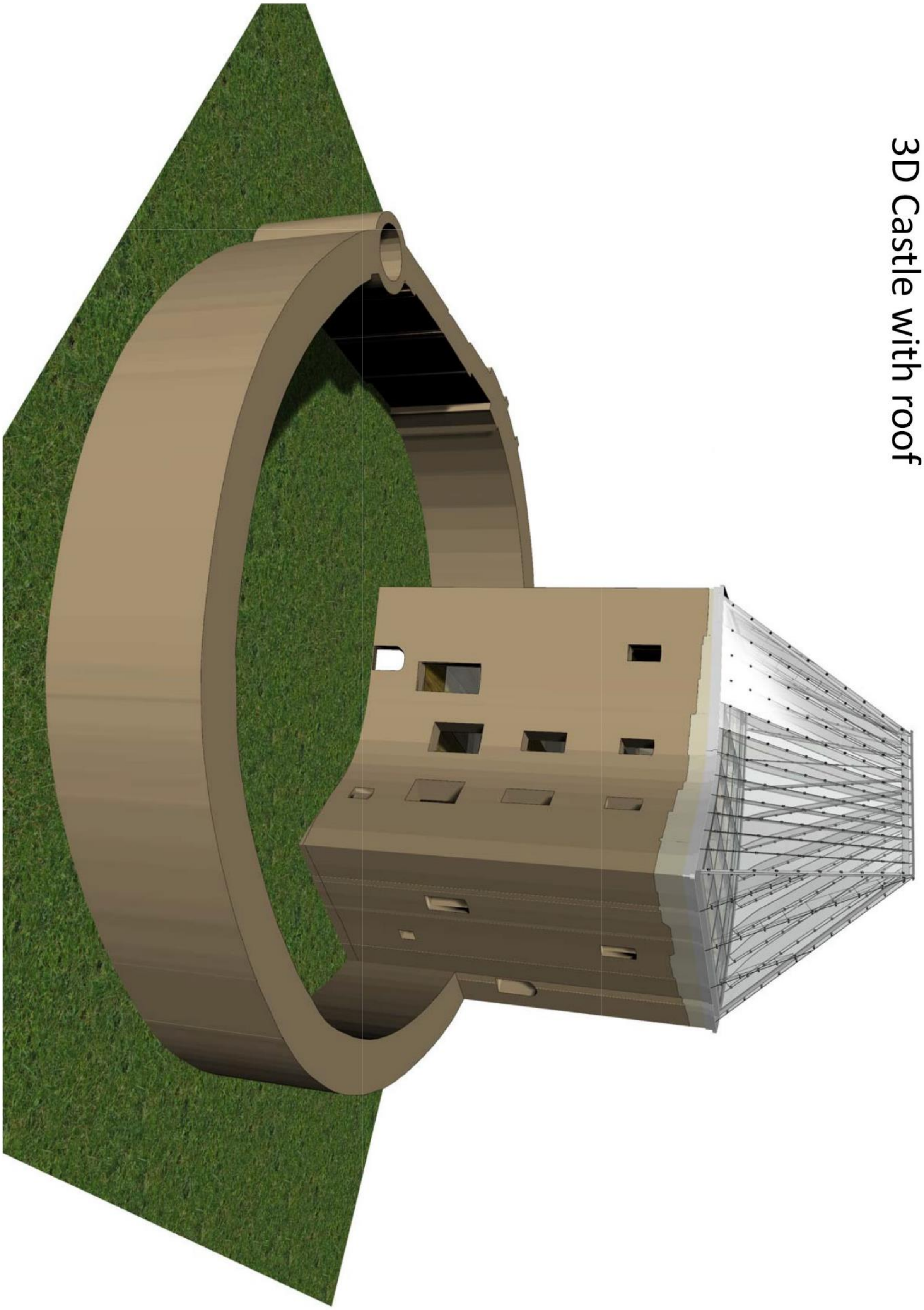


Figure 7.6. 3D image of the model of the castle and new glass roof. Source: own ill.

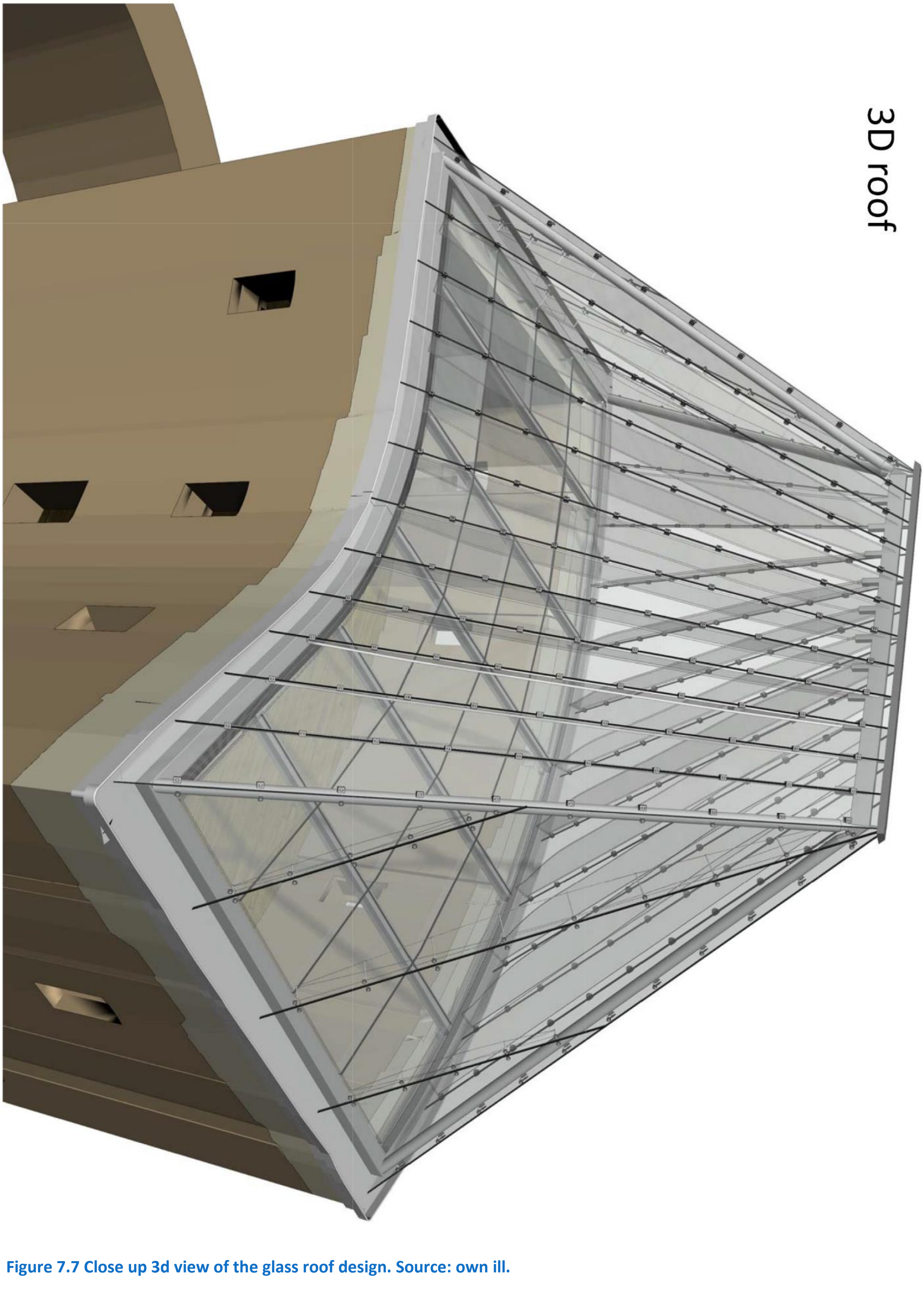


Figure 7.7 Close up 3d view of the glass roof design. Source: own ill.

7.2 Elevations and plans

Figure 7.8-7.11 shows all four elevations of the roof. Here each element can well be seen. Especially in the north and south views the complex and changing curvature of the roof is well visible.
Again, the height difference in the old wall stands out. This is why this leveling was clearly needed.

Figure 7.12 is a top view of the roof. In this top view the location of the two sections shown in paragraph 7.3 is illustrated. Also the position of horizontal details 5, 9 and 10.

1: 100 West view

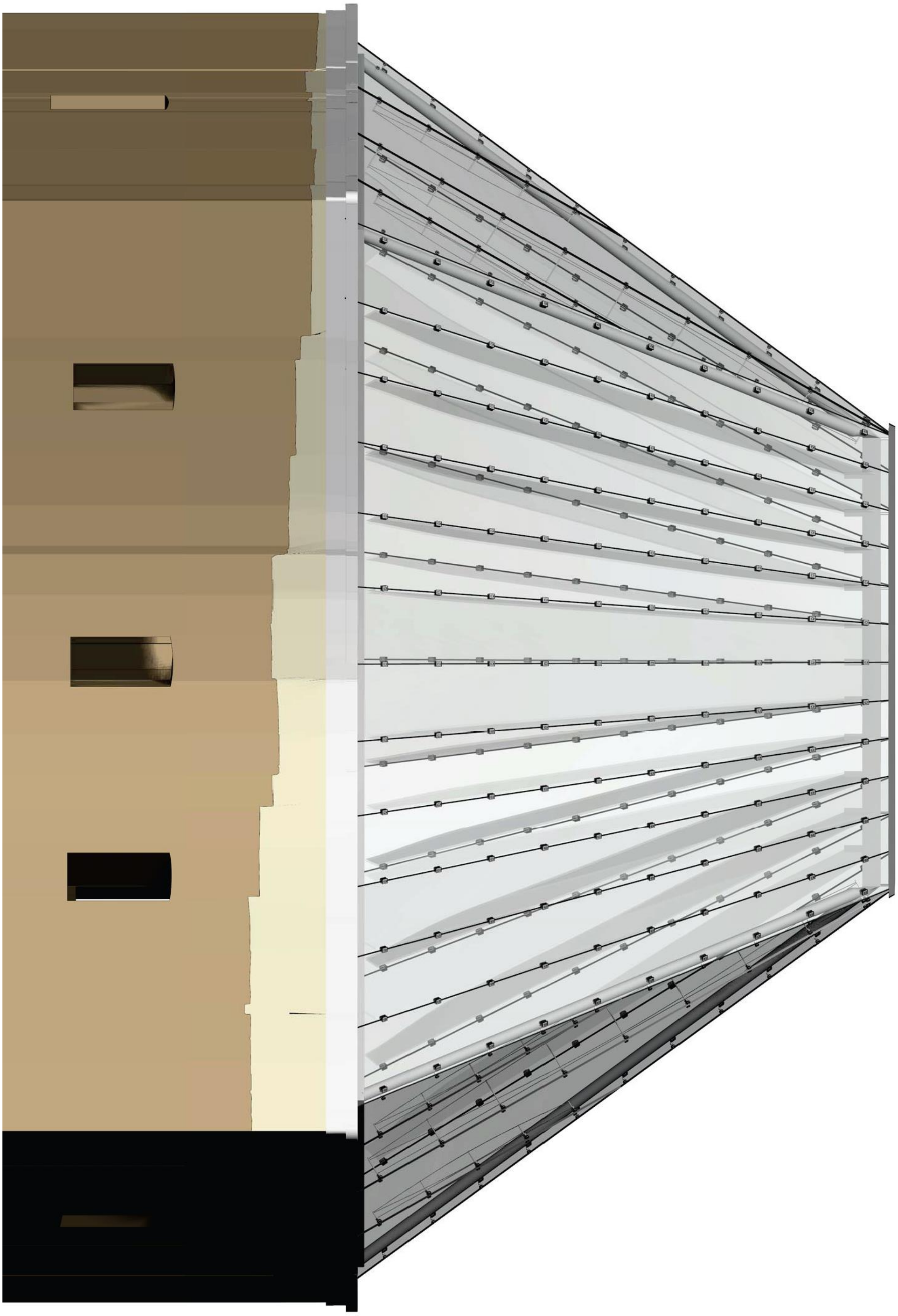


Figure 7.8 West elevation 1:100 of the glass roof design. Source: own ill.

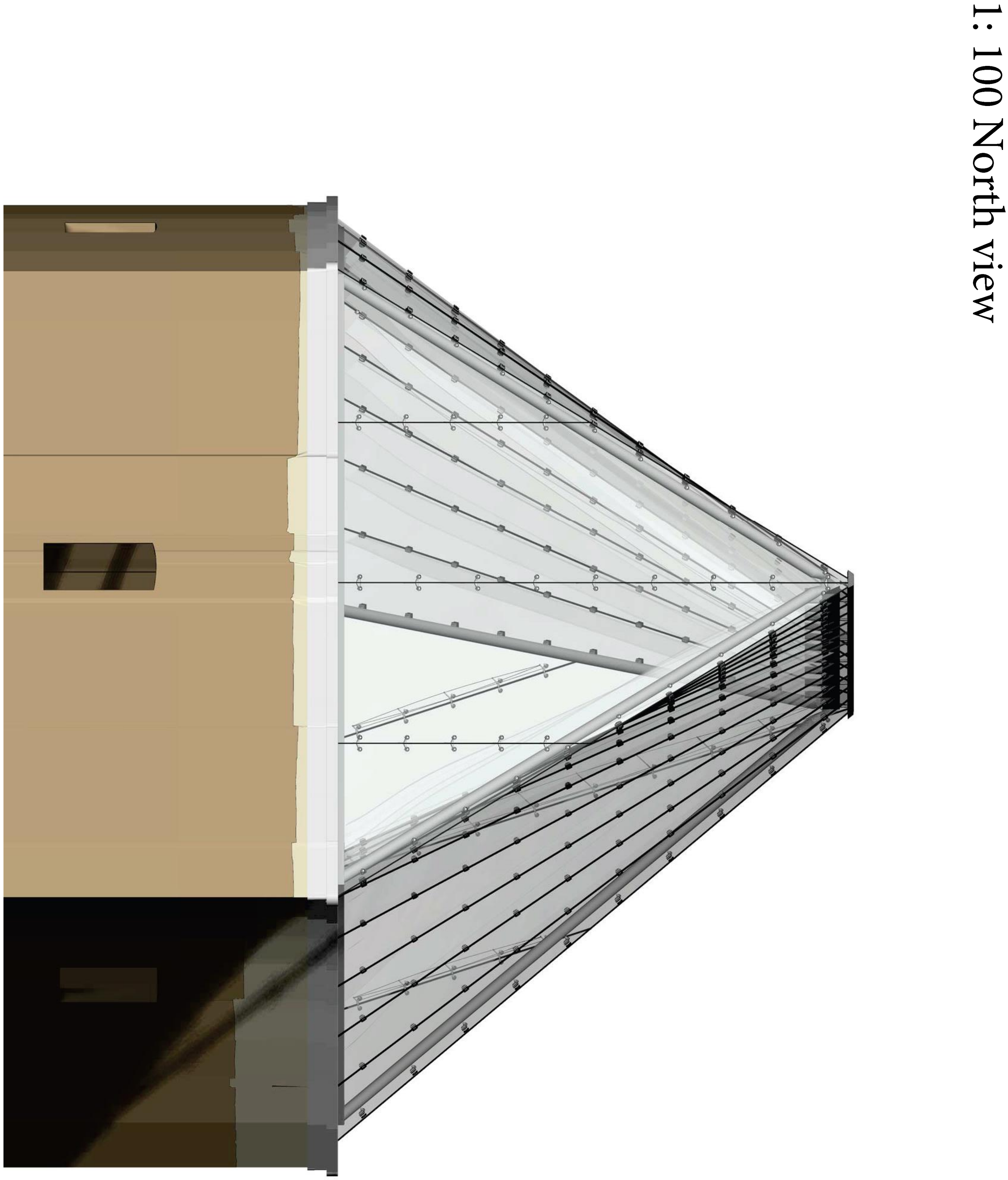


Figure 7.9 North elevation 1:100 of the glass roof design. Source: own ill.

1: 100 East view

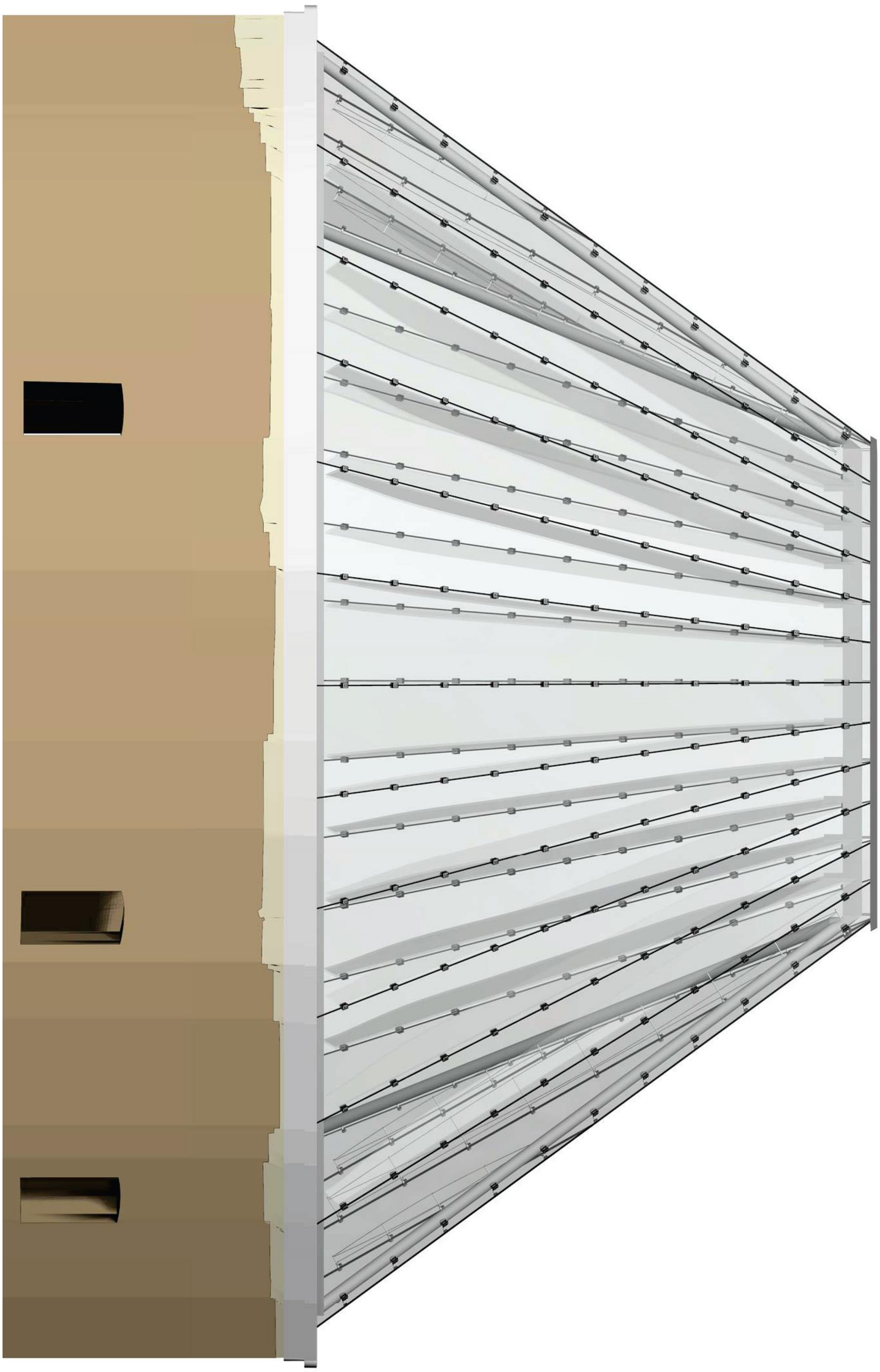


Figure 7.10 East elevation 1:100. Source: own ill.

1: 100 South view

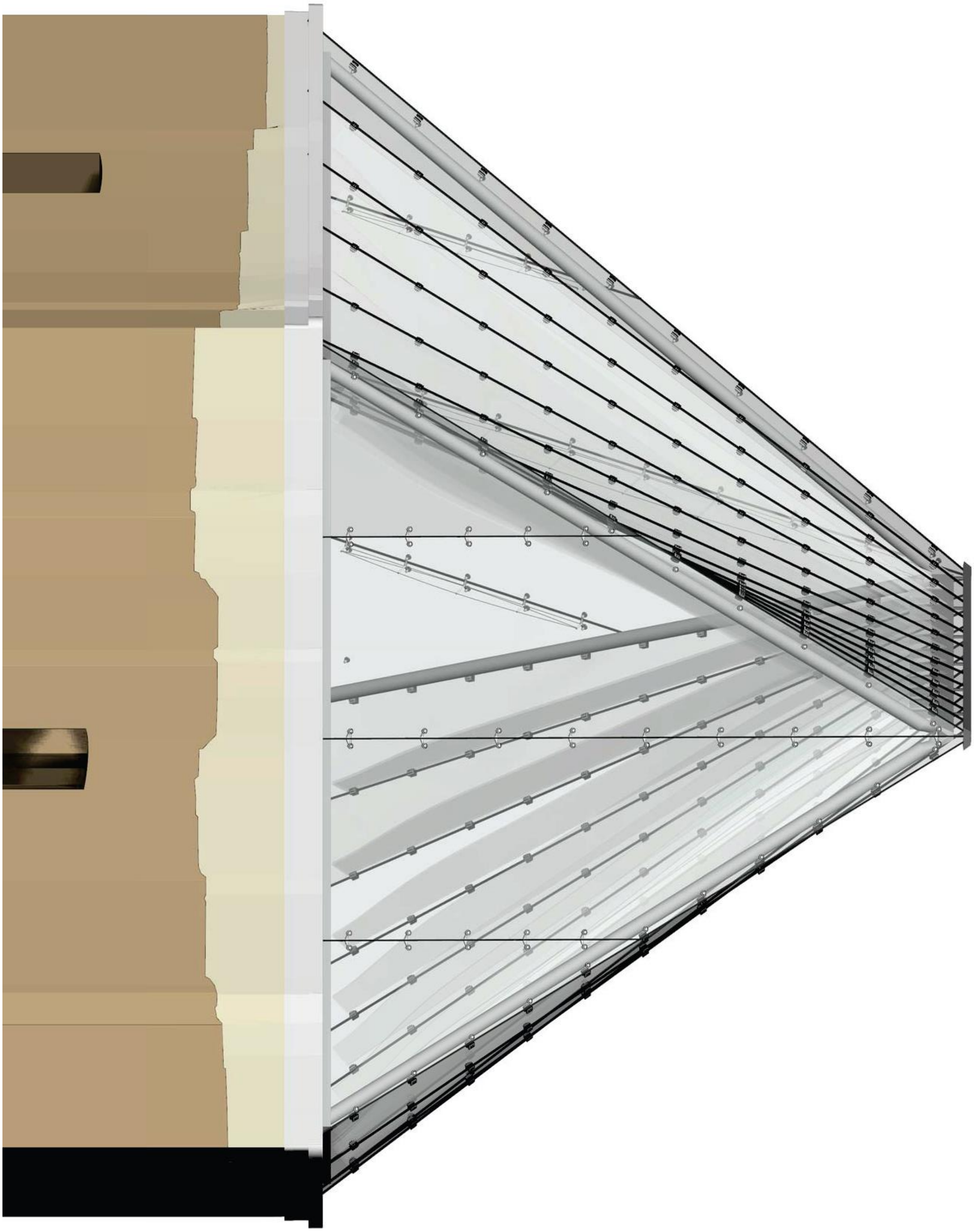


Figure 7.11 South elevation 1:100. Source: own ill.

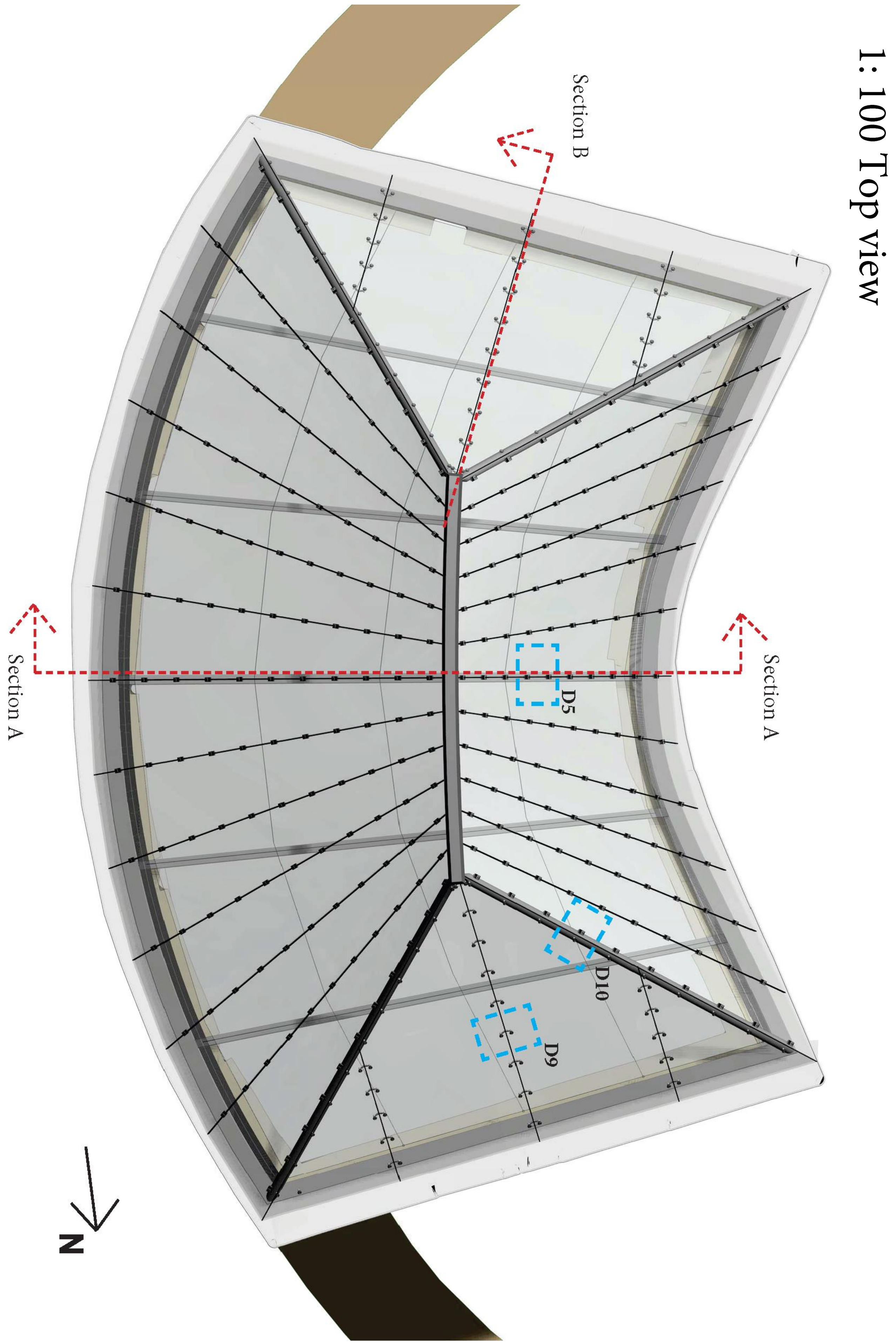


Figure 7.12 Top view of the roof 1:100. Note the location fo the details and sections. Source: own ill.

7.3 Sections and detailing

Figure 7.13 with section A shows the section straight through the middle of the roof, where the glass beams are placed. Notice the different in angle of the roof which changes along the length. This is why the in the background the glass and old walls give such a distorted view. The roof is roughly 8.5 meters high. The position of D1-D4 is shown.

Figure 7.14 with section B shown a section of the roof with the flat sheets of glass, and steel cable trusses. An fish-eye shaped cable truss has been used, in order to keep the transparency at maximum. Just as in section A, notice the steel support legs in the background which sit in between the new masonry bricks. This will be further explained in the detailing.

Figure 7.15-7.27 show the technical drawings of detail 1-10 in 2D and 3D. Each detail is explained with its numbering.

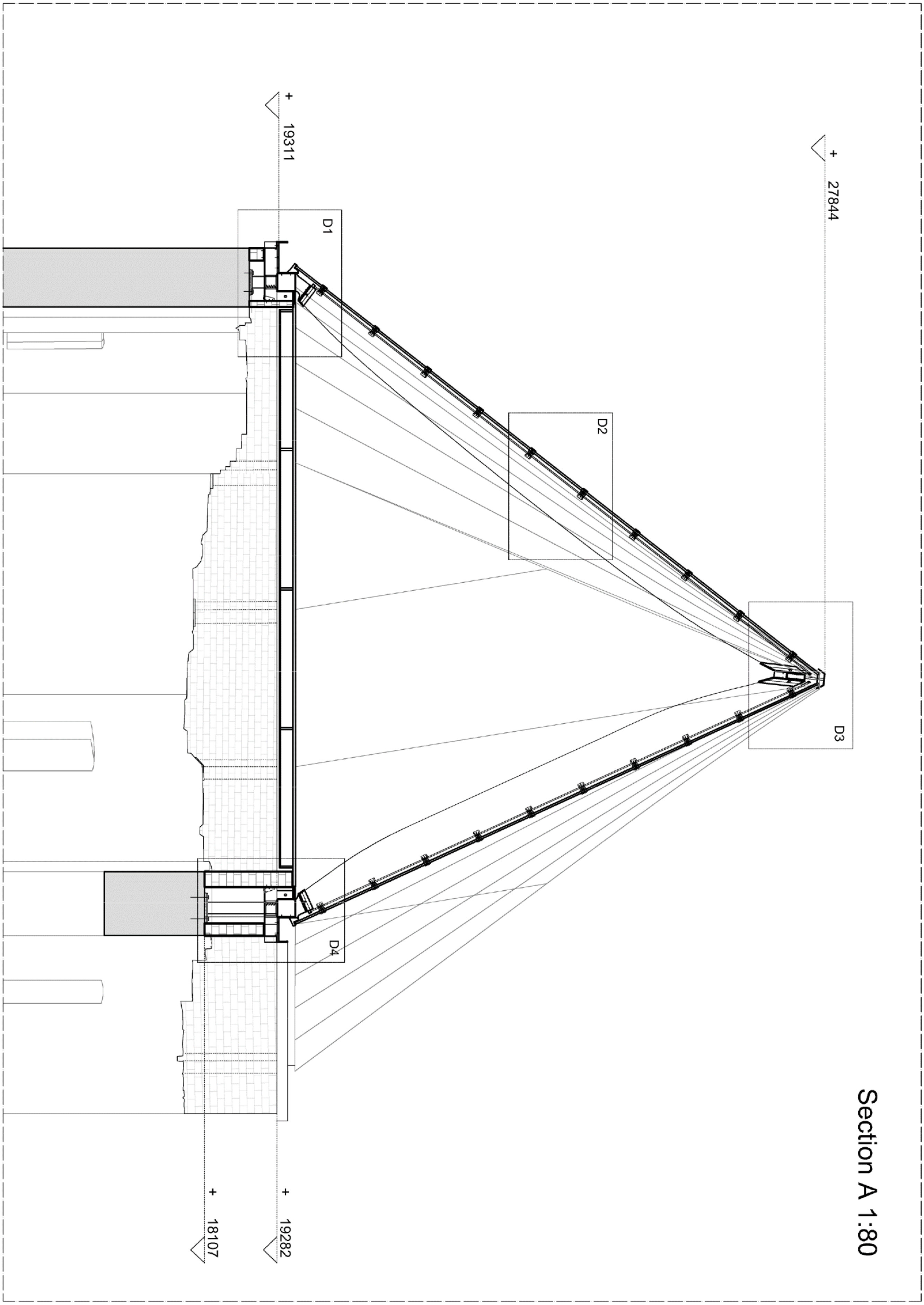


Figure 7.13 Section A 1:80 scale. Source: own ill.

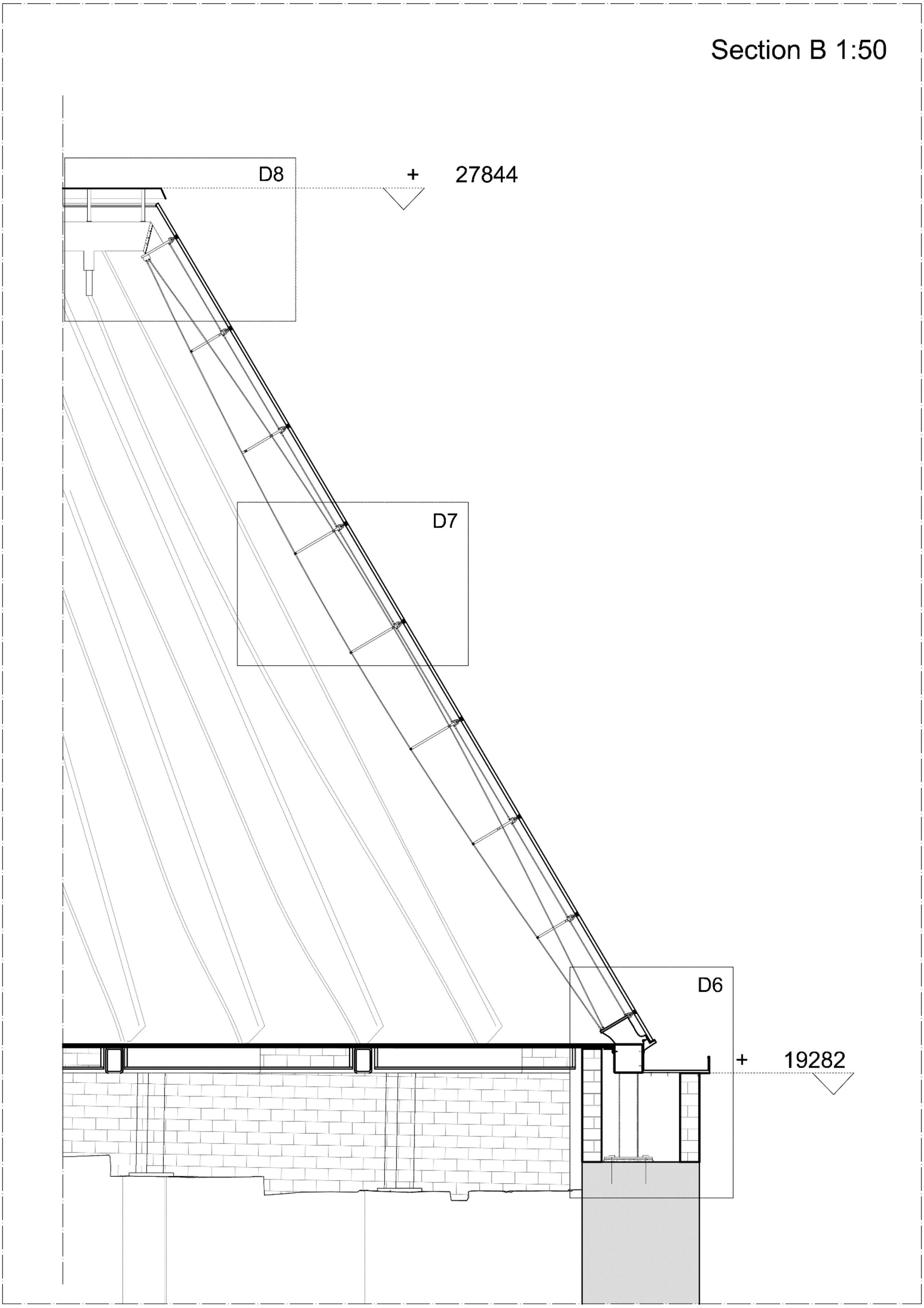


Figure 7.14. Section B 1:50 scale. Source: own ill.

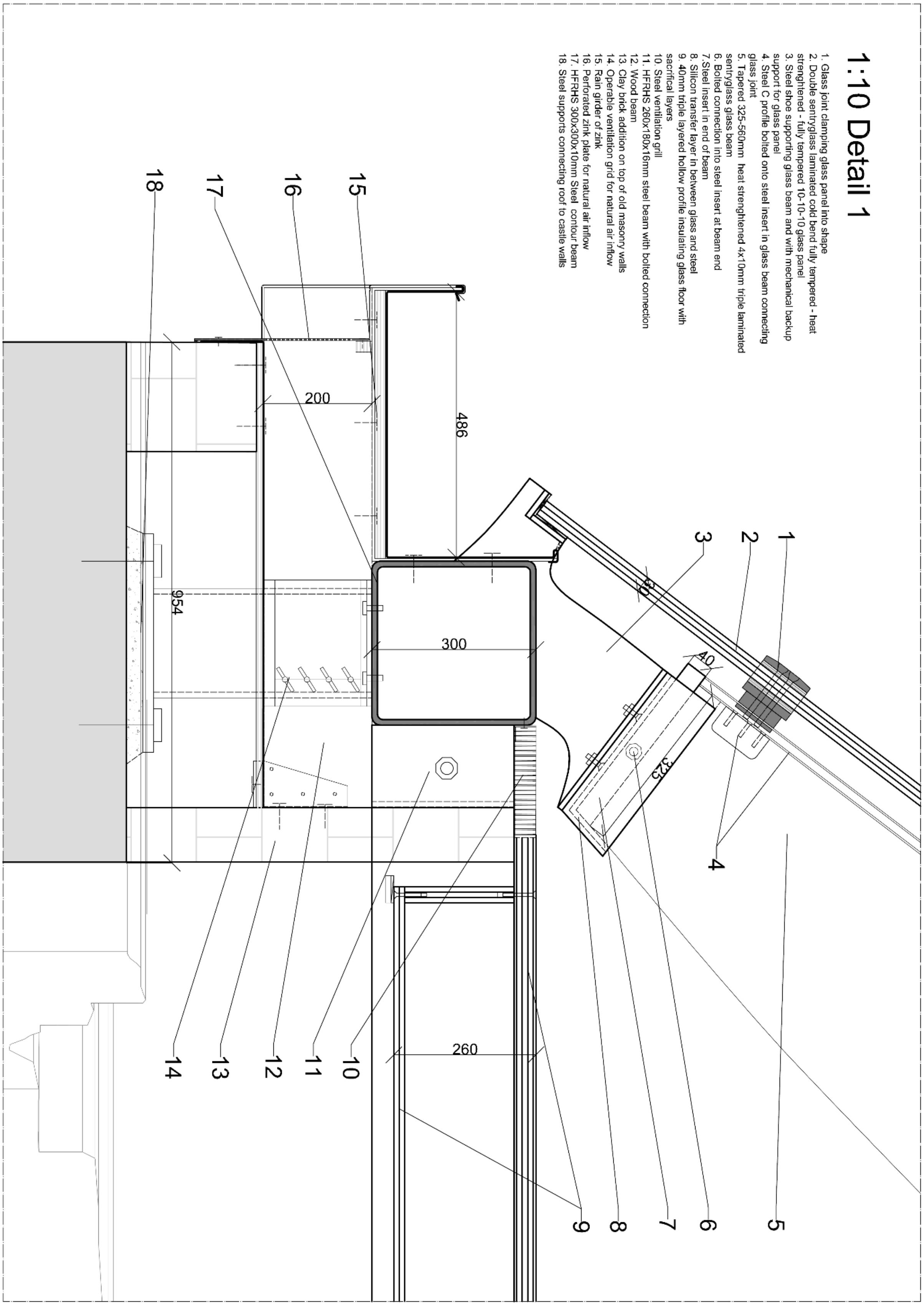
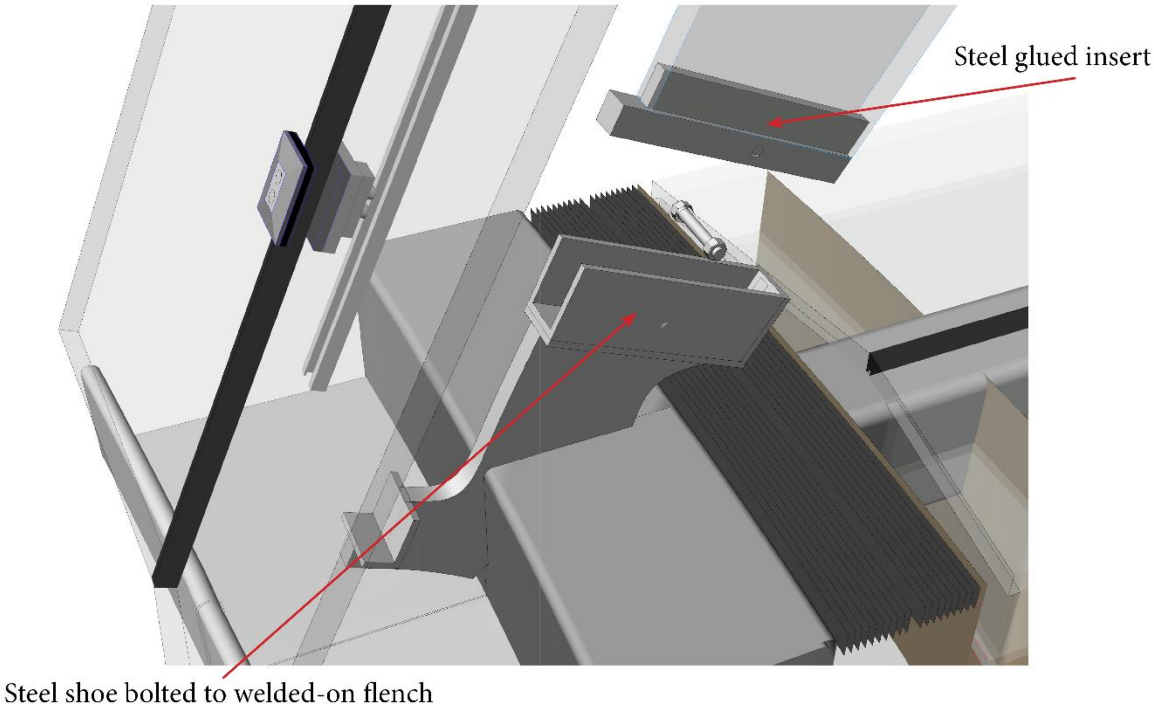


Figure 7.15 Detail 1. Source: own ill.

Detail 1

Exploded view



Assembled

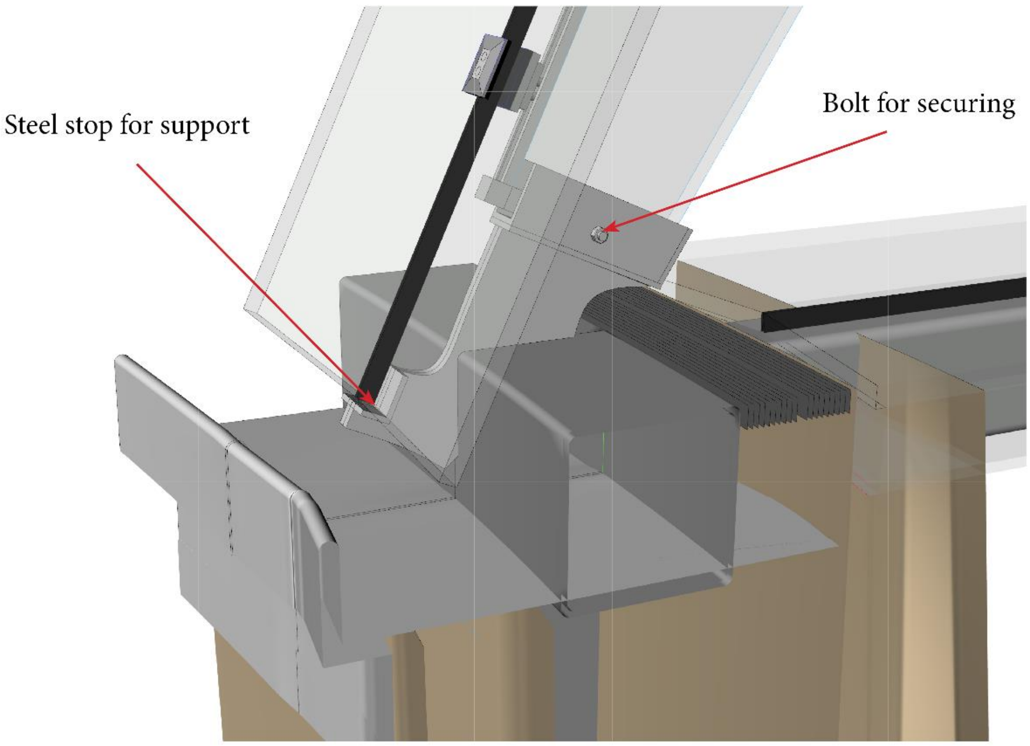


Figure 7.16. 3D image of Detail 1. Source: Own ill.

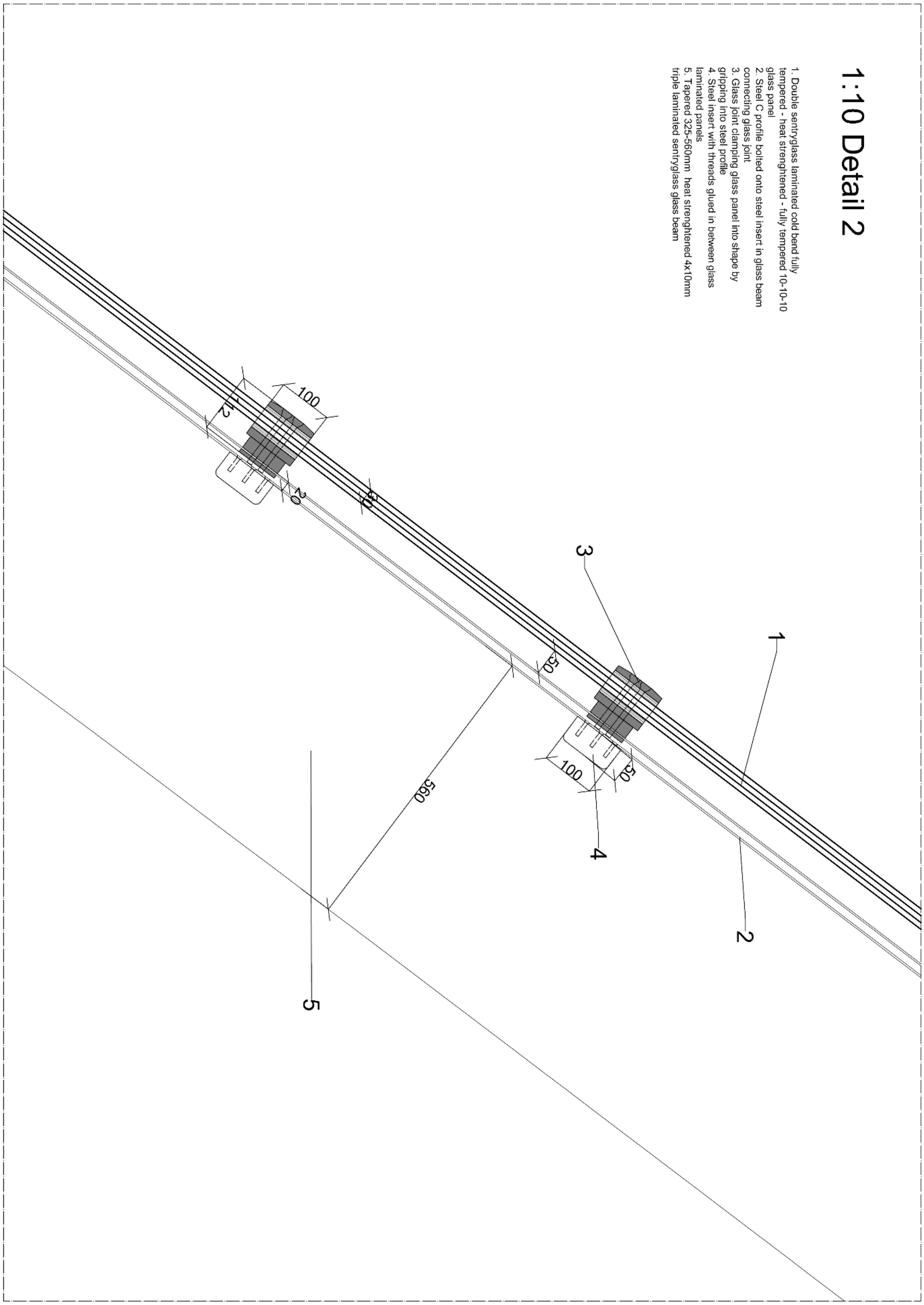
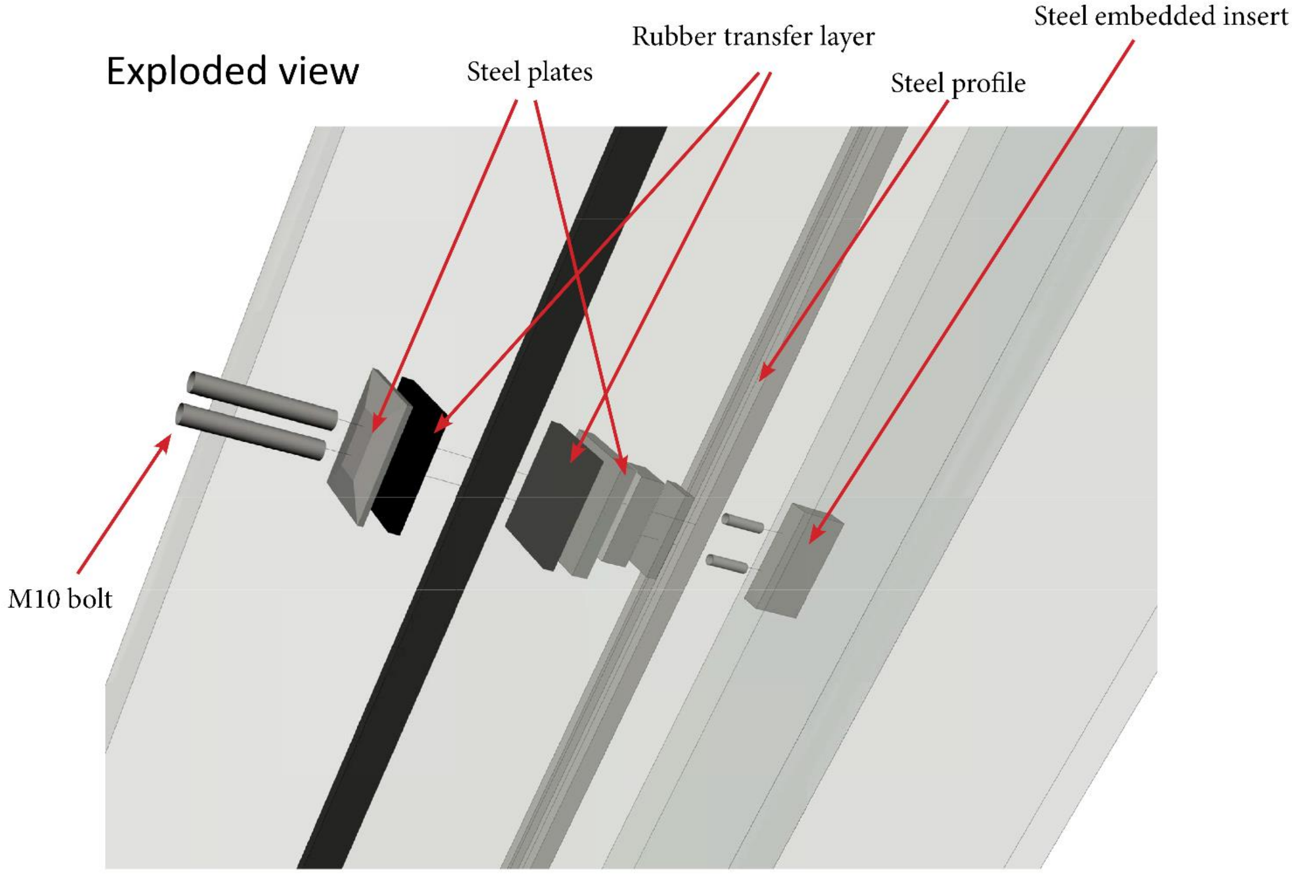


Figure 7.17 Detail 2 1:10 scale. Source own ill.

Detail 2

Exploded view



Assembled

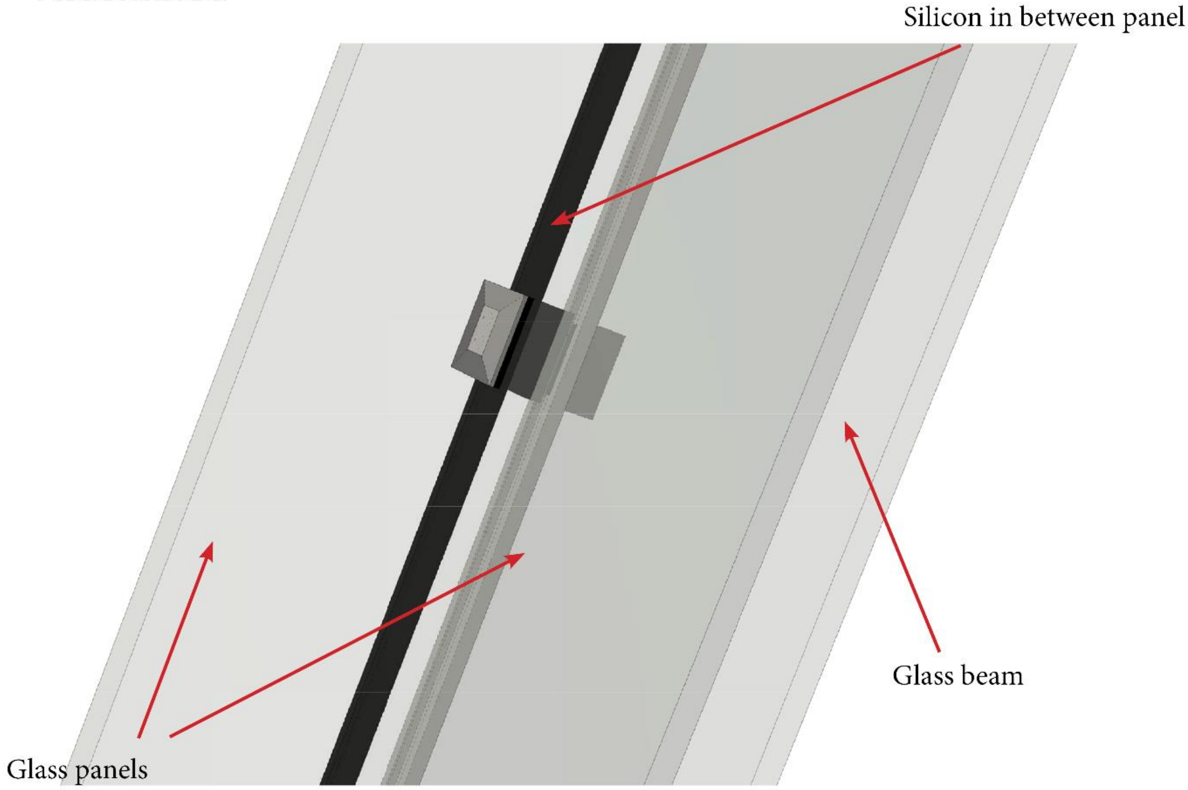


Figure 7.18. 3d image of detail 2. Source: own ill.

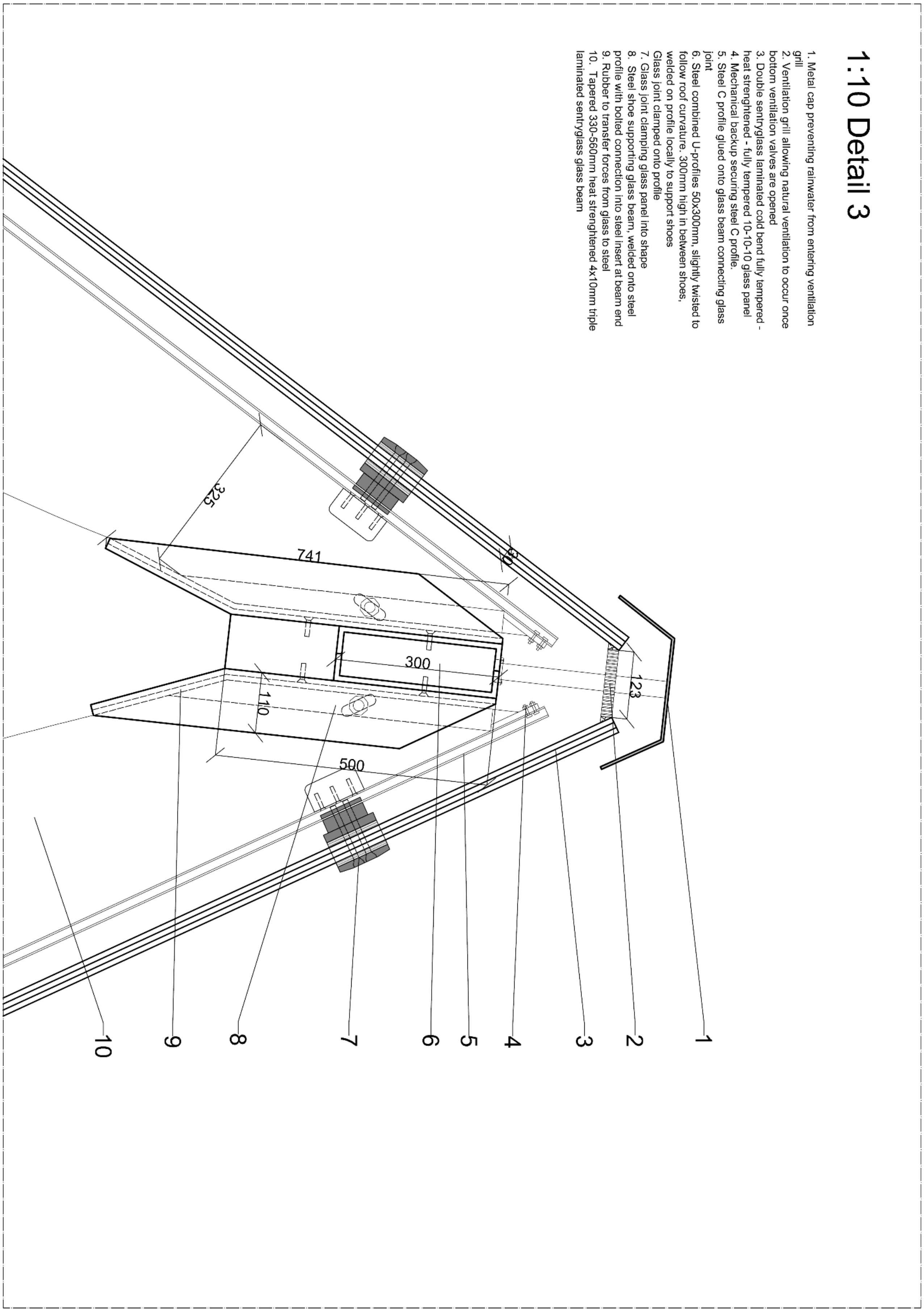
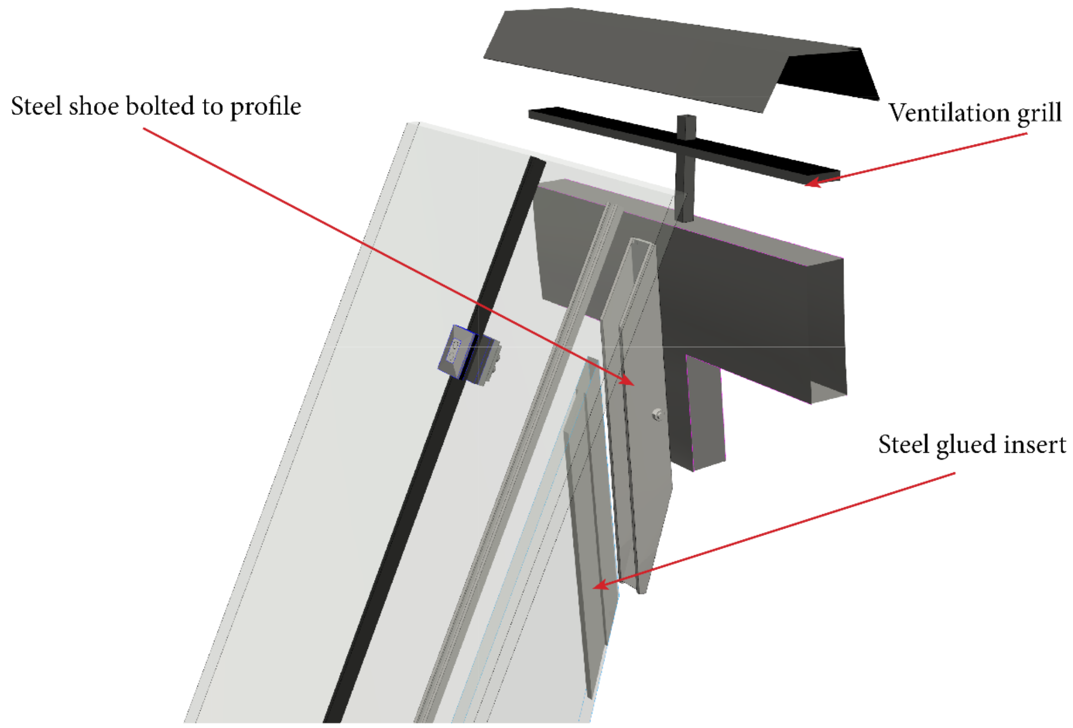


Figure 7.19 Detail 3 1:10 scale. Source: own ill.

Detail 3

Exploded view



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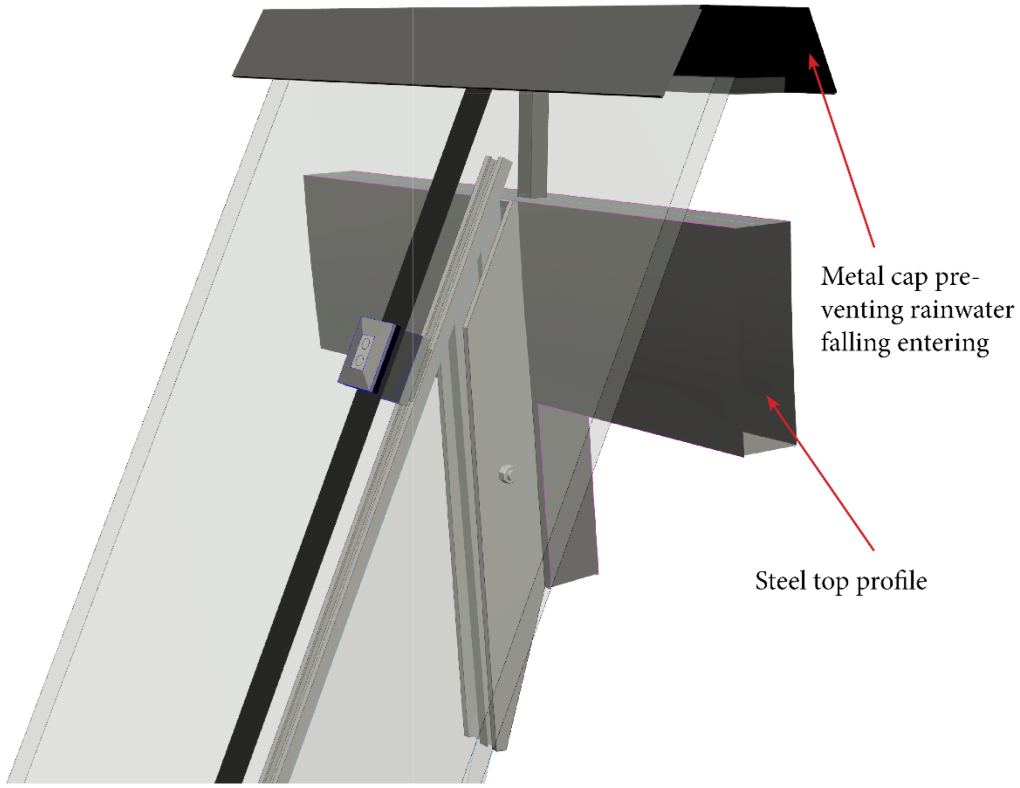


Figure 7.20. 3d image of detail 3. Source: own ill.

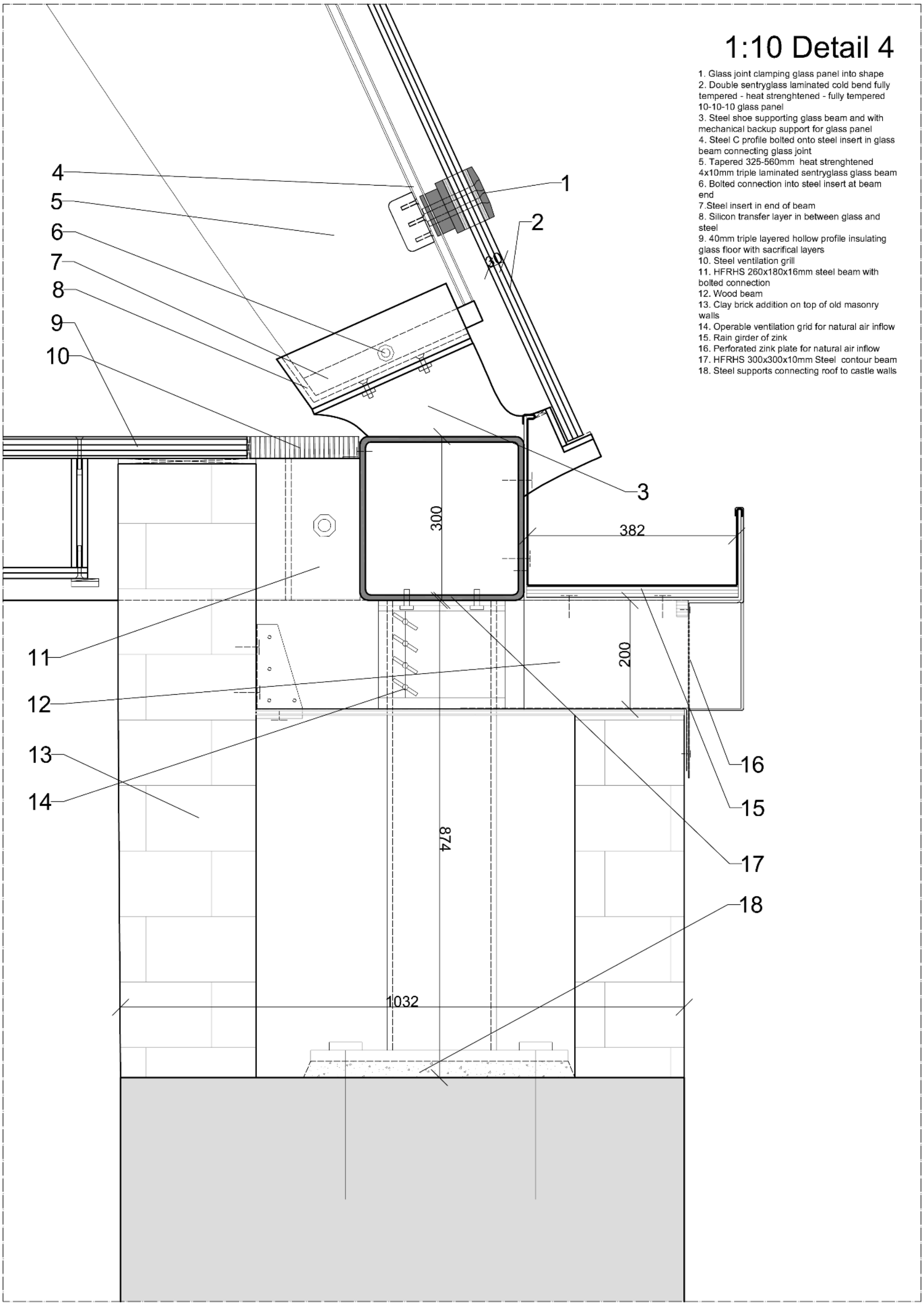


Figure 7.21 Detail 4 1:10 scale. Source: own ill.

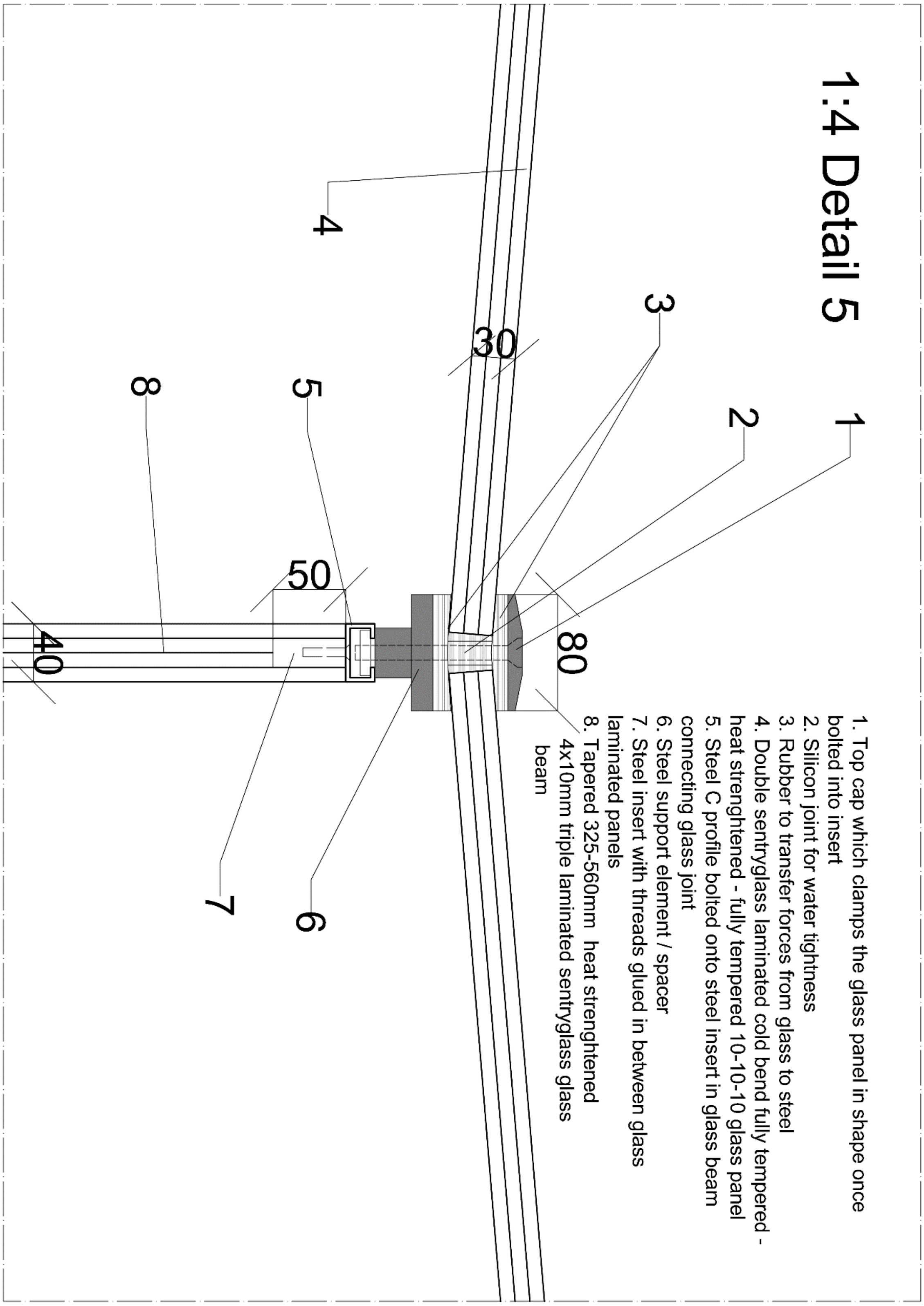


Figure 7.22 Detail 5 1:4 scale. Source: own ill.

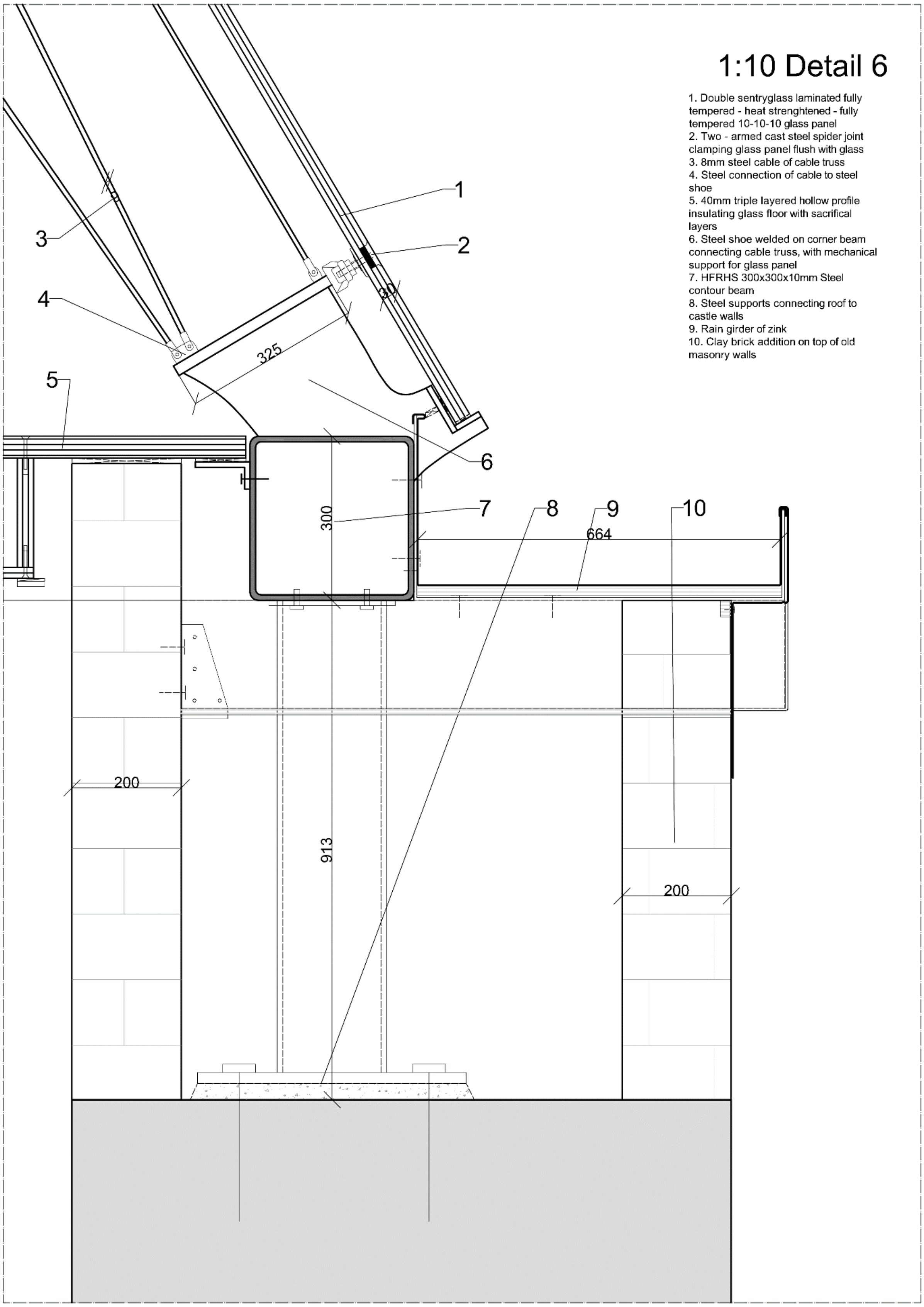


Figure 7.23 Detail 6 1:10. Source own ill.

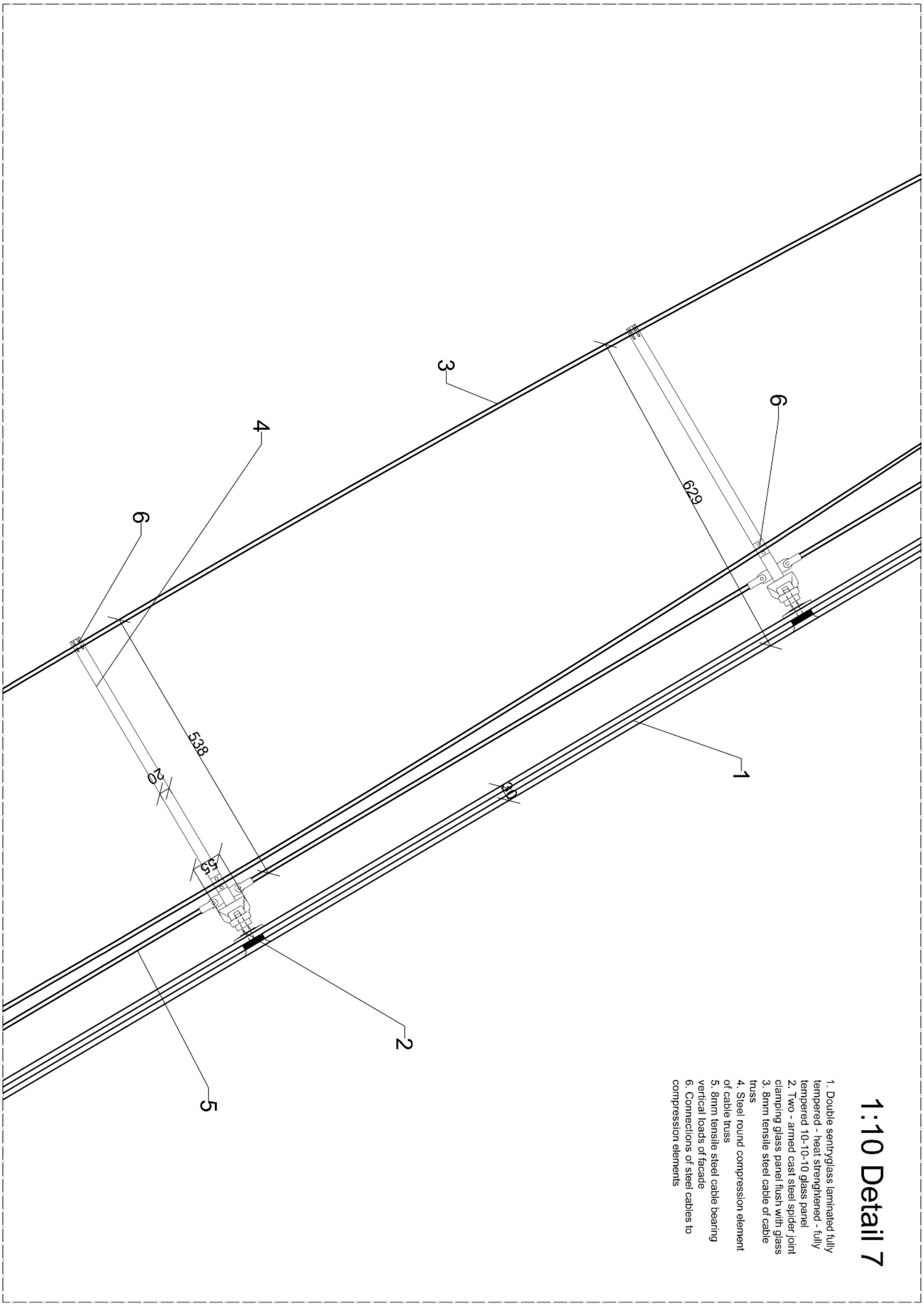


Figure 7.24. Detail 7 1:10 scale. Source: own ill.

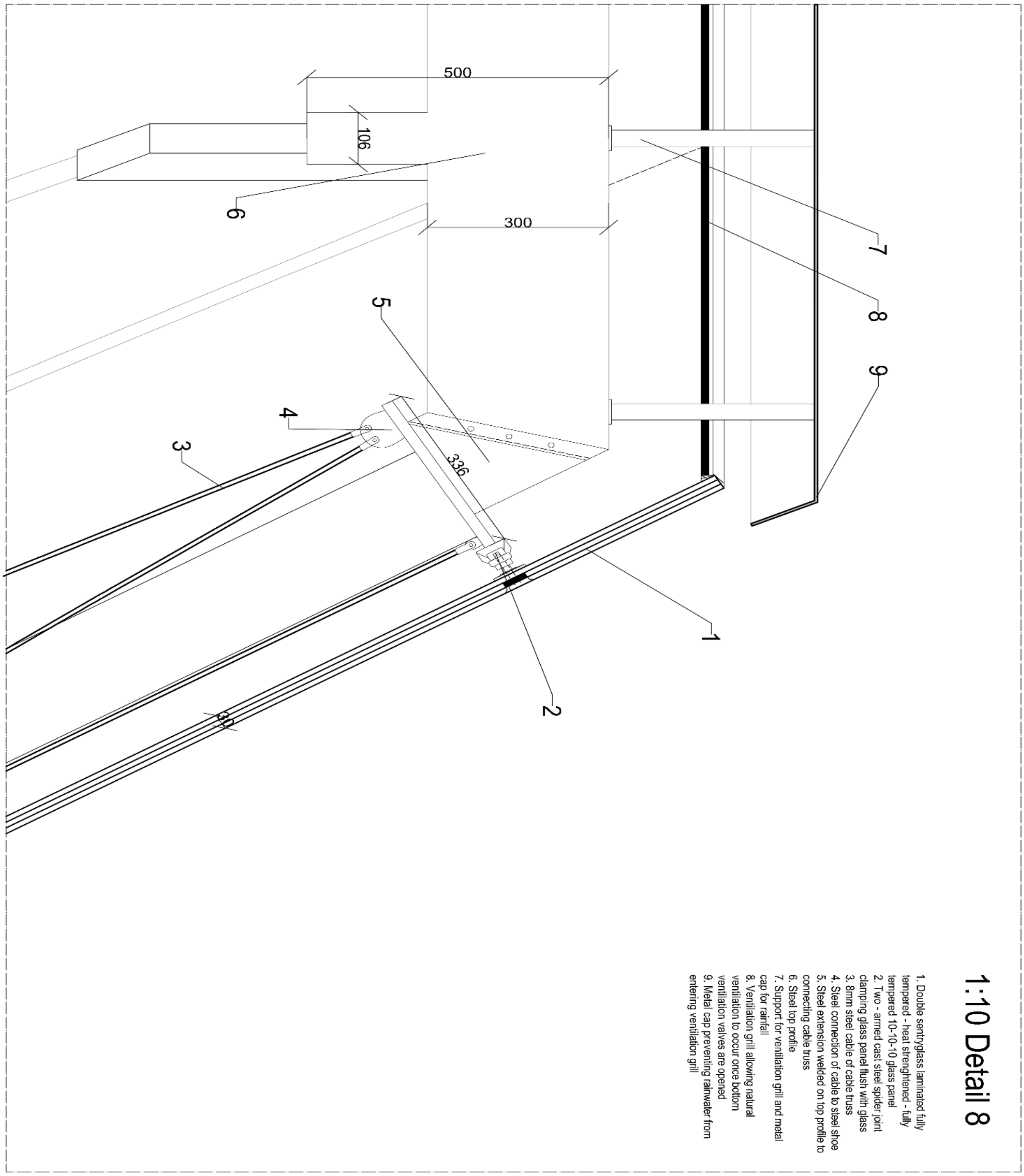


Figure 7.25. Detail 8 1:10 scale. Source: own ill.

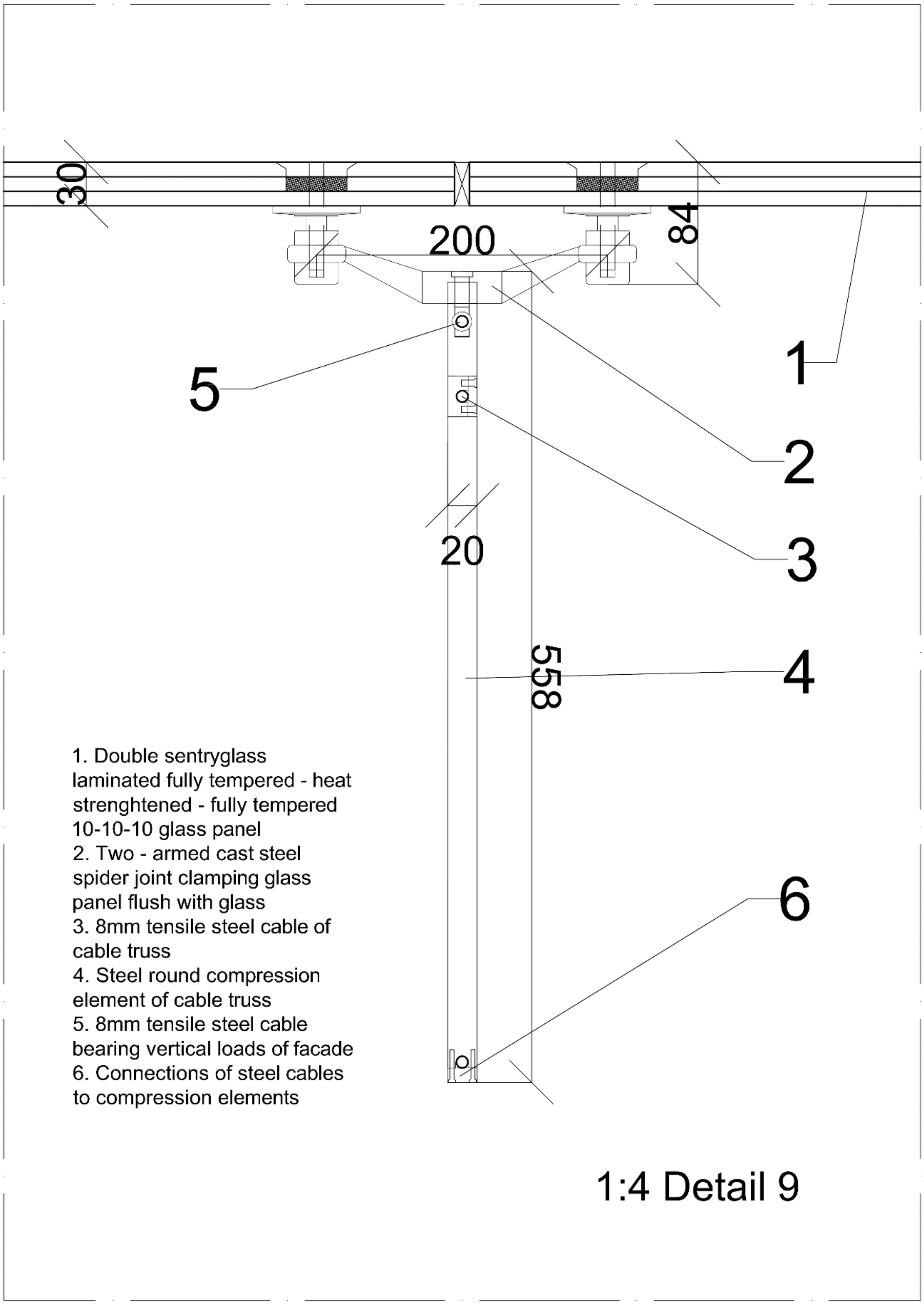


Figure 7.26. Detail 9 1:4 scale. Source: own ill.

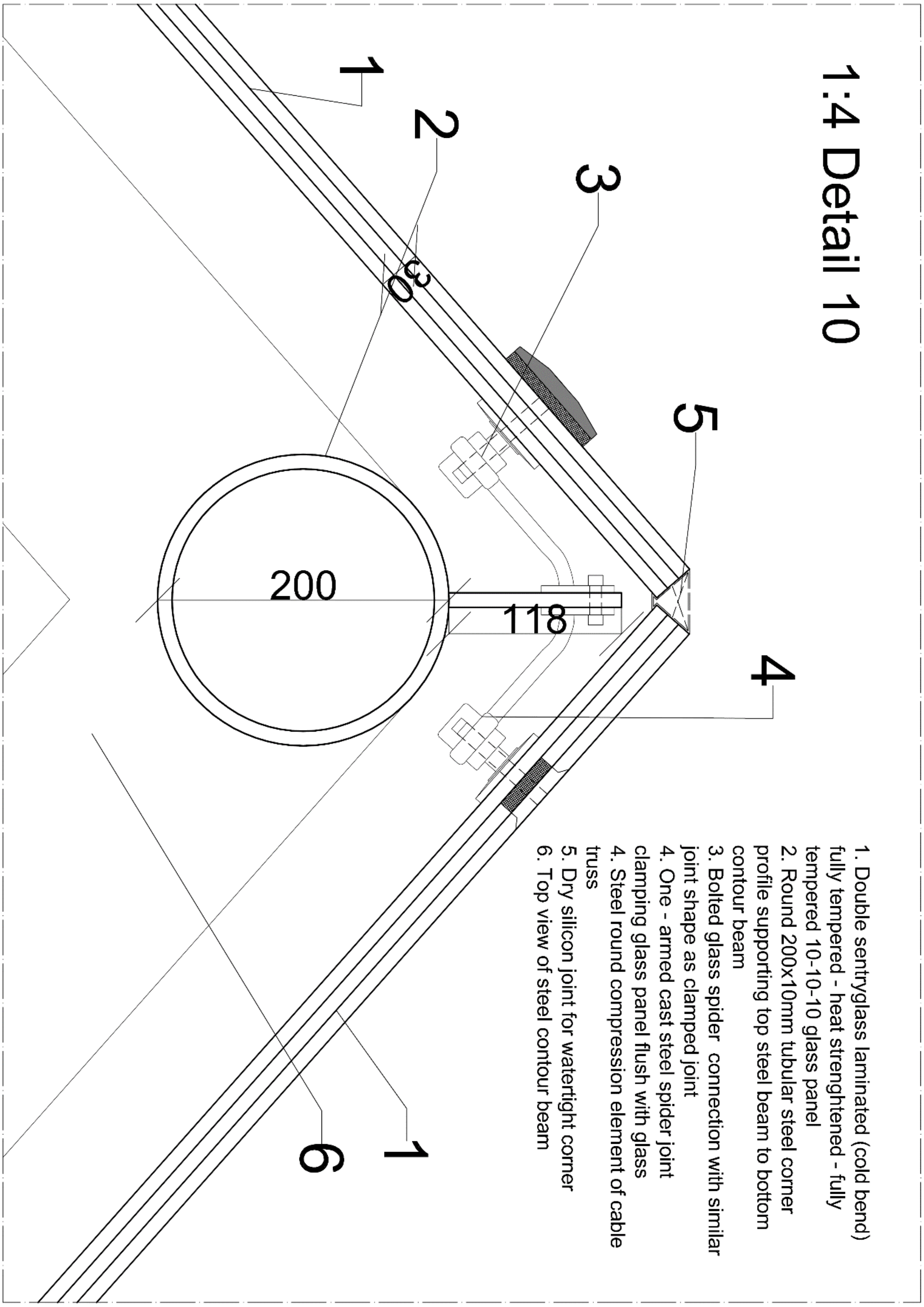


Figure 7.27. Detail 10 1:4 scale. Source: own ill.

7.3 Structural performance of roof

In figure 7.28 the main structure of the roof has been isolated from the total roof, to clearly show its components.

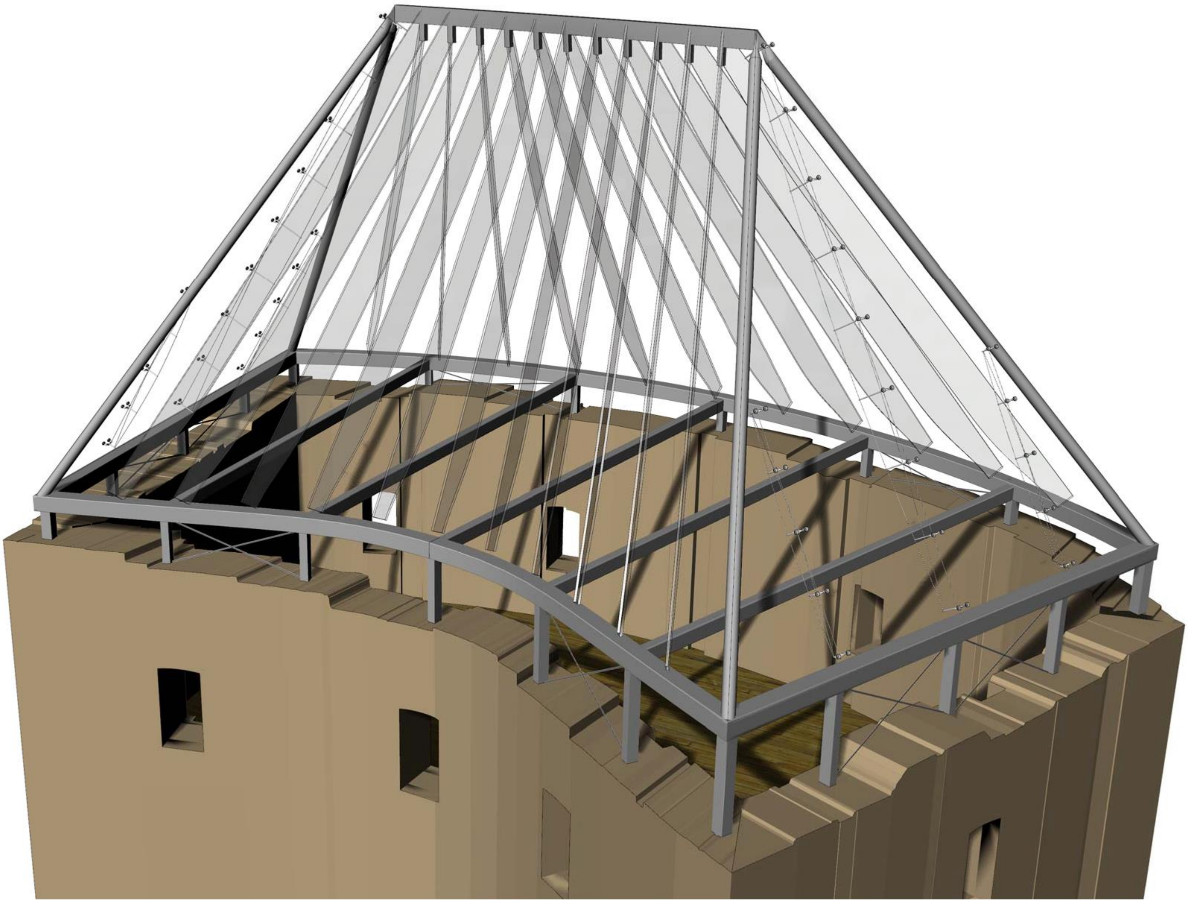


Figure 7.28 The main structure of the roof. Source: own ill.

7.3.1 Stability

If a slice would be taken of the roof, as shown in figure 7.29, it can be seen that the roof partially consists of portals. The connections of the beams are all hinged connections.

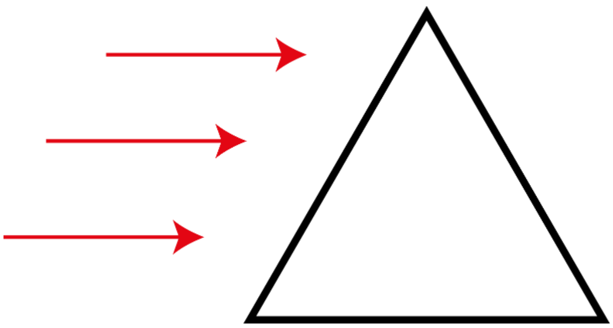


Figure 7.30 Triangle shaped portals. Source: own ill

Figure 7.29 Schematization of a portal of the roof structure. Source: own ill.

Although hinged connections would mean the structure is not capable of resisting horizontal forces, the shape of the structure does make it stiff. This is because the roof is consisting of triangle shaped portals, fig. 7.30. The triangle by itself is a table shape, which does not allow for deformations easily. This is why it able to resist horizontal loading so well. With these portals place along the length of the roof, this helps for establishing stability in once direction.

Another mechanism that is present, is the shear transferring through the seams of the glass panels. The horizontal wind loads will be translated into shear forces in between the panel. If the connections allow for this, this will make the panels work as one stiff whole.

The steel structure also has a rigid connection in the top, which helps making the structure rigid in length direction.

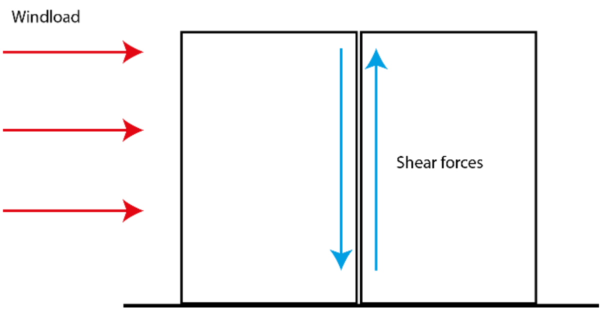


Figure 7.31 Shear forces in plate behavior. Source: own ill

However, the entire structure will not be stiff or stable if only the top part acts as one stiff whole. The horizontal forces also need to be transferred into the support of the structure, meaning into the walls of the castle. If the steel support legs are connected to the steel contour frame using hinged connections, these are not able to transfer horizontal forces. In order for the connections to do allow for transferring horizontal loads, two measures could be taken. The legs could be braced using steel cables, or the legs could be connected with moment stiff connections. Since the legs are rather short (200-1600mm), and they will not be visible due to the new masonry fill-up, it was chosen to use moment-stiff connections together with a few braces. The bending moments will not be that great, it was possible to make a rather large connection to the steel contour beam creating a moment stiff connections. This resulted in the following mechanical scheme's.

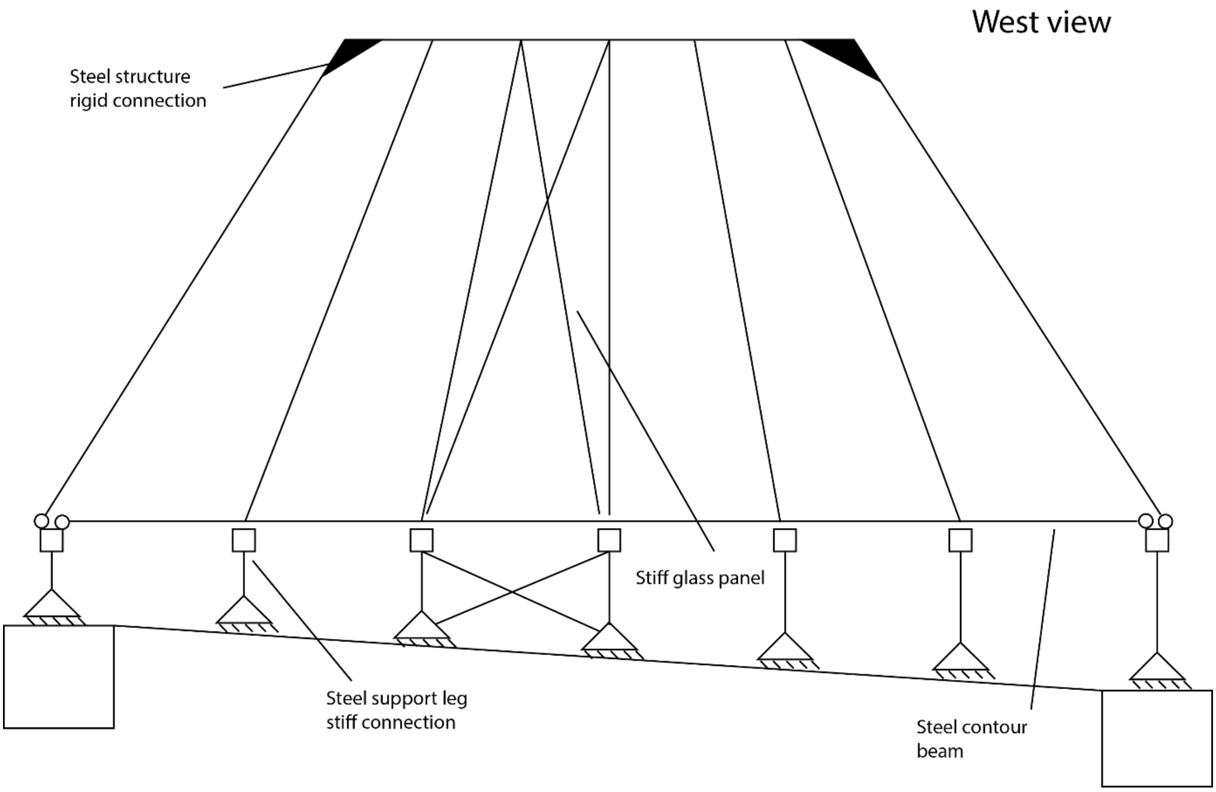


Figure 7.32. Mechanical scheme, west view of the roof. Source: own ill.

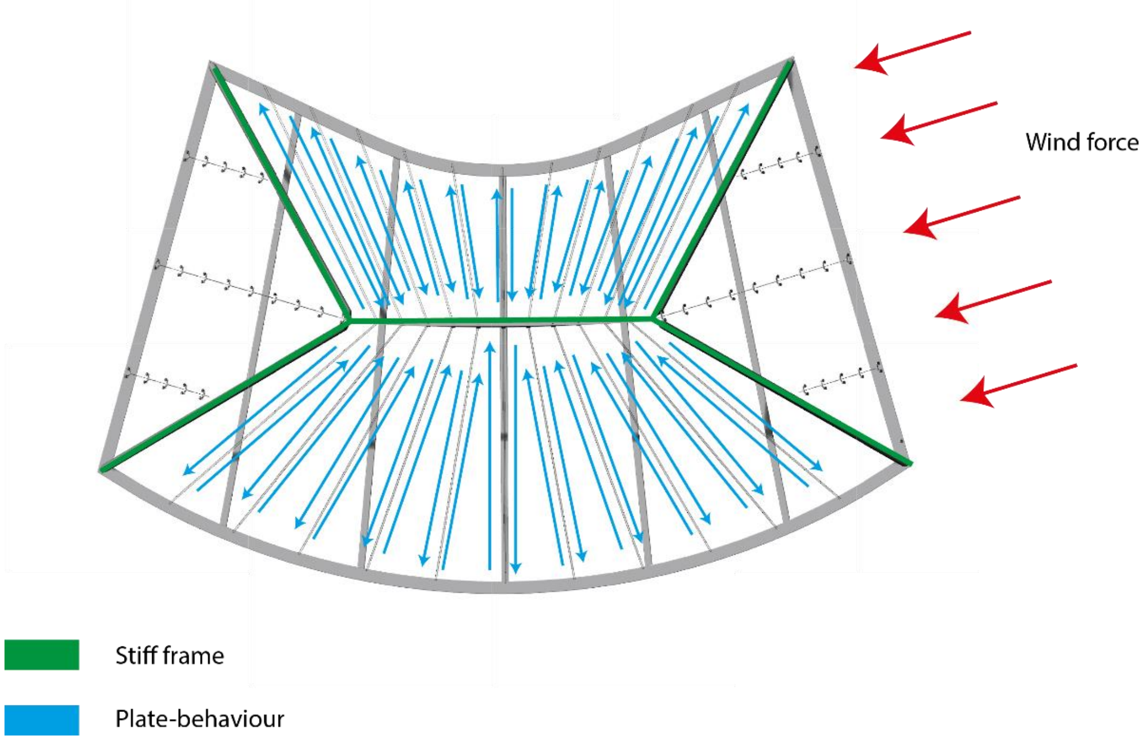


Figure 7.33. Transfer of forces on the north or south facade. Source: own ill.

As seen in figure 7.32 and 7.33, for forces from the north or south direction, the plate behavior of the glass plates helps to stabilize the structure, creating mono-lithic behavior. Also, the steel structure helps, since the connection of the side steel beams to the top beam are stiff connections. By these stiffening corners, the structure becomes one stiff whole. The moment stiff connections of the steel supports transfer loads from the roof to the wall structure.

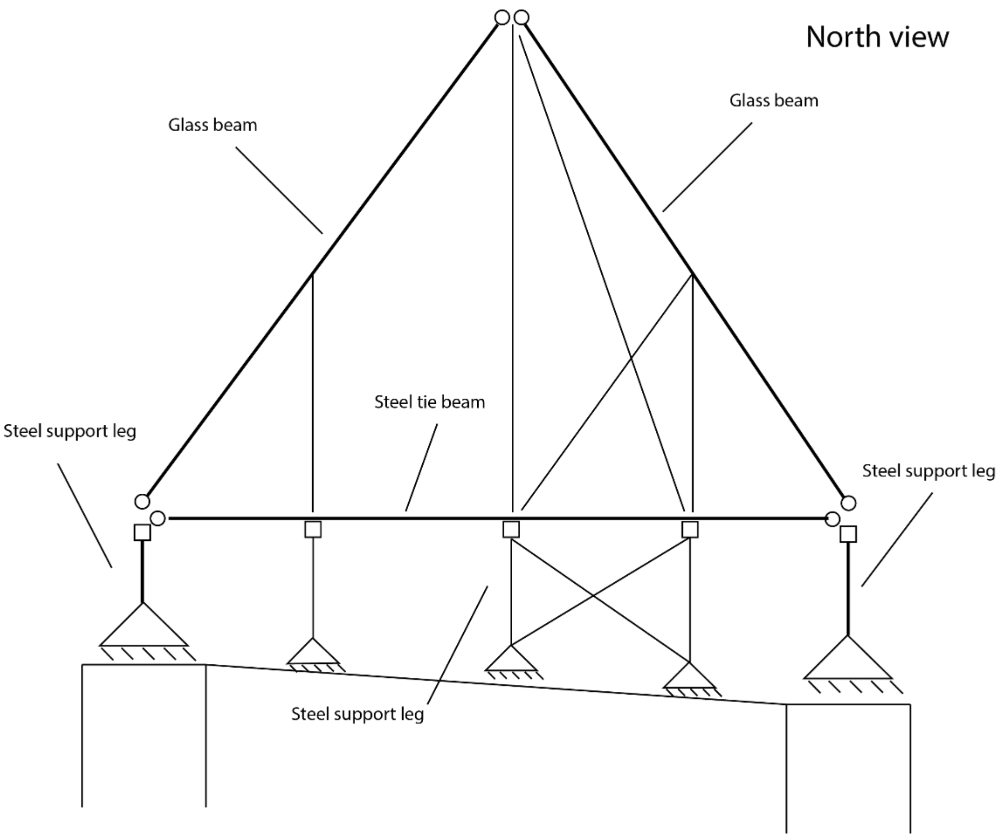


Figure 7.34. Mechanical scheme of north view of the roof. Source: own ill.

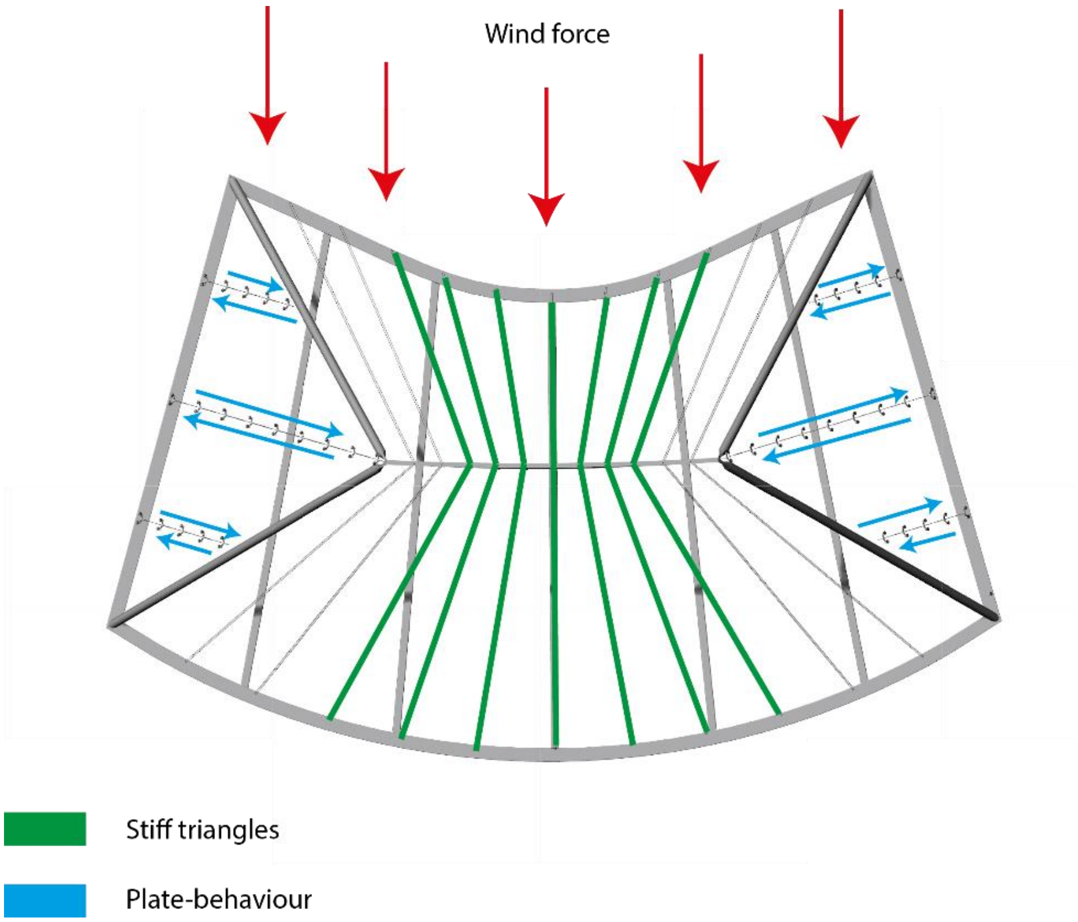


Figure 7.35. The stability mechanism for wind loads to the west or east facade. Source: own ill.

As seen in figure 7.34 and 7.35, for wind loads to the long edges of the roof, the force is transferred by two methods. First of all the stiff triangle portals in the middle of the roof will resist the first forces and translate that into support reactions forces which are lead into the wall. The sides of the roof also work as one plate, creating shear forces in order to act as one stiff plate.

7.3.2 Safety through build-up of elements

The glass beams used consist of 10x4 mm heat strengthened laminated glass panes, with 3 sentry glass adhesive foil interlayers. The sentry glass interlayer (SGP) is of vital importance for the safety of the structure. Even though the heat strengthened glass panes reduce the probability of failure of the beam due to higher strength, in case the glass does break, the sentry glass foil layer with keep the broken glass together. Compared to PVB foil the SGP has 5 times higher tear strength, and makes the laminated component 100 times more rigid(Faidra Oikonomopoulou, 2012). This means even after that all the panes have broken, the beam is still capable of carrying some loads.

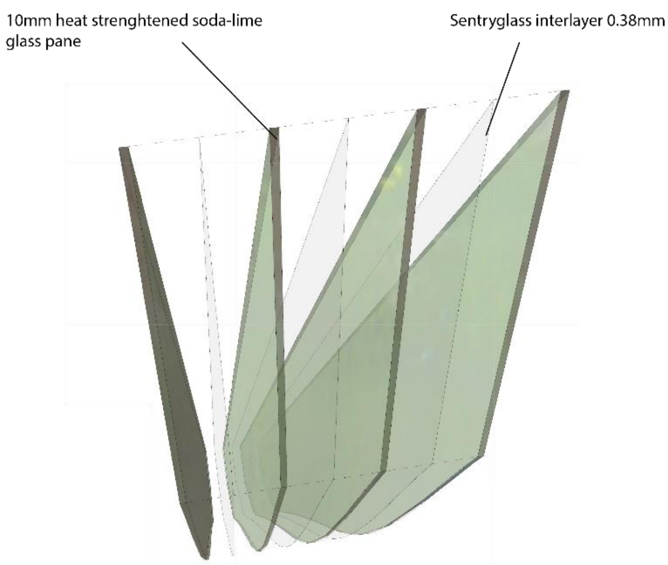


Figure 7.36 Laminated glass beam. Source: own ill.

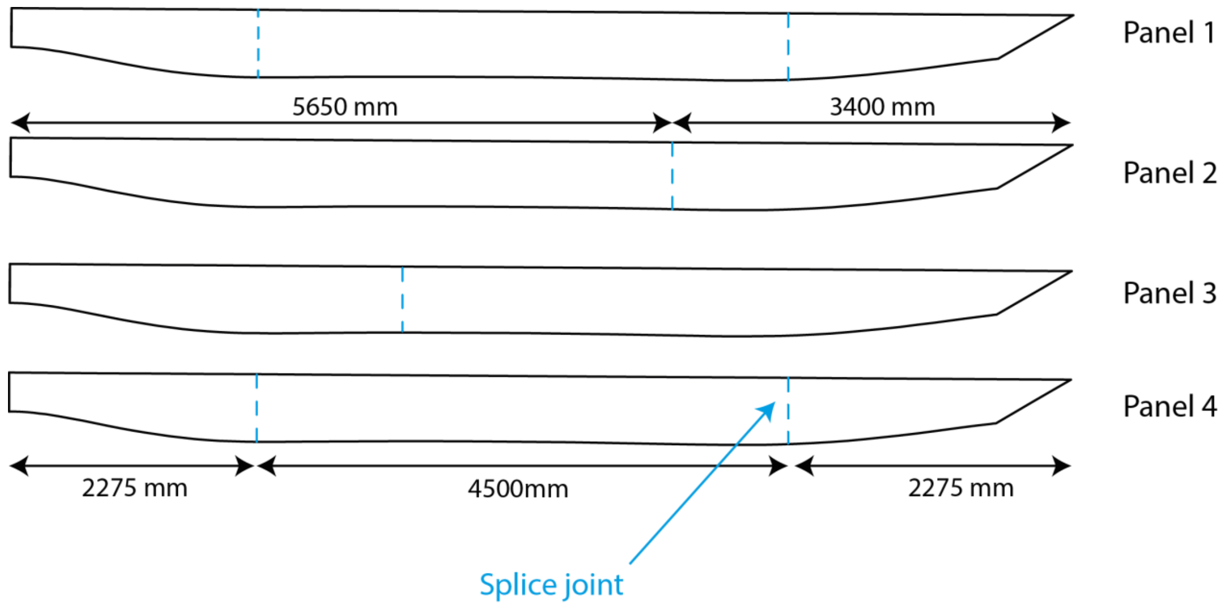


Figure 7.37 Spliced laminated glass beam. Source: own ill.

To reduce the cost of the structure, the 9-11 meter long beams are build up several smaller glass elements. This process is called splice laminations, where smaller panes of glass are laminated such with careful positioning of the joints, that together this forms a strong and stiff beam. The joint should barely be visible.

7.4 Façade design

In figure 7.38 the façade of the structure is isolated to take a better look.

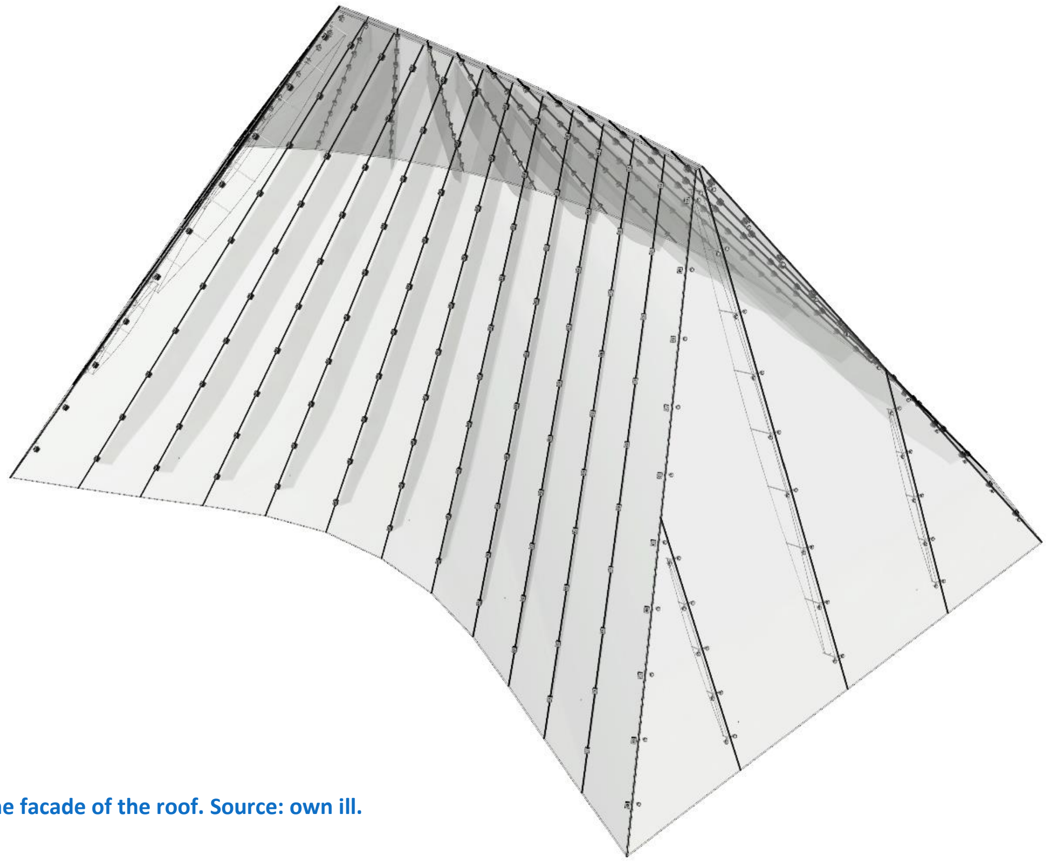


Figure 7.38 The facade of the roof. Source: own ill.

7.4.1 Elements used

The west and east side of the roof consists of cold bend glass panels. As seen in detail 5, a clamping joint is used to push a flat piece of glass into shape to fit the curvature. This cold bending is done on-

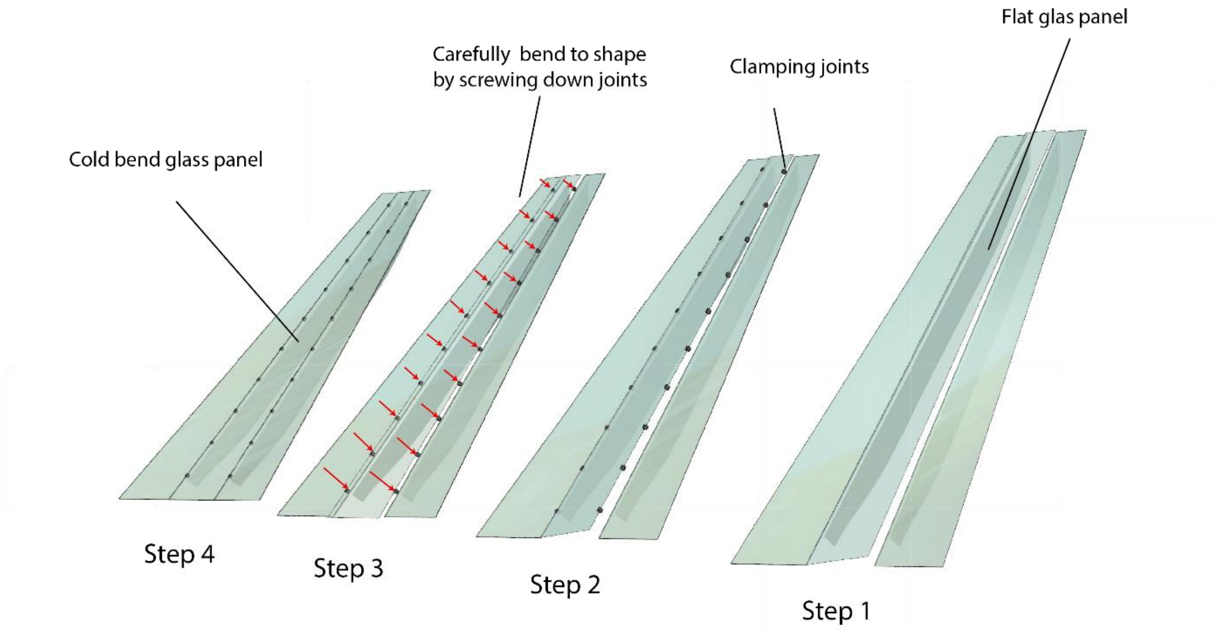


Figure 7.39 The cold bending process of a flat panel of glass. Source: own ill.

site. Figure 7.39 illustrates the cold bending process.

Since the curved glass panels require special connections which can exert a large force, these connections are not specifically required for the two flat surfaces of the roof. Here steel cable trusses are used as primary support structure, which are inevitably slightly flexible. This means that the joint to the glass panels therefore requires to be flexible to bending moment on the glass panels. This is why glass spider connections are used, which allow for some movement of the glass panels. The two types of connections and its locations are illustrated in figure 7.40.

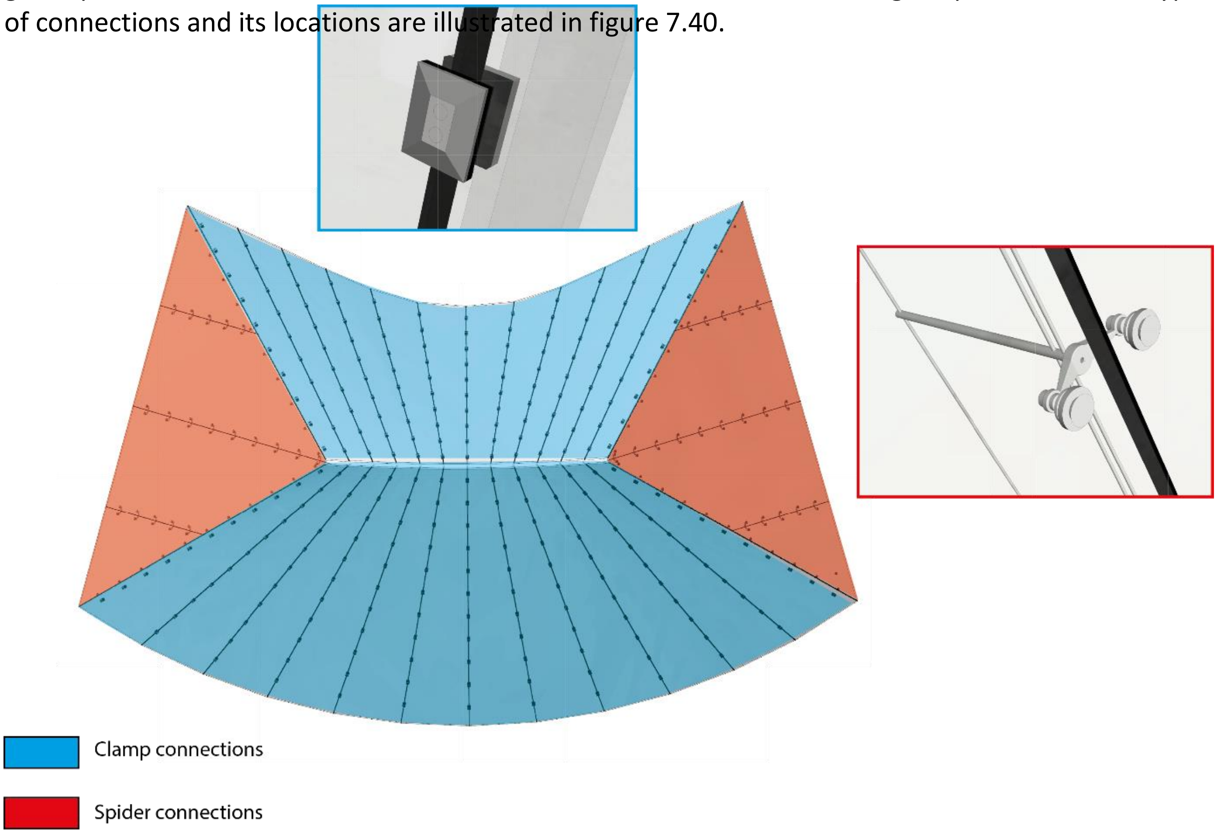


Figure 7.40 The two types of glass connections and its corresponding location. Source: own ill.

7.4.2 Establishing safety

The glass panel consist of 3 layers of 10mm soda lime glass, laminated together with 2 layers of SGP adhesive foil, see figure 7.41. In case the glass panels does break, the panel will be held together by the SGP foil. In order to minimize the probability of failure of the glass panels, heat-treated glass is used. Instead of using the same type of glass, the two outer layers of the panels are fully tempered glass panels, and the middle layer is heat strengthened glass. This combination of types is used to combined the two properties of both glass type. The high tensile strength of the fully tempered glass is used to bear the high stresses in the glass due to torsion of cold bending, and the point loads due to the point clamped fixations which deform the glass panels. In case three layers of fully tempered glass will be used and these panels do break, even despite the SGP interlayer foil the glass breaks in many small pieces, which will deform that much that the entire 1000 kg panel may fall down from the glass beams. This is why the middle layer of heat-strengthened glass is used. Since this glass breaks in larger pieces, it acts as a stabilizing element, keeping the large panel intact and in shape.

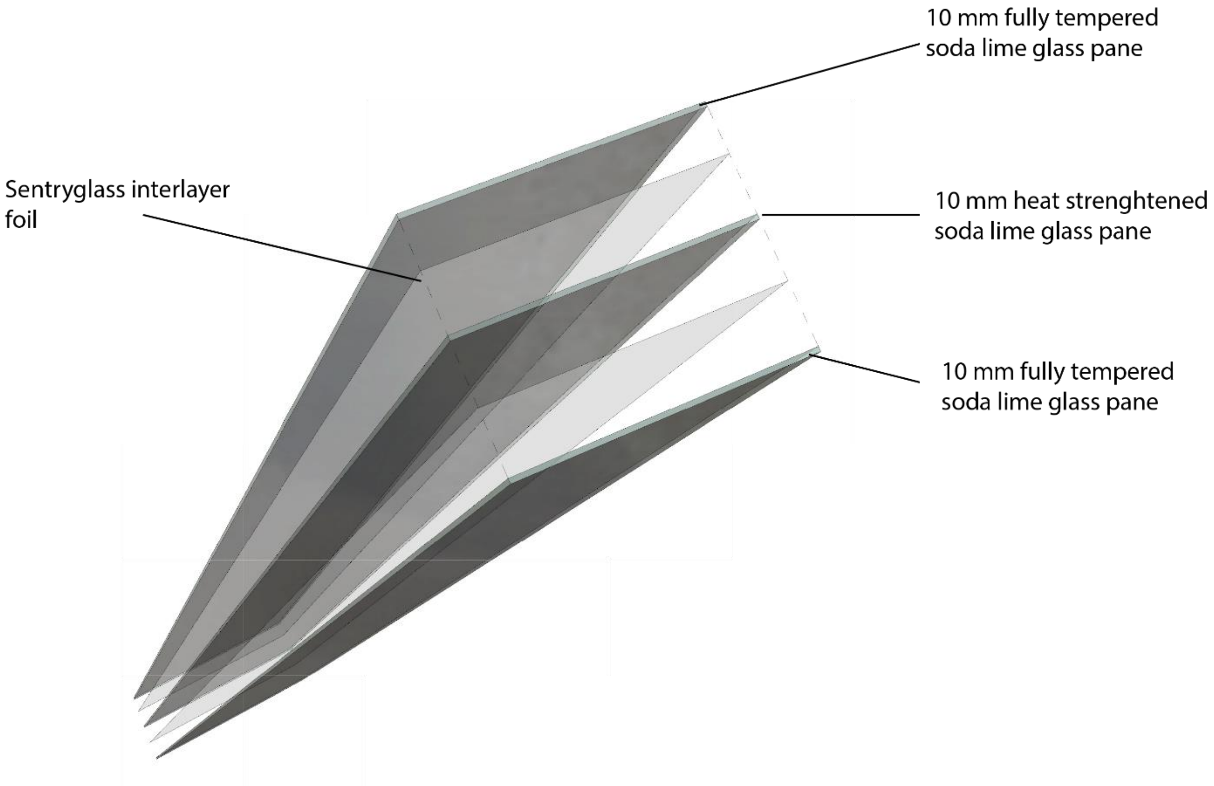


Figure 7.41. The laminated buildup of the glass panels. Source: own ill.

7.5 Climatic performance

As explained in paragraph 6.4.1, if no measures will be taken against sun load, there is a serious risk of heavy overheating of the roof. Therefore measure are integrated in the roof design, which will be explained in this chapter. No further calculations have been made, since this was not the focus of this research.

7.5.1 Climatic scheme's

7.5.1.1 Ventilation

In order to prevent overheating of the roof, the roof will be naturally ventilated. Ventilation inlets are integrated in the rain girder to let in air. These inlets can be operated to either be closed or open, according to the ventilation need in winter or summer. At the top of the roof a grill is added, which is always open. This way cold air enters the roof, heats up creating a vertical draft and then flows out outside at the top.

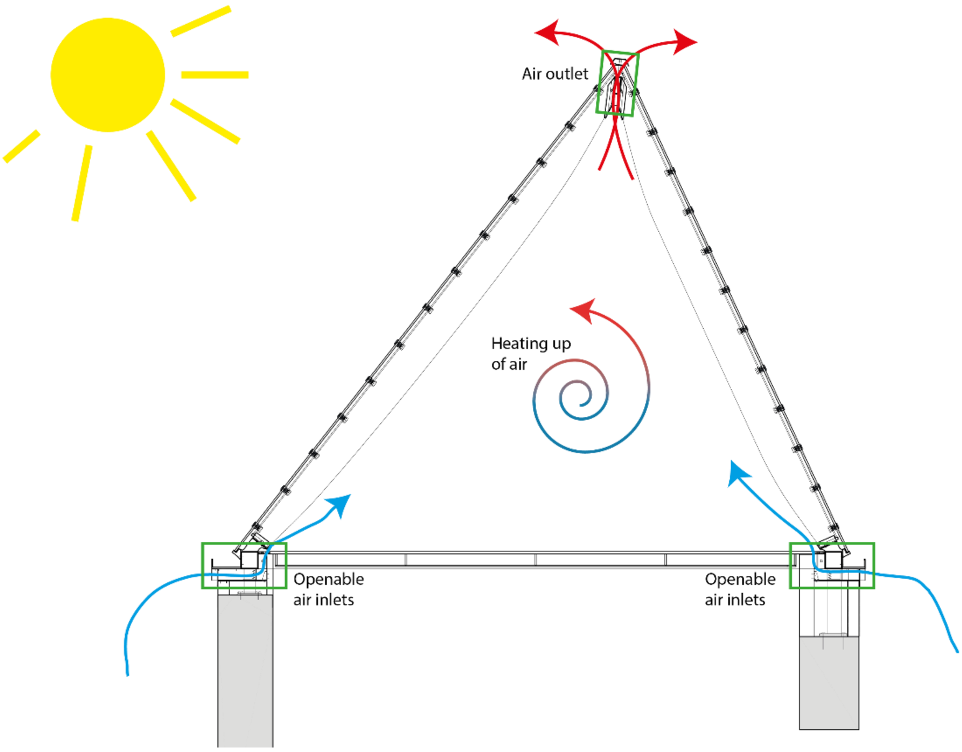


Figure 7.42 The natural ventilation scheme for the roof. Source: own ill.

7.5.1.2 Insulation barrier

In figure 7.43 the insulation barrier is explained. The glass panels from the roof itself are not functioning as insulation layer, since they consist of solid single panes of glass. This is done because insulating layer is located in the hollow floor of the roof. This allowed the glass panels to be single panes instead of insulated glass panel, which is cheaper and less complicated to cold bend. This results in the fact that the inside climate of the roof is a semi-outdoor climate, with partial comfort. This means temperature are allowed between 18-35 degrees(Faidra Oikonomopoulou, 2012). Therefore it is allowed to use non-insulating panes of glass.

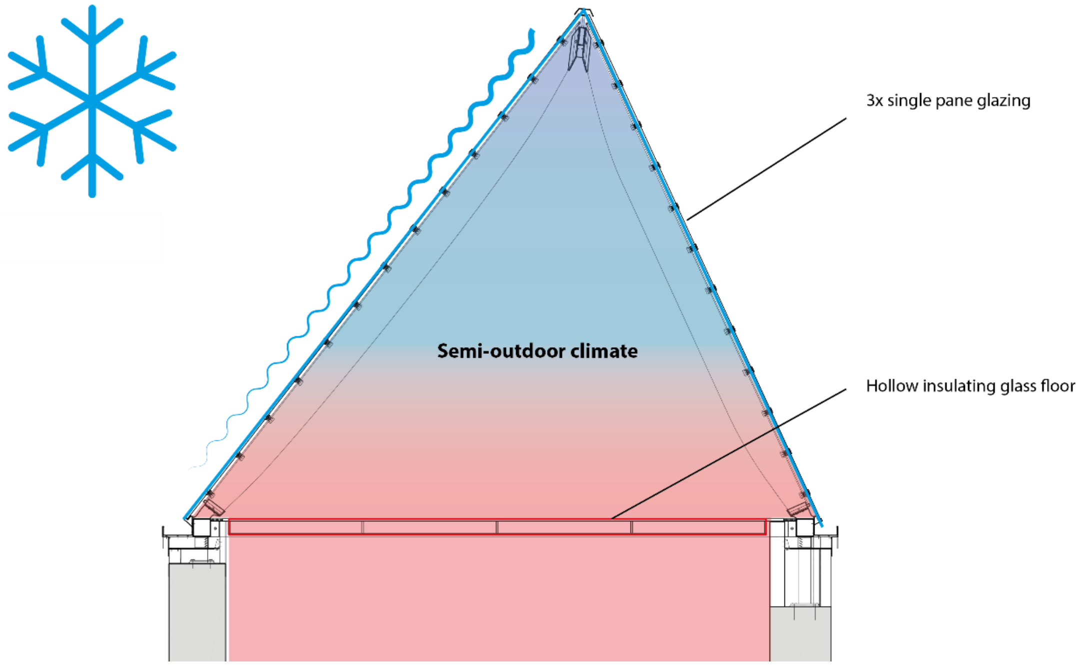


Figure 7.43 The insulation barrier. Source: own ill.

7.5.1.3 Water barrier

Figure 7.44 illustrates the water barrier of the roof. Although the interior is a partial-outdoor climate, this does not mean water is allowed inside the structure. Therefore the barrier is located at the exterior surface of the roof. At the top a metal cap is placed above the air inlet to prevent water from entering the structure. In between the panels a silicon seam is located which is watertight. The water flows down the roof towards the rain girders, where it can be drained away downwards. This prevents water from hitting the masonry walls, there for protecting it from erosion.

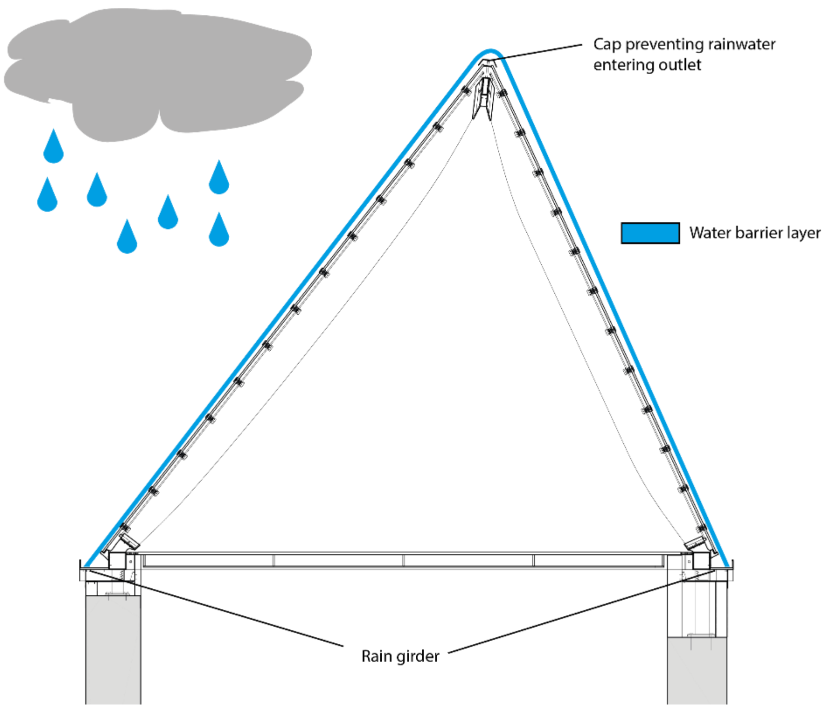


Figure 7.44 The water barrier of the roof. Source: own ill.

7.5.2 Low-e glass

In order to reduce the sun load in the summer, and heat loss during winter, Low-emissive (Low-e) glass is used. One material that could be used in the Pilkington Activ Suncool™ glass. This float glass is given a coating during the manufacturing process., which combines the advantages of self-cleaning with sun protective properties. The coating prevents organic filth to stick to the glass, which therefore requires less cleaning. UV-radiation is used from daylight to break down the organic filth, which is then washed off by the rain. The sun protective coating consists of a very thin metaloxid layer, which allows for maximum light penetration while reducing the amount of heat by sunlight entering the glass, and reducing the emission of heat from inside to outside. This way during summer the heat is kept out, and in winter the warmth is kept inside. By these means a comfortable climate all year is created inside.

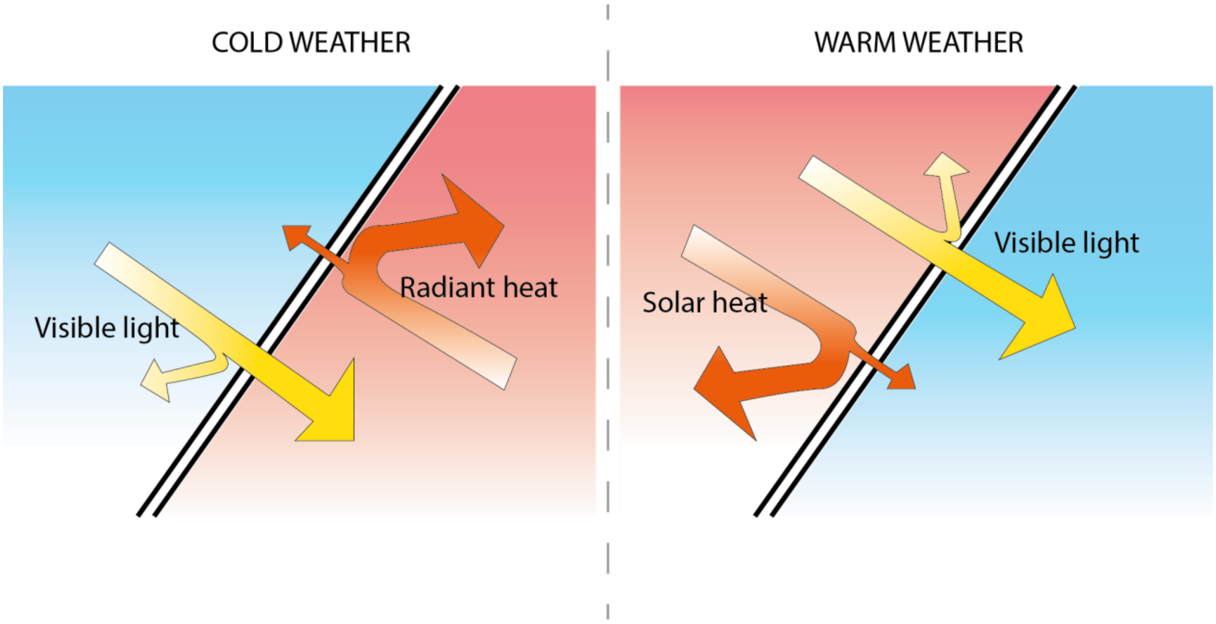


Figure 7.45. The working of low e-glass. Source: own ill.

7.5.3 Fritting on the glass

In case the heat-load caused by sunlight is still too high during summer, an additional measure can be taken. A pattern can be printed on the glass, consisting of white dots on the exterior of the glass.

These white dots reflect a part of the sunlight, although they are barely visible for when looking from a small distance. In this way the sun load is reduced while slightly reducing transparency. To further reduce impact on transparency of the fritting on the glass, the dots are given a size gradient along the length off the panel, with smaller dots at eye height level, and increasing in size towards the top.

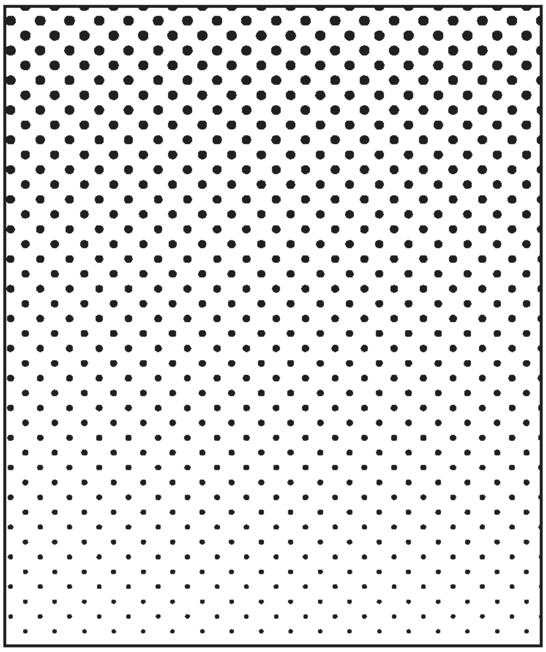


Figure 7.46. Fritting pattern on the glass. Source: own ill.

7.6 Building assembly

Next the building assembly of the roof is discussed. First the build-up procedure is illustrated, followed by the demount ability of some of the large parts.

7.6.1 Chronological build-up structure

See figure 7.47 for the overview of the assembly. In eight major steps the structure can be installed on top of the walls of Slot Teylingen.

Step 0: At the start the ruin is in its current state.
Step 1:The first step is placing the new masonry on top of the walls to level the surface as a starting point.
Step 2: Next is the installation of the steel contour frame. The frame is bolted into the old wall.
Step 3: The steel side profiles and steel top profile is bolted together.
Step 4: Now the glass floors can be installed
Step 5: The glass beams are bolted and positioned into the steel shoes.
Step 6: The steel cable trusses are connected onto the steel frame
Step 7: The glass panels can now be installed, and cold bend on site.
Step 8: At last the finishing can be installed, with the rain girder and the ventilation in-and outlets.

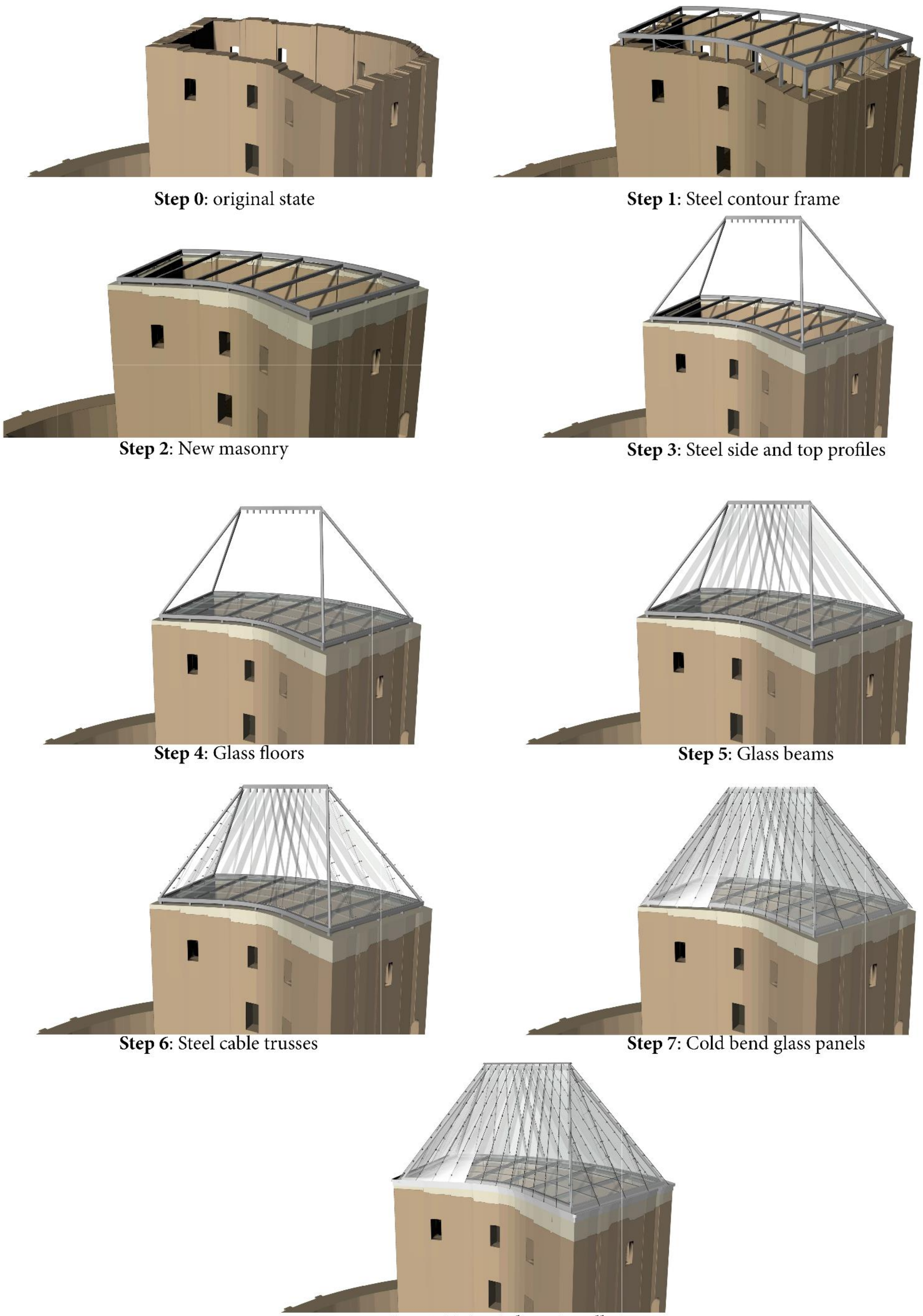


Figure 7.47. Building assembly of the roof. Source: own ill.

7.6.2 Demountable parts for transportation

Since there is a limit in the size of elements that can be transported, some elements cannot be transported as a whole. If extra-long 40-foot containers would be used to transport the structure, 12 meters is roughly the maximum length an element can have. Since the contour frame is the only element in the structure which contains elements longer than 12 meters, this part will need to be build-up out of segments, and joined together on site. Strong joints should be located at the joints, which could either be a bolted connections or on-site welding. The location of the seams are shown in fig. 7.48.

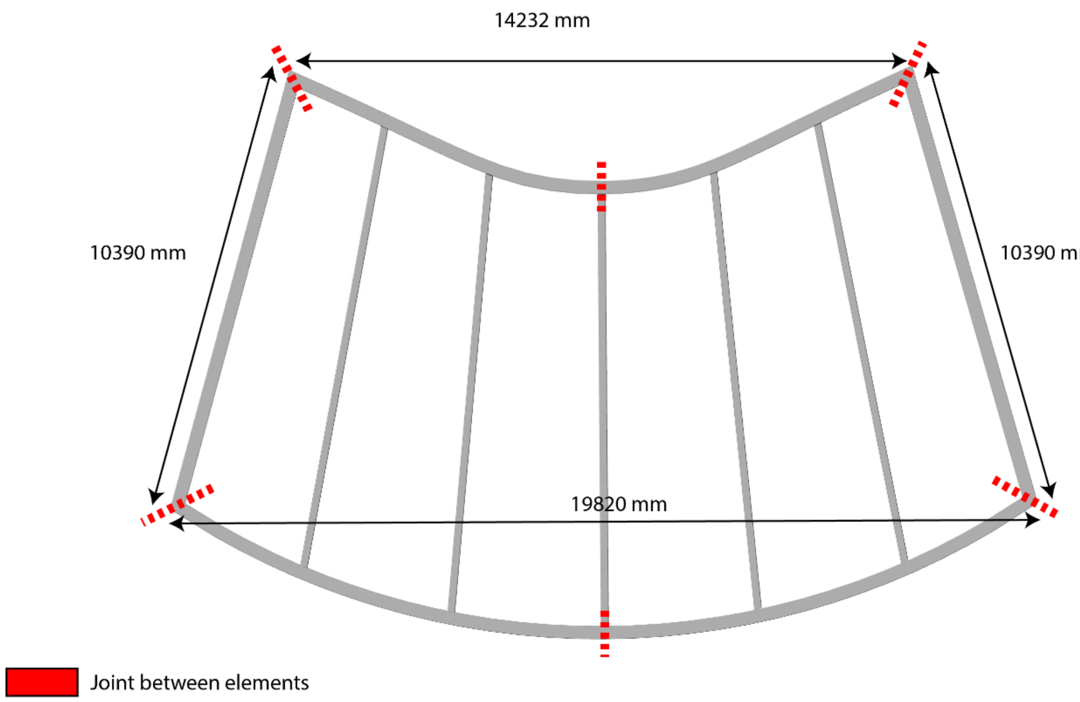


Figure 7.48 The steel contour frame which is build up in segments. Source: own ill.

All the other elements fit in the 40 foot containers. An great benefit of cold bending can be noticed here, due to the fact that flat pieces are float glass are used in this process, this helps for much more efficient transportation. This reduces cost and transportation time.

8. Feedback on research

Now that the design process is finished, and the final design results are discussed and illustrated in chapter seven, it is time to reflect on the research. A critical look is taken at the design results, and based on the findings of the research, general design guidelines are formulated for future transparent restorations.

8.1 Conclusion of design

As stated in chapter one, the main research objective was to do a case-study research where for a chosen case study, an original element will be replaced by a glass structure. The chosen case study should be a vacant building that has an iconic value, and plays an important visual role to its surroundings. The building should be of monumental cultural-historical or architectural value, and has excellent opportunities for repurposing. This lead to the decision of using Slot Teylingen as the case study, since the building has great historical value and it was in relatively good condition for its very old age. Due to its good location in the vicinity of Leiden, repurposing this building could make it functional again and becoming attractive to visit. The repurposing could be done by enclosing the structure off the castle and putting back a roof on it, thereby bringing the castle back to life and protecting it from future deterioration.

However, replacing an original element of a historical building is an complex and delicate intervention. The Venice Charters state that the replacing element should integrate harmoniously into the old structure, while also being distinguishable from the original. The restoration process should be based on respect for the original material and the building, and the aim of the process should be to preserve and reveal the aesthetic and historic value of the monument.

With the design finished, is this intervention a success? Does the roof allow the castle to become functional again? And is the design a befitting addition to the historical building? An attempt has been made to make an objective reflection on these topics.

8.1.1 New functionality of Slot Teylingen

For the castle to become functional again, the roof has to fulfill mainly practical and technical requirements. The roof should enclose the walls, creating an indoor climate inside, where shelter is found from the elements. This means the roof has to be watertight and insulating. However, the roof should not only be protecting the human visitors in the castle, it should above all protect the monument. Nearly 350 years of exposure to the elements have badly deteriorated the castle, and with this intervention the castle should now finally be protected again.
As shown in in chapter seven, the roof design fulfills these requirements. The roof is watertight, and lets rainwater flow towards the rain girders which are placed along and on top of the wall. The addition of the layer of new masonry of the bricks also preserves the historical masonry beneath. The connections which join the new structure to the old walls is detailed in such a way that the old walls can bear the forces induced. The rain girder closes off the top of the masonry wall so that direct rainfall is kept away from intruding in the stone.
Although not mentioned previously because it is not in the scope of the research, in order to reach a comfortable indoor climate, this also means the old windows of the castle need to be closed off. The old windows are now still holes in the walls, and some type of window should be put here. This of course also has to fit the restoration criteria. But, this is not elaborated.

The new functionality of the Ruin is however not purely based on functional requirements. The restored ruin should have an element of attractiveness to it. The castle should become a place which people like to visit. Next to the fact that the castle will get new functions as a bar and small museum, the idea was that the whole appearance of the area should breathe an medieval atmosphere. The area around the castle will receive a new function, as described in paragraph 3.3.1.5. The restored castle should be the centerpiece of this area. Because the roof has the same shape and size as the original roof, the building references to the original state of the building, bringing back the medieval authentic atmosphere. The new modern materials are at the same time a clear distinction from the old, creating a combination of old and new, an attractive atmosphere where people would like to go to.

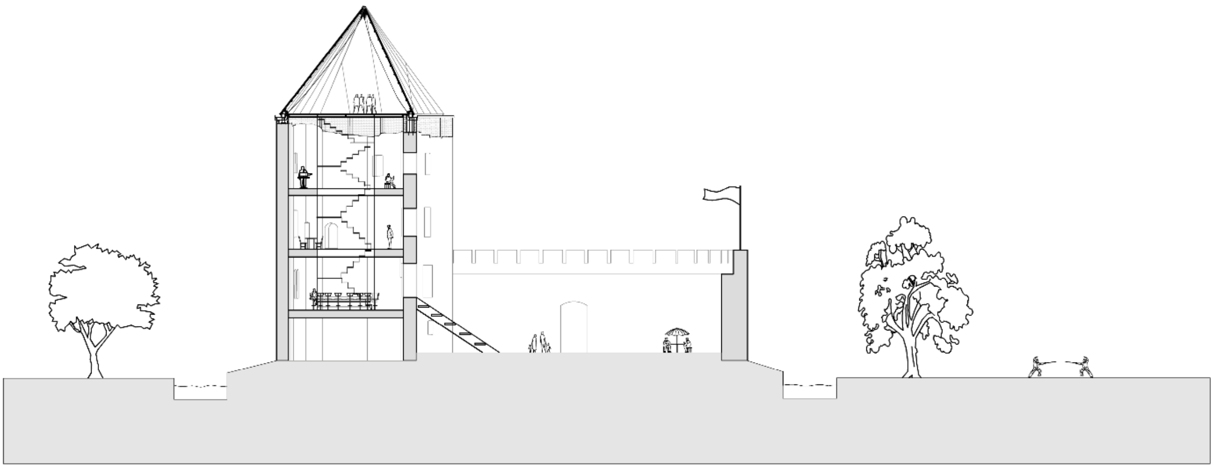


Figure 8.1 Section of the refurbished castle. Source: own ill.

8.1.2 Impact on the original building

Although the roof has proven to be functional and working to functionally restore the building, the question from an architectural point of view rises whether the roof is also an appropriate addition to the building. Given the strict demands formulated in the Venice charters, does this intervention enhance the historical and aesthetical value of the Slot Teylingen? The proper integration of the new roof and a design which respects the old building is of critical importance. When this is not done right, the addition actually damages the historical or architectural qualities of the building, and restoration could even be named as failed. Although it is difficult to quantify the success of a restoration, something can be said in relation to the Venice charters.

All along the design process and on every level, the historical context has been taken into account. This because these demands are translated into the design requirements, which have been used to value every design decision. In the end this has resulted in a design which on every level relates to the context, the original shape and atmosphere of the area. A roof has been designed in the shape and size of the original roof. The visual language of the structure engages with its context, by aligning the grid of new with old and emphasizing the contour of the roof shape. Because the roof has been designed with maximum transparency, the roof is not too intrusive to the old building. The rain girder with integrated ventilation mimics the original girder that used to be there, thereby being a reference to the past. The combination of old and new materials creates a diverse final result.

The difficulty with any restoration is that adding new material is inevitable. It would be preferred to keep to the old materials for maximum authenticity, but this is many times simply not an option because this causes the structure not to function properly. Although done very carefully and delicately, the addition of the clay bricks to level the top of the donjon walls was one of the difficult decisions in this restoration. But the argumentation that justifies the addition is that in the end the structure benefits from this addition of new material.

Figure 8.2. Combination of new materials, transition from old to new. Source: own ill.

8.1.3 Transparency

Looking back on the most fundamental property of this roof, how transparent has the roof really become? One of the design requirements was to achieve a *maximized* transparency. Although in the design process this has been an important requirement on every design level, it is not true that the roof has an maximized transparency. This is because the roof design would have probably been very different if the goal was to maximization. In the end, the overall shape of the roof, and the integration with the old and new was the ultimate goal, while using the transparent material as a method of preventing large intrusiveness.

Next to that, glass as a material is never completely transparent. Especially on a sunny day, the material tends to reflect and distort the (sun)light quite heavily, which emphasizes the presence of the roof. But this is probably not a bad thing, because the roof shoúld also be visible. Also, depending on the type of glass, there is usually some color still present. In order to further increase the transparency, low iron glass could be used which is almost colorless.

Transparency is however not just material property, it can also be achieved by means of geometry. On every design level this has been taken into account by choosing the most visual transparent method.

To conclude regarding the transparency of the final roof design, within all design requirements, there has been strived for a balance, and it is therefore better to speak of an *optimized* transparency.

8.1.4 Conclusion

It can now be concluded that structural glass can be used to successfully restore historical monumental buildings. If the design is made in respect to the original building, and intertwines with key appearances of the original building a coherent structure can be achieved which integrates harmoniously while being distinguishable. If the appropriate technical measures are taken to produce a comfortable indoor climate, and the proper detailing and structural measures are applied, these sort of glass structures are technically possible. This research has in theory shown what organic shapes could be possible in float glass, if more research is done into this. This opens new possibilities for the application of glass. Calculations have shown that the glass can be dimensioned slender, in order to achieve a transparent integrated architectural and technical design which suits the building. Restoring the castle with glass is likely a very expensive operation, compared to a roof made of traditional materials, but glass structure have a unique appearance unlike any else. Especially because of the good location of Slot Teylingen, if an company could be found that thinks the flagship appearance of such an restored castle could be linked to their brand or company, the investment in the glass roof could be understandable. With the castle located nearby ‘’de Keukenhof’’, another internationally famous Dutch attraction, the restored Slot Teylingen could join the tourist visitor stream, getting many visitors and thereby paying itself back. This opens possibilities!

8.2 Formulating design guidelines for future transparent restorations

Although in this design research many very project specific decisions have been made, it is possible to formulate some general guidelines.

- A proper case study research needs to be done to the learn about the original shape of the missing element, the material and method of construction used.
- Clear appropriate design requirements should be formulated based on the study of the authentic documents of the building, and the Venice Charters
- A slender well considered design should be made that reflects the restoration philosophy, and therefore integrates harmoniously with the old structure.
- Good detailing in glass structures is crucial in order for the structural use of glass to be safe, and that glass is as strong as predicted
- Measures should be taken to minimize the probability of the failure of glass
- Measures should be taken to minimize the consequences in case of total failure of the glass.
- The force introduction of the new structure on the old structure should be done very carefully and well-considered. If done right, the new structure could cause detrimental permanent damage to the monument.
- The design should have integrated technical solutions, to become a slender and transparent whole.

8.3 Further recommendations

Based on this research, a few recommendations can be formulated for future research to further prove the feasibility of this glass roof design.

- More research should be done in high level of cold bending of laminated glass panels. This amount of curvature due to cold bending has thus far rarely been done in practice, and this should be looked after. It this is possible, this opens a new field possibilities where float glass can be used to make organic free-formed shapes. This roof design is acting as a teaser for the building industry, that shows that if such shapes are possible, glass can be used in applications as monument restoration.

- More calculations should be done in the climate aspects of this roof design. This to check whether overheating or too much heat loss can occur during the summer or winter season.

- To prevent permanent damage to the old structure, research could be done into a reversible joint between new and old masonry. In this way the added bricks to level the donjon wall could be more easily removed.

- Further FEM calculations should be done to check the total deformation and stiffness of the overall structure. Also the stability mechanism should be checked for proper working.

- The support forces of the entire structure on the old wall should be checked by calculations. In this way it can be made sure that the walls will not be damaged by the forces.

Appendix A – Structural calculations

A.1 Glass panel calculation

Properties		
Lx	1693,5	mm
Ly	11600	mm
Thickness glass plate	10	mm
Amount of glass panes	3	
Thickness whole panel	30	mm
Structural thickness	20	mm
E	70000	Mpa
Density glass	2400	Kg/m3
Span length	1693,5	mm
Element width	1000	mm
I total	666667	mm4
Loads per m2		
Consequence class CC3 Kfi	1,10	
Safety factor DL	1,2	
Safety factor LL	1,5	
Dead Load		
Own weight panel	0,72	Kn/m2
Calculation value	0,95	Kn/m2
Live Load		
Windloads on glasspanel		
Value height+location	1,2	kn/m2
Windsuction factor roof angle	-0,3	suction
Windpressure factor roof angle	0,7	pressure
Windload pressure	0,84	Kn/m2
Windload suction	-0,36	Kn/m2
Calculation value pressure	1,386	Kn/m2
Total load with safety factor	2,34	Kn/m2
Q load		
qtotal	2,3	N/mm
Bending		
W	1,07	mm
W allowed	6,774	mm
Succeeds?	YES!	
Bending moments		
M	558388	Nmm
M	330	Nmm/mm
Bending stress		
σm	8,38	N/mm^2
Max stress	40	N/mm^2
Succeeds?	YES!	

Torsional shear stress		
Thickness	30	mm
Width	1693,5	mm
Angle top bottom	28,898	degrees
	0,504	rad
Length	11600	mm
Torsional rigidity glass	28807,11	Mpa
k1	0,333	
k2	0,333	
Jr	15226258,5	
Torque T	19071289,32	nmm
τ	37,58	Mpa
Total stresses		
σm	8,38	N/mm^2
τ	37,58	N/mm^2
Total σ	45,95	N/mm^2
Max stress	40	N/mm^2
Succeeds?	NO!	

A.2 Glass beam calculation

Properties

Length	11566	mm
Height	485	mm
Thickness glass plate	10	mm
Amount of glass panes	4	
Thickness whole panel	40	mm
Structural thickness	30	mm
Angle of placement	50,9	°
E	70000	Mpa
Density	2400	Kg/m3

Moment of Inertia

	285210312,5	mm4
	19400	mm2
	19400	

Loads ULS

Consequence class CC3 Kfi	1,10	
Safety factor DL	1,2	
Safety factor LL	1,5	

Area resting on beam

Length	11566	mm
Width	1201	mm
Surface area	13,89	m2

Permanent Loads

Own weight beam	538,5	kg
Weight per m1	0,47	kn/m1
Rekenwaarde permanente belasting	0,61	Kn/m1
Perpendicular to beam	0,39	Kn/m1
Weight glass panels	0,72	Kn/m2
Total weight	10,00	Kn
Load per m1	0,865	Kn/m1
Calculation value	1,14	Kn/m1
Perpendicular to beam	0,72	Kn/m1

Varying loads

Windloads on glasspanel

Value height+location	1,2	kn/m2
Windsuction factor roof angle	-0,3	suction
Windpressure factor roof angle	0,7	pressure
Windload pressure	0,84	Kn/m2
Windload suction	-0,36	Kn/m2
Calculation value pressure	1,39	Kn/m2
Calculation value per m1 pressure	1,66	Kn/m1

Q load

qtotal	2,772	N/mm

Bending moment

Due to windload, dead load and own weight	**46353239**	Nmm

Bending stresses

σm	39,41	N/mm2
Max stress	40	N/mm2
Succeeds?	YES!	

Shear stress

Vd	16030,86	N
I	285210312,50	mm4
S	3528375	mm3
B	30	mm
τ	6,61	N/mm2

Deflection

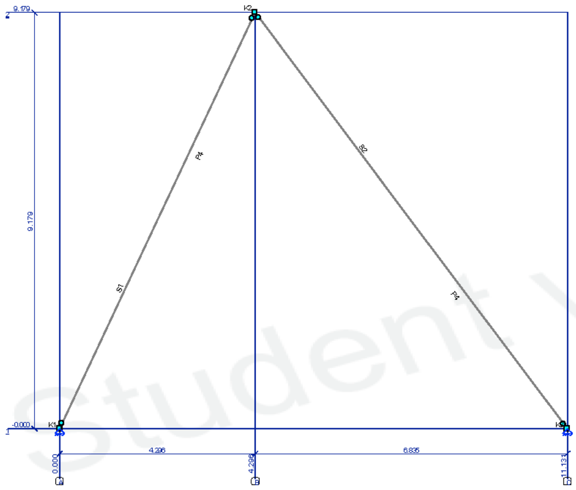
w	32,4	mm
W allowed	46,3	mm
Succeeds?	YES!	

A.3 Glass floor panel calculation

Properties		
Lx	2299	mm
Ly	1000	mm
Thickness glass plate	10	mm
Amount of glass panes	3	
Thickness whole panel	30	mm
Structural thickness	20	mm
E	70000	Mpa
Density glass	2400	Kg/m3
Span length	2299	mm
Element width	1000	mm
Surface	2,3	m2
I total	666667	mm4
Loads per m2		
Consequence class CC3 Kfi	1,10	
Safety factor DL	1,2	
Safety factor LL	1,5	
Dead Load		
Own weight panel	0,72	Kn/m2
Calculation value	0,95	Kn/m2
Varying loads		
Floor loading Cat C-C3	2,5	Kn/m2
Calculation value	4,13	Kn/m2
Total load with safety factors	5,08	Kn/m2
Q load		
qtotal	5,1	N/mm
Bending		
W	7,91	mm
W allowed	9,196	mm
Succeeds?	YES!	
Bending moments		
M	2235460	Nmm
M	972	Nmm/mn
Bending stress		
σm	33,53	N/mm^2
Max stress	40	N/mm^2
Succeeds?	YES!	

A.4 Matrixframe calculation report

Projectnaam	Graduation BT	Projectnummer	
Omschrijving	Glass roof frame	Constructeur	Jasper Smilde
Opdrachtgever	4092368	Eenheden	m, kN, kNm
Bestand	D:\Jasper\Dropbox\Jasper doorspeel data\Graduation BT\P4\Week 17\Matrixframe calculations\Total frame\Roof frame calculation.mxe		



Afb. Geometrie: Raamwerk

Student versie

Staven

Staaf	Knoop B	B	Scharnier E	Knoop E	Profiel	X-B	Z-B	X-E	Z-E	Lengte
S1	K1	NV-	NV-	K2	P4	0,000	0,000	4,296	-9,179	10,135
S2	K2	NV-	NV-	K3	P4	4,296	-9,179	11,131	0,000	11,444
-	-	-	-	-	-	m	m	m	m	m

Profielen

Profiel	Profielnaam	Oppervlakte	Iy	Materiaal	Hoek
P4		2.2400e-02	4.3900e-04	C12/15	0
-	-	m2	m4	-	°

Materialen

Materiaalnaam	Dichtheid	E-Modulus	Uitzettingcoeff
C12/15	25.00	2.7000e+07	10.0000e-06
-	kN/m3	kN/m2	C°m

Opleggingen

Oplegging	Knoop	X	Z	Yr	HoekYr
O1	K3	vast	vast	vrij	0
O2	K1	vast	vast	vrij	0
-	-	kN/m	kN/m	kNmrad	°

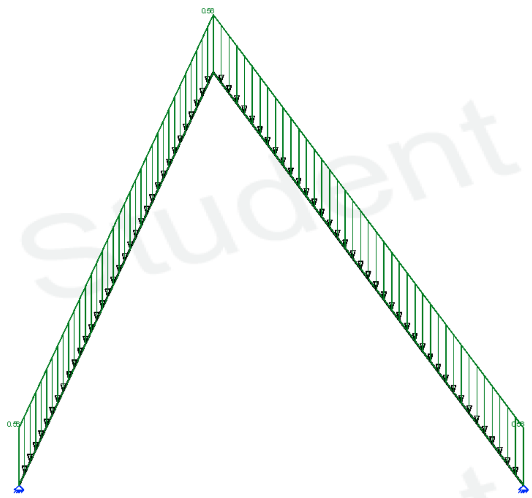
Belastingsgevallen typen

Oplegg.	Staven	B.G.Type	Gunstig/On g.	Element	Niveau	Veld	Psi0	Psi1	Psi2
B.G.1	Permanent	Permanent	+		N.v.t.	N.v.t.	0.00	0.00	0.00
B.G.2	Windbelasting	Windbelasting	+		N.v.t.	N.v.t.	0.00	0.20	0.00
B.G.3	Rustende belasting	Permanent	+		N.v.t.	N.v.t.	0.00	0.00	0.00

7-5-2016 19:31:13 MatrixFrame® 5.0 SP8 1

B.G.1: Permanent

Type	Beginwaarde	Eindwaarde	Beginafstand	Eindafstand	Richting	Staaf of knoop
B.G.1: Permanent						
qG	0,56 (1.00x)	0,56 (1.00x)	0,000	10,135(L)	Z"	S1
qG	0,56 (1.00x)	0,56 (1.00x)	0,000	11,444(L)	Z"	S2
Som lasten	**X: 0,00**	**kN Z: 12,08**	**kN**			
-	**-**	**-**	**m**	**m**	**- -**	

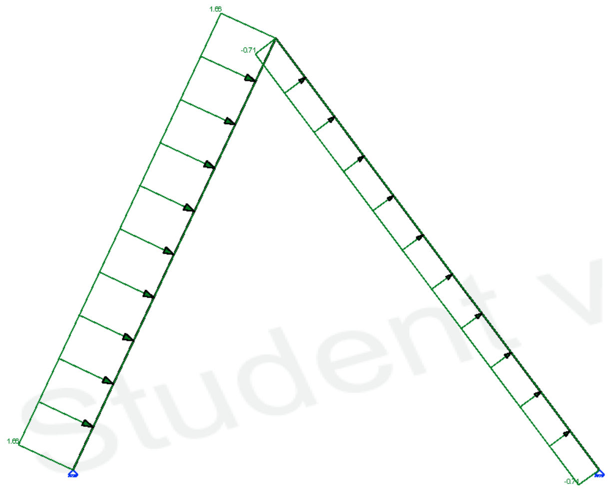


B.G.1: Permanent

Student versie
Student versie

B.G.2: Windbelasting

Type	Beginwaarde	Eindwaarde	Beginafstand	Eindafstand	Richting	Staaf of knoop
B.G.2: Windbelasting						
q	1,66	1,66	0,000	10,135(L)	Z'	S1
q	-0,71	-0,71	0,000	11,444(L)	Z'	S2
Som lasten	**X: 21,75**	**kN Z: 2,28**	**kN**			
-	**-**	**-**	**m**	**m**	**- -**	

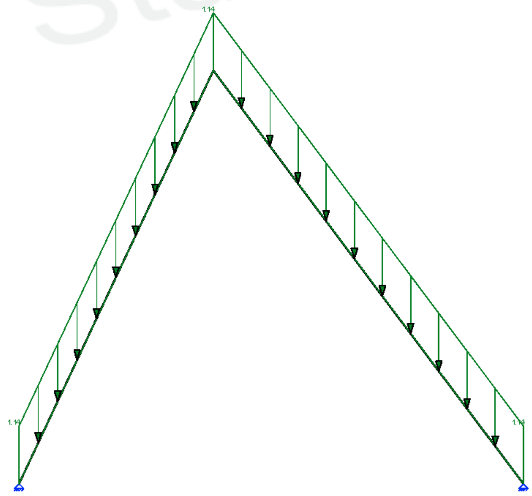


B.G.2: Windbelasting

B.G.3: Rustende belasting

Type	Beginwaarde	Eindwaarde	Beginafstand	Eindafstand	Richting	Staaf of knoop
B.G.3: Rustende belasting						
q	1,14	1,14	0,000	10,135(L)	Z"	S1-S2
Som lasten	**X: 0,00**	**kN Z: 24,60**	**kN**			
-	**-**	**-**	**m**	**m**	**- -**	

Student versie



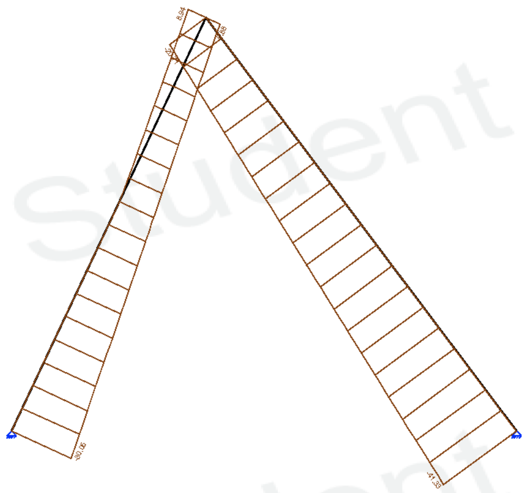
B.G.3: Rustende belasting

Fundamenteel Belastingscombinaties

B.G.	Omschrijving	Fu.C.1	Fu.C.2
B.G.1	Permanent	1.32	1.49
B.G.2	Windbelasting	1.65	-
B.G.3	Rustende belasting	1.32	1.49

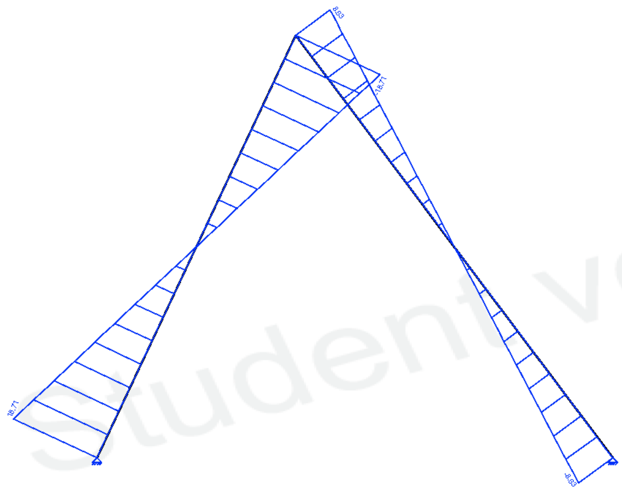
Uitgangspunten van de analyse

Lineaire Elastische Analyse uitgevoerd

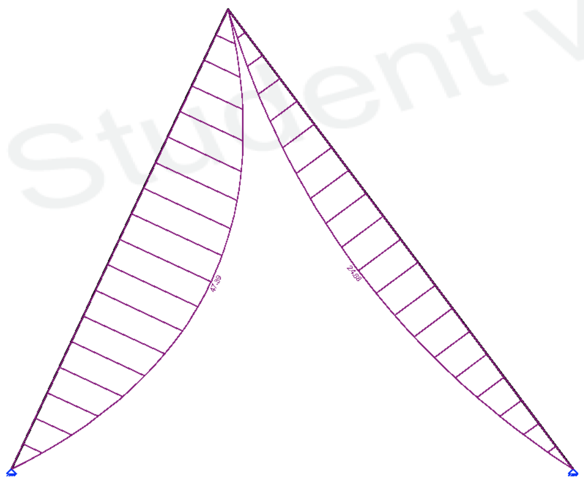


Student versie
Student versie

Afb. Fu.C. Normaalkracht (Nx) Omhullende



Afb. Fu.C. Dwarskracht (Vz) Omhullende

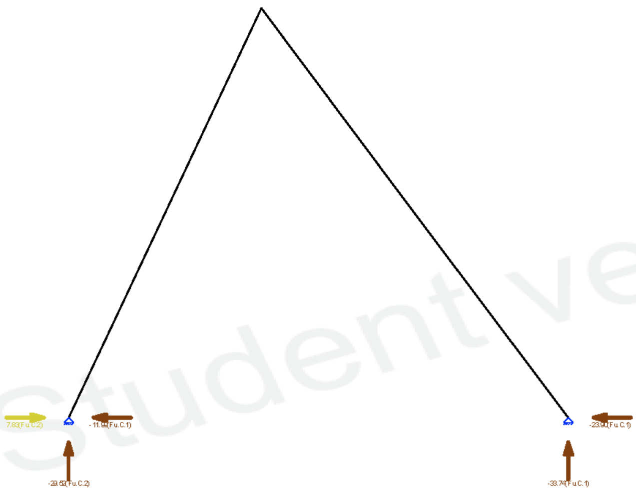


Afb. Fu.C. Momenten (My) Omhullende

Student versie

Fu.C. Omhullende

Staaf	Nx Minus	Nx Plus	Vz Minus	Vz Plus	My Minus	My Plus
S1	-30.05	8.94	-18.71	18.71	0.00	47.39
S2	-41.33	0.00	-8.63	8.63	0.00	24.68
-	kN	kN	kN	kN	kNm	kNm

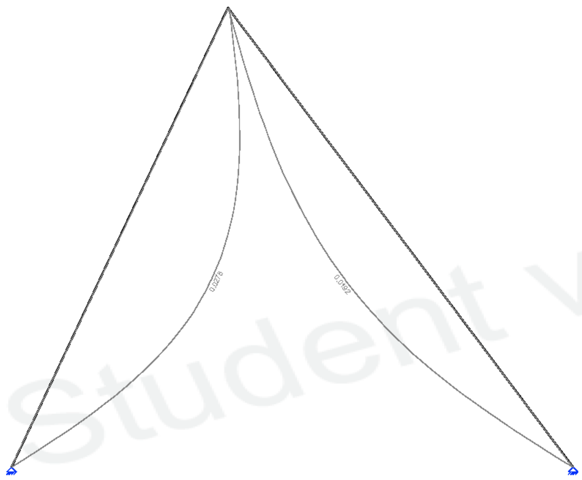


Afb. Fu.C. Oplegreacties Omhullende

Student versie

Fu.C. Extreme oplegreacties

Oplegging	Knoop	B.C.	Xmax	Z	My	B.C.	X	Zmax	My	B.C.	X	Z	Mymax
O1	K3	Fu.C.1	**-23.90**	-33.74	0.00	Fu.C.1	-23.90	**-33.74**	0.00				
O2	K1	Fu.C.2	**7.83**	-29.52	0.00								
O2	K1	Fu.C.1	**-11.99**	-18.51	0.00	Fu.C.2	7.83	**-29.52**	0.00				
Globale extreme waarden													
O2	K1	Fu.C.2	**7.83**	-29.52	0.00								
O1	K3	Fu.C.1	**-23.90**	-33.74	0.00								
O1	K3					Fu.C.1	-23.90	**-33.74**	0.00				
-	**-**	**-**	**kN**	**kN**	**kNm**	**-**	**kN**	**kN**	**kNm**		**kN**	**kN**	**kNm**



Afb. Ka.C. Verplaatsingen Omhullende

Student versie

Ka.C. Extreme Knoopverplaatsingen

Knoop	B.C.	X	Z	Ry
K2	Ka.C.on	**0,0000**	**0,0002**	0.000e-03
	Ka.C.2	**0,0003**	0,0002	0.000e-03
-	-	m	m	rad

Student versie

Ka.C. Extreme doorbuigingen

Staaf	B.C.	Knoop Begin		Staaf		Knoop Eind	
		X	Z	Z'afst	Z'	X	Z
S1	Ka.C.2	0,000	0,000	5.067	**0.0276**	0,000	0,000
S2	Ka.C.on	0,000	0,000	5.722	**0.0191**	0,000	0,000
S2	Ka.C.1	0,000	0,000	5.722	**0.0191**	0,000	0,000
-	-	m	m	m	m	m	m

A.5 Steel tie beam calculation

Properties		
Length	9987	mm
Height	260	mm
Width	180	mm
Thickness	16	mm
Area	19950	mm2
E	210000	Mpa
Density	7850	Kg/m3
Moment of inertia Iy	97930000	mm4
Moment of inertia Iz	54840000	mm4
Loads ULS		
Consequence class CC3 Kfi	1,10	
Safety factor DL	1,2	
Safety factor LL	1,5	
Area resting on beam		
Length	9987	mm
Width	2879	mm
Surface area	28,75	m2
Permanent Loads		
Own weight beam	93,9	kg
Weight per m1	0,94	kn/m1
Rekenwaarde permanente belasting	1,24	Kn/m1
Weight glass panels	0,72	Kn/m2
Total weight	20,70	Kn
Load per m1	2,073	Kn/m1
Calculation value	2,74	Kn/m1
Varying loads		
Floor loading Cat C-C3	2,5	Kn/m2
Total load	71,88	kn
Load per m1	7,20	kn/m1
Calculation value	11,88	Kn/m1
Q load		
qtotal	15,851	N/mm
Bending moment	**131748689**	Nmm
Bending stresses		
σm	174,89	N/mm2
Max stress	235	N/mm2
Succeeds?	YES!	

Shear stress		
Vd	79152,11	N
I	97930000,00	mm4
S	2593500	mm3
B	180	mm
τ	11,65	N/mm2
Deflection		
w	20,0	mm
W allowed	30,0	mm
Succeeds?	YES!	

A.6 Steel contour beam calculation

Properties		
Length	2566	mm
Height	300	mm
Width	300	mm
Thickness	10	mm
Area	19200	mm2
E	210000	Mpa
Density	7850	Kg/m3
Moment of inertia Iy	160250000	mm4
Moment of inertia Iz	160250000	mm4
Forces		
Horizontal pointload	23,9	Kn
Vertical pointload	34,74	Kn
ULS		
Bending moment horizontal	15,33	Knm
Bending moment vertical	22,28571	Knm
Bending stress horizontal	14,35	N/mm2
Bending stress vertical	20,86	N/mm2
SLS		
Deformation horizontal	0,25	mm
Deformation vertical	0,36	mm
Max deformation	5,132	mm

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