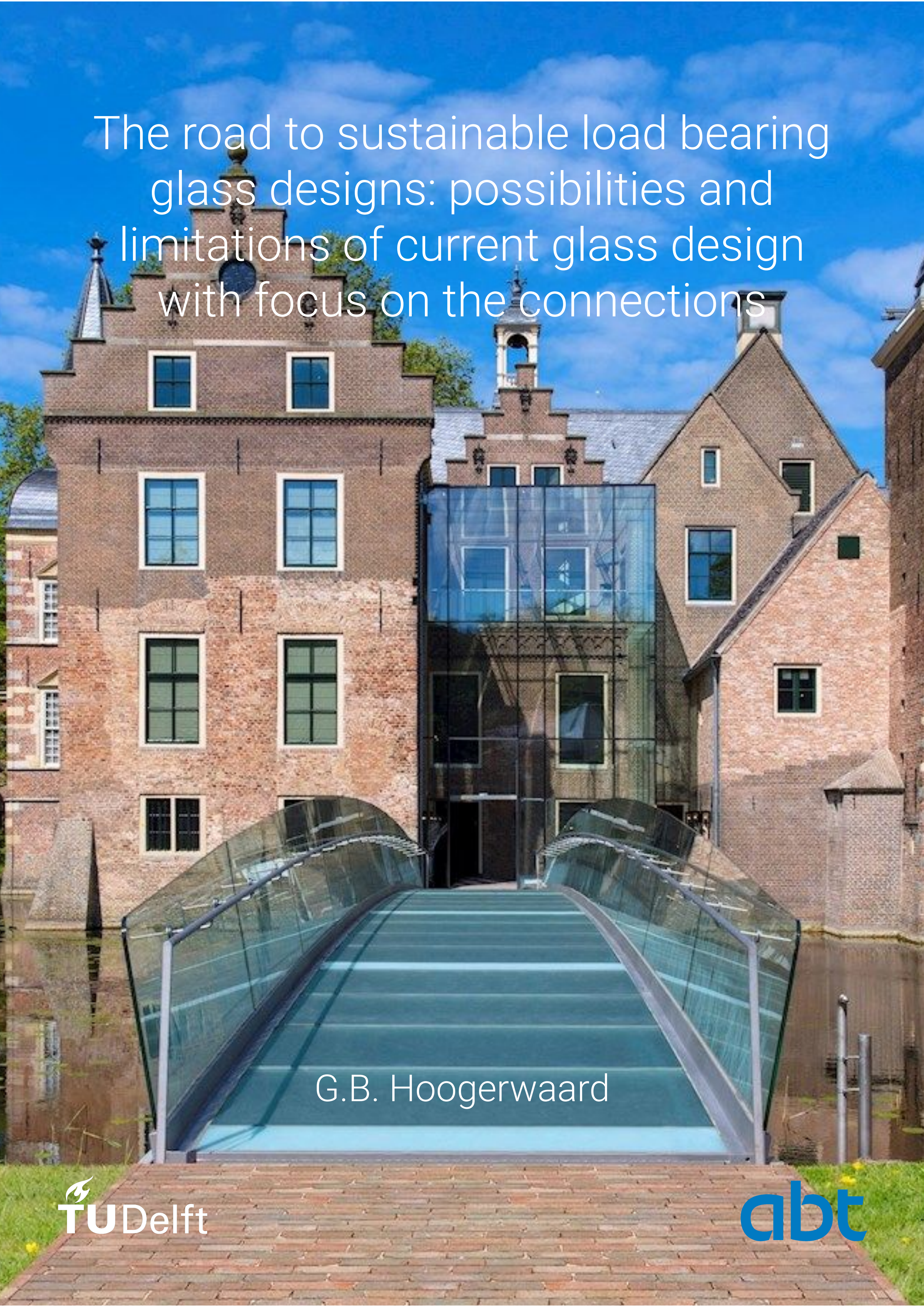
The road to sustainable load bearing glass designs: possibilities and limitations of current glass design with focus on the connections



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The road to sustainable load bearing glass designs: possibilities and limitations of current glass design with focus on the connections

by

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Preface

Dear reader,

This thesis was written as the final part of my Master in Building Engineering, with a specialization in Structural Design at the Delft University of Technology. The research has been performed together with engineering company ABT b.v., who is specialized in glass structures.

My interest in glass structures started years ago ever since I was introduced to it at the TU Delft. The material is fascinating, it is stronger than concrete and transparent. Another important interest of mine is sustainability. I am sure the climate goals set for 2050 are a big challenge, and as an engineer, I want to contribute to a better world, not only in my personal lifestyle, but also in my profession. Given the large amount of energy required in order to produce glass, I was skeptical about it being applied as a load bearing material in terms of sustainability. Therefore, combining these two fields of interest from an engineering standpoint was the direction I chose for my thesis.

Writing a thesis in the midst of a pandemic was hard, but with the right schedule, deadlines and a good balance between working, sports and whatever other distraction there was, I was motivated enough to finish this thesis in a reasonable time. I am proud of the result and I am hopeful that with the awareness created from this thesis, the necessary adjustments will be made in the industry so that load bearing glass can be designed in a sustainable way.

Without my supervisors, this thesis would not have been a success. I would like to thank professor Rob Nijsse whom let me never forget the bigger picture of my thesis when the questions became too detailed and who inspired me to look into structural glass in the first place. Next, I would like to thank Diana de Krom, my daily supervisor for answering all the questions I had about glass in practice, since not everything is being taught at the university. Also, I would like to express my gratitude to Henk Jonkers, who, as a result of a lot of conversations, made me critically think about sustainability. Finally, I would like to thank Fred Veer, who gave me so much more insight and knowledge of the issues glass as a material has.

This thesis is the final work for me as a student at Delft University of Technology and looking back on those years, I am extremely grateful for all the valuable experiences that I've had and the friends that I've made, Dutch and international. This was of course not possible without the support of my parents, to whom I'd like to express my appreciation by encouraging me to go to the university, by allowing me to also develop myself as a person and to finally help me finish this thesis. At last, I'd like to thank all my friends who helped me out, without their support I could not have done it.

G.B. Hoogerwaard
Delft, August 7, 2020

Abstract

Despite the increased popularity of the application of load bearing glass in the built environment, its design does rarely address sustainable or circular aspects. This Master's Thesis analyses what the influence of connections is on the sustainable performance of structural glass and informs about the limitations and possibilities of sustainable glass design. To answer this question, sustainability has been defined from literature which resulted in ten sustainable, circular design methods. The role of load bearing glass and its connections is discussed in these methods, and it is concluded that there are two main possible design strategies for a sustainable design. First, the biggest impact in design can be made when focus is on reuse as an afterlife application to increase the lifetime of glass elements. Secondly, impact can be made by limiting the environmental footprint of the structure in the initial design by material minimization and selection.

Recycling is left out of the scope since recycling on a world-wide scale barely occurs. Even in a country with a well developed recycling network like the Netherlands, just 5-10% of discarded flat glass waste ends up back in the float glass industries and the rest is downcycled to container glass or glass fibres. Besides, the sustainable impact from recycling compared to reuse is far smaller, and measures to limit contamination are out of control of the designer.

At first, in order to design for reuse as an end-of-life application, demountable connections are essential and adhesive based connections should be avoided. Although demountability is a key to the circular economy, this study concludes that there are various technical barriers to overcome to make glass elements actually reusable. One important barrier is the lack of standardization in glass structures. As is shown in the redesign of "Kasteel Ruurlo", implementing standardization leads to a modular design and is integrated by using minimum size deviation and the use of a single type of connection. However, as a result of standardization, the design freedom of the architect is taken away and the mechanical connections lead to a less elegant design. Therefore, it is recommended to further development these modules and discuss elegance and design freedom in standardization. Another technical barrier to overcome is the performance and quality of glass elements which makes current reuse impossible: insulated glass units will loose their insulating performance due to failure of the edge sealant after 20 to 25 years, and laminated glass is prone to delamination over time. There is a lack of legislation which sets requirements to the quality and performance of these elements. Only for laminated glass, there is a potential reuse strategy which has been used in the redesign of "Kasteel Ruurlo". It is proposed to use a high quality interlayer as SentryGlas or Trofisol. For both interlayers, delamination problems should be further researched in order to assure a long technical lifetime.

Secondly, in order to minimize the environmental impact of the structure, the impact has been quantified using Life Cycle Analysis data and Environmental Product Declarations. With the method by "Stichting Bouwkwaliteit", this data is converted to shadow costs which is used to calculate the environmental footprint of a connection. Different structural connections are considered: various facade connections, different moment rigid frame connections and various ways to connect a panel. From this calculation, the different connections are compared and it is concluded that adhesive based connections have both a smaller environmental footprint than mechanical connections, and that these result in less material use in the overall structure and thereby limiting the environmental footprint. This is also reflected in the redesign of "Kasteel Ruurlo", where due to the mechanical demountable connections, the environmental impact increases compared to the current design. With current possibilities, the relation between the connection and a sustainable design depends on the type of connection: an adhesive based connection will result in an overall low environmental impact but makes reuse unlikely. A mechanical connection could be an outcome here, but with current possibilities, reuse cannot be guaranteed either. The application of current demountable connections on the reuse possibilities can therefore be argued.

In order to succeed with structural glass in the circular economy, this research emphasizes the need for legislation, standardization and to solve problems like delamination and leaking insulated glass units which now determine the lifetime of glass structures. It also shows the need for demountable connections which increase the reuse potential and which ideally do not increase the environmental footprint.

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RESEARCH DEFINITION

1
Introduction

In this chapter, the research is introduced. First, some context is given which shows the main problems. Then, in Section 1.2 the problem statement is given, followed by the scope and delimitations in Section 1.3. The research objective and questions are given in Section 1.4. The goal and methodology of each research question are discussed in Section 1.5. Finally, the research outline is presented in Section 1.6.

1.1. Context

With the need for a circular economy to become climate neutral in 2050, a lot of challenges arise in the design of the built environment. Current challenges focus on the energy efficiency of buildings and the load bearing structure is considered in a "sustainable" design more often as well. In the past two decades, the application of glass facades, roofs and other glass load bearing structures has become increasingly popular, but the implementation of circular design principles such as reuse and recycling have not been incorporated in these designs. Given the limited and often unique applications done where glass has played a major role in the load bearing structure, no explicit advice exists on how to cope with the circular economy.

Glass is a unique material which is both transparent and can be load bearing. Because of this double function, application of glass can result in reducing the use of other materials in a facade. However, from a sustainability point of view, a lot of energy is needed to produce glass, which results in a relatively high environmental impact compared to other materials. Also, relatively unusual materials are used in the connections of glass structures like adhesives and metals like stainless steel and titanium. The environmental impact is often neglected when considering glass structures, since the focus is usually on the energy efficiently of buildings. Besides, since glass itself is a 100% recyclable material, sustainability of glass is often not thought of as a big issue. However, in the Netherlands just 5-10% of discarded flat glass waste ends up back in the float glass industries and the rest is downcycled to container glass or glass fibres [47][48]. On a worldwide scale, this recycling percentage is even lower, in comparison, steel has a recycling rate of 93%[49]. The main reason why glass is not being recycled is due to contamination which affects the new glass products and contamination is hard to remove. This is very unfortunate, because when glass is recycled, much pollution is prevented. An even bigger gain can be made by reusing glass elements. However, this is rarely done due to the limited technical lifetime of both laminated glass by delamination and insulating glass due to leakage of the edge sealant, but also due to unique projects which do not easily allow for reuse of any kind.

Given these challenges in glass, improvements in design should be made by implementing circular design methods. This is certainly not only about minimizing the environmental impact or allowing for better recycling possibilities, it is more about reuse or extending the service life of the structure. Here, connections need to be discussed, since connections have a big impact on the afterlife possibilities, but meanwhile also seem to have a big environmental impact. At the same time, from an architectural point of view, any joint in a glass structure is highly visible and plays a major role in the final design.

1.2. Problem statement

From the context, a lot of questions arise like “what is a sustainable glass design?” and “how to deal with sustainability in these unique projects in which glass is involved?”. For both questions an answer can be formulated when focus is on the connections of glass structures since these are inevitable in a circular design: connections allow for a demountable structure and have a big role in the reusability of glass elements. Besides, connections are vital for the architectural and structural design of all glass structures and use relatively unusual materials. Additionally, no quantification of the sustainable performance of different connections and glass structures is present. It is therefore hard to make a well-weighted decision which connection to choose in a sustainable, circular design.

In line with this problem statement is the following hypothesis: “the sustainability of structural glass structures is mainly determined by the connections”.

1.3. Scope and delimitations

The study covers the analysis of different connections and the application of these in the building envelope. This includes the structural application in glass, integrated in the building envelope. Therefore, other structural applications as glass stairs are not considered in this research. Additionally, the study focus is on 2D elements, meaning laminated glass and insulated glass units (IGUs). These are of interest given its wide application, but also limiting technical lifetime (see Section 2.1 for a definition and more relevant background information of laminated glass and IGUs).

Cast glass, or 3D elements, are left out of the scope given its limited application, but are referred to throughout the research when interesting with regard to sustainability. Another limitation is within the different sorts of connections. Lots of connections are described, but only for a few, a more in dept analysis is done. Just like for 3D elements, when interesting with regard to sustainability these connections are mentioned, but the more in dept analysis is performed on more regular or promising connections.

A different way of dealing with sustainability is when focus is on the energy performance of a building. In this research, this is not considered but is focus on the energy (so-called embodied energy) and environmental footprint of materials used for construction (see Section 2.2 for background information). Additionally, with regard to sustainability, this research focus is on the "planet" aspect when spoken of "people, planet and prosperity".

1.4. Research objective and questions

1.4.1. Research objective

By researching the influence of connections on the sustainable performance of glass structures, one can advise a client in the (conceptual) design stage on the connections to apply to achieve a sustainable design.

1.4.2. Research questions

In order to fulfill the research objective, the research questions formulated in this section should be answered. The questions are split into a main question and various sub-questions and provide answers to the hypothesis.

Main question

What is the influence of connections on the sustainable performance of glass structures?

Sub-questions

What is sustainability in glass structures?
What kind of connections are possible in glass structures?
How sustainable are the connections?
How can a connection be designed to improve its sustainable performance?

1.5. Methodology

First, the goal of each research question is elaborated and a method is introduced which serves as a framework to answer all research questions.

1.5.1. What is sustainability in glass structures?

Goal

Define "sustainability" of a glass structure and and the role of glass in different circular design methods. The focus is on the environmental aspects of sustainability and on the building envelope.

Explanation

Different types of glass are discussed and what their role is in a sustainable design. Examples of glass types are regular annealed glass and tempered glass, but also various glass products like the two main groups laminated glass and IGUs. More variants exist within these glass products and will be discussed too.

Methodology

1) Perform a literature study on "sustainability" of structural glass and its connecting materials.
2) Address "sustainability" in glass structures considering IGUs, laminated panels and coated panels.

1.5.2. What kind of connections are possible in glass structures?

Goal

Get an insight into the possible applied connections in structural glass. Make an inventory/catalogue of the different glass connections that are applied.

Explanation

Focus is on different sorts of connections. The two main categories are mechanical and adhesive based connections. Other connections are formulated, but are out of the scope of this thesis.

Methodology

Analyse different projects by ABT b.v..

1.5.3. How sustainable are the connections?

Goal

Quantify the sustainability of the different connections considered and to compare them.

Methodology

The sustainable performance is assessed in three steps:
1) By performing an LCA (life cycle analysis) with EPD (environmental product declaration) data, the environmental impact of a connection can be characterized. This means that the connection is assessed on 11 impact categories including use of resources (materials and energy) and various harmful emissions. The LCA will be performed according to the SBK (Stichting Bouwkwaliteit) method, as introduced in Chapter 2.
2) Ten different "sustainable" design methods are possible to include sustainability in the design. See Chapter 2 for these methods. All ten are discussed in the design of a glass structure and relevant methods are discussed in the different types of connections.

After assessing the sustainability of the connections, the connections should be compared:
3) By making use of a scoring system, sustainability for the two parts can be compared among each other. Other characteristics should also be included in the scoring system, as for example transparency, strength, structural performance, service life characteristics and aesthetics. A scoring system for example is a Multi Criteria Analysis (MCA).

1.5.4. What are the design requirements for a sustainable glass design and what is the role of connections here in?

Goal

The outcome of the previous questions pose a direction for this research question, since among the many connections that will be considered, positive (environmental) aspects will be encountered. The outcome shows where and how sustainability can be integrated in the design of a glass structure and at what cost this will have to be done.

Methodology

With the result of the previous research questions, a redesign can be done as case study to implement the obtained knowledge.

The case study will be performed on a glass extension of "Kasteel Ruurlo", a project by ABT b.v.. The sustainable performance can be measured in environmental impact and the other ten sustainable design methods. The efforts to make the design sustainable are also noted, which are in the form of actual costs, safety, makeability, transparency and lifetime.

Figure 1.1: Kasteel Ruurlo, a glass structure designed by ABT. Photo by [1].

1.6. Research outline

This Master's Thesis consists of five parts. In the first part, the research is defined as is done in this chapter. In the second part, also called the theoretical framework, a literature review is conducted. In Chapter 2, background information is given on the material glass and sustainable design methods. In Chapter 3, glass and sustainability are linked together and and as a result, possibilities and limitations are discussed within glass and sustainability. Then, in Chapter 4, the different connections possible in glass structures are introduced and discussed on their "sustainable" performance. Also, reference projects are described which will be repeatedly referred to in the thesis.

The third part is a quantification of "sustainability" done for various connections. First, in Chapter 5, the method is described and topics as lifetime, environmental impact and end-of-life scenarios come by in Chapter 6. A discussion of the findings is done in Chapter 7. This discussion is a base for the case study (Chapter 8), which is done in the fourth part.

At last, the research is finalised in part five. At the end of each chapter, conclusions of that particular chapter are given. In Chapter 9 then, the main conclusions are given, in Chapter 10, the overall discussion is performed. Also recommendations for future research are given in Chapter 11.

II

THEORETICAL FRAMEWORK

2

Background information

2.1. Glass

2.1.1. A brief history

One of the stories of the origin of glass is by the Roman Plinius, who claimed that glass was created by lost sailors who lighted up some sodium carbonate on a beach in Lebanon, which mixed with sand and shells (made from lime) and resulted in glass as a coincidence [50]. What the origin might be, it is a fact that it took some time for glass to become as applied as it is today. After the discovery of glass around 2500 BC in Mesopotamia, the development of glass was very slow. Over time, one of the first big developments was glass blowing that was invented in the 1st century. Around that time, the Romans applied glass as first as architectural application. Multi-colored glass was first applied in the 7th century, but again, it took a long time for colored glass to become widely applied. Namely, in the 13th and 14th century, when stained-glass became popular to apply in churches. Furthermore, very little development was made in the Middle Ages. However, in the 17th century the development of glass rapidly increased. New types of glass were discovered, plate glass was developed and finally in 1959, Alastair Pilkington developed a technique to develop high quality glass sheets, namely float glass. [51]

2.1.2. Chemistry

In fact, only silica is needed for the production of glass. But since pure silica is hard to find, it has a high melting point of 1723°C and is then extremely viscous, additives are added to lower the melting temperature and improve the workability of glass during manufacturing. For the production of float glass, the main materials are silica, soda oxide and lime. Glass is then formed out of the following main chemical reaction:

$$Na_2CO_3 \longrightarrow Na_2O + CO_2$$

$$Na_2O + SiO_2 \longrightarrow Na_2SiO_3$$

Main materials

Main materials added to the mix are [52]:

- Silica (SiO_2): the main constituent of glass is sand (silica).
- Sodium carbonate (Na_2CO_3): lowers the temperature and increases the elasticity but also makes glass soluble in water.
- Calcium oxide (CaO): Adding calcium oxide, (quicklime) to the mixture solves the soluble problem and stabilises the glass melt. It also increases the resistance of glass to a chemical attack [53]. It is often added as limestone ($CaCO_3$), which results in a CO_2 release. An alternative source is dolomite ($CaMg(CO_3)_2$), which also contains magnesium [54].
- Magnesium oxide (MgO): Adding magnesium to the mix improves the strength and durability of glass, as well as the water solubility. Often is dolomite added as a source for magnesium.

Additives

Other additives are added to the glass to create specific characteristics and are not always added in the float glass industry. Some examples of additives according to [55].

- Aluminium oxide (Al_2O_3): is added to improve the durability
- Boron oxide (B_2O_3): increases the chemical resistance
- Lead oxide (PbO): increases the refractive index and increases the dispersive power (more sparkling) and makes glass x-ray adsorbing. Also known as “crystal”. It is used in glazing but is considered dangerous to drink out of due to possible lead-poisoning. [56]
- Barium oxide (BaO): increases the refractive index but does not increase the dispersive power as lead oxide did. It is often used in cathodes.
- Sodium sulfate , sodium chloride, or antimony oxide prevents the creation of air bubbles in the glass mixture.
- Iron(III) oxide (Fe_2O_3): iron(III) oxide often comes with sand and gives a green tint to the glass.

Making colorless glass is difficult since sand with a low iron(III) oxide (0,01%) is needed, where for normal float glass, the percentage of iron(III) oxide is 0,1%. Colored glass can be made by adding specific oxides to the mixture. [57]

Consistency

Now it is clear what in general the materials are for different glass products. However, according to [58], glass compositions differ significantly and variations can even be found within the same factory. Also the end product is rarely checked by the end user. The composition is modified to lower the glass melting temperature to reduce costs. A different composition affects the quality, consistency and affects processing temperatures for bending and tempering.

2.1.3. Float glass

Production

Nowadays, float glass is the most popular applied technique to produce glass and over 80% of the global production of float glass is used in the construction industry. The raw materials needed to produce float glass are sand (silica), soda ash, limestone and dolomite. The materials are added together and heated to around 1600°C to create molten glass. The molten glass is poured onto a layer of molten tin, which has a temperature of around 400-500°C. Due to gravity, the tin bath is flat and since it has a higher density, the glass floats onto the tin bath. At the end of the tin bath, the glass ribbon is slowly cooled down and fed into the annealing lehr where glass is controlled cooled down. The annealing lehr is a long kiln where glass is annealed. The annealing process prevents glass from creating internal stresses. The speed in the annealing lehr determines the thickness of the glass ribbon, a higher speed results in a thinner ribbon and vice versa. At the end of the annealing lehr, the glass is cut to large sheets of 6.0 x 3.21 meters which is handleable for transport and further processing.[2]

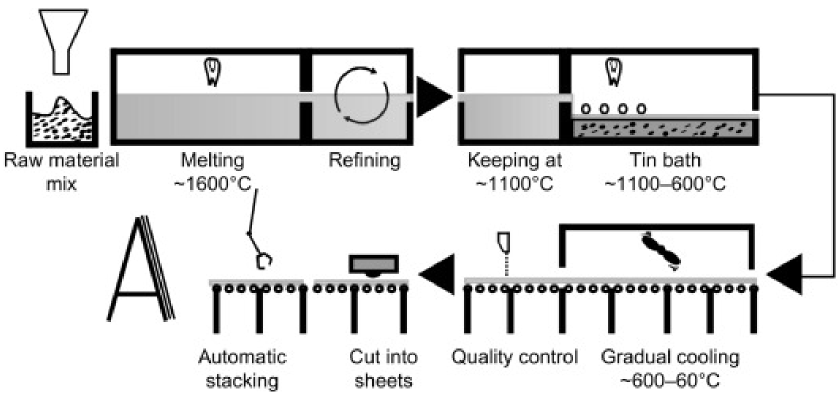


Figure 2.1: Float glass production process [2]

Treated glass

The cooling rate of glass in the production determines whether internal stresses are present in the glass or not. The annealing process prevents glass from creating internal stresses resulting in when annealed glass breaks, it breaks in large, sharp pieces. When glass is rapidly cooled down, it is called “tempering”, or “toughening”. Hereby the outer layer is cooled down rapidly, causing the outer layer to be in compression while the inside is still hot and will result in tensile stresses after further cooling down. This process is done after production of regular annealed glass and after applying finishes to the glass. When tempered glass breaks, it breaks into small pieces. This is considered to be safer than annealed glass, but the glass sheet does not have any strength after breakage compared to annealed glass. Due to the compressed outer layer, the tensile strength is bigger than annealed glass.[18]

There are two types of heat treated glass, heat-strengthened and fully tempered glass. The difference between the two is that heat-strengthened glass is cooled down slower than fully tempered glass, making the tensile strength of fully tempered glass higher, around four times higher than annealed glass where heat-strengthened glass is about twice as strong. When fully tempered glass fails, it has even smaller pieces than heat-strengthened glass or annealed glass.[18] Fully tempered glass is also known as “safety glass” and can for example be found in windshields or in buildings [59]. Both heat-strengthened glass and fully tempered glass can’t be drilled or cut after the heat treatment.[60]

Another way of treating the glass is chemically. The glass is submerged in a molten potassium salt bath, “causing sodium ions in the glass to be replaced by potassium ions from the bath. The potassium ions, which are larger than the sodium ions, squeeze themselves into the gaps left by the smaller sodium ions when migrating to the potassium solution.” [61]. This results in a compressed outer layer and a core in tension.

Chemical strengthened glass can be made very thin and is in general not applied in buildings. It knows its application for example in conductors and medicine but also GorillaGlass is made via chemical treatment.

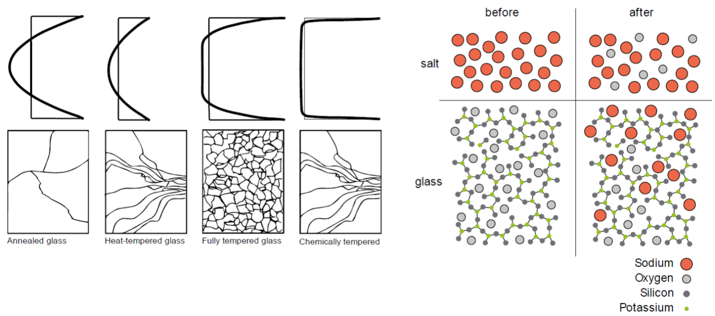


Figure 2.2: Failure pattern of different types of glass.[3]

2.1.4. A transparent structural element

Glass is applied in almost every modern building because of its unique characteristics: it is transparent, strong, chemically inert, easy available, recyclable and relatively cheap [2]. As a result of a lot of research, glass has become the past 25 years a common structural material and is therefore not only applied as just a window, but as material for load bearing structures, meaning that glass is used as material to transfer loads and to ensure stability. The main reasons for glass being so popular as structural material, is its strength and transparency. Glass is stronger than concrete, although it has a relatively low tensile capacity and it is brittle too, indicating that it will all of a sudden fail, often without any warning before failure. Transparency has always fascinated people [62] and because of that, architects and engineers were challenged to design more transparent buildings with glass as the main (load bearing) material.

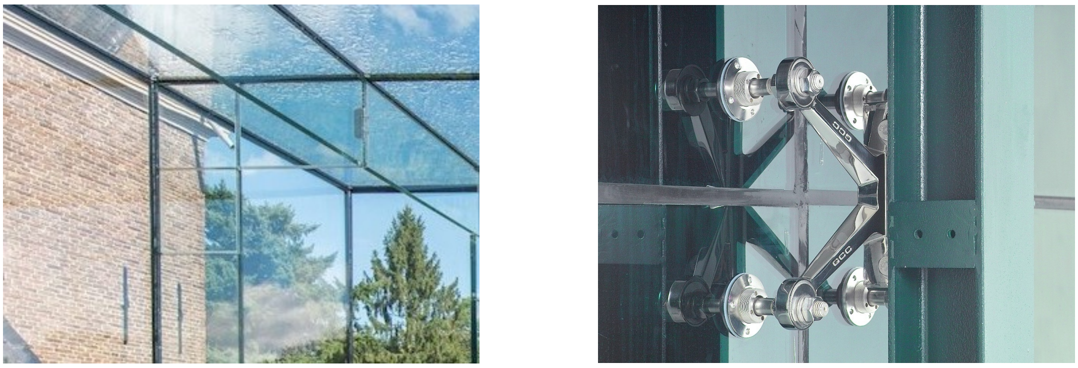
Glass applied as structural material can also be split up into two categories: laminated panels and cast glass elements. As mentioned in the scope (Section1.3), laminated glass panels and IGUs form important product groups in this research, nonetheless, a short description of cast glass is given.

Laminated glass

A laminated panel is composed of at least two pieces of glass with one or more adhesive films [59]. Laminated glass had its first applications in the automotive industry in the early 20th century. The adhesive film prevented glass from shattering in case of an accident. Laminated panels were applied in buildings as first in the 1970s [63].

In order to use flat glass panels as structural elements, different glass panels can be connected via lamination. Lamination is the process to bundle two or more sheets of glass with a polymeric interlayer. Lamination makes it possible to create thicker panels than is possible in an autoclave. Different adhesive films are possible to apply in laminated glass. PVB (polyvinyl butyral) is the most applied adhesive. Other, less popular, adhesives are SentryGlas and ethylene-vinyl acetate copolymer (EVA). The different adhesives have different characteristics, in short: SentryGlas is stiffer than PVB and EVA has a better tensile strength and performs better in humid conditions than PVB. [59]

Since the need for transparent buildings became the reason for structural glass to be developed, it led at the same time to the development of different kinds of connections to connect glass to. There are two categories in connections: mechanical and adhesive based connections [63]. Different connections can be seen in Figure 2.3 and will be more elaborated in this research.



(a) Adhesive connection. Photo by [64].

(b) Mechanical connection. Photo by [25]

Figure 2.3: Different glass to glass connections.

Cast glass

Cast glass elements were highly popular in the 1930s and meant modernity and innovation for that time. However, not all glass elements were used as structural material back then. Due to a change in architecture in the 1950's, the glass brick lost its popularity [65]. In recent years, research has been done in cast glass bricks and has led to the built of the Crystal House on the PC Hooftstraat in Amsterdam [66]. These glass bricks are load bearing and are solid glass, whilst the blocks applied in the 1930s were mainly hollow.

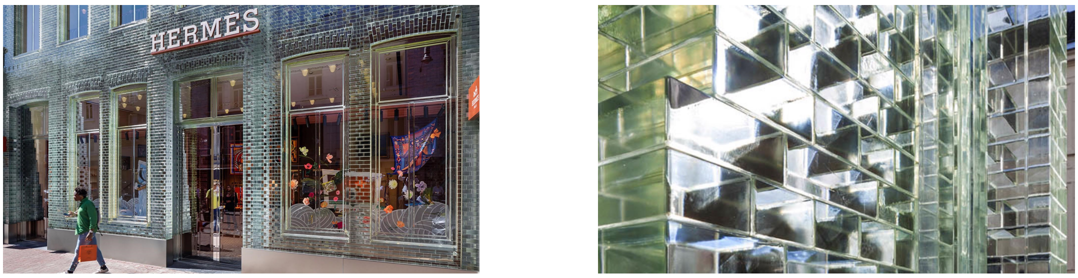


Figure 2.4: Facade made of cast glass bricks at the P.C. Hooftstraat in Amsterdam. Photos by [4]

2.1.5. Insulating glass

The second main product group is insulating glass. Given that a single pane of glass does not have any insulating performance, this led to the development of double glazing and in recent years even insulated glass with three panes, or called "triple glazing". Insulating glass, or here referred to by an IGU, are "two or more lites of glass sealed around the edges with an air space between to form a single unit" [67].

IGUs can be laminated or coated, all to the benefit of for example insulating, acoustical, visual or structural performances. The IGU is sealed off with a sealant so that moisture cannot enter the cavity and gases (e.g. air, crypton, argon) can be kept inside the IGU. A panel is highly vulnerable, especially the sealant, which fails after 20-25 years [68] and is therefore highly important in the technical lifetime of glass structures.

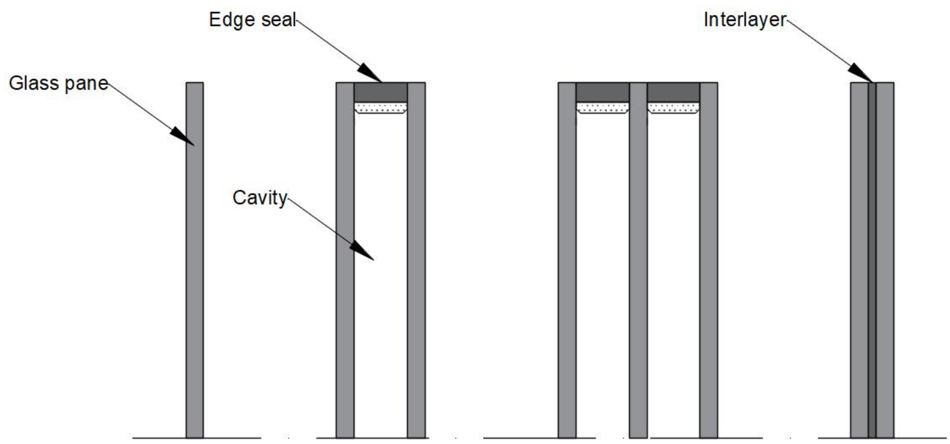


Figure 2.5: Single, double and triple glazing and a laminated glass panel.

2.1.6. Safety in design

A material that in non-load bearing applications tends to break easily now is applied as the main load bearing material. This brings some challenges in the design with it. Some important issues with the mechanical behaviour of glass and in design with glass are discussed here, but noted is that not all issues are described here.

Safety strategies

Due to the brittle failure behaviour of glass, failure should not result in any fatalities. Tempering glass is next to its higher load bearing capacity also a safer alternative, since breakage results in small pieces of glass. The loss of shape should be accounted for in the design as a consequence. In addition to safety, as prescribed in the Eurocode, glass structures have to be designed with one broken layer. An extra sacrificial layer can be added to prevent breakage of the main load bearing elements.

Static fatigue

Glass is “able to withstand a higher load for a shorter time than it will for longer times” [5] and that is explained by the phenomenon of static fatigue. The mechanical behaviour of glass is dependent on load duration and humidity since glass reacts with water molecules. When loaded, “defects present at the surface grow under the action of the corrosive environment through a surface stress-enhanced chemical reaction”[5] . These defects are also called Griffith flaws. The effect is shown in Figure 2.6 and its result is implemented in the Eurocode by a factor “k_{mod}”. Surface flaws are naturally present and are also created by manufacturing of glass (drilling, cutting), transportation or damage during its lifetime. The flaws cause a reduction in tensile strength, so limits in strength are given in the Eurocode. This strength is also called extrinsic strength.[69]

Clearly, the reaction between glass and water should be prevented but is unavoidable. Additionally, “glass is hydrophilic, meaning it attracts and holds moisture. All glass has a molecular layer of moisture on the surface. When this layer increases because of humidity or rainfall, it can obscure visibility and create a risk to comfort or safety. But most of all, it participates greatly in the destruction of the surface of the glass” [70].

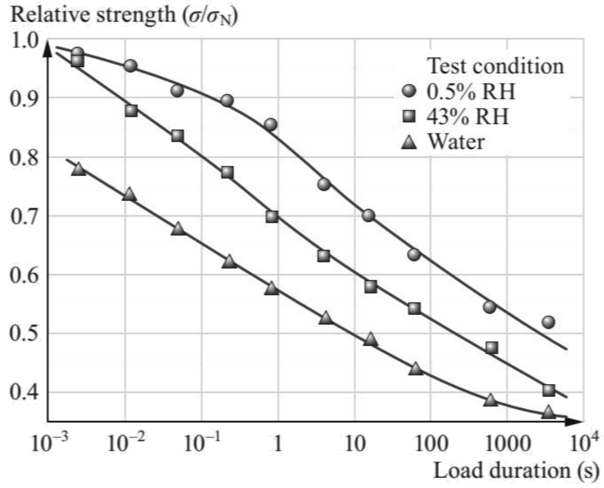
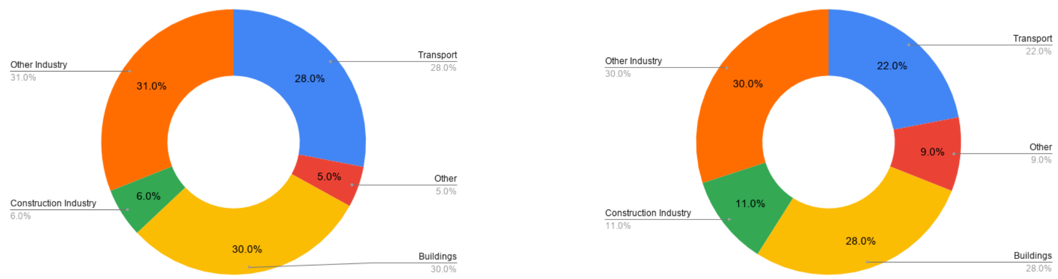


Figure 2.6: Relative strength to moisture and load duration [5].

2.2. Sustainable design

A definition by Oxford of sustainability is “the ability to be maintained at a certain rate or level” [71]. This has been interpreted in three domains: environmental, economical and social. To create a sustainable world, 17 sustainable development goals have been developed by the United Nations, varying from ending poverty to fighting climate change [72]. Currently, these three domains are interpreted as “people, planet and prosperity” and lead to sustainable development. This research focuses on the environmental impact of glass structures. When “sustainability” is referred to, “environmental impact” is meant.

In 2015, 175 parties signed the Paris Agreement which aims for a global temperature rise well below 2°C but with an attempt to limit the temperature increase to 1.5°C relative to 1990 [73]. To achieve this, the emission of greenhouse gasses (GHG) should drastically decrease. In 2015, the building and construction industry worldwide was accountable for 39% of CO_2 emissions. This includes usage of energy and emissions related to the manufacturing of building materials such as steel, cement and glass[6]. The Dutch government aims to reduce CO_2 emissions by 49% in 2030 relative to 1990 and wants to become climate neutral by 2050, meaning that there is netto no emission . Furthermore, in this economy, there is no waste and resources are being reused all over again [74].



(a) Share of global final energy consumption by sector

(b) Share of global energy-related CO_2 emissions by sector

Figure 2.7: Influence of the building sector on the environment in 2015 [6]

To achieve these ambitious goals, lots of buildings have to be transformed and new houses have to be designed and built in a sustainable way. The Dutch government has thereby four strategies: 1) use of mainly renewable resources, 2) optimization of material use over the service life, 3) reducing as much as possible emissions and 4) an innovative role which can adjust to the needs of the users and market.[75]

As indicated in Figure 2.7a, the building industry is responsible for 30% of the global energy use. According to [76], 80-85% of the total energy use is during the usage of the building. This is energy related to for example cooling, heating, and ventilation and is called operational energy[77]. The other part of energy usage is called embodied energy which resembles "the total energy consumed by all the materials and processes associated with the construction of the building including mining, processing of the materials, transport and product delivery" [77].

Life Cycle Analysis

All used energy is related to emission of hazardous GHG and can be analysed with a so-called life cycle assessment (LCA). In an LCA, the environmental impact of materials used and energy consumed is quantified over the expected life of the building and includes acquiring and processing the material, use and its final disposal.[78]

Besides an LCA, other methods are also possible to apply, but usually those methods only have focus on one component of an LCA, so-called single issue methods. Examples of single issue methods are the Carbon Footprint Method and the Cumulative Energy Demand method [79]. Another method is to calculate the embodied and operational energy. However, in this method only CO_2 emissions related to the production of energy is assumed, and other harmful emissions are ignored. An LCA therefore gives better insight into the entire environmental impact of a product.

Environmental Product Declaration

In order to quantify the LCA, different life stages should first be considered. As presented in Figure 2.8, four stages are known: product stage, use stage, end of life stage and the beyond-the-system-boundary stage, respectively Module A-D. All modules are subdivided in different phases and are determined in standard EN 15804. The quantification of the environmental impact via an LCA should be done for each phase. The sum of the impact per phase is the entire impact and is documented as an Environmental Product Declaration (EPD). Important to notice here is that having done an LCA it does not mean that the product is environmentally friendly. The EPD only offers to compare products among each other and based on comparison, a more sustainable alternative can be chosen.

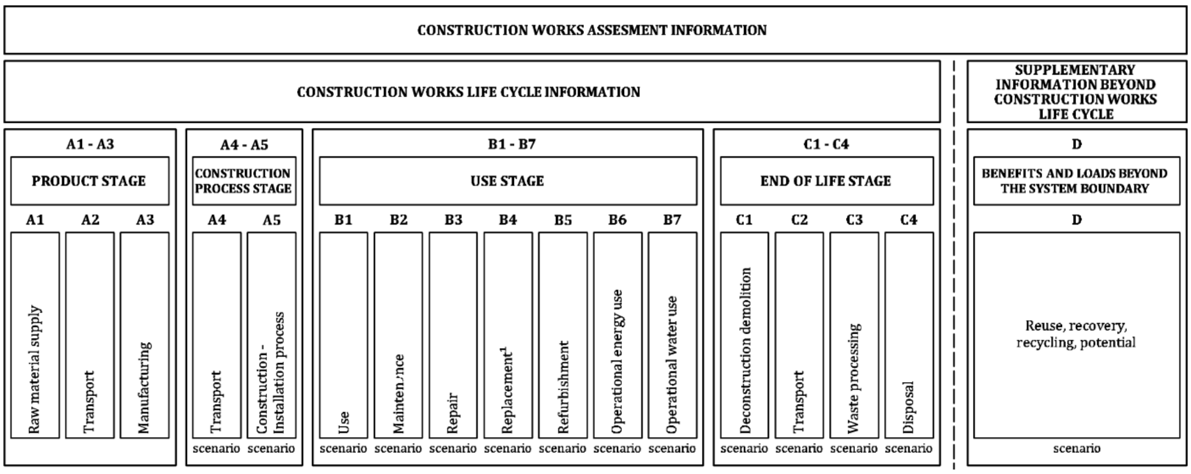


Figure 2.8: Different modules within an EPD according to standard EN 15804

A few possible EPDs can be determined considering one or more modules. The more modules are implemented in the EPD, the more work the LCA is, but the better it informs about the products environmental impact. The EPD considering all modules is called "cradle-to-grave" and implies that the entire life of the product is considered, from raw material extraction to its disposal. A less extensive EPD is "cradle-to-gate", where only the manufacturing of the product is considered, until it leaves the factory gate. A variant of "cradle-to-gate" is "cradle-to-cradle", here in the after use phase, waste is used for a new cycle. This can be done in two ways, up- and downcycling, with upcycling (or closed-loop recycling) making sure that the quality of the material is at least equal to when it entered the cycle for the first time and downcycling (open-loop recycling) meaning that in the new cycle, the quality of the material is less. There are more EPDs possible to consider when designing, in which different modules are optional, but the impact of a module can be significant, especially when considering module D: this impact can determine up to 50% of the entire environmental impact of the product .[80] [81]

To measure the environmental impact within an LCA, different impact categories are distinguished over time. In essence they all come down to three impact categories: human health, ecological quality and impact on resources. The method used in the built environment in the Netherlands is determined by SBK ("Stichting Bouwkwaliteit" or "Institution for the Quality of Buildings"). In this method, the environmental impact has to be measured for eleven categories as shown in Table 2.1.[42]

Table 2.1: Eleven impact categories to assess the environmental impact including shadow costs according to [42]

	Impact category	**Equivalent unit**	**Shadowcosts, €/equivalent**
Human toxicity	Human toxicity	1,4 DCB-eq	0.09
	Climate change	kg CO_2-eq	0.05
	Ozone layer depletion	kg CFC-11-eq	30
	Photochemical oxidants (smog)	kg C_2H_4	2
Ecotoxicity	Acidification	kg SO_2-eq	4
	Eutrophication	kg $(PO_4)_3$–eq	9
	Ecotoxicity, fresh water	1,4 DCB-eq	0.03
	Ecotoxicity, salt water	1,4 DCB-eq	0.0001
	Ecotoxicity, terrestical	1,4 DCB-eq	0.06
Depletion of abiotic resources	Non energy containing resources, as for example minerals	kg SB-eq	0.16
	Energy containing resources, fossil fuels	kg Sb-eq	0.16

DCB = Dichlorobenzene
CFC = Chlorofluorocarbons
Sb = Measured compared to antimony, or stibium (Sb)

To quantify the environmental impact, the LCA is converted to monetary impact, so-called shadow costs. Measuring all the shadow costs per step in the life cycle of a product, the entire shadow costs can be determined of the product. In the NMD ("Nationale Milieu Database" or "Dutch National Environmental Database") data is available of materials for the eleven impact categories. Interesting to mention here is that measuring the environmental impact in money is according to the Dutch standards, and not to European standards.

Life-span

The shadow costs should be divided over the expected life-span of the material or structure. However, there is a difference in technical or functional life-span. The technical life-span is "the period that a building component can physically supply the required performance"[82]. This life-span can be extended by performing maintenance and repairs, but lasts until replacement is done. The functional life-span is the period that the building component is actually used. It is the period where the building component can fulfil the function for which it was designed. It can be extended by allowing for future applications in the design. [82]

Beforehand, the life-spans of the structure should be determined. Here, an optimization can be done. The technical life-span of building materials is often endless, whilst the functional life-span can be more in the order of a few decades. If for example it is known that the building is known or expected to be demolished after 30 years, matching design principles (materials, maintenance) can be used in the design.

2.2.1. Circular design methods

To obtain a better score in an EPD, a design should be made considering the after use phase. This is done by using the principle of the circular economy: "an industrial system that is restorative or regenerative by intention and design" [7]. Within the circular economy, the after use phase is changed from waste, or so-called leakage from the system, to some sort of reuse or recycling, as indicated in Figure 2.9. However, that is easier said than done. According to [7], the current industry never changed since the start of the industrialisation: it has always been a linear economy following a "take-make-dispose" pattern. After production and use, the product has no function anymore and is disposed. Waste means losses and has "negative effects along the material chain" [7].

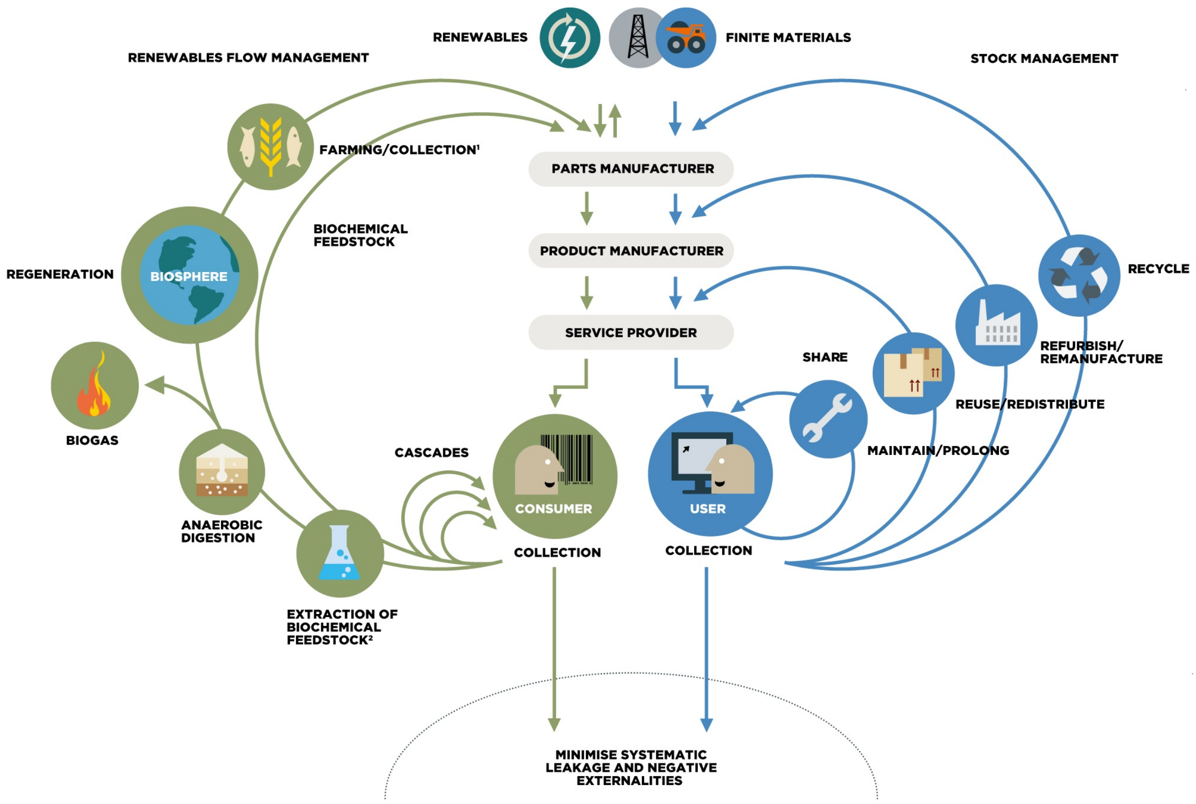


Figure 2.9: Circular economy according to [7]. In this research, the main focus is on the technical cycle. The smaller the circle, the larger the potential savings in for example costs and GHG emissions.

To include circular principles in the design, multiple design strategies are possible but basically come down to three design approaches: 1) conservation of materials, 2) extend cycles and 3) allow for cycles in the future [83]. From Figure 2.9 a few design strategies can already be derived, namely design for limited maintenance or allow materials to last longer because of maintenance, design for reuse in the after-use phase, or design for recycling. Besides these three methods, seven other design strategies are available to implement sustainability in the design and make a total of ten strategies:

1. Adaptability
2. Disassembly
3. Durability
4. Flexibility
5. Maintenance
6. Material minimization
7. Material selection
8. Recyclability
9. Reusability
10. Waste minimization

Adaptability

Adaptable buildings are designed to allow for change. This change can be for specific components in the building which can be adapted towards the like of the owner or users. By allowing for change, the building remains "fit for purpose". Another interpretation of adaptability is "maximizing its productive use", meaning that the building can be changed towards the likes of every use, thereby maximizing the satisfaction of the users. Thereby, according to [84], the definition of adaptability is "the capacity of a building to accommodate effectively the evolving demands of its context, thus maximizing value through life". Within the design approaches, adaptable buildings allow for longer cycles. [84]

For a facade, adaptability means being able to "provide adequate response to changes in the internal and external environment to ensure or to improve the functional requirements" [85]. It can also result in reducing the buildings energy demand [86]. This results in the integration of sensors in the facade to measure the indoor and outdoor conditions so that the building management system can act accordingly. According to [87] "adaptive facades can provide controllable insulation and thermal mass, radiant heat exchange, ventilation, energy harvesting, daylighting, solar shading or humidity control". In a facade, active systems can be found as for example inlets and outside shading.

Disassembly

Design for disassembly means that it is possible to take the building, or take a part of the building, apart. Disassembly should be done carefully, to minimize waste and maximise reuse. Meanwhile, design for disassembly allows for flexibility, addition and convertibility. [88]

Durability

Durability can be defined as "the ability of a building and its parts to perform its required functions over a period of time without the need for maintenance or repair". The longer this period is, the more durable the building is.[89]

Flexibility

Flexibility is about the transformability and convertibility of a building, meaning that the building allows for sufficient space for other functions. This can be done in an active way, meaning that the building for example has openable spaces, but also in a passive way which is done by having large open areas or large floor-to-ceiling heights.[90]

Maintenance

By considering maintenance in the design, there are two strategies, namely with as goal to limit maintenance throughout the life of the building or by taking maintenance into account to extend the life of the building.

Material minimization

By limiting material use, less resources are needed which results in less environmental impact.

Material selection

Selecting the right material can have a significant impact on the environmental impact.

Recyclability

The material or product which was assumed to be waste is reintroduced in the production cycle again, following the "cradle-to-cradle" principle. Therefore, less raw materials have to enter the cycle, benefiting the environmental impact.

Reusability

Making use of reusability means that in a future stage, the building or product can be reused in a new cycle.

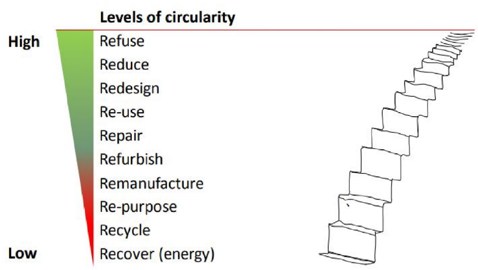
Waste minimization

The goal is to reduce the amount of waste produced during construction and demolition. Waste can involve a lot of valuable resources, which is considered to be a loss.

2.2.2. Impact

In order to make an impact in the design in terms of sustainability, various rankings have been introduced of the mentioned methods. The higher the method in this ranking, the more influence or impact is made. An example of a ranking is via the "Ladder of circularity: 10 R's" as shown in Figure 2.10a. A better sustainable performance and thereby impact is created higher up in the ladder. Methods as "refuse" and "reduce" are thereby the impacts with the biggest impact, while methods as "recycling" and "recovering [of energy]" are found at the bottom of this ladder with the least impact. A variant is the "ladder of Lansink", which is shown in Figure 2.10b, and shows a similar but more general approach in making impact. "Prevention" and "reuse" are thereby key words.

Where the biggest impact can be made by "not doing it", is in this research focus on the next levels of circularity since simply "not doing it" is not the solution. It is more the question, "how to make a sustainable impact?" by finding a solution to the problem of integration of "sustainability in glass structures".



(a) Levels of circularity[91]

(b) Ladder of Lansink[92]

Figure 2.10: Circular design methods ranked on impact

3

Glass and sustainability

3.1. Glass in general

3.1.1. Embodied energy

For the production of glass, high temperatures are needed of 1600°C, which results in a high embodied energy and carbon impact. Since the total embodied energy and carbon impact depends on the actual application, a rough comparison of glass with concrete and steel is given from literature, as indicated in Table 3.1. Float glass has a higher embodied energy and carbon impact than concrete, but a lower embodied energy and carbon impact than steel.

Table 3.1: Embodied energy and carbon of various materials, derived from [2] unless other stated. Shadow costs are also given.

Material	**Embodied energy (MJ/kg)**	**Embodied carbon (kgC/kg)**	**Shadow costs eu/kg**
Float glass	15 - 15.9 [55]	0.232 [93]	0.113 [93]
Tempered glass	23.5 - 26.2 [55]	0.346	
Laminated glass	16.3 [55]	n.a.	
Reinforced concrete	1.39	0.057	0.010 [79]
Steel	24.6	0.466	0.657 [79]

Although glass has a higher embodied energy and carbon impact, "the mass/volume of glass needed to construct members of buildings is less than that required for an equivalent concrete member"[2] and glass has a double function, meaning that glass also is useful to reduce the operational energy.

3.1.2. Emissions

Producing glass is a highly energy intensive procedure and therefore, various harmful emissions are the result. The process is shown in Figure 3.1, which summarizes the production process of glass, including all the needed energy input and resulting emissions.

Interesting to point out is that GHG emissions both result from chemical reactions for the raw materials and from energy related sources. Sodium carbonate reacts with heat to sodium oxide and CO_2, and the same holds for calcium carbonate which reacts to calcium oxide and CO_2.

$$Na_2CO_3 \longrightarrow Na_2O+CO_2$$

$$CaCO_3 \longrightarrow CaO+CO_2$$

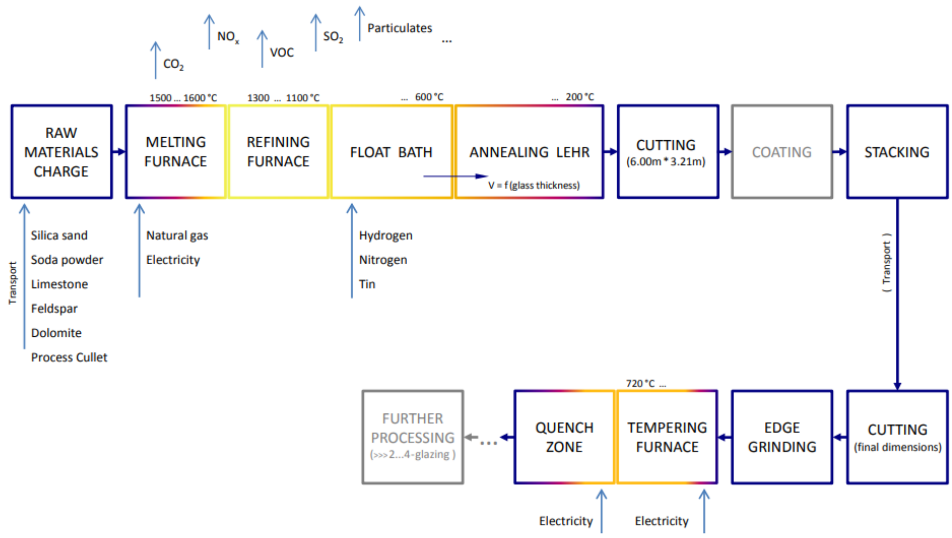


Figure 3.1: Energy processes and emission during glass production. In the top, the float glass process is shown and in the bottom, the tempering process is described. Among others, these emissions come from the production process. [8]

Using cullet in the production results in less GHG emissions since the Na_2CO_3 and $CaCO_3$ reaction does not need to take place (at high temperature), which can save up to 250 to 300 kg CO_2 per tonne cullet [49]. In Table 3.2, a simplified batch is shown for the production of glass, which shows an emission of 336 kg CO_2 for the production of 1444 kg glass, or 232 kg per tonne glass. This is a large difference compared to the data presented in Table 3.1. This can be explained by the fact that the batch presented in Table 3.2 is an uncontaminated batch, which results in mainly CO_2 being emitted. Another reason is that natural gas and electricity are needed to acquire high temperatures, which result in volatile GHG emissions too. Due to many impurities in cullet and raw materials, extra and other stronger GHG emissions like SO_2 and NO_X are emitted. These GHG can also be emitted because of additives to improve the batch, like fining agents which are used to limit bubbles in the batch.[43]

Table 3.2: Composition of a batch to produce glass. Derived from [43].

Raw material	**Composition (wt%)**	**Quantity in batch (kg)**	**Amount of oxide entering the glass (kg)**	**Melting loss (kg CO_2)**
Sand	99.95 SiO2 0.05 Fe_2O_3	1000	999.5 SiO_2 0.5 Fe_2O_3	
Soda ash (Na_2CO_3)	50 Na_2O Rest CO_2	350	175 Na_2O	175
Limestone ($CaCO_3$)	56 CaO Rest CO_2	150	84 CaO	66
Dolomite (1-x)$CaCO_3$ * x$MgCO_3$	30.5 CaO 22 MgO Rest CO_2	200	61 CaO 44 MgO	95
Sodium feldspar Na_2O * Al_2O_3 * SiO_2)	68.7 SiO_2 19.5 Al_2O_3 11.8 Na_2O	80	55 SiO_2 15.6 Al_2O_3 9.4 Na_2O	
	Total	1780	1444	336

3.1.3. Developments

Electrical oven

Especially the energy needed to produce glass causes the large GHG emissions. An electrical oven is therefore a potential, as long as the energy needed comes from green sources. Ovens already have an electrical booster, which contributes 10% to 50% of the melting power. There are however a few implications to use a fully electrical oven, like the energy prices which need to go down to become interesting for the market and the energy should come from green sources, but also methods should be developed in order to reach the high temperatures that are needed without too much wear of the electrodes. [94]

Glass compositions

Another solution to make the production of glass less energy consuming is by adjusting the composition of glass which lowers the temperature for the production of glass. Important is of course that the final product has similar (or better) characteristics as the current glass. An example of a new type of glass is by [95], who researches the effect of industrial waste on the production of glass other than float glass.

Market

The developments in the requirements and demands by the market are of course of big interest but also prone to change, since only recently the phenomenon of the circular economy became popular. The current trend is towards less energy demanding buildings, if not energy neutral buildings, the insulating performance of glass is very important. New glass panels with better insulating performances require the production of new glass, but have energy savings, and thereby CO_2 savings, as a positive impact. Besides, a lot of development and research is going on, among many others, in the aforementioned topics of the electrical oven and glass compositions and also in energy saving glazing. A recent example of research and development led to vacuum glazing by AGC, a highly insulating window.

3.2. Glass and circular design methods

As indicated in Section 2.2, there are various methods to incorporate sustainability into the design of a structure. All methods are being discussed for glass, some more elaborate than others given that not every method suits the application best. In each method, laminated glass and IGUs are discussed separately.

First the method with the most sustainable impact is discussed, reuse. Then, recycling is discussed, since a lot of information is known on this topic. Related and important to both reuse and recycling is disassembly. Then the related topics durability and maintenance are discussed and are followed up by material minimization and selection. The section is ended with the three less important methods, adaptability, flexibility and waste minimization.

3.2.1. Reuse

Reuse is one of the most sustainable ways of dealing with sustainability and a discarded product. It limits waste, and for the circular economy it is essential since it introduces a new, extra cycle. Reuse is far more impactful than other methods presented in this chapter, which makes reuse inevitable in the circular economy. Just like recycling, an organisation to handle reuse is necessary to collect all glass sheets. For container glass, this is quite well developed in for example the Netherlands and Germany. A deposit on a bottle is the incentive for people to return the bottle.

There are a few levels on which reuse can be seen: entire structure/building level, component level, or reuse of stripped float glass. Reuse of glass structures are not known, likewise reuse of stripped float glass, which indicates that there issues with glass. However, a rare example of reuse of components is shown in Figure 3.2, where in the headquarters of the Council of the EU in Brussels 3750 old timber window frames and glass panels are reused in the new facade. More reuse takes place in greenhouses, where greenhouses are demounted and rebuilt. This is possible due to the repetition in the greenhouse and demountable connections, often glass is placed in an aluminum frame. Furthermore, reuse of glass is rare.

Figure 3.2: Old timber frames are reused in the facade of the European Union Headquarters in Brussels. [9]

In order to reuse construction materials, there are several barriers to overcome: technical, logistical, costs and liability. Since there are no examples of reuse of structural glass, only technical barriers are elaborated in relation to glass. Without overcoming technical barriers, other barriers are not of interest. Given the need for a circular economy, it is likely that logistical, cost and liability barriers will be overcome in time since the same problem also has to be solved for other materials. In order to have glass reused by the time those barriers are overcome, technical barriers are of interest now. [96]

Technical barriers are: 1) standardized components, 2) performance and quality of reused components, 3) lack of properties and in-use history, 4) robustness of products in the deconstruction process and 5) practicalities of economic deconstruction.[96]

Standardized components

Given the unique character of all projects containing a load bearing glass structure, reusing the elements of the structure per component is also not directly possible. Standardization of components would overcome this barrier. In glass, only the thicknesses of the panels are standardized, but panel size, colors and other additives are variable. Developments in casted glass, as shown in Section 3.2 and Section 4.4 do implement a form of standardization since many glass bricks are needed.

Performance and quality assurance

The performance and quality of the reused element should be guaranteed, for a certain technical and functional time. If this cannot be done, it is useless to reuse a component since it wouldn't comply with the expectations, unless less quality is expected. This is exactly the problem with IGUs and laminated glass, which both lack this aspect and have a limited technical lifetime: a minimum of 5 years is guaranteed for laminated glass and an IGU will have started leaking after 20-25 years. This is all elaborated, including the reuse aspect, in Section 3.3.

Lack of products properties and in-use history

Without proper transfer of knowledge of the product and history of application, the component could be wrongly applied. Not all characteristics are visible from the outside, which means to get to know all the properties, research should be done to the glass which can become too costly. Also regarding the history of application, the loading conditions could influence the load bearing capacity. For glass this means that detailed product information should be transferred. Since this also has to be done for other materials it is believed that this barrier will be overcome.

Robustness of products in the deconstruction process

The extraction of a panel at a demolition site should be done carefully in order to prevent damage, with a potential delay as a consequence, which might be unacceptable. This can be better facilitated with demountable connections of the panel, or more on component level where a spacer of an IGU can be removed for example. Also, the type of glass and its mechanical characteristics can be a valuable measure to increase robustness.

Practicalities of economic deconstruction

To allow for reuse, deconstruction should be possible and economically feasible. Design for disassembly is a key to deconstruction and is discussed in this section. Practicalities of deconstruction should be considered in the design, to allow for an economic deconstruction. Without it is unlikely that deconstruction is considered in the after-life phase.

Other barriers

When technical barriers are overcome, logistical barriers, costs and liability are other issues. Logistical barriers are for example availability of supply, demolition programs should allow for deconstruction and storage space for the components. Costs will play a role in storage, demolition and testing of the product and should meanwhile be a commercial driver for companies.

3.2.2. Recycling

When assessing sustainability in glass, the general response is that glass is a 100% recyclable material which makes it therefore sustainable to apply. However, the sustainable impact done by recycling is far lower than would have been done for reuse, both in environmental impact as in value. That glass can be recycled is in theory correct, glass can be infinitely recycled, but in practice, recycling flat glass is a difficult process. In fact, just 20-30% of the raw materials in the production of flat glass is replaced by waste glass and meanwhile, the main after-life application for flat glass is in a landfill or ends up as aggregate in concrete and asphalt. In all situations, glass is heavily downcycled. In order to consider whether to use recycling as a goal or not in a design, an understanding of the current status of recycling is needed.[97]

Global glass production and recycling rates

In Table 3.3 is an overview given of the production of glass world wide. As can be concluded, container glass, also called glass for the packaging industry, and float glass are the main glass produced products. They both account for 48% and 42% of the production, respectively.

Table 3.3: Global production of glass [44]

Region	Production (Mto)	Devision	Mto	%
Global (2017)	128	Container	61.4	48
		Float	53.8	42
		Table ware	6.4	5
		Other	7.7	6
EU (2017)	35.8	Container	22.2	62.1
		Float	10.4	29.2
		Table ware	1.3	3.6
		Other	1.9	5

A lot of data is unknown about the global recycling rates of glass, as is shown in Table 3.4, especially considered the float glass industries. More data is known about the container glass industries, which has varying recycling rates across the globe. Europe has an average recycling rate of container glass of 74%, which is compared to world wide outstanding. In Europe alone, 11.6 Mto of container glass is recycled, while the USA only just recycles 3.35 Mto. Most of the data comes from Europe and is collected by FERVER, the European Federation of Glass Recyclers.

Table 3.4: Global overview of known data regarding amounts of cullet added to production and recycling rates.

Region	Industry	Cullet added to production	Recycling rate		Year	Note	Source
		%	%	Mto			
Global	Float glass		11	27	2018		[44]
	Container glass		32		2018		
USA	Float glass			3.35	2018	1	
	Container glass	35					
Russia	Float glass	10-20			2012		[98]
	Container glass						
Europe	Float glass	20-30		1.5		2	[44]
	Container glass	50-80 [45]	74	11.6	2015	3	
China	Float glass						
	Container glass		20		2018		

1: Mainly container glass is recycled
2: FERVER states that they recycle 70% of the glass in Europe, of which 1.5 Mto is float glass
3: EU is leading in recycling container glass, but it varies per country, Sweden has a rate of 95% while Turkey has a rate of 14%

Cullet use

As has been indicated in Table 3.4, lots of data is unknown in the production of both float and container glass, especially regarding the raw materials replaced by old glass added to the production. Replacing raw materials is done via so-called cullet: crushed waste glass. There are three types of cullet: internal cullet, pre-customer cullet and post-consumer cullet, also called external cullet. Internal cullet is broken glass coming from the manufacturing process, pre-customer cullet is broken glass from glass processing and post-consumer glass comes from the end-of-life stage, from for example demolishment. [99]

When cullet is added to the production, there are some environmental benefits. First, glass is a replacement for raw materials. For each tonne of recycled glass, 1.2 tonnes of raw material is saved. Secondly, cullet has a lower melting temperature, resulting in saving 3% in energy demand per each 10% of cullet added to the mix. Thirdly, 250 to 300 kg of CO_2 emissions is saved per tonne of cullet added [49]. Also, when cullet is used, the service life of a furnace is expected to increase up to 30% due to lower temperatures and less corrosive fumes [100].

To design a "sustainable" building, various certificates have been introduced, for example BREEAM (Building Research Establishment Environmental Assessment Method) and LEED (Leadership in Energy and Environmental Design). Since the definition of "sustainability" varies for different design approaches, the criteria for the different programs vary as well. For each criteria in each program, points can be scored. LEED has been developed by the US Green Building Council and is highly popular in the USA. BREEAM has been developed in the UK and is widely applied in the EU.

Within the LEED v4 program, criteria have been set to the material use with as a goal "to reduce construction and demolition waste disposed of in landfills and incineration facilities by recovering, reusing, and recycling materials" [101]. Given the popularity of the LEED program, glass manufacturers have published the amount of credits they can contribute to within the LEED program. In the case of glass, replacing 20-30%, or in a single case up to 41% [102] of the raw materials by cullet seems as a beneficial and sustainable way of producing glass, but in practice that turns out differently. As stated before, there is a difference between internal and external cullet use and that is where it actually comes forward that barely any post-consumer (external) cullet is used. Big float glass producers such as AGC, NSG and Saint-Gobain do not use post-consumer cullet.

Table 3.5: Use of cullet in the production of flat glass

Manufacturer	Internal cullet %	Pre-consumer cullet %	Post-consumer cullet (external) %	Year	Source
AGC	21.8	8.6	0	2017	[103]
NSG (incl. Pilkinton)	20	n/a	0		[104]
Saint-Gobain Europe	19	11	<1	2018	[105]

Limitations in recycling

The reason for glass being so little applied in the recycling industry is that the production of glass is highly sensitive for impurities. Small contaminations may lead to “1) quality problems such as for example color changes or inclusions, 2) glass melting disturbances and 3) effects on the glass furnace lifetime“[106]. Also, “different types of glass like tempered, silver-based varnish or laminated glass have different chemical compositions and impurities which prevent conventional recycling”[107]. To improve the recycling process, glass should be disassembled from the building carefully on the construction site without becoming contaminated, contamination should be removed and glass should be sorted according to their chemical composition.

High requirements on the level of contamination have been set since contamination will influence the quality of the product. Most of the contamination comes from plastics, metals, coloured glass and most importantly ceramics, stones and porcelain (CSP). CSP has a higher melting point than is reached in the oven, therefore strict demands have been set, which are shown in Table 3.6. Various requirements are set per industry, where the stricter requirements are set in the float glass industry, and less strict in other glass industries.

Table 3.6: Cullet requirements for various industries, derived from [45]. The second column is European legislation

Contamination	European legislation for glass cullet [108]	Particle weight/size	Container glass maximum (ppm)	Flat glass maximum (ppm)	Insulation mineral wool
Ferrous metals	< 50 ppm	> 0.5 g	50	None (2 if < 0.5 g)	10
Non-ferrous metals	< 60 ppm	> 0.1 g	20	None (0.5 if < 0.1 g)	20
Inorganics	< 100 ppm, > 1 mm < 1500 ppm, < 1 mm	> 0.2 mm	20	None	25
Organics	< 2000 ppm	> 2 mm	3000	None (45 if < 2 g)	3000

The composition of glass is important, since quality demands determine whether cullet is added to the mix or not. For example, clear glass requires a lower iron amount in the batch, causing not all cullet to be added. This means that cullet from the container glass industries will not be used in the production of float glass and it also means that only float glass cullet can be used in the production of new float glass. Colored glass is considered to be impossible to decolor [109]. Within recycling of container glass this has been found to be a problem.

Figure 3.3: The visual difference between low-iron glass and regular glass. The low-iron glass is more colorless than the greenish regular glass. [10]

Additional to the difficulties in recycling, the European goal to reuse, recycle or recover 70% of the non-hazardous construction and demolition waste (by weight) in 2020 can be accomplished without reusing, recycling or recovering glass, since glass is often less than 1% of the total waste. [110]

Further processing of glass, as printing and laminating or other forms of contamination limits conventional recycling too, more on this in Section 3.3.

Recycling programs

According to Glass for Europe, most of the post-consumer glass waste is used in a landfill. This is confirmed by the data of the factories, as indicated in Table 3.5, but that does not mean that post-consumer glass is not being recycled. In Europe, some recycling of float glass takes place, as for example in the Netherlands, Belgium and Germany, but there is a lack of a well organised system to encourage recycling.

In the Netherlands, Vlakglas Recycling Nederland (VRN) is a non-profit organisation which coordinates and collects all waste glass, both float and container glass. To finance this organisation, a fee of €0,30 per square meter insulated glass is charged for newly sold glass. After removing all kinds of contamination of the glass, most of the glass is transferred to Maltha Recycling, where the glass is crushed to cullet and transported to producers of various glass products. [47]

In 2018, VRN has collected over 73.000 tonne of float glass (in Germany, over 400.000 tonne [48]), of which just 7% is again used in the production of new float glass (in Germany, this is 20% [111]), 35% is used for the production of insulation materials and 47% of the cullet is used in the container glass industry. 2% is applied in a different sector. 8% of the collected materials is different from glass, of which most of this can be applied in a useful manner. This leaves only 0.1% of the total collected glass to end up in a landfill. [47]

The Netherlands, Belgium and Germany are some of the few countries of which actual data is known of glass recycling and have a well developed recycling network, however, most of the float glass cullet is downcycled into other applications than float glass. According to VRN, there are three reasons for this in the Netherlands. First, the quality of the cullet related to contamination does not fulfill the requirements of the float glass producers. Second, a couple of factories for IGUs were closed in the Netherlands, which decreased the availability of float glass for recycling and third, in 2017, there was less demand for cullet by the float glass industry and more demand by other glass industries. It is not reported what the reasons are.

Since glass is inert and non-hazardous, it can be dumped without any harm into a landfill. To prevent waste ending up in a landfill, landfill taxes have been introduced. However, from research can be concluded that taxes vary per region (in Germany only already from 20 to 220 euro per tonne and on a European level, large differences are present [48]) and in order to increase the recycling rate of float glass (also in form of downcycling in the insulation or container glass industry), actions should be taken. Transport facilities should be optimized, landfill taxes should be increased and for demolition projects, dismantling costs should be addressed [110]. A proper collection and recycling system does not exist on European level.

Downcycling programs

Glass waste, mixed or contaminated, can also be recycled into different glass elements, as is shown in the "Re3 Glass" project from the TU Delft where (discarded) glass waste is recycled into load bearing building applications. "Such components can tolerate a higher percentage of inclusions, without necessarily compromising their mechanical or aesthetic properties" [112].

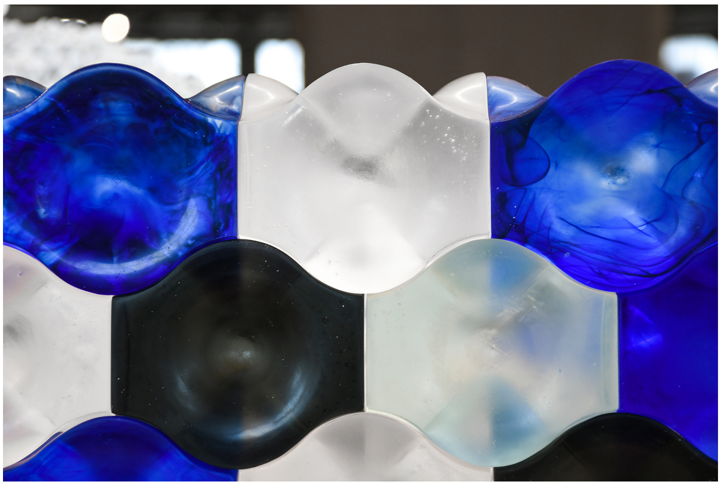


Figure 3.4: Glass waste is recycled into load bearing building applications.[11]

Design for recyclability

Before a building or structure is recycled, first often other forms of afterlife use are considered before recycling is of interest. If then recycling is considered, there are a few requirements in order to make recycling possible.[83]

First, the glass structure should not be contaminated, since that limits recyclability. This means that during demolishment of the structure the glass should be made free of impurities, like the remains of connections, frames or lamination. This starts with good separation of waste at the construction site. Just like when glass is reused, the extraction of the glass panels and structure should be done carefully, which could lead to an unacceptable delay of the demolition project [55]. This is out of the hand of the designer.

Secondly, related to contamination are the design decisions made. Influences of processing influence the level of contamination, which is elaborated in Section 3.3. Also, the choice of type of connection influences the recyclability of glass structures, this is discussed in Chapter 4. One can already state that different connections have different kinds of contamination, which influence and limit conventional recycling, but can also allow for easier demounting of the structure and thereby preventing contamination. However, even when glass is demounted properly, free from contamination, contamination can still take place in the container when other materials are (un)intentionally added to the container. Again, this is out of hand of the designer.

Thirdly, a recycling network is necessary, which is location dependent. Well developed recycling networks can be found in the Netherlands and Germany. However, even when the cullet is not contaminated, it can still be possible that the cullet is downcycled, into glass containers for example.

Future

With the market changing to a circular economy, different demands might be a result. Reuse will become more important since the value and environmental impact are far bigger for reuse than recycling. Technology improved recycling rates since better separation of (glass) waste could take place and is expected to improve even further.

It is possible that requirements to the contamination of cullet might be lowered too, in order to make better use of (contaminated) cullet. Hereby, different levels in the quality of float glass might become the standard, with contaminated, slightly colored, glass in the lowest level and clear, non-contaminated glass in the highest level. Thereby, for different demands, the right application of glass can be found. Not all applications require the highest quality glass. Besides, bringing contaminated or colored panels on the market can also result in new applications.

3.2.3. Disassembly

When disassembly is considered, 27 strategies are researched by [88] in order to improve disassembly. Examples of these strategies are to design with mechanical connections, to avoid toxic and hazardous materials, to avoid secondary finishes, to minimize the amount of materials but also to provide access to all parts of the building components.

According to [83], design for disassembly comes down to two principles: 1) easy detachable structural components via easily demountable joints and 2) loose structural components. It can be achieved by applying for example screws, bolts, nails, hinges and clamps. Important for both methods is to consider different stability measures, since non rigid connections can cause stability problems.

For a glass structure, design for disassembly is achieved if use is made of bolted or clamped connections. Also, these connections improve the reusability, flexibility and adaptability of the load bearing elements. Another benefit is in the case of damage, the structure can be dismantled and restored. Especially in glass structures, damage is an important aspect in the design, not only from a disassembly perspective, but mainly for structural safety.

Using loose structural components might be difficult in glass, since standardisation in load bearing elements is limited. Also for regular IGUs, standardization is limited, given the nature of unique dimensions of windows in buildings. However, standardization is not necessary to design with loose structural components, since the component should allow for future use by designing for disassembly [83]. A positive result of design for disassembly is the reuse and recycling potential of the loose elements.

3.2.4. Durability

Glass is mostly chemically inert, meaning that it won't chemically react making it a very durable material. It is therefore an ideal material to store for example food and beverages in. The glass in a glass structure can be considered durable, but that does not necessarily mean that the glass structure is durable. This is of course dependent on other components of the structure too, as for example lamination and connections which will be addressed later in this research.

Although glass is a durable material, in certain conditions glass does react with water and alkaline products. By considering these conditions in design, storage and construction, damage of the glass is prevented.

Glass reacts in a static humid environment. "The film of water formed on the surface of the glass reacts becomes highly alkaline and very corrosive as sodium ions are leaked out from the glass"[113]. This causes a haze on the glass. In a dynamic humid environment, in "runoff or evaporation conditions, a rather uniform dealkalized and passivated surface layer is developed which will protect the glass from severe optical damage" [114]. The limestone added to the production of glass increases the durability because of its protection against water solubility of the glass but does not protect the glass entirely from a reaction in a humid environment. Also, pollution of NO2 and SO2 increases the speed of decay of glass [115].

Also, glass is damaged by alkaline products because of the alkali-silica reaction. Alkalines are found in cements, which makes the glass vulnerable during construction. Run-off water from brickwork and concrete can cause a chemical attack and will cause a haze on the glass. Glass applied as aggregate in concrete might experience alkaline damage, although it can be prevented by using finely grained cullet [2].

A problem which can also occur is a nickel-sulfide attack. During the production of glass, nickel can be captured in the glass, which reacts with sulfur. The nickel sulfide is unstable, and will over time retransform to its stable state. This is accompanied with expansion, causing internal stresses which will lead to breakage of the glass. This can happen spontaneously and will only take place in tempered glass. Nickel sulfide inclusions are very hard to detect, although a heat soak test of the glass panel will fail most of the panels with a nickel sulfide inclusion. The longer the heat soak test takes place, the more likely it is to find a panel with nickel inclusion, but it is not 100% guaranteed that the inclusion is found. This is of course also more expensive. [18]

As mentioned in Section 2.1, surface flaws influence the tensile strength of glass. Since damage can occur over the lifetime of glass, the strength can be reduced over time up to 85% [69]. This is also referred to as ageing. In order to cope with this potential danger, careful design considerations should be made with regard to durability. For example protection measures can be taken in an highly abrasive environment or load situations with tensile stresses should be avoided or minimized.

Despite the mentioned dangers, glass is in general a very durable material. Whether glass is affected by these issues is hard to tell, since it depends on the application and local conditions in terms of weathering. Besides, processing glass might influence the durability of the glass and likewise, processings have a varying durability too. The same holds for the various connections, which is elaborated in Chapter 4. In general, glass is not affected by limitations in durability.

3.2.5. Maintenance

By considering maintenance in the design, there are two strategies: limiting actual maintenance and incorporating maintenance in the design to extend the service life. By limiting actual maintenance, no service persons have got to come by, thereby saving energy and materials and other additional benefits as saving costs. However, occasionally maintenance has got to be done, which can be unscheduled maintenance, which occurs when a glass panel is damaged or broken for example. By performing maintenance, the service life is extended, if the complete structure still fulfills the needs and requirements.

Alternatively, with a maintenance plan, the service life can be extended since items can be preventively replaced and repairs can be done so that complete failure is prevented and thereby is the service life guaranteed and extended. A lot of resources and energy have been put in the product, unnecessary maintenance and thereby waste would mean additional environmental damage.

Scheduled maintenance is for example cleaning of the glass, which is considered in the design. The glass itself does not need to be inspected, unless otherwise decided due to higher risks caused by environmental reasons.

Connections, or (structural) sealants on the contrary are scheduled to be inspected and where necessary to be replaced. This has to do with the guaranteed quality of the sealant, which is 5 years and for which an inspection protocol has to be written [116]. More about the use of sealants and its life-time expectancy in Chapter 4. Important for both scheduled and unscheduled maintenance is accessibility.

A development is “self-cleaning glass” which is created by applying a coating of titanium oxide on the glass, which might decrease maintenance of the panels. The coating is hydrophilic, rain and dirt is not kept on the glass surface as beads but spreads the water evenly along the glass, leaving no stains compared to regular glass. Applying such a coating does not mean that maintenance has become unnecessary, rain (or water) is necessary in order to have the panel work. This means that in long dry periods, maintenance can be necessary. [57]

3.2.6. Material minimization

Minimizing material use is beneficial to the environment because less resources are used and potentially less or lighter transport is needed, which again benefits the environment. However, using less materials has a negative impact on the flexibility of the design, since the material amount is optimised to the demanded load bearing capacity while a flexible design requires redundant load bearing capacity.[83]

For a glass structure, material minimization is difficult to implement in the facade. This is because of various reasons. First, glass panels have a double function, glass is both load bearing and insulates. That means that if a high insulation is necessary, extra, not necessary, load bearing capacity is generated. On the contrary, material is minimized since use is made of the double function of glass since other materials are unnecessary. Second is because of safety. Laminated glass panels have extra sacrificial layers applied to limit the consequences of failure of one of the panels [3]. Clearly safety should always be prioritized over material minimization. The third reason is because of practicalities. Laminated slender fins are hard to produce and result in larger fins [117]. A smart design is one of the few possibilities to limit material use.

Material minimization of glass or other materials involved in glass structures do influence the environmental impact directly, but are relatively low when compared to the impact reuse can make. Designing with the goal to use the least amount of material as possible can be doubted, also in terms of absolute value, since the main (raw) material needed to produce glass is sand which is a widely available material of a low value, both in costs as in environmental impact. Also processing or other alterations are more expensive than the raw materials.

3.2.7. Material selection

The material choice influences the sustainable character of the building a lot, especially considering materials as steel or concrete. For a glass structure, the material choice has obviously already been made, leaving little gain in sustainability by material selection. Influences of type of treatment of glass can, to a certain extent, make a difference in sustainability since not all types of glass is highly applicable for all sorts of sustainable design methods. For example, a tempered glass panel cannot be cut in a later stage, which limits reuse and adaptability in a different shape but allows for other structural applications. More on influences of types of glass in Section 3.3. Other material or product choices can be made for the connections, where sustainability can play a role.

A promising example of using treatments of glass is shown in Figure 3.5, where the embodied energy and various emissions are decreased when a thinner, tempered, variant is chosen. Both panels do have different characteristics, like load bearing capacity and thermal insulation, which have to be considered.

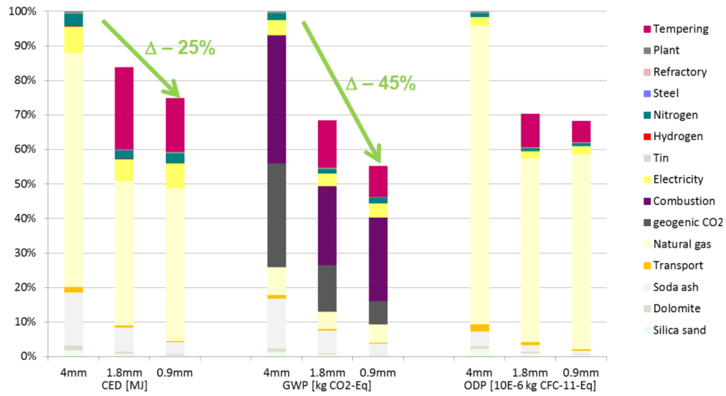


Figure 3.5: Allocation of environmental impacts: production of stadard float glass (4 mm) and tempered thin glass (1.8 and 0.9 mm). Values are related to the production of a single glass pane of 1 m^2. A thinner tempered glass pane has a lower CED (Cumulated Energy Demand), GWP (Global Warming Potential) and ODP (Ozonlayer Depletion Potential). [8].

3.2.8. Adaptability

For a glass structure, adaptability is both interesting from a facade point of view and a structural point of view. According to [83], an adaptable load bearing structure can be made in three ways: 1) by creating redundancy in load bearing elements, 2) to allow for future expansion and 3) a modular design. For a load bearing glass facade, redundancy is created by for example applying bigger fins, thicker panels or by applying different types of glass which have better characteristics. To allow for future expansion, the role of connections is inevitable since connections can mean whether it is possible to expand, but whether glass structures will be expanded in the future can be doubted. Also connections are of importance in modularity, although it can be questioned what the benefit is of a modular glass structure. Glass is already prefabricated, and modularity is interesting if strong repetition takes place in the design, not on component level, but repetition of functional units [118].

An adaptable facade can be made in various ways, but come down to the principle of implementing technology in the facade which “efficiently contribute to the energy balance of the building, limiting the need to use air conditioning devices, with a consequent reduction in energy consumption”[87]. An adaptable glass facade can be generated by applying newly developed techniques, like an adjustable translucency by applying an electrical current on the glass [12]. Shading techniques can be considered too, however those impact the transparency of the facade. Also having ducts or openable windows impact the transparency of the facade, but can benefit the energy balance of the building.

Figure 3.6: An electric current makes a glass panel translucent [12].

3.2.9. Flexibility

According to [83], flexibility can be incorporated in the design in four ways: 1) create an open structure, 2) create redundancy in the load bearing structure, 3) take into account future openings and 4) use demountable connections.

With an open structure it is meant to have no load bearing walls and to minimize load bearing elements by using a column-beam structure. For a glass structure, open structures can be achieved, if load bearing glass panels are replaced by load bearing fins.

For the other measures, it is possible to take future openings into account in the design, however, it might be limited to openings for doors and openable windows. This is often already done, unintentional or not, in the design by having repetitive elements and by working with a grid. Also, load bearing glass panels are not used as walls to separate buildings, which is a simple reason why flexibility is limited to integrate. In a traditional design, if choice is made of a lightweight separating wall in combination with a column beam structure instead of a load bearing masonry or concrete wall, it is more likely to create future openings.

Applying demountable connections do create easier possibilities to create future openings, but the panel size is also important. The panel size determines the size of the possible future openings and determines the amount and location of connections.

3.2.10. Waste minimization

By reducing waste during construction, the loss of valuable resources is prevented. According to the Waste and Resources Action Programme (WRAP) in the UK, there are five design strategies to limit waste: 1) design for reuse and recovery, 2) design for offsite construction, 3) design for material optimisation, 4) design for waste efficient procurement and 5) design for deconstruction and flexibility. [119] [83]

In order to minimize waste, mainly early in the design phase choices have to be made. This considers all methods, except for design for the fourth measure, waste efficient procurement, which is according to [83] "more a question of contracts than of design decisions". Design for offsite construction has the potential to minimize waste on site, and to increase the assembly pace which "can provide many environmental, commercial and social benefits"[83].

For a glass structure, most of the waste is generated in the production process, which involves cutting of the panels. Suppliers can optimize this in contact with the contractor or designer. The generated waste during this process is often returned to the float line. Other waste can be generated during transport [120], in the case that a panel breaks. Reuse and recycling of this waste is limited, given the limited possible applications of glass, especially on a construction site. On the other hand, little waste is generated on site, given that a glass structure is prefabricated.

Since most of the waste is created during production of the panels, it can be argued whether that can be optimized further on, given various optimization methods that already have been presented over time. Also, from a business point-of-view in glass processing, little waste means that the various panels are cut to size optimally out of a bigger panel. However, glass processor Scheuten in the Netherlands argued in an interview that unique panel size or shape can increase glass waste during production. Glass panels are delivered to Scheuten with a standardized size (6.0 x 3.21 meters) which are cut and processed to the final size. In some cases, up to 50% of the original panel is waste and cannot be used for other panels, due to unique dimensions and shapes demanded by the client and architect. Costs are accounted for by the client and waste is recycled. In order to reduce waste from cutting, AGC considers to enlarge the standardized size, however, that would mean that entire factories would have to be renewed in order to facilitate these sizes.

3.3. Altering glass

Altering and processing glass panels influence the characteristics and thereby possibilities of glass. Here, insight is given of the influence of altering and processing glass on the product and its "sustainability".

3.3.1. Treated glass

Heat treating the glass panels limits the possibility to use the glass in other applications, with a different shape, as stated in Section 2.1, both heat-strengthened glass and fully tempered glass can't be drilled or cut after the heat treatment and "any alterations, such as edge grinding, sand blasting or acid etching can cause premature failure"[121]. Recycling is possible with heat treated glass. Heat treating glass has a larger environmental impact, but is potentially less volatile than the production of new glass since it can be done electrically. Also, heat treating does increase the load bearing capacities and thereby the redundancy of structural glass applications. It is often a safety requirement and therefore makes applications possible. Heat treating glass is an addition to its value and without, glass structures would have had large dimensions.

3.3.2. Coated glass

Coated glass is produced via a chemical vapor deposition which results in an optical change (refraction and color) or improves insulation. Examples are low-E glazing, heat-reflecting glass, solar control glass, mirrors, anti-static coatings, abrasion-resistant coatings, sodium-diffusion barriers, or thin-film solar cells [122]. Coatings can be applied either online, or offline. Online coatings are sprayed on the glass during production of the float glass panel, when the glass is still hot. Offline coatings are applied after manufacturing of the glass, where a thin film is applied on the glass in a vacuum or the panel is dipped into a chemical substance.

Online coatings are more durable than offline coatings due to the strong bond. Recycling can be limited due to the coatings, but according to [49], coatings are burnt off in the remelting process. It is also possible that coatings are adsorbed in the glass, this can cause a visual disturbance () . When an offline coating is applied, the coating is removed where possible in the recycling process.

Coatings can be colorless or colored, but even colorless, coatings can become visible in certain conditions. For example, with a titanium dioxide coating for self-cleaning glass, rain and dirt is not kept on the glass surface as beads but spreads the water evenly along the glass, leaving no stains compared to regular glass. This leaves differences in appearance between panels. When a coated panel is reused in a later stage, again good mapping of the characteristics is needed to not forget these characteristics, especially those which might not be directly visible. Coatings do not affect the other characteristics of the original glass. [2]

3.3.3. Laminated glass

Function

Lamination is the process to bundle two or more sheets of glass with a polymeric interlayer [123]. Lamination makes it possible to create thicker panels than is possible in a float line. Various interlayers can be applied, to bundle to glass panels and therefore to create stronger and stiffer panels. PVB is the most applied interlayer, and because of its popular application in windshields, most is known of PVB with regard to sustainability. SentryGlas, EVA and other interlayers cover a small percentage of the total market.

Glass failure due to delamination

Ageing or weathering can affect the durability of the interlayer material and can lead to (local) delamination and is caused by humidity, solar radiation and temperature changes. Big delamination is not frequently reported, but discolouration, small bubbles or edge delamination does occur more often, especially with open edges. [123]

Since weathering depends on the local climate conditions, it is hard to tell whether or when delamination will happen. In order to assure a long (50+ years) technical lifetime, delamination should be further researched, also for different interlayers. For PVB laminated glass, manufacturers guarantee no significant lamination (up to 10 to 15 mm from the edge) and no discolouring of the interlayers for 5 years, for example see [124] [125]. Since the edges of a glass structure are open, in contrast with the car industry where a black edge covers po-

Figure 3.7: Delamination of a PVB interlayer [13].

tential delamination, even 10-15 mm delamination is fatal for the design, not even spoken of discolouration after 5 years. A frame would be an outcome, since contact with water is prevented but that would influence the design highly [123].

Many different studies have been performed on the ageing of laminated panels, and according to [126], there is a lack of “unanimous methodology in order to compare ageing studies with different materials”. It is therefore hard to conclude on the effect of humidity, solar radiation and temperature changes. However, it is clear that for PVB, the interlayer water content can affect the adhesion and therefore structural integrity to the glass. The use of acid sealants around the edges could also be a cause of edge delamination. [127]

Another reason for edge delamination is because of poor manufacturing. This can be caused by the clamping devices on the edges of laminated tempered glass during the autoclave process to laminate glass. Stress release over time causes local delamination. It can also be related to the way the laminated glass is cut. [127]

That poor manufacturing a reason is for delamination indicates the importance of quality, but also the lack of legislation to handle quality aspects related to delamination. Interlayers as SentryGlas and Trofisol (a high quality PVB interlayer) are known perform better than other PVB interlayers, but given its small share on the total market, it is not proven that delamination will not occur [128]. Additionally, the few applications are often in inside conditions, which are not the most extreme conditions, and only a few companies are allowed to manufacture these specific interlayers due to the high quality demand. To make the quality aspect even more difficult, the final product is hard to check on quality, since delamination will occur over time.

Forced delamination process

In order to recycle a laminated panel, separation of the glass and the interlayer is necessary. There are two possible techniques to delaminate, by heat and steam and via mechanical separation. Delamination via heat and steam separates the glass panel and PVB entirely, according to [14], on the condition that the glass is not too damaged. The glass panel can be reused after lamination and the interlayer can be recycled.

(a) First, the panel is exposed to heat and steam (b) The interlayer comes loose and can be removed (c) The result is two glass panels and an interlayer.

Figure 3.8: Glass and interlayer recovery after separation. [14]

Mechanical separation of the panels and the film can be done, for which machines have been developed. According to [15], first mechanically 50-70% of the glass is removed from the PVB layer. Then, nearly all of the remaining crushed glass is removed by a chemical substance in a “wet process”, with as final result a PVB layer and glass cullet which are ready for recycling. In the Netherlands, laminated glass up to 30 mm is accepted for recycling, thicker panels are not accepted due to limitations in separation [129].

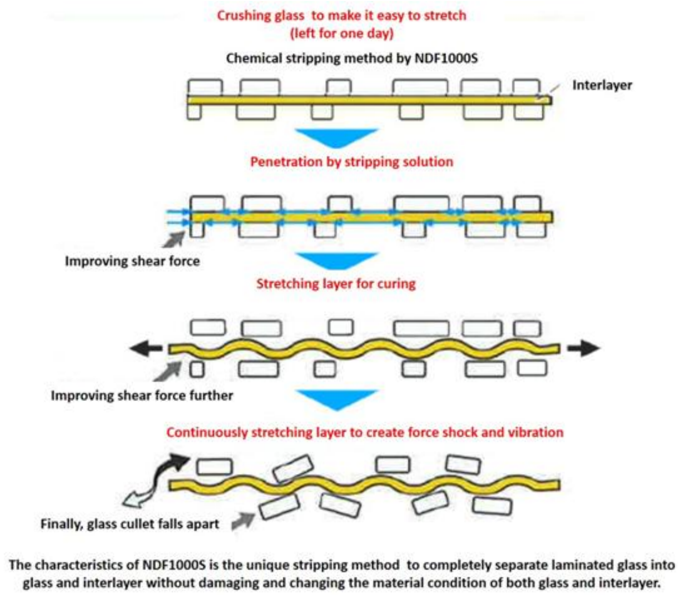


Figure 3.9: Destructive method to separate glass and interlayer.[15]

Sustainability of various interlayers

PVB

Both delamination techniques are promising, but still most of the PVB layers are not recycled and end up in a landfill or are incinerated. Besides delamination, recycled PVB has a varying structure and lower properties than the original PVB. Also the transparency is decreased by 0.2% after each cycle. [126]

In the Netherlands, VRN and UpcyGran have experimented with recycling PVB. The PVB is mechanically separated from the glass, after which the PVB is remolten to other applications as cladding, insulation or as water barrier along window frames. [130]

SentryGlas and EVA

Given the limited applications of SentryGlas and EVA related to PVB, limited information is known in relation to sustainability. According to [15], the heat and steam delamination method is also suitable for EVA and SentryGlas layers but whether SentryGlas and EVA are actually recycled is not known. However, the main advances can be found in both its characteristics. SentryGlas is more resistant to moisture, salt and effects of weather, allowing for laminated glass to be applied in different, more extreme, environments [131]. Also, SentryGlas is a hundred times stiffer and five times stronger than PVB, allowing for thinner and therefore lighter structures. SentryGlas and EVA are adhesive to materials other than glass, which makes them suitable to use in glass-to-steel connections. [3]

Reuse

Concluding on the findings before, in order to reuse a laminated glass panel, the most important technical issue is the performance and quality assurance. Hereby should delamination be prevented by using high quality interlayers as SentryGlas and Trofisol, but it is not guaranteed that delamination will not occur using these interlayers. The need for legislation to have high performing interlayers for a certain amount of time will improve the reuse possibilities. Despite this demand, SentryGlas and Trofisol seem to increase the reuse potential, which is different to an IGU, which is not suitable for reuse, see the next paragraph, and makes a different design strategy possible.

3.3.4. Insulated glass

Already indicated is the limited technical lifetime of an IGU. This is cause by the sealant, which will start leaking because of pressure/temperature variations over time in the panel. This will cause all the gas to leak out of the panel and moisture to enter, leading to decreased insulating performance and condensation inside the panel. This often happens after 20-25 years, but examples are known of a shorter technical lifetime. A shorter lifetime is guaranteed of 10 years. This indicates the importance of quality of the product, but also shows the lack of quality demand by legislation. The leaking glass panel results in a replacement of the panel, or if not even the entire facade since facades consist of more than one IGU. Even though the rest of the panels can still fulfill a longer service life, the sealant might determine the service life of an entire facade. [68]

Figure 3.10: A leaking IGU. Photo by [16].

Reuse

Given the lack of quality, reuse is unlikely. Another reason which limits reuse possibilities are the higher demands of the insulating performance. Another potential issue with a second application of an IGU is that it is more likely to start leaking due to different settlements than the glass at that moment is used to. Even if reuse is considered, challenges arise with as main concern the differences in IGU, which might be limited if large buildings are dismantled, since then a large batch of similar IGUs is available for reuse, but will differ among a few individual panels.

The lack of possibilities for reuse makes refurbishment a viable possibility (discussed in the next paragraph), or the market should find a different solution to integrate the circular economy in design.

Refurbishment

Given that the edge seal has a limited technical lifetime compared the other materials of an IGU made [132] propose a solution to increase the technical lifetime is by refurbishment. There, the edge sealant is replaced every ten years, which allows the other materials to use its full technical lifetime potential. Additionally, a check valve type is integrated in the IGU to refill the cavity with argon glass with each manufacturing cycle. It still has to be proven to become a cost-effective solution.

Recycling

A different end-of-life use is recycling. Recycling of IGUs does already take place and requires the IGU to be dismantled. Aluminum spacers are removed, likewise other contamination is removed with special machines and finally the glass panes are crushed in order to end up with a clean cullet. If design for disassembly is considered in the design of a panel, all materials would have been easier to dismantle and therefore have a higher recycle and reuse potential.

3.3.5. Processing of glass

At the end of the production line, glass undergoes final processing. This can involve bending of the glass or edge finishing. In this section, the impact of these final processes on the sustainable performance of glass is explained.

Bent glass

Glass can be either hot or cold bent. Both techniques do not limit recycling possibilities of glass. In the case of lamination, due to the (double) curvature, full separation of the interlayer and glass panels might be difficult, although it is shown to separate windshields too. Because of its uniqueness, reusing might be limited but is not excluded, proper disassembly should be done to allow for this.

Finishes

Cutting

Cutting is necessary in order to use the glass pane in the first place. Cutting old glass makes new applications possible. In the production of glass panels, as stated before, remains of cutting are recycled as internal or pre-consumer cullet. Cutting glass damages the edges, which should be treated since surface flaws have an impact on the strength of glass.

Polishing

Polishing of glass is widely done in the automotive industry and sometimes also in buildings. Scratched, stained or hazed glass can be restored, which gives the glass another lifetime. Polishing of glass does not affect the sustainability of glass, as long as it is done properly without damaging the panel. However, polishing is often done with cerium oxide polish, but cerium is a rare earth material [133]. Polishing can, from a sustainability point of view, better be performed with aluminium oxide polish.

Grinding

Grinding is essential for edge finishing. Edge quality is dominant in strength [134]. Grinding chamfers the sharp edges, which is visually pleasing and improves the workability of glass but not every grinding process allows for a structural application [3]. After grinding, the edges are polished to improve its quality.

3.4. Conclusions and discussion

From this chapter many conclusions with regard to sustainable design methods can be made. A summary and conclusions of the findings are summarized per main design goal and the effect of altering the panel are also summarized and concluded. Only the most important findings of altering glass are mentioned per design method. In the final paragraph, the first sub-question "what is sustainability in glass structures?" is answered.

3.4.1. Summary and Conclusions

Allow for future cycles

Reuse

- The most sustainable end-of-life application is reuse. Currently, reuse of glass panels is not done, with a few exceptions here and there. Without overcoming technical and logistical barriers, and costs, reuse is also unlikely to happen more often in the future. However, given the need for a circular economy, it is likely that such barriers will be overcome. In order to have glass reused by then, the focus should be on overcoming technical barriers and principles of design for disassembly should be integrated.
- There are a few levels on which reuse can be seen: entire structure/building level, component level, or reuse of float glass. Reuse of a component or entire structure is more likely with robust modules and demountable connections. If reuse of float glass is considered, all processes should be revertable, including those of coatings and lamination, which is difficult and the value is relatively low. Reuse should be considered on building or component level.

- Reuse of an IGU does not take place and suits no possibilities for reuse. Only refurbishment can be considered, although it has to be proven to become a cost-effective solution.
- In order to reuse laminated glass, performance and quality should be assured. Hereby should delamination be prevented by using high quality interlayers as SentryGlas and Trofisol, but it is not guaranteed that delamination will not occur using these interlayers.
- There is a need for legislation for IGUs and laminated glass to be able to guarantee a certain technical lifetime.
- A different strategy is needed for laminated glass than for an IGU to implement circular design principles.

Disassembly

- Design for disassembly is implemented in the design by using demountable connections as clamps and bolts or other mechanical connections. Crowther introduced other ways of implementing design of disassembly in the design. Disassembly increases the reuse, recycle possibilities, as well as adaptability and flexibility possibilities. Disassembly to float glass level is difficult, given the many processes glass has had.

Recycling

- On a world-wide perspective, flat glass is barely being recycled. However, in the Netherlands, a glass recycling network has been developed. Only 0.2% of the glass waste is unusable and ends up in a landfill, but nearly all the glass and other materials accompanied with glass are recycled. However, just 5-10% of flat glass cullet ends up back in the float glass industries and the rest is downcycled to container glass or as glass fibres.
- With the recycling, per tonne recycled glass, 1.2 tonnes of raw material is saved and 250 to 300 kg of CO_2 emissions is prevented. Also, 3% less energy is required per each 10% of cullet added to the mix. Also the service life of a furnace is expected to increase up to 30% due to lower temperatures and less corrosive fumes.
- Producers as Saint-Gobain, AGC and Pilkington do not use old float glass waste from building sites, but use cullet from internal processes.
- Problems in recycling are contamination and less demand by float glass producers, however, contamination of plastics (silicones/sealants/adhesives) is less strict. Some contamination is allowed, as long as it does not come in large batches. For other contamination, especially CSP, strict requirements are set on the level of contamination. There are very high standards for sources and cullet within the float glass industry
- Within the glass recycling market, there is a large demand by the container glass and fiber glass industries for cullet.
- Recycling, and downcycling, are both good end-of-life applications of flat glass waste, however, in order to increase the recycling potential, contamination should be avoided. This can be done by using demountable panels which improves the demountability, however, not all the contamination is of influence by the designer. Besides, the market demands cannot be changed.
- Altering glass
  - Lamination is possible to remove, it requires more effort, but recycling plants are already able to separate PVB. A sustainable end-of-life use of interlayers is limited, so far it stays mainly with experiments of very limited recycling to new PVB. Other interlayers are not yet common to be discarded.
  - At VRN, laminated glass with a maximum thickness of 30 mm is accepted.

Extend cycles

Durability

- Glass is a durable material which can exhibit a few problems with salt and water, but with a proper maintenance plan and a proper design, these problems can be avoided. Also, nickel sulfide attack can be avoided by a heat soaking test, or by avoiding fully tempered glass.
- The durability is governed by the alterations (to produce an IGU or laminated glass). Also other finishes can influence the durability.

Adaptability

- Adaptability of a glass structure can be integrated both in the load bearing structure as in the facade, but in general the sustainable impact is limited.
- In the load bearing structure, adaptability is created by redundancy in load bearing elements, to allow for future expansion and to make a modular design. As long as the panels and connections allow for a future change, adaptability can be incorporated in the design, but no examples are known about integrating adaptability in the design of a glass structure.
- An adaptable facade can be made in various ways, but come down to the principle of implementing technology in the facade in order to manage the energy balance of the building.

Flexibility

- Flexibility can be created by an open structure, redundancy in the load bearing structure, taking into account future openings and use of demountable connections, but in general the sustainable impact is limited.

Maintenance

- By considering maintenance in the design, there are two strategies: limiting actual maintenance and incorporating maintenance in the design to extend the service life.
- Limiting maintenance can be done by for example self cleaning glass, but that does not make maintenance unnecessary.
- Incorporating maintenance in the design can be done with a maintenance plan and providing accessibility and also demountable connections make replacement of panels possible.

Conservation of materials

Material minimization

- Material minimization is a difficult to implement method given safety, practicalities and the insulating function glass panels also have. On the contrary, material minimization is achieved by integration of glass structural elements and thereby eliminates the need for other structural materials.
- With alternative designs, material can be minimized, resulting in a smaller environmental footprint. However, the method is the inverse of redundancy, which is to the benefit of flexibility and adaptability.

Material selection

- Glass clearly already has been chosen as material, which makes material selection only interesting on altering level, or selection of connection type and material.

Waste minimization

- As long in the design the dimensions and shape of panels are considered to the standardized panel size (6.0 x 3.21 meters), further waste minimization cannot be implemented as a design strategy for glass structures since little waste is present on the building site and most waste is already optimized in the production. The remaining waste during production is already recycled as cullet.

Altering glass

- Most of the processing or altering cannot be done or undone after finalizing the panel.

3.4.2. Discussion

In order for a glass structure or element to be sustainable, the relation between glass and various sustainable design methods have been researched. In the previous sections, elaborate conclusions have been given. Here, the overall conclusions are discussed.

Reuse is the most sustainable design method and is the key to the circular economy. Reuse of glass is barely done, given the limited standardization and other technical problems. Besides that, current glass projects are unique and tend to have a prestigious character which do not improve the reusability. Whether and how reuse and prestige can be combined is a question. Also the level of reuse is a point of discussion, since for a single component, standardization is important but for reuse of an entire structure, standardization is less important. In either case, principles of design for disassembly play a vital role and come down to the use of demountable connections.

Recycling of float glass is on a world wide level not done, but in the Netherlands, the recycling network is well developed. In this recycling network, many alterations do not play a vital role in recyclability as long as coatings and adhesives are limited. Limiting these alterations in the design is a possibility to increase the recycling potential, but will not mean that glass is recycled. Using easy demountable connections does increase the potential of glass being recycled, but will, again, not mean that glass is recycled. Contamination by sealant/adhesive/coatings does to a certain amount limit recyclability, but is not governing. Governing contamination, as for example CSP, is out of control of the designer. As long as the recycling industry is unable to remove very small pieces of contamination, downcycling will most likely be done, since quality demands are lower in other industries. Although this process is irreversible, benefits can be found in other sectors. Design for recyclability means changing the market, which is difficult, if not impossible.

Concerning durability, glass is a durable material, but the technical lifetime is determined by leakaging IGUs and delamination. Maintenance can play a role in the durability, but is a small measure. Design decisions will influence the durability and maintenance, as demountability does for maintenance.

Methods as adaptability and flexibility are not the most suitable design methods for glass structures, given the unique projects in glass. Only when demountable connections and a way of modularity or standardization are considered, adaptivity and flexibility become interesting. By then, later changes can be facilitated. Hereby, disassembly plays a role, but that will again depend on the demountability of the structure.

Minimizing waste is hard, only when unusual shapes and sizes are considered in the design, a glass processor can give advice on limiting waste or not. There is barely any waste on the construction site.

The material choice has obviously been made, so only different alterations can be selected. This could benefit material minimization too, since heat treated glass has better structural characteristics than annealed glass. Both methods have the potential of a big sustainable impact when this is prioritized in design.

3.4.3. Answer to research question

Summarized and concluded, the answer to the sub-question “what is sustainability in glass structures?” is the following. Sustainability can be integrated by different sustainable, circular design methods. Demountability plays the biggest role in the design of a glass structure in the circular economy and should be implemented in the design to improve sustainability. Demountability is important for the end-of-life phase, since recycling is improved and reuse is allowed for by demountability, on the condition that other elements also allow for reuse. This is difficult due to the problems with the main components IGUs and laminated glass. Most direct gain can be made with material minimization, since large emissions are related to the production of glass. Also, material selection can play a role, but more on the level of processing (lamination, connections).

4
Connections and sustainability

Clearly, a type of connection influences the overall design but also the structural system. Connections in glass structures are often governing in design, just like in timber, since higher stresses are related to the connection. This leads to extra material use, so to make “impact by design” in terms of sustainability, selection of the right connection should be done.

In this chapter, first, the issues and possibilities of connection design is discussed. Then in Section 4.2 adhesive based connections are discussed, in Section 4.3 mechanical connections are discussed and in Section 4.4, other alternative connections are introduced. In the last section reference projects are shown to which much reference is made throughout the report.

4.1. Connection design

Connections can be integrated on many different locations along a panel, fin or other structural element. A small impression is given in Figure 4.1, where a few variants are shown. Clearly, the amount of different possibilities in connection design is infinite, but come down to two main groups: mechanical and adhesive based connections. The focus will therefore be mainly on these two groups.

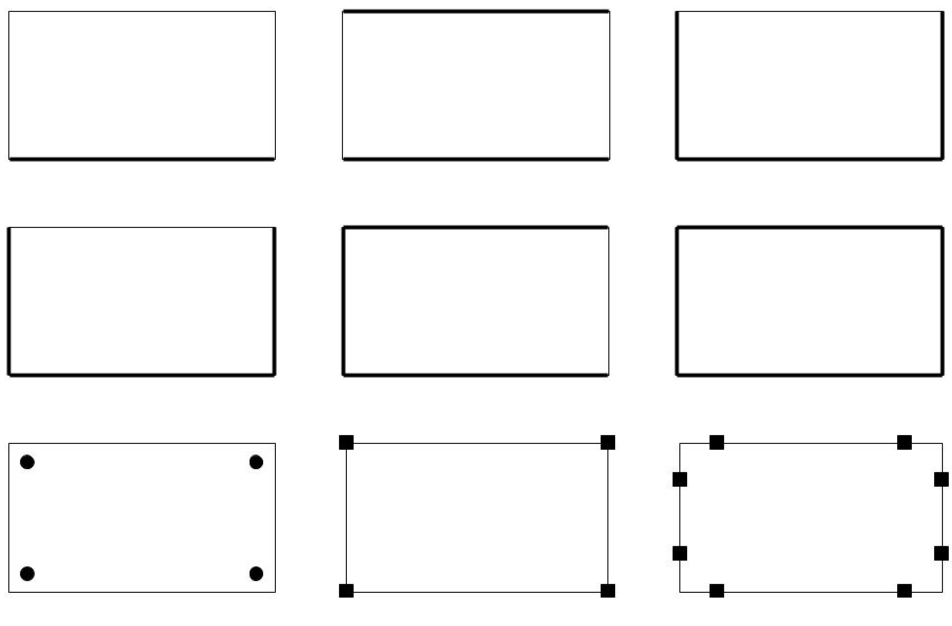


Figure 4.1: A few principles to connect a panel. Adjusted from [17].

4.1.1. Requirements

For the design of a connection, various requirements have a priority in the design and before, sustainability was an unspoken topic. In general, the traditional requirements for a glass structure have to do with structural performance (rigid or hinged), transparency and air- and watertightness and tolerances. Other requirements become more project specific, but can have to do with integration of rainwater systems or cables for electricity. Recently, sustainability has become a point of discussion in the design, which leads to requirements as demountability or overall impact.

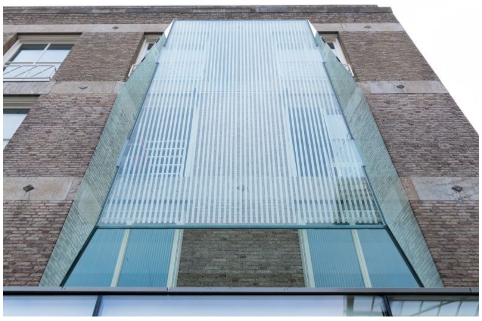
4.1.2. Materials

Lots of different connections can be considered, especially considering that glass can be connected to various materials. Important in the design of glass connections is an interlayer between the materials, since glass has a bad resistance to peak stresses. Glass is mainly connected to glass and steel, but can also be connected to timber. Connections to other materials exist, but are considered irrelevant. In this chapter various connections will be introduced.

4.1.3. Standards

For glass structures, (national) standards have been developed over time which allowed (structural) glass to be applied more. However, given the rapid development and specific applications in structural glass, not for every connection type standards exist. For example, there are no European standards for the design of adhesive connections but also varying requirements per country.

Even on a local level in the Netherlands there are varying requirements. For example, the mirrored glass facade panels of “Depot Boijmans van Beuningen” in Rotterdam are required to be secured mechanically, next to the sealant, while the protruding glass boxes for the “18 Septemberplein” in Eindhoven were allowed to only rely on the structural sealant, without an extra mechanical connection.



(a) Project "18 Septemberplein". Photos by [33]

(b) Project "Depot Boijmans van Beuningen". Photo by author.

Figure 4.2: The mirrored glass panels of "Depot Boijmans van Beuningen" had to be secured while a protuding glass box at "18 Septemberplein" did not have to be secured.

The guidelines used for design with adhesives in the Netherlands is the ETAG 002 (European Technical Approval Guideline). Another requirement is that the structural performance of adhesives should be 50 years, otherwise the connection should be mechanically secured [21]. Additionally, inspections of the structural sealant is often required when a long lifetime cannot be guaranteed.

4.2. Adhesive connections

Different adhesives have been developed over time which all have unique characteristics in order to be suitable in glass applications[135]. There are four main groups of adhesives which can be applied in glass structures: epoxy, methacrylate, polyurethane and silane-terminated polymers (silicone) [18]. First an introduction is given, then for each adhesive, a short description is given and an application in practice is shown. Next to structural adhesives, also other kinds of adhesives are shown, a mortar for example. All EPD material data is given in Appendix F to quantify the environmental impact and to compare the different materials.

4.2.1. Introduction

An adhesive has the structural characteristics to hold and bond two elements while sealants are meant to fill larger spaces and are not meant to structurally bond two elements. Adhesives can exist out of one or two components. One component adhesives react with the atmosphere (air, moisture or even UV light) whilst two component adhesives react with each other to form a bond. This bond is accompanied with stiffening via crosslinking of the large molecules. The structural characteristics of the four main groups of adhesives is shown in Figure 4.3. Epoxy adhesives tend to have a higher strength than silicone sealants, but silicone sealants have a better strain. This is related to the amount of crosslinking that happens on a molecular level.

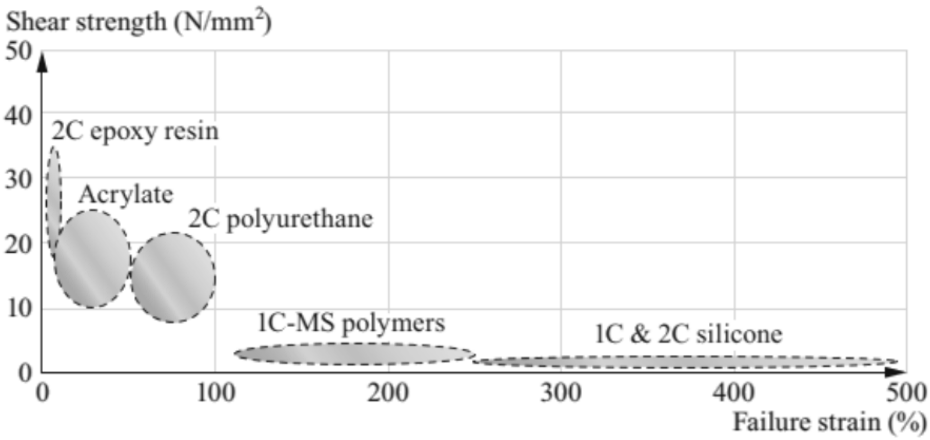


Figure 4.3: Mechanical behaviour of different adhesives [18]

Safety

Various failure mechanisms of an adhesive bond are possible as shown in Figure 4.4 whereas the overall goal is not to have an adhesive (bonding) failure. This leaves therefore the problem that the adhesive will always remain present to the glass, which is in the application not an issue but when problems arise, the sealant is hard to detach.

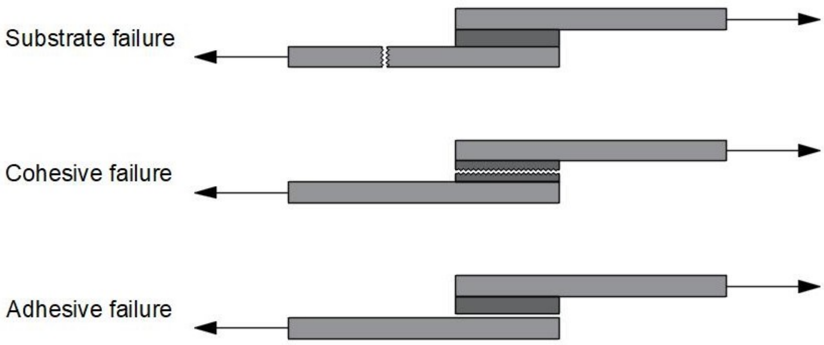


Figure 4.4: Failure mode of adhesives. An adhesive failure should be avoided.

A few other interesting characteristics of adhesives with regard to safety and design are listed:

- Since an adhesive is not applied on a local level, the adhesives spread the load and thereby preventing peak stresses.
- Some adhesives warn when extremely loaded by a kind of “whitening” that occurs, which can be irreversible. In terms of sustainability, this could mean the end of the functional lifetime.
- Adhesives are susceptible to ageing and weathering which could lead to the end of the technical lifetime, which is not considered to be durable. [136]

Practicalities

In terms of practicalities, adhesives should be carefully selected. Not all adhesives are easy to apply and when starting to apply the adhesive on the building site, there is little room for error and there is no way back since it is hard to remove. However, when applied correctly, the connection is stunning.

Often next to the function of structural adhesives, the adhesive leads to an air- and watertight barrier. This barrier is very important for building physics, but also the aesthetics are directly influenced by such a sealant. Due to tolerances, extra material use could be inevitable and should not be the main goal in the design. Besides, some places are hard to reach to apply an adhesive, which again makes other issues more important than sustainability.

Toxicity

The EPD data is presented in Appendix F, but that does not mean that adhesives are “good” or “bad”. Adhesives are chemical substances which, if applied wrongly or are carelessly handled toxic, if not deadly, for humans. Also if it ends up in the environment, harm is done. This is all not “sustainable” at all, but when carefully handled and the adhesive is not liquid anymore, the adhesive is less of a danger to the environment.

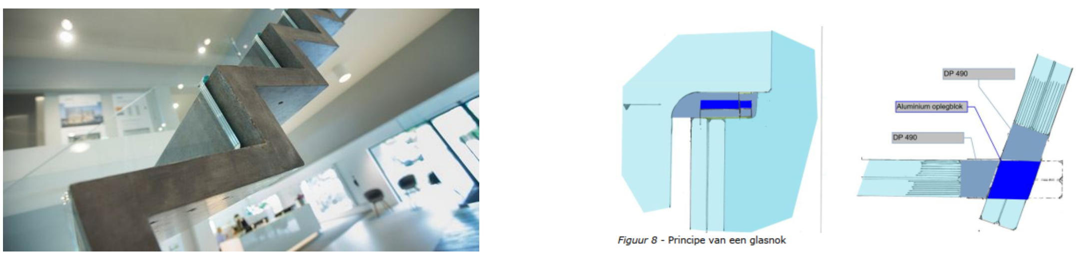
Sustainability

Because adhesives are difficult to remove, the adhesive is not being recycled in the end-of-life stage. This can also be concluded from NMD data presented in Appendix A. Mainly, adhesives are incinerated or end up in a landfill. Also reuse is not possible of both the element (due to bad removal) and the adhesive itself. Proper selection of adhesives is necessary to not have problems with durability, since adhesives have time depending properties, like weathering could cause problems. From these points of view, adhesives are not sustainable at all, but very little material is needed and in some applications, a sealant is already needed to form an air- and watertight barrier. Combining this with a structural performance, makes material selection interesting from a sustainability point of view.

4.2.2. Epoxy

An epoxy connection is the result of a reaction between two components, an epoxy resin and a hardener. An epoxy connection is a stiff and brittle connection and is used to make rigid points. Examples of application are in the embedded joints in the “stairs” and in the corners of “18 septemberplein”.

Some EPDs are available of epoxies, since production is highly energetic, but as much as data is presented from the NMD and of products that ABT b.v. has used. Also much research, among others [137], [138], is performed to produce biobased epoxy (differences in epoxies exist, therefore it is not confirmed that this is explicitly done for glass applications). However, biobased production does not necessarily mean that this is more sustainable.



(a) Epoxy has been applied to create a local stiff point to connect the concrete and glass. Photo by [139]

(b) Epoxy has been applied in the corners of the protruding boxes of "18 Septemberplein".

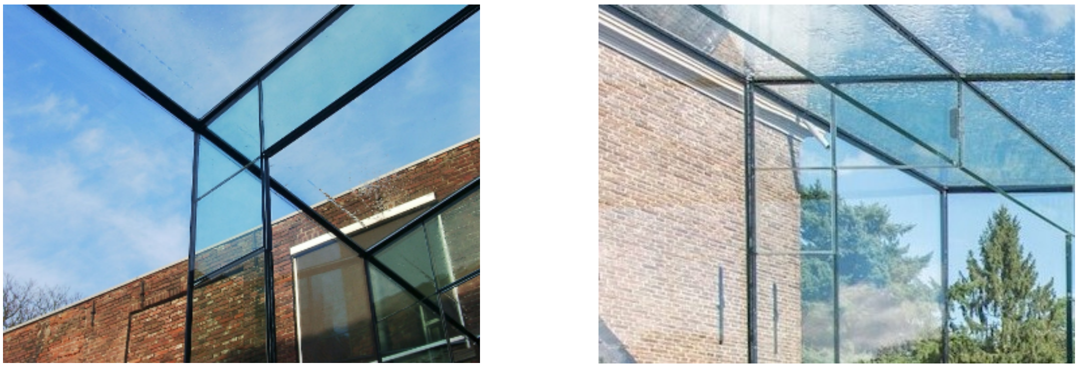
Figure 4.5: Applications of epoxy connections.

4.2.3. Acrylates

There are a few acrylates possible to apply: UV-curing and a methacrylate, although mainly a UV-curing acrylate is applied since the bonding of methacrylates and glass is doubtful and is to be further researched.

UV-cured acrylates are transparent and used on large areas, like in consevatories shown in Figure 4.6. UV-cured adhesives should be applied in a thin layer and are viscous, but tend to be brittle.

Since this a specific acrylate, few EPDs of UV-curing adhesives were found. One EPD of a UV-curing adhesive has been found ([140]), but it has to be noted that this adhesive was used as coating of biobased timber. This source also addressed that the production of UV-curing acrylics from biobased sources does not per se result in less environmental impact, since the farm equipment used to obtain the corn stover does use a lot of diesel.



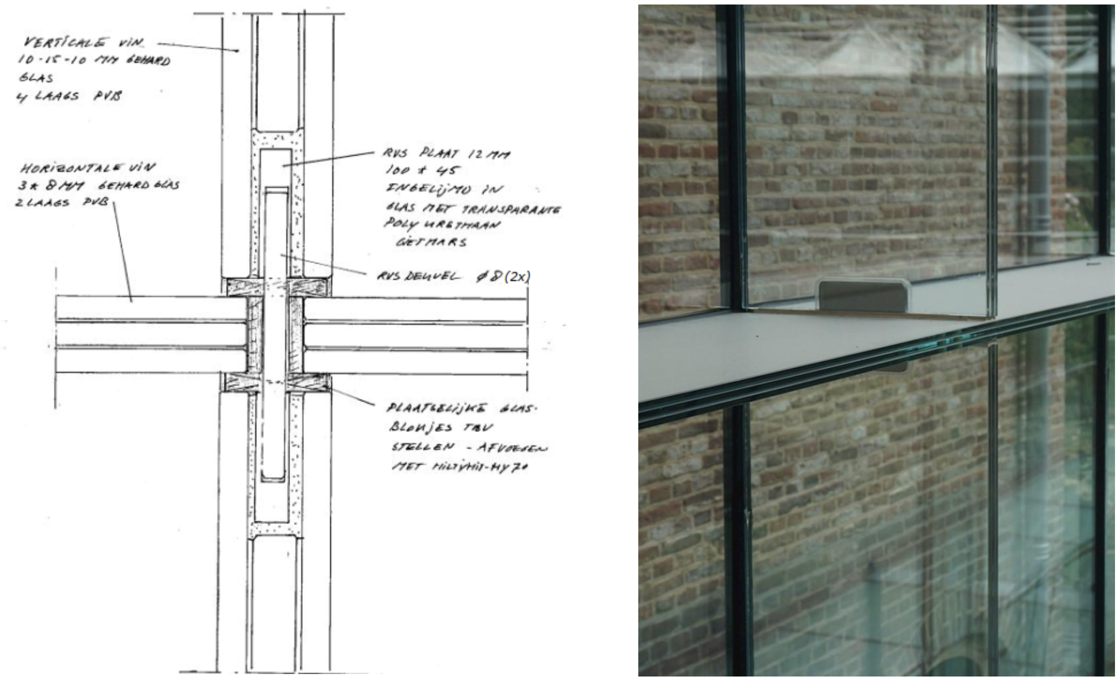
(a) Conservatory Leiden. Photo by [141]

(b) Conservatory "Kasteel Ruurlo". Photo by [1]

Figure 4.6: A, transparent, UV-cured adhesives connection.

4.2.4. Polyurethane

A polyurethane (PU) adhesive knows fewer applications in glass structures. It is a two component adhesive where the bond is created by a polyol and an isocyanate chemical reaction. By using specific solvents, various characteristics can be adjusted (viscosity, bonding quality, temperature resistance, strength) [142]. This results in the application of PU-adhesives in various situations. An example is in “Kasteel Ruurlo” where it has been used as interlayer and filler in the facade fins. Despite the few applications in glass, some (product specific) EPDs were found, but given the large variety of different PU-adhesives, only product specific data is presented of PU-adhesives that have been applied by ABT b.v..



(a)

(b)

Figure 4.7: A PU-adhesive has been used in the embedded connection applied in "Kasteel Ruurlo". Photo by [19].

4.2.5. Silicone

A silicone adhesive, also known as a silane-terminated polymer or structural silicone, is a sealant which is applied structurally. Silicone adhesives can be applied both in a one- or two-component from and are very elastic compared to the other adhesives. Silicone adhesives are widely applied and can be cut loose if necessary. Also here, many different (structural) silicones exist which again leads to many different EPDs. Data is presented from the NMD and of products that ABT b.v. has used. [18]

According to [143], silicone adhesives have three main roles: it resists the effect of the wind, also permanent loads can be greatly resisted (combined with wind) and it withstands the movement caused by temperature differences. This all has to do with the great bonding with glass. An example of a structural sealant in the facade is in “Co Creation Centre”.

(a) Silicone is applied in the edges of the glass box.

(b) Silicone is applied to connect the fins and facade panels.

Figure 4.8: The application of silicone structural sealants in two projects by ABT b.v.

4.2.6. Mortars

Mortars are used as gap filling material and as suitable interlayer material. It is often applied with mechanical connections, where small gaps needed to be filled in order to cope with deviations and as interlayer as for example with point fixings or balustrades. ABT b.v. uses a specific mortar in their projects, of which EPD material data has been acquired.

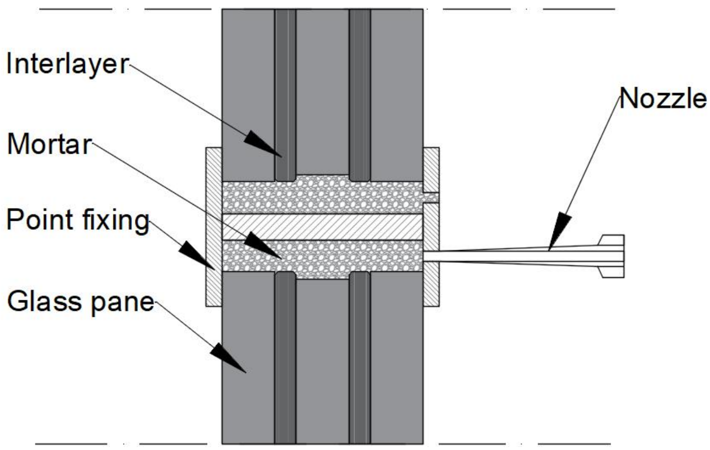


Figure 4.9: Application of a filler. Adjusted from [20].

4.2.7. Others

Various other adhesive connections exist, of which a few are noted here but furthermore of which no EPD data is known and therefore left out of scope. An example is a heat based resin, but is difficult to apply since interlayers should be able to cope with the heat from the resin. Another example is transparent structural silicone adhesive (TSSA), developed by DowCorning. TSSA is an adhesive film which is a hot curing and can be applied on point fixings, which bonds to the glass. No drilled holes are needed.

Figure 4.10: TSSA joint.[21]

4.3. Mechanical connections

Mechanical connections know a lot of variants, of which the main variants are introduced in this section. The main variants are point fixings, spider fittings, embedded and clamped connections. First an introduction is given, then for each mechanical connection, a short description is given and an application in practice is shown. Also other kinds of mechanical connections are possible, but are less frequently applied. All EPD material data is given in Appendix F to quantify the environmental impact and to compare the different materials.

4.3.1. Introduction

Safety

In terms of safety, a mechanical connection is way different than an adhesive. Important is to consider the peak stresses in the design to prevent failure and to do so, an interlayer should be selected. Interlayer material of glass can be among others a (silicone) rubber, neoprene, EPDM, POM-C or mortars. The choice of an interlayer varies per application, but it is the goal to evenly spread the load to the glass. In the case of a soft interlayer, limited force distribution is achieved which could lead to failure due to uneven loading in the glass.

Materials

A mechanical connection is made of a metal, or better said an alloy. Since the metal disturbs the glass, the metal should have characteristics that match the glass best. Also corrosion resistance is important, which makes metals as stainless steel, titanium and aluminium are often chosen as metal. Additionally, the thermal expansion coefficient of the metal is an important characteristic and is preferred to match glass best, although it should be determined for each application whether it is necessary. Titanium has a similar thermal expansion coefficient to glass, but the choice of a connection is a combination of esthetics, strength and costs. [144]

Table 4.1: Thermal expansion coefficients of various metals (alloys). [46]

	Thermal expansion coefficient μ strain/C
Glass	8.73 - 10
Titanium	8.47 - 9.34
Stainless steel	10.8 - 16.5
Aluminium	19.5 - 23.3

4.3.2. Practicalities

A few practicalities are important for a mechanical connection. Firstly, tolerances are very important since misalignment is not desired and the connection should still fit. Secondly, since the glass and metal are connected (via an interlayer), a thermal bridge is important to consider, likewise is to assess whether a drilled hole does not interfere with the air- and watertightness.

4.3.3. Sustainability

It is assumed that a mechanical connection is demountable, unless otherwise stated. This assumption can be argued about, but in general a mechanical connection is a dry connection with little influence of adhesives. Due to the demountability of the connection, reuse is likely of the connection itself and potentially also the glass it is attached to. In addition, recycling (see Appendix A for data of the NMD), flexibility and adaptability possibilities of the glass and metal are improved by the demountability. Material minimization and selection is addressed in Section 3.2, since that is a more elaborate topic, but it depends on the connection whether sustainable improvement can be made here given peak stresses in the glass which need to be avoided.

4.3.4. Point fixing

General

An often applied connection is the point fixing. A point fixing is a local support which can be pierced through the glass, embedded in (countersunk) or fixed on a glass panel as indicated in Figure 4.12. The point fixing consists of two disks connected by a bolt, which pierces the glass through a pre-drilled hole. The load is transferred via an interlayer, which can be of either a hard or soft material. This bolt makes the connection demountable.

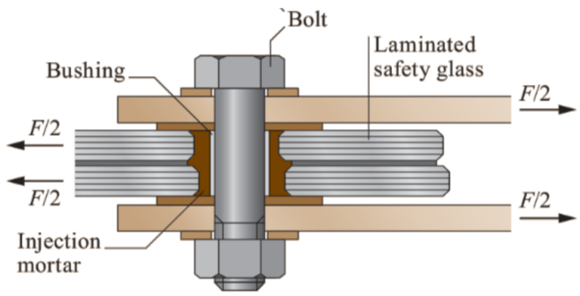


Figure 4.11: Load transfer of a point fixing in a laminated glass application. [18]

A point fixing which pierces the glass via a pre-drilled hole does increase risks to the air- and watertightness and insulation in the case of an IGU. To cope with these risks and to avoid stresses by allowing rotation of the connection, a swivel connection can be applied, as shown in Figure 4.13.

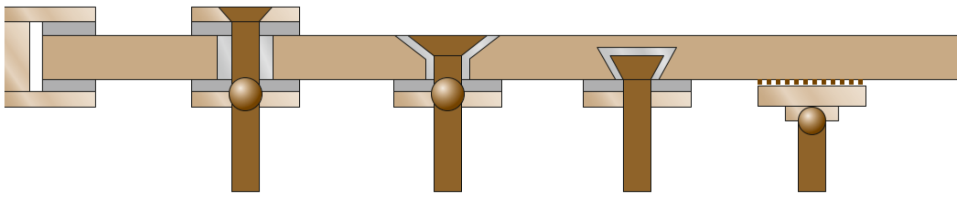


Figure 4.12: Various point fixings. From left to right, clamped on the side, a glass piercing point fixing, pierced and champfered hole, countersunk (embedded) and adhesive based. [18]

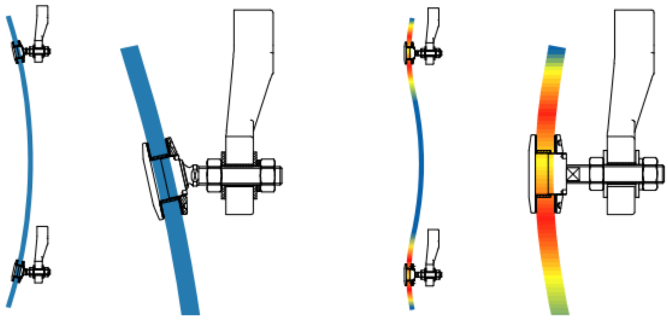


Figure 4.13: A swivel fitting decreases stresses in the glass. Red indicate higher stresses than blue. [22]

Frame

Bolted connections can also be applied in a connection between fins, as is shown in Figure 4.14. The application is entirely different, but the bolt transfers forces between the fins. From sustainability point of view, the bolts are demountable which makes fins reusable. Given that due to the spans, the forces increase, also the diameter of the bolt increases, or amount of glass needed increases. Calculations show this in Chapter 6.

Figure 4.14: The bolted frame connection can be found in the left corner.[23]

"Shoe"

Another connection in a fin is a "shoe", which is used to bear a beam or fin in. An example is shown in Figure 4.15. This one has holes in the glass to have a bolted fixing, but can also come in an u-profile type where the fin is clamped in the u-profile. The rigidity of the connection can be varied, likewise the amount of point fixings depending on the structural requirements.

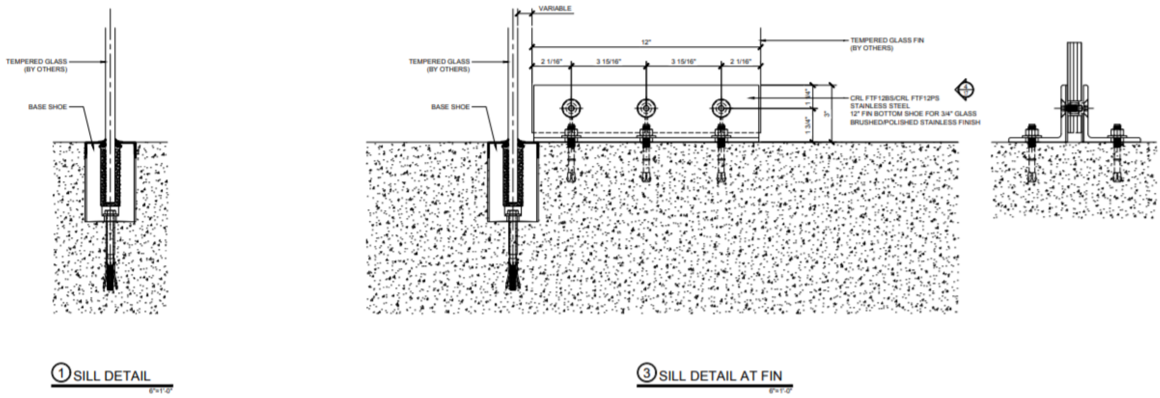


Figure 4.15: A base shoe: a mechanical connection which connects a fin to other materials. [24]

Fin-fin connection

Another connection with regard to fins is the fin-fin connection, or also called "splice connection". Two fins are connected via two steel strips which are bolted through the glass. In Figure 4.16 use is made of this connection to connect also a facade element with a spider connection. Also for this connection, many variants exist.

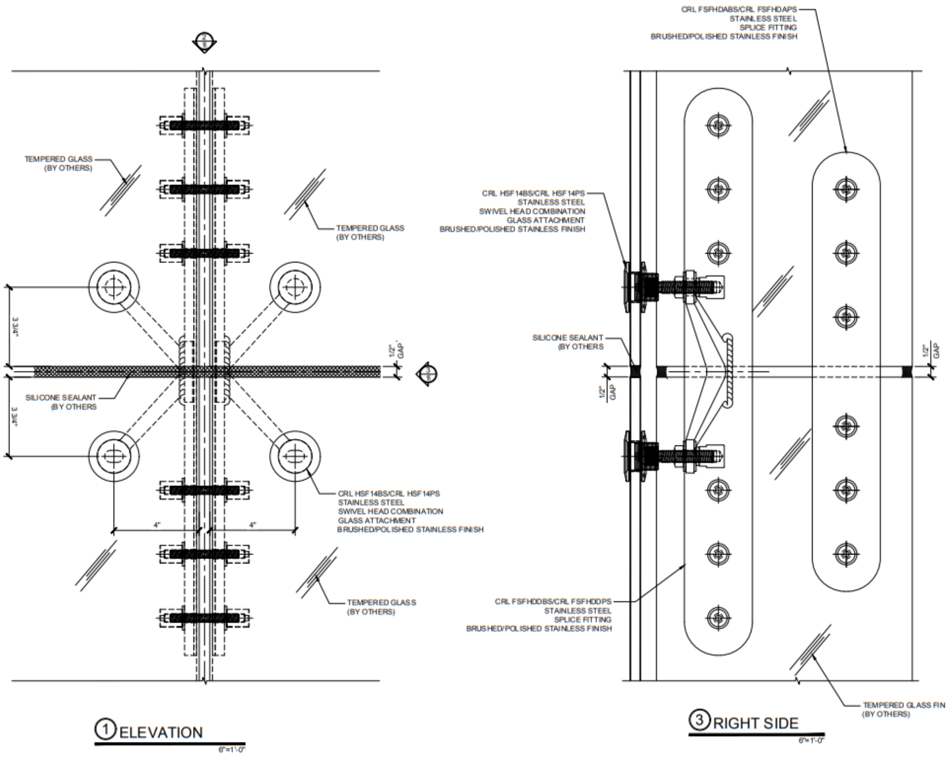


Figure 4.16: A splice fitting: a mechanical connection which connects two fins. [24]

4.3.5. Spider

A spider connection is the application of multiple point fixings. A spider connection has 2, 3 or 4 arms, with each a point-fixing at the end. A spider connection can be connected to a steel frame, glass fins, a cable net facade or other type of substructure. Over time, spider connections have been developed to elegant facade elements and are made from a solid, casted metal.

Figure 4.17: A spider connection. [25]

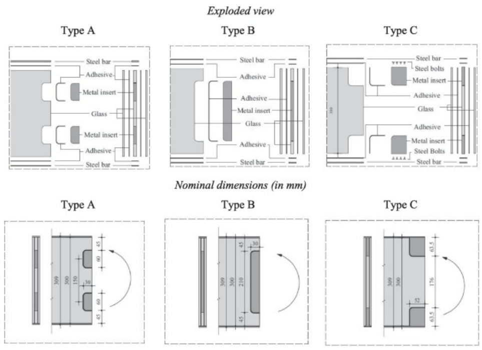
Since in the facade, small deviations could be present and thermal deformation takes place, it is important to consider tolerances. As shown in Figure 4.18, the spider has different hole sizes to allow for horizontal and vertical tolerances.

Figure 4.18: A spider connection with different hole shapes and sizes to cope with tolerances. [26]

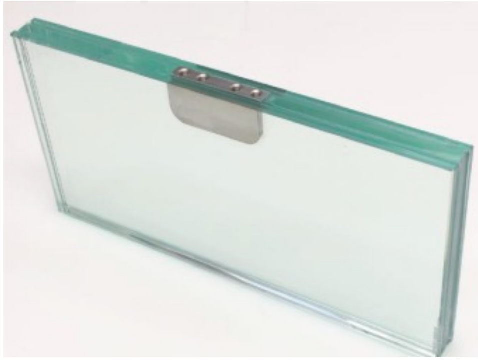
4.3.6. Embedded

Embedded connections are metal inserts, via an adhesive bonding, in a laminated glass panel. There are few examples of embedded connections. One of the more often applied embedded connections is shown in Figure 4.19 and has been applied in Apple Stores. Different embedded connections are being researched as shown in Figure 4.20. Important is the production to limit the development of peak stresses. This is done by carefully making the inserts and proper finishing to limit the amount of flaws. Both the Apple Store embedded connection as the connections which are being researched have a SentryGlas interlayer.

Figure 4.19: Titanium embedded connection in the Apple Store at the Omotesando, Tokyo, Japan. Photo by author.



(a) Embedded connections by [39]



(b) Embedded connection by [145].

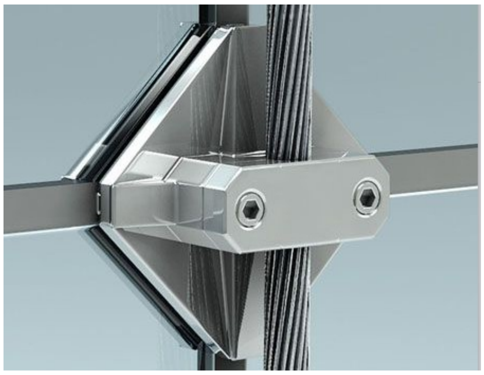
Figure 4.20: Various research on embedded connections.

As indicated in Section 4.3, the choice of material is important considering thermal expansion. Titanium has a comparable thermal expansion coefficient as glass, but this does not mean that titanium is required from this point of view. Less expensive and more environmentally friendly (from shadow costs point of view, see Appendix F) materials such as aluminium and stainless steel could be used too. When determining the choice of materials, thermal expansion should be looked at to prevent stresses and delamination of the interlayer. A variant of an embedded connection is in “Kasteel Ruurlo”, shown in Figure 4.7, although it should be noted that here the connection is inserted the other way around, namely it is mounted in the gap in the glass panel instead that the metal insert is first embedded in the glass.

4.3.7. Clamped

Different than the previously mentioned metal connections is a clamped connection. A clamped connection is a cost saving connection which clamps the glass at points around the edges. Clamped facade connections are shown in two variants, as spider and as local point support. Clamped connections are easy to mount and demount and do not require any drilling or other alterations on the glass which make them highly suitable for the circular economy.

(a) Spider clamp [146]



(b) Corner clamp in a cable net facade. [147]

Figure 4.21: Clamps applied in practice

A different clamped connection is in the application of balustrades, where a (laminated) glass panel is inserted into a u-profile bearing. With an interlayer, a rubber or mortar, the glass is clamped into the metal.

Figure 4.22: An example of a line support with an u-profile bearing. This variant uses a dry connection which is ideal for deconstruction. [27]

4.4. Alternative connections

Given the development of structural glass, a lot of alternative connections have been developed too. A few are highlighted and discussed. Given the unique character of most of these connections, it can be argued whether from a sustainability point of view this is the right direction to take. However, all connections have something special and positive with regard to sustainability, which is highlighted.

4.4.1. No connection

In this example, the glass fin and beam are not connected but consist of one piece. It is a stunning connection, but from a sustainability point of view, a lot can be argued. The glass should be cut out from one panel, which results most likely the rest of the glass being discarded and also reuse becomes difficult given the specific design. A positive point is that besides an interlayer, the connection is only made of glass, which thereby eliminates the use of other metals or adhesives.

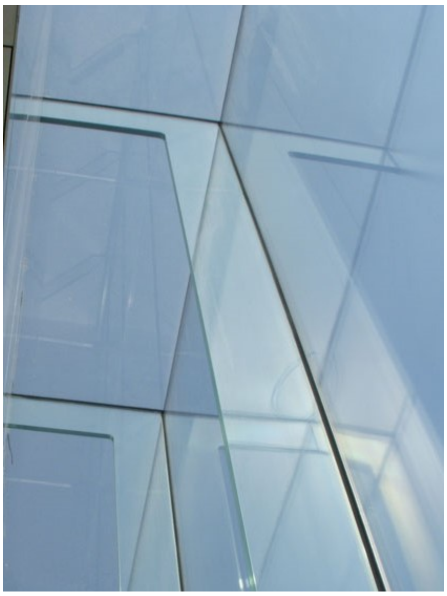
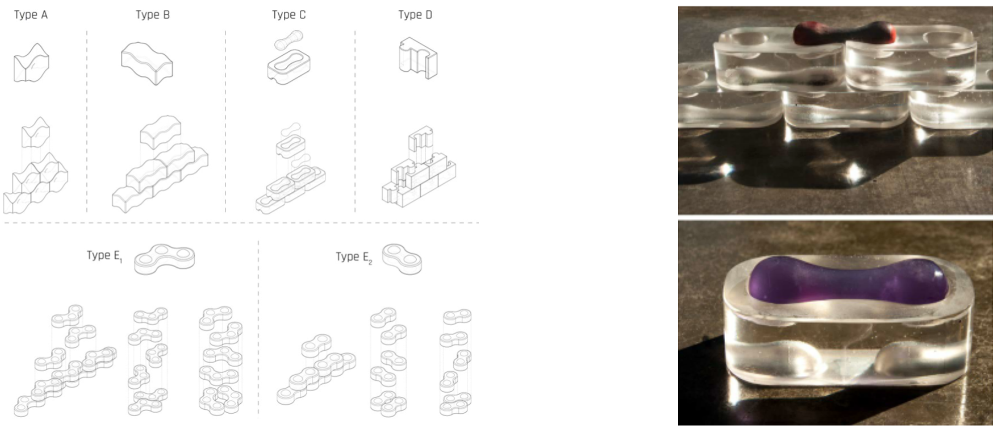


Figure 4.23: The fin at the Apple Store located at Sanlintun, Beijing, China. [28]

4.4.2. Dry stacked connections

The use of stacked glass bricks as a facade has gotten more attention since the completion of the Crystal House at the P.C. Hooftstraat in Amsterdam. Where this facade is composed of glass bricks and an adhesive, research is now going to make a dry stacked glass brick facade, without the need of an adhesive. The advantages from this concept is that there is no contamination of the glass brick by the glass brick, so that recycling for sure can happen. Also reuse becomes more likely, since a form of standardization is introduced and the bricks can easily be demounted. Besides, bricks like these also suit other forms of circularity, such as flexibility and adaptability.

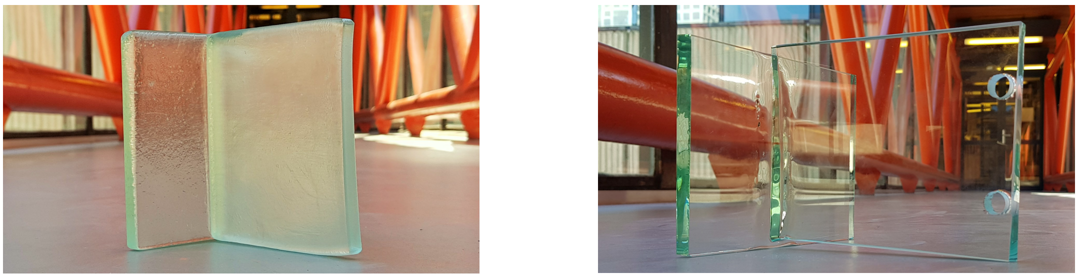


(a) (b)

Figure 4.24: Dry stacked interlocking glass components. [29]

4.4.3. Heat bonded connections

Another glass connection is a heat bonded connection. This can be achieved via welding and heat fusing. Since it has to be bonded in a controlled environment, the connection is not easy to produce and uses a lot of energy. Also demountability is not possible, which makes reuse also unlikely, but again the interesting point is that it is only made of glass. [30]



(a) (b)

Figure 4.25: Heat bonded connections. [30]

4.4.4. Glass to timber

The structural performance of a glass to timber connection is researched by [31]. Both soft- and hardwood connections with different curing adhesives are addressed. Just like with other adhesives, demountability is an issue, but the interesting thing is that it connects to timber, a natural material. The glass and timber combined can most be demounted, but replacement of the glass panel is hard. In order to be applied on a wide scale, more research has to be done on the durability, long-term behaviour and impact of environmental influences on strength and stiffness. The research by was done to be used for restoration projects.

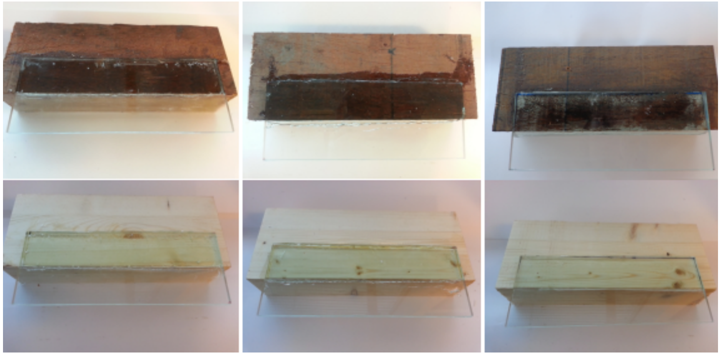


Figure 4.26: A timber to glass connection. [31]

4.5. Reference projects

As referred to before in this research and further to be referred to, in this chapter more background information is given of some reference projects. ABT b.v. has worked on a variety of projects with structural glass, which makes it possible to give more detailed insight on these projects with regard to sustainability. In Appendix B are detailed sketches given with dimensions of various connections from the reference projects.

4.5.1. Glass conservatory of Museum MORE, Ruurlo ("Kasteel Ruurlo")

The glass conservatory of Museum MORE is located in the medieval castle in Ruurlo, in the east of the Netherlands. In this research it's called "Kasteel Ruurlo". The glass conservatory is used as an entrance and exists of many different connections, which makes this project very interesting. Among others, an UV-adhesive and embedded connection have been used.

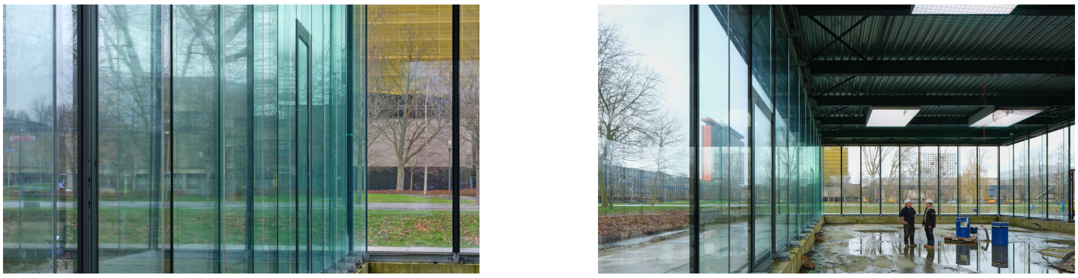
(a) Inside view. Photo by [64].

(b) Front view. Photo by [1].

Figure 4.27: "Kasteel Ruurlo".

4.5.2. Co Creation Centre, Delft

Located on the Delft University of Technology campus, the "Co Creation Centre" is a building designed for congresses, but is at the same time an experiment for various newly developed techniques. The glass facade is a load bearing facade and no other columns are used in the building to bear the load of the facade. The integration of the load bearing structure and facade is interesting. Triple glazing is used, supported by laminated glass fins. A silicone joint connects both the fins and facade.

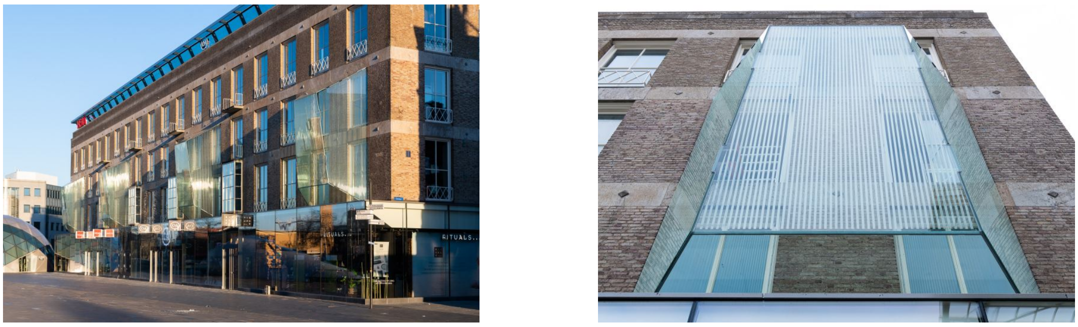


(a) (b)

Figure 4.28: Co Creation Centre. Photos by [32].

4.5.3. Glass boxes at 18 Septemberplein, Eindhoven

In Eindhoven, located on the square in the city centre named “18 Septemberplein”, four protruding glass boxes can be found. The boxes are anchored in the facade, but because of the unique shape, forces can be transferred in the glass. The boxes host a few interesting materials for the connection, namely a silicone sealant and an epoxy.



(a) (b)

Figure 4.29: Glass boxes at the 18 Septemberplein. Photos by [33]

4.6. Conclusions

The sub-research question “what kind of connections are possible in glass structures?” can now be answered. The biggest two groups of connections in glass structures are mechanical connections and adhesive based connections. Also some alternative connections exist, like heat bonded and dry stacked connections. Within each group of connections, many different variants are developed over time, which are often project specific connections.

III

QUANTIFYING SUSTAINABILITY

5
Methodology

5.1. Introduction

In order to be able to make a well-weighted decision in a sustainable glass design, background information has been given on glass, connections and sustainability in the previous chapters. In Section 5.2, the observed connections are described. Each connection is assessed for its structural feasibility and compared to other connections which could have been applied too in a similar way. The structural design of “Kasteel Ruurlo” has been chosen as a base for loading conditions and practical applications and is also part of a case study in Chapter 8.

For each connection, all the materials used are quantified and with EPD data, as presented in Section 6.2, the environmental impact is derived in terms of shadow costs. Also, the extra environmental impact caused by the connection, for example, a connection that needs extra glass to allow for the same functional application, is discussed in Chapter 6. Important is the technical lifetime of a connection and module, which are both discussed in Chapter 6.1. When the environmental impact is known, the end-of-life scenarios as introduced in Chapter 6.3 are discussed for each connection.

When both the environmental impact and end-of-life possibilities are known for the assumed connections, a comparison can be done. In order to provide a good discussion for this comparison, a MCA is performed as the base of this discussion.

Next to the connections, modules within the glass structure are important too. Modules, or elements, joined together form the total design. Modules within glass structures are facade panels in the form of an IGU or laminated glass panels, beams and fins, or combined as a frame. Beams and fins are most often laminated but also facade or roof panels can be laminated. Modules are important, since also these can determine the total lifetime of a structure, as for example the IGU which with a lifetime of approximately 20-25 years can determine the lifetime of a facade, as mentioned in Chapter 3.

5.2. Connections observed

5.2.1. Scope

In structural glass applications there are different glass to glass connection types, depending on which modules have to be connected. With regard to the modules, the connection types are: IGU-IGU, IGU-fin/beam, fin-beam and connections where three modules join, like an IGU-IGU-fin/beam. An IGU-IGU connection is left out since this mainly happens via a frame or beam/fin.

Connections that are not considered are the alternative connections as introduced in Section 4.4, which know no or rare examples in practice. Top/bottom shoe fittings at the end of a glass beam or fin, are left out since in general only on material level difference can be made considering sustainability.

The considered connections are a fin-beam connection (the corner connection in a frame since this is highly important in the design and dimensions), and a IGU-IGU-fin/beam connection, now both called respectively a frame connection and facade connection as shown in Figure 5.1. It is important to give the designer a few alternative connections for the same, or similar, purpose. For that reason, six variants are introduced for each connection.

(a) A frame with an adhesive. Photo by [141].

(b) A silicone sealant facade connection. Photo by [32].

Figure 5.1: Observed connections.

The observed connections are related to “Kasteel Ruurlo” and “Co Creation Centre”, but also from literature or other projects, thereby not all connections know examples in practice or have limitations by design which could lead to no or few applications.

Frame connection

The observed connection types for a moment rigid connection for a frame are shown in Figure 5.2. Both adhesive and mechanical connections are observed, where within mechanical connections both embedded and bolted connections are considered. Only the adhesive connection and bolted hinged connections know applications in practice, the embedded connections are from [39] and a bolted rigid connection is proposed by the author.

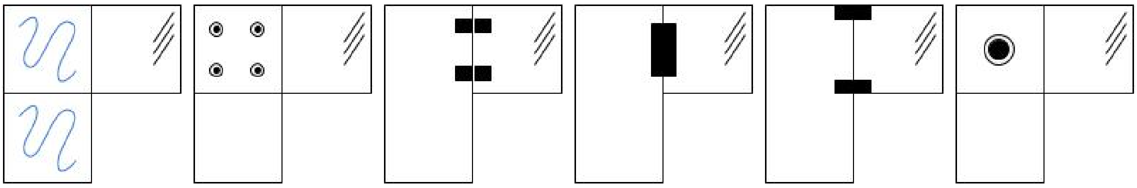


Figure 5.2: From left to right: UV-acrylic adhesive, bolted rigid, embedded connection (3x), bolted hinged.

Facade connection

The observed connection types within a facade are shown in Figure 5.3. Both adhesive and mechanical connections are observed, where within mechanical connections embedded, clamped and bolted connections are considered. All connections are examples from practice.

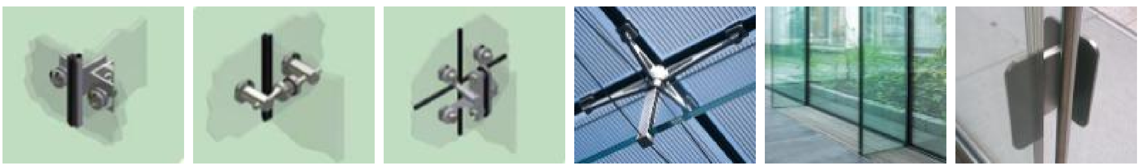


Figure 5.3: From left to right: angle spring plates [34], spider connected to a glass fin [34], fitting to a glass fin [34], point-fixed clamped [35], structural silicone adhesive [36], titanium embedded [author].

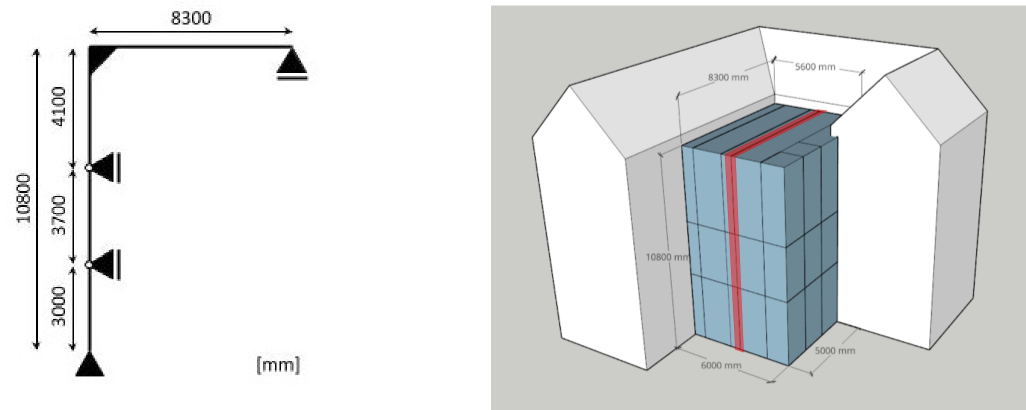
5.2.2. Assumptions

The frame connection has structural requirements based on “Kasteel Ruurlo”, since a moment rigid connection is part of the main load bearing system. Next to a moment rigid connection, an alternative hinged connection is introduced too.

The facade connection has not been checked on load bearing conditions, since the main goal of the connection is to hold the facade panel in place and to ensure cooperation between the fin and facade panels. However, the facade panels are checked on structural feasibility. Additional requirements to this connection become project specific, for example extra (vertical) load bearing capacity of the fin is not standard for such a connection. Therefore the facade has set dimensions based on “Kasteel Ruurlo” and “Co Creation Centre”. Different connection types have influence on the glass usage, which is further elaborated in Section 6.2.

Frame connection

The frame in “Kasteel Ruurlo” is not a regular frame, and is designed in a smart way to shorten the buckling lengths and create extra moment-zero points by adding two horizontal fins, or supports in a way. The glass extension is a box of 8.3 x 6.0 x 10.8 meters (Figure 5.4) and consists of four main frames which act as main load bearing structure. The frame consists of a connected facade fin and roof beam with a depth of 400 mm and 10-15-10 mm fully tempered laminated PVB glass panels. All assumptions and calculations can be found in Appendix C.



(a) Current frame with two hinges in the facade fin. Horizontal fins are the local supports.

(b) Current design.

Figure 5.4: A frame of the current design.

In order to compare the different frame connections structurally, a governing moment and shear force should be derived. For the calculation of the governing situation and whether the connection is structurally safe, use has been made of hand calculations and examples from practice. No frame models or finite element modelling (FEM) has been used since it is believed that that encompasses the goal of the research. In order to be sure to get a structurally safe connection it is recommended to perform more advanced calculations and further research.

In Appendix C, the derivation of the governing moment is given, here the result is presented. The governing moment and shear force in ultimate limit state for the frame connection are $Med = 15.60 kNm$ and $Ved = 10.09 kN$. In the situation with a broken panel, these values are $Med = 12.31 kNm$ and $Ved = 7.67 kN$.

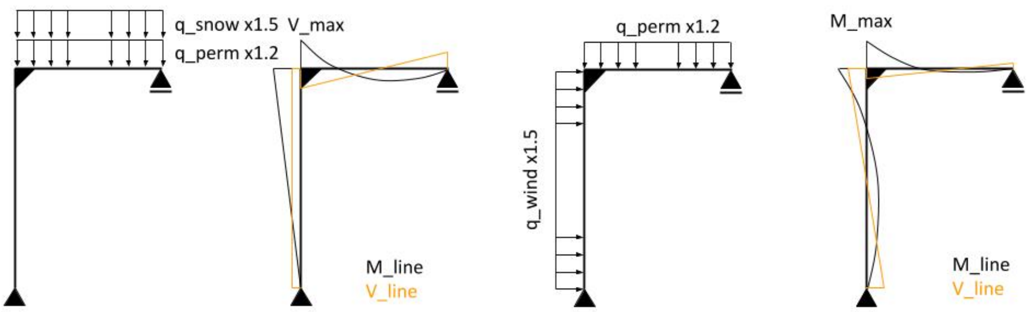
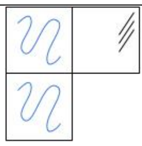
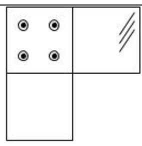
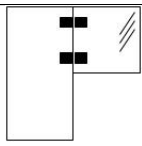
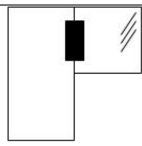
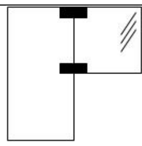
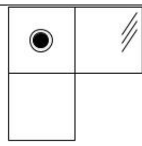


Figure 5.5: M-line and V-line sketch.

In Appendix D, the structural design based on the loading condition of the six connections is given. From the unity checks (UCs) can be seen that the adhesive has an overcapacity and that the mechanical connections vary in capacity, but have a lower (over)capacity. Especially the bolted moment rigid connection does not suffice with regular dimensions, resulting in larger glass dimensions. With the size of each application known, the material use is calculated so that later the environmental impact can be calculated.

Table 5.1: Dimensions and important notes of the frame connections. Given the simplistic calculations used, it is believed that with a more advanced calculations, these dimensions can be obtained, if not decreased. Therefore this unity check suffice in this exercise.

Type	 Adhesive	 Bolted, rigid	 Embedded	 Embedded	 Embedded	 Bolted, hinged
UC	Glass: 0.03	Glass: 0.78 Filler: 0.75	Glass: 0.68 [1]	Glass: 0.44[1]	Glass: 0.27 [1]	Glass: 0.57 Filler: 0.76
Dimension $[mm]$	400x400	600x600	400x400	400x400	400x400	400x400
Comment	Currently applied in "Kasteel Ruurlo"	Not applied in practice, but calculations indicate larger dimensions.	Capacity based on literature, no proof of application in corners.			No moment capacity

[1]: This UC is based on the capacity from experiments with a beam height of 300 mm. This will improve with a higher beam of 400 mm.

Facade connection

In order to compare different facade connections an application is assumed. The facade is supported by a glass fin and has a height of 4 meter. Other dimensions are not relevant. It is interesting to see how many connections are necessary of each type over the height of the fin, so that later the environmental impact can be calculated based on the material use. All assumptions and calculations can be found in Appendix E.

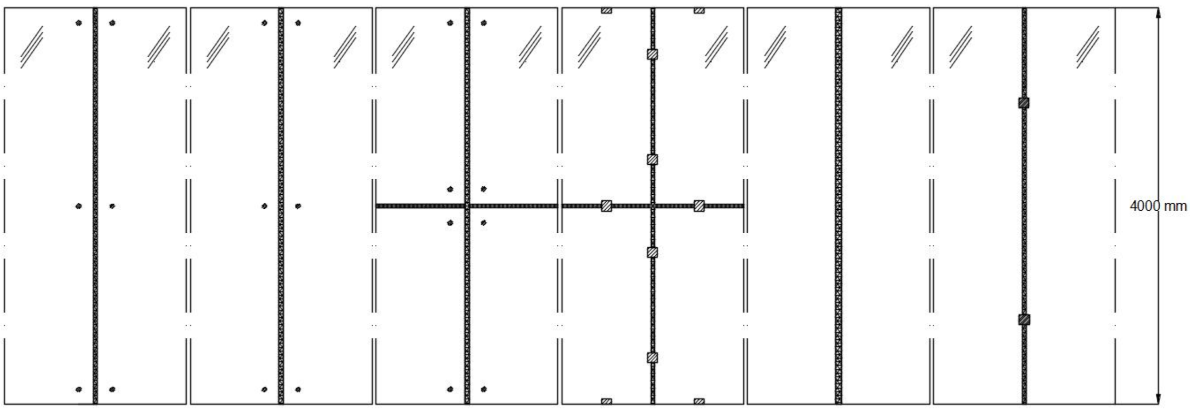


Figure 5.6: Facade connection front view. From left to right: angle spring plates, spider connected to a glass fin, fitting to a glass fin, structural silicone adhesive, point-fixed clamped, titanium embedded.

The basis for the calculations is shown in Figure 5.6. Some assumptions are further explained:

- For a spider connection, smaller glass panels can be used in the facade as is shown in Figure 5.6. The (dis)advantages regarding smaller panels are neglected.

- For a spider connection, half spiders are considered at the top and bottom of the facade.
- All connections, except for the structural sealant, use a silicone sealant as air and water barrier. This is taken into account by determining the material use and shadow costs. There is less silicone sealant needed than for the structural sealant.
- For the structural silicone sealant, dimensions and thereby total material use are based on "Co Creation Centre". Since triple glazing is applied, this could lead to extra material used. See Appendix B for a detailed drawing.

Table 5.2: Amount of applied connections of the facade connections per 4 meter.

Type	 Angle spring plates	 Fitting to a glass fin	 Spider connected to a glass fin	 Clamp spider	 Structural silicone sealant	 Titanium embedded
Amount needed over height	3	3	2	2	-	2

5.3. EPD material data

In order to quantify the environmental impact of a connection, EPD material data is used. The result is shown in Appendix F which includes a description of the assumed values. By using EPD data, shadow costs are calculated of the material based on factors presented in [42]. Assumptions regarding this database are given first and then early findings based on this database, or relevant information is given.

5.3.1. Assumptions

In order to make a good comparison of connections in terms of environmental impact, as much data as possible originates from the NMD. However, given the specific materials that are used in glass structures, company specific data has been acquired too. If these methods were not successful, other sources have been used, but have been checked to obtain an as representative as possible EPD. Nonetheless, it is still possible that not all data is available, or parts of data are not available, which results in an incomplete database.

Unfortunately, the result is incomplete, only for 2 of the 11 impact categories assumed in the LCA were in common for all materials which are the Global Warming Potence (GWP), measured in CO_2 equivalent and Acidification Potential (AP), measured in SO_2 equivalent. The materials with most lacking data are titanium and a UV acrylic (adhesive). The consequence is that applications become harder to compare over all environmental impact data and conclusions can only be given over the available categories. Both the database based on 2 impact categories and 11 impact categories are given in Appendix F but when spoken of a database, the database with 2 impact categories is meant, unless explicitly mentioned otherwise.

Additionally, for some materials, no data was available at all (or any similar material comparable), and were therefore left out of scope, also because their application is minor or specific in application in glass structures, both in weight and application in general. The materials left out are neoprene (minor contribution), POM-C (limited applications as filler in point fixings) and galvanised steel (depends on the application). Unfortunately, there is no EPD material data of interlayer materials available. Only available is the embodied energy of laminated glass as presented in Chapter 3, but no details or assumptions of this value is known.

The shadow costs are both presented in cradle-to-gate as in cradle-to-grave, although it should be noted that the data of cradle-to-grave is not available for every material. The available data is then considered. Some materials consider in their LCA all lifetime modules A-D (see Section 2.2 for more information regarding this LCA modules) and others partly, like the more product specific data for structural sealant DowCorning 993 which only has A1-A5 modules as available data.

The final assumptions are listed:

- For most materials both data concerning cradle-to-cradle and cradle-to-gate is given
- Shadow costs are usually expressed in costs per gross floor area (GFA) and per (technical) lifetime (€ / m^2 GFA / yr) but since the GFA depends on an application, the shadow costs are presented in € and € / yr
- Note that shadow costs only represent the environmental impact to produce 1 kg of material and that shadow costs regarding manufacturing of the final product are excluded. For example, for a mechanical connection, shadow costs regarding manufacturing the connection are left out, only the shadow costs of the material itself are included.

5.3.2. Findings

There are a few findings that can be done based on the database. The first finding is that adhesives have a lower environmental impact than any metal, both for 2 impact and 11 impact categories and for cradle-to-gate and cradle-to-cradle.

The second finding is the spread of data within a material category. This is because data is acquired from both the NMD and companies. In order to cope with this spread, for each material category, e.g. an acrylic or epoxy, both the upper and lower boundary are accounted for since it could lead to different conclusions. Therefore, a so-called sensitivity analysis is done in Section 6.2 on the spread of the data.

5.4. MCA

In order to choose a “sustainable” connection, “sustainability” has been defined.For glass structures, methods as design for disassembly, reuse, recycling and material minimization play a role in the design of a “sustainable” glass structure. In order to measure the impact of a connection on each method and in order to compare connections for each method, a multi criteria analysis (MCA) is introduced.

The criteria are divided in two main groups: environmental impact and end-of-life possibilities. Environmental impact consists also of two parts, namely direct and an indirect environmental impact. Direct environmental impact is related to the shadow costs of a connection and indirect environmental impact is related to the consequence of a connection on other parts, for example a connection could lead to more glass use meaning higher environmental impact. The end-of-life possibilities are related to reuse and recycling. Not every connection is demountable or allows for reuse of a module or as whole and connections differ in limitations in recycling.

The criteria are rated from positive impact to negative impact, where positive impact is expressed in “++” or “+” and negative impact is expressed in “–” or “-”. Also, a neutral score is available, namely “0”. This rating is assumed for all criteria, since only shadow costs can be quantified and other parts not.

The MCA gives insight in the performance of different connections on various criteria and lays a base for discussion to make a well-weighted decision for a connection or method to choose in the design of glass structures. In order to make a well-weighted decision, factors can be added to each criterion. Factors are related to the importance of a certain criterion. Since the most positive impact can be made with reuse, both environmentally as in value of a module, reuse is by far the most important criterion. It is therefore useless to introduce other factors and discuss the magnitude of these factors. Therefore, the MCA functions as a base for discussion and leads to insight for the designer to cope with sustainability in glass structures with regard to the connections.

6
Sustainability quantified

In this chapter, sustainability is expressed in numbers to compare connections and glass modules with each other. In order to do so, first the lifetime of a module and connection is discussed. In Section 6.2 then, the environmental impact is expressed in shadow costs. In the final Section 6.1, end-of-life scenarios are discussed. An overview of the performance of all connections can be found in Appendix G. The reasoning behind Appendix G is mainly discussed in this chapter.

6.1. Lifetime

6.1.1. Functional lifetime

The functional lifetime is related to the use of the structure and is not determined by technical issues. Functional requirements evolve over time. An example of changing functional requirements is an office, where changing needs lead to a new office configuration and which could determine, if these changes are not accounted for in the design, the end of the lifetime of the office, while it technically still would suffice. [148]

The functional lifetime is determined beforehand to fulfill a specific function, but is prone to change over time given changing needs. For a glass structure, dealing with change is even more challenging since facade and structure are integrated. Changes in configuration could lead to changing structural requirements, which are not perse accounted for in the design. Since glass structures have a certain overcapacity in the design, changes within the plot might be possible but are restrained by the modules from which it consists and will always have to be checked by an engineer.

Changes in building physics can be expected given stronger need for less energy demanding buildings or more comfort over time. Therefore is the functional lifetime of a facade in general shorter than for a structure. Since glass integrates both, the functional lifetime is interesting. When changes are needed, also the changes will have to comply with the new, stricter standards which govern at that time, potentially increasing the requirements even further. With regard to building physics, many different things can change (insulation, acoustics, (active) shading) of which some can be integrated easily but others maybe not.

In order to cope with change, as has been indicated in Chapter 3, flexibility (or adaptability) should be integrated in the design. This is allowed for the best, by working with demountable connections, but that differs per module. This is fully discussed, besides the technical lifespan of a module, in Section 6.1.

6.1.2. Technical lifetime

The technical lifetime is the period of time in which the module can perform the function before replacement. Durability is highly related to the technical lifetime. If the technical lifetime is longer than the functional lifetime, reuse might be a possibility. Within the circular economy, the technical lifetime should be longer than the functional lifetime. If the technical lifetime is shorter than the functional lifetime, maintenance (in form of replacement) is necessary to fulfill the functional lifetime. When the technical and functional lifetime are similar, reuse does not have to be considered since the material has no technical lifetime anymore. In that case, measures to allow for reuse do not have to be considered in the design.

6.1.3. Lifetime of modules

Since the lifetime of modules differ, likewise the deterioration of modules and materials used in glass structures differ. Throughout the research, the technical lifetime has been mentioned and is here summarized. The NMD has indicated the technical lifetime of some modules and materials too, which is addressed as well, but in general little is known about the technical lifetime of the modules and connections. In order to prevent issues with durability for any module and connection, extra research is recommended. The main limiting modules are laminated glass and IGUs. An overview can be found in Table 6.1 which is elaborated in this chapter.

Table 6.1: Lifetime of certain glass modules

Type		**Lifetime**
Module	IGU	20-25 years
	Laminated beams and fins	>5 years, but depends on quality of interlayer
Material	Glass	No clear limitations, although harmful environments might be limiting lifetime
	Metal	No clear limitations of the material itself
	Adhesive	No clear limitations of the material itself
Interlayer	PVB	5 years guarantee of no significant delamination.
	SentryGlas	Better performance than PVB, but not a set lifetime
Connection	Bolted	No limitations of the connection when properly manufactured and right materials are selected.
	Embedded	No clear limitations of the connection when properly manufactured, but no examples are known.
	UV-adhesive	No clear limitations of the application itself
	Sealants	5-20 year, possibly even longer but replacement is possible for non structural sealants
	Filler	No clear limitations of the material itself. Hilti HY 270 has a guarantee of 50 years.

IGU

As mentioned in Section 3.2, an IGU has a lifetime of 20-25 years, after which the panel has lost its insulating performance due to leakage of the edge sealant. Also functionally, higher requirements to its insulating performance could lead to replacement of the panel. The NDM uses similar technical lifetimes for an IGU, coated or uncoated. Also manufacturers give a guarantee of performance of about 10 years, which indicates the lack of durability for an IGU, see for example ([149]).

Laminated glass

Delamination is extensively addressed in Section 3.3. In essence, the technical lifetime is limited by the use of low quality materials and originates to the lack of legislation which demands a longer technical lifetime. Only a 5 year guarantee is given on interlayers which is too short. Higher quality interlayers as SentryGlas and Trofisol are not known to delaminate, but are not proven to assure a long (50+ years) technical lifetime.

Frame

To connect beams and fins to form a connection in a frame, different connections have been introduced in Chapter 5. Given that the development of adhesives and embedded connections took place in recent years, there are no examples of such connections that already have lasted for 50 years. On the other hand, a lot of research has been done to see whether such a connection is viable or not and there are examples of structures that already last for over 20 years without sign of deterioration.

Adhesive connection

If an adhesive discolours, it still might be structurally feasible, it by then has lost its function. There is no technical lifetime known of a transparent adhesive for a glass frame. It is therefore assumed that such an adhesive can be long lasting (50+ years). A benefit of an UV-adhesive applied in a frame connection is that it will not deteriorate when exposed to UV, since it needs UV to bond.

Mechanical connection

There are a few important things with regard to mechanical connections, which have the main goal to prevent peak stresses in glass, namely an interlayer or filler and grinded and or polished edges. With a proper design, right selection of materials and good manufacturing, the connection and glass can have a long lasting lifetime. Additionally, grinded (or polished) edges prevent peak stresses, they also prevent delamination in a frame connection.

There is no technical lifetime known of mechanical connections. Proper manufacturing of the drilled holes and embedded metal inserts lowers the risk of glass failure but avoiding drilled holes or inserts by using clamps prevents most likely failure of the glass. In the case of a frame is the latter not possible. Assuming a proper manufacturing of both the connection and glass, it is therefore assumed that such a connection can be long lasting (50+ years).

Fin-facade system

To connect a fin with a facade, various connections have been introduced in Chapter 5. Whereas for a fin and facade system, connections also have been developed in recent years, the system is totally different than a frame.

Adhesive

The fin-facade system is dependent on (silicone) sealants to keep the facade air- and watertight, but can be applied structurally too. Sealants are prone to weathering and ageing and could lead to replacement before the end of the overall lifetime. This is not specific for a glass structure of course, since regular buildings also encompass maintenance of the sealants. Sealants have a varying lifetime. Where a structural sealant has a guaranteed strength of 5 years, they potentially could last longer, but inspections should find out whether the quality still suffices [150]. The NMD uses a lifetime of 20 years for regular sealants for glass (see Appendix A).

Important to notice within the entire system is that the facade often has an IGU, which also has a limited technical lifetime of 20-25 years. The total lifetime and afterlife use possibilities go hand in hand in such a system whereby the IGU or structural sealant could mean the total lifetime of the structure. This is because an old (structural) sealant is hard to remove from glass, and a new (structural) sealant needs to be applied on a clean surface in order to be structurally safe, which cannot be guaranteed at the time of writing. Reuse of this system is therefore difficult given the restraints.

Mechanical connection

Mechanical connections connect the fin with the facade and are combined with a (silicone) sealant to maintain the air- and watertightness. Since the facade often consists of an IGU, one could risk leakage of the IGU by using a mechanical connection which pierces through the IGU and thereby shortening the technical lifetime. Unlike the case with a structural silicone, this mechanical connection itself does not influence the overall technical lifetime of a sealant, but again, there is no given technical lifetime of such a connection. It is therefore assumed that such a connection can be long lasting (50+ years), but an IGU determines the lifetime of the facade. Avoiding glass piercing connections improves this even more and is recommended.

Materials

Besides modules, also the materials in general can deteriorate over time. However, the deterioration of glass and metals does barely happen. Glass is a durable material, but can also undergo ageing or weathering over time. In this research it is assumed that with proper maintenance, the glass itself is not a limitation in lifetime, so that glass can last a long (50+ years) time. The same holds for metals, when proper maintenance is done, the metal can be long lasting. Adhesives and interlayer material (neoprene, POM-C) might cope as indicated before with durability problems, given weathering and ageing processes. This is reflected in the lifetime of such materials.

Another example is, EPDM is worth mentioning since it, as a seal, functions as an air- and watertight barrier in a frame. When the EPDM is subjected to a longer period of heat and drought, the EPDM will dry out and will have to be replaced. However, still the NMD assumes a lifetime of 20 years (see Appendix A)

Overview

An overview of the lifetime of discussed main materials is given in Table 6.2 and Table 6.3. In the tables, the lifetime is given of two glass structures, one mainly constructed from adhesives and one mainly from mechanical connections. Lifetime of various materials is unsure. In the case of a structural adhesive connection, when failure of one of the components occurs, this often means failure of the entire design. For a design based on mainly mechanical connections, this also could lead to failure of the total, but replacement is also possible, then a new cycle is started.

Table 6.2: Potential lifetime of a glass structure connected with adhesives.

Lifetime of a structure based on adhesives connections	Likely minimum lifetime	Replacement is possible?	When one component fails, entire structure is replaced/demolished?	Waste/ Recycling/ Incineration	Reuse
Glass (not processed /altered)	50+	No	Yes	Yes	No
(UV-)adhesive	50+	No	Yes	Yes	No
IGU	20-25	No	Yes	Yes	No
Structural silicone sealant	5-25+	No	Yes	Yes	No
SentryGlas	5-25+	No	Yes	Yes	No
PVB	5-15+	No	Yes	Yes	No

Table 6.3: Potential lifetime of a glass structure connected with mechanical connections.

Lifetime of a structure based on adhesives connections	Likely minimum lifetime	Replacement is possible?	When one component fails, entire structure is replaced/demolished?	Waste/ Recycling/ Incineration	Reuse
Glass (not processed /altered)	50+	Yes	Yes	Yes	No
Metal connection	50+	Yes	Yes	Yes	Yes
IGU	20-25	Yes/No	Yes/No	Yes	No
Silicone (non-load bearing)	5-25+	Yes	Yes	Yes	No
SentryGlas	5-25+	Yes	Yes	Yes	Yes
PVB	5-15+	Yes	Yes	Yes	Yes

6.2. Environmental impact

In this section the environmental impact of a connection is described and quantified. Two kinds of environmental impact can be considered, direct and indirect. Direct environmental impact is related to the material impact which can be expressed in shadow costs. Indirect environmental impact is the consequence of a connection on the material use on other parts of the structure. First the direct environmental impact is described and quantified and then in the indirect environmental impact is characterised.

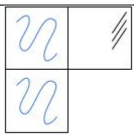
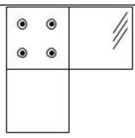
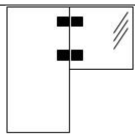
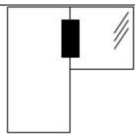
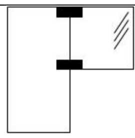
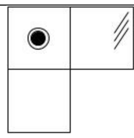
6.2.1. Direct environmental impact

In this section, the shadow costs of different connections are determined. In order to get an idea of the order of magnitude of these shadow costs, a comparison is done with a regular facade in Section 6.2. This is shortly done, since it is not the aim of the research. Also, the standard set in 2018 in the Dutch standards, ("Bouwbesluit") are maximum shadow costs of € 1,- / m^2 GFA / yr.

Shadow costs

With the assumptions regarding the observed connections the material use of each connection is derived and the result is shown in Table 6.4 and Table 6.5 and more elaborate in Appendix G. Also, the MCA score is given in these tables which will be used later on. With the EPD material data, the shadow costs of each connection can be determined and is presented for both the 2 impact categories (which are known for all connections) and 11 impact categories where possible. Also, the shadow costs are both presented in cradle-to-gate as in cradle-to-grave, please note the aforementioned assumptions in Section 5.3.

Table 6.4: Shadow costs of six frame connections

Type	 Adhesive [1]	 Bolted, rigid	 Embedded	 Embedded	 Embedded	 Bolted, hinged
Material use [kg]	UV acrylic: 0.33	SS[2]: 5.16 Filler: 1.21 Glass[3]: 17.50	SS: 0.85	SS: 1.10	SS: 1.57	SS: 2.71 Filler: 0.10
Cradle-to-gate 2 impact cat. €	0.11	3.74	0.31	0.40	0.57	1.58
Cradle-to-grave 2 impact cat. €	0.11	2.82	0.14	0.18	0.26	1.05
Cradle-to-gate 11 impact cat. €	0.11	39.24	6.07	7.84	11.13	20.11
Cradle-to-grave 11 impact cat. €	0.11	32.17	4.88	6.30	8.95	16.35
MCA score	++	–	0	0	0	-
Motivation		Given material use, this one is by far the most impactful connection.	Embedded connections are similar in material use, but better than a bolted connection.			

[1]: Only 2 out of 11 impact categories are available.
[2]: SS = stainless steel
[3]: Extra necessary glass is accounted for, more on this topic in Chapter 5.

Table 6.5: Shadow costs of six facade connections

Type	 Angle spring plates	 Fitting to a glass fin	 Spider connected to a glass fin	 Clamp spider	 Structural silicone sealant	 Titanium embedded[1]
Material use [kg]	SS: 4.03 Silicone: 2.81	SS: 6.58 Silicone: 2.81	SS: 4.00 Silicone: 2.81	SS: 4.00 Silicone: 2.81	Struct. Silicone: 7.03	Titanium: 2.04 Silicone: 2.81
Cradle-to-gate 2 impact cat. €	1.85	1.84	1.84	1.84	0.96	5.91
Cradle-to-grave 2 impact cat. €	1.28	1.28	1.28	1.28	1.54	6.14
Cradle-to-gate 11 impact cat. €	29.29	29.07	29.07	29.07	1.56	6.15
Cradle-to-grave 11 impact cat. €	23.93	23.76	23.76	23.76	2.19	6.40
MCA score	-	-	-	-	++	–
Motivation	Less material use than any other				The silicone can be compared to a stainless steel connection, since all 11 impact categories are available	titanium is worse than stainless steel, based on 2 impact categories

[1]: Only 2 out of 11 impact categories are available.

From both tables the following can be noticed.

- The shadow costs of a connection are of course highly related to the costs per kilogram, but also related to the material use. In both connections, a metal connection uses more material, and thus weight, and has higher shadow costs per kilogram compared to the adhesive based connections
- Considering 11 impact categories over 2 does not make a difference to the previous finding. The metal outweighs the adhesive strongly.
- Considering cradle-to-grave, metals have a lower impact than cradle-to-gate, however, in absolute terms, by considering 11 impact categories over 2, the metal has still a far higher impact than the adhesive.
- A relatively small titanium connection has by far the highest impact relative to other metal connections or adhesives, of course noted that only 2 categories are available for this connection.

Shadow costs and lifetime

As indicated, the unit in which the shadow costs usually are expressed are in € / yr/ m2 GFA. Now that there is no GFA, the shadow costs can be expressed in € / yr. However, this is not presented and here is explained why.

In general, there is too little known about the technical lifetime and functional lifetime of glass buildings. This could be because structural glass is a specific application, especially the connections that have been discussed. On the other hand, since little is known, it might also be a good sign since little problems then are found and reported. Despite this little knowledge, glass does know some problems (leaking IGUs, delamination).

Looking at the connections, it is a matter of how to compare connections on lifetime. If all modules have a PVB interlayer, then the comparison is useless since the playing field is equal, unless specific connections are proven better or worse than others. The same goes for the facade application with an IGU. If all facade connections have an IGU which is at the end of its lifetime, clearly the connection did not influence this. Besides, as discussed in this section, there are no clear signs of a limited lifetime by connections, although there are some uncertainties about the quality of materials.

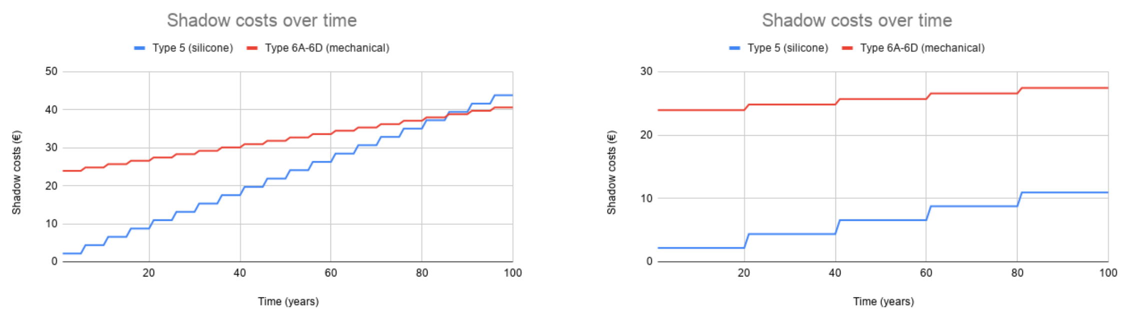
Concluding, it is useless to compare the shadow costs of connections in € / yr and it is far more useful to select the right materials for the expected lifetime.

Shadow costs over time

As stated in the previous section, the technical lifetime of a connection is of interest. Since in a facade connection the (structural) silicone has an expected lifetime from 5 to 20 years (see Table 6.1), it is of interest to know whether and in which conditions a structural silicone connection is more interesting to apply in a facade connection than a mechanical connection from an environmental impact point of view.

Assumptions:

- The same assumptions hold as is done to calculate the shadow costs of the connections
- The technical lifetime of a (structural) silicone joint is varied between 5 and 20 years
- It is assumed that a solution is found for the bonding of a new structural silicone connection and the glass



(a) 11 impact cat., cradle to grave, replacement of silicone after 5 years

(b) 2 impact cat., cradle to grave, replacement of silicone after 20 years

Figure 6.1: Shadow costs over time

A structural silicone connection would be more interesting to apply in a facade connection when the structural silicone has a life expectancy of 5 years, combined with a lifetime of the structure of 80 years. When the silicone has a lifetime of 20 years, this point lays much further into the future. If the glass also has to be replaced, the shadow costs will rise tremendously every time replacement due to the sealant is needed. Please note that this calculation is highly dependent on the amount of silicone used.

Given that research shows that structural silicone can last longer than 20 years, it is likely that a lifetime of 5 years is too low for a structural sealant. From both figures can be concluded that structural silicone has lower shadow costs than a mechanical connection on the condition that a new structural silicone can be applied on an old, previously used glass surface. If that is not possible, then the mechanical connection is more of interest after the first life cycle, since the glass panel then also has to be replaced.

Sensitivity of data

In order to see what the impact is of an upper and lower boundary data, a sensitivity analysis is done. The result is shown in Table 6.6, where the lower boundary and upper boundary for each connection has been presented.

Table 6.6: Sensitivity analysis of used EPD data. Both the lower and upper boundary are given.

Type	 Angle spring plates	 Fitting to a glass fin	 Spider connected to a glass fin	 Clamp spider	 Structural silicone sealant	 Titanium embedded*
Material use $[kg]$	SS: 4.03 Silicone: 2.81	SS: 6.58 Silicone: 2.81	SS: 4.00 Silicone: 2.81	SS: 4.00 Silicone: 2.81	Struct. Silicone: 7.03	Titanium: 2.04 Silicone: 2.81
Cradle-to-gate 2 impact cat. €	1.85 → 2.84	1.84 → 2.83	1.84 → 2.83	1.84 → 2.83	0.96 → 3.45	5.91 → 6.90
Cradle-to-grave 2 impact cat. €	1.28 → 2.08	1.28 → 2.07	1.28 → 2.07	1.28 → 2.07	1.54 → 3.54	6.14 → 6.93
Cradle-to-gate 11 impact cat. €	29.29 → 30.13	29.07 → 29.91	29.07 → 29.91	29.07 → 29.91	1.56 → 3.66	6.15 → 6.98
Cradle-to-grave 11 impact cat. €	23.93 → 24.66	23.76 → 24.48	23.76 → 24.48	23.76 → 24.48	2.19 → 4.00	6.40 → 7.12

[1]: Only 2 out of 11 impact categories are available.

Even with assuming the upper boundary of the EPD material data, the previous findings still hold except for one finding. The one that changes is that for the cradle-to-gate and considering 2 categories, the adhesive does have higher shadow costs, but when considering 11 categories, a large difference in shadow costs remains visible. Important note here is that for the upper boundary data EPD data of only 6 impact categories is known. Also the result of the MCA score has not been influenced.

Context

As indicated in Figure 6.2, a large part of the total shadow costs is related to the facade. Glass has been found as a large contribution to the shadow price of facades and is considered not sustainable since the amount of glass is related to the energy performance of the building. More glass results in more required energy and higher shadow costs than for closed parts [151]. Clearly, 1 m2 of glass with two panes of 8 mm thickness has already a shadow cost of € 3.84, which if compared with a connection in application will contribute to a large part to the total shadow cost of a facade. A rough calculation of the shadow costs of "Kasteel Ruurlo" is done in Chapter 8, which also proves this.

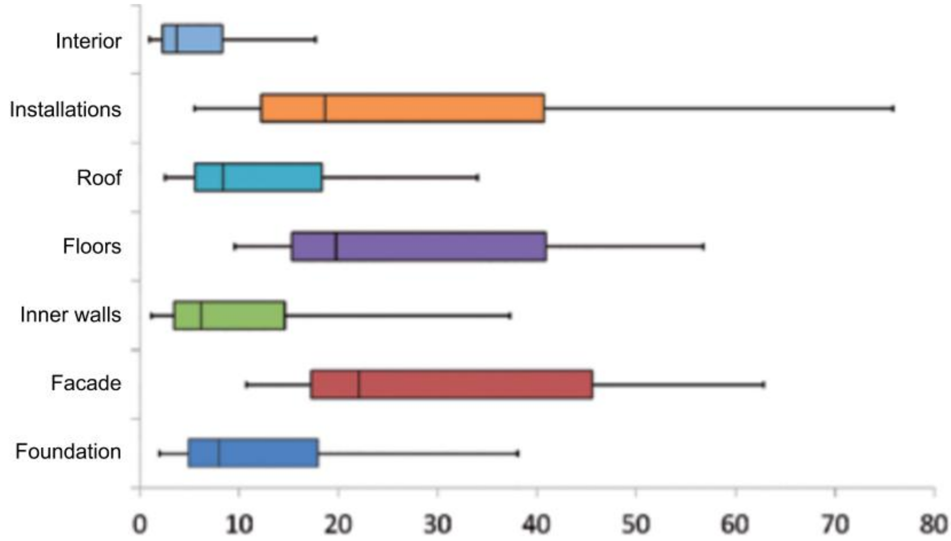


Figure 6.2: Impact of various parts on the shadow costs [37]

6.2.2. Indirect environmental impact

As shown for moment rigid frames, the choice of a mechanical connection leads to additional glass and interlayer use. This "indirect environmental impact" is further addressed by calculating the the glass usage of a few common connection types. Then, in the second paragraph, the outcome of the first paragraph is discussed and more consequences of connections are discussed.

Glass usage by connection type

Glass usage and related shadow costs have so far not been indicated because those tend to become quite project and design specific. In order to still indicate the glass usage and the influence of a connection on the glass usage, a comparison between connections has been done. For the mechanical connections, a fixed bolt with a pre-drilled hole, a countersunk fixed bolt and clamps along the side are assumed. As adhesive, a structural sealant is used to represent a line support. Both a double glazed IGU and a laminated panel are compared, but since a countersunk connection does not work in a IGU, unless also the IGU consists of a laminated panel, this one is left out. That leaves the comparison to seven situations.

Further assumptions for this exercise:

- The panel has a size of 2.0 x 2.0 meters
- The panel is loaded with a uniform load of $1kN/m^2$
- IGU is as basis built up out of a 16 mm cavity and the panel thickness is further derived
- The laminated panel is as a basis built up out of a 6 - 0.75 - 6 mm (glass-PVB-glass) panel and the plate thickness is further optimized.
- Possible glass thicknesses are: 2 / 3 / 4 / 5 / 6 / 8 / 10 / 12 / 15 / 19 mm
- Float glass is used as base for this experiment, since it suits the application. If float glass does not suit the connection, it obviously results in either thicker glass or heat treated glass.
- Float glass has a characteristic strength of $f_{mt;u;d} = 20N/mm^2$, considering a wind load with t = 5 s.
- The stresses are assumed to be leading for optimization, if deformation has been considered too in the optimization, comparing connections and panels would become too difficult
- SJ Mepla (FEM based) has been used as program to assess the stresses
- The principal stresses are given in Appendix H, but due to limitations in mesh size, the result could lack accuracy. However, SJ Mepla does use a small mesh size around the connections, so the stresses around the connections are considered realistic.

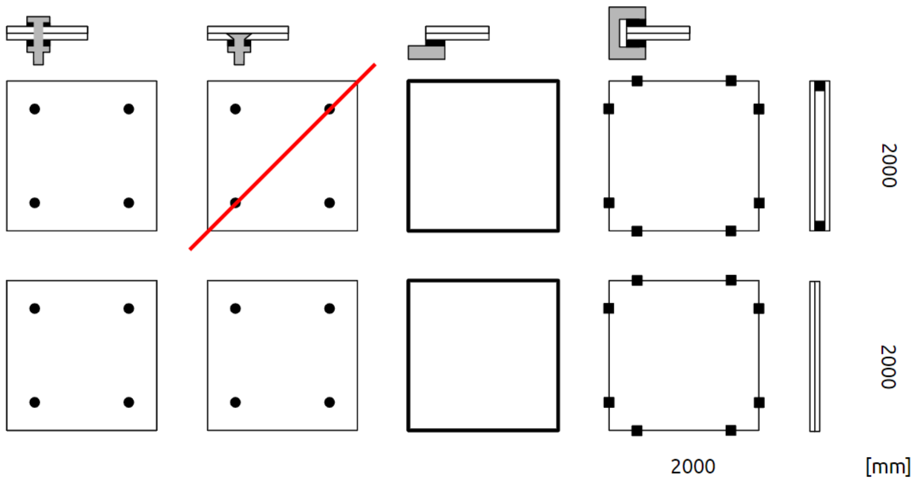


Figure 6.3: Presumed connection types. From left to right, point fitting, countersunk point fitting, structural sealant and edge clamped.

The minimal pane thicknesses are shown in Figure 6.4. Already known is that mechanical connections lead to peak stresses, which if governing could lead to more glass usage. Proper detailing is therefore important, further assumptions and detailed information can be found in Appendix H.

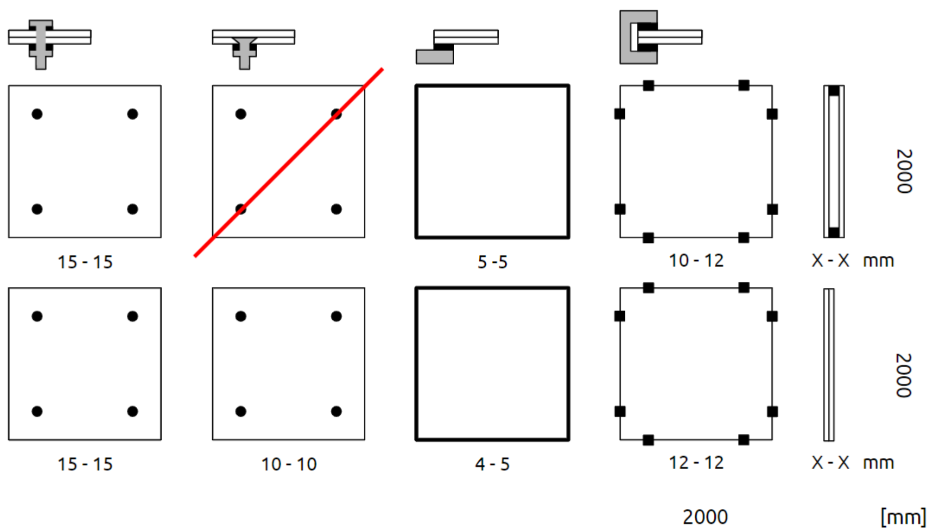


Figure 6.4: Pane thicknesses optimized to above mentioned assumptions.

The following can be concluded from this exercise. If properly detailed, the (tensile) peak stresses around the supports do not necessarily need to be governing but are governing in the cases as assumed now. The adhesive connection resulted in the least amount of stresses and glass usage based on stresses. Another option is to heat treat the glass in order to allow for higher stresses instead of applying thicker panels.

Other consequences

Glass use

In Section 4.3 various examples of mechanical connections have been shown. For all mechanical connections, glass treatment or extra glass (or a combination) is needed to make it structurally feasible. A similar conclusion can be drawn from the previous paragraph, where a mechanical connection also leads to governing stresses and the need for extra or treated glass whilst an adhesive connection does not require both in order to deal with stresses.

A mechanical connection leads to more glass use and/or heat treatment of the glass module which from a structural point of view can be prevented by choosing adhesives. However, also safety and practicalities should be considered, which still could lead to heat treatment or lamination.

Heat treatment

In line with the statements regarding extra glass use, heat treatment is often needed to have better performing load bearing characteristics which are for mechanical connections of great value. Heat treated glass does have a slightly bigger environmental impact (see Table 3.1), but it could also lead to an overall smaller environmental footprint (see Figure 3.5). Given the specific application, here the need for heat treatment is seen as a negative impact on the overall environmental footprint. Noted again, it is important to view the entire design and consider safety and practicalities.

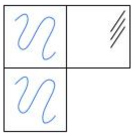
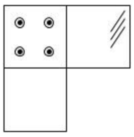
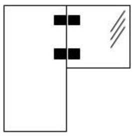
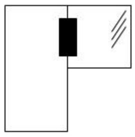
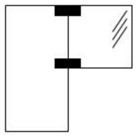
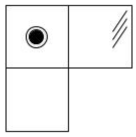
Interlayer

Many of the presented connections do result in laminated glass panels. For some connections, a PVB interlayer would suffice, but for the embedded connections a SentryGlas interlayer is necessary. This is assumed to have a higher environmental impact than PVB. The environmental impact of other interlayers is not known. A similar assumption is made for interlayers as for heat treatment, since the use of SentryGlas could also lead to less material use. Here the use of SentryGlas is seen as a negative impact on the overall environmental footprint.

Score

Based on the performance and impact of each connection, the impact (relative to other connections) is shown in Tables 6.7 and 6.8. Together with the score related to the shadow costs, these tables form the basis of the MCA result and summarizes the score of the environmental impact as discussed in this chapter.

Table 6.7: Effect of connection on interlayer type and heat-treatment in a frame connection.

Type	 Adhesive*	 Bolted, rigid	 Embedded	 Embedded	 Embedded	 Bolted, hinged
Extra and /or treated glass[1]:	Heat-strength-ened is recomm ended, but not necessary	Heat-strength-ened is possible	Heat-strength-ened is possible	Heat-strength-ened is possible	Heat-strength-ened is done in literature	Heat-strength-ened is possible
Type of lamination [2]:	PVB	PVB	SentryGlas	SentryGlas	SentryGlas	PVB
Total indirect impact score	+	0	-	-	-	0

The total indirect environmental impact score is the sum of the "extra and/or treated glass" and "type of lamination".
[1]:This is a combination of extra glass needed and/or heat treated glass in order to suffice with the structural requirements.
[2]:SentryGlas has a higher environmental impact than PVB. This is reflected in the score, a SentryGlas interlayer has a score of “- “ and PVB a “0”, since it is a widely applied interlayer.

Table 6.8: Effect of connection on interlayer type and heat-treatment in a facade connection.

Type	 Angle spring plates	 Fitting to a glass fin	 Spider connected to a glass fin	 Clamp spider	 Structural silicone sealant	 Titanium embedded
Extra and/or treated glass[1]	Peak stresses, so more glass	Peak stresses, so more glass	Peak stresses, so more glass	Peak stresses, so more glass	Limited extra glass needed	Heat-treated glass and extra layers
Type of lamination [2]	PVB	PVB	PVB	PVB	PVB	SentryGlas
Total indirect impact score	-	-	-	-	+	–

The total indirect environmental impact score is the sum of the "extra and/or treated glass" and "type of lamination".
[1]:This is a combination of extra glass needed and/or heat treated glass in order to suffice with the structural requirements.
[2]:SentryGlas has a higher environmental impact than PVB. This is reflected in the score, a SentryGlas interlayer has a score of "- " and PVB a "0", since it is a widely applied interlayer.

6.3. End-of-life scenarios

In order to consider the circular economy in the design of glass structures, various circular design methods have been introduced in Chapter 3. Also introduced in Section 2.2 is a ranking of impact of various methods, the so-called "10 Rs". By considering a circular design method it is important to think of the impact that that specific method has. In this chapter, the most impactful method (for glass structures) "reuse" and most discussed method "recycling" are discussed as end-of-life scenarios.

6.3.1. Reuse

Reuse is a key to the circular economy where a building or component is used for a new cycle. Reuse of a glass structure can take place on building level, or on component level. In this section, reuse is discussed on these various levels, indicating the possibilities, limitations, value and likeliness of reuse. This is done by assessing the different alterations that glass undergoes as material towards the final product.

Possibilities and limitations

Glass as a material is a durable material that has the potential of a long technical lifetime, given previous mentioned issues. However, the application of glass and alterations that glass undergoes causes it not to last a long time. The main components of which a glass structure consists of, an IGU and laminated glass panels, are technically not suitable to last a long time, given delamination problems and leakage of the IGU. A connection thereby does not have any influence on these two major problems but can also cause leakage or delamination.

Reuse of an IGU or laminated panel does not take place at this moment due to these problems and repair or refurbishment can allow for reuse, but do simply not happen due to the high cost of this and the relative low value of a glass panel. Besides, there is not even spoken of the uncertainties with regard to recurring leakage or delamination after refurbishment. Glass modules are at this moment not suitable for reuse and thereby the circular economy since it is discarded when problems arise.

Also on an even lower level, on component level, reuse does not take place even though it is technically possible, as for example separation of glass and interlayer reuse of the glass solely possible (see Section 3.3). It is possible, but due to a low value, laminated glass is discarded instead of fully delaminated and prepared for a new application. The glass panel is simply too low in value, both financially and on (raw) material level. A similar situation holds for IGUs, where the glass spacer and panels can be reused (on the condition that proper separation is possible, which is already doubtful) but does not happen due to the low value of the glass and aluminium spacer.

The only reuse potential in a glass structure is when for laminated glass an interlayer is chosen of high quality, like SentryGlas and Trosifol. The use of mechanical connections is hereby a necessity.

Value and impact

Compared to other end-of-life scenarios, reuse is the most valuable and most impactful of all on the environmental impact, which makes reuse the key to the circular economy. Thereby is on one hand the connection which plays a very important role to allow for demountability and thereby reuse, but on the other hand, the problems that glass modules have encompass this importance that connections have and make reuse at this moment impossible.

What if: no delamination and IGU issues?

Supposedly, if problems with leakage and delamination do not occur, then the importance of demountable connections is inevitable to allow for reuse. Therefore, in this paragraph the previously introduced connections are shortly discussed for this scenario.

Adhesive connections

Structural adhesive connections play no role for demountability, unless there are forms of removal possible. For example, the structural silicone sealant of the facade connection is not demountable, but by removing the silicone, the panels seem to be reusable, only a new silicone joint has to be applied. Interestingly, applying new structural silicone would have in total, also accounted for the first silicone joint, lower shadow costs and thereby a smaller environmental footprint than a mechanical connection. There is one important condition, namely proper removal is needed of the old structural sealant in order to guarantee a proper load bearing connection which cannot be guaranteed at this moment. This is important since an adhesive failure may not happen.

Also for other structural adhesives proper removal is important so that in a new application no remains are visible of either the adhesive or that the glass is damaged by the equipment used to remove the adhesive. In all adhesive cases, it can be argued whether this is an interesting direction to take, since it requires a lot of effort to allow for reuse, especially with regard to proper cleaning and it can be questioned whether it is worth the value.

Mechanical connections

Mechanical connections on the other hand are interesting for demountability and reuse. Both the connection itself and the glass modules can be reused. To make optimal use of such a module, a module needs to be designed which allows for reuse. The role of flexibility can be questioned, since with standardization a lot of flexibility can be created by implementing different sizes.

Important is to still address the demountability of a mechanical connection. The use of an injection mortar as an interlayer to improve the spreading of a load, like shown in Section 4.3, can limit the demountability of a mechanical connection. In theory it should be possible to manually remove this mortar, but no examples are known by the author. This leaves the question, how demountable and reusable are demountable connections?

The question is a very practical question and includes lots of practical issues, like whether the glass is not damaged by removal, if the connection is demountable and reusable in various climate conditions and whether it is possible to demount and reuse it after a very long time. The technical lifespan is hereby very important, both of the module and connection. Tolerances play a vital role in the demountability of connections. Clamped connections are best in tolerances, while an embedded connection barely allows any deviation. For now, these questions remain unanswered, but are important to consider when designing a module.

IGU and laminated glass

With no issues, it is more likely to reuse both IGUs and laminated glass as long as the connection allows for this. Other technical barriers are now more important, where standardization should be prioritized in research.

Likeliness of reuse

Besides the previously discussed issues, there are a few other requirements and issues which influence the likeliness of reuse. Obviously, the technical lifespan should allow for reuse of a module or as building as whole. The role of the connection, glass and as a module have been discussed in order not to be a limiting factor. One other factor, not mentioned before, is the esthetics. Glass has been widely applied because of its unique characteristics and is associated with luxury and prestige. Over time this resulted in transparent buildings, minimalistic designs and lots of development. A modular system is the next development, but should combine these characteristics in order to be a success in the circular economy. That glass is associated with luxury and prestige might therefore pose problems since a “secondhand, reused item” is not luxurious. How to deal with this is an interesting question. Glass may be a structurally durable material, but when glass has the slightest stains, decolouring, or another form of damage, it might still end up being recycled.

6.3.2. Recycling

Although the facilities for recycling are present, still a lot of downcycling happens. This is not a bad thing, since the environmental benefits are made in another industry, but that means that the float glass industry does face challenges to improve this. As an end-of-life scenario, recycling is a good cause as it contributes to a positive environmental impact by handling waste and it results in less energy consumption for the production of new glass. This impact, however, is by far not as big as an element would have been reused, both in value as in environmental impact.

Broken glass has the value of the raw material, which is in the case of glass mainly a widely obtainable material, namely sand. A reused panel on the contrary does keep its production value and potentially can be used as a whole. As good as recycling may seem as an end-of-life scenario, recycling has a low value. Of course, it is still better than a waste scenario, but reuse by far outweighs recycling.

As discussed in Section 3.2, contamination plays a large role in whether recycling is done or not and this is partly out of control of the designer. Demountable connections might improve recycling rates, but when a small element of CSP is included in the glass batch by accident on the building/demolition site, recycling of the glass becomes more unlikely. Other contamination by adhesives might influence recycling, but it is believed that it is partly removable and that the remaining amount is either incinerated or taken up in the batch and that the stains that are left in the glass pose minimal harm to the end product.

6.3.3. Waste

Besides reuse and recycling, the least beneficial alternative is ending up in a landfill. The NMD presented some data about the percentage of a material that is being recycled, incinerated or ends up in a landfill. An overview including sources is given in Appendix A. Here, the waste scenario is shortly given by the NMD for the materials that have come by.

- Glass is mainly being recovered and recycled, whether this is correct given other found data and literature can be argued. According to the NMD, 70% of the glass is recycled and just 30% ends up in a landfill.
- Adhesives are incinerated since they are hard to recover. A future exception might become silicone adhesives/sealants, since DowCorning already is recycling silicone via internal processes, there is potential for external gathering of silicones.
- Metals are already being recycled, although small percentages still end up in a landfill.

7

Multi Criteria Analysis

In line with the discussion in the previous chapter, the sub-question “How sustainable are the connections?” comes to light, since all connections now can be compared on various levels. First, the MCA result is given and which is discussed in Section 7.2. In the last section, conclusions are given.

7.1. MCA result

In the previous chapter, different scores have been given to the connections to various criteria which are summarized in Tables 7.1 and 7.2. Usually in an MCA, factors to each category should be appointed with as goal to make a well weighted decision. However, since glass structures should also be designed according to the principles of the circular economy, reuse is inevitable in the design and outweighs therefore other principles such as recycling or material selection and minimization. Appointing factors to each of these categories is unnecessary since reuse is the most important category. This does not make the other presented information useless, since it still gives insight in the possibilities of connections.

Table 7.1: Summary of score of various frame connections. Reuse, recycling and demountability scores are elaborated in Appendix G.

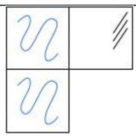
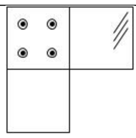
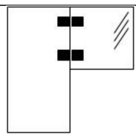
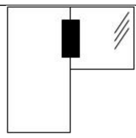
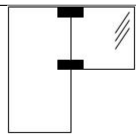
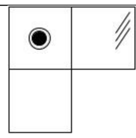
Type	 Adhesive*	 Bolted, rigid	 Embedded	 Embedded	 Embedded	 Bolted, hinged
Direct impact	++	–	0	0	0	-
Indirect impact	+	0	-	-	-	0
Reuse	–	+	+	+	+	+
Recycling	-	0	–	–	–	0
Demountability	–	+	+	+	+	+

Table 7.2: Summary of score of various facade connections. Reuse, recycling and demountability scores are elaborated in Appendix G.

Type	 Angle spring plates	 Fitting to a glass fin	 Spider connected to a glass fin	 Clamp spider	 Structural silicone sealant	 Titanium embedded
Direct impact	-	-	-	-	++	–
Indirect impact	-	-	-	-	+	–
Reuse	+	+	+	+	–	+
Recycling	0	0	0	0	–	-
Demountability	+	+	+	++	–	+

7.2. Discussion

Reuse is the most impactful end-of-life scenario. That means that all connections that have a positively rated score on “reuse” should be used in the design of glass structures. Reuse and demountability are related, so from a connection point of view, the connection should be demountable. However, it is not just the connection that makes glass reusable, since the technical lifetime is determined by IGUs and laminated glass, which indirectly comes down to the quality of the product. As discussed in Section 3.4, IGUs are not suitable for reuse and laminated glass is reusable, as long as a quality interlayer is used and the connections allow for that. A different design strategy is needed for IGUs and laminated glass, which is discussed in this section.

Standardized components

Standardization in the form of modules is needed in a circular economy. The connection is a key here, since a standardized connection leads to interchangeable components. However, standardizing leads to limitations in design, which is not desired. There are two approaches: modules are designed which serve as basis for design, or only the (demountable) connection is set and sizes are allowed to deviate. The latter is chosen given freedom of design. Of course, it is natural that repetition of elements takes place, which is not only from a sustainability point of view beneficial, but also economical and practical.

Performance and quality of reused components

Quality of the components is very important, which means that the manufacturing should be done carefully to prevent failure of any kind. While considering a connection, both aspects should be addressed critically, but the shown connections do not influence performance of quality directly.

Laminated glass

The best performance and quality are assured by using a SentryGlas or Trofisol interlayer since these interlayers are the least sensitive to delamination. When SentryGlas is chosen, an additional beneficiary is the improved structural performance of a SentryGlas interlayer compared to other interlayers.

Another way of improving the (structural) performance is by using tempered glass. The structural performance increases compared to annealed glass and nickel sulfide issues will not happen since these only occur at fully tempered glass panels. Clearly, a larger capacity also improves the robustness of products. Heat treated glass cannot be processed or altered after heat treatment, but it is believed that that will not be done either in a new (after-life) application since the (economical) costs and effort in order to do so outweigh a newly built element. Also combined with SentryGlas, safety in design is assured.

In terms of connections, the influence of a mechanical connection on the technical lifetime is unknown, but it is assumed that with proper manufacturing, the technical lifetime is not governed by the connection. In order to allow for reuse, the use of a structural silicone should be avoided. Related to the example connections discussed before, the embedded connections and bolted connections in a frame do suffice the requirements and for a facade connection, all mechanical connections are possible.

IGUs

The lack of performance of an IGU is discussed trhoughout the report, clear is that quality of the edge sealant does make a difference in lifetime, but will not allow the IGU to be technical feasible for a long (50+ years) time.

With regard to the connections, connections which are likely to limit the technical lifetime even more (glass piercing connections) should be avoided, but a waste/recycling scenario is not avoided on the long term. The choice of connection is also related to the glass fins, so that reuse could be possible of these fins. A structural silicone sealant should be avoided in terms of reuse, but when a lower quality interlayer is chosen for the fins, it becomes less of an requirement since reuse of the fin then is already unlikely. Any mechanical connection then suffices, although in terms of tolerances, clamped connections are preferred.

Lack of properties and in-use history

This aspect is not affected or influenced by the connection or any decision in design. It should be noted that for an interlayer, it is hard to determine the type and quality of the interlayer. This is not limited to only the interlayer, likewise is this the case for the type of glass and other materials.

Robustness of products

Robustness should be considered by choosing the connection type. It influences the robustness during (de)construction and during use-phase. Tolerances are important to consider here and is one of the key influences of design for disassembly. The use of embedded connections thereby is not ideal given high requirements set by the connection, unless a way can be found to deal with these tolerances. The point fixings perform better with tolerances since a filler can handle slight deviations. A clamped connection deals even better with tolerances and so does a structural sealant.

Practicalities of economic deconstruction.

Deconstruction is covered by the demountable connections, although still the following question should be asked “how demountable are demountable connections?”. This is important since the use of mechanical connections does not automatically mean that a connection is demountable since fillers or other interlayers could pose difficulties in deconstruction.

7.3. Conclusions

The conclusions are given for two research questions: "how sustainable are the connections" and “what are the design requirements for a sustainable glass design and what is the role of connections here in?”.

7.3.1. Sustainability of connections

The sub-question “how sustainable are the connections?” is answered in Tables 7.1 and 7.2. Here, the performance of connections is rated to environmental impact, reuse, recycling and demountability possibilities. From an environmental impact point of view, the use of adhesives is recommended since these result in a lower direct and indirect impact. From a reuse perspective, any demountable connection is recommended, although the technical lifetime is determined by IGUs and laminated glass. Recycling is improved when demountability is integrated, since the structure then is easier to take apart. Adhesives are not recyclable where mechanical connections are. However, again, the overall design should be considered since alterings, like SentryGlas, limit recycling.

7.3.2. Design requirements for a sustainable design

The final sub-question “what are the design requirements for a sustainable glass design and what is the role of connections here in?” is answered based on the requirements demanded by a circular design. The answer is given in two parts, for both reuse and environmental impact.

Reuse

Reuse should be prioritized in a sustainable, circular design, but current designs do not allow for reuse. Conclusions are given for three technical barriers: "performance and quality of reused components", "standardization" and "robustness of products".

At first, performance and quality of reused components should be assured, which is currently impossible. When a quality product as SentryGlas or Trofisol is used, a longer technical lifetime is expected. The lack of legislation is the base of the current low performance by interlayers and IGUs in general and is needed to set requirements to the technical lifetime. Only then it is possible to implement design strategies for the circular economy. This legislation is necessary for both laminated glass and IGUs, to allow for a minimum performance without deterioration over this set time. A connection should by then not be a clear limitation in design, in technical lifetime but also in possibilities.

Secondly, standardization is necessary to increase the reuse potential. In here, the connection is important, since this could allow for a system which makes reuse possible, especially when a certain modular design is integrated.

Thirdly, a robust module is created by using tempered glass, the extra environmental impact is limited and compensates for the better structural characteristics than annealed glass. Fully tempered glass is not chosen given the risks of a failure by nickel sulfide. Additionally, when a SentryGlas interlayer is chosen, the structural performance is improved, although this is not a requirement to create a robust module. For a connection, the main requirement is demountability. The use of (structural) adhesives should thereby be minimized and mechanical connections should be used.

Environmental impact

A different approach is to focus on limiting the environmental impact to create a sustainable design. With this approach it is clear that the focus is on the design itself, than rather on the end-of-life possibilities as has been done when spoken of reuse. Design principles for material minimization and material selection play an important role. Concerning these methods, design plays an important role to limit material use. With regard to material selection, different (quality) interlayers can be selected and combined with heat treated glass, this could result in less environmental impact (indicated in Figure 3.5)

The design requirements can already be given based on the third research question, "how sustainable are the connections". Adhesive based connections have a lower environmental impact than mechanical connections and also result in less material use since peak stresses are avoided by using adhesive connections in design.

IV

CASE STUDY

8

Redesign of "Kasteel Ruurlo"

An impressive glass conservatory has been made which functions as the entrance of "Kasteel Ruurlo". Since "sustainability" and "circular economy" were less important at the time of construction, it is now the question how the glass conservatory could have been designed when "sustainability" and "circular economy" are prioritized. In this chapter this is done, with the knowledge gathered in this research so far as base for the redesign.

First the main assumptions and design aspects are explained in the first section. Then, in Section 8.2, the connection type is elaborated, which directly also explains the design, since in glass structures all aspects are related to each other. In Section 8.3, the result of the redesign is shown and in the final section, the current design and redesign are compared from a "sustainability" point of view.

8.1. Assumptions

8.1.1. Architectural design

In short, the glass conservatory functions as an entrance to the museum located inside the castle. The current conservatory has dimensions of 10.8 x 6.0 x 8.3 meters. Similar dimensions are striven for in the redesign although the main priority is reuse.

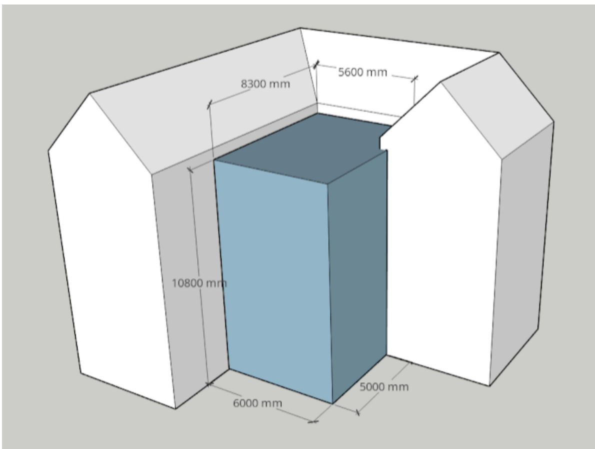


Figure 8.1: Sketch of the current design with indication of size with in white the castle.

8.1.2. Reuse

The assumptions to increase the reuse potential are given in this paragraph. First, the general assumptions are listed, then design for disassembly is discussed and other topics as makeability, size, tolerances, processings and IGUs are discussed too.

General

With reuse being the most impactful aspect of dealing with the circular economy, aspects that positively influence the reuse potential are used in the redesign. As discussed and concluded elaborately in Chapter 7, the current way of designing load bearing glass applications does not guarantee reuse to succeed. Therefore, the following assumptions in the design have been made to increase the reuse potential with the current possibilities:

- SentryGlas has been chosen as interlayer with the largest potential to not delaminate and has an added beneficial structural performance which improves the robustness of the system over a Trofisol interlayer, which is PVB based.
- Tempered glass is used to avoid nickel sulfide problems and increase structural performances and thereby robustness
- High-quality materials and production is advised to increase the reuse potential
- Although standardization is hard to introduce, the aim is to use as much as repetitive elements in design. This automatically leads to the use of a modular design. Other requirements to this module are discussed hereafter.
- Other logistical barriers, costs and liability issues are assumed to be solved or solvable by the time that reuse will take place, since the need for the circular economy is also for other materials, which encounter the same issues.

Design for disassembly

Design for disassembly also benefits reuse. As mentioned in Chapter 3, Crowther introduced various measures to improve for design for disassembly, of which a few are already mentioned. Additional to those, the following other important measures are noted: “make components and materials of a size that suits the intended means of handling”, “minimise the number of different types of components” and “use lightweight materials and components”. For a glass component all these measures are interesting, since a 10.8 meter long fin is not suitable for easy handling due to both the size and weight. This leads to the following design requirements:

- Small and light modules are needed
- Different types of components should be minimized, ideally the facade fins and roof beams are the same, or similar, both in dimension as in connection type.

Makeability, size and tolerances

Important is to consider the makeability of the fins, since a 10.8 meter facade fin cannot be manufactured in a regular factory. Examples of such fins can be found in various Apple Stores, but in the Netherlands, no such application can be found. This leads to creative solutions to still make this kind of designs and is done too in this redesign.

Assumptions with regard to makeability, size and tolerances are listed:

- A module with dimensions of 2.0 x 0.5 meters is assumed as base, which suits the main dimensions of the case study. Where unavoidable, there can be deviated from this size given project specific dimensions but it is striven for to use as little deviation as possible in design.
  The size of 2.0 x 0.5 meters is chosen as base because a few reasons, but it is recommended to further research this with regard to construction and production.
  - The facade panels have an economical size.
  - When the module becomes smaller, more connections are needed and thereby decrease the transparency even further. When the module becomes bigger, it is believed that reuse becomes more unlikely due to an impractical dimension.
- The module consists of three laminated glass panels and has a thickness of 12-15-12 mm. These dimensions have to do with structural feasibility (see Section 8.3) but do not influence other requirements. These dimensions, namely allow for some transparency (limited visual disturbance), are possible to handle on site and in transport.

- As a consequence of these dimensions, the module weighs about 100 kg. Smaller and therefore lighter modules will interfere with transparency, since more elements result in less transparency. Besides, given the height of application of these modules, a crane is a necessity anyhow.
- The facade and roof panels have a size of 2.0 x 2.0 meters which match the fin size.
- Tolerances are best covered by using clamped and bolted connections.

Processing

The way of processing does not matter in terms of reuse potential, as long as carefully has been assessed whether and which type of processing is necessary. Since tempered glass is recommended, no more processing can be done hereafter.

IGUs

It has been shown that an IGU has an important role in buildings and that it has plenty of challenges ahead to become circular. Since much research on a sustainable, longer lasting, IGU has already been performed (see for example among others [132] and [68]), it is assumed that solutions will be found for the IGU in a circular economy. The following requirements and assumptions are therefore set to the IGU in this exercise:

- Given that IGUs are not reusable, the design should allow to demount the panel.
- The IGUs should not affect the laminated glass fins to make reuse of fins possible.
- The technical lifetime should not be further decreased, so the use of (glass piercing) point fixings is not recommended due an increased risk of leaking. It is assumed that clamps are not likely to increase the risk of a leaking IGU and can be integrated with other connections of the fin, when sizes match the fins.

8.1.3. Structural system

Given the height of 10.8 meter of the glass extension, the use of fins is inevitable. Also, in order to prevent buckling of fins, buckling supports need to be integrated. This can be done in various ways: glass beams, metal supports or integrated with the fin-facade connection. Since short modules are used, joints can be used as a location as buckling support. Here, horizontal glass beams are used. All fins combined result in a grid or pattern, and as aforementioned this grid has dimensions of 2.0 x 2.0 meters, which suits the application in Kasteel Ruurlo. Due to this grid, it is chosen to deviate from the initial dimensions to a conservatory with dimensions of 10.8 x 6.0 x 8.0 meters.

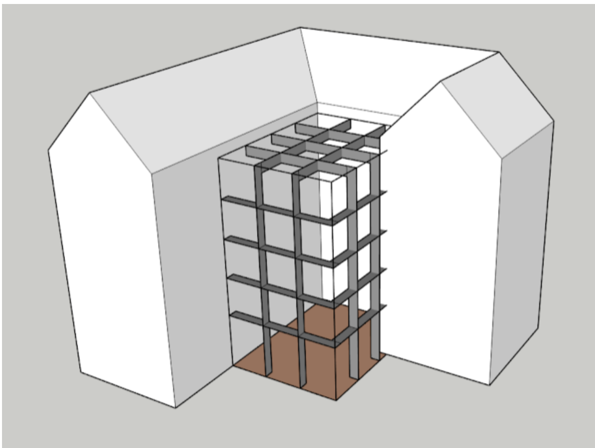


Figure 8.2: Fins are required in design for both facades and result in the roof grid.

8.2. Connection type

In the redesign, three types of connections are considered: a fin-fin connection in a frame, a perpendicular fin-fin connection and a fin ending, or shoe connection. Also the connection with the facade/roof is discussed.

In line with the restraints by design for disassembly, a single type of connection is striven for which allows for all three types of connections. Because of the required stability ensured by the frame, the connection should be moment rigid. Additionally, in order to connect modules of 2.0 x 0.5 meters and make a fin of 10.8 meter, a moment rigid connection is needed. A hinged connection does not meet these desires, or a different system should be researched which does allow for this. Integration of stability in the facade could be an outcome, but needs further research. The moment rigid connection does result in more material in both the steel use as in glass use due to expected peak stresses.

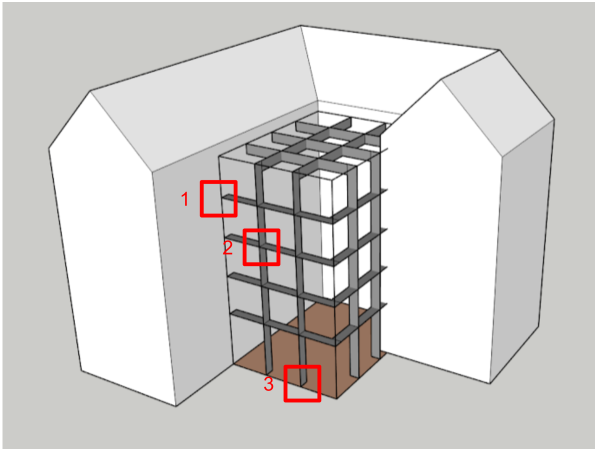


Figure 8.3: Three main types of connections for the fin. 1: fin-fin in a frame, 2: fin-fin crossing, 3: fin ending.

8.2.1. Perpendicular fins

Two possible ways of constructing a roof structure are shown in Figure 8.4. Either a hinged system is used, or a moment rigid roof structure is used. The advantage of the hinged connection is simplicity in design and limiting peak stresses, but will have to be constructed of two different lengths. Stability will have to be ensured in the facade. The moment rigid frame allows for stability and can be constructed from modules from a single length. Due to additional forces in the modules, the modules will have a larger size.

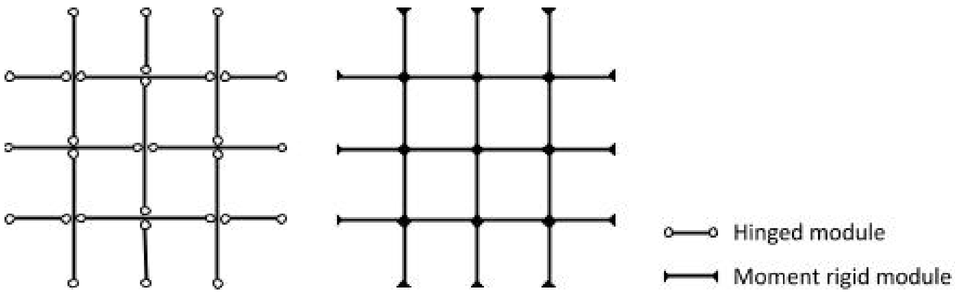


Figure 8.4: Two ways of a roof structure when continuous modules are not possible. Left: a modular structure with hinged connections built from modules with two lengths (also used in Appple Cube 1). Right: a modular structure with moment rigid connections built from a single length. Another possibility is by using continuous beams or a combination of both.

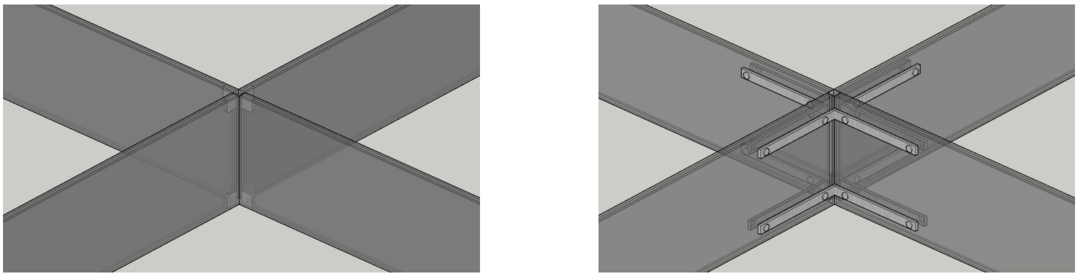
The hinged variant is applied in the Apple Cube 1, as is shown in Figure 8.5a). Use is made of a continuous laminated glass beam, with secondary beams in Figure 8.5b or Figure 8.5c). No examples are known of projects which only make use of moment rigid connections.

(a) Apple Cube 1 roof structure, New York [23] (b) TU Dresden roof structure, Dresden [152] (c) Kasteel Ruurlo facade structure [19].

Figure 8.5: Fins are required in design for both facades and result in the roof grid.

In the redesign, the use of long span beams is undesired from disassembly point of view. Another reason to choose a moment rigid connection over a hinged connection is the the ensured stability by a moment rigid connection. In an afterlife application this is an advantage. However, also hinged connections are believed to be of interest for reuse.

Possible configurations of demountable moment rigid connections are shown in Figure 8.6. Embedded connections or a splice (bolted fin-fin) connection suits this application. Splice connections know applications in practice but both have never been applied with perpendicular fins.



(a) Embedded crossing. (b) Bolted crossing.

Figure 8.6: Perpendicular moment rigid crossing.

As discussed before, a bolted rigid connection in the corner of a rigid frame results in larger glass fins, and thereby decreases the handling of such a module. On the contrary, a bolted rigid connection deals greatly with tolerances and knows more examples in practice then embedded connections. More (dis)advantages are listed in Table 8.1. From Table 8.1 can be concluded that the many advantages with regard to increased reuse potential of a bolted connection outweigh the advantages of embedded connections, besides the embedded connections know many uncertainties. A more detailed drawing of the splice connection is shown in Figure 8.7.

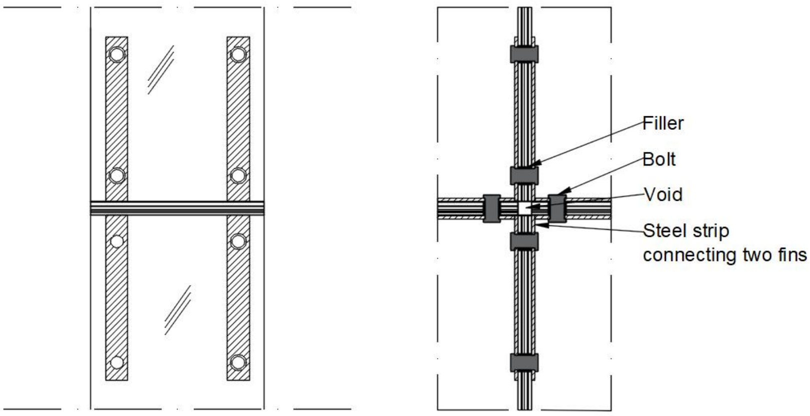


Figure 8.7: Detail of a perpendicular fin-fin crossing. Scale 1:20.

Table 8.1: (dis)advantages of an embedded and bolted fin-fin crossing (splice).

	Embedded	**Bolted**
Applied in practice	No	Yes
Crossing of two perpendicular beams possible?	Yes	Yes
Moment rigid frame connection possible	Potential	Potential, possibly larger fins needed.
Structural capacity	Higher, but needs to be researched	Lower
Connectivity as base or to existing structure(s)	Requires a custom made base plate	Requires a custom made base plate
Integration of connection with facade or roof glazing	Good, but needs more research	Good since it already knows various applications.
Demountability	Needs to be reviewed in order to guarantee demountability	Good, depending on the filler.
Tolerances	Lower performance	Good
Makeability of the connection in the factory	Difficult due to tolerances	Good
Constructability of the structure	Difficult due to tolerances	Good
Reusability	Good	Good
Elegant	Yes	No
Transparency	Smaller influence	Bigger influence
Costs	Higher	Lower

8.2.2. Fin-fin frame connection

As introduced in Section 5.2, many different connections are possible as moment rigid frame connection to connect two fins. Most have been discussed and elaborated before. The consultation of the decision of the connection in the previous section has been done by considering the frame connection too. Here the decision for this connection in a frame is discussed.

Whether the connection would use embedded connections, a hinged connection or a bolted connection, in all cases the frame connection will be unique. Therefore it is decided to use a similar layout of the bolts (2x2 holes) and deviate from the set size and to use a size of 1.5 x 0.5 meters for those spots where a moment rigid frame connection is needed. By doing so, the facade panels can still maintain their size of 2.0 x 2.0 meters.

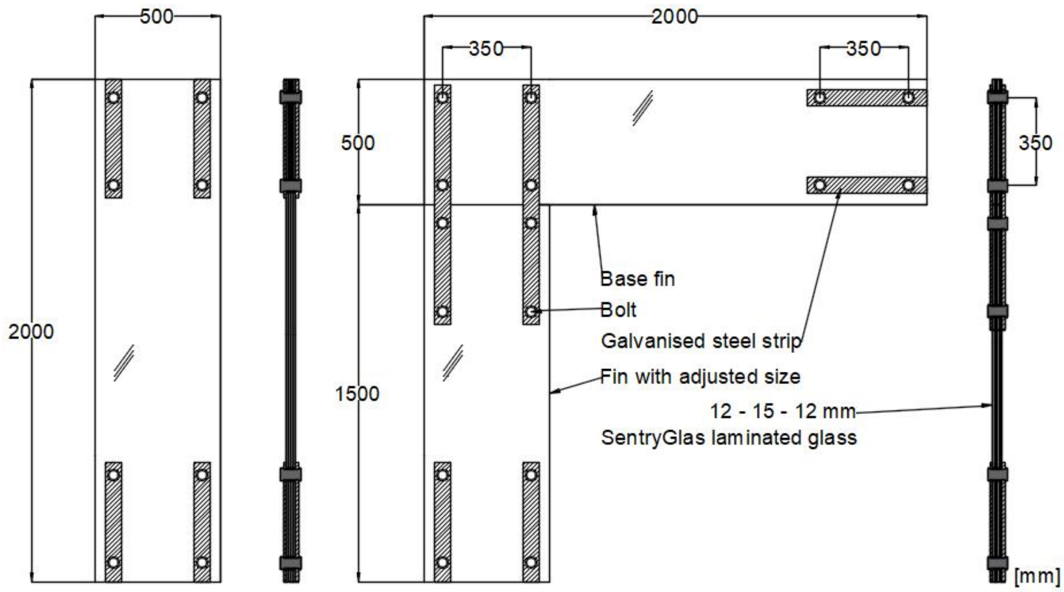


Figure 8.8: Detail of fins. Scale 1:30.

8.2.3. Fin shoe

In order to design the desired structural system, a hinged connections at ground level and at the existing masonry is needed. Hereby should the rigidity be researched of this connection to avoid unexpected stresses in the total system. Since these elements are unique due to the project desired dimensions, see Figure 8.18, it is possible to leave out the drilled holes for this element and ensure sufficient rotational capacity in the steel shoe in order to allow for a hinged connection. Potential designs are shown in 8.9.

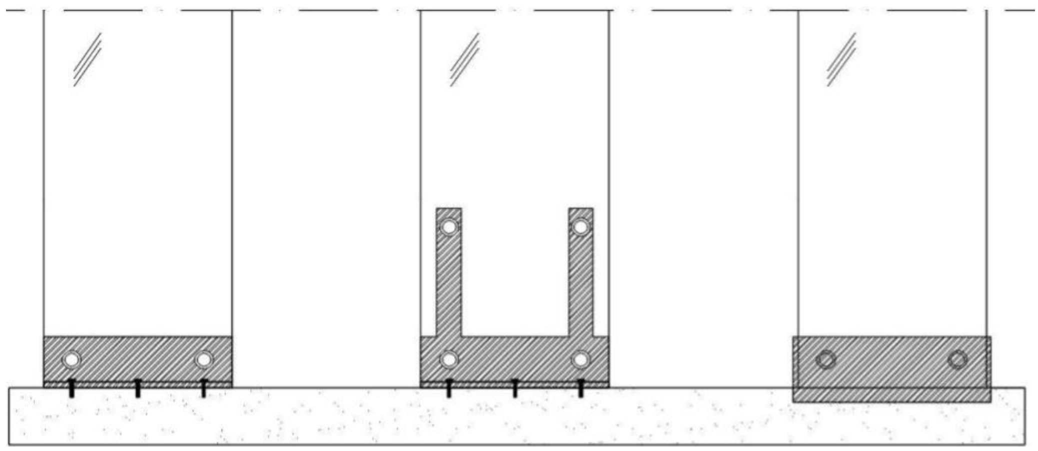


Figure 8.9: An impression of rigid shoe alternatives. It is best to use the four glass holes with a bolt. From structural alternatives, a rigid or hinged alternative should be deigned. Scale 1:20.

8.2.4. Fin-facade/roof connection

Because of all the extra required processing and risk some connections are accompanied with it is chosen to take the clamped connection as main fin-facade connection. It can be integrated easily with the already present fin-fin connections.

In the current design, it has been chosen to use a structural sealant without any mechanical securing or connection. As indicated in Chapter 4, a structural silicone cannot be applied on a surface priorly used by a structural silicone due to remains of the sealant, which would make reuse of the fins and beams hard. In the redesign, a sealant is needed to make the facade air- and watertight, for which the requirement of a clean surface does not hold up, since it is not necessary to have a load bearing sealant. It is assumed that air- and watertightness can be achieved in a second application with a regular sealant.

For the sake of simplicity, for the facade and roof the same thicknesses are used as the current design given the similarities in spans of those panels.

The clamp can be a four sided clamp or a clamp in the corners. Both are possible to apply and it is a matter of right detailing to make it work. From a reuse perspective, both are good. The point fixing uses less material in the connection itself, but a fixing in the utmost corner of the pane is likely to use more material due to higher stresses and larger deflections. Although thicknesses of the facade panels are also determined by building physics requirements, it is now decided to choose the four point spider clamps.

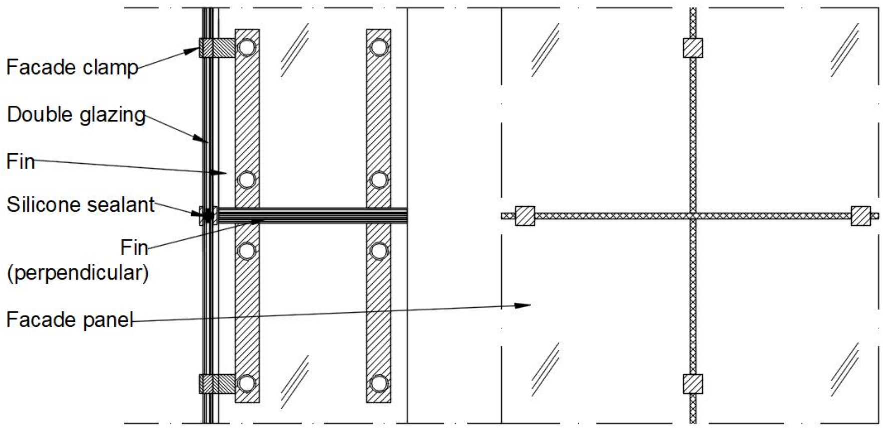


Figure 8.10: Sketch of the four point supported facade detail.

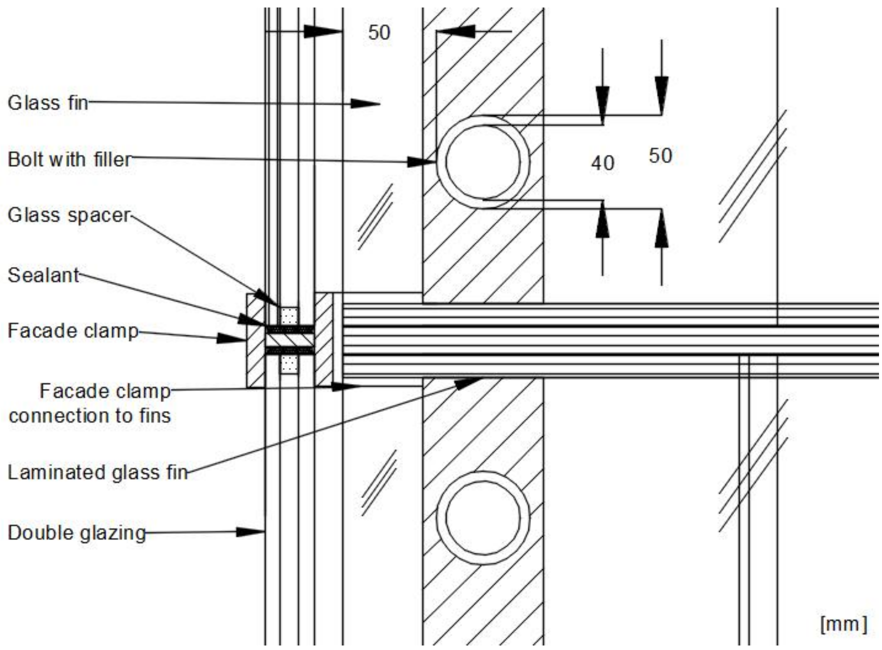


Figure 8.11: Detail of fin-facade connection. Scale 1:4.

8.3. Design

8.3.1. Overview

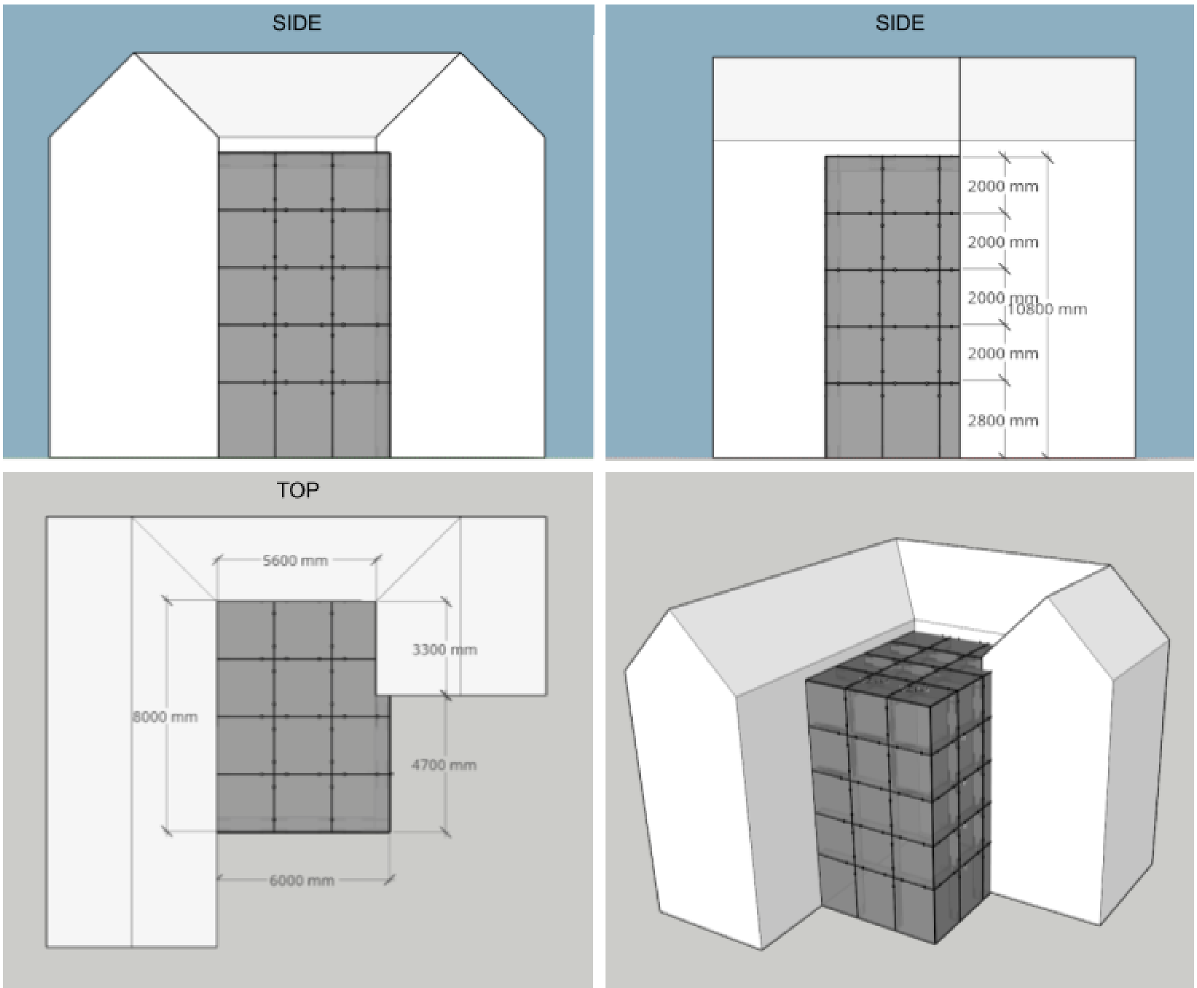


Figure 8.12: An overview of the redesign. Similarities with the current design can be found.

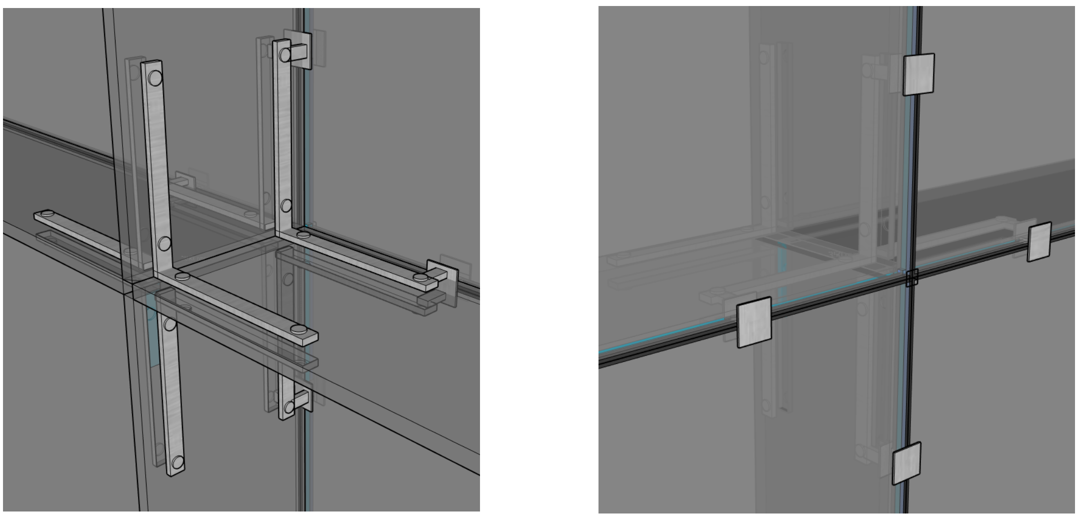


Figure 8.13: An impression of a four point spider facade clamp integrated with perpendicular connections

8.3.2. Calculations

With regard to the calculations many assumptions have been made. The calculations and load bearing conditions itself can be found in Appendix I. Where necessary calculations are elaborated in this section. Assumptions are listed per subject.

Main load bearing structure

- The frame with the long span is governing over the frame facing the short span, see Figure 8.14.

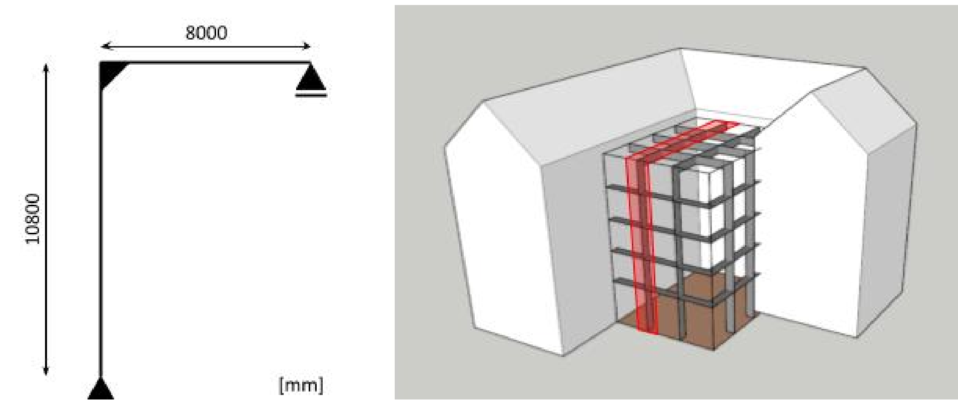


Figure 8.14: The governing frame.

- Since the perpendicular fins are connected rigidly, a load on the facade spreads in four directions. In order to cope with this effect, more extensive calculations should be done. Now a factor depending on the ratio of the rectangular surface is considered to cope with this load spread. First, all forces on the surface around the fin are assumed to be taken by the fin, then the force, moment or shear force, is multiplied by this factor. The factor is $\frac{h}{h+b} = \frac{10.8}{10.8+6.0} = 0.64$. This is also shown in Figure 8.15.

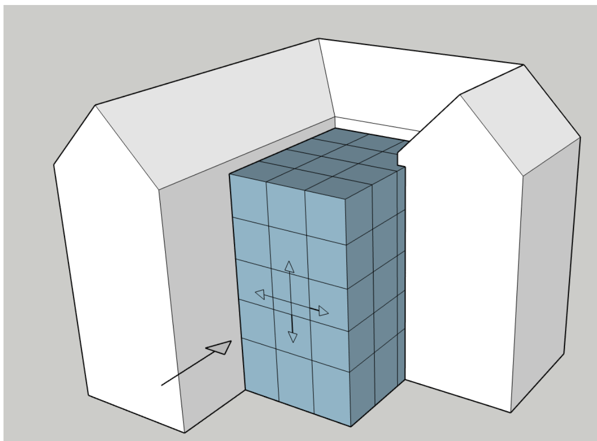


Figure 8.15: Since the moment rigid frame makes a stiff grid, the force distribution is not equal to all four sides, but dependent on the geometry.

- A structural optimization has been partly conducted to the loads specific for Kasteel Ruurlo due to limitations of this research. Only the governing moments (hogging and sagging bending moment) are accounted for. The optimization has been done for both snow and wind load and since these are accompanied with a time dependent structural capacity, a different capacity in the glass is used in these cases. For a glass module in wind load, $f_{m,tu,d} = 36.7N/mm^2$, and for a snow load this is $f_{m,tu,d} = 25.4N/mm^2$. See Appendix J or the Eurocode for more information.

Module

- The method by [38] is used to calculate the peak stresses in the glass near the holes. For a better calculation, more advanced calculations are recommended.
- A filler should be used in between the glass and bolt. POM-C is proposed because of its mechanical strength, but POM-C is not ideal in terms of tolerances. A different interlayer could be used, like Hilti HY-270.

The maximum governing moment can be found in the frame in the case of a wind load. The maximum moment is derived without supports of perpendicular fins and is $21.8 kNm$. Also the situation with a broken panel is considered, but is not governing. Including the factor, the moment capacity of a single module is $14.0 kNm$.

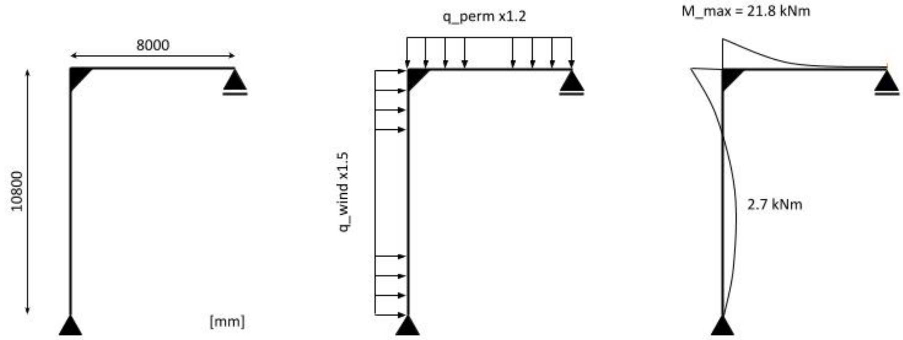


Figure 8.16: The governing loading situation.

Buckling

Buckling is checked by using [153] . Since horizontal glass fins are used as buckling supports, buckling is not expected. The maximum shear force is used as load to check for buckling.

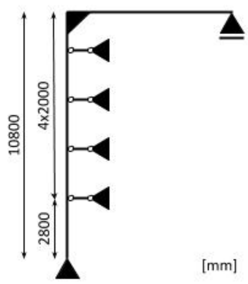


Figure 8.17: Buckling supports along the facade fin due to the perpendicular fins. The governing situation is the situation with the longest unsupported part (2.8 m). Buckling support against lateral torsional buckling in the roof beam are not shown.

Stability

Stability is ensured by the frame.

After life application

A modular system with standardized connections indicates that in a different (after life) application, a different facade, roof or other structure can be made. The modules in this calculation do not allow for this new application. In order to allow for a different application than the application at “Kasteel Ruurlo” clearly some boundaries and guidelines are needed, if not a new check by an engineering company.

8.4. Comparison

8.4.1. Cost of reuse

Environmental impact

The focus of this redesign has reuse in the afterlife phase as the main goal. This potential has been maximised by using similar demountable connections, repetitive modules and by using materials which are less likely to deteriorate over time. Bolted galvanised steel strips are used as a frame connection and clamped connections are used for the roof and facade. Although the design may from an architectural point of view look slightly different, still similarities can be found in the design. These were partly inevitable.

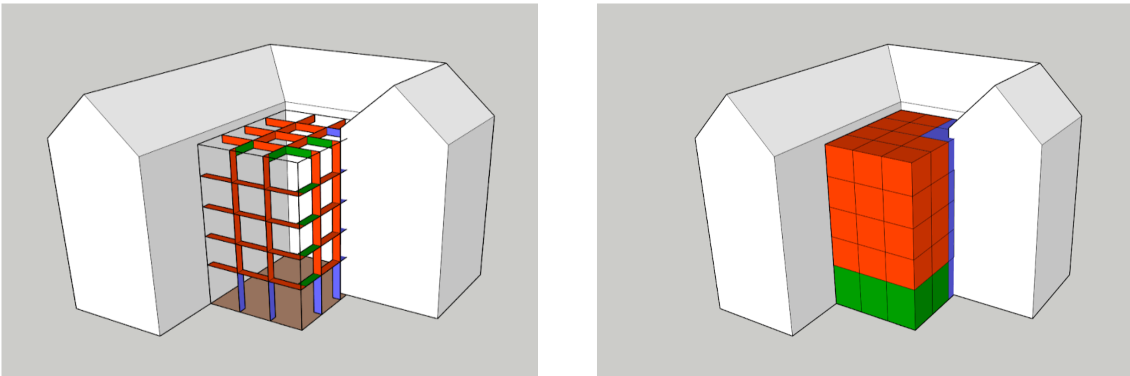


Figure 8.18: Repetition in the new design.
In red: modules with the same size In green: modules with little repetition, as for example the lowest facade panels or the fins at the very top. In blue: modules which know very little or no repetition due to the unique application.

It is now interesting to compare the original design and the newly proposed design in terms of shadow costs in order to get an idea of what the additional environmental effort is in order to allow for reuse in this design. An important note is that of course plenty of other connections, assumptions and designs are possible for a reusable glass extension and that thereby the outcome of this comparison is not governing for those designs. Also please note that this is an estimation and that the proposed reusable system is limited in optimization and that this could highly influence these shadow costs!

Since the facade and roof have the same panel thicknesses, these are left out of the comparison.

Table 8.2: An estimation of the environmental impact of the current design. Note that this remains an estimation and that the facade and interlayer material not have been implemented in the comparison.

	Description	Amount	Mass [kg]	Shadow costs[1] [€]
Facade fins	10-15-10 x 400 mm	64.8 m	2268	
	8-8-8 x 400 mm	22 m	528	
Roof fins	10-15-10 x 400 mm	35.6 m	1246	
Total			4042	550
Connection	UV-Adhesive	8 x 0.33 kg	2.64	1
	RVS	10 x 0.5 kg	5	29
	Filler	10 x 0.2 kg	2	1
Total				581

[1]: Shadow costs in cradle-to-grave, 11 impact categories are usedin the derivation.

Table 8.3: An estimation of the environmental impact of the redesign. Note that this remains an estimation and that the facade and interlayer material not have been implemented in the comparison.

	Description	Amount	Mass [kg]	Shadow costs[1] [€]
Facade fins	12-15-12 x 500 mm	43.2 m	2106	
	12-15-12 x 500 mm	44 m	2145	
Roof fins	12-15-12 x 500 mm	34.6 m	1686	
Total			5937	807
Connection	Perpendicular[2]	22 x 20 kg	440	78
	Frame[3]	8 x 10 kg	80	14
	Aluminium clamp	54 x 0.27	15	13
Total				912

[1]: Shadow costs in cradle-to-grave, 11 impact categories are usedin the derivation.
[2]: 16 steel strips per perpendicular fin-fin connection.
[3]: 8 steel strips per moment rigid fin-fin frame connection

Interesting to see is that due to the amount of steel in the connections and the larger fins the shadow costs rise massively. This has to do with the choice of a moment rigid connection which leads to additional material use of both steel and glass. Although this remains an estimation, it can be carefully concluded that in order to be also in shadow costs more beneficial than the current design, a second application (or doubling of the lifetime) should be assured.

Aesthetics

In terms of aesthetics, the current design is the result of a development which leads to what architects strive for: minimalizing the design and transparency. But, in order to allow for reuse with current possibilities, the aesthetics will be affected due to the demountable connections and can be considered to be a step back. Larger fins and less transparency are the result of using a demountable and modular system. The proposed redesign for sure comes with an extra architectural cost next to an already increased environmental footprint.

Design freedom

Additionally, the design freedom has been taken away from architects by introducing a certain amount of standardization. Clearly, different dimensions could have been chosen in this redesign and thereby allowing for more size deviation, but the initial goal was to have as few different sizes as possible. On that condition, the redesign is successful, but in order to scale up this system towards different applications, design freedom should be better prioritized. This can partly be compromised by introducing more standardized dimensions and connectivity. It is recommended to research standardization and design freedom in this form.

8.4.2. Others

Constructability

Given the changes made, the constructability is improved due to the more modular system that has been implemented combined with the demountable connections.

Maintenance

If replacement is necessary, this can be easier done due to its demountable connections, although the accessibility for example is not improved. Overall can be concluded that the demounability does improve maintenance possibilities, but still replacement of a panel is a lot of work. Also cleaning is not made easier with all demountable connections.

Project specifics

In the redesign, deviations of the modules are clearly as much as possible prevented but due to the unique project with old existing masonry, most of the beams, fins and panels which are bordering the masonry will be unique in a way. It is up to the designer to make as few deviations in size as possible.

Lifetime

An IGU does not improve the overall lifetime of the glass extension, but since due to the demountable connections IGUs are easier replaced, the potential of a longer lasting glass structure is created. The only requirement is that the glass fins will have to last long and time will tell whether this interlayer does delaminate since no literature can confirm a long (50+ years) lifetime.

Costs

No estimation of the difference in cost is done, but the redesign is expected to be more expensive than the current design. Reasons for this are that more glass is used (the fins have become bigger in size and more fins are applied), metal connections are used, holes have to be drilled in the glass and SentryGlas is used. The only cost limiting measure is the amount of repetition which is introduced.

Safety

In terms of safety, no concessions have been made.

V

FINAL REMARKS

9 Conclusions

The objective of this research was: "by researching the influence of connections on the sustainable performance of glass structures, one can advise a client in the (conceptual) design stage on the connections to apply to achieve a sustainable design".

Throughout this research, the sub-research questions have been answered and elaborate conclusions have been given in Chapter 3 and Chapter 7. To conclude this research, the hypothesis is tested and the main research question is answered. Conclusions of Chapter 3 and Chapter 7 are partly repeated in order to answer the main research question. For more elaborate conclusions there is referred to these chapters.

9.1. Hypothesis

The hypothesis is: "the sustainability of structural glass structures is mainly determined by the connections". The hypothesis is partly true. In terms of environmental impact, the connection influences both the direct (shadow costs) and indirect environmental impact (the extra use of material due to the connection). An adhesive connection clearly makes a positive difference compared to mechanical connections, both in direct environmental impact as in indirect environmental impact. Also, the choice for mechanical connections makes demountable connections possible and are a key in reusability to allow for a circular design. However, the hypothesis is partly incorrect since the limitations for a reusable design are not set by the connections: leakage of an IGU and delamination of interlayers are the main problems and are in general not related to the connections.

9.2. Research question

The main research question of this research is "what is the influence of connections on the sustainable performance of glass structures?". In line with the tested hypothesis, the following answer is given to the main research question. The answer is split up in three parts related to the definition of sustainability in design: to allow for future cycles, by conservation of materials and to extend cycles. Where the first two definitions pose the biggest impact, the latter one is of minor importance. Additionally, a small reflection is given about sustainability in glass structures.

Allow for future cycles

To allow for future cycles, reuse and recycling have been discussed as possible methods, whereby reuse makes a bigger sustainable impact than recycling. It is concluded that recycling barely happens (5-10 % in the Netherlands) mainly due to contamination and that the rest is mainly downcycled to container glass or to glass fibres. Contamination can partly be avoided in design, but is in the end out of control of the designer. Additionally, three large glass manufactures do not use a significant amount of flat glass cullet in the production of new float glass. Even though recycling is better than downcycling, environmental benefits are made in other industries, which is good.

To make a large sustainable impact, reuse should be prioritized in design. In order to do so, principles of design for disassembly should be integrated in design. Hereby is the role of a connection inevitable and should allow for demountability which is allowed for by using mechanical connections. Recycling is improved when demountability is integrated, since the structure then is easier to take apart. In order to allow for future reuse, various (technical) barriers should be overcome, in which performance and quality, standardization and robustness are the most important aspects and conclusions with regard to these are listed:

- Performance and quality
  - Performance and quality is related to durability (extend cycles) and is essential for reuse. Current applications in glass lack performance and quality due to a limited technical lifetime: IGUs will loose their insulating performance due to failure of the edge sealant after 20-25 years and laminated glass is prone to delamination over time. Laminated glass only has a guaranteed technical lifetime of 5 years in which a limited edge lamination is already allowed for. These essential elements in glass structures do not allow for a long technical lifetime.
  - Glass and connections have a limited influence on the technical lifetime. Embedded connections or glass piercing connections do pose a higher risk to leaking and delamination and are recommended to avoid.
  - IGUs are not suitable for reuse
  - When laminated glass is properly manufactured and quality materials as Trofisol or SentryGlas are used, reuse is more likely to happen since no delamination issues are known when these interlayers are used. However, it is not proven that delamination will not happen.
  - Currently there are no set requirements and performance to IGUs and laminated glass. Therefore can be concluded that in order to make reuse likely, there is a need for legislation. The main requirement is to increase the technical lifetime of these products. When this is integrated, the use of an LCA is also improved given a minimum known lifetime.
- Standardization
  - In glass design, there is a lack of standardization and often unique projects which makes reuse hard.
  - When standardization is integrated in design, it results in a way in a certain modular design. This is shown in the redesign of "Kasteel Ruurlo", where a proposal is made for a glass fin/beam module which can be applied in the roof and facade. Little size deviation, the use of a single type of connection to connect perpendicular fins, fins to the existing structure and fins in a moment rigid connection in a frame leads to a certain amount of standardization.
  - The result of standardization is less stunning as the current design but can be further developed.
- Robustness
  - Robustness is integrated by using a SentryGlas interlayer, which next to its high quality also additional beneficial structural performances has.
  - Also tempered glass is advised to use, to allow for a certain structural capacity and to avoid problems with nickle sulfide.

It is clear that reuse is not guaranteed from the start of design and that a different strategy is needed in terms of reuse for IGUs and laminated glass. When reuse is possible, the only role of connections is to facilitate demountability. Mechanical connections allow for this and with regard to design for disassembly, tolerances in these connections are important. This research used clamped connections in a facade connection, and a bolted connection for a connection in a (moment rigid) frame in order to allow for reuse. A consequence of using mechanical connections is the increased environmental impact. This is caused by direct higher shadow costs of the connections and the extra needed other materials which is caused by peak stresses by the connection.

Conservation of materials

Although the biggest sustainable impact can be made with reuse, impact can also be made by limiting the environmental footprint in design. Hereby are material minimization and selection important methods. Waste minimization has a minor importance in design, since little waste is present on site and the waste in production is already limited or recycled.

Design plays an important role to limit material use. With regard to material selection, different connections can be selected. Adhesive connections perform better than any mechanical connection in terms of environmental impact. This has been shown in two applications, a connection in a (moment rigid) frame and a facade connection (IGU-IGU-fin/beam connection). Both the direct and indirect environmental impact of the connection itself is lower than any other mechanical connection. This is also confirmed by the connection type of a 2.0 x 2.0 meters panel, where an adhesive resulted in less material use compared to mechanical connections. Another selection can be made with different (quality) interlayers combined with heat treated glass, this could result in less environmental impact (indicated in Figure 3.5).

An important exception is when an adhesive is used and replacement or disassembly is expected (before failure of an IGU or delamination) this will result in a higher environmental impact over time (shadow costs per year) due to replacement of glass since a new structural bond cannot be guaranteed.

Extend cycles

When spoken of to extend cycles, only durability is important as briefly mentioned before. Important processings (IGU and laminated glass e.g.) are likely to encounter durability issues, while the glass itself will in general not encounter durability issues.

Other methods as adaptability, flexibility and maintenance are less important when considering sustainability in the design of glass structures. When design for disassembly is integrated in design, these methods will as a result become of interest since change can be allowed for.

Reflection

Although the design of glass structures is a very small part of the built environment, the goals for the circular economy will also have to be integrated in design of glass structures. This poses difficult challenges as has been shown in this research, but when spoken of sustainability, it also refers to "people" and "prosperity". In line with these two aspects, the elegance of a glass structure and the value in use are also a form of sustainability, which are difficult to measure. The added value of a glass structure to a building should be part of the discussion when speaking of sustainability within glass structures.

10 Discussion

With this research, limitations and possibilities for a sustainable glass design have been presented. The strong relation between architectural and structural aspects comes forward in the connections, which is also related to a circular and sustainable design too. Throughout the report, discussion has been given on many detailed aspects. Therefore, in this chapter, the overall research is discussed. This discussion bases it on the difficulties, dilemmas and assumptions made which can affect the research.

10.1. Results

An interesting finding is that currently barely any flat glass is being recycled, even though lots of float glass is being collected in the Netherlands. This has been reported by the collector of flat glass waste "Vlakglas Recycling Nederland", but also glass manufacturers show no use of used flat glass in the production of new float glass. In the Netherlands some recycling does happen, but most of the waste is being downcycled.

Even though it is important to use demountable connections, this does not automatically mean that glass modules are being reused. This research has shown the lack legislation on the performance and quality of products and standardization. A major dependency in the reuseability of glass products lays in the technical lifetime of products as IGUs and laminated glass, which now are limted. A potential solution is given to use SentryGlas and Trofisol as interlayer since no delamination is reported, but given the few applications one could argue this decision. Besides, other barriers as costs, liability, logistics should also be overcome to allow for reuse and whether an elegant material as glass suits reuse can be argued too.

Further more, in order to increase the reuse potential, a certain amount of standardization is needed. Again, whether standardization and elegance go together can be argued. This has also been discussed in the redesign of "Kasteel Ruurlo". Since no standardization is known, a form of standardization had to be introduced in order to make it reusable, which can be argued on whether this is the solution or not.

Another finding is that adhesives have a smaller environmental footprint than mechanical connections. Here should be argued that most adhesives are made from fossil sources, which is not considered sustainable. Besides, when wrongly applied, adhesives are toxic and could be dangerous to the health of humans and harmful to nature.

10.2. Limitations

The many assumptions and data that has come by also indicates some limitations in the research. Most of these limitations have been substantiated and assumed best, but are open for discussion.

EPD Data

Within the derivation of the environmental impact in shadow costs, lots of data is gathered. Part of this data is incomplete, which made comparison difficult. There has been tried to implement as much as this data to come to these conclusions, but clearly the result is not entirely complete. Use has been made of the method prescribed by the SBK, but various other methods exist. For example, the embodied energy of a material could have been used. Also the environmental impact caused by the manufacturing is not implemented.

Assumptions regarding indirect environmental impact

It is assumed that heat treatment and the type of interlayer have a negative impact on the overall environmental footprint due to the extra or more energy intense processes the materials have to undergo. However, it is clear that these extra added processes also save material in the overall design when compared to regular annealed glass or PVB interlayers and thereby it benefits the environmental footprint. Since it tends to become very project specific and the main focus is on the connections, this is not further researched in this research.

Structural calculations

With regard to the structural capacity of the observed connections, calculations based on literature are done and examples of practice are used. To make the connection as viable as possible based on these calculations, realistic assumptions have been made and a unity check is performed which was close to 1.0. However, given the complexity of the connections, it is not guaranteed that the presented connections are viable in this configuration. A FEM calculation or more advanced calculations would be required for this. For the environmental impact it is believed that these calculations suffice.

Additionally, the comparison of various connections on the material use of glass is quantified of a 2x2 meter facade panel (see Section 6.2. The deflection is not considered and various dimensions could have been adjusted for a further optimization in order to end up with a percentage which indicates the extra material use for a specific connection. In this research, this example just showed that extra glass is needed when applying a mechanical connection, but not by how much.

Also for the facade connections, no calculations are done but example is made from various projects. Also of these projects, not all details were known. Therefore this calculation can be argued, but it is believed that the amount of connections are realistic and support the conclusion that adhesive based connections have a smaller environmental footprint than mechanical connections.

Shadow costs

In terms of shadow costs of the observed connections, estimations are made of the material use when exact data was not available of the product. These could clearly also deviate and weight is an important factor considering shadow costs, so some deviation can be important in the end result.

Case study

With regard to the structural calculations, the same holds for the case study. A more detailed calculation is needed to ensure the possibilities of design, although the presented system is believed to be a good basis. Besides the modules, also the influence of the module on the entire design is interesting, like the total stiffness loss due to the mechanical connections. Also the design of the module itself is from an architectural point of view not yet done. It would be highly interesting to find more elegant solutions.

Demountability

It is believed that mechanical connections are demountable connections, but this is not proven for every type. Especially when fillers are used in bolted connections, the demountability can be argued. In general, it is believed that also fillers can be removed, but practice should find this out for all types.

Optimal design

This research did not find any optimum, which is always of interest to make a decision based on optimum reasons. In line with the objective, the only well-weighted decision that can be made are the reasons to choose or not to choose for a specific connection based on a future reuse potential. The alternative is a design with a low environmental impact. Within a specific case, different alternatives can be researched to improve either environmental impact or reuse, but a generic conclusion or optimum cannot be found.

The reason for not finding an optimum is because the shadow costs of a mechanical connection and adhesive connection differ too much. Besides, the limited technical lifetime and the limited EPD data known of interlayers makes this difficult. An optimum for laminated glass can be calculated once the environmental impact of SentryGlas is known. The expectation is that SentryGlas performs better than PVB, since SentryGlas has a longer technical lifetime.

10.3. Implications

Current design in glass

The current glass designs are not suitable for reuse. Besides, the environmental impact of glass structures is relatively high when compared to alternatives. Also from an energy efficiency point of view, glass is not desired since it either requires cooling or heating due to limited insulation. disadvantages, glass applications can be doubted. However, the opinion of the author is to not do that, but to find a way to make it work in the circular economy. First directions are given in this research and limitations are given.

Circular economy

Obviously, to make glass work in the circular economy, there are plenty of challenges ahead of which a few are listed here. These are also recommended for future research and are in full discussed in Chapter 11.

- Will reuse focus on the entire structure, or rather on component level? How can this be realised?
- How to deal with aesthetics considering reuse? And, how to deal with standardization and freedom in design? Without overcoming these barriers, reuse is unlikely from an architectural point of view.
- Glass is associated with luxury and prestige, which might pose problems since a "secondhand, reused item" is not luxurious. How to deal with this is an interesting question.
- Glass may be a structurally durable material, but when glass has the slightest stains, decolouring, or another form of damage, it might still end up being recycled.
- Besides technical issues, other issues should not be forgotten about, since costs are of high importance.

11

Recommendations

In this chapter, recommendations for future research are formulated.

- A structural sealant (for example in "Co Creation Centre") can clearly not be demounted and constructed again. However, the silicone can be cut loose and a new structural silicone can be applied. However, in this second application, a structural bond cannot be guaranteed due to the contaminated glass surface the silicone has to bond to. Since the structural sealant has a low direct and indirect environmental impact compared to mechanical connections, it is highly interesting to research how to ensure a new bond of a structural sealant to a contaminated glass surface and how this is done in an economical way. Formulated in a more generic way, it is intereting to research demountable connections that also have a low environmental impact.
- In order to have a complete comparison of all connections in terms of environmental impact, it is recommended to study the materials which lack EPD data. This involves interlayers, adhesives and metals. This benefits to the comparison, but also when in design is aimed to limit the environmental footprint, this data is necessary.
- In line with the previous recommendation, a comparison of different interlayers and types of heat treatment of glass in terms of environmental is recommended to perform too. When focus is on limiting the environmental impact in design, the impact of different interlayers and treatment should be researched since the relation between saving material (due to the improved structural characteristics) and increasing the environmental footprint (due to more energy intense materials) is unknown.
- As mentioned throughout the report, SentryGlas and Trofisol are high quality interlayers but are not proven to not delaminate over time. In order to see whether this is correct or not, delamination is advised to research to be able to guarantee a long technical lifetime. When SentryGlas or Trofisol are also likely to delaminate over time, clearly an alternative interlayer should be found which suits the requirements for a long technical lifetime.
- Although mechanical connections seem to be demountable, it is interesting to know how demountable these connections actually are in practice. Although it is a practical issue, it is necessary to test and review this, given the need for actual demountability of a modular design. Without an easy demountable connection, reuse will not take place.
- The development of a standardized system is necessary in order to reuse glass elements. A proposal for reusable components has been given in Chapter 8 but it is recommended to further research and develop this solution, or to find a different solution based on for example already presented alternatives. Important technical barriers are among others the technical lifetime of the element, its interchangebility, structural limitations in a (new) design and practicalities. It would be highly interesting to develop this solution towards a more elegant solution. In this development, the aspect of design freedom should be discussed too, since that is limited by the proposed solution.
- With regard to the technical lifetime of connections, it is assumed that connections are in general not governing in this research. When the interlayers have a guaranteed minimum technical lifetime, this clearly is also necessary to have for the connections and it is recommended to further research this.
- In this research it is addressed that there is a need for legislation for laminated glass and IGUs in order

to cope with the requirements set by the circular economy. This involves a certain quality and performance as for example a minimum technical lifetime of IGUs and laminated glass. It is recommended to research and formulate these requirements. When legislation based on these requirements is set, it should also be possible to check if the desired quality is met of the product, so it is recommended to develop such a check too.

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VI

APPENDICES

A

Technical lifespan of materials and end-of-life scenario

Technical lifespan of specific materials in glass structures						End-of-life use when reuse is not possible				
material	**sort**	**Guaranteed by industry**	**NMD**	**Other**	**comment**	**Landfill**	**Incineration**	**Recycling**	**Source**	**Productode NDM**
Acrylic	Adhesive, Acrylic		75	not governing		0.00	1.00	0.00	NMD	21.04.001
UV adhesive	Adhesive, Acrylic UV			not governing	Bohle & Delo not ETAG certified	0.00	1.00	0.00	Assumed based on similar applications	
Epoxy	Adhesive, Epoxy			not governing		0.00	1.00	0.00	Assumed based on similar applications	
PU	Adhesive, PU			not governing	According to DowCorning, PU will last shorter than silcicone	0.00	1.00	0.00	Assumed based on similar applications	
Silicone	Adhesive, Silicone	5		25	Research shows a 25+ year lifetime. Can degrade over time, qualitity of product and assembly is important. ETAG assumes 25 year	0.20	0.80	0.00	From NMD, DowCorning has (in the near future) a program for recycling of silicone	42.02.004
Glass	Glass			not governing		0.30	0.00	0.70	NMD	31.07.001
Aluminium	Metal		75	not governing		0.03	0.03	0.94	NMD	21.03.010
Titanium	Metal		75	not governing		0.00	0.00	1.00	Assumed based on similar applications	
Stainless steel	Metal		75	not governing		0.00	0.00	1.00	Assumed, but NMD says 0.0 recycling	45.03.010
Steel	Metal		75	not governing		0.01	0.00	0.87	NMD says 0.01, 0, 0.87	22.02.001
EPDM	Other		20		20-50, Can degrade over time, qualitity of product and assembly is important	0.20	0.80	0.00	NMD	34.01.011
Hilti HY 270	Other			not governing	ETA-13/1036	0.00	1.00	0.00	Assumed	
Neopreen	Other			not governing		0.00	1.00	0.00	Assumed, such a small element which will not be recovered	
POM-C	Other			not governing	Can degrade over time, qualitity of product and assembly is important	0.20	0.80	0.00	Assumed	

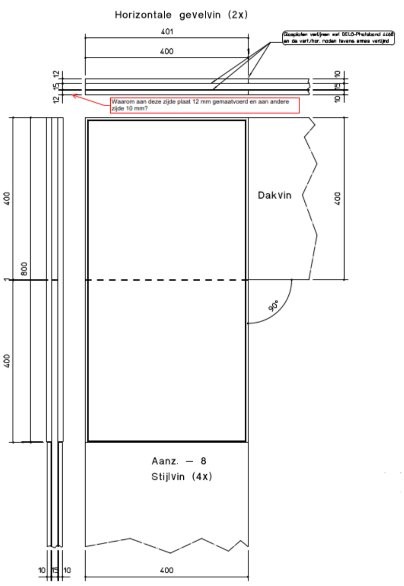
B

Connections in practice

In this appendix, relevant details of "Kasteel Ruurlo", "Co Creation Centre" and the "18 Septemberplein" are given. All projects know very different connections and these drawings are to support the main chapters.

Source: all detailed drawings are by ABT b.v..

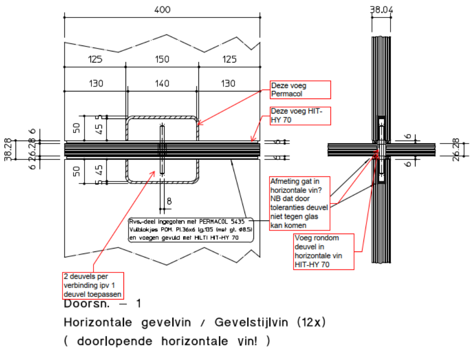
B.1. "Kasteel Ruurlo"



(a) A rigid corner connection. $A = 400 * 400mm2 = 160000mm2$, t $0.1mm$

(b) At every corner, an overlap joint has been applied, which connects the fins and beams. Also in the facade this connection is applied horizontally. Use is made of "Delo-Photobond 4468", which is a UV-curing adhesive. Photo by [64].

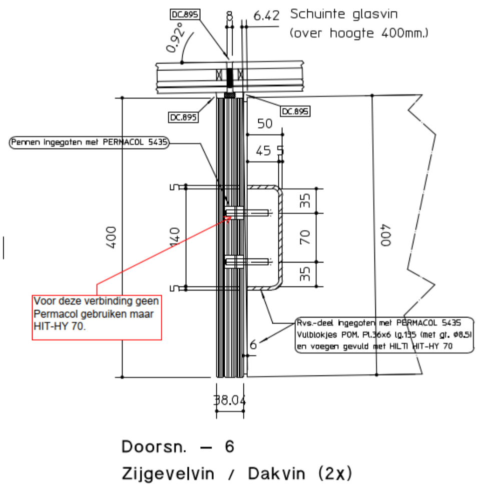
Figure B.1: Detail of the corner connection.



(a) A stainless-steel element is embedded in the glass fins and is covered on both sides with another glass panel. To connect the glass to the element, use is made of Percamol 5435, a 2 component PU-adhesive which serves as interlayer between the glass and glass and allows for some tolerances. The remaining gap is filled up with Hilti-HY 70, a mortar (Hybrid Urethane Methacrylate). 6x6x400 mm3 (4x)

(b) At every crossing of a beam and fin in the facade, an embedded connection is applied. Photo by [64].

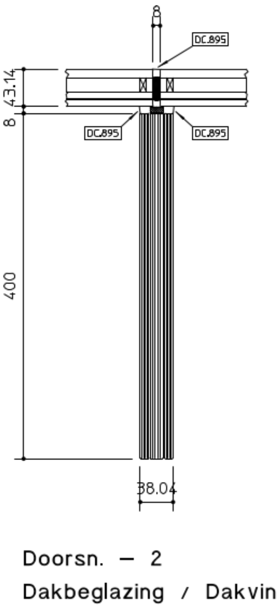
Figure B.2: Detail of the embedded connection.



(a) similar embedded connection, only here it is used at a T-section

(b) Detail of embedded connection. Photo by [64].

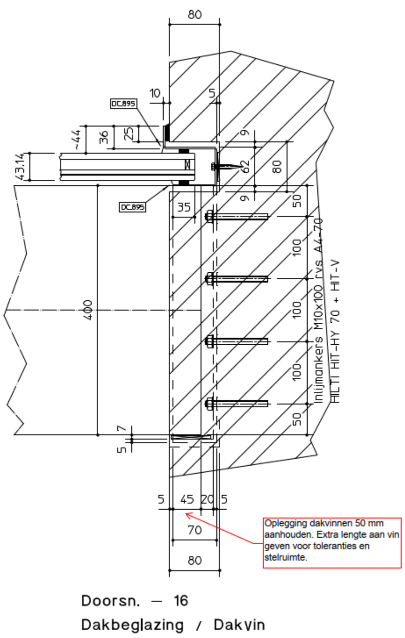
Figure B.3: Detail of the connection at a T-section.



(a) Connection glass beam/fin to the roof. This is done with DC895, a black 2 component silicone adhesive.

(b) Detail of fin to facade and roof connection.Photo by [64].

Figure B.4: Detail of the fin-roof connection. The fin-facade connection is similar.



(a) Horizontal connection embedded in the existing masonry.

(b) Detail of shoe connection. Photo by [64].

Figure B.5: Detail of the fin connection with the existing masonry.

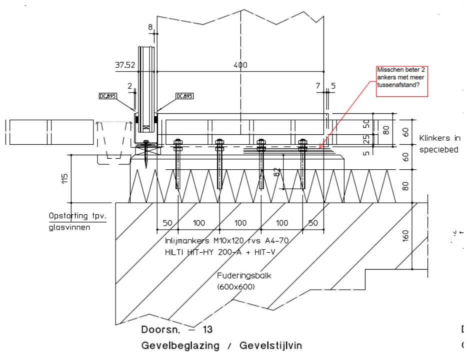
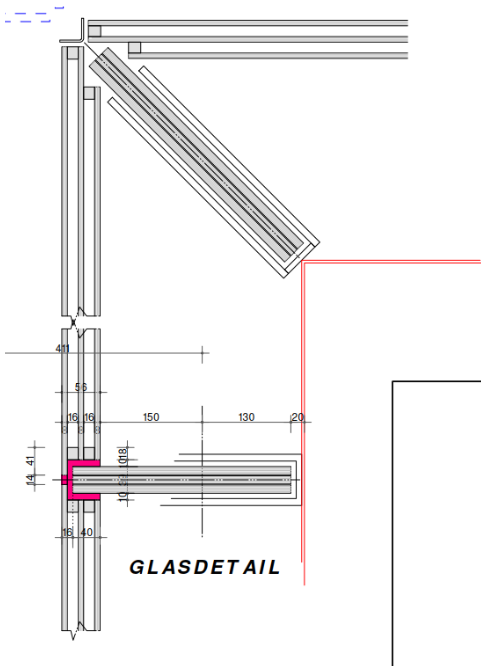


Figure B.6: Base connection of the fin.

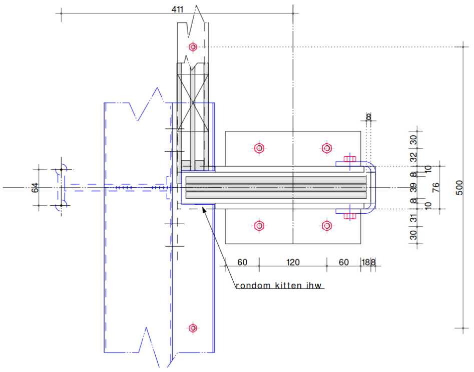
B.2. "Co Creation Centre"



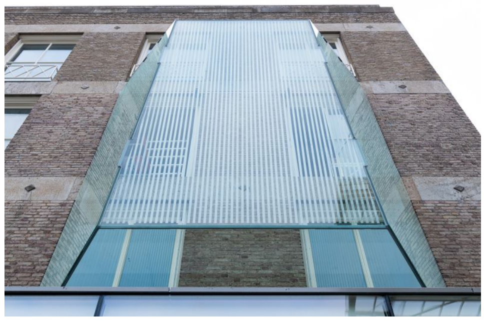
(a) Fin-facade connection with a structural sealant. (pink)

(b) Connection in practice. Photo by [32].

Figure B.7: Fin-facade connection with a 2 component structural silicone sealant.



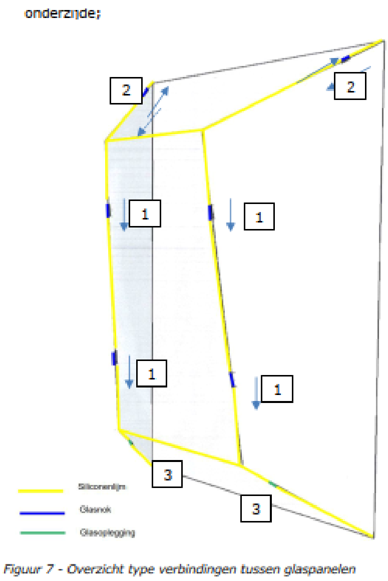
(a) Top view.



(b) Side view.

Figure B.8: Detail of the base connection of the fin.

B.3. "18 Septemberplein"



(a) Top view.

(b)

Figure B.9: DC993 is applied in the edges (yellow).

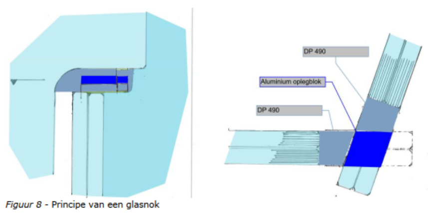


Figure B.10: Epoxy 3M DP490 is applied in the corners.

C
Loading situation

C.1. Loading situation

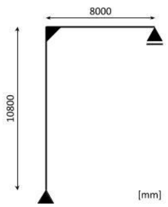
The loading situation for the connection deign is given. The governing moment is derived by the use of "forget-me-nots", and the following formula is the result:

$M_{d,corner} = M_{d,hogging} = 3/24 \times q_{wind,facade} \times h^3/(h + l_{roof}) + 3/24 \times q_{perm} \times l_{roof}^3/(h + l_{roof}))$

The shear force V_d is derived from equilibrium.

A final note is made to the governing situations. This calculation is already quite simplified due to the limited input of loads and combinations, but since the most essential loads are used in this calculation an order of magnitude of all moments can be found, which is the goal of this practice. In order to use the highest order of loads, the maximum bending moments have been used which occur in different load combinations. For example, $M_{d,corner} = 15.6kNm$ occurs in the wind situation of the facade, and the $V_d = 10.09kN$ occurs in the situation with permanent load and snow load combined.

Thickness			equivalent		
tp1	10	mm	tp1	9.7	mm
tp2	15	mm	tp2	14.5	mm
tp3	10	mm	tp3	9.7	mm
t_tot	35	mm	t_tot	33.9	mm



ULS (with a broken panel)						Governing frame		
tp1	9.7	mm	h_fin	400	mm	h fin	10.8	m
tp2	14.5	mm	width_to_fin	1.425	m	l dak beam	8.3	m
tp3	0	mm	t_roof_tot	26	mm			
t_tot	24.2	mm						

NOTE: The intermediate supports are removed in order to derive the maximum occuring situation

Roof beam

Permanent						**Safety factor**		
Beam	= 2500*0.4*0.035 =				0.35	kN/m		
Roof glazing	= 2500*0.026 =	0.65	kN/m2	x 1.42 m =	0.93	kN/m		
				q,k_permanent	1.28	kN/m	x 1.2 =	1.53 kN/m
							x 0.9 =	1.15 kN/m
Variable								
q,k,snow		0.56	kN/m2	x 1.425 m =	0.80	kN/m	x 1.5 =	1.20 kN/m
q,k,wind		-0.49	kN/m2	x 1.425 m =	-0.70	kN/m	x 1.5 =	-1.05 kN/m
(suction, zone H)								
q,d,snow	= q_permanent + q_snow =			2.07	kN/m			
q,d,wind	= q_permanent + q_wind =			0.58	kN/m			

Loading situations

1	q,d,snow	= q_permanent x 1.2 + q_snow x 1.5 =	2.73	kN/m
2	q,d,wind	= q_permanent x 0.9 + q_wind x 1.5 =	-0.10	kN/m
3	q,d,permanent	= q_permanent x 1.35 =	1.72	kN/m

ULS (broken situation), no safety factors

1	q,d,snow	= q_permanent + q_snow =	2.07	kN/m
2	q,d,wind	= q_permanent + q_wind =	0.58	kN/m

Facade fin

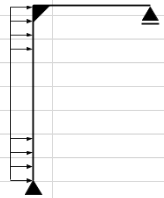
Permanent

Variable

q,k,wind	0.56	kN/m2	x 1.425 m =	0.80	kN/m	
(pressure, zone D)				x 1.5 =	1.20	kN/m

Loading situations

q,d,wind	= q_wind x 1.5 =	1.20	kN/m
q,d,winddruk			



Loading situations

q,d,wind	= q_wind x 1.0 =	0.798	kN/m

Moment and shear force derivation:

Governing situation:

ULS (broken situation)		
Md,hogging	-12.31	kNm
Vd	7.67	kN

Regular

1	Ved	10.09	kN	Md,hogging	-10.21	kNm	Md,bending	13.29	kNm
2	Ved	-0.37	kN	Md,hogging	0.38	kNm	Md,bending	-0.49	kNm
3	Ved	6.37	kN	Md,hogging	-6.45	kNm	Md,bending	8.39	kNm

Broken

1	Ved	7.67	kN	Md,hogging	-7.76	kNm	Md,bending	10.10	kNm
2	Ved	2.14	kN	Md,hogging	-2.16	kNm	Md,bending	2.81	kNm

Wind governing		
Md,corner	-15.60	kNm
Vd	10.09	kN

Regular

Md,hogging	-15.60	kNm
Md,bending,roof	-2.41	kNm
Md,bending,faca	1.85	kNm

Broken

Md,hogging	-12.31	kNm
Md,bending,roof	0.88	kNm
Md,bending,faca	5.14	kNm

D

Design frame connections

In this appendix, the environmental footprint of different connections is derived. In order to do so, the connections are loaded by the loads presented in C and depending on the configuration of the connection, the connections are compared.

The loading condition for these connections is: Med = 15.6 kNm and Ved = 12.31 kN.

D.1. UV-curing adhesive

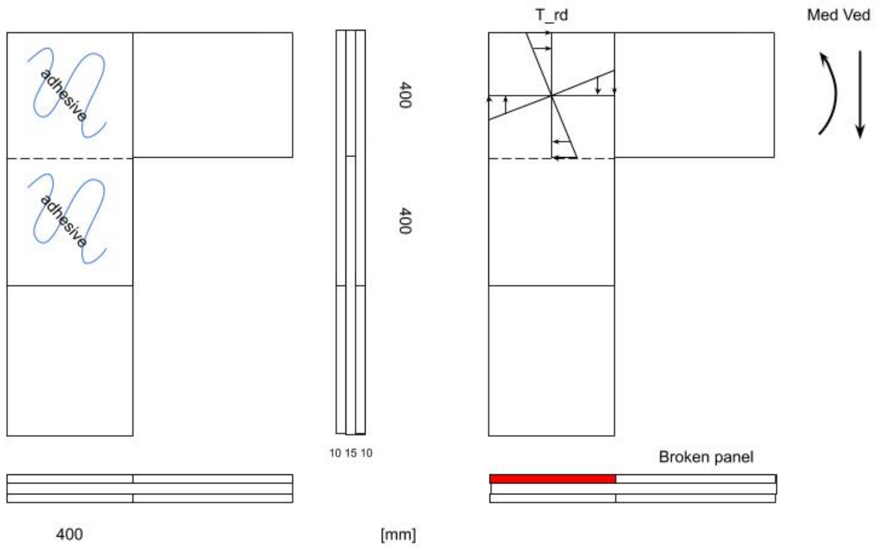


Figure D.1: Sketch of the UV-curing adhesive.

$M_{ed} = 15.6kNm$
$V_{ed} = 10.09kN$
$M_{ed,broken} = 12.31kNm$
$V_{ed,broken} = 7.67kN$

Assumptions

- Governing situation: broken panel, which leaves one load bearing area of the adhesive

- Bohle MV-760, UV curing adhesive
- $t_{rd} = 25N/mm^2$
- $p = 1.04g/cm^3$

Calculations

Adhesive

$t_{ed,M} = 4.81Med/b^3 = 0.91N/mm^2$
$t_{ed,V,avg} = V/(b*h) = 0.06N/mm^2$
$t_{max} = t_{ed,M} + t_{ed,V,avg} = 0.97N/mm^2 << 25N/mm^2$

Large overcapacity of this connection. Since a smaller connection is not realistic, this dimension is kept.

Material use

4 contact area, 400x400 mm, t = 0.5 mm

adhesive: 333 g

D.2. Connection bolted, rigid

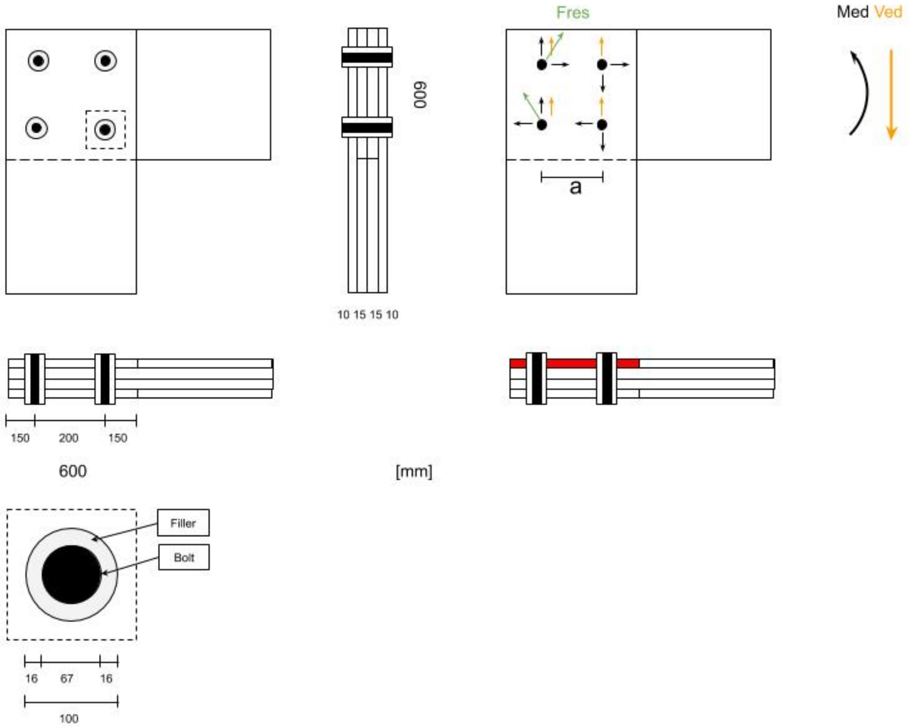


Figure D.2: Sketch of the bolted rigid connection.

$M_{ed} = 15.6kNm$
$V_{ed} = 10.09kN$
$M_{ed,broken} = 12.31kNm$
$V_{ed,broken} = 7.67kN$

Assumptions

- Governing situation: broken panel, which leaves one load bearing area
- Filler is Hilti HY 70; a frequently applied filler
  - $\sigma_{rd} = 31 N/mm^2$
  - $p = 1.66 g/cm^3$
- For thermally toughened glass, the distance between the hole and edge should be at least 2.0 times the diameter of the borehole [154].

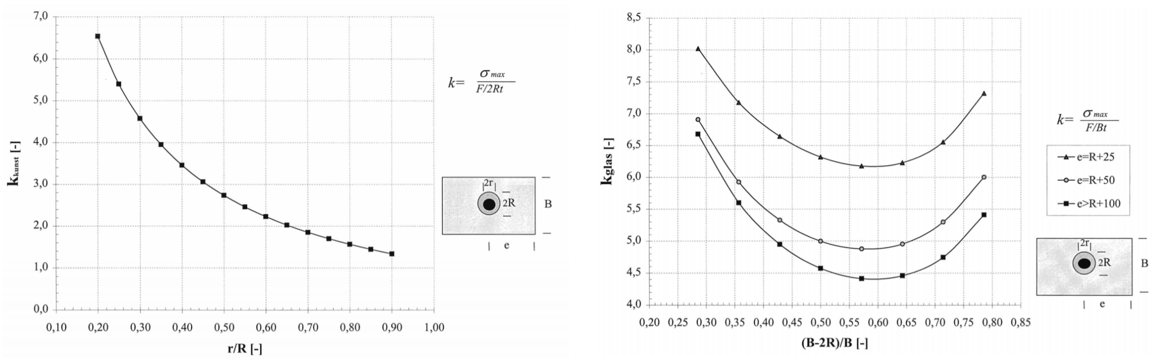
Calculations

$F_{hole,M} = M_{ed}/(4 * a)/2 = 15.7kN$

$F_{hole,M,ver} = F_{hole,M,hot} = 11.14kN$ (black arrows)
$F_{res,gov} = \sqrt{}((F_{hole,V} + F_{hol,M,ver})^2 + F^2_{hole,M,hor}) = 17.6kN$ (broken situation $F_{res,gov} = 13.9kN$)

With the method of [38], stresses in the glass can be calculated by considering a factor k_{glas} or k_{kunst} over the theoretical stresses, this is due to peak stresses.

$2r = 70mm$ (diameter bolt)
$2R = 80mm$
$B = 300mm$
$(B - 2R)/B = 0.73$
$e = 200mm; e >= R + 100 = 125mm$
$r/R = 67/100 = 0.88$
$k_{glas} = 6.0$
$k_{filler} = k_{kunst} = 1.3$



(a) (b)

Figure D.3: Relations to derive the stresses in the glass and the filler. [38]

$t_1, t_4 = 10mm$, due to deviations according to Eurocode, $t_{1,eq}, t_{4,eq} = 9.7mm$ (thickness glass)
$t_2, t_3 = 15mm$, due to deviations according to Eurocode, $t_{1,eq}, t_{4,eq} = 14.5mm$ (thickness glass)

one broken glass panel assumed, so all bolt forces will be transferred via 1 panel, t_4. t_4 is governing since this is the thinnest panel.

Regular situation

From [38] method:
$\sigma_{glass,max} = k_{glass} * F_{res,gov}/(t_{4,eq} * B) = 6.0 * 17.6/(14.5 * 300) = 24.32N/mm^2$
$\sigma_{glass,max} = 24.32N/mm^2 < 36.7N/mm^2$; see Appendix J

$\sigma_{filler,max} = k_{filler} * F_{res,gov}/(t_{4,eq} * 2R) = 1.3 * 17.6/(14.5 * 80) = 19.76N/mm^2$
$\sigma_{filler,max} = 19.76N/mm^2 < 31N/mm^2$

Broken situation

$\sigma_{glass,max} = 28.57 N/mm^2 < 36.7 N/mm^2$; see Appendix J

$\sigma_{filler,max} = 23.22 N/mm^2 < 31 N/mm^2$

Material use

- Filler: 0.47 kg
- Bolts (stainless steel) total: 13.25 kg
- Glass (extra glass compared to appendix D.1, one extra glass layer and increased dimension): 38.5 kg

D.3. Embedded connections

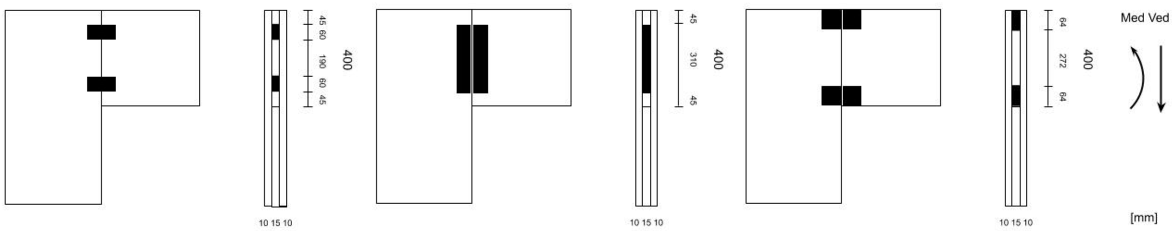


Figure D.4: Sketch of the embedded connections.

$M_{ed} = 15.6 kNm$
$V_{ed} = 10.09 kN$
$M_{ed,broken} = 12.31 kNm$
$V_{ed,broken} = 7.67 kN$

Assumptions

- Research has been performed by [39] on embedded connections. The load at the moment of failure in this experiment is 26.25 kNm. The derived capacity from a FE model is 23.1 kNm. This experiment was done for a beam similar to this beam, except for the height, in the experiment the height was 300 mm, and here 400 mm. It is therefore assumed that this type of connection is possible with a load like this. See Table D.1 for type embedded connection and corresponding load bearing capacity.

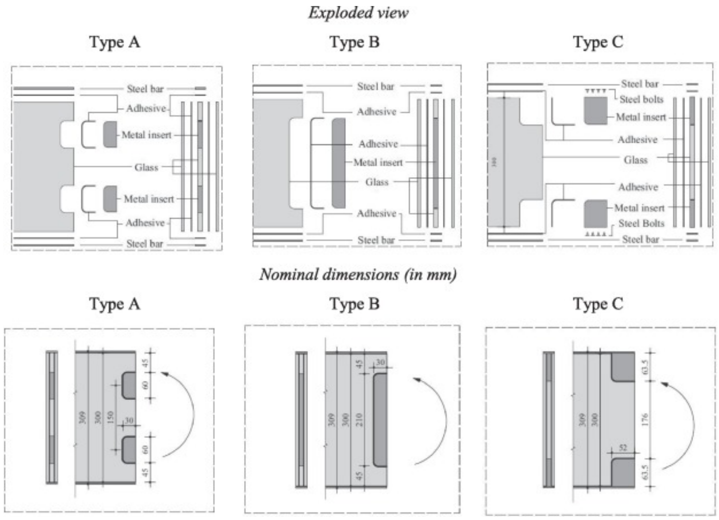


Figure D.5: Embedded connections by [39]

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Table D.1: Derived capacity of the embedded connections in [39]. Both the test result and finite element (FE) capacity are given.

Type connection	Test or FE	Moment at failure [kNm]
A	Test	26.25
	FE	23.1
B	Test	38.55
	FE	35.55
C	Test	66.75
	FE	57.9

- In the research by [39] a beam is researched, and here this type of connection is used in a corner. This can have a negative influence on the load bearing capacity, since stresses are spread less.
- Summarized, only the height is adjusted (as a benefit to the capacity), other dimensions (like of the embedded metal parts) are kept the same size.
- A situation with a broken panel is left out.
- Stainless steel embedded connections
  - $p = 7.9 g/cm^3$

Calculations

More research is needed in order to derive the capacity of this connection.

$M_{ed,h=400mm} = 15.6 kNm < M_{rd,h=300mm} = 23.1 kNm$

Material use

- Type A: 0.85 kg
- Type B: 1.10 kg
- Type C: 1.57 kg

D.4. Connection bolted, hinged

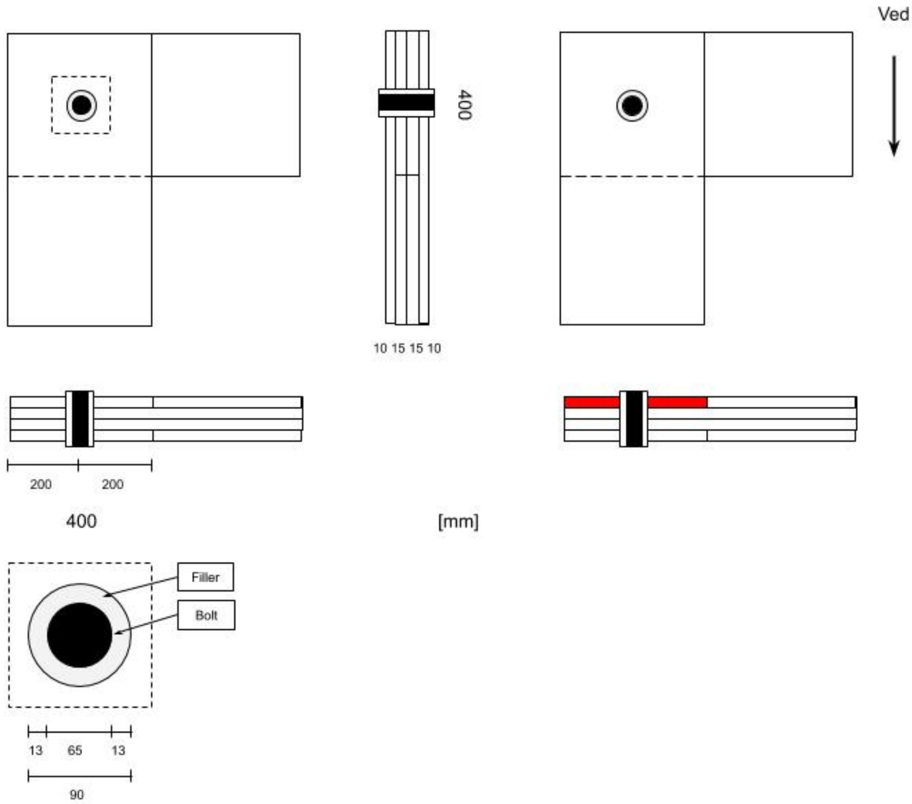


Figure D.6: Sketch of the bolted rigid connection.

$V_{ed} = 10.1kN$ (broken, $V_{ed} = 7.7kN$)

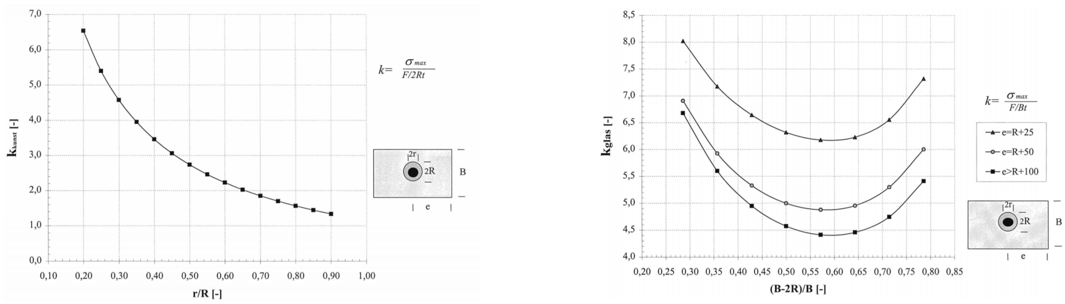
Assumptions

- Governing situation: broken panel, which leaves one load bearing area
- Filler is Hilti HY 70; a frequently applied filler
- $\sigma_{rd} = 31N/mm^2$
- $p = 1.66g/cm^3$
- For thermally toughened glass, the distance between the hole and edge should be at least 2.0 times the diameter of the borehole [154]

Calculations

With the method of [38], stresses in the glass can be calculated by considering a factor k_{glas} or k_{kunst} over the theoretical stresses, this is due to peak stresses.

$2r = 70mm$ (diameter bolt)
$2R = 80mm$
$B = 400mm$
$(B - 2R)/B = 0.82$
$e = 200mm; e >= R + 100 = 135mm$
$r/R = 65/90 = 0.72$
$k_{glas} = 6.0$
$k_{filler} = k_{kunst} = 1.8$



(a) (b)

Figure D.7: Relations to derive the stresses in the glass and the filler. [38]

$t_1, t_4 = 10mm$, due to deviations according to Eurocode, $t_{1,eq}, t_{4,eq} = 9.7mm$ (thickness glass)
$t_2, t_3 = 15mm$, due to deviations according to Eurocode, $t_{1,eq}, t_{4,eq} = 14.5mm$ (thickness glass)

one broken glass panel assumed, so all bolt forces will be transferred via 1 panel, t_4. t_4 is governing since this is the thinnest panel.

Regular situation

From [38] method:
$\sigma_{glass,max} = k_{glass} * F_{res,gov}/(t_{4,eq} * B) = 6.0 * 10.1/(14.5 * 400) = 20.88N/mm^2$
$\sigma_{glass,max} = 16.78N/mm^2 < 36.7N/mm^2$; see Appendix J

$\sigma_{filler,max} = k_{filler} * F_{res,gov}/(t_{4,eq} * 2R) = 1.8 * 10.1/(9.7 * 80) = 23.42N/mm^2$
$\sigma_{filler,max} = 23.42N/mm^2 < 31N/mm^2$

Broken situation

$\sigma_{glass,max} = 23.73 < 36.7N/mm^2$; see Appendix J

$\sigma_{filler,max} = 17.80N/mm^2 < 31N/mm^2$

Material use

- Filler: 0.25 kg
- Bolt (stainless steel): 2.82 kg

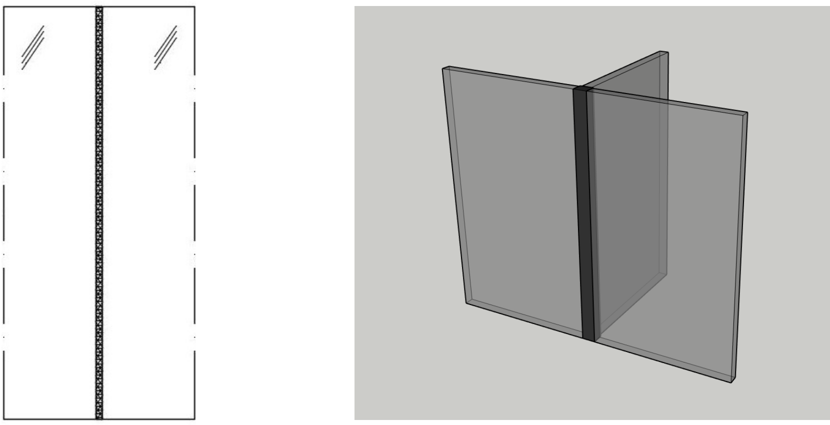
E

Design facade connections

Assumptions for all facade connections:

- Objective is to connect two facade panels and fin with a height of 4000 mm.
- All facades need a sealant in order to ensure an air- and watertight barrier. The structural silicone sealant is an exception. A silicone sealant seam of 30x15 mm is assumed.
- An impression of all facades is shown in Figure 5.6.

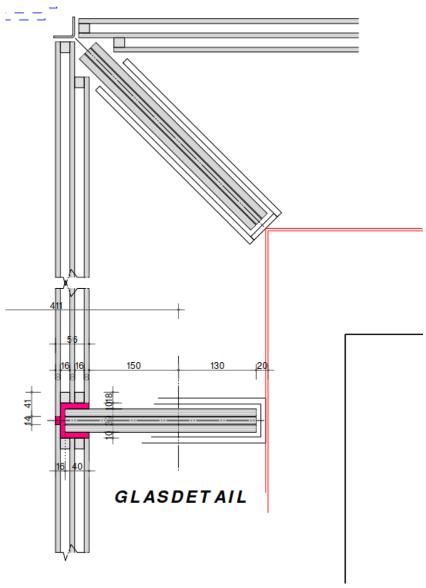
E.1. Structural silicone



(a) (b)

Figure E.1: Structural silicone sealant to connect facade and fin.

Example of application



(a)

(b) Connection in practice. Photo by [32].

Figure E.2: Fin-facade connection with a 2 component structural silicone sealant.

Assumptions

- Co Creation Centre as main reference
- Pink area E.2 used as area, more than a regular sealant.
- Structural silicone sealant as load bearing sealant, Dow Corning 993 (= Dow Corning 895) is chosen
- $p = 1.3 g/cm^3$

Calculations

Material use

- Silicone: 7.0 kg

E.2. Angle spring plates

(a) (b)

Figure E.3: Angle spring plates with point fixing to connect facade and fin.

Example in practice

Figure E.4: A large glass facade. Photo by [40].

It is assumed that a facade panel with a height of 4 meter can be supported by three (double) point fixings, as shown in Figure E.4. Whether this then concerns an angle cleat, point fixing, or (clamped) spider, this is an example of application for all.

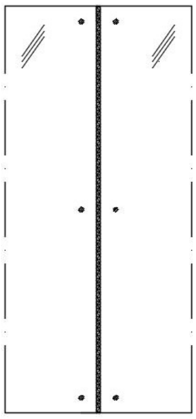
Assumptions

- Three fittings over a height of 4 meter
- Stainless steel angle cleats, $p = 7.9g/cm^3$
- Silicone sealant Dow Corning 993 (= Dow Corning 895) is chosen as reference sealant, $p = 1.3g/cm^3$
- Other interlayer material neglected, like EPDM or neoprene.
- Assumed is that an angle cleat is about 1.3 kg.

Material use

- Silicone: 2.8 kg (significantly less than a structural silicone joint as presented in E.1)
- Stainless steel: 4.0 kg (total of 6 bolts.)

E.3. Point fixing



(a)

(b)

Figure E.5: Point fixing to connect facade and fin.

Example in practice

An example of practice is shown in Figure E.4.

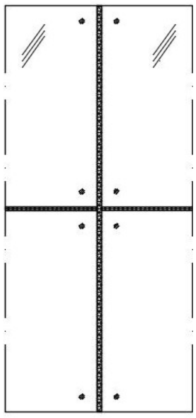
Assumptions

- Three fittings over a height of 4 meter
- Stainless steel angle cleats, $p = 7.9g/cm^3$
- Silicone sealant Dow Corning 993 (= Dow Corning 895) is chosen as reference sealant, $p = 1.3g/cm^3$
- Other interlayer material neglected, like EPDM or neoprene.
- Assumed is that an angle cleat is lighter (circa 1.3 kg) than a fitting (circa 2 kg) since it is a solid connection, based on [26].

Material use

- Silicone: 2.8 kg (significantly less than a structural silicone joint)
- Stainless steel: 6.0 kg (total)

E.4. Spider connection



(a)

(b)

Figure E.6: A spider connection to connect the facade and fin.

Example in practice

An example of practice is shown in Figure E.4.

Assumptions

- Two fittings over a height of 4 meter, which is comparable with Apple Stores.
- Stainless steel spider, $p = 7.9 g/cm^3$
- Reference spiders have a weight of 1.42 - 2.6 kg. [26]. Assumed is a weight of 2 kg per spider.
- Silicone sealant Dow Corning 993 (= Dow Corning 895) is chosen, $p = 1.3 g/cm^3$

Material use

- Silicone: 2.81 kg (significantly less than a structural silicone joint)
- Stainless steel: 4.00 kg (total)

E.5. Spider, clamped

(a) (b)

Figure E.7: A clamped spider connection to connect the facade and fin.

Example in practice

An example of a clamped spider in a facade fin is not known, although similar applications exist. The viability is therefore assumed, and that three clamps (of points of fixing) are needed over an height of 4 meter is shown in Figure E.4.

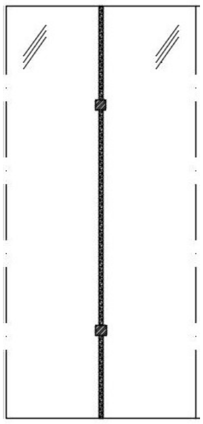
Assumptions

- Two spiders needed on a 4 meter high facade
- The same weight is assumed as the spider in E.4 a (2 kg)
- Stainless steel spider, $p = 7.9g/cm^3$
- Silicone sealant Dow Corning 993 (= Dow Corning 895) is chosen, $p = 1.3g/cm^3$

Material use

- Silicone: 2.81 kg (significantly less than a structural silicone joint)
- Stainless steel: 4.0 kg (total)

E.6. Embedded, titanium



(a)

(b)

Figure E.8: An embedded connection to connect the facade and fin.

Example of application

Figure E.9: Example of an application of this connection, in the Apple Store, Stanford [41]. Estimated height of facade is 4-5 meters, and two embedded connections have been used.

Assumptions

- Two fittings over a height of 4 meter, which is comparable with projects in practice
- Titanium embedded connection, $p = 4.5g/cm^3$
- Silicone sealant Dow Corning 993 (= Dow Corning 895) is chosen $p = 1.3g/cm^3$

Material use

- Silicone: 2.81 kg (significantly less than a structural silicone joint)
- Titanium: 2.04 kg (total)

F

EPD data

In this chapter, EPD data is given of various materials. Both the 2 and 11 impact categories can be found in the appendix.

Shadow costs

The shadow costs are derived by multiplying each amount of impact times the corresponding shadow prize equivalent by [42]. Perform that for 11 impact categories and the total sum is the shadow costs per kg. Since not all data is available, in the 2 impact categories database (the first), a factor is applied for the missing data. Data that not has been used in the derivation of shadow costs is shown in red (in the top).

Sources

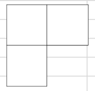
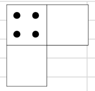
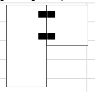
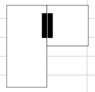
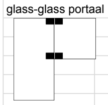
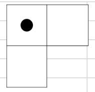
Sources have been referred to in the sheets and have here to correct reference. When referred to by "NDM", the environmental impact database is meant, combined with the product number, for example "SBK107". No further reference is given for those cases. Also, some data is been obtained from the company itself, which is further excluded in this appendix. This is indicated with "-mail-".

Sheet reference	Reference
APP1	NMD, SBK 107
APP2	NMD, SBK 107
APP3	[140]
APP4	[155] Epoxy resin, unfilled/solvent-free with low content of reactive diluent
APP5	[155], Epoxy resin, unfilled/solvent-free with low content of reactive diluent
APP6	[155], Epoxy resin, unfilled/solvent-free with low content of reactive diluent
APP7	[155], Epoxy resin, unfilled/solvent-free with low content of reactive diluent
APP8	NMD, SBK 127
APP9	NMD, SBK 127
APP10	[155], Polyurethane or SMP, filled or aqueous, solvent-freem [156]
APP11	[155], Polyurethane or SMP, filled or aqueous, solvent-freem [156]
APP12	[155], Polyurethane or SMP, filled or aqueous, solvent-freem [156]
APP13	[155], Polyurethane or SMP, filled or aqueous, solvent-freem [156]
APP14	- mail -
APP15	- mail -
APP16	[155], Silicone-based construction sealant, filled or unfilled, transparant or pigmented
APP17	[155], Silicone-based construction sealant, filled or unfilled, transparant or pigmented
APP18	NMD, SBK 236
APP19	NMD, SBK 236
APP20	NMD, SBK 072
APP21	NMD, SBK 072
APP22	NMD, SBK 007
APP23	NMD, SBK 007
APP24	NMD, SBK 331
APP25	NMD, SBK 331
APP26	NMD, SBK 248
APP27	NMD, SBK 248
APP28	[157]
APP29	NMD, SBK 060
APP30	NMD, SBK 060
APP31	- mail -
APP32	- mail -

Materials																				
extra factor to turn data on or off (because of lacking data)			*impact categories*	*2*		*0*	*1*	*0*	*0*	*0*	*0*	*0*	*0*	*1*	*0*					
Shadow prize (Euro) per kg equivalents						0.16	0.05	30	0.09	0.03	0.0001	0.06	2	4	9					
Impact category	**Note**	**useful?**	**sort**	**amount**	**Unit**	Abiotic depletion	Global warming (GWP100)	Ozone layer depletion (ODP)	Human toxicity	Fresh water aquatic ecotox.	Marine aquatic ecotoxicity	Terrestrial ecotoxicity	Photochemical oxidation	Acidification	Eutrophication	Shadow prize	**cradle to**	**comments**	**Official name**	**source**
Unit						**kg Sb eq**	**kg CO2 eq**	**kg CFC-11 eq**	**kg 1,4-DB eq**	**kg 1,4-DB eq**	**kg 1,4-DB eq**	**kg 1,4-DB eq**	**kg C2H4**	**kg SO2 eq**	**kg PO4--- eq**	**eu/kg**				
Acrylic	cradle to gate		Adhesive, Acrylic	1	kg	1.54E-02	1.14E+00	5.66E-08	2.72E-01	6.65E-03	1.71E+01	5.37E-03	8.72E-04	6.36E-03	7.64E-04	0.083	cradle to gate		SBK 107 Kit / lijm, acryl [VLK] (of project Nationale Milieudatabase SBK versie 2.2 (ecoinvent 3.4))	APP1
Acrylic	cradle to grave		Adhesive, Acrylic	1	kg	1.64E-02	2.27E+00	1.22E-07	3.37E-01	7.65E-03	2.15E+01	5.97E-03	9.57E-04	7.19E-03	9.00E-04	0.142	cradle to grave		SBK 107 Kit / lijm, acryl [VLK] (of project Nationale Milieudatabase SBK versie 2.2 (ecoinvent 3.4))	APP2
UV adhesive	cradle to gate		Adhesive, Acrylic U\	1	kg		4.82E+00	5.36E-07						2.61E-02		0.345	cradle to gate		UV adhesive	APP3
Permacol 2240, 2242	A1-A3	underbound	Adhesive, Epoxy	1	kg	2.47E-05	5.81E+00	5.96E-10					2.28E-03	1.19E-02	1.51E-03	0.338	cradle to gate		Permacol 2240, 2242	APP4
Permacol 2240, 2242	A1-A5+D	underbound	Adhesive, Epoxy	1	kg	2.47E-05	5.80E+00	5.86E-10					9.39E-03	1.15E-02	1.50E-03	0.336	cradle to grave		Permacol 2240, 2242	APP5
Permacol 2240, 2242	A1-A3	upperbound	Adhesive, Epoxy	1	kg	4.44E-05	1.17E+01	1.17E-09					3.80E-03	2.25E-02	3.42E-03	0.675	cradle to gate		Permacol 2240, 2242	APP6
Permacol 2240, 2242	A1-A5+D	upperbound	Adhesive, Epoxy	1	kg	4.44E-05	1.17E+01	1.16E-09					1.09E-02	2.21E-02	3.41E-03	0.673	cradle to grave		Permacol 2240, 2242	APP7
Epoxy	cradle to gate		Adhesive, Epoxy	1	kg	5.00E-02	4.91E+00	1.20E-07	7.24E-01	1.27E-02	4.71E+01	1.66E-02	3.90E-03	2.66E-02	4.38E-03	0.352	cradle to gate		SBK 127 Lijm, epoxy 2 componenten [VLK] (of project Nationale Milieudatabase SBK versie 2.2 (ecoinvent 3.4))	APP8
Epoxy	cradle to grave		Adhesive, Epoxy	1	kg	5.09E-02	6.04E+00	1.86E-07	7.89E-01	1.37E-02	5.15E+01	1.72E-02	3.99E-03	2.75E-02	4.51E-03	0.412	cradle to grave		SBK 127 Lijm, epoxy 2 componenten [VLK] (of project Nationale Milieudatabase SBK versie 2.2 (ecoinvent 3.4))	APP9
Permacol 5435	A1-A3		Adhesive, PU	1	kg	1.92E-05	5.03E+00	1.86E-08					1.96E-03	1.07E-02	1.35E-03	0.294	cradle to gate		Permacol 5435	APP10
Permacol 5435	A1-A5+D		Adhesive, PU	1	kg	1.92E-05	5.09E+00	1.86E-08					1.88E-03	1.05E-02	1.35E-03	0.297	cradle to grave		Permacol 5435	APP11
Permacol 5450	A1-A3		Adhesive, PU	1	kg	1.92E-05	5.03E+00	1.86E-08					1.96E-03	1.07E-02	1.35E-03	0.294	cradle to gate		Permacol 5450	APP12
Permacol 5450	A1-A5+D		Adhesive, PU	1	kg	1.92E-05	5.09E+00	1.86E-08					1.88E-03	1.05E-02	1.35E-03	0.297	cradle to grave		Permacol 5450	APP13
DowCorning 993	A1-A3		Adhesive, Silicone	1	kg	1.45E-05	2.02E+00	6.26E-07					8.07E-04	1.06E-02	1.09E-03	0.144	cradle to gate		DowCorning 993	APP14
DowCorning 993	A1-A5		Adhesive, Silicone	1	kg	1.54E-05	2.23E+00	6.65E-07					8.93E-04	1.13E-02	1.19E-03	0.157	cradle to gate (2nd)		DowCorning 993	APP15
DowCorning 995			Adhesive, Silicone	1	kg	4.74E-04	7.08E+00	1.77E-09					3.15E-03	3.41E-02	2.71E-03	0.490	cradle to gate		DowCorning 995	APP16
DowCorning 995	A1-A5+D		Adhesive, Silicone	1	kg	4.74E-04	7.39E+00	1.66E-09					2.11E-02	3.33E-02	2.67E-03	0.503	cradle to grave		DowCorning 995	APP17
SIlicone	cradle to gate		Adhesive, Silicone	1	kg	2.09E-02	2.02E+00	7.67E-07	6.77E-01	2.37E-02	6.32E+01	3.27E-03	1.89E-03	8.91E-03	1.18E-03	0.137	cradle to gate		SBK 236 Kit / lijm, siliconen [VLK] (of project Nationale Milieudatabase SBK versie 2.2 (ecoinvent 3.4))	APP18
SIlicone	cradle to grave		Adhesive, Silicone	1	kg	1.39E-02	3.72E+00	7.63E-07	7.57E-01	3.17E-02	8.39E+01	3.45E-03	1.83E-03	8.31E-03	1.02E-03	0.219	cradle to grave		SBK 236 Kit / lijm, siliconen [VLK] (of project Nationale Milieudatabase SBK versie 2.2 (ecoinvent 3.4))	APP19
Glass	cradle to gate		Glass	1	kg	6.58E-03	1.13E+00	9.77E-08	2.80E-01	8.33E-03	4.38E+01	9.96E-04	4.93E-04	9.85E-03	8.62E-04	0.096	cradle to gate		SBK 072 Glas (of project Nationale Milieudatabase SBK versie 2.2 (ecoinvent 3.4))	APP20
Glass	cradle to grave		Glass	1	kg	6.65E-03	1.13E+00	9.94E-08	2.82E-01	8.37E-03	4.39E+01	1.00E-03	4.98E-04	9.88E-03	8.69E-04	0.096	cradle to grave		SBK 072 Glas (of project Nationale Milieudatabase SBK versie 2.2 (ecoinvent 3.4))	APP21
Aluminium	cradle to gate		Metal	1	kg	2.60E-02	4.49E+00	1.52E-07	5.36E+00	3.15E-02	5.10E+02	1.36E-02	1.85E-03	2.52E-02	2.17E-03	**0.325**	cradle to gate		Aluminium, SBK	APP22
Aluminium	cradle to grave		Metal	1	kg	2.63E-02	4.52E+00	1.62E-07	5.40E+00	3.18E-02	5.11E+02	1.36E-02	1.90E-03	2.55E-02	2.25E-03	0.328	cradle to grave	0.03/0.03/0.94, zie lifespan	Aluminium, SBK	APP23
Steel	cradle to gate		Metal	1	kg	1.40E-02	2.59E+00	1.02E-08	1.16E-01	2.92E-03	1.33E+01	9.99E-04	1.23E-03	6.63E-03	6.00E-04	0.156	cradle to gate		331 Steel, Medium Construction Products PRODUCTIE, BmS, 2013, c2	APP24
Steel	cradle to grave		Metal	1	kg	1.40E-02	2.59E+00	1.05E-08	1.16E-01	2.93E-03	1.33E+01	1.00E-03	1.23E-03	6.64E-03	6.01E-04	0.156	cradle to grave		331 Steel, Medium Construction Products PRODUCTIE, BmS, 2013, c2	APP25
Stainless steel	cradle to gate		Metal	1	kg	3.26E-02	5.07E+00	2.46E-07	7.42E+01	7.18E-02	2.75E+02	9.09E-02	3.31E-03	2.73E-02	2.69E-03	0.363	cradle to gate		Stainless steel, SBK	APP26
Stainless steel	cradle to grave		Metal	1	kg	1.89E-02	2.73E+00	2.33E-07	6.28E+01	6.54E-02	-1.14E+03	-5.71E-02	2.00E-03	7.10E-03	1.33E-03	**0.165**	cradle to grave		Stainless steel, SBK	APP27
Titanium	cradle to gate		Metal	1	kg		3.57E+01							2.30E-01		2.705	cradle to gate	CES edupack gives a similar result	Titanium	APP28
EPDM	cradle to gate		Other	1	kg	3.86E-02	2.67E+00	6.40E-07	1.08E+00	1.76E-01	3.44E+02	8.57E-03	6.27E-04	1.08E-02	8.83E-04	0.177	cradle to gate		EPDM, SBK	APP29
EPDM	cradle to grave		Other	1	kg	3.86E-02	2.67E+00	6.40E-07	1.08E+00	1.76E-01	3.44E+02	8.57E-03	6.27E-04	1.08E-02	8.83E-04	0.177	cradle to grave	0.2/0.8 zie lifespan	EPDM, SBK	APP30
Hilti HY 270	cradle to gate		Other	1	kg	3.29E-06	2.33E+00	1.02E-08					1.16E-03	1.09E-02		0.160	cradle to gate		Hilti HY 270	APP31
Hilti HY 270	cradle to grave		Other	1	kg	3.28E-06	3.45E+00	1.14E-08					1.63E-03	1.48E-02		0.232	cradle to grave		Hilti HY 270	APP32

Materials																				
extra factor to turn data on or off (because of lacking data)			*impact categories*	*11*		*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*					
Shadow prize (Euro) per kg equivalents						0.16	0.05	30	0.09	0.03	0.0001	0.06	2	4	9					
Impact category	**Note**	**useful?**	**sort**	**amount**	**Unit**	Abiotic depletion	Global warming (GWP100)	Ozone layer depletion (ODP)	Human toxicity	Fresh water aquatic ecotox.	Marine aquatic ecotoxicity	Terrestrial ecotoxicity	Photochemical oxidation	Acidification	Eutrophication	Shadow prize	**cradle to**	**comments**	**Official name**	**source**
Unit						**kg Sb eq**	**kg CO2 eq**	**kg CFC-11 eq**	**kg 1,4-DB eq**	**kg 1,4-DB eq**	**kg 1,4-DB eq**	**kg 1,4-DB eq**	**kg C2H4**	**kg SO2 eq**	**kg PO4--- eq**	**eu/kg**				
Acrylic	cradle to gate		Adhesive, Acrylic	1	kg	1.54E-02	1.14E+00	5.66E-08	2.72E-01	6.65E-03	1.71E+01	5.37E-03	8.72E-04	6.36E-03	7.64E-04	0.120	cradle to gate		SBK 107 Kit / lijm, acryl [VLK] (of project Nationale Milieudatabase SBK versie 2.2 (ecoinvent 3.4))	APP1
Acrylic	cradle to grave		Adhesive, Acrylic	1	kg	1.64E-02	2.27E+00	1.22E-07	3.37E-01	7.65E-03	2.15E+01	5.97E-03	9.57E-04	7.19E-03	9.00E-04	0.188	cradle to grave		SBK 107 Kit / lijm, acryl [VLK] (of project Nationale Milieudatabase SBK versie 2.2 (ecoinvent 3.4))	APP2
UV adhesive	cradle to gate		Adhesive, Acrylic U\	1	kg		4.82E+00	5.36E-07						2.61E-02		0.345	cradle to gate		UV adhesive	APP3
Permacol 2240, 2242	A1-A3	underbound	Adhesive, Epoxy	1	kg	2.47E-05	5.81E+00	5.96E-10					2.28E-03	1.19E-02	1.51E-03	0.356	cradle to gate		Permacol 2240, 2242	APP4
Permacol 2240, 2242	A1-A5+D	underbound	Adhesive, Epoxy	1	kg	2.47E-05	5.80E+00	5.86E-10					9.39E-03	1.15E-02	1.50E-03	0.368	cradle to grave		Permacol 2240, 2242	APP5
Permacol 2240, 2242	A1-A3	upperbound	Adhesive, Epoxy	1	kg	4.44E-05	1.17E+01	1.17E-09					3.80E-03	2.25E-02	3.42E-03	0.713	cradle to gate		Permacol 2240, 2242	APP6
Permacol 2240, 2242	A1-A5+D	upperbound	Adhesive, Epoxy	1	kg	4.44E-05	1.17E+01	1.16E-09					1.09E-02	2.21E-02	3.41E-03	0.725	cradle to grave		Permacol 2240, 2242	APP7
Epoxy	cradle to gate		Adhesive, Epoxy	1	kg	5.00E-02	4.91E+00	1.20E-07	7.24E-01	1.27E-02	4.71E+01	1.66E-02	3.90E-03	2.66E-02	4.38E-03	0.479	cradle to gate		SBK 127 Lijm, epoxy 2 componenten [VLK] (of project Nationale Milieudatabase SBK versie 2.2 (ecoinvent 3.4))	APP8
Epoxy	cradle to grave		Adhesive, Epoxy	1	kg	5.09E-02	6.04E+00	1.86E-07	7.89E-01	1.37E-02	5.15E+01	1.72E-02	3.99E-03	2.75E-02	4.51E-03	0.546	cradle to grave		SBK 127 Lijm, epoxy 2 componenten [VLK] (of project Nationale Milieudatabase SBK versie 2.2 (ecoinvent 3.4))	APP9
Permacol 5435	A1-A3		Adhesive, PU	1	kg	1.92E-05	5.03E+00	1.86E-08					1.96E-03	1.07E-02	1.35E-03	0.310	cradle to gate		Permacol 5435	APP10
Permacol 5435	A1-A5+D		Adhesive, PU	1	kg	1.92E-05	5.09E+00	1.86E-08					1.88E-03	1.05E-02	1.35E-03	0.312	cradle to grave		Permacol 5435	APP11
Permacol 5450	A1-A3		Adhesive, PU	1	kg	1.92E-05	5.03E+00	1.86E-08					1.96E-03	1.07E-02	1.35E-03	0.310	cradle to gate		Permacol 5450	APP12
Permacol 5450	A1-A5+D		Adhesive, PU	1	kg	1.92E-05	5.09E+00	1.86E-08					1.88E-03	1.05E-02	1.35E-03	0.312	cradle to grave		Permacol 5450	APP13
DowCorning 993	A1-A3		Adhesive, Silicone	1	kg	1.45E-05	2.02E+00	6.26E-07					8.07E-04	1.06E-02	1.09E-03	0.155	cradle to gate		DowCorning 993	APP14
DowCorning 993	A1-A5		Adhesive, Silicone	1	kg	1.54E-05	2.23E+00	6.65E-07					8.93E-04	1.13E-02	1.19E-03	0.170	cradle to gate (2nd)		DowCorning 993	APP15
DowCorning 995			Adhesive, Silicone	1	kg	4.74E-04	7.08E+00	1.77E-09					3.15E-03	3.41E-02	2.71E-03	0.521	cradle to gate		DowCorning 995	APP16
DowCorning 995	A1-A5+D		Adhesive, Silicone	1	kg	4.74E-04	7.39E+00	1.66E-09					2.11E-02	3.33E-02	2.67E-03	0.569	cradle to grave		DowCorning 995	APP17
SIlicone	cradle to gate		Adhesive, Silicone	1	kg	2.09E-02	2.02E+00	7.67E-07	6.77E-01	2.37E-02	6.32E+01	3.27E-03	1.89E-03	8.91E-03	1.18E-03	0.223	cradle to gate		SBK 236 Kit / lijm, siliconen [VLK] (of project Nationale Milieudatabase SBK versie 2.2 (ecoinvent 3.4))	APP18
SIlicone	cradle to grave		Adhesive, Silicone	1	kg	1.39E-02	3.72E+00	7.63E-07	7.57E-01	3.17E-02	8.39E+01	3.45E-03	1.83E-03	8.31E-03	1.02E-03	0.312	cradle to grave		SBK 236 Kit / lijm, siliconen [VLK] (of project Nationale Milieudatabase SBK versie 2.2 (ecoinvent 3.4))	APP19
Glass	cradle to gate		Glass	1	kg	6.58E-03	1.13E+00	9.77E-08	2.80E-01	8.33E-03	4.38E+01	9.96E-04	4.93E-04	9.85E-03	8.62E-04	0.136	cradle to gate		SBK 072 Glas (of project Nationale Milieudatabase SBK versie 2.2 (ecoinvent 3.4))	APP20
Glass	cradle to grave		Glass	1	kg	6.65E-03	1.13E+00	9.94E-08	2.82E-01	8.37E-03	4.39E+01	1.00E-03	4.98E-04	9.88E-03	8.69E-04	0.136	cradle to grave		SBK 072 Glas (of project Nationale Milieudatabase SBK versie 2.2 (ecoinvent 3.4))	APP21
Aluminium	cradle to gate		Metal	1	kg	2.60E-02	4.49E+00	1.52E-07	5.36E+00	3.15E-02	5.10E+02	1.36E-02	1.85E-03	2.52E-02	2.17E-03	**0.888**	cradle to gate		Aluminium, SBK	APP22
Aluminium	cradle to grave		Metal	1	kg	2.63E-02	4.52E+00	1.62E-07	5.40E+00	3.18E-02	5.11E+02	1.36E-02	1.90E-03	2.55E-02	2.25E-03	0.895	cradle to grave	0.03/0.03/0.94, zie lifespan	Aluminium, SBK	APP23
Steel	cradle to gate		Metal	1	kg	1.40E-02	2.59E+00	1.02E-08	1.16E-01	2.92E-03	1.33E+01	9.99E-04	1.23E-03	6.63E-03	6.00E-04	0.178	cradle to gate		331 Steel, Medium Construction Products PRODUCTIE, BmS, 2013, c2	APP24
Steel	cradle to grave		Metal	1	kg	1.40E-02	2.59E+00	1.05E-08	1.16E-01	2.93E-03	1.33E+01	1.00E-03	1.23E-03	6.64E-03	6.01E-04	0.178	cradle to grave		331 Steel, Medium Construction Products PRODUCTIE, BmS, 2013, c2	APP25
Stainless steel	cradle to gate		Metal	1	kg	3.26E-02	5.07E+00	2.46E-07	7.42E+01	7.18E-02	2.75E+02	9.09E-02	3.31E-03	2.73E-02	2.69E-03	7.111	cradle to gate		Stainless steel, SBK	APP26
Stainless steel	cradle to grave		Metal	1	kg	1.89E-02	2.73E+00	2.33E-07	6.28E+01	6.54E-02	-1.14E+03	-5.71E-02	2.00E-03	7.10E-03	1.33E-03	**5.720**	cradle to grave		Stainless steel, SBK	APP27
Titanium	cradle to gate		Metal	1	kg		3.57E+01							2.30E-01		2.705	cradle to gate	CES edupack gives a similar result	Titanium	APP28
EPDM	cradle to gate		Other	1	kg	3.86E-02	2.67E+00	6.40E-07	1.08E+00	1.76E-01	3.44E+02	8.57E-03	6.27E-04	1.08E-02	8.83E-04	0.330	cradle to gate		EPDM, SBK	APP29
EPDM	cradle to grave		Other	1	kg	3.86E-02	2.67E+00	6.40E-07	1.08E+00	1.76E-01	3.44E+02	8.57E-03	6.27E-04	1.08E-02	8.83E-04	0.330	cradle to grave	0.2/0.8 zie lifespan	EPDM, SBK	APP30
Hilti HY 270	cradle to gate		Other	1	kg	3.29E-06	2.33E+00	1.02E-08					1.16E-03	1.09E-02		0.162	cradle to gate		Hilti HY 270	APP31
Hilti HY 270	cradle to grave		Other	1	kg	3.28E-06	3.45E+00	1.14E-08					1.63E-03	1.48E-02		0.235	cradle to grave		Hilti HY 270	APP32

G
Connection impact

Type	Require	Variant	Sort	Details	Characteristics				Materials used	
					Glass		Structural	-	Part	kg
Type 1	Rigid	Adhesive	UV Acrylic	UV adhesive	Height [mm]	400	Mrd [kNm]		Glass	X
glass-glass portaal				Bohle MV-760	Width [mm]	400	Vrd [kN]		UV adhesive	0.33
					tp1 [mm]	10	UC_glass		Metal	
					tp2 [mm]	15	UC_adhesive	0.02	Filler	
					tp3 [mm]	10	UC_metal		Lamination - PVB	X
							UC_filler			
Type 2	Rigid	Mechanical	Pinned	Stainless steel	Height [mm]	600	Mrd [kNm]		Glass	17.50
glass-glass portaal				Hilti HY 270	Width [mm]	600	Vrd [kN]		Adhesive	
					tp1 [mm]	10	UC_glass	1.07	Stainless steel	5.16
					tp2 [mm]	15	UC_adhesive		Hilti HY 270	1.21
					tp3 [mm]	10	UC_metal		Lamination - PVB	X
							UC_filler	1.03		
Type 3A	Rigid	Mechanical	Embedded	Stainless steel	Height [mm]	400	Mrd [kNm]		Glass	X
glass-glass portaal				or	Width [mm]	400	Vrd [kN]		Adhesive	
			Apple...	Titanium	tp1 [mm]	10	UC_glass	0.68	Stainless steel	0.85
					tp2 [mm]	15	UC_adhesive		Filler	
					tp3 [mm]	10	UC_metal		Lamination - Sentr	X
							UC_lamination			
Type 3B	Rigid	Mechanical	Embedded	Stainless steel	Height [mm]	400	Mrd [kNm]		Glass	X
glass-glass portaal				or	Width [mm]	400	Vrd [kN]		Adhesive	
				Titanium	tp1 [mm]	10	UC_glass	0.44	Stainless steel	1.10
					tp2 [mm]	15	UC_adhesive		Filler	
					tp3 [mm]	10	UC_metal		Lamination - Sentr	X
							UC_lamination			
Type 3C	Rigid	Mechanical	Embedded	Stainless steel	Height [mm]	400	Mrd [kNm]		Glass	X
glass-glass portaal				or	Width [mm]	400	Vrd [kN]		Adhesive	
				Titanium	tp1 [mm]	10	UC_glass	0.27	Stainless steel	1.57
					tp2 [mm]	15	UC_adhesive		Filler	
					tp3 [mm]	10	UC_metal		Lamination - Sentr	X
							UC_lamination			
Type 4	Non-rigi	Mechanical	Pinned	Stainless steel	Height [mm]	400	Mrd [kNm]		Glass	6.00
glass-glass portaal		Adhesive	Mortar	Hilti HY 270	Width [mm]	400	Vrd [kN]		Adhesive	
					tp1 [mm]	10	UC_glass	0.65	Stainless steel	2.71
					tp2 [mm]	15	UC_adhesive		Hilti HY 270	0.10
					tp3 [mm]	10	UC_metal	0.01	Lamination - PVB	X
							UC_filler	0.41		
Type 5	Rigid	Adhesive	Silicone	Silicone	Height facade [m	4000	Mrd [kNm]		Glass	X
glass-glass facade support				DowCorning 993	Width fin [mm]	400	Vrd [kN]		Silicone	7.03
							UC_glass	0.30	Metal	
							UC_adhesive		Filler	
							UC_metal		Lamination - PVB	X
							UC_filler			
Type 6A	Non-rigi	Mechanical	Pinned	Stainless steel	Height [mm]	4000	Mrd [kNm]		Glass	X
glass-glass facade support			Filler	Silicone	Width [mm]	400	Vrd [kN]		Adhesive	
					tp1 [mm]	10	UC_glass	0.21	Stainless steel	4.03
					tp2 [mm]	15	UC_adhesive		Silicone	2.81
					tp3 [mm]	10	UC_metal		Lamination - PVB	X
							UC_filler			
Type 6B	Non-rigi	Mechanical	Pinned, spider	Stainless steel	Height [mm]	4000	Mrd [kNm]		Glass	X
glass-glass facade support			Filler	Silicone	Width [mm]	400	Vrd [kN]		Adhesive	
					tp1 [mm]	10	UC_glass		Stainless steel	4.00
					tp2 [mm]	15	UC_adhesive		Silicone	2.81
					tp3 [mm]	10	UC_metal		Lamination - PVB	X
							UC_filler			
Type 6C	Non-rigi	Mechanical	Pinned	Stainless steel	Height [mm]	4000	Mrd [kNm]		Glass	X
glass-glass facade support			Filler	Silicone	Width [mm]	400	Vrd [kN]		Adhesive	
					tp1 [mm]	10	UC_glass		Stainless steel	6.00
					tp2 [mm]	15	UC_adhesive		Silicone	2.81
					tp3 [mm]	10	UC_metal		Lamination - PVB	X
							UC_filler			
Type 6D	Non-rigi	Mechanical	Point-fixed clam	Stainless steel	Height [mm]	4000	Mrd [kNm]		Glass	X
glass-glass facade support			Filler	Silicone	Width [mm]	400	Vrd [kN]		Adhesive	
					tp1 [mm]	10	UC_glass		Stainless steel	4.00
					tp2 [mm]	15	UC_adhesive		Silicone	2.81
					tp3 [mm]	10	UC_metal		Lamination - PVB	X
							UC_filler			
Type 6E	Non-rigi	Mechanical	Embedded	Titanium	Height [mm]	4000	Mrd [kNm]		Glass	X
glass-glass facade support			Filler	Silicone	Width [mm]	400	Vrd [kN]		Adhesive	
					tp1 [mm]	10	UC_glass		Titanium	2.04
					tp2 [mm]	15	UC_adhesive		Silicone	2.81
					tp3 [mm]	10	UC_metal		Lamination - Sentr	X
							UC_filler			

Type	Shadow costs: cradle-to-gate			Shadow costs: cradle-to-grave			Lifetime		Design	
	Part	€	€/year	Part	€	€/year	Technical vs functional lifetime		Demountability	
Type 1	Glass			Glass			The technical liftime is not limited by the connection or lamination.		This conneciton is not designed for demountablility, although with some chemical solutions the connection might be demountable.	
	UV adhesive	0.11	0.002	UV adhe	0.11	0.002				
	Metal			Metal						
	Filler			Filler						
	Lamination - PVB			Laminati						
	Element			Element						
	Total	**0.11**	**0.002**	**Total**	**0.11**	**0.002**	**Conclusion**	**75**	**Conclusion**	**No**
Type 2	Glass	1.68	0.022	Glass	1.68	0.022	The technical liftime is not limited by the connection or lamination. The filler has a guaranteed technical lifetime of 50 years, which does suffice the first lifetime application.		A bolted connection is designed for demountability, although the filler might make demountability a bit difficult.	
	Adhesive			Adhesive						
	Stainless steel	1.87	0.025	Stainless	0.85	0.011				
	Hilti HY 270	0.19	0.004	Hilti HY 2	0.28	0.006				
	Lamination - PVB			Laminati						
	Element			Element						
	Total	**3.74**	**0.050**	**Total**	**2.82**	**0.038**	**Conclusion**	**75**	**Conclusion**	**Yes**
Type 3A	Glass			Glass			The technical liftime is not limited by the connection or lamination, although few or no examples exist in practice for a moment rigid connection in this configuation. SentryGlass lamination and titanium inserts seem to have a long technical lifetime, but is not confirmed in practice.		An embedded connection is designed for demountability.	
	Adhesive			Adhesive						
	Stainless steel	0.31	0.004	Stainless	0.14	0.002				
	Filler			Filler						
	Lamination - Sen			Laminati						
	Element			Element						
	Total	**0.31**	**0.004**	**Total**	**0.14**	**0.002**	**Conclusion**	**75**	**Conclusion**	**Yes**
Type 3B	Glass			Glass			The technical liftime is not limited by the connection or lamination, although few or no examples exist in practice for a moment rigid connection in this configuation. SentryGlass lamination and titanium inserts seem to have a long technical lifetime, but is not confirmed in practice.		An embedded connection is designed for demountability.	
	Adhesive			Adhesive						
	Stainless steel	0.40	0.005	Stainless	0.18	0.002				
	Filler			Filler						
	Lamination - Sen			Laminati						
	Element			Element						
	Total	**0.40**	**0.005**	**Total**	**0.18**	**0.002**	**Conclusion**	**75**	**Conclusion**	**Yes**
Type 3C	Glass			Glass			The technical liftime is not limited by the connection or lamination, although few or no examples exist in practice for a moment rigid connection in this configuation. SentryGlass lamination and titanium inserts seem to have a long technical lifetime, but is not confirmed in practice.		An embedded connection is designed for demountability.	
	Adhesive			Adhesive						
	Stainless steel	0.57	0.008	Stainless	0.26	0.003				
	Filler			Filler						
	Lamination - Sen			Laminati						
	Element			Element						
	Total	**0.57**	**0.008**	**Total**	**0.26**	**0.003**	**Conclusion**	**75**	**Conclusion**	**Yes**
Type 4	Glass	0.58	0.008	Glass	0.58	0.008	The technical liftime is not limited by the connection or lamination. The filler has a guaranteed technical lifetime of 50 years, which does suffice the first lifetime application.		A bolted connection is designed for demountability, although the filler might make demountability a bit difficult.	
	Adhesive			Adhesive						
	Stainless steel	0.98	0.013	Stainless	0.45	0.006				
	Hilti HY 270	0.02	0.000	Hilti HY 2	0.02	0.000				
	Lamination - PVB			Laminati						
	Element			Element						
	Total	**1.58**	**0.021**	**Total**	**1.05**	**0.014**	**Conclusion**	**75**	**Conclusion**	**Yes**
Type 5	Glass			Glass			The silicone sealant has a guaranteed lifetime of 5 years, but is designed for a 25 year lifetime. This is a structural sealant. It connects an IGU and a glass fin. The IGU has a lifetime of 25 years too, the fin can be used longer. 25 years is assumed.		This connection is not designed for demountability, although with some effort, the silicone can be cut away.	
	Silicone	0.96	0.038	Silicone	1.54	0.062				
	Metal			Metal						
	Filler			Filler						
	Lamination - PVB			Laminati						
	Element			Element						
	Total	**0.96**	**0.038**	**Total**	**1.54**	**0.062**	**Conclusion**	**25**	**Conclusion**	**No**
Type 6A	Glass			Glass			The silicone sealant has a limited guaranteed lifetime. This is a regular sealant which has as function to keep it water and airtight. The IGU and fin are connected mechanically, which can last a long time, just like the fin. The IGU has a lifetime of 25 years.		This connection is demountable.	
	Adhesive			Adhesive						
	Stainless steel	1.46	0.020	Stainless	0.67	0.009				
	Silicone	0.38	0.015	Silicone	0.62	0.025				
	Lamination - PVB			Laminati						
	Element			Element						
	Total	**1.85**	**0.074**	**Total**	**1.28**	**0.051**	**Conclusion**	**25**	**Conclusion**	**Yes**
Type 6B	Glass			Glass			The silicone sealant has a limited guaranteed lifetime. This is a regular sealant which has as function to keep it water and airtight. The IGU and fin are connected mechanically, which can last a long time, just like the fin. The IGU has a lifetime of 25 years.		This connection is demountable.	
	Adhesive			Adhesive						
	Stainless steel	1.45	0.019	Stainless	0.66	0.009				
	Silicone	0.38	0.015	Silicone	0.62	0.025				
	Lamination - PVB			Laminati						
	Element			Element						
	Total	**1.84**	**0.073**	**Total**	**1.28**	**0.051**	**Conclusion**	**25**	**Conclusion**	**Yes**
Type 6C	Glass			Glass			The silicone sealant has a limited guaranteed lifetime. This is a regular sealant which has as function to keep it water and airtight. The IGU and fin are connected mechanically, which can last a long time, just like the fin. The IGU has a lifetime of 25 years.		This connection is demountable.	
	Adhesive			Adhesive						
	Stainless steel	2.18	0.029	Stainless	0.99	0.013				
	Silicone	0.38	0.015	Silicone	0.62	0.025				
	Lamination - PVB			Laminati						
	Element			Element						
	Total	**2.56**	**0.102**	**Total**	**1.61**	**0.064**	**Conclusion**	**25**	**Conclusion**	**Yes**
Type 6D	Glass			Glass			The silicone sealant has a limited guaranteed lifetime. This is a regular sealant which has as function to keep it water and airtight. The IGU and fin are connected mechanically, which can last a long time, just like the fin. The IGU has a lifetime of 25 years.		This connection is demountable and since this connection performs best on tolerances, this connection is the best demountable.	
	Adhesive			Adhesive						
	Stainless steel	1.45	0.019	Stainless	0.66	0.009				
	Silicone	0.38	0.015	Silicone	0.62	0.025				
	Lamination - PVB			Laminati						
	Element			Element						
	Total	**1.84**	**0.073**	**Total**	**1.28**	**0.051**	**Conclusion**	**25**	**Conclusion**	**Yes**
Type 6E	Glass			Glass			The silicone sealant has a limited guaranteed lifetime. This is a regular sealant which has as function to keep it water and airtight. The IGU and fin are connected mechanically, which can last a long time, just like the fin. The IGU has a lifetime of 25 years.		This connection is demountable.	
	Adhesive			Adhesive						
	Titanium	5.52	0.074	Titanium	5.52	0.074				
	Silicone	0.38	0.015	Silicone	0.62	0.025				
	Lamination - Sen			Laminati						
	Element			Element						
	Total	**5.91**	**0.236**	**Total**	**6.14**	**0.246**	**Conclusion**	**25**	**Conclusion**	**Yes**

Type	End-of-life use		Waste scenario		Recycling			End-of-life score	
	Reuse		% Landfill	% Incineration	% Recycling	Impact of connection		Part	-- / - / 0 / + / ++
Type 1	This connection is not designed for demountablility, reuse in a different application is unlikely. The silicone connection to connect the portal with IGU is limiting reuse since that requires removal of the silicone, however, since this is a non structural part, only water/airtightness can be guaranteed in a second application.		30	0	70	A non-demountable connection does negatively influence recyclability. However, since the total adhesive is such a minor part, contamination will be little.		Reuse	--
			0	100	0			Recycling	-
								Demountability	--
	Conclusion	**No**				**Conclusion**	**-**		
Type 2	Demountability has been taken care of, the filler can be removed and has to be replaced in a new application. It might be possible that the pin has to be replaced.		30	0	70	A demountable connection improves recycling. The filler is a little contamination and has to be removed. If the pins are not reused, the metal can be recycled.		Reuse	+
								Recycling	0
			0	0	100			Demountability	+
			0	100	0				
	Conclusion	**Yes**				**Conclusion**	**0**		
Type 3A	Reuse of the elements is possible, further there are no constraints.		30	0	70	A demountable connection improves recycling. A SentryGlass interlayer is not common in recycling, which makes recycling more difficult. If the embedded connections are not reused, the metal can be recycled.		Reuse	+
								Recycling	--
			0	0	100			Demountability	+
	Conclusion	**Yes**				**Conclusion**	**--**		
Type 3B	Reuse of the elements is possible, further there are no constraints.		30	0	70	A demountable connection improves recycling. A SentryGlass interlayer is not common in recycling, which makes recycling more difficult. If the embedded connections are not reused, the metal can be recycled.		Reuse	+
								Recycling	--
			0	0	100			Demountability	+
	Conclusion	**Yes**				**Conclusion**	**--**		
Type 3C	Reuse of the elements is possible, further there are no constraints.		30	0	70	A demountable connection improves recycling. A SentryGlass interlayer is not common in recycling, which makes recycling more difficult. If the embedded connections are not reused, the metal can be recycled.		Reuse	+
								Recycling	--
			0	0	100			Demountability	+
	Conclusion	**Yes**				**Conclusion**	**--**		
Type 4	Demountability has been taken care of, the filler can be removed and has to be replaced in a new application. It might be possible that the pin has to be replaced.		30	0	70	A demountable connection improves recycling. The filler is a little contamination and has to be removed. If the pins are not reused, the metal can be recycled.		Reuse	+
								Recycling	0
			0	0	100			Demountability	+
			0	100	0				
	Conclusion	**Yes**				**Conclusion**	**0**		
Type 5	This system is not designed for reuse, since new silicone will have to be applied in a new application. Since structural silicone will have to be bonded with glass properly, a good bonding can only be assured with new glass.		30	0	70	A non-demountable connection does negatively influence recyclability. The silicone joint will have to be removed, which is not being recycled.		Reuse	--
			20	80	0			Recycling	--
								Demountability	--
	Conclusion	**No**				**Conclusion**	**--**		
Type 6A	The system is reusable. New silicone will have to be applied, but since it is the water/air barrier, this is possible.		30	0	70	A demountable connection improves recycling. The filler in the bolt is a little contamination and has to be removed. If the pins are not reused, the metal can be recycled. The silicone joint will not be recycled and will have to be removed.		Reuse	+
								Recycling	0
			0	0	100			Demountability	+
			20	80	0				
	Conclusion	**Yes**				**Conclusion**	**0**		
Type 6B	The system is reusable. New silicone will have to be applied, but since it is the water/air barrier, this is possible.		30	0	70	A demountable connection improves recycling. The filler in the bolt is a little contamination and has to be removed. If the pins are not reused, the metal can be recycled. The silicone joint will not be recycled and will have to be removed.		Reuse	+
								Recycling	0
			0	0	100			Demountability	+
			20	80	0				
	Conclusion	**Yes**				**Conclusion**	**0**		
Type 6C	The system is reusable. New silicone will have to be applied, but since it is the water/air barrier, this is possible.		30	0	70	A demountable connection improves recycling. The filler in the bolt is a little contamination and has to be removed. If the pins are not reused, the metal can be recycled. The silicone joint will not be recycled and will have to be removed.		Reuse	+
								Recycling	0
			0	0	100			Demountability	+
			20	80	0				
	Conclusion	**Yes**				**Conclusion**	**0**		
Type 6D	The system is reusable. New silicone will have to be applied, but since it is the water/air barrier, this is possible.		30	0	70	A demountable connection improves recycling. The interlayer has to be removed for recycling. The silicone joint will not be recycled and will have to be removed.		Reuse	+
								Recycling	0
			0	0	100			Demountability	++
			20	80	0				
	Conclusion	**Yes**				**Conclusion**	**0**		
Type 6E	The system is reusable. New silicone will have to be applied, but since it is the water/air barrier, this is possible.		30	0	70	A demountable connection improves recycling. If the embedded inserts are not reused, the metal can be recycled. The silicone joint will not be recycled and will have to be removed. A SentryGlass interlayer is not common in recycling, which makes recycling more difficult.		Reuse	+
								Recycling	-
			0	0	100			Demountability	+
			20	80	0				
	Conclusion	**Yes**				**Conclusion**	**-**		

H

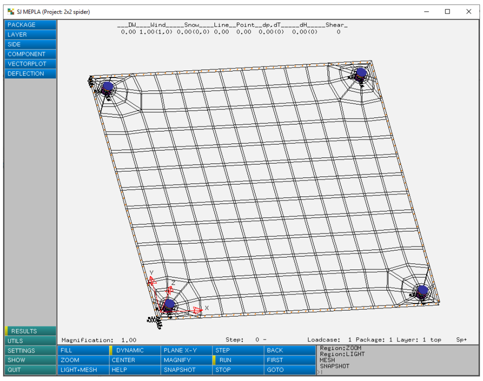
SJ Mepla calculations

H.1. General

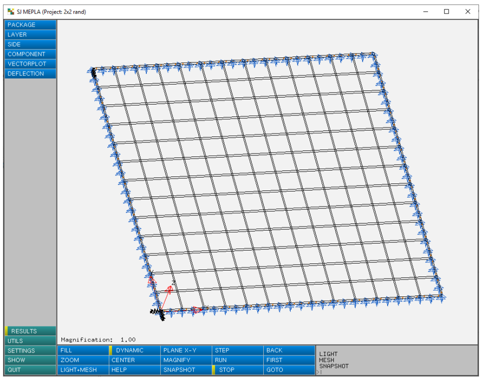
Relevant input data is given for a 2x2 meter panel of for example the supports. In the result, the panel thicknesses are given for this situation. Since the glass consists of two panels, two thicknesses are given, for the inside and outside panel, respectively "XX - XX mm".

Mesh

An indication of the mesh size is shown in Figure H.1. The mesh size for point supported connections is similar to the one shown in Figure XX for all point supported panels. Although the mesh becomes smaller near the corners, the mesh is not extremely refined. Also for an edge supported panel, an evenly distributed rectangular mesh is shown. For a practical application, it is recommended to further refine the mesh.



(a) Mesh of a point supported panel.



(b) Mesh of an edge supported panel.

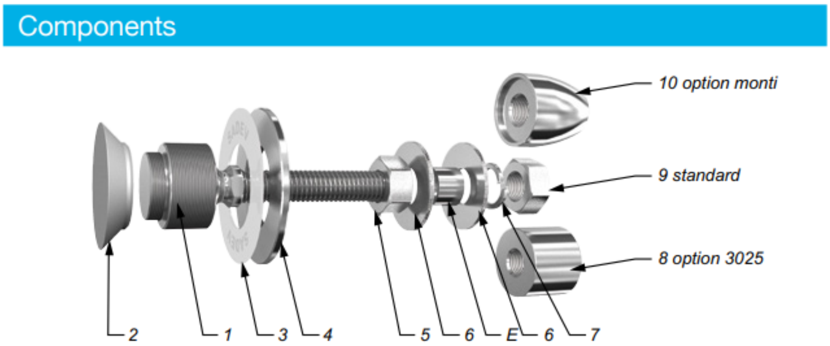
Figure H.1: Mesh size is limited by the program, but the presented mesh size is considered to be viable.

Glass fixing

The glass fixing is based on an example of practice. Sadev has developed many glass fixings and for the assumptions with regard to dimensions and interlayer material, the "Sadev V 2003" and "Sadev R 1019" have been chosen as base for a glass piercing fixing and countersunk glass fixing respectively. Additionally, some relevant material data can be found in Table H.1.

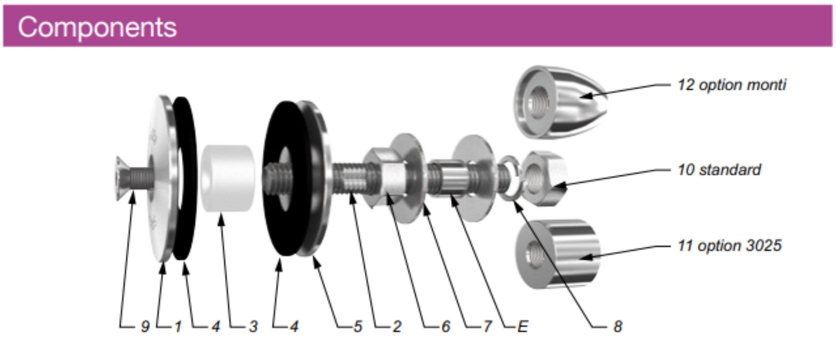
Table H.1: The Young's modulus of various input materials.

Material	**Young's modulus [N/mm2]**
EPDM	6
POM (polyacetyl)	3.000
EN-AW 6060 [AlMgSi] (aluminium alloy)	70.000



MARK	QUANTITY	DESIGNATION	MATERIAL
1	1	Swivel body	X2 Cr Ni Mo 17.12.2 as per EN 10088-3
2	1	Countersunk bush	AW-6060 T5 as per EN 573-3 / Al Mg Si0.5
3	1	Contact washer	White polyacetyl / white polyethylene
4	1	Glass nut Ø60	X2 Cr Ni Mo 17.12.2 as per EN 10088-3
5	1	Nut DIN 934	A4
6	2	Washer	A4
7	1	Washer DIN 127	A4
8	1	3025 Cap nut - Option	X2 Cr Ni Mo 17.12.2 as per EN 10088-3
9	1	Nut DIN 934	A4
10	1	Monti cap nut - Option	X2 Cr Ni Mo 17.12.2 as per EN 10088-3

(a) Material input source of a countersunk connection.



MARK	QUANTITY	DESIGNATION	MATERIAL
1	1	External plate	X2 Cr Ni Mo 17.12.2 as per EN 10088-3
2	1	Threaded axle	A4
3	1	Spacer Ø 25	Polyacetyl
4	2	Contact washer	EPDM
5	1	Glass nut Ø 60	X2 Cr Ni Mo 17.12.2 as per EN 10088-3
6	1	Nut DIN 934	A4
7	2	Washer	A4
8	1	Lock washer127	A4
9	1	Bolt DIN7991 M8x20	A4
10	1	Nut DIN 934	A4
11	1	3025 Cap Nut - Option	X2 Cr Ni Mo 17.12.2 as per EN 10088-3
12	1	Monti Cap Nut - Option	X2 Cr Ni Mo 17.12.2 as per EN 10088-3

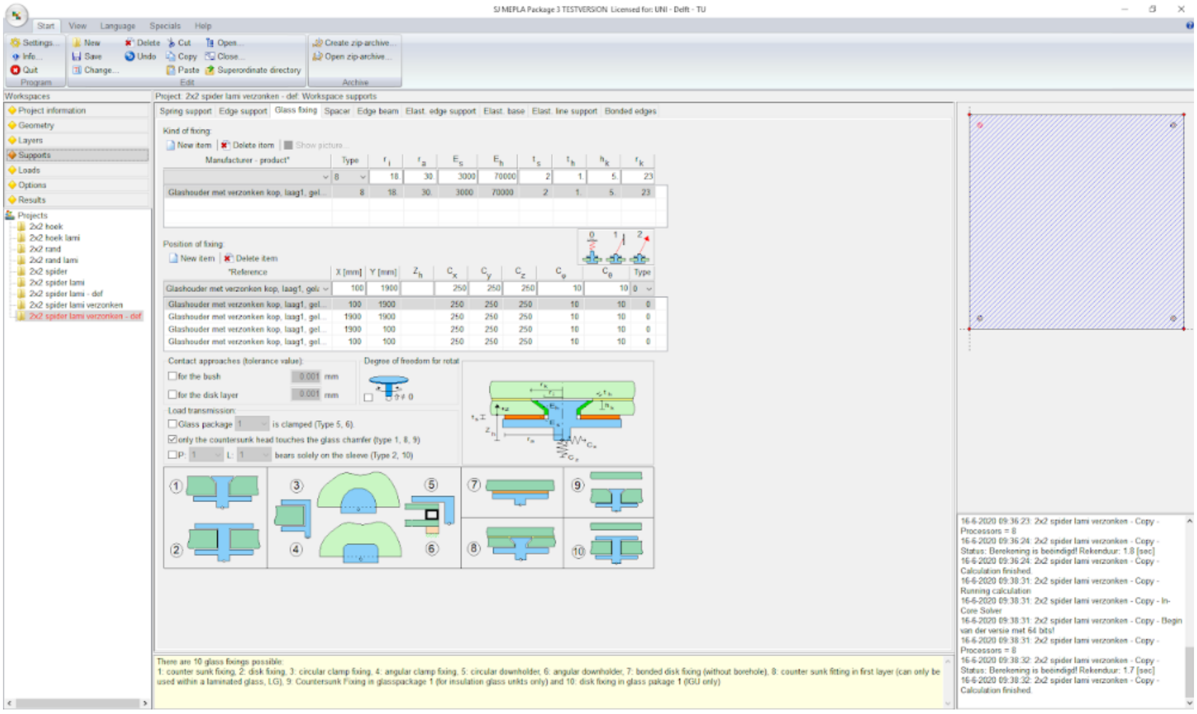
(b) Material input source of a point fixed connection.

Figure H.2: Material input by [26].

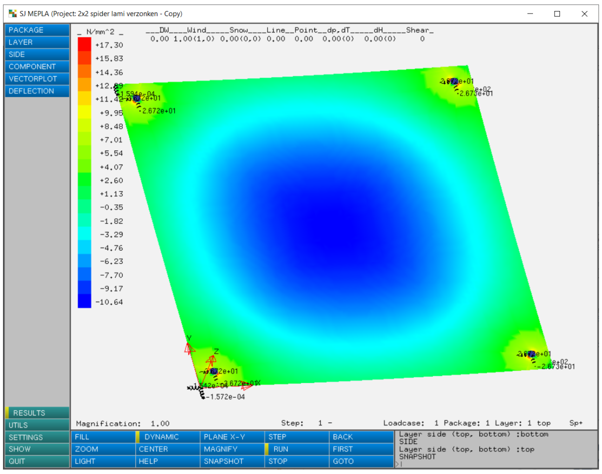
H.2. Spider connection, countersunk

Note that this connection is not viable with an IGU, unless use is made of a laminated glass panel. This is excluded in this exercise.

Laminated glass panel



(a) Input in SJ Mepla

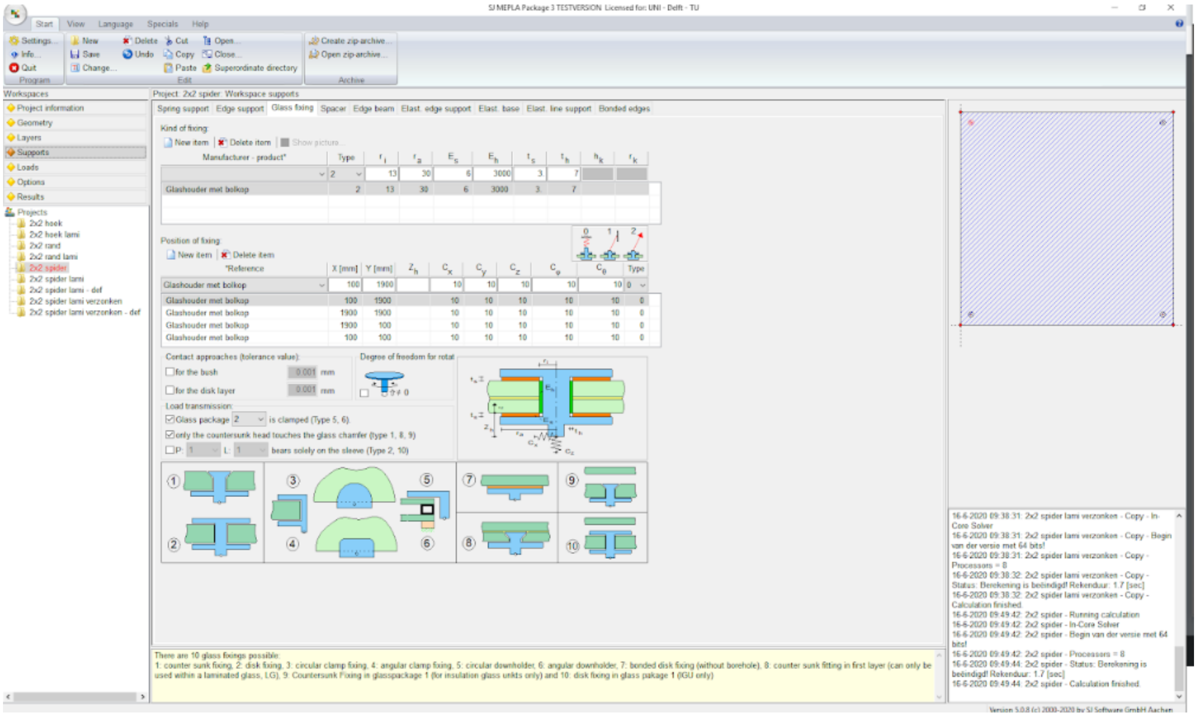


(b) Stresses are well below $20N/mm^2$.

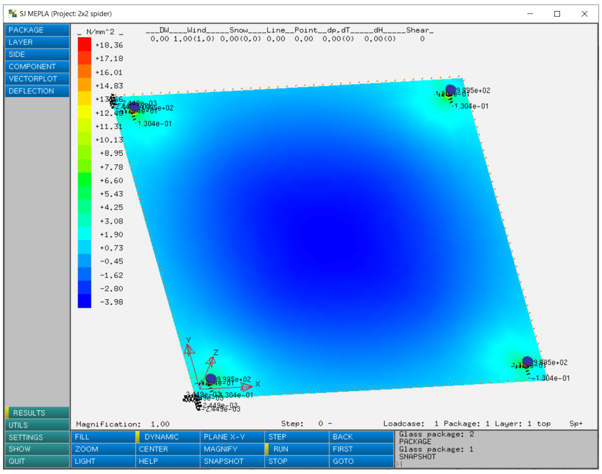
Figure H.3: The panels have a thickness of 10 - 10 mm. This is thinner than a similar connection with pierced connections (Figure H.5) due to allowed shearing of the panels, which is restrained by the pierced bolted connections in Figure H.5. This indicates the importance of input and tolerances, as well as the interlayer.

H.3. Spider connection

IGU



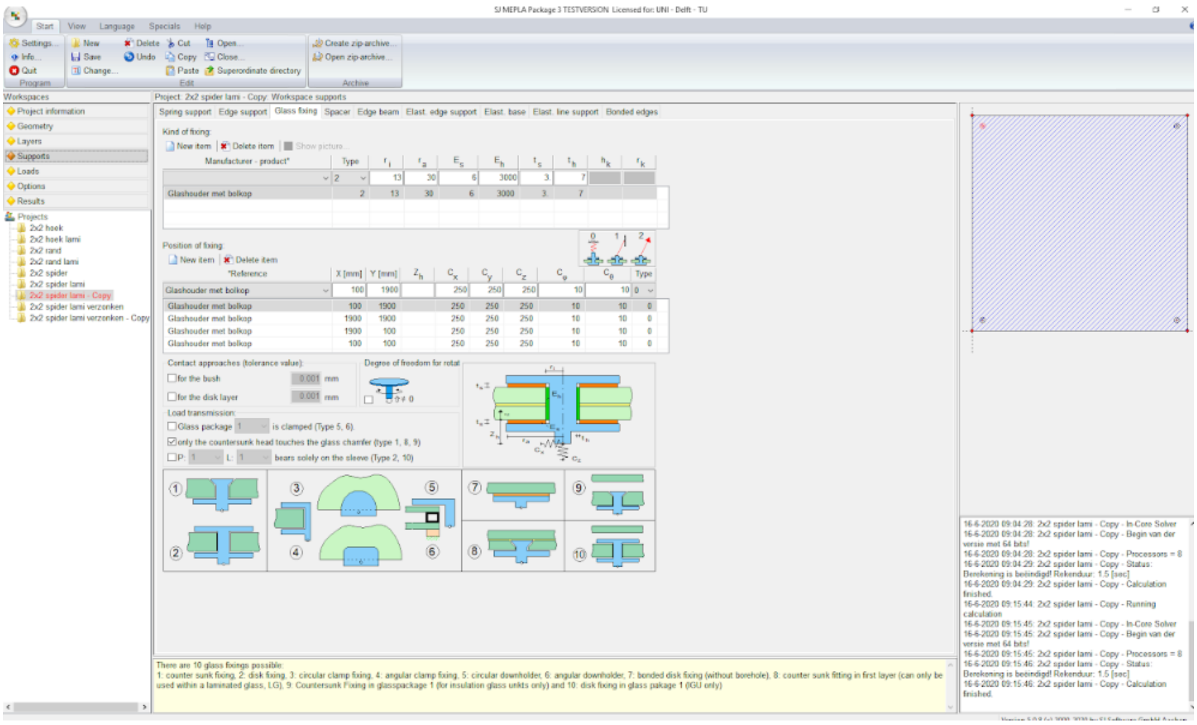
(a) Input in SJ Mepla



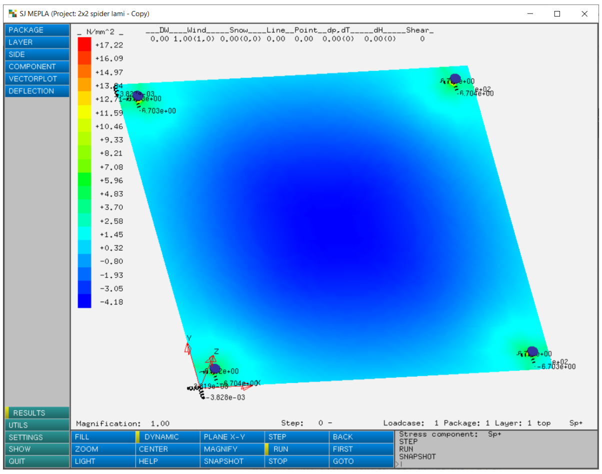
(b) Stresses are just below $20N/mm^2$.

Figure H.4: The panels have a thickness of 15 - 15 mm. Since these are thick panels, a different solution should be considered.

Laminated glass panel



(a) Input in SJ Mepla

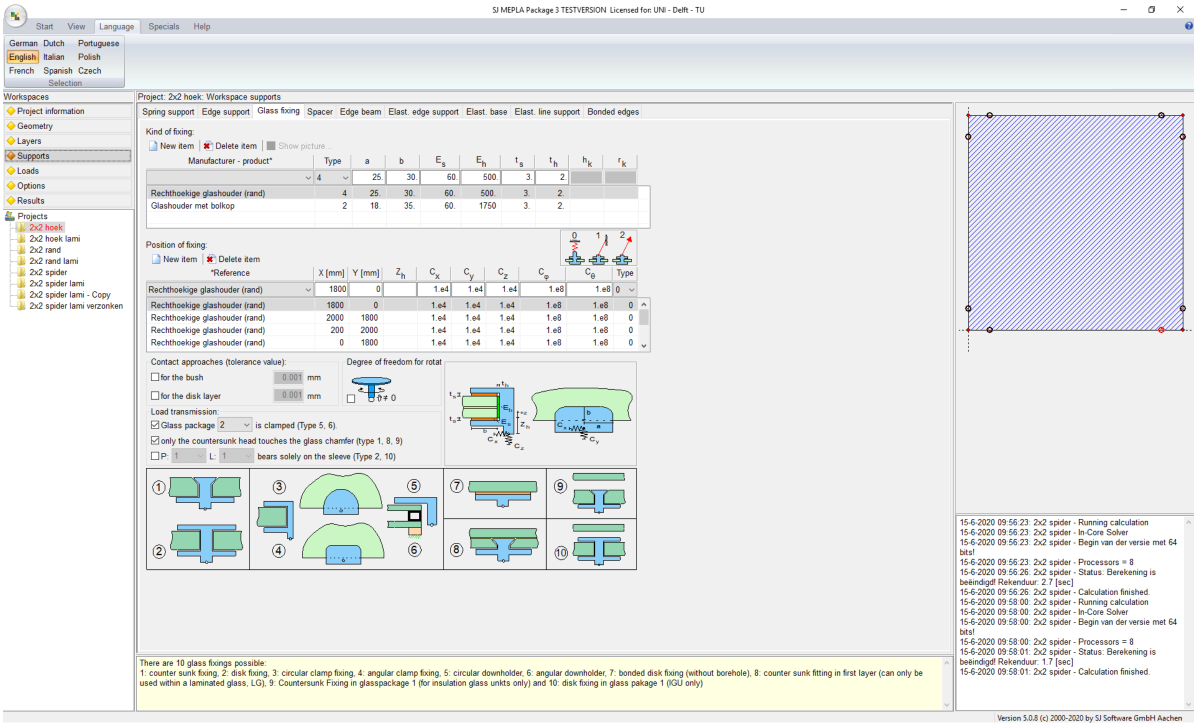


(b) Stresses are just below $20N/mm^2$.

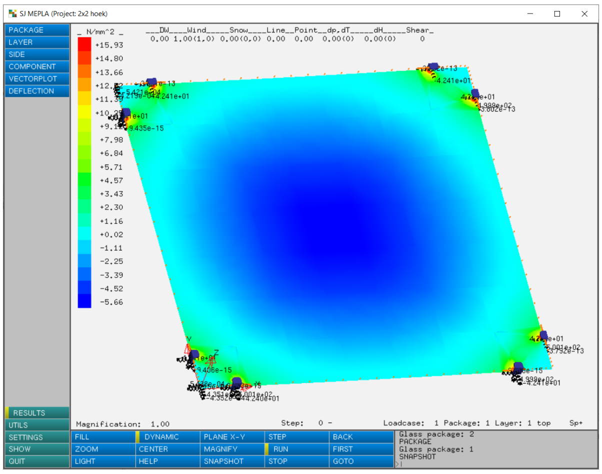
Figure H.5: The panels have a thickness of 15 - 15 mm. Since these are thick panels, a different solution should be considered.

H.4. Glass edge clamps

IGU



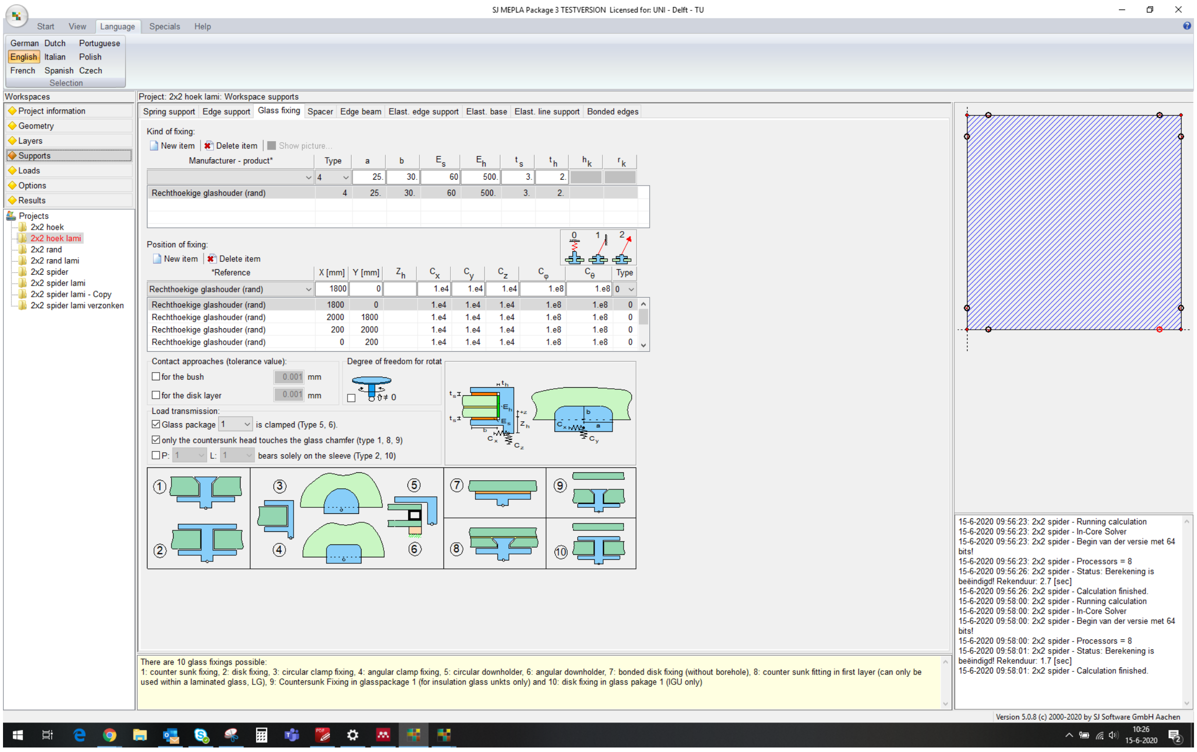
(a) Input in SJ Mepla



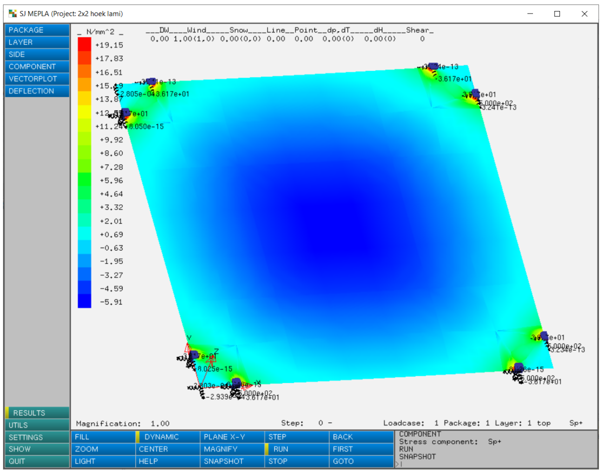
(b) Stresses are just below $20 N/mm^2$.

Figure H.6: The panels have a thickness of 12 - 12 mm.

Laminated glass panel



(a) Input in SJ Mepla

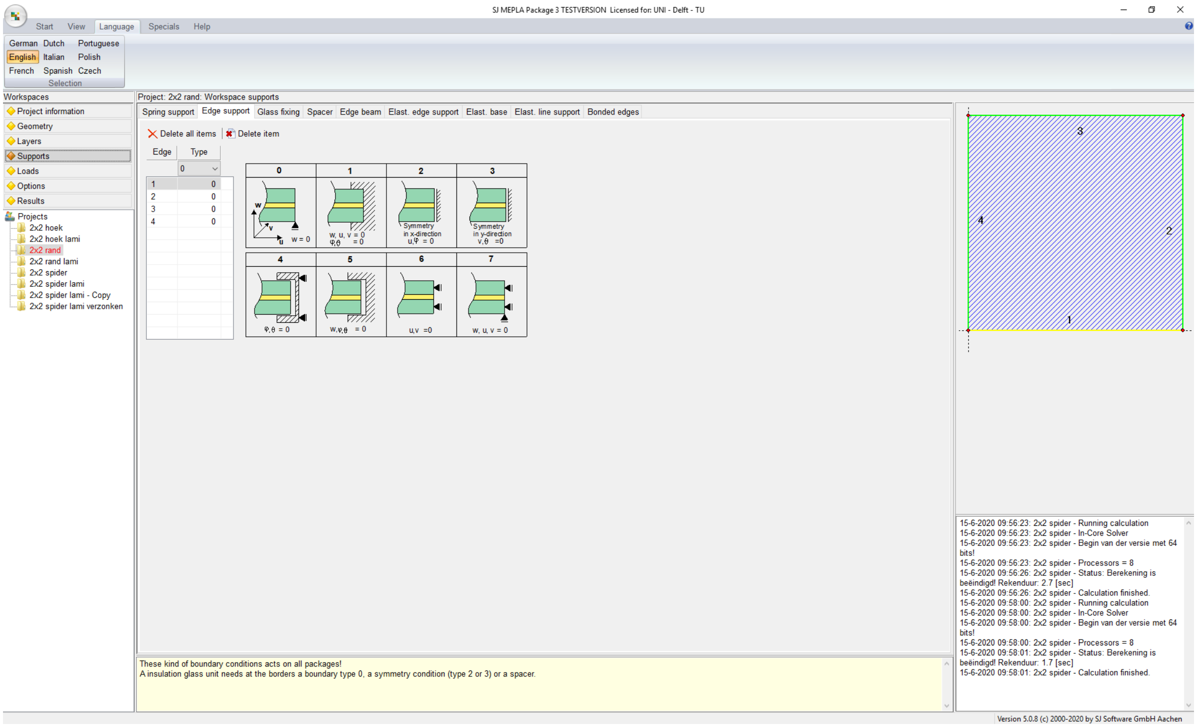


(b) Stresses are just below $20 N/mm^2$.

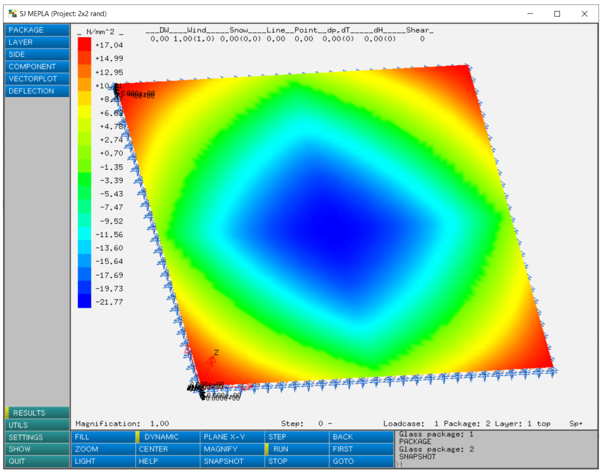
Figure H.7: The panels have a thickness of 10 - 12 mm.

H.5. Edge sealant

IGU



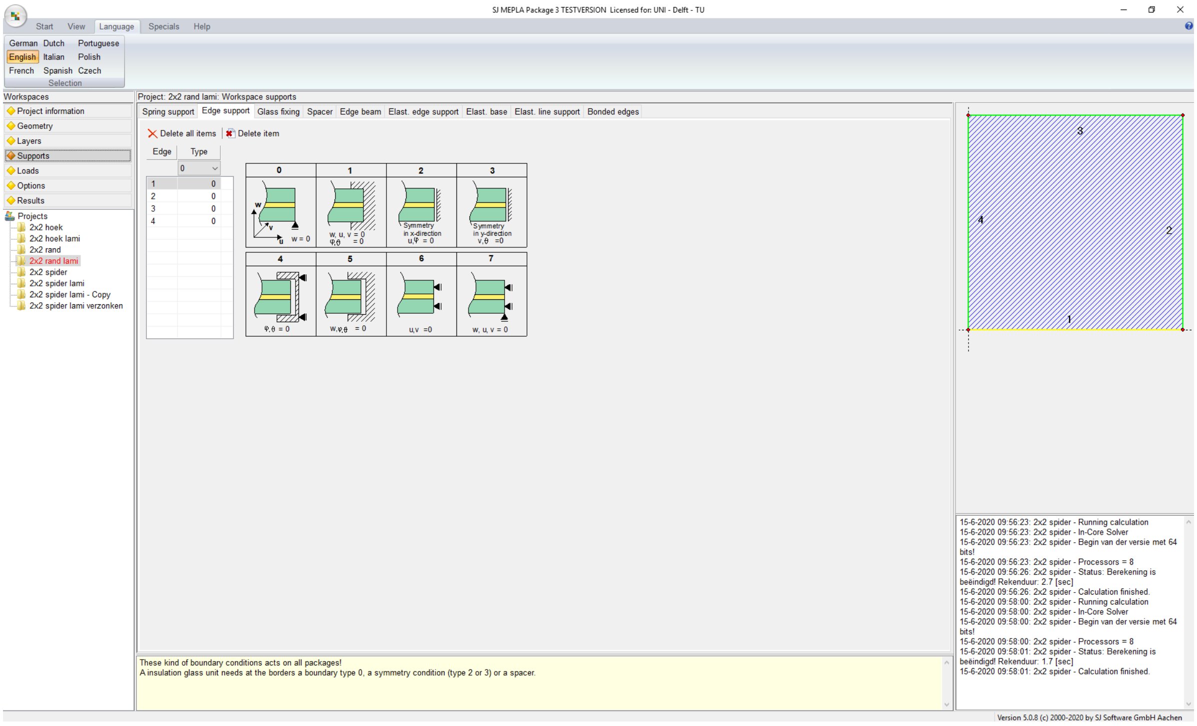
(a) Input in SJ Mepla



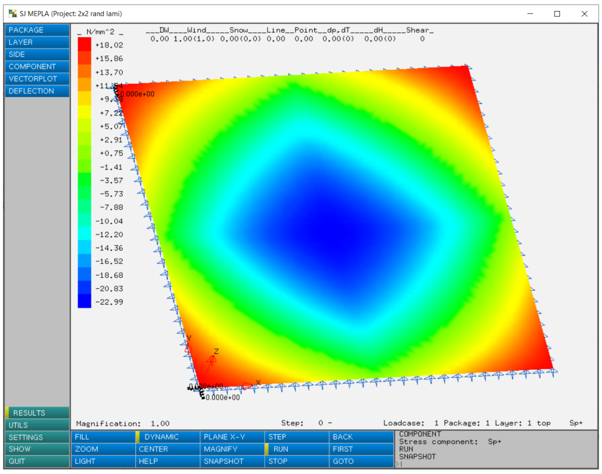
(b) Stresses are just below $20N/mm^2$.

Figure H.8: The panels have a thickness of 5 - 5 mm.

Laminated glass panel



(a) Input in SJ Mepla



(b) Stresses are just below $20N/mm^2$.

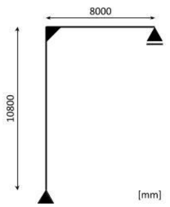
Figure H.9: The panels have a thickness of 4 - 5 mm.

I

Redesign calculations

I.1. Load conditions

Thickness			equivalent		
tp1	12	mm	tp1	11.7	mm
tp2	15	mm	tp2	14.5	mm
tp3	12	mm	tp3	11.7	mm
t_tot	39	mm	t_tot	37.9	mm



ULS (with a broken panel)						Governing frame		
tp1	11.7	mm	h_fin	500	mm	h fin	10.8	m
tp2	14.5	mm	width_to_fin	2	m	l dak beam	8	m
tp3	0	mm	t_roof_tot	26	mm			
t_tot	26.2	mm						

NOTE: The intermediate supports are removed in order to derive the maximum occuring situation

Roof beam

Permanent							Safety factor		
Beam	= 2500*0.4*0.035 =				0.49	kN/m			
Roof glazing	= 2500*0.026 =	0.65	kN/m2	x 1.42 m =	1.30	kN/m			
				q,k_permanent	1.79	kN/m	x 1.2 =	2.15	kN/m
							x 0.9 =	1.61	kN/m
Variable									
q,k,snow		0.56	kN/m2	x 1.425 m =	1.12	kN/m	x 1.5 =	1.68	kN/m
q,k,wind		-0.49	kN/m2	x 1.425 m =	-0.98	kN/m	x 1.5 =	-1.47	kN/m
(suction, zone H)									

q,d,snow	= q_permanent + q_snow =	2.91	kN/m
q,d,wind	= q_permanent + q_wind =	0.81	kN/m

Loading situations

1	q,d,snow	= q_permanent x 1.2 + q_snow x 1.5 =	3.83	kN/m
2	q,d,wind	= q_permanent x 0.9 + q_wind x 1.5 =	-0.14	kN/m
3	q,d,permanent	= q_permanent x 1.35 =	2.41	kN/m

ULS (broken situation), no safety factors

1	q,d,snow	= q_permanent + q_snow =	2.91	kN/m
2	q,d,wind	= q_permanent + q_wind =	0.81	kN/m

Facade fin

Permanent

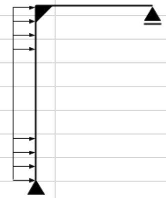
Variable							
q,k,wind	0.56	kN/m2	x 2 m =	1.12	kN/m		
(pressure, zone D)				x 1.5 =		1.68	kN/m

Loading situations

q,d,wind	= q_wind x 1.5 =	1.68	kN/m
q,d,winddruk			

Loading situations

q,d,wind	= q_wind x 1.0 =	1.12	kN/m



Moment and shear force derivation:

Governing situation:

ULS (broken situation)		
Md,hogging	-9.90	kNm
Vd	10.39	kN

Regular									
1	Ved	13.67	kN	Md,hogging	-13.02	kNm	Md,bending	17.58	kNm
2	Ved	-0.50	kN	Md,hogging	0.47	kNm	Md,bending	-0.64	kNm
3	Ved	8.63	kN	Md,hogging	-8.21	kNm	Md,bending	11.09	kNm
Broken									
1	Ved	10.39	kN	Md,hogging	-9.90	kNm	Md,bending	13.36	kNm
2	Ved	2.89	kN	Md,hogging	-2.75	kNm	Md,bending	3.71	kNm

Wind governing		
Md,corner	-21.37	kNm

Regular		
Md,hogging	-21.37	kNm
Md,bending,roof	-4.21	kNm
Md,bending,faca	3.12	kNm
Broken		
Md,hogging	-16.68	kNm
Md,bending,roof	0.48	kNm
Md,bending,faca	7.81	kNm

I.2. Stresses in rigid frame

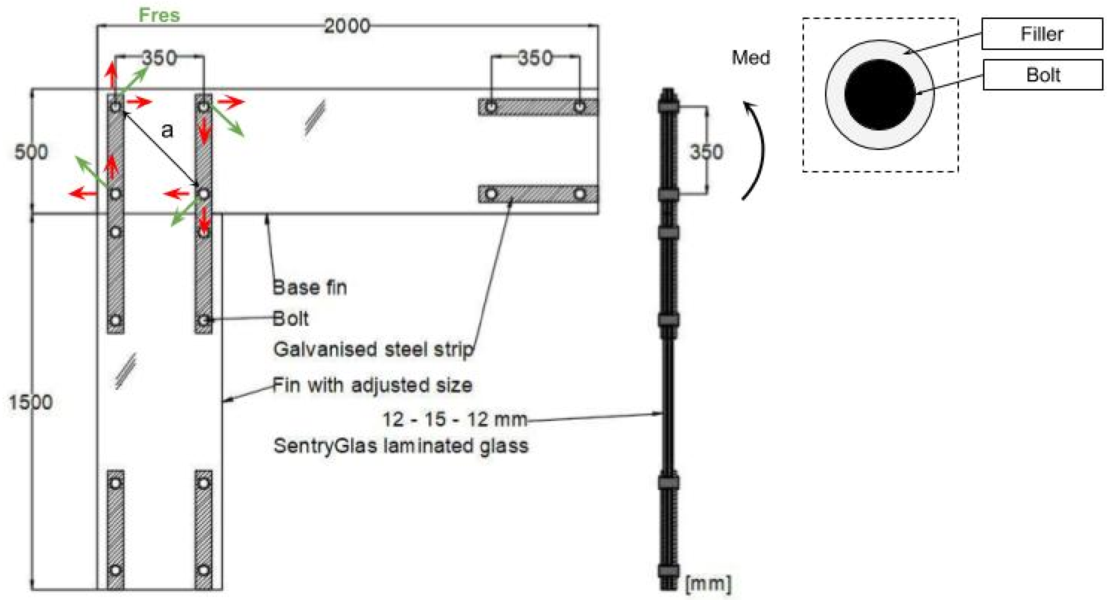


Figure I.1: Sketch of the bolted rigid connection.

A factor due to load spread is applied, which is dependend on the dimensions (10.8 x 6 meter), $F_{loadspread} =$ 0.64, see Chapter8.

$M_d = M_{d,general} \times F_{loadspread} = 21.4 \times 0.64 = 13.7kNm$
$M_{d,broken} = M_{d,general,broken} \times F_{loadspread} = 16.7 \times 0.64 = 10.7kNm$

Assumptions

- Two situations: wind load is governing, check situation with a broken panel and normal situation.
- When wind is governing, $f_{mt;u;d} = 36.7N/mm^2$, see Appendix J
- Filler is Hilti HY 70; a frequently applied filler, $\sigma_{rd} = 31N/mm^2$

Calculations

$a = 495mm$, see Figure I.1

$F_{res,gov} = M_{ed}/(4 * a)/2 = 21.6kN$
$F_{res,broken} = M_{d,broken}/(4 * a)/2 = 21.6kN$

With the method of [38], stresses in the glass can be calculated by considering a factor k_{glas} or k_{kunst} over the theoretical stresses, this is due to peak stresses.

$2r = 40mm$ (diameter bolt)
$2R = 50mm$
$B = 250mm$
$(B - 2R)/B = 0.80$
$e = 75mm; e >= R + 50 = 75mm$
$r/R = 40/50 = 0.8$
$k_{glas} = 6.0$
$k_{filler} = k_{kunst} = 1.4$

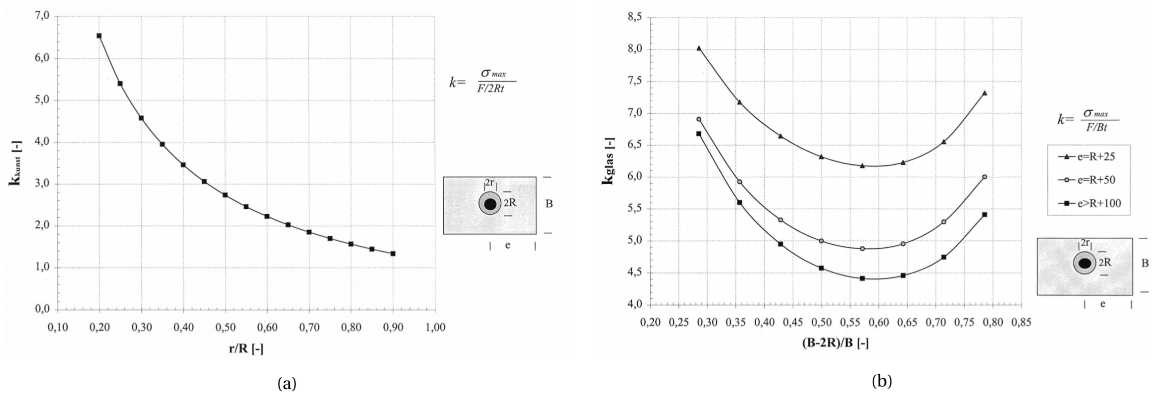


Figure I.2: Relations to derive the stresses in the glass and the filler. [38]

$t_1 = 12mm$
$t_2 = 15mm$
$t_3 = 12mm$

In broken situation, maximum stresses in $t_1 \, or \, t_3$, in the regular situation, maximum stresses in t_2.

From [38] method:
$\sigma_{glass,max} = k_{glass} * F_{res,gov} / (t_{4,eq} * B)$
$\sigma_{filler,max} = k_{filler} * F_{res,gov} / (t_{4,eq} * 2R)$

material		σ_{max}			**Wind load governing, a 36.7 MPa**		**UC**
glass	regular	22.97	N/mm2	<	36.7	N/mm2	0.63
	broken	22.22	N/mm2	<	36.7	N/mm2	0.61
filler	regular	26.80	N/mm2	<	31	N/mm2	0.86
	broken	25.93	N/mm2	<	31	N/mm2	0.84

I.3. Stresses in straight connection

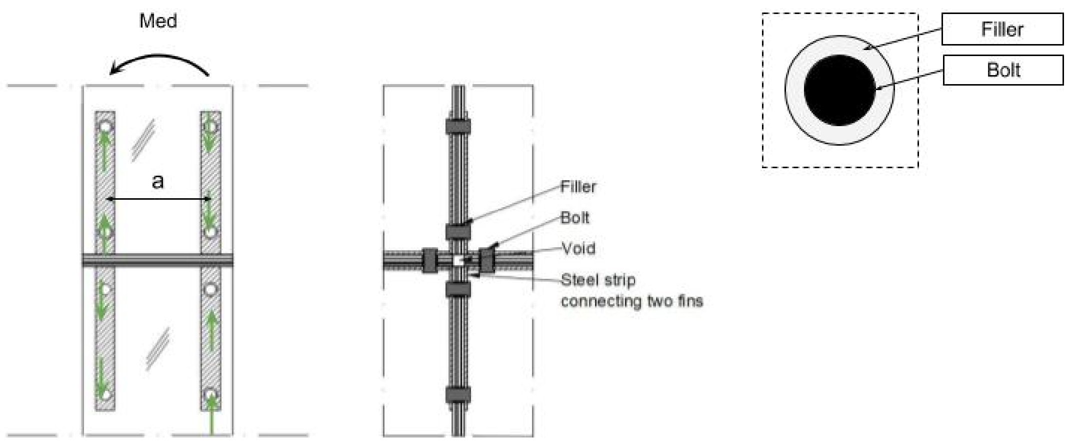


Figure I.3: Sketch of the bolted rigid connection in a straight segment.

In this section, the stresses due to the bending moment are calculated. In the first section, the maximum bending moment in the frame is derived, next to the hogging bending moment of course. This occurs in the roof beam, in the case of a snow load.

A factor due to load spread is applied, which is dependend on the dimensions (8 x 6 meter), $F_{loadspread} = 0.57$, see Chapter8.

$M_d = M_{d,general} \times F_{loadspread} = 17.6 \times 0.57 = 10.4 kNm$
$M_{d,broken} = M_{d,general,broken} \times F_{loadspread} = 13.4 \times 0.57 = 7.6 kNm$

Assumptions

- Two situations: snow load is governing, check situation with a broken panel and normal situation.
- When snow is governing, $f_{mt;u;d} = 25.4 N/mm^2$, see Appendix J
- Filler is Hilti HY 70; a frequently applied filler, $\sigma_{rd} = 31 N/mm^2$

Calculations

$a = 350 mm$, see Figure I.3

$F_{res,gov} = M_{ed}/(a)/2 = 14.3 kN$
$F_{res,broken} = M_{d,broken}/(a)/2 = 10.9 kN$

With the method of [38], stresses in the glass can be calculated by considering a factor k_{glas} or k_{kunst} over the theoretical stresses, this is due to peak stresses.

$2r = 40 mm$ (diameter bolt)
$2R = 50 mm$
$B = 250 mm$
$(B - 2R)/B = 0.80$
$e = 75 mm; e >= R + 50 = 75 mm$
$r/R = 40/50 = 0.8$
$k_{glas} = 5.5$
$k_{filler} = k_{kunst} = 1.7$

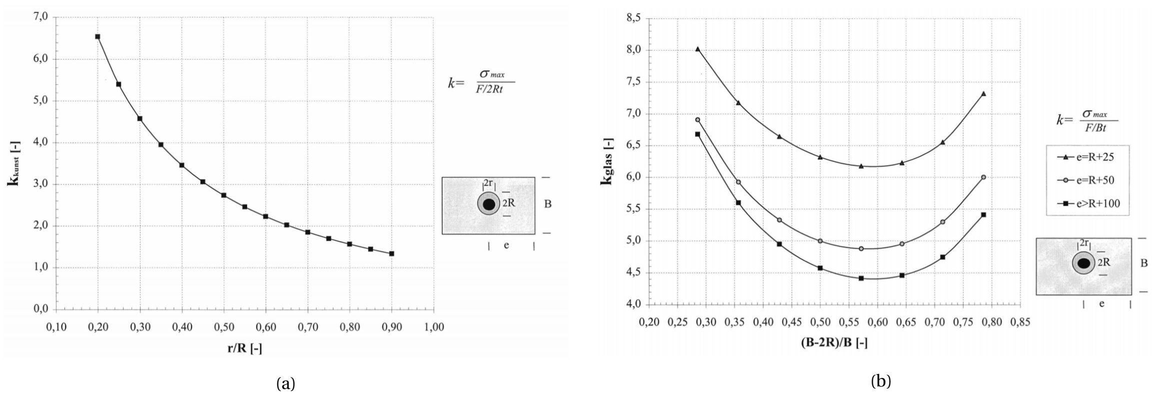


Figure I.4: Relations to derive the stresses in the glass and the filler. [38]

$t_1 = 12 mm$
$t_2 = 15 mm$
$t_3 = 12 mm$

In broken situation, maximum stresses in $t_1 \, or \, t_3$, in the regular situation, maximum stresses in t_2.

From [38] method:
$\sigma_{glass,max} = k_{glass} * F_{res,gov}/(t_{4,eq} * B)$

$\sigma_{filler,max} = k_{filler} * F_{res,gov}/(t_{4,eq} * 2R)$

material		stresses			Snow load governing, a 25.4 MPa		UC
glass	regular	21.77	N/mm2	<	25.4	N/mm2	0.86
	broken	20.51	N/mm2	<	25.4	N/mm2	0.81
filler	regular	33.65	N/mm2	<	31	N/mm2	1.09
	broken	31.70	N/mm2	<	31	N/mm2	1.02

I.4. Buckling check

Buckling is checked by using [153] . Since horizontal glass fins are used as buckling supports, buckling is not expected. The maximum shear force is used as load to check for buckling, which comes from the first load combination and is $13.67kN$.

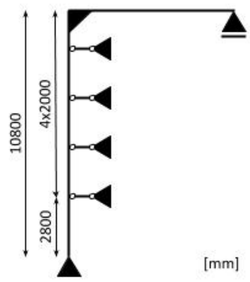


Figure I.5: The governing situation is the situation with the longest unsupported part (2.8 m).

Input

$t_1 = 12mm$
$t_{interlayer} = 1.5mm$
$t_2 = 15mm$
$t_{interlayer} = 1.5mm$
(broken) $t_3 = 12mm$
(broken) $h = 2800mm$
$b = 500mm$
$G_s = 209N/mm2$ (SentryGlas)
$w_0 = l/400 = 7mm$
$P = 13.67kN$
$f_t = 20N/mm2$ (Design tensile stress, Eurocode)

Geometry

$e = 15mm$
(internal lever arm, between the two glass panes) $A_1 = 6000mm2$
$A_2 = 7500mm2$
$I_1 = 72000mm4$
$I_2 = 140625mm4$
$E = 70000N/mm2$

Stiffness

$k = \frac{\pi^2 EA}{l^2}$
$k = \frac{G_s b}{t_s}$
$f = 1/k$

$k_1 = 528.73 N/mm2$
$k_2 = 660.91 N/mm2$
$k_s = 69666.67 N/mm2$
$f_1 = 0.0019 mm2/N$
$f_2 = 0.0015 mm2/N$
$f_s = 0.0000 mm2/N$

Limits

$P_L = 18737 N$ (lower limit)
$P_U = 84828 N$ (upper limit)

$\xi = 1.00$
$P_{cr} = 84550 N$

$n = P_{cr}/P = 6.18$
$n/(n-1) = 1.19$

$w = n \times w_0 = 8.35 mm$
$M = w \times P = 114168 Nmm$
$M_{tot} = M_m + M_n = 114168 Nmm$
$M_m = P_L/P_{cr} * M_{tot} = 25300 Nmm$
$M_n = 88868 Nmm$

$N_e = 5925 N$

$W_1 = 12000 mm3$
$W_2 = 18750 mm3$

$N_1 = 6077 N$ (follows from force distribution of P over A_1 and A_2) $N_2 = 7596 N$
$M_1 = 8567 Nmm$ (follows from force distribution of M over I_1 and I_2)
$M_2 = 16733 Nmm$

$\sigma_1 = \frac{-N_e - P_1}{A_1} + \frac{M_1}{W_1} < f_1$
$\sigma_2 = \frac{-N_e - P_2}{A_2} + \frac{M_2}{W_2} < f_1$

$\sigma_1 = -1.29 N/mm2$ UC = OK
$\sigma_2 = 0.67 N/mm2$ UC = OK

A large capacity remains, even with a broken panel.

J

Glass strength

From Eurocode NEN 2608, the following formula is presented in order to derive the strength of glass. Only the relevant values presented in this research are given.

$$f_{mt;u;d} = \frac{k_e \times k_a \times k_{mod} \times k_{sp} \times f_{g;k}}{y_{m;A}} + \frac{k_e \times k_z \times (f_{b,k} - k_{sp} \times f_{g,k})}{y_{m,V}}$$

$f_{mt;u;d}$	is the tensile strength of glass in N/mm^2
k_e	is a factor related to the edge quality and load direction. $k_e = 0.8$
k_a	is a factor related to the surface and the load, $k_a = 1.0$
k_{mod}	is a factor related to the load duration and reference period
k_{sp}	is a factor related to the surface quality, $k_{sp} = 1.0$
$f_{g;k}$	is the characteristic strength of glass, $f_{g;k} = 45N/mm^2$
$y_{m;A}$	is the material factor of glass, $y_{m;A} = 1.8$.
k_z	is a factor considering a specific zone of glass, further elaborated in Eurocode NEN 2608. $k_z = 1.0$
$f_{b,k}$	is the characteristic strength due to heat treatment (pretensioning), $f_{b,k} = 70.0$
$y_{m,V}$	is the material factor of pretensioned glass, $y_{m,V} = 1.2$

Wind load and float glass

$t = 5s$
$k_{mod} = 1.0$
$f_{mt;u;d} = 20.0N/mm^2$

Wind load and tempered glass

$t = 5s$
$k_{mod} = 1.0$
$f_{mt;u;d} = 36.7N/mm^2$

Snow load and tempered glass

$t = 1month$
$k_{mod} = 0.44$
$f_{mt;u;d} = 25.4N/mm^2$