A study about the structural and thermal performance of large glass masonry façade

Master of Science Thesis

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Abstract

Key words:

Structural glass, Solid glass brick, UV-curing adhesive, Glass connections, Soda-lime glass, Glass masonry, Transparency, Passive measures

There are already lot of glass structures, using big size elements that prove that glass is a strong material that can compete the other more conventional building materials. However, the use of solid cast glass bricks glued with a transparent UV cured adhesive is not common and it is first utilized in the façade of the Crystal House in Amsterdam, designed by MVRDV and Gietermans & Van Dijk (the project is under construction by the time that this report is written). The structure is exclusively constructed by monolithic glass blocks, bonded with a colorless, UV-curing adhesive, obtaining thus a maximum transparency. In contrast with other structural systems that used solid glass bricks in the past, the desired structural performance is achieved solely through the masonry system, without any opaque substructure.

In the present design, there is an attempt of exploring the structural and thermal potentials of this new technology, by studying them in a 4 times bigger scale than the one in P.C. Hooftstraat. It provides an elaborated research of the integrated architectural, structural and thermal design and discusses the choice of materials, structural solutions, passive and active measures. The structural verification of the system is enhanced by experimental tests about the structural and thermal integrity of the glass block system. More specifically, compression and four point bending experiments demonstrate the required monolithic structural performance of the glass block-adhesive assembly. All specimens failed in the glass; no delamination occurred.

At the same time, an elaborated architectural and structural design in the interior of the building with the use of only structural glass elements is illustrated in the research. Apart from the bigger scale of the glass brick façade compared to the one in Amsterdam, a challenge in the research is the innovative approach of the construction of the column. There are two slender columns in the design that are made by glass bricks glued with the transparent adhesive as in the façade. The results show that the adhesively bonded glass block structure has the required self-structural behavior, but only if strict tolerances are met in the geometry of the glass blocks.

The connections between the two materials (glass and concrete) as well as between the cast and float glass have been structurally calculated accompanying by 3d impressions.

Finally, several thermal simulations of different scenarios in the design of the building in three different climate zones (Amsterdam, Valencia, Tampere) are given, showing the importance of the application of passive measures in order to improve the thermal performance and increase the sustainability value of the design.

At the end of this report, alternatives in the design are given in order to stimulate future research on this new, lot of promising technology. Undoubtedly, there are still lot of potentials to be explored.
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The topic of the research was picked when a lecture from Rob Nijsse during the structural glass course about the design of the glass brick façade in the PC Hooftstraat in Amsterdam intrigued me to start an extended research on the potentials of this new technology of the self-supporting glass brick façade. I was always curious and intrigued in obtaining knowledge about the potentials glass can offer. It can be used to create impressive designs and as a material has bright future in the construction world.

Many people contributed their time, effort and ideas to the development of this research. First of all, I would like to express my sincerest gratitude to all my mentors Rob Nijsse, Vred Veer, Regina Bokel and Phaedra Oikonomopoulou. Their contribution was significant and decisive for the completion of this research.

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Delft, June 2015

Varvara Gatsiou
“We live for the most part within enclosed spaces. These form the environment from which our culture grows. Our culture is in a sense a product of our architecture. If we wish to raise our culture to a higher level, we are forced for better or for worse to transform our architecture. And this will be possible only if we remove the enclosed quality from the spaces within which we live. This can be done only through the introduction of glass architecture that lets the sunlight and the light of the moon and stars into our rooms not merely through a few windows, but simultaneously through the greatest possible number of walls that are made entirely of glass. The new environment that we shall thereby create must bring with it a new culture.”

By Paul Scheerbart
Glasarchitektur
Berlin, 1914
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Introduction

Glass

Glass can be characterized as an innovative and desired material in the recent world of structural engineering. It is the only material that gives to the architects and engineers the chance to erect transparent, open and seemingly weightless buildings which alters the correlation between interior and exterior world, a relationship between humankind, space, light and nature (Schittich, 1999).

The very special properties obtained by the material glass were responsible for establishing it as the main material used in the building construction and led engineers and architects to constantly think of ways to use it in larger extent and scale. Reflections, shadows effects and different light patterns are some of the characteristics that this material offers to the architects who have a fondness for big expanses of glass.

Moreover, the mechanical properties of glass and its high strength makes glass a good competitor among other common materials (concrete, timber, steel) that are used for load-bearing components. The main difference and blemish compared to the more conventional materials though is the uncertainty in the values of its strength. The reason for that is because glass is highly prone to imperfections on the surface. Scratches and flaws during the manufacturing process can cause a certain loss of strength. In addition, the compressive and tensile strength of glass differs enormously. Due to advanced production techniques glass can handle high compressive stresses. The weakness of the material lies in its inability to handle large tensile stresses. Once a fracture occurs, the element will lose all its strength and stiffness, leading to collapse of the structure. However, there is an enormous innovative boost in the different way of using glass as a structural element. Lot of researches have been conducted on how to comply with this brittle behavior of the glass and the stringent demands of fire protection and safety when designing with glass elements, resulting in new strategies and developments on the process of manufacture.

Equally important is the classification of glass as a sustainable material. Lately, glass is considered as the red-hot green building material. The reason for that given title to glass is because it can control light, letting in the good rays and keeping out the bad ones in a way that saves on energy costs, providing natural daylighting and it harmonizes a structure with its environment. The glass industry has brought an increasing array of energy-efficient glass products to market and will likely keep bringing enhancements in glass coating and insulation technology in the future (Ebeid, Group, Hills, & Carney, 2002).
Case studies/Existing examples

Some of the most stunning glass structures in the architecture world that shows the creativity that architects have when using glass are illustrated in the following pictures. Its transparency creates amazing reflections and looks airy and light, whilst at the same time when used in the right way it can be incredibly strong despite the vulnerability and fragility that it shows.

The Glass Cube house by Carlo Santambrogio in Milan

A blue-tinged glass cube sits in the middle of a wooded clearing – a location private enough to reasonably place a home that is made almost entirely of 7 mm glass. The material can be specially heated during the winter. Almost every feature or piece of furniture is made from glass as well, from the dining room table, to the stairs, to the bookcase (www.dailymail.co.uk).

Figure 1.1: The exterior and interior of the glass house (www.dailymail.co.uk)
The Entrance cube to the Apple store in New York by Eckersley O'Callaghan

The entrance cube to Apple’s underground store on Fifth Avenue represents probably the purest form of transparent architecture. The 9.8 m cube at the Apple Store is made from structural glass, with no metal framing; and its rectilinear profile blends in with the General Motors skyscraper behind it.

Figure 1.2: Apple Store Fifth Avenue (www.galinsky.com)
The Kanagawa Institute of Technology in Atsugi, Japan by Junya Ishigami

Tokyo designer Junya Ishigami’s Kanagawa Institute of Technology (KAIT) Workshop is one of the buildings that seems to transcend architecture’s inherent limitations. While the transparent enclosure exposes everything inside, the delicate steel columns define scattered oases of open space, each one a different functional component. Even from the middle of the structure one can have a clear view of the outside environment due to the pure glass walls of the enclosure. It consists of three main steel components: a conventional two-way roof frame, 42 compression columns for vertical loads, and 263 post-tensioned columns that carry horizontal loads like mini sheer walls (www.archrecord.construction.com).

Figure 1.3: Renders and photos of the Kanagawa Institute of Technology (www.wordpress.com)
Glass elements can be used as well for renovation or extension of existing buildings, adding transparency, open, airy and light living environment while creating contradiction between the classic and modern architecture.

**The Glass House in Winchester, England by AR Design Studio**

Hidden from view behind the buildings traditional façade, the finished extension is an elegant piece of modern contemporary glass architecture. The concept was to provide a clean and light architectural intervention alongside the traditional shell of the building which would positively affect the feel and functionality of the property. The spaces are designed to accentuate a play between light and dark; contrasting from the bright and open communal spaces to the more subtle and secluded, almost cave-like retreat spaces in the old house (www.archdaily.com).

![The glass house by AR Design Studio in Winchester, England](www.architectscorner.info)

However, architects worldwide have been striving in the last decades to develop a self-supporting glass block façade which would allow them to provide their buildings with the maximum transparency possible by minimizing the obstructions of any skeleton made of steel or other opaque materials appearing. Although, self-supporting glass block facades have already been realized in several architectural projects, none of them have managed to meet the structural requirements in a flat wall without the use of added metal substructure or reinforcement. Some of the projects that this technology has been applied are illustrated in the following.

Glass blocks are commonly produced in a hollow form that are unsuitable for load bearing components as their compressive strength value is insufficient to accommodate the vertical load of a stacked wall (Oikonomopoulou, Veer, Nijssse, & Baardolf, 2015). In that case, steel reinforcement are embedded in the glass blocks and carry all the load. Case studies that use that method are the *Maison Hermes* store (figure 1.5) and *Maastricht academy of Arts* (figure 1.7).
Maison HERMES in Tokyo by Renzo Piano

The concept of this building was to make it look like the “magic lamp” inspired by Japanese paper lamps, and for that purpose Renzo Piano coated the facade, 13 m high, of a grid of 13,000 translucent glass blocks, 42.8 x 42.8 x of 12 cm, specially made for this occasion. The glass screen looks like a skin, slightly separated from the building by a metal structure that protrudes from the concrete slabs on each floor. Inside the skin there is also a metal frame that prevents the collapse of the glass blocks, behaving like a skeleton with moving joints, filled with elastic silicone sealant that allows a controlled displacement and deformation of the wall. The blocks have been specially designed to hide the metal gasket inside. A detail can be observed in the corner with the special curved blocks that were created to give continuity to the skin effect (figure 1.6) (www.simlievler.wordpress.com).

Figure 1.5: Glass blocks in the façade of HERMES in Tokyo (left) and the main entrance (right) (www.simlievler.wordpress.com)

Figure 1.6.: Corner detail with special curved blocks (left) and impression of the HERMES in Tokyo (right) (www.simlievler.wordpress.com)
Academy of Arts in Maastricht by Wiel Architects

The school is an addition to an existing arts academy on the northern edge of Maastricht’s city center. The school’s exterior is draped in a glass-brick veil that shields interior inhabitants from the city during the day by providing a layer of visual protection. This same glass-brick veil simultaneously reveals the interior inhabitants at night, as their silhouettes cast shadows onto its skin. The loads are carried entirely through the opaque metal grid that the glass blocks are mounted in, minimizing the transparency of the façade (www.wielaretsarchitects.com).

On the other hand, the solid glass blocks present a much higher compressive strength, makes them suitable to be used as loadbearing components. However, they are not commonly used for exterior glass walls due to their comparable higher manufacturing cost and a non-standardized manufacturing process. The most well-known projects that solid glass blocks have been used for the façade are the Optical House by Hiroshi Nakamura (figure 1.8), the Crown Fountain in Chicago by Jaume Plensa (Krueck and Sexto Architects) (figure 1.10) and the Atocha Memorial in Madrid by FAM Arcitectura y Urbanismo (figure 1.11).
Optical Glass House in Hiroshima by Hiroshi Nakamura

The architect wanted to create a private oasis behind the glass block façade where residents could still make out the movements of the people and the traffic in the street without the noise of this scenery. As Hiroshi Nakamura said: "The serene soundless scenery of the passing cars and trams imparts richness to life in the house". This articulated garden that admits the city scenery is created by the 6000 pure glass blocks in the façade which with their large mass per unit area isolate the sound. To realize such a façade, glass casting was employed to produce glass of extremely high transparency from borosilicate, the raw material for optical glass. Being a large slender façade, and not able to stand independently if only was constructed by laying rows of glass blocks 5 cm deep, the glass blocks were punctured with holes and strung them on 75 stainless steel bolts suspended from the beam above the façade. Since the glass block façade weights around 13 tons, the steel supporting beam is pre-tensioned and was given an upward camber before casting it with concrete and placing it in the façade. Moreover, there are stainless steel flat bars (40mm X 40mm) at 10 cm intervals to take over the lateral stresses (www.dezeen.com).
The Crown Fountain in Chicago by Jaume Plensa

The fountain is composed of a black granite reflecting pool placed between a pair of glass brick towers. The towers are 15.2 m tall and they use light-emitting diodes (LEDs) to display digital videos on their inward faces. To increase the clarity the glass is white glass, rather than the usual green glass that results from iron impurities. Each block is 127 by 254 by 51 mm with glass thin enough to avoid image distortion. On each block, one of the six faces is polished, and the other five surfaces are textured. The structure is based on individual metal grids (1.5 m tall and 4.9 m-7 m wide) that have cell capacity of an average of 250 blocks and carry the load of the wall and resist the lateral wind forces. Each tower is composed of 44 grids stacked and welded. The combination of the refraction of the glass and the thinness of the metal make the grid virtually invisible (en.wikipedia.org).

Figure 1.10: Photos of the Crown Fountain in Chicago (www.archdaily.com)

Atocha Memorial in Madrid by FAM Architectura y Urbanismo

The most innovative structure worldwide above all for its time is the monument glass cylinder that was built in 2007 in the memory of the victims of the terror attacks in Madrid.

Figure 1.11.: Atocha Memorial in Madrid (www.us.schott.com)
For the first time massive glass blocks will be connected to form a structure using a transparent adhesive and no additional mechanical elements, achieving the entirely transparent visual effect. The 11 meter tall monument consists out of approximate 15100 massive glass blocks that are connected using just a transparent adhesive. The top portion of the glass structure consists out of 5 glass beams with a length of 8.50 m that are supporting 12 glass top plates. The blocks made of borosilicate glass had to be manufactured in round shapes, convex on the one side, concave on the other. This shape made it possible to bond them together in circular rows of blocks and, thus, create the cylindrical shape of the monument. The weight of a glass block is 8.4 kg and the dimensions that were used are 200 mm X 300 mm X 70 mm (www.e-architect.co.uk).

Summing up, when hollow glass blocks are used in a façade, a supporting structure is required to counteract the buckling and lateral loads. This supporting structure usually is a metal grid or thin steel channels embedded in cavities along the edges of the hollow blocks. In the case of solid blocks, due to the lack of standardized structural specifications and strength data on transparent adhesives, steel reinforcement can be used by puncturing the bricks for carrying the vertical loads and withstanding lateral forces. The only case that the entirely transparency has been achieved by using only glass blocks and adhesive is the Atocha Memorial in Madrid, in which the cylindrical shape of the structure assure the structural performance and integrity (figure 1.13).
However, there is no existing project in which a completely transparent glass block system consisting of adhesively bonded solid glass blocks in a flat wall has been applied.

Trying to keep the balance between transparency, structural performance and restrictions on planning regulations which requires the new façade to maintain the same rhythm and composition as the existing 19th century buildings in Amsterdam, MVRDV and Gietermans & Van Dijk architectural offices, ABT company and the glass research group of TUDelft are to take this to the next level and develop a new era of facades that will achieve maximum transparency. This new, innovative structural system consists of only monolithic solid glass blocks bonded with a colorless, UV treated, adhesive that replace the conventional clay brickwork.
Case study: P.C. Hooftstraat (The Crystal House Facade)

The building is located in the historic Pieter Cornelisz Hooftstraat in Amsterdam. PC Hooftstraat was created at the time of the construction of the Vondelpark. Initially, the street was an ordinary residential street, and the houses along it were based on designs by Dutch architect Pierre Cuypers who designed buildings such as the Dutch national museum (Rijksmuseum) and Amsterdam Central Station. The street is named after historian, poet and playwright, Pieter Cornelis Hooft. Close to the late 70s the street slowly transformed from an ordinary neighborhood to the most luxurious shopping area. The street is known for its sleek and stylish ambience with international allure. The world’s finest brands are located here, making the PC Hooftstraat the perfect location for viewing and purchasing exclusive, unique and high quality clothing, accessories and other products. It is considered one of the top ten of the most chic shopping streets in the world (www.pchooftstraat.nl).

Fig. 1.14: P.C. Hooftstraat in Amsterdam (www.pchooftstraat.nl)
It is fact that tourists account for more than half of the sales in famous shopping streets such as Champs-Élysées in Paris and Oxford Street in London. The location of the PC Hoofstraat is the most touristic attraction in Amsterdam because of the most well-known museums (Museumkartier) of Netherlands. Undoubtedly, the facades of the buildings are the most interactive and flexible element and the most important aspect in a design as it sets the tone for the rest of the building. It is really common for architects to use glass when designing the facades of expensive brands shopping stores after the desire of the clients to impress and to attract public showing off their expensive products. Since the building is in a historic street there are local zoning regulations about the composition of the facades. Taking into account all these aspects, MVRDV and Gietermans & Van Dijk architectural offices came up with the brilliant idea of replacing the brickwork with glass bricks keeping the existing building’s historic façade pattern. The end result is a building that will stand out, and at the same time will naturally blend into the urban fabric of the historic street (Oikonomopoulou, 2015).

For a structural point of view, this idea is considered feasible due to the high compression strength of the annealed glass. Actually the compression strength of the annealed glass (typically 200 MPa) is approximately ten times higher than the tension, making solid glass bricks suitable for load-bearing material in a wall structure without the need of any supporting structure. As it can be seen in the figure the façade consists of glass blocks at the lower part (10 m height and 12 m width) and at the top part the existing clay brickwork remains. Between these two parts, there is an intermediate zone where glass and clay bricks are blended creating a prototype composition.
This intermediate zone lies in the level of the second floor, makes it structurally convenient to place a steel beam connected to the slab of the second floor, which will carry the whole load of the upper conventional clay brick façade. Four buttresses which project inwards from the façade, is the solution to the in-plane buckling due to the self-weight of the wall and the out-of-plane buckling due to the lateral wind forces. The buttresses are 5.5 m tall and are made of glass blocks interlocking to the ones of the façade. In order to eliminate the unnecessary joints that can affect both the structural and optical performance/ clarity of the glass wall, the glass wall’s thickness is covered by the width of one brick (210 mm) instead of two as in normal masonry. In favor of conserve the pattern of the historic brick facade, all glass blocks have the same width (210 ±0.25 mm) and height (65 ±0.25 mm) but are cast in three different length sizes (105, 157.5 and 210 ±0.25 mm) (figure 1.16) (Oikonomopoulou, 2015).

Since a solid glass bricks weights much more than a conventional clay brick due to the higher density of glass, reinforcement of the foundation is of important issue for this project. In addition, the mechanical properties of the chosen adhesive are equally critical to the properties of the glass blocks, as the structural performance of the façade lies on the interaction between these two elements rather than on their properties. For this project, a one-component transparent UV-modified acrylate adhesive has been used for the glass to glass bonding. This adhesive develops its strength after being cured photo catalytically where it becomes moisture and water resistant. However, there is an optimum strength level that can be reached in correlation with the thickness of the applied layer. This optimum thickness is approximately 0.1 mm - 0.3 mm (figure 1.17).
Another factor that is significant for the performance of the adhesive is the irregularities on the glass block surfaces since they can lead to the uneven spread of the adhesive affecting the load bearing capacity of the wall. Furthermore, big tolerances per block can create a sizeable offset in height or width of the construction causing architectural flaws. Therefore, high dimensional accuracy of the glass blocks during the manufacturing process should be followed. After testing several architectural prototypes made by the glass research group of TUDelft, this tolerance was found to be ±0.25 mm in both flatness and dimensions.

Even though in the most of the previous cases, borosilicate glass has been used since it has lower coefficient of thermal expansions and less shrinkage on cooling, leading to higher dimensional accuracy of the end product, soda-lime glass was selected for the casting of the glass blocks in the P.C. Hooftstraat project. The main reason is that the strength of the cast solid objects of considerably large thickness is less than the given for soda-lime and borosilicate glass since the manufacturing process is more difficult to control and thus the number and size of defects increase. However the cast and float manufacturing processes of soda-lime glass lead to closely comparable mechanical properties and less defects than this of borosilicate glass. The custom-made fabrication of the final blocks was assigned to Poesia Company in Italy.

More details about the glass block technology and the properties of the transparent adhesive can be found in the next chapter: Glass Technology Analysis
Scope of the work

This research is inspired by the design of the P.C. Hooftstraat project. The scope of this work is the investigation of the structural and thermal performance of the self-supporting glass block façade based on the technology that has been applied in the case study PC Hooftstraat. The main challenges that this research faces are the structural integrity of the four times bigger surface of the glass block façade (20 m X 20 m) instead of (10 m X 12 m) and the building physics of the interior in two more extreme climate conditions compared to that one in Netherlands such as the climate in Finland and in Spain.

In particular, the proposed design in this research lies in the optimal integration of the three disciplines: architecture, structural and building physics.

It offers ideas in architectural designs for renovations of existing buildings focused on enhancing transparency by adding, apart from the glass façade, other glass structural elements, such as glass floor, glass beam, glass column and glass roof.

The main challenge of this new façade, however, is to combine an interesting and innovative design with a safe structure. The use of glass in construction must be treated with the utmost attention. Thus, the concept will be oriented towards the structural performance of the façade and the added glass components. Furthermore, crucial is the design of the connections between the glass load bearing components and the existing concrete structure.

As a typical envelope it should accommodate to a certain level other functionalities as well such insulation, weatherproofing, possibility of sun protection and serviceability. All these are the challenges that have to be taken into account and result in an interesting design that will utilize the state of the art technologies in glass structures in a sustainable way. For this purpose, the energy and thermal performance of the renovated building will be thoroughly explored through software simulations and evaluated. Passive energy systems such as natural ventilation and glass coatings will be utilized, in order to minimize the power demand of the mechanical systems for achieving the desired interior thermal comfort conditions.

Thus, the ultimate goal of this research, is to highlight the potentials of this innovative technology and together with the realized project in Amsterdam will trigger future designs on either renovation of existing buildings or on new structures where the primary concern is transparency.

In conclusion the research question can be formed as follows:

What are the design strategies that one can employ when applying the glass brick structural wall technology? How this innovative technology can work in a bigger scale than the one in PC Hooftstraat from an architectural and structural point of view? And what will be the consequences in the interior climate when this type of façade is applied in colder and warmer climate than in Netherlands?
This question is further broken down in sub questions such as:

- What are the design principles for glass structural elements?
- How should a structural joint between glass components be designed in order to enhance transparency? How the concrete and glass elements are connected?
- What are the ways in which we can enhance the safety of the glass brick façade and the glass structural elements?
- What are the parameters that can influence the performance of a glass component?
- What sustainable measures can be used in order to minimize the power demand when applying such big exterior glass surfaces?
Methodology

The purpose of the present work is to provide an integrated design which can be used for renovations of existing buildings making use of the self-supporting glass block façade technology.

The five main steps that have been followed in this research are:

**Step 1 ➔ Glass Technology Analysis**

In this first chapter, there is an analysis about the material glass and its thermal and structural properties. An overview of the different types of glass and the considerations one can take into account when designing with glass can be found. Moreover, there is an elaborated description of the safety concepts that can ensure the structural integrity of glass components. The factors that have been affected the choice of the safety factor for the design are also part of this chapter. Last but not least, information about the construction of the structural glass block wall and its components, glass block and adhesive, is given.

**Step 2 ➔ Architectural Design**

Some architectural principles were taken into consideration at the very first step of the design, with pure transparency being the main one. One can see in this part the steps that led to the final design and how this had been affected by the application of the passive systems such as the chimney effect that the cut glass floors behind the façade combined with the glass roof creates. Impressions and views of the final design, as well as plans of each of the floors indicating the functions and the escape routes can be found in this chapter. The design principles of the glass lift and glass staircase are also viewed in this step. It should be noted that the building in which the interventions have been applied is not real and it is a virtual creature, its structure and style are following these of the building in P.C. Hooftstraat.

**Step 3 ➔ Structural Design**

The most crucial part of the design is the attestation of the structural integrity of the system. After studying the design principles of each of the structural components that have been used, the whole structure is tested under loads by simulating it using the Finite Element Method (FEM) with the help of ANSYS software. The output of these simulations has determined the final optimum dimensions of the structural elements. The results of the laboratory tests and experiments that have been conducted by the glass research and transparency group of TUDelft are cited at the final part of the chapter validating as well the structural integrity of the components and as a consequence of the design.

**Step 4 ➔ Connection Details**

The use of glass in construction must be treated with the utmost attention. It is due to wrong handling during the installation or not carefully designed details that the probability of failure from local stress peaks can be increased. Therefore the connections that are assigned to transfer the loads and to join the pieces must be very thoughtfully designed and realized. This step is focused on the most crucial details of the whole design.
Step 5 ➔ Thermal Performance

Last, but equally important in the determination of the final design, is the evaluation of the thermal performance using the Design Builder software which is based on the Energy Plus simulation tool. It is common that such a big glass surface develops really high temperatures in the interior leading to a really unsustainable design. In this part, after defining the adaptive thermal comfort model for each of the three different climates, the passive measures that can be applied in such design and their results are thoroughly described. Finally, thermal shocks tests have been conducted on the bricks in order to clarify the behavior of the last in an extreme climate situation when high temperatures can be occurred causing overheating in the blocks following by sudden showers.
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Glass technology analysis

This chapter gives an introduction to the fundamental aspects of glass as a building material, providing information about properties of glass and basic structural design considerations. While it is by no means exhaustive, it provides the information required to understand subsequent chapters. More information can be found at the literature given at the end of this chapter.

Glass

The word glass is derived from glaza, the Germanic term for “amber”, “glare” or “shimmer”. Glass is produced by a mixture of silicon oxide, alkaline oxides and alkaline earth oxides that is heated up to temperatures exceeding 1100°C. There are general differences in the molecular structure of a material between its 3 different states, solid, liquid, gas. These changes can be observed in strength as well as density. When a material changes state from liquid to solid then a lattice structure is formed from the molecules that causes its volume to decrease. This phenomenon is the so-called crystallization. The molten state cools to a solid amorphously form without crystallization. This happens because of the controlled cooling down process during the primary production of glass. It is due to that disordered crystal structure lacking a periodic geometry that makes glass behavior so difficult to study and not have a fixed melting point. Its structural state can be compared with that of liquids and molten materials, which like glass do not possess any properties dependent on direction. The transformation point from melt to solid or vice versa, lies around 600°C (Schittich, 1999).

Figure 2.1: The amorphous structure of glassy silica (SiO2) in two dimensions (left) (en.wikipedia.org/wiki/Glass)
Basic types of glass

Glasses may be devised to meet almost any imaginable requirement. There are many different types of glass with different chemical and physical properties and each can be made by a suitable adjustment to chemical compositions. The properties of the most common type of glasses used in the construction field are presented in the following table.

<table>
<thead>
<tr>
<th></th>
<th>Quartz</th>
<th>Soda lime</th>
<th>Basic types of glass</th>
<th>Lead</th>
<th>Alumino silicate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price (euro/kg)</td>
<td>5140-8580</td>
<td>1160-1370</td>
<td>3430-5150</td>
<td>3300-5100</td>
<td>1170-1370</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>2170-2200</td>
<td>2440-2490</td>
<td>2200-2300</td>
<td>3950-3990</td>
<td>2490-2300</td>
</tr>
<tr>
<td>Young’s Modulus</td>
<td>68-74</td>
<td>68-72</td>
<td>61-64</td>
<td>53-55</td>
<td>85-89</td>
</tr>
<tr>
<td>Hardness (kg/mm²)</td>
<td>450-950</td>
<td>440-485</td>
<td>84-92</td>
<td>472-525</td>
<td>68-75</td>
</tr>
<tr>
<td>Tensile Strength (Mpa)</td>
<td>45-155</td>
<td>30-35</td>
<td>22-32</td>
<td>23-24</td>
<td>40-44</td>
</tr>
<tr>
<td>Compressive Strength (Mpa)</td>
<td>1100-1600</td>
<td>360-420</td>
<td>264-348</td>
<td>232-244</td>
<td>400-440</td>
</tr>
<tr>
<td>Yield strength elongation 0% (Mpa)</td>
<td>45-155</td>
<td>30-35</td>
<td>22-32</td>
<td>23-24</td>
<td>40-44</td>
</tr>
<tr>
<td>Thermal expansion coefficient (10⁶/K)</td>
<td>0.55-0.75</td>
<td>9.1-9.5</td>
<td>3.2-4</td>
<td>8.82-9.18</td>
<td>4.11-4.28</td>
</tr>
<tr>
<td>Thermal conductivity (W/(m*K))</td>
<td>1.4-1.5</td>
<td>0.7-1.3</td>
<td>1-1.3</td>
<td>0.82-0.86</td>
<td>1-1.5</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.15-0.19</td>
<td>0.21-0.22</td>
<td>0.19-0.21</td>
<td>0.23-0.24</td>
<td>0.23-0.24</td>
</tr>
<tr>
<td>Softening point (°C)</td>
<td>1665</td>
<td>726</td>
<td>820</td>
<td>631</td>
<td></td>
</tr>
<tr>
<td>Strain point (°C)</td>
<td>1070</td>
<td>510</td>
<td>510</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2.1: Properties of the different glass types (Schittich, 1999)
Manufacturing of glass

The main ingredients of structural glass are high quality sand, soda ash, limestone, salt cake, dolomite and melt heated until the mixture reaches a highly viscous consistency. Although there are lot of different production processes and methods, the basic production steps are always similar and consist of: melting at 1600°C – 1800°C, forming at 800°C – 1600°C and cooling at 100°C – 800°C. Currently, the float process is the most popular primary manufacturing process and accounts for about 90% of today’s flat glass production worldwide. The major advantages of this production process are its low cost, its wide availability, the high optical quality of the glass and the large size of panes that can be reliable produced.

The float glass production process is shown schematically in figure 2.2. The raw materials are melted in a furnace at temperatures of up to 1560 °C. The molten glass is then poured continuously at approximately 1100 °C onto a large bath of molten tin whose oxidation is prevented by an inert atmosphere consisting of hydrogen and nitrogen. The glass then floats on the tin, spreading and seeking a controlled level surface. In the controlled production process, the molten glass is allowed to spread to a width of 300 to 360 cm, depending on the glass thickness being produced. The thickness is controlled by the speed at which the slowly solidifying glass ribbon is drawn through the tin bath. Reducing the speed increases glass thickness and vice versa. After about 120 m of travel through the cooling Lehr, in order to prevent residual stresses being induced within the glass, it emerges as a continuous ribbon of glass at merely room temperature. After annealing, the float glass is inspected by automated machines to ensure that obvious visual defects and imperfections are removed during cutting. Automatic cutters are used to trim the edges and to cut across the width of the moving glass ribbon. This creates sizes which can be shipped or handled for further processing. Any unwanted or broken glass is collected and fed back into the furnace to reduce waste (Haldimann, 2006).

![Figure 2.2: Production process for float glass (www.guardian-russia.ru)](image-url)
Material properties of glass

Transparency

This property is based on the atomic structure of the material (figure 2.1) and the non-crystallization as well as the special bonds developed within it (Schittich, 1999). In other words, this property is based on the non-absorption of visible spectrum of glass. When the light cross the material, only UV and infrared wavelengths are absorbed letting visible light to cross without any restrictions. In general, optical properties depend on the glass thickness, the chemical composition and the applied coatings.

![Figure 2.3: Glass plates (left), Riverside Clubhouse, Jiangsu by TAO Trace Architecture Office (right)](image)

Thermal properties

Glass has a very much lower thermal expansion coefficient $a = 9 \times 10^{-6}$ (1/K) compared to that of steel $a = 12 \times 10^{-5}$ (1/K) (Schittich, 1999). This difference can cause problem when there is connections between these two materials, creating local stress concentration in the glass. These stresses in the connection can be caused by solar radiation concentration or the material being subjected to artificial heating or cooling. Therefore, a thermal stress break occurs when the center of the glass in a window unit becomes hotter than the edge of the glass that is inside the framing and the center expands. The resulting tensile stress placed on the glass edges can exceed the strength of the glass causing the glass to break (figure 2.4).

A glass fracture can be identified as a thermal stress breakage if the start of the crack is at $90^\circ$ to both the edge of the glass and the face of the glass (figure 2.5).

The temperature stresses can be calculated as follows:

$$
\sigma = (\Delta \alpha \ast T + \alpha \ast \Delta T) \ast \frac{E_1}{(1 + \frac{E_1 A_1}{E_2 A_2})}
$$

or for large steel cross sections:

$$
\sigma = (\Delta \alpha \ast T + \alpha \ast \Delta T) \ast E
$$
where:

\[ \sigma = \text{stress} \]
\[ \alpha = \text{coefficient of thermal expansion} \]
\[ T = \text{temperature} \]
\[ \Delta = \text{difference} \]
\[ E_1E_2 = \text{modulus of elasticity of glass/ steel} \]
\[ A_1A_2 = \text{cross sectional area of glass/ steel} \]

*Figure 2.4: Thermal stress break in a window (www.educationcenter.ppg.com/glasstopics/thermal_stress.aspx)*

*Figure 2.5: Identifying thermal stress glass breakage (AGGA, 2011)*
Strength

The words that one can describe easily the glass are: "transparent," "fragile," "brittle," "light," "sharp," and "shatter." Given the historic fragility of glass in any of its uses, this would be appropriate terminology for its description. The maximum elongation is in the area of 0.1%. After the slightly extension out of the boundaries of elastic deformation glass is led to abrupt failure. There is no plastic behavior zone and therefore it is not possible to anticipate its failure.

![Graph comparing stress–strain curves for brittle (e.g. glass) and ductile (e.g. steel) materials](www.anasys.co.uk/library)

Based on atomic bond strength glass seems quite strong in compression with a strength calculation of approximately 21000 N/mm² and weak in tension with stress level below 100 N/mm². In theory, given its commonly accepted chemical bonds and the energy it would take to break them, the values for the tensile strength of manufactured glass is much lower than expected. The failure point is not easy to be defined and only by performing stress and breakage tests on an established size of glass the results will set the value.

In general, the strength of materials are determined by conducting tensile, bending and compression tests. For most of the structural materials the failure stress for a large enough test series shows an average and a standard deviation. However, this is not applied for glass due to the fact that the brittle failure behavior of glass is not solely stress based but also flaw based. The strength of glass is determined by the processing, as the results from one of the experiments conducted by Veer at TUDelft shows (Figure 2.7 and table 2.2) (Veer, Riemslag, & Romein, 2007). Impurities or imperfections, such as invisible, irregular cracks in the surface of the glass can generate stress concentrations and induce tensile stresses within the glass that often lead to failures at much lower and wildly varying failure stresses, even between otherwise seemingly identical test samples (Ledbetter, Keiller, & Walker, 2006).
Besides, large flaws on the surface of glass will destabilize glass, since it reduces its ability to handle localized, concentrated stresses. Scratches and chipping creates raw edges, and edges of glass are usually weaker than the surface, since its inherent brittle properties allows shearing into razor-thin shards. Once an edge is exposed, glass is much more vulnerable to accidental damage and environmental wear. Even small flaws and scratches on the surface can lead to extremely high stress peaks when the element is subjected to mechanical actions. These flaws in the surface is unlikely to be avoided during the manufacturing and transportation process and during the life of the element. Three distinct regions can be seen on the fracture surface (figure 2.8). In the past, these inherent flaws limited the structural use of glass.

Table 2.2: Bending strength of machine cut glass, specimens 400 long and 40 mm wide, 6 mm thick (Veer et al., 2007)

<table>
<thead>
<tr>
<th>Test configuration</th>
<th>Average failure stress (Mpa)</th>
<th>Standard deviation (% of average)</th>
<th>Number of tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed</td>
<td>65.6</td>
<td>21.7</td>
<td>30</td>
</tr>
<tr>
<td>Bur up</td>
<td>100.3</td>
<td>32.8</td>
<td>30</td>
</tr>
<tr>
<td>Bur down</td>
<td>49.4</td>
<td>12.6</td>
<td>30</td>
</tr>
<tr>
<td>Cut and ground</td>
<td>82.5</td>
<td>8.5</td>
<td>30</td>
</tr>
</tbody>
</table>

Figure 2.7: Weibull plot of data in table 1 (Veer et al., 2007)

Figure 2.8: SEM micrograph of a glass fracture (right) surface Fracture surface of glass (10x) (left) (www.doitpoms.ac.uk - university of Cambridge)
Moreover, glass will break when the stress is applied for a longer period of time but can be strong enough to endure stress for a brief period of time. Another factor that influence the strength of the glass is the integrity of the surface. Larger the sheet of glass, higher the potential for surface flaws and in consequence more likely to fail. Even though the modulus of elasticity of glass is higher than others materials, apart from this of steel, glass appears a brittle mechanism that will not allow large deformations under substantial stress. Finally, the sharp fragments after shattering that can cause injury to those below, can characterize glass as unsafe material (Leitch, 2005).

Structural Design with Glass

Codes and Standards

Currently, there is little industry standardization, and consequently no comprehensive design code or independent regulating body for glass comparable to the American Concrete Institute or the American Institute of Steel Construction. National governments or local municipalities may have loose guidelines or rules of thumb that each follows, but there is a distinct need to provide a more comprehensive glass design code if architects and engineers plan to gain acceptance for their load-bearing glass structures. European nations are at the forefront of structural glass technology. The Netherlands is home to many of the notable examples of structural glass and the United Kingdom's Institute of Structural Engineers has published the most thorough design guidelines to date. There are simple design tables offered by manufacturers, like Pilkington and DuPont, for patented glazing systems for pin connections, cable-trussed panes, glass handrail and guardrails and other systems after conducting extensive testing and quality assurance assessments before marketing a product. Proprietary information has made it difficult to standardize methods and material information at this level. In order to produce a definitive text for the design of glass, much more research must be conducted and an overarching authoritative body must be formed (Connor, 2011).

Design Methodology

As mentioned, there is no standard method of designing structures that use glass in an innovative or creative way. Glass behaves basically as an elastic material. This means that the theory of elasticity is directly applicable for determining stresses and strains. It can be expected that all calculations also in the future will be based on the theory of elasticity. However, this theory is derived for small strains and corresponding stresses, without giving information about the failure stress. Failure stress is size, time, temperature and sometimes humidity dependent, which need to be addressed.

Fracture mechanics and stochastic mechanics are methodologies which can be seen as “add on” theories to the theory of elasticity to explain the failure behavior of glass. Both theories have their advantages and disadvantages. These methods are the most well-known among designers and although they have a distinct theoretical approach, they are not contradictory and thus can be used in combination with one another. Modern design philosophy is based on statistical principles where the goal is that the failure stress should reflect a certain failure probability.
More specific, fracture mechanics is a deterministic method which gives the stress concentration at the tip of a crack as a function of geometry and loading conditions. This can be compared with a critical value to establish whether a crack will grow or not. The basic theory of fracture mechanics assumes that a critical crack exist perpendicular to a tensile stress field. No explicit consideration of a possible size and time dependence is included in the theory. It is very possible that this flaw information can be characterized with a statistical distribution, perhaps a Weibull distribution. With this technique it is possible to estimate the influence of a size and time dependence (Connor, 2011), (Khorasani, 2004).

In stochastic mechanics it is initially assumed that flaw characteristics are size and time dependent and the result is that the failure stress can be characterized with a Weibull distribution. Besides the influence of these flaws depend on the total stress field within a body or acting on surfaces. The result is directly applicable to body shape and loading conditions. Moreover, as it is mentioned above, since the mechanical resistance of glass depends essentially on the presence of superficial cracks of random size and orientation, experimental data generally turn out to be broadly dispersed and require a statistical basis for interpretation, which must rely upon a micromechanically-motivated model. Failure of glass is in fact associated with the progression of one dominant defect (micro-crack), i.e., the one which undergoes the most severe combination of stress with respect to its intrinsic size (crack width and stress intensity factor). This is why the weakest-link model of failure, usually interpreted at the macroscopic level by a Weibull statistical distribution of material strengths, is usually considered the one which best adapts to this case (Badalassi, Biolzi, Royer-Carfagni, & Salvatore, 2014).

Summing up, the design methods are:

- **Allowable Stress**
  This design method is based on permissible stresses. It is the simplest method compared with the rest. However, it does not do justice to the materials behavior, leading to relatively high safety factors.

- **Probabilistic Approach**
  This method uses fracture mechanics to describe the statistical nature of usable strength in glass and the influences of load duration, area under stress and ambient humidity. It is far more accurate than the allowable stress design method, but often much more complicated to implement it.

- **Limit State Design**
  The limit state design method is the most common approach for designing glass. It takes into account different statistical distributions on the material’s strength and the loading stresses (e.g. wind, snow). It is based on the principles of **fail-safe** concept where the system is examined under different failure scenarios and it must possess a residual stability after the failure of individual components. However, it is complicated method that requires an explicit examination of the failure behavior of individual components under different and multiple forms of failure scenarios in a structural system. Moreover, due to the fact that glass strength is extremely scattered for any particular glass pane, a safe-life guarantee for every individual glass component is not attainable. Thus, it is wise, when designing with glass, to divide glass components into those that require a safe-life guarantee and those that could cause local failure but may not severely affect the structural integrity of the structural purpose as a whole.
Risk analysis

“Engineering risk is the product of the chance that something happens multiplied by the consequences of it happening.” (Fred Veer, structural glass course lectures) In any kind of structural work, a certain level of stability and safety against failure is required. Such a level is assessed on a statistical basis, defining the probability of collapse that is reputed acceptable as a function of the consequences of the collapse itself and the nominal lifetime of the construction. According to the EN 1990, there are three classes which categorized the constructions based on their importance (residential, office, agricultural buildings) depending on the potential consequences of the failure of a structure in economic, social and environmental terms including loss of human life.

<table>
<thead>
<tr>
<th>Class</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC0</td>
<td>Specifically non-structural elements. Following failure, negligible economic, social and environmental consequences and practically null risk of loss of human life.</td>
</tr>
<tr>
<td>CC1</td>
<td>Following failure, low risk of loss of human life and modest or negligible economic, social and environmental consequences. Glass structural elements whose failure involves scarce consequences fall into this category.</td>
</tr>
<tr>
<td>CC2</td>
<td>Following failure, moderate risk of loss of human life, considerable economic, social and environmental consequences. Glass structural elements whose failure involves medium-level consequences belong to this category.</td>
</tr>
<tr>
<td>CC3</td>
<td>High risk of loss of human life, serious economic, social and environmental consequences: for instance, the structures of public buildings, stages and covered galleries, where the consequences of failure can be catastrophic (concert halls, crowded commercial centers, etc.). Glass structural elements whose failure involves high-level consequences fall into this category.</td>
</tr>
</tbody>
</table>

Table 2.3: Proposal of classes of consequences for glass elements, according to their specific importance (Badalassi et al., 2014)

Glass structural elements can thus be divided into the following classes:
- **Class zero**: elements with no structural function, with a consequence class CC0
- **First class**: elements with a consequence class CC1
- **Second class**: elements with a consequence class CC2
- **Third class**: elements with a consequence class CC3

Each class of structural element can generally be assigned a decreasing probability of collapse, from the zero class to the third class, as they correspond to ever-more significant and serious consequences as a function of the design lifetime of the structure in question.

<table>
<thead>
<tr>
<th>Class</th>
<th>Probability of collapse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero</td>
<td>probability of collapse to be evaluated in consideration of costs of maintenance and repair</td>
</tr>
<tr>
<td>First</td>
<td>4.83<em>10^-4 over 50 years; 1.335</em>10^-5 in 1 year</td>
</tr>
<tr>
<td>Second</td>
<td>7.235<em>10^-5 over 50 years; 1.301</em>10^-6 in 1 year</td>
</tr>
<tr>
<td>Third</td>
<td>8.54<em>10^-6 over 50 years; 9.960</em>10^-8 in 1 year</td>
</tr>
</tbody>
</table>

Table 2.4: Probability of collapse as a function of the different structural element classes (Badalassi et al., 2014)
There are two main tools to classify risks. The risk matrix and the Fine & Kinney method. For this design, the risk of damage is determined according to the method of Fine & Kinney, as described in the Dutch code: NEN 2608:2011/C1. The risk is defined as the factor \( RD = PD \times ED \times SD \). Where \( PD \) is the probability that damage will occur, \( ED \) is the exposure of the object to possible damage and \( SD \) is the seriousness of the injury when the object collapses totally.

The factor has the following relationship with glass breakage:
- \( RD < 70 \) : glass layer breakage, single sided
- \( 70 < RD < 400 \) : glass layer breakage, double sided
- \( RD > 400 \) : complete breakage of the constructive element

When \( RD \) is smaller than 70, it means that in a structure of 2 layers of glass, one layer should be considered broken and the remaining layer must be capable of carrying all the load, whereby the load factors are reduced from 1.2 and 1.5 to 1.0.

When \( RD \) is between the values 70 and 400, it means that 2 layers should be considered broken. That consequently demands a structure with 3 layers at least.

When, finally, \( RD \) is higher than 400, then the whole element is considered broken. In this case some additional secondary structure systems are necessary. (Louter, Bos, Belis, Lebet, 2014)

This factor can be estimated for each glass structural component separately in a design. **Follows the estimation of RD for the glass beams which support the glass floors in the design.**

<table>
<thead>
<tr>
<th>Probability intentionally or unintentionally</th>
<th>WS</th>
<th>Exposure of the structural element</th>
<th>BS</th>
<th>Consequence at complete failure</th>
<th>ES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virtual impossible</td>
<td>0.1</td>
<td>Very rarely</td>
<td>0.5</td>
<td>First aid</td>
<td>1</td>
</tr>
<tr>
<td>Practically impossible</td>
<td>0.2</td>
<td>Several times a year</td>
<td>1</td>
<td>Minor injury</td>
<td>3</td>
</tr>
<tr>
<td>Possible, but very unlikely</td>
<td>0.5</td>
<td>Monthly</td>
<td>2</td>
<td>Serious injury</td>
<td>7</td>
</tr>
<tr>
<td>Only possible in the longer term</td>
<td>1</td>
<td>Weekly</td>
<td>3</td>
<td>One dead</td>
<td>15</td>
</tr>
<tr>
<td>Uncommon, but possible</td>
<td>3</td>
<td>Daily</td>
<td>6</td>
<td>More than one dead</td>
<td>40</td>
</tr>
<tr>
<td>The best possible</td>
<td>6</td>
<td>Constantly</td>
<td>10</td>
<td>Catastrophe, many deaths</td>
<td>100</td>
</tr>
<tr>
<td>Can be expected</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Table 2.5: Determination of RD-value (ABT Technoledge lecture – Nijss, 2014)*

\[ RD = PD \times ED \times SD = 0.5 \times 6 \times 15 = 45 < 70 \]

Thus, by the definition of risk, it is clear that two principle ways exist in order to minimize it: diminish consequence or reduce probability (or both) [Bos, 2009]. In the following section are presented the main measures that can be taken for reducing the risk.
Safety

One of the most critical and challenging question regarding the safety and structural integrity of the glass structures is:

‘How can one achieve safe failure behavior in glass structural components and structures?’

The strategies for reducing the risk in failure for the glass structures are based on three levels. The level of material, the level of elements and the level of the complete structure. In the first level, the change of the type of glass can add redundancy to the structural element while in the second level the goal is to increase a margin between initial failure and collapse. Finally, for the third level, the goal is to sustain the principle that the local damage (the element failure) should not result excessive global failure (Bos, 2009).

The measurements for the scale level of elements are:

- Thermal prestressing (strengthening or tempering) as they are described in the following section. The failure stress is increased while the sensitivity to certain common failure causes such as thermal breakage is decreased.
- Laminating (foil or resin interlayers are applied to compose components that consist of multiple glass layers).
- Dimensioning with high safety factors (overdimensioning).
- Applying sacrificial sheets, where is possible, which when they fail, the rest of the layers are still able to carry the load.
- Minimizing the surface defects which decreases the strength of the glass. These defects are caused by the process of manufacturing, cutting, polishing, grounding the edge and during the transport and assembling. Therefore, these processes should be controlled and conducted thoroughly using the right settings and maintenance of the machines and having designed with details the transportation and installation of the glass components before the execution (Faidra Oikonomopoulou, 2012).
- Proving the structural integrity of each element by conducting laboratory experiments where is possible.

These techniques are based on the idea that safety is ensured by the fact there is always at least a part of glass that is never broken and that this part is dimensioned so that it will be able to carry the applied loads on its own.

The measurements for the scale level of structure are:

- Providing alternative load paths, for example by having components span more than one field or the interconnection of multiple components.
- Loading structures in compression rather than tension (stacking components instead of hanging them; i.e. using gravity to keep components in place).
- Designing hyperstatic structures (like three dimensional lattices), thus ensuring that the failure of a single component or a limited amount of components does not lead to global instability and complete structural failure.
- Providing back-up in joints.
Assuming a compressive strength equal to the tensile. After lot of research and laboratory tests conducted by Fred Veer in TUDelft at 2006, it is proved that glass breaks in compression in much lower values than the named one. More particularly, the bottom line of the stress failure for all the specimens was 20 MPa, making this value a conservative design strength for annealed glass. The respective value for heat strengthened is 40 MPa (Veer, 2007).

Running dynamic, apart from static, and thermal, apart from structural, simulations since the strength of glass is dependent on the duration of the application of load and on the temperature. Since in this project, many design innovations have been explored, it is vital that various design concepts for safety to be analyzed and tested.

**Strengthening of Glass**

There are a lot of different processes that one can follow in order to overcome the brittle and unpredictable failure behavior of glass under tension. The type of glass, the adhesive and the coatings play a critical role in the overall stiffness, strength and post-breakage behavior of these components. The choice of the type of glass is based on the type of structural element that will be used. Each element has its own requirements and design safety margins in terms of deflection and stresses. The material properties and the manufacturing process should be examined thoroughly before the use of the glass as structural material. The processes that enhance the safety and strength performance of glass can be conducted during basic manufacturing: annealing, tempering, heat treating and laminating process (Louter, 2011). This section provides an overview of these processes and the final choice of the type of glass that is used for this project.

**Thermal treatment**

**Annealed Glass**

Annealing is a process of slowly cooling hot glass to relieve internal stresses. The glass is manufactured as float glass heated to about 15000°C, and then cooled slowly under controlled conditions that avoid the introduction of new stresses. If annealed glass breaks, the shards can be extremely dangerous. Glass which has not been annealed is liable to crack or shatter when subjected to a relatively small temperature change or mechanical shock and it will retain many of the thermal stresses caused by quenching and significantly decrease the overall strength of the glass. The characteristic tensile bending strength of annealed glass is 45 MPa (Leitch, 2005).
Toughened (Tempered) Glass

It is the process of enforcing compression in the outside “skin” of a glass panel. It is this compressive stress that gives the toughened glass increased strength. This is because any surface flaws tend to be pressed closed by the retained compressive forces, while the core layer remains relatively free of the defects which could cause a crack to begin. The glass is then more resistant to impact loads since the induced peak tensile stress at the point of impact is compensated by the compression of the skin (Figure 2.10). Any cutting or grinding must be done prior to tempering. Cutting, grinding, and sharp impacts after tempering will cause the glass to fracture. Toughened glass is used when strength, thermal resistance, and safety are important considerations. An important effect of glass toughening is a change in the fracture pattern. When the stresses exceed the allowable stress, the balance between the compressive skin and the tensile core of the panel is destabilized. The result is an explosive release of the stresses that causes the panel to break into hundreds of small fragments (Figure 2.11), called dice that are less dangerous than the large sharp fragments that result from the shattering of non-toughened glass. The characteristic tensile bending strength for fully tempered glass is 110 MPa (Leitch, 2005).
Heat Strengthened Glass (HS)

Heat strengthened glass is similar to tempered glass except that the cooling is done at a much slower pace. Although heat-strengthened glass appears to fracture like annealed glass, it is approximately twice as strong to a comparable thickness and configuration of annealed glass. It is valued for its mechanical strength which is twice of normal annealed and half of fully tempered glass. Heat strengthened has a comparatively flatter finish than fully tempered glass. It therefore has lesser optical distortions and so can be used in places where high optical quality is required. It can be used for general glazing where additional strength or resistance to mechanical/thermal loads caused by certain tinted or coated glass. The characteristic tensile bending strength for HS glass is 70 MPa (Leitch, 2005).

![Figure 2.12: Fracture pattern of Heat Strengthened Glass](image)

Fully Tempered vs Heat Strengthened

The choice between these two is taken after taking into account the advantages and drawbacks (table 2.6), the fracture pattern (Figure 2.13), the characteristic tensile bending strength and the requirements that each structural element should satisfy in the design.
# Heat Treated Glass Comparison

<table>
<thead>
<tr>
<th>Heat Strengthened</th>
<th>PRO'S</th>
<th>CON'S</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Increased resistance to wind and snow loads</td>
<td>Does not meet safety glazing requirements unless laminated</td>
</tr>
<tr>
<td></td>
<td>Increased resistance to thermal stresses</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Typically remains in opening if broken</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Heat soaking not required</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Full Tempered</th>
<th>PRO'S</th>
<th>CON'S</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Meets safety glazing requirements</td>
<td>Evacuates opening upon breaking</td>
</tr>
<tr>
<td></td>
<td>Increased resistance to wind and snow loads</td>
<td>Increased probability of breakage due to NiS stones</td>
</tr>
<tr>
<td></td>
<td>Increased resistance to thermal stresses</td>
<td>Increased cost and risk of damaging product due to heat soaking and the associated extra steps and handling required</td>
</tr>
</tbody>
</table>

*Table 2.6: Heat Treated Glass Comparison (Glass Technology, 1992)*

*Figure 2.13: Fracture patterns of HS Glass (left) and Tempered Glass (right)*
Laminated glass

Laminated glass is a type of safety glass that holds together when shattered. A thin layer of adhesive permanently bonds together two or more sheets of annealed, heat-strengthened, or fully-tempered glass (Figure 2.14). When the sheets are joined under 250°C heat and compression, they create a single panel that has significantly greater strength and ductility than its single laminate counterpart. The interlayer keeps the layers of glass bonded even when broken, and its high strength prevents the glass from breaking up into large sharp pieces. This produces a characteristic "spider web" cracking pattern when the impact is not enough to completely pierce the glass. As the glass fragments stick to the foil, a residual structural capacity is obtained through an arching or interlocking effect of the glass fragments (Louter, 2011) (Figures 2.15, 2.16).

Figure 2.14: Two or more panes bounded together by some transparent plastic interlayer. Glass panes may have identical thickness and heat treatment or different ones.

Figure 2.15: After breakage the glass fragments adhere to the film/interlayer so that a certain remaining structural capacity is obtained as the glass fragments "arch" in place (Ungureanu, 2011)
The most common foil interlayers are polyvinyl butyral (PVB), Ethylene-vinyl acetate (EVA) and SGP (DuPont’s Sentryglass). PVB, under elevated temperature and pressure, is bonded to glass sheets in autoclaves (figure 2.17). This material has little strength and stiffness of its own and is mainly used to prevent glass shards from coming off. It usually relies on the load carrying capacity of some unbroken glass sheets for residual strength (Bos, 2009). In the case of the EVA, the thermoset EVA, offers a complete bounding (crosslinking) with the material whether it is glass, polycarbonate, P.E.T. or other types of products and it is used mostly in solar applications. Finally, SGP interlayer has been developed for hurricane, vandalism and burglary resistant glazing. SGP has already been applied in the glass structure of the Apple Stores in New York and Boston, laminating components up to 15 meters long, the largest laminated component that Sedak industry has achieved. Compared to common PVB, SGP has 5 times higher tear strength and makes the laminated component 100 times more rigid. Moreover, it offers higher transparency with low haze index and it is less vulnerable to moisture exposure and to yellowing over time (figure 2.18). The main disadvantage compared to PVB is the high price of Sentryglass (Ungureanu, 2011).
The advantages of laminated glass are numerous and extend beyond the obvious safety benefits that multiple lites of bonded glass provide. It is normally used when there is a possibility of human impact or where the glass could fall if shattered and also for architectural applications. Skylight glazing and automobile windshields typically use laminated glass. In geographical areas requiring hurricane-resistant construction, it is often used in exterior storefronts, curtain walls and windows. Moreover, tinted and
translucent interlayers can absorb and refract light so as to minimize solar gains within the interior of a building. These spectrum-specific adhesives can be designed to block high altitude summer sun radiation, while permitting low altitude winter sun. These properties translate into energy and financial savings. Finally, the interlayer provides a damping effect that minimizes unwanted external noise—truly a boon to high-density urban areas where noise reduction can lower stress and increase productivity (Schimmelpenninck & Schimmelpenninck, 2012).

Given the developments and the above factors, it is clear a laminated glass interlayer in combination with tempered or heat-strengthened glass may offer the optimal blend of characteristics for applications where the risk of injury from glass fallout is a primary concern. For non-safety glass applications, where strength and resistance to spontaneous breakage is desired, non-laminated heat-strengthened glass should be considered due to its lower costs.

**Limitations in size**

There are some limitations in post processing for the size of the element. Due to the manufacturing process, the maximum raw glass pane dimensions are usually 6 m x 3.21 m. What limits the glasses length is not the production process but the overhead cranes that handle the glass from the cutting table to the storage. Longer panes (8-12 meters long) can be produced on demand, yet with a significant increase in cost. Nowadays, China claims the biggest glass sheets dimensioning 4.2 m x 25 m. Hence, except of the limitations in size, there are also the restraints of glass processing: the tempering ovens in glass facilities in Europe can temper up to 8 m and in China up to 14 m. Limitations on width tend to be typically at 2.7 m with a very few reaching 3 meters maximum. Lastly, laminating autoclaves in glass facilities are also limited in size, existing up to 15 m x 3 m in Sedak Company [O’ Callaghan, 2009]. However, in the present design, the biggest glass laminated element is below the limit (6m X 2m, which is the glass fin that supports the glass floors).
Safety factor

The safety factor (SF), also known as Factor of Safety (FoS) is a term describing the structural capacity of a system beyond the expected loads or actual loads. It is applied in order to reduce the chance of failure in a structure. So the safety factor is a ratio of maximum strength to intended load for the actual item that was designed.

\[
\text{Factor of Safety} = \frac{\text{Material Strength}}{\text{Design Load}}
\]

The greater the safety factor, the lower the likelihood of structural failure and the more stress cycles the structure can take. However, an increased factor of safety follows a heavy component and as a result to a more expensive structure. Thus, the choice of the right safety factor should be studied carefully and only after evaluation of both safety and cost.

The considerations that should be taken into account before determining the factor of safety in a structure are:

- The accuracy of predictions on the imposed loads, strength, wear estimates, and the environmental effects to which the product will be exposed in service
- The consequences of engineering failure (risk analysis)
- The cost of over-engineering the component to achieve that factor of safety
- The manufacturing flaws (variability in quality of workmanship)
- The type of load (static or dynamic)
- The variation in the material’s properties
- Uncertainty

When the properties of the material are known in detail and accurate laboratory tests and simulations of the imposed loads have been realized, it is more likely to choose a lower safety factor. Ductile, metallic materials tend to use the lower value while brittle materials use the higher values. The field of aerospace engineering uses generally lower design factors because the costs associated with structural weight are high (i.e. an aircraft with an overall safety factor of 5 would probably be too heavy to get off the ground). This low design factor is why aerospace parts and materials are subject to very stringent quality control and strict preventative maintenance schedules to help ensure reliability.

Components whose failure could result in substantial financial loss, serious injury, or death may use a safety factor of four or higher (often ten). Non-critical components generally might have a design factor of two. Risk analysis, failure mode and effects analysis, and other tools are commonly used. Design factors for specific applications are often mandated by law, policy, or industry standards.
For loading that is cyclical, repetitive, or fluctuating, it is important to consider the possibility of metal fatigue when choosing factor of safety. A cyclic load well below a material's yield strength can cause failure if it is repeated through enough cycles.

Below is presented a table with the safety factors for different materials depending on the properties and application, according to the British Standards.

<table>
<thead>
<tr>
<th>Applications</th>
<th>Factor of Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>For use with highly reliable materials where loading and environmental conditions are not severe and where weight is an important consideration</td>
<td>1.3 - 1.5</td>
</tr>
<tr>
<td>For use with reliable materials where loading and environmental conditions are not severe</td>
<td>1.5 - 2</td>
</tr>
<tr>
<td>For use with ordinary materials where loading and environmental conditions are not severe</td>
<td>2 - 2.5</td>
</tr>
<tr>
<td>For use with less tried and for brittle materials where loading and environmental conditions are not severe</td>
<td>2.5 - 3</td>
</tr>
<tr>
<td>For use with materials where properties are not reliable and where loading and environmental conditions are not severe, or where reliable materials are used under difficult and environmental conditions</td>
<td>3 - 4</td>
</tr>
</tbody>
</table>

*Table 2.7: Factor of Safety for different materials, according to their known properties and applications (www.roymech.co.uk)*

For ductile materials (e.g. most metals), it is often required that the factor of safety be checked against both yield and ultimate strengths. The yield calculation will determine the safety factor until the part starts to plastically deform. The ultimate calculation will determine the safety factor until failure. On brittle materials these values are often too close as to be indistinguishable, so it is usually acceptable to only calculate the ultimate safety factor. Moreover, the values presented in the table 2.7 should be approximately doubled for brittle materials. Thus, a glass structural component should be designed with a safety factor which lie between 3 – 8. Truly, till now, glass structures designers have used safety factors around 5. Rob Nijsse used a safety factor of 5 over the tensile value of glass to obtain the maximum design strength for the ING Vastgoed-office building in Budapest and the Sonsbeek pavilion [Bos, 2009]. However, through the application of all the safety measures that have been analyzed in this chapter, it is expected that the factor of safety in a glass structure can be further reduced below 5.
Glass brick

Glass brick, also known as glass block, is an architectural element made from glass. The first application of glass brick in architecture was appeared in the early 1800’s when individual glass blocks were used to provide light to cellars and ships’ bowels, first as cut squares of simple conventional glass, then prism shaped pressed glass which allowed light to be dispersed. In order to fix this prismatic glass, they were fitted into steel frame structures in the form of intermediate ceilings or skylights which allowed larger surfaces to become translucent. Later, glass brick walls were used as internal partitions either to separate the space in a room or to create private spots. A function that is still quite popular (figure 2.19). These glass block walls are not intended to support the weight of walls, floors or roofs. To prevent the blocks from carrying the weight of construction above and to accommodate thermal movement, glass block installations are typically isolated into small panels, which are subdivided with vertical and horizontal expansion joints. When a long, uninterrupted glass block wall panel lacks expansion or isolation joints, bowing, cracking and crushing tends to occur.

![Figure 2.19: Photos from the Catalog Poesia 2013](image)

Regarding transparency, bricks can be completely colorless. However, there is a range of different colored glass bricks that can be found in the market, meeting the designer’s needs. Moreover, glass blocks are manufactured in different sizes and patterns in accordance with the various requirements and applications (figure 2.20).

![Figure 2.20: Photos from the Catalog Poesia 2013 (right) and Seves Glass Block (left)](image)
Glass blocks can be produced solid or hollow. The fabrication process, the thermal and mechanical properties of these two types of glass differs. The development of hollow glass blocks for vertical structures offer the advantage of better noise and thermal isolation in comparison to the solid blocks. A recent innovation in the manufacture of glass blocks is the inclusion of argon gas within the hollow centre of glass wall blocks. This advancement in production technique has resulted in a glass block which is able to offer significantly improved thermal insulation properties. Moreover, the manufacturing cost is noticeably less than this of solid glass which follows a more non-standardized manufacturing process. However, when hollow bricks need to carry extra load than their own weight, supporting construction is essential due to its low compressive strength. Another drawback of the hollow block is the optical distortion of the objects which are projected behind them due to the multiple layers from different transmission mediums (glass, air). The thickness and whether the block is hollow or solid affect the heat transmission value (U-value). Some indicative values of the U-value for sheet glass is 1.04, for solid glass block is 0.87, for thin glass block is 0.57 and for hollow block is 0.51 (W/m²K).

*Figure 2.21: Hollow glass blocks and different wall pattern from the Catalog Poesia 2013*
Manufacturing process

Liquid glass, which has been melted at approximately 1200°C, is poured into steel moulds and left to cool down to 700°C. The moulds should be designed with high precision and coated with nickel, which helps in producing smooth surfaces and in taking out the block easily. After the block reaches the 700°C temperature, it is removed from the mould and is placed in an oven to slowly cool down till it gets the room temperature. This process should be carefully performed by doing continuing controls in temperature and time, in order to avoid thermal cracking, internal residual stresses and any flaws in the final product. After this cooling procedure, the final block is placed in a CNC machine, which removes the convex top face and processes the block to the precise height required. The final stage consists of polishing the two horizontal faces of the block resulting in smooth flat surfaces avoiding any local stresses.

As mentioned above, solid and hollow glass blocks have different fabrication process, following though same principles. Hollow glass wall blocks are manufactured as two separate halves and, whilst the glass is still molten, the two pieces are pressed together and annealed. A sealed interior air chamber is formed that gives the glass block its thermal and acoustical insulating properties (Murray, 2013). The fabrication process of the glass brick should be an accurate procedure since it influences the structural and thermal properties of the product.
Adhesive

There are lot of different ways and types of adhesives to use for the construction of a glass brick wall. In the following only the adhesive that is used in the PC Hooftstraat project and it is proposed for the studied design is elaborated.

The kind of adhesive that will be used should follow some specific rules and meet some strict requirements, since is equally important as the chosen glass brick to the structural performance of the wall. Thus, the adhesive should:

- fast curing in just seconds
- be colorless and completely transparent
- be resistant to yellowing and discoloring when exposed to sunlight
- be resistant to climatic condition and chemicals
- have good compressive behavior in short and long term loading
- develop high bond strength with the glass surface
- provide a rigid monolithic structure

The adhesive that meets all these requirements is the **DELO PHOTOBOND 4468 for the horizontal bonding and 4497 for the vertical sealing**, a one component transparent UV-modified acrylate. It is completely cured by being exposed to the UV light lamp (figure 2.23).

![DELO PHOTOBOND adhesive and lamp](Glass Bonding, DELO brochure 2011)

The thickness of the applied layer should be limited in the range 0.1-0.3 mm and the blocks need to be fabricated with high dimensional accuracy, so the adhesive will be distributed evenly in the whole surface of the brick. Due to the low viscosity of the adhesive, the vertical joints of the blocks cannot be homogeneously glued, thus only the horizontal surfaces of the blocks are bonded.
Steps of the construction of a self-supporting glass brick wall

All the information and photos are taken from the journal “A Completely Transparent, Adhesively Bonded Soda-Lime Glass Block Masonry System” written by F. Oikonomopoulou and the paper “Application of DELO PHOTOBOND 4468/4497” written by T. Bristogianni and F. Oikonomopoulou.

- The glass surfaces of the glass bricks that will be bonded need to be cleaned thoroughly with 2-propanol soaked paper tissues. Then they should be cleaned with a dry paper tissue (figure 2.24).

- The DELO PHOTOBOND 4468 adhesive is applied on the fixed glass brick surface in an “X” shape with the aid of a PURE mold. This mold has been designed to assure an evenly distributed glue to all the surface of the brick and as a result to minimize the capillary effect (it is when adhesive is going up along the vertical sides of the bricks due to pressure) (figure 2.25).

- After applying the adhesive, the mold is removed and the glass brick is pushed towards the fixed brick till the adhesive is evenly spread throughout the entire brick surface (figure 2.26). The excessive adhesive should be cleaned with paper tissue. If air bubbles or dirt are noted, the brick should be removed and the procedure is repeated (figures 2.27, 2.28).

- When the adhesive is properly spread, it is cured for 2 seconds using the UV lamp, while the brick is still kept in position and under pressure. After cleaning any possible excess of the adhesive, it is cured with the UV light lamp for 50 more seconds (figure 2.29).

- Before bonding a new brick layer on top, all the horizontal and vertical joints must be sealed (figures 2.30, 2.31). For the vertical joints the thicker DELO PHOTOBOND 4497 is used.
Figure 2.26: Removing the PURE mold

Figure 2.27: Placing properly the brick to the fixed one

Figure 2.28: Air gaps have been noted. The brick shall be removed

Figure 2.29: UV curing

Figure 2.30: All the horizontal and vertical joints must be sealed then

Figure 2.31: First the vertical joints must be sealed and the horizontals
As it was expected, there were lot of tests and mock-ups of the masonry wall till the desired result will be achieved. Some of the mock-ups that the glass and transparency research group from TUDelft built can be seen in the figures 2.32, 2.33 (Oikonomopoulou, 2015).

Figure 2.32: Photographs of the three mock-ups

Left: The first mock-up (A) was made with lower tolerances. As a result there were significant offsets in both height and width and also open joints between blocks.

Centre: Mock-up (B) Higher accuracy in the size of the blocks counteracted the offset. Nevertheless, an unevenness of up to ±0.5 mm in flatness, resulted to cavities and bubbles in the bond layer.

Right: Mock up (C). All blocks meet the ±0.25 mm tolerance, resulting in an even spread of the adhesive and thus homogeneous bonding with an optimum visual result with no cavities or bubbles.

Figure 2.33: Photographs of the final mock-up which includes the buttress’s construction by interlocking glass blocks.

More details and information about all the steps regarding the preparation, the bonding, the sealing and the procedure of bonding between the ceramic strips and glass bricks can be found in the paper /manual “application of DELO PHOTOBOND 4468/ 4497 written by F. Oikonomopoulou and T. Bristogianni.”
Maintenance

Glass block is a durable building material and generally weathers well. Typical maintenance of glass blocks should include repointing when joints are deteriorated or missing. Glass blocks may also have small chips or minor cracks. Such aging effects, like slight fogging, normally do not adversely affect the blocks’ structural performance and are not generally grounds for replacement. Replacement should be confined to areas where blocks have lost significant structural strength, have cracks that have separated or a shard that might fall or have cracks that allow moisture to enter (Neumann, 1940).

Cleaning

A hydrophilic coating, (e.g. Vindico) can be applied at the external surface of the wall in order the rainwater to clean the façade, without the need of an extra cleaning. There should be a repetition in applying every 10 years. Sealing the joints between the glass blocks with a water and aging resistant adhesive will protect the joints from the entry of moisture and dirt.

Repairs

If a crack due to a thermal shock or due to an impact load occur in one or more glass blocks then the damaged glass block should be broken out as far as possible, taking care not to damage adjoining glass blocks. The opening should then be trimmed to accommodate the new block; this can be achieved either by the use of hand tools or mechanical grinder/cutter. The replacement glass block should then be set in place with the same procedure.
Conclusion

Undoubtedly, the last several decades, advances in glass strengthening technology and structural adhesives have permitted fascinating aesthetic concepts and engineers and architects are pushing the limits of glass strength by specifying the material in novel applications including floors, beams, walls, columns, and roofs. Almost everything can be made by glass with great potentials, enhancing aesthetics and create the best open and clear space, full of light in a safety way. Glass is not lagging behind other structural materials and with the proper design considerations a safe structure can be guaranteed.

To sum up, according to the above considerations, for the present design the following values and methods have been followed:

- The design method is based on permissible stresses using high safety factor.
- Glass structures represent localized parts of the construction (façade, beam, floor, staircases) which their failure can certainly have very serious consequences, though hardly ever accompanied by collapse of the entire building (table 2.3). Therefore, the glass structural elements can be categorized in the second class.
- The estimation of RD for the glass beams which support the glass floors in the design is (see table 2.5): \[ RD = PD \times ED \times SD = 0.5 \times 6 \times 15 = 45 < 70 \]
  For the glass brick column, though, the ES factor can be 40, since if the glass columns break, then the concrete beam that support can reach the failure stress resulting in the collapse of a part of the roof. The RD factor for the glass brick column is \( RD = 0.5 \times 6 \times 40 = 120 \). The glass brick in the column can be broken from two sides.
- Sacrificial layer in the glass floor that covers all the above surface and protect the connection between the glass fins and the glass floor panes
- For the design, heat strengthened laminated glass, bonded with a SGP interlayer, is used for all the structural elements with only fully tempered the sacrificial top layer of the glass floor.
- The biggest glass laminated element is below the limit (6m X 2m), makes no need for extra measures in the manufacturing and transportation process.
- The glass structure that added in the building will be calculated with a **factor of safety equal to 4**. One would expect even lower safety factor, since there is huge development in designing with glass and there is more knowledge on the properties of this material. However, one of the reasons for this choice in this design, is the psychological factor. When there is big glass structures, such as the glass floors, the glass brick façade and the slender glass brick columns, that people are not familiar with, there is always the fear of whether the structure is durable and safe enough to use it. Therefore, it was considered wise, to follow the overdimensioning path.
- The adhesive that is used for the glass bricks in façade and in column is **DELO PHOTOBOND 4468 for the horizontal bonding and 4497 for the vertical sealing**.

More specific and elaborated design principles and considerations for each of the glass element that is used in this design can be found in the next chapter.
References

- AGGA. (2011). AGGA TECHNICAL FACT SHEET THERMAL STRESS GLASS BREAKAGE.
Architecture

This chapter focuses on the architectural principles of the design, from the general concept and the main design principles to the interior design of the whole building.

The concept

As it has been mentioned in the introduction, the basic/ initial architectural idea of this transformation of existing facades belongs to the MVRDV architect offices, which has designed it for one of the buildings in the P.C. Hooftstraat street in Amsterdam. The idea is to demolish the conventional clay brick façade and replace it with glass bricks, with the size of 10 m X 10 m (figure 3.1).

The present design expands this idea to a four times bigger surface of the façade. The result is an eye catching and stunning façade which will reveals the inner luxury products of the shop. The main and primary goal of the project remains the same as in the original project in Amsterdam and it is to attract attention of the public and especially of the customers while marking a landmark for the city and upgrading the area.

The main design principle is to increase the transparency and to link the inside world with the outside.
The building is assumed that it is adjacent to two other building same or higher height for structural reasons. At the early stage of the design some draft drawings have been used in order to visualize the façade. The dimensions of the whole building can be seen in these drawings as well.

Figure 3.2: Increasing the size increases the transparency

Figure 3.3: Sketch of the conventional façade at the back street (left), elevation of the roof (right)
Figure 3.4: Sketch of the glass brick façade (top), conventional façade at the back street (middle), glass roof (bottom)
Usually, a renovation work, apart from the aesthetic uplift, aim to improve the structural and mechanical system of the existing building, following more sustainable guidelines. However, in this design, not only this is not the case, but more structural and building physics challenges arise. This is inevitable when large glass surfaces take the place of conventional wall made by clay bricks or concrete. Based on the concept of improving the thermal performance of this design, a glass roof, (1.8mX20m) was built allowing for the warm air to flow out of the building. Moreover, this glass surface offers more natural light and increase the view to the outside.

Figure 3.5: Sketch of the perspective view of the building with the glass brick façade (initial design)
Even though, the main design is the replacement of the conventional brick façade with the innovative new glass brick façade, the renovation is extended to the interior structure of the building as well. Therefore, some part of the concrete structure behind the front façade structure is demolished and is replaced by glass components. This intervention will highlight the façade even more and will increase the depth of the transparency and reflection.

After trying different designs and configurations of the floors (see Appendix B), the final selection was based on structural, architectural and thermal criteria. First the concrete floors were cut, in order to be replaced by glass floors. In the following figure some configurations of the concrete floors can be seen with the respectively daylight simulation in Design Builder software.

![Figure 3.6: Configurations of the concrete floors and the respectively daylight simulations](image)

The choice of the third configuration takes advantage of not only the maximum daylight resulting in less energy consumption (see “thermal performance” chapter), but enhancing the transparency by using the maximum structurally possible length of one unit glass beam (see “structure” chapter).

The design of the glass floors have been determined after taking into consideration structural and building physics factors. Glass floors bridge the existing concrete structure with the façade, while forming two
atriums at the two sides allowing air to flow through the whole width of the building (cross ventilation) and through the whole height of the building (stack ventilation) (see the 2D plans drawings). Moreover, the atriums offer the impressive view of the whole façade as one transparent slender unit.

Not surprisingly, all the interventions in this project are an extravagant investment and the depreciation comes through the increases in the sales. This has been proved with numerous studies that demonstrates that human health, happiness and wellbeing are inextricably linked to daylight.

Some of the benefits of the daylight, hence big glazing surfaces, in retail buildings can be found in the study of the California Energy Commission in 2003, which was undertaken by HMG59 regarding the impact of daylight and retail sales. The key conclusions from this study are summarized in the following:

- Average effect of daylighting on sales for all daylit stores in this chain was variously calculated at 0% to 6%, depending on the type of model and time period considered.
- A dose/response relationship was found, whereby more hours of useful daylight in a store are associated with a greater daylight effect on sales.
- A bound of an empirical daylight effect for this chain was detailed, with a maximum effect found in the most favorable stores of about a 40% increase in sales. This upper bound is consistent with our previous finding.
- Daylight was found to have as much explanatory power in predicting sales as other more traditional measures of retail potential, such as parking area, number of local competitors, and neighborhood demographics.
- Along with an increase in average monthly sales, the daylit stores were also found to have 1-2% increase in the number of transactions per month.
- No seasonal patterns to this daylight effect were observed. The value of the energy savings from the daylighting is far overshadowed by the value of the predicted increase in sales due to daylighting: by the most conservative estimate of at least 19 times, and more likely, under current conditions, by 45-100 times.
- During the California power crises, when almost all retailers in the state were operating their stores at half lighting power, the stores in this chain with daylight were found to benefit dramatically, with an average 5.5% increase in sales relative to the other stores in the chain (which also increased their sales compared to the previous period).
- Employees of the daylit stores reported slightly higher satisfaction with the lighting quality conditions overall than those in the non-daylit stores. Most strikingly, they perceived the daylit stores to have more uniform lighting than the non-daylit stores, even though direct measurements showed the daylight stores to have much greater variation in both horizontal and vertical illuminance levels.
- Store managers did not report any increase in maintenance attributable to the skylights. The chain studied was found to be saving about $0.24/sf per year (2003 energy prices) due to use of photo controls, which could potentially increase up to $0.66/sf per year with an optimized daylighting system.

(An earlier 1999 study for Pacific Gas and Electric Company on behalf of the California Board for Energy Efficiency Third Party Program by HMG60 examining the impact of sky lighting and retail sales found; (Strong, 2012).)
Some retailers have already discovered the benefit or the affects that daylight can have on the retail environment. Retailers are starting to use daylighting in their stores specifically to enhance their store environment, increase sales, create a more pleasant shopping environment, attract customers, and improve color rendering. Using daylighting also has aesthetic benefits that encourage customers to enter the store.

One remarkable example can be found in the project of the chief architect of Southern California Edison, Gregg D. Ander, who designed the largest retailer in the country and possibly the world. Ander said this retail chain has had successful sales for the daylit stores when compared to the non-daylit stores in the district. When comparing about 11 stores in one district, the daylit stores sold 28% more product than the other stores.

Another example is the first Wal-Mart Eco-Mart store which was built with half the store having skylights. Increases in sales, employee perspective, and shopping habits have occurred in the section of the store with skylights compared to the section without skylights. The effects of the skylights on retail sales, the employees, and shopper reactions were unexpected. Retail sales in the daylit area of the store are higher than the area without skylights, and other Wal-Mart stores in the area.

As a conclusion, there are more factors that lead to the final shape of the whole design, apart from maximum transparency and elegant and luxurious appearance. Such factors are the design considerations of structural glass and the thermal performance of the building resulting in a desired and pleasant indoor climate using as much as sustainable measures. For example, the final configuration of the floors has been determined after daylight, CFD and structural calculations.

The financial budget of the project is not one of the determined factors, since it would limit the architectural innovative ideas, and it is not the purpose of this research.

The architectural design is divided into two parts: the exterior design which consists of the glass brick façade and the glass roof and the interior design which consists of the glass floors, elevators and staircases as well as the functionality of each of the floor assuring the fire and safety regulations. Since the building is not real and it is a virtual creature, the interior design and the configuration of each floor has to be determined.

Analytically the design can be found in the following two sections, which gives information for the exterior and interior design.
Exterior Design

**Design principles**

- Elegant connection between the existing structure and the added new glass structure
- Maximum transparency
- Connection with the outside world/view (big glass surfaces)

The visualization of the façade was guided by the appearance of the façade in the P.C. Hooftstraat (figures 3.7-3.9).

*Figure 3.7: Glass brick façade under construction (Photos taken in the construction site of the P.C. Hooftstraat)*
Figure 3.8: Glass brick façade under construction (Photos taken in the construction site of the P.C. Hooftstraat)

Figure 3.9: Measuring the transparency of the facade (Photo taken in the construction site of the P.C. Hooftstraat)
Figure 3.10: View from the pavement of the glass brick façade

Figure 3.11: View from the pavement of the back façade
It can be noticed from the figures 3.7-3.9 that the transparency of the facade varies according to the corner of visual approach. From a close approach, the transparency is high, whilst from a remote spot, the façade becomes blurry and each of the side of the bricks are visible due to the reflection of the light. This is illustrated well in the following figure (based on the figures 3.7-3.9 of the real project).

Figure 3.12: An impression of the building in Amsterdam
Another rendered view of the building can be seen in the following figure. This is less realistic than the previous one, because it does not provide the reflection of the glass. However, it illustrates clearly all the glass elements that have been added in the building and the levels of the glass floors.

Figure 3.13: Impression of the building in Amsterdam, Netherlands
In the following figures, impressions of the building located in the warm climate of the city of Valencia in Spain and in the cold climate of the city of Tampere in Finland are illustrated.

In both pictures, the glass brick façade offers an elegant and bright touch in the surroundings.

*Figure 3.14: Impression of the building in Valencia, Spain*
Figure 3.15: Impression of the building in Tampere, Finland
The section of the two sided wall of the existing building is covered with aluminum sheet (figure 3.16) in order to cover the layers of all the materials in the wall and achieve better external appearance of the façade.

*Figure 3.16: Aluminum sheets*

*Figure 3.17: Natural light entering from the façade in the interior*
Interior Design

Design principles

- Visual connection to the exterior (Glass columns, glass floors, glass beams, glass elevators, glass staircase)
- Maximization of natural lighting
- Thermal and psychological comfort due to the atriums and the open space
- Sustainability (energy savings)

![Figure 3.18: Impression of the interior of the 3rd floor](image)

In the figure 3.18 an impression of the transparency of the façade where one stands in the interior of the shopping store is illustrated. The building in the opposite street can be clearly distinguished through the façade. At the right part of the picture, the glass elevator with the glass staircase enhance the elegance of the interior design of the building.

The different configuration of the floors can be seen in the following figures where 3D impressions and 2D drawings of plans and sections are given.
The division of the functions in each floor follows the pattern of the most well-known brands of shopping store which is based on marketing principles (increase the sales etc.). Thus,

**Basement**: Storage room, Mechanical room

**Ground Floor**: Accessories department, toilets for disabled accessible facilities

**First Floor**: Men department, toilets for the public

**Second Floor**: Women department, storage room

**Third Floor**: Women department, storage room

**Fourth Floor**: Offices, Kid’s department, toilets for the staff
Figure 3.20: 2D plan of the 5th floor
There are pressurized elevators and staircases and the escape routes follow a path below the 20m obeying the national fire regulations (figure 3.22).
Figure 3.22: Fire regulations (ground floor)

Figure 3.23: 2D section through facades
One of the design principles as well, for the design as a whole, is that every vertical element (façade, columns) is made by glass bricks and every horizontal (floor, beam, panes) is made by float glass (figure 3.24-3.25). This homogeneity is essential key in a good design among the architects.

Figure 3.24: The glass elements without the façade

Figure 3.25: Detail of the glass brick column next to the glass floor of the 1st floor
Glass staircase and glass elevator

The main staircase and elevator are made by glass, having inspired by the design of the Apple Store in New York.

In the present design, the shape of the shaft is rectangular instead of circle. Each glass tread consists of 3 laminated glass layers with sentry glass interlayer. The top layer has antislip coating which is used as well for privacy reasons (for women who wear skirts etc.). The same coating is used for the glass floors. The following figures illustrates the milky effect of this coating and the connection detail of the tread and the glass railing.
Figure 3.28: Detailing of the glass staircase (Apple store in New York)
Glass internal partitions

In order to create private rooms at the top floor, glass partitions are used. For safety reasons the glass partitions are at least 8mm toughened safety glass to withstand the impact of any furniture or hit by any objects thrown by people. For privacy reasons, they will be milky and not clear glass. To maintain light penetration but provide privacy there are glass products that are designed to scatter light or appear translucent. Pilkington Optifloat™ Opal and Pilkington Optilam™ I Translucent White, laminated glass with a white interlayer, give a translucent effect to partitions. The Pilkington Texture Glass range add relief to the glass and can provide varying degrees of obscurity.

In the present design, the partitions do not reach the ceiling, in order to allow the airflow to cross the rooms and reach the windows at the back façade. In that way, there are no extra climate zones needed or different mechanical design (See “thermal performance” chapter).

Figure 3.29: Milky glass internal partitions
Conclusions

The aspiration to create a crystalline architecture has long inspired architects in the modern era. From Bruno Taut’s Glashaus at the 1914 German Werkbund Exhibition, to Pierre Chareau’s Maison de Verre, to Kengo Kuma’s Water/Glass House (AR March 2000), glass has had the transformative power to shape space, as it is technically both a solid and liquid with extremely high viscosity. The glass house has once again been ingeniously reinvented through the use of an optical glass facade by Hiroshi Nakamura.

In optics, transparency refers to a material that transmits light so that we can see through it. In architecture, this usually translates into the use of glass as the primary building material. Another interpretation of the term that is often used in the architectural world, is the fascination of making interior and exterior spaces continuous (Roest, Hauptmann, & Radman, 2008). It refers to the ability of allowing the visitor to perceive different spaces simultaneously or even conceive them as one unified space, creating different perception inside or outside the space. Thanks to its transparency, glazing enables daylight to penetrate the interiors of buildings and provides a view to the outside world. This is, besides, the main leading point of this project. To achieve total transparency with the most elegant feasibly way. The use of glass also creates the illusion of a more spacious and open room letting the natural light get into the building. These characteristics are unique among building materials and provide many benefits to building occupants. By providing daylight and a connection with the outside world, glazing enhances the interiors of buildings, and improves comfort and the sense of wellbeing. Numerous research studies have found that access to daylight in various types of buildings provides a healthier – and healing – environment (e.g. hospitals), and increases focus, learning and productivity (e.g. educational buildings and offices) while enhancing the aesthetic of internal spaces with direct economic benefits, for example with boosted sales in daylit retail establishments.

Last, but not least, glass generates minimal environmental impact, which makes it a product of choice for sustainable buildings. In fact, glass is made of abundant non-polluting raw materials, its manufacturing process is highly energy efficient, requires low levels of water and generates little waste. Moreover, the vast majority of glass products for buildings are recyclable at the end of their lives. This contributes to even lower environmental impact. When recycled in new glass products, glass waste helps to economize both raw materials and energy in manufacturing new glass products (Strong, 2012b).

As mentioned in the first chapter, the building does not exist and it is a created by the writer for research purposes. However, this technology of the glass bricks self-standing wall can be applied in different type of buildings as well, but mostly in public buildings, since it would be really expensive and insufficient thermally for a residential building. However, with the proper design it is not impossible.

The main and initial purpose of the design is to attract attention of the world and buyers with an innovative and highly impressive façade. It is no intended to improve any thermal or structural conditions, like most of the renovations these years.
Arising challenges

Undoubtedly, lot of challenges are arise with this architectural design. As it has described in this chapter the final design has been formed by following structural and building physics rules.

The most challenging aspect is the structural feasibility of the building. The design not only consists of glass, but it also exhibits very slender elements (glass brick façade and glass brick columns). Its structure is made by cast solid glass bricks which is yet an innovative element that needs more research and testing.

Furthermore, glass surfaces of that scale absorb lot of solar gain leading to overheating problems and unsustainable designs. However, there are lot of passive measures that can be applied in order to minimize the energy consumption for heating and cooling the building.

All these structurally and thermally issues are dealt with in the following chapters.
References


Structure

The main goal of this project is an eye catching and stunning façade which will reveal the inner luxury products of the shop and attracts the public and the purchasers. The ultimate transparency that can be reached with structural elements is one of the most primary point in the design. Thus, some part of the concrete structure, behind the front façade, is demolished and is replaced by glass components, such as glass floor, glass beams, glass brick columns, glass panes in the roof and glass brick façade. Glass, as structural material, can be used for every element nowadays and with great potential for covering a lot of different and often contradicting needs.

Over the next several decades, advances in glass strengthening technology and structural adhesives have permitted fascinating aesthetic concepts, but have given glass designers the responsibility of not only providing a unique identity for the building, but also protecting its occupants, controlling the interior climate of the building through thermal transmission, reflectivity, illumination, ventilation, and other climatic conditions that were previously unrelated to the glass elements of construction. Today, engineers and architects are pushing the limits of glass strength by specifying the material in novel applications including floors, beams, walls, columns, and roofs (Leitch, 2005). For all the reasons that has been described in the previous chapters as well, glass is not lagging behind other structural materials and with the proper design considerations a safe structure can be guaranteed.

However, such a big scale structural glass brick façade using an adhesive combined with such a long glass brick column has never been realized before, therefore this chapter aims to give arguments about the feasibility in terms of structural integrity and safety. Moreover, the feasibility in terms of a safe structure lies on the validity and the detailed design of the connection between the existing structure and the new. Concrete and glass are two materials with different thermal and mechanical properties, making the connection between them intriguing and more demanding.

The general design principles when designing with glass are mentioned in the chapter Glass Technology Analysis, therefore in that chapter the design principles will be focus on each of the element that has been used in this project, following by the simulation of the renovated building with the help of the FEM software ANSYS. The chapter ends with the results of the laboratory tests in glass brick specimen, which validate the structural integrity of the glass brick elements.
Structural elements

In this chapter the principles that have been followed for the design of each of the structural elements that was added in the existing building are elaborated.

The glass structural elements that are added in the structure are summarized in the following figure.

*Figure 4.1: The glass elements that are added in the existing building (3dsMax)*
Glass Brick Façade

The load bearing element that dominates for its innovation and its scale in this project is the glass brick façade. The dimension of the façade is 20 m X 20 m X 0.21 m.

![Figure 4.2: The glass brick facade (3dsMax)](image)

The wall consists of only glass bricks of three different dimensions glued together with the DELO PHOTOBOND 4468 for the horizontal bonding and 4497 for the vertical sealing (figure 4.3). The properties of these materials and the steps of the construction of the façade are given in the chapter “Glass Technology Analysis”.
Loads for the facade

- Vertical load due to the glass roof and the glass beams (approximately 1/3 of the loads) and self-weight of the facade
- Horizontal load due to the wind

![Diagram showing loads and wind on the facade](image-url)
Due to slenderness of the façade, buckling can be critical. Thus, measures to prevent that and to assure the integrity of the façade shall be taken.

The loads and the measures that are taken to prevent buckling of the façade will be illustrated in the next section.

- Thermal stresses due to the weather conditions or due to a neighbor building that cause range in the temperature in the façade with its shadow

Materials expand when subject to rises in temperature. The degree to which this happens varies from one material to another. It is expressed in the linear expansion coefficient \( \alpha \), which for soda lime glass is \( \alpha = 9 \times 10^{-6} \text{ m/(m*°C)} \). In the following, the thermal expansion of the bricks of the whole façade is calculated in order to assure that the margin that the glue in the joints provide is enough to absorb the expansion and avoid the cracks in the bricks.

The difference in temperature for Netherlands between the two surfaces of the bricks in the façade is \( \Delta T = 3.67^\circ \text{C} \). It is calculated for the non-occupancy hours since then it is the biggest difference between outside and inside air in the summer.

<table>
<thead>
<tr>
<th>Construction layer</th>
<th>( d ) (m)</th>
<th>( \lambda ) (W/m*K)</th>
<th>( R_n = \frac{d}{\lambda} \text{ (m}^2\text{K/W)} )</th>
<th>( (R_n/R_1) \Delta T = \Delta T_n \text{ (°C)} )</th>
<th>( T_n ) (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside air</td>
<td></td>
<td></td>
<td></td>
<td>0.04</td>
<td>0.3125</td>
</tr>
<tr>
<td>Glass brick</td>
<td>0.21</td>
<td>0.447</td>
<td>0.47</td>
<td><em><strong>3.671875</strong></em></td>
<td>31.98438</td>
</tr>
<tr>
<td>Inside air</td>
<td>0.13</td>
<td>1.015625</td>
<td>1.015625</td>
<td>1.015625</td>
<td>33</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td><strong>0.64</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1: Calculation of progression of the temperature in the glass brick facade
Linear expansion

\[ \varepsilon_{xx} = \frac{1}{E} \left( \sigma_{xx} - \nu \sigma_{yy} \right) \]

\[ \varepsilon_{yy} = \frac{1}{E} \left( \sigma_{yy} - \nu \sigma_{xx} \right) \]

\[ \varepsilon_{xy} = \frac{\sigma_{xy}}{2G} \], where \( G = \frac{E}{2(1+\nu)} \)

Stress due to restricting thermal expansion

\[ \sigma = E \cdot \varepsilon = E \cdot \alpha \cdot \Delta T \]

\[ \sigma_{xx} = \sigma_{yy} = E \cdot \alpha \cdot \Delta T = 70 \cdot 10^9 \cdot 9 \cdot 10^{-6} \cdot 3.67 = 2312100 \text{ N/m}^2 \]

\[ \varepsilon_{xx} = \frac{1}{70 \cdot 10^9} \left( 2312100 - 0.2 \cdot 2312100 \right) = 2.64 \times 10^{-5} \]

\[ l = 20 \cdot 10^3 \text{ mm} \]

\[ \Delta l = \varepsilon_{xx} \cdot l = 2.64 \cdot 10^{-5} \cdot 20 \cdot 10^3 = 0.528 \text{ mm} \]

Assuming the number of the vertical sealing gaps in this direction based on the dimensions of the bricks, the margin that the glue provides is 94 * 0.3 mm = 28.5 mm >> 0.528 mm

Moreover, silicon sealant is applied at the both sides between the façade and the existing building, taking over all the expansions.

- Impact load due to unintentionally or intentionally hit of the façade (accident with car, vandalism with hammer or other tool)

This type of load has been tested by conducting laboratory tests by the glass research group in TUDelft. Impact load was applied in a specimen made of glass brick same characteristics as the façade. The results are given at the end of this chapter.
The concept of the maximal transparency and luxury of this project follows the design of the glass floors as well in each floor. The use of glass as a flooring material is known for over a century. It was seen mostly as an ideal way of letting natural light into large and potentially gloomy areas of buildings. Glass flooring technology has made considerable strides in the last hundred years (Figure 4.4).

Above all the other structural components that glass can be used as material, floors are the one with the highest safety demands. Therefore, only safety glass, heat strengthened or fully tempered laminated is the only choice among the types of glass for this application. The two major types of laminated glass for floors are the PVB or Sentry laminated glass and cast in place resin-bonded glass. The main difference between them is that PVB and Sentry laminate system is usually used for large commercial applications since it is most appropriate on cost and safety grounds, while the resin-bonded system is used for small applications or for these using highly specialized or highly textured materials and the cost is not the overriding concern. The number of glazing, the type of glass, and the dimensions of the glass panes of the glass floors as well as the thickness of the layers are discussed in the following.

The glass tends to be relatively thick and heavy even with toughened laminated constructions so the support system for the glass needs to be adequate to prevent distortion under load. The thickness of glass has a major relation with the cost of the project. The large increase in weight of the glass means higher cost for transportation and installation costs. Therefore, the main factors which affect the thickness of the glass and should be considered and examined thoroughly before the final design, are:

- **Design load**
  The higher the loading the glass floor is required to take, the thicker the glass floor will need to be. The design load is defined by the type of the building and the occupancy.

- **Supporting system**
  The amount and the type of the supports given to the glass flooring panel has an effect on the thickness of glass required. For example, when a glass panel is supported by two sides it needs thicker pane in order to carry the same load as if it was supported by four sides.
- **Type of glass**
  As it is described in previous chapter, safety glass is the heat strengthened or fully tempered laminated glass. Despite the fact that tempered glass is stronger than the heat strengthened, for glass floors the latter is preferred. This is because the tensile stress inside toughened glass does not only give added strength, but also give an increased vulnerability to sort sharp shocks particularly at exposed edges. This, subsequently, can result in an explosive release of stress producing the fracture characteristics of small, relatively harmless fragments. Since the glass panes are laminated, having glass sharper fragments has little extra safety benefit over the larger sharper fragments resulting from the breakage of float or heat strengthened glass since all the fragments are held safely in place by the lamination (Michael S. Rae, n.d.).

- **Span of the glass**
  Given the load and the type of the glass, the thickness is determined from the maximum width that the glass has to span and the type of the supporting system. Approximately 1m$^2$ is usually considered to be a practical maximum area for each pane of glass due to handling considerations. With the diagrams in table 4.2 one can estimate the thickness of the glass pane depending on the supporting system and the length of the span.

![Diagram](image)

*Table 4.2: Relationship between spans and laminate thickness required for an imposed loading of 5 KN/m$^2$ for panes supported on two sides (left) and four sides (right) for a system comprising a heat strengthened 6mm top sheet and two lower layers of float glass (Michael S. Rae, n.d.)*

These diagrams follows the rule of the 1m$^2$ maximum area, so they are not used for the estimation of the thickness of the glass floor for this design, where the path of innovation and maximum transparency override this rule and disobey the market standards. The glass beams have been placed every 2 meters in the longer dimension of 12 meters and the other dimensions is different for each floor. The configuration of the glass panes can be seen in the drawings given in the appendix A. The glass size panels are:

<table>
<thead>
<tr>
<th>1st floor</th>
<th>2nd floor</th>
<th>3rd floor</th>
<th>4th floor</th>
</tr>
</thead>
<tbody>
<tr>
<td>5mm X 1.8m</td>
<td>5mm X 3.2m</td>
<td>5mm X 4.6m</td>
<td>5mm X 6m</td>
</tr>
</tbody>
</table>

*Table 4.3: The dimensions of the glass floors*
Taking into account all the above factors, the first estimation of the glazing for the glass floors will be laminated heat strengthened and consists of 3 layers of 12.7 mm each and 1 sacrificial fully tempered layer of 4 mm at top (figure 4.5).

![Layers of the glass panes for the glass floor (first estimation)](image)

Last but equally important is the safety in using the glass floor. It is common the manufactures to add some sand-blast or acid-etched finishes in order to reduce the risk of slippage. At the same time, this protection can work for enhancing the privacy as well.

![The glass has been sandblasted in a foggy pattern (left) and in a striped pattern (right) for a non-slip surface and extra privacy (www.floorglaze.com)](image)

Hand calculations have been preceded the complete simulation of the building in ANSYS software for the validity of the first estimation of the dimensions of the glass floor.
**Loads for the glass floor**

The self-weight of the glass panes and the live load are the main load cases for the thickness determination of the panels.

- The self-weight of the glass panes (t=0.0421 m) is \( G = 0.0421 \times 25 \text{ kN/m}^3 + 0.107 \text{ kN/m}^3 \times 2 \times 1.52 \text{ mm} \times 10^{-3} = 1.053 \text{ kN/m}^2 \)
  
  *(for more accuracy the weight of the sentryglass interlayer should be taken into account as \( 0.107 \text{ kN/m}^3 \times 2 \times 1.52 \text{ mm} \times 10^{-3} = 3.25 \times 10^{-4} \text{ kN/m}^2 \))

- Live load that for shopping areas (category D2) and for glass floors is \( Q = 5 \text{ kN/m}^2 \)

**Load combinations for the glass floor**

**Design situation 1**

\[ 1.35 \times G + 1.30 \times 0 \times Q = 1.35 \times G = 1.35 \times 1.053 = 1.42 \text{ kN/m}^2 \]

**Design situation 2**

**ULS**

\[ 1.20 \times G + 1.30 \times 0 \times Q = 1.20 \times G = 1.2 \times 1.053 = 1.263 \text{ kN/m}^2 \]

\[ 1.20 \times G + 1.30 \times Q = 1.20 \times G + 1.3 \times 5 = 7.763 \text{ kN/m}^2 \]

*(factor 1.3 instead of 1.5 for the glass calculations)*

**SLS**

\[ 1 \times G + 1 \times 0 \times Q = 1 \times G = 1.053 \text{ kN/m}^2 \]

\[ 1 \times G + 1 \times Q = 1 \times 1.053 + 1 \times 5 = 6.053 \text{ kN/m}^2 \]

The highest stress happens at the glass centre for a four sided supported panel (figure 4.7).

![Maximum deflection and maximum bending stress](image.jpg)

*Figure 4.7: Maximum bending stress and maximum deflection exist at the centre of a rectangular thin plate that is supported around all the four edges (ZHOU, n.d.)*

**Central bending stress** of a panel supported on all the four sides (of a rectangular shape, every support in simple) is given by the formula:
\[ \sigma_c = \beta \cdot p \cdot a^2 / t^2 \]

where,

- \( p \) is the uniform load
- \( a \) is the length of the short side of the rectangle
- \( t \) is the glass thickness and,
- \( \beta \) is a parameter determined based on the ratio of longer side to the shorter side (\( b/a \), where \( b \) is the longer side) as shown below

<table>
<thead>
<tr>
<th>( b/a )</th>
<th>1.0</th>
<th>1.2</th>
<th>1.5</th>
<th>2.0</th>
<th>3.0</th>
<th>4.0</th>
<th>5.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \beta )</td>
<td>0.270</td>
<td>0.360</td>
<td>0.474</td>
<td>0.602</td>
<td>0.711</td>
<td>0.740</td>
<td>0.748</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>0.047</td>
<td>0.065</td>
<td>0.089</td>
<td>0.116</td>
<td>0.140</td>
<td>0.147</td>
<td>0.149</td>
</tr>
</tbody>
</table>

*Table 4.4.: Linear interpolation can be adopted to determine the \( \alpha \) and \( \beta \) should the \( b/a \) value be other than listed (ZHOU, n.d.)*

The maximum deflection of the glass pane is given by the formula:

\[ \delta = \alpha \cdot p \cdot a^4 / E \cdot t^3 \]

where,

- \( E \) is the elastic modulus of glass (\( E = 70000 \) N/mm\(^2\)) and
- \( \alpha \) is a parameter that is determined using the table above.

The calculation is implemented for the biggest pane (2m X 6m) since it is the most critical one.

- \( b/a = 6/2 = 3 \) so from the table above \( \alpha = 0.140 \) and \( \beta = 0.711 \)
- \( p = 7.763 \) kN/m\(^2\)
- \( E = 70000 \) N/mm\(^2\)
- \( t = 0.0421 \) m

Thus, \( \sigma_c = 0.711 \cdot 7.763 \cdot 2^2 / (0.0421^2 \cdot 1000) = 12.45 \) N/mm\(^2\) > 10 \( \) N/mm\(^2\) = \( \sigma_{max} \)

And \( \delta = 0.140 \cdot 6.053 \cdot 2^4 / (70000 \cdot 0.0421^3 \cdot 1000) = 2.6 \) mm << 16 mm = \( \delta_{max} = L / 125 \) (allowable deflection of glass, defined by BS 6262 (ZHOU, n.d.).

The stress check is not satisfied, but it was considered that it is small difference (3 N/m\(^2\)) to take into account and place thicker glass panes or more layers or the solution of the vertical glass fin, compared with the changes that this will bring in the design. Besides, taking into account the high safety factor that has been chosen for the glass components and the fact that homogeneity is one of the main architectural principles, this choice was considered wise. In any case, glass pane consisting of 3 layers of 15mm each and a 4 mm top sacrificial layer satisfies the deflection check, which is normally more critical factor for floors.

The calculation is implemented for the smallest pane (2m X 1.8m) as well, in case it is over dimensioned and uneconomical.
b/a=2/1.8=1.11 so from the table above α=0.0551 and β=0.3195
p=7.763 kN/m²
E=70000 N/mm²
t=0.0421 m
Thus, \( \sigma_c = 0.3195 \times 7.763 \times 1.8^2 / (0.0421^2 \times 1000) = 4.53 \text{ N/mm}^2 < 10 = \sigma_{\text{max}} \)
And \( \delta = 0.0551 \times 6.0525 \times 1.8^4 / (70000 \times 0.0421^3 \times 1000) = 0.67 \text{ mm} << 16 \text{ mm} = \delta_{\text{max}} = L/125 \)

As it can be resulted from the above calculations, for economic reasons, different thickness can be used for the different dimensions of the glass floors in each of the floor. In favor of the homogeneity and for making easier the manufacturing process, since the thickness of the glass panes will be the same and the only difference will be the size of the panel, it was considered to keep the same thickness everywhere.

![Impression of the glass floors (3dsMax)](image)

*Figure 4.8: Impression of the glass floors (3dsMax)*
Glass Beams

One of the main structural elements that help in maximizing the transparency of the whole structure is glass beam. Glass beam is very popular in courtyard extension projects of various building types, as it is almost perfect for architects to create “invisible buildings” where people could live or play in a controlled climate and at the same time enjoy natural views and sunshine. Glass beam design is very flexible. It can be connected to almost all kinds of architecture elements, such as steel beams, masonry walls, concrete columns, glass columns and fins. Theoretically, it could be strong enough to support decks made of different kinds of materials. However, because of its transparency and other issues, most of the time, glass beams are used to support clear glass panes, and sometimes they are used to support patterned or frosted glass panes. Typically, because of the restrictions of glass manufacturing, single span glass beams are limited to 6 meters. Composite glass beams with reinforcement spanning more than 15 meters have been realized and tested, and the potential and capacity of this kind of structural elements are still being explored. Some examples of using glass beams can be seen in the figure 4.9.

![Figure 4.9: Glass Bridge of Kraaijvanger Urbis Architectural Practice, 1994, Rotterdam, Netherlands (left), Apple retailer on 5th Avenue, 2006, New York, USA (middle), Workshop of Museum de Louvre, 1993, Paris, France (right)](image)

The architectural office of Kraijvanger and Urbis in Rotterdam built a glass bridge 3.2 m long to provide a first floor link between the offices of two adjacent buildings. The glass beams consist of 3 layers of 10mm each and 300mm height.

The roof beams of the Apple cube in New York with 3.3m span, are laminated from 5 pieces of 12.7mm heat strengthened glass with both ends laminated toe thin stainless steel she insert that allows the post connection of a fin plate.

The glass construction in the workshop of Museum de Louvre in Paris covers a three-story light well that is 16m long and 4m wide with laminated skylight panes which are supported by 600mm high laminated glass beams of 4 pieces of 15mm thick strips of toughened glass. Those beams were estimated to support 5 tones. After exhaustive tests, taken later to study the behavior of the material, revealed that the glass beams could actually resist of 12.2 to 14 tones (Fu Lei, 2010).
In order to deal with the brittleness of glass, minimize the potential for damage on tensile edge of the glass beam and improve the residual load-bearing capacity, researchers are trying to apply additional reinforcement to glass beams. This can happen by bonding a small stainless steel reinforcement in the tensile zone along the edge of the glass beam. The transparency of the beam is not influenced of this steel reinforcement because it is placed in the tensile zone along the edge of the glass beam. Crack propagation will be limited when overloads happens, due to dissipation of fracture energy by deformation of the reinforcement, which will take over the tensile forces. An internal couple of compression force in uncracked area and a tensile force in the tension area will assure redundancy of the system providing time to bystanders to evacuate the building or to experts to take measures before it collapses.

Every glass beam with **span higher than 2m** needs to be reinforced with metal fibers or sheets at its bottom.

**Cross section**

There are several section geometries available for the adhesively bonded reinforced glass beam. The choice of the proper geometry of the cross sections depends on the design and the load-bearing needs of the structure (figure 4.11).
One of the main factors of this choice, is the lateral stability of the beam. The flanges of the Box and T section beam are provided this stability. For the full section though, the beam can become laterally instable (C. Louter, Belis, Bos, Veer, & Hobbelman, 2005). If the crack growth increases, a separation of the upper compression zone from the lower tensile zone is possible to happen, make the beam laterally unstable. Therefore, it is important to consider for the design of the glass beam the laterally stability of the uncracked and the cracked cross section geometry (P. C. Louter, 2007).

In the present design, the full section is preferred for the glass beams with the reinforcement placed at the bottom of the beam. At the top edge, the steel channel that is used for the connection with the glass floor panes can be worked as reinforcement as well (see next chapter).

**Buckling**

The extraordinary slenderness of glass beams leads to great concern regarding buckling damage. There are two main types of buckling, global buckling of beams and local buckling of beams. “Buckling of beams” refers to the phenomenon that whole beam will displace out of plane under in plane load by twisting, while “local buckling” refers to the phenomenon that a part of the beam will deform and fold out of plane. Buckling only happens under compression and bending. Even a beam that has almost ideal pinned supports has compression on top and any fixity of the supports or imperfections in the beam geometry or load direction can cause the beam to buckle if the loads are large enough.

One factor that can diminish this phenomenon is the sealing with silicon between the sides of beams which are connected with the roof or floor. That way, the roof or floor panels could work as braces to prevent the beams from buckling and out of plane bending damage.

In the present design, the lateral torsional buckling check can be sidestepped, since the beams are fixed in the connections at both edges. All the glass beams rest on the shoes fixed to the wall while at the other side they are connected to the glass brick façade. The detail in the connection can be found in the next chapter.

**Limits in the length**

Because of the industry capacity of glass manufacturing and laminated glass fabrication, the largest span of glass beams is 6 m. This is the size of the jumbo sheets before cutting and there will be a high price premium for manufacturing transporting and resembling oversized glass sheets (P. C. Louter, 2007).

In the present design, the maximum glass beam spans 6m, avoiding any extra measures in production or transportation of big glass pieces.

There are lot of design consideration one can take into account before determine the dimension of glass beam. However, there are some rule of thumbs that have been followed in the present design as well.
Rules of Thumb: Heat-treatment, Depth, Layers and Thickness

**Heat-strengthened glass** shall be the first choice for the glass beam design, because it is strong enough to sustain load and does not have the problem of spontaneous breakage and waste of material.

The beam height to span ratio should be in the range of 1/20 and 1/10. If the same type of glass is used, increasing depth is a powerful strategy to reduce the cross-section area of beams and use less material. It is also a powerful strategy to reduce the damage of buckling. As a result, *1/10 ratio* is recommended for glass beam design (P. C. Louter, 2007).

For glass beams with sliding, the thickness of the beam, which equals the number of layers X the thickness of one sheet of glass, is another crucial factor for design. Increasing layers could increase the safety factor in design and reduce the thickness of a single sheet of glass as well as the overall area of beam cross-section. However, it is not practical to use laminated glass made up of thin glass sheets and too many layers, because of the capacity of the glass fabrication industry, the more layers they have on laminated glass, the less available those glass beams are. And also, by doing so, the beams get more surface area and edge and introduce more Griffith Flaws, which leads to reduction of the strength quality. As a result, **3 or 4 layers** are recommended, and the thickness of every sheet should be **between 9 mm and 16 mm**.

**Design of the glass beams**

Taking into account all the above factors the glass beams consists of heat strengthened glass panes with sentryglass interlayer. The span of the beam ranges from 6m to 1.8m. From an economical point of view it is considered wise to have different configuration in the thickness depending on the span. In favor of the homogeneity though, all the beams consists of 3 layers of 12mm thick, satisfying the most critical beam with 6m span (figure 4.12).

![Cross section of the glass beams that support the glass floor in the design](image)

The beam height to span ratio of the glass beams should not exceed 1/10 as it has been described above. Therefore, the first estimation of the beam height for each of the floor is given in the following table.
Steel reinforcement is placed in all the beams apart from the glass beams of the first floor which span is less than 2m (figure 4.13).

The stresses, bending moments, shear forces and the deflections for all the beams are calculated by the ANSYS software, assuming for safety reasons that one layer of the glass has been broken resulting in \( t=24 \) mm instead of 36 mm. However, some hand calculations for the validity of the estimation of the dimensions of the beam has been done for the most critical beam.

The area and moment of inertia for the biggest beam are:

\[
A = 0.6 \times (0.036 - 0.012) = 0.0144 \text{ m}^2 \\
I = \frac{1}{12} \times 0.024 \times 0.6^3 = 0.000432 \text{ m}^4 \\
E = 70000 \text{ N/mm}^2
\]

The total area of the loads that are transferred to each of the beams is \( A=2 \times 6=12 \text{ m}^2 \). In the following figure, the separation of the load surface for each beam is illustrated:
Figure 4.14: Load surface for the critical glass beam (4th floor)

Loads for the beam

The self-weight of the glass panes (t=0.0421 m) is
\[ G = (0.0421 \times 25 \text{ kN/m}^3 + 0.107 \text{ kN/m}^3 \times 2 \times 1.52 \times 10^{-3}) \times 12\text{m}^2/6\text{m} = 2.11 \text{ kN/m} \]

The self-weight of the glass beam is
\[ G_1 = 0.6\text{m} \times 0.036 \times 25\text{kN/m}^3 = 0.54 \text{ kN/m} \]

So \( G_{\text{total}} = G + G_1 = 2.65 \text{ kN/m} \)

The live load (persons, maintenance) is \( Q = 5 \text{ kN/m}^2 \)

Load combinations for the beam

**Design situation 1**

1.35*G + 1.30*0*Q = 1.35*G = 1.35*2.65 = 3.58 kN/m²

**Design situation 2**

**ULS**

1.20*G + 1.30*0*Q = 1.20*G = 1.2*2.65 = 3.18 kN/m²
\[ 1.20^*G + 1.30^*Q = 1.20^*G + 1.3^*Q = 1.2^*2.65 + 1.3^*5 = 9.68 \text{ kN/m}^2 \]

*Factor 1.3 instead of 1.5 for the glass calculations*

**SLS**

\[ 1^*G + 1^*0^*Q = 1^*G = 2.65 \text{ kN/m}^2 \]
\[ 1^*G + 1^*Q = 1^*2.65 + 1^*5 = 7.65 \text{ kN/m}^2 \]

\[ M = \frac{1}{8}q*l^2 = \frac{1}{8} \times 9.68 \times 6^2 = 43.56 \text{ kNm} \]
\[ W = \frac{1}{6}b*d^2 = \frac{1}{6} \times 0.024 \times 0.6^2 = 0.00144 \text{ m}^3 \]
\[ \sigma = \frac{M}{W} = 30.25 \text{ MPa} < 40 \text{ MPa} \checkmark \]
\[ \mu = \frac{30.25}{40} = 0.756 < 1 \text{ (75\% utilization)} \checkmark \]
\[ \delta = \frac{5^*q*l^4}{(384^*I^*E)} = \frac{5^*7.65^*6^4}{(384^*0.000432^*70^*10^9)} = 4.27 \times 10^{-6} \text{ m} = 0.00427 \text{ mm} < l/250 = 24 \text{ mm} \checkmark \]
Glass roof

There have been huge technical advances in roof glazing in recent years, giving the opportunity to increase natural light whilst still retaining a high performance, weather tight roof. This growth in demand has been partly driven by the move away from fully air conditioned buildings with centralized building management systems, towards naturally ventilated and naturally lit environments that give more control to occupants. A reason that the glass roof design for this project as well was driven by. In addition to the considerations of thermal and solar control that also apply to vertical façades, sloped glazing is overhead, so it has to be safe. And if the glass forms part of a roof area that needs to be accessible, for example for cleaning, it may need to be treated and specified as a glass floor.

General design considerations

Many of the key considerations for specifying roof glazing are no different to designing vertical façades. The design considerations that one should take into account are the glass and frame U values, air and water tightness, safety to ISO standards, as well as solar control and ventilation for occupier comfort. Some additional requirements are the cleaning and maintenance of the roof, the effective drainage from rainwater and the effective design of the smoke vents (www.wicona.co.uk). More specifically:

- For overhead glazing, regulations generally require the use of safety glass for the inner pane. The internal pane should then be laminated so in the event of breakage, the glass will not shatter and fall, causing injury. The external pane, particularly if it is solar control glass, should be toughened to prevent cracking as a result of thermal shock. The thickness of the glass specified will also affect the loading the system has to accommodate.
- Profiles should be sized to meet the appropriate loadings. These could include wind, snow, glass and cleaning loads.
- Controlling solar gain with selecting glass with high level of light transmission as well as high reflection. Controlling solar gain can have important implications for heating and cooling the building.
- Adequate slope that will ensure effective water runoff and application of silicone sealant in the connections between the glass panes.
- Cleaning and maintenance considerations from the early stage of the design.

Roof glass panels

The configuration of the grid of the glass panes in the roof is based mostly on safety issues than on architectural. The fixed dimension of the roof is the width which is 2.15m, which is the required dimension in order to achieve the natural ventilation with the stack effect in the atrium and to maximize the natural light coming into the building. The other dimension which can be divided in different sizes, is 20m. The first alternative of the panes configuration, based on the maximum transparency, is to use big sizes of glass panes such as 2.15m X 5m. However, to reduce the risk of injury, it is recommended to minimize the size (area less than 3m²) and the thickness of the glass pane, when the roof is more than 13m above the
floor. In this design, the clear height of the roof and the ground floor is 20m, increasing the risk of injury when the glass breaks and either small particles can fall down in case of a bad heat treatment of the glass or the whole pane can fall down in case of a bad connection with the surrounding structural elements (www.pilkington.com). Therefore, each panel of glass is 2.15m long by 1.35m wide (2.9m²) (figure 4.15). (It follows the pattern of the glass roof of the York dale Shopping centre in Toronto, Ontario).

Since not only safety, but thermal isolation is important for the glazing in the roof, double glazing is preferred over single glazing. Thus, the upper part consists of 2 glass panes of 8mm each, heat strengthened laminated with 1.52mm Sentryglass foil Pilkington Optifloat, which reduces the glare and offers a degree of solar control performance, whilst the lower part consists of 2 glass panes 8mm each, heat strengthened laminated with 1.52mm Sentryglass foil Pilkington Optilam, which provides both impact resistance and security. At the air gap, argon gas 16mm is preferred for better thermal insulation (figure 4.16).

To sum up, each of the glass pane is heat strengthened laminate double glazing with 1.3m X 2.15m size and thickness 16mm outer pane, 16mm argon air gap and 16 mm inner pane (88.2). Thus, total thickness is 48 mm. Thickness without the gap (glass thickness) is t=0.032m. Single glazing thickness without the gap (glass thickness that is assumed to take over all the load) is t=0.016m.

The structural calculation will be held for only the upper part of the roof glazing, since it is assumed that this takes the whole load, being in the safety side.
Loads for the glass pane

The self-weight of the glass panes and the snow are the main load cases for the thickness determination of the panels.

- **The self-weight of the glass panes (for the exterior glazing only)** (t=0.016m) is \( G = 0.016 \times 25 \text{ kN/m}^3 + 0.107 \text{ kN/m}^3 \times 1.52 \text{ mm} \times 10^{-3} = 0.40 \text{ kN/m}^2 \)
  
  The weight of the air is (t=0.016m) \( G_1 = 0.016 \text{ m} \times 12.75 \text{ kN/m}^3 = 0.204 \text{ kN/m}^2 \)

\[ G_{al} = 0.40 \text{ kN/m}^2 \]

- **Snow load for Netherlands**
  
  The snow load is \( S = \mu_i \times C_e \times C_t \times s_k \)
  
  In Netherlands \( s = 0.7 \text{ kN/m}^2 \)
  
  For \( \alpha = 0 \) (flat roof) \( \mu_i = 0.8 \)
  
  \( C_e = 1 \) and \( C = 1 \).
  
  So the snow load is \( S = (0.8 \times 1 \times 1 \times 0.7) = 0.56 \text{ kN/m}^2 \)

  (For simplicity reasons for the hand calculations, it is assumed that the maintenance and snow load can be taken as one load with the value 1 kN/m² since the situation where there might be snow and people on the roof is considered highly unlikely.)

  Therefore \( S = 1 \text{ kN/m}^2 \)

- **The wind load for a flat roof** is \( W_i = c_s c_d c_f q_p(z_e) \)
  
  The structural factor \( c_s c_d \) = 1 for regular low-rise buildings.
  
  For S-W wind orientation the windzone for flat roofs is \( G \), so the \( c_f = -1.2 \)
  
  \( z_e = h = 20 \text{ m} \) so \( q_p(z_e) = 1.07 \text{ kN/m}^2 \) (Amsterdam belongs to Urban area I in the wind regions in Netherlands)
  
  So the wind load is \( W_i = 1 \times (-1.2) \times 1.07 = -1.284 \text{ kN/m}^2 \)

Load combinations for the glass roof

**Design situation 1**

\[ 1.35 \times G_{al} + 1.30 \times 0 \times W + 1.30 \times 0 \times S = 1.35 \times G_{al} = 1.35 \times 0.40 = 0.54 \text{ kN/m}^2 \]

**Design situation 2**

**ULS**

\[ 1.20 \times G_{al} + 1.30 \times 0 \times S = 1.20 \times G_{al} = 1.2 \times 0.40 = 0.48 \text{ kN/m}^2 \]

\[ 1.20 \times G_{al} + 1.30 \times S = 1.20 \times G_{al} + 1.30 \times S = 1.2 \times 0.40 + 1.3 \times 1 = 1.78 \text{ kN/m}^2 \]

\[ 0.9 \times G_{al} + 1.30 \times W = 0.9 \times 0.4 + 1.30 \times (-1.284) = -1.31 \text{ kN/m}^2 \]

*(the factor 1.3 instead of 1.5 for the glass calculations and for the roof 0.9 factor, concerning the negative external pressure where the permanent roof weight acts as favorable)*

**SLS**
\[ 1 \times G_{ol} + 1 \times 0 \times S = 1 \times G_{ol} = 0.40 \text{ kN/m}^2 \]
\[ 1 \times G_{ol} + 1 \times S = 1 \times 0.40 + 1 \times 1 = 1.40 \text{ kN/m}^2 \]

It is assumed that only the exterior glazing will take the whole load. That means that there is no working collaboration between the double glazing glass panels. Even though there is some collaboration due to the common air pressure between the glazing (ZHOU, n.d.).

The calculation is implemented for the one size pane (1.3m X 2.15m) which is four sided supported.

\[ \frac{b}{a} = \frac{2.15}{1.3} = 1.65 \] so from the table above doing interpolation \( \alpha = 0.0971 \) and \( \beta = 0.5124 \)

\[ P = 1.78 \text{ kN/m}^2 \]
\[ E = 70000 \text{ N/mm}^2 \]
\[ t_1 = 0.16 \text{ m} \]
Thus, \( \sigma_{\text{cr}} = 0.5124 \times 1.78 \times 1.3^2 / (0.016^2 \times 1000) = 6.02 \text{ N/mm}^2 < 10 = \sigma_{\text{max}} \)

And \( \delta_1 = 0.0971 \times 1.40 \times 1.3^4 / (70000 \times 0.016^3 \times 1000) = 1.35 \times 10^{-3} \text{ m} = 1.35 \text{ mm} < 7.43 \text{ mm} = \delta_{\text{max}} = L/175 \)

**Glass beams for the glass roof panes**

The design considerations are the same as the one mentioned for the glass beams which support the glass floor.

Since the spans are only 2.15m and 1.35m, the thickness of the glass beam can be less than before. For the first estimation 3 layers of 10mm heat strengthened with sentryglass lamination is preferred. The height of the beams has been selected 0.20 m for both beams in order to simplify the connection between the beams and the column (see next chapter) keeping same height for the three beams coming together above the glass brick column.

![Figure 4.17: Cross section of the glass beam in the roof](image)

The surface load for each of the beams can be seen in the figure 4.18.

\[ A_1 = 2 \times (1.50 + 2.15) \times 0.65 / 2 = 2.38 \text{ m}^2 \]
\[ A_2 = \frac{1}{2} \times 1.3 \times 0.65 = 0.42 \text{ m}^2 \]
The stresses, bending moments, shear forces and the deflections for both of beams have been calculated by the software ANSYS, assuming for safety reasons that one layer of the glass beam has been broken resulting in \( t=20 \text{ mm} \) instead of 30 mm. Thus, the area and moment of inertia are:

\[
A = 0.20 \times (0.030 - 0.010) = 0.004 \text{ m}^2 \\
I = \frac{1}{12} \times 0.020 \times 0.20^3 = 1.33 \times 10^{-5} \text{ m}^4 \\
E = 70000 \text{ N/mm}^2
\]

Loads for the beam \( B_1 \)

- The self-weight of the glass panes (\( t=0.032 \text{ m} \)) is \( G = 0.032 \text{ m} \times 25 \text{ kN/m}^3 \times \frac{2.38 \text{ m}^2}{2.15 \text{ m}} + 0.107 \text{ kN/m}^3 \	imes 1.52 \text{ mm} \times 2 \times 10^{-3} \times 2.38 \text{ m}^3/2.15 \text{ m} = 0.886 \text{ kN/m} \)
- The weight of the air is (\( t=0.016 \text{ m} \)) \( G_1 = 0.016 \text{ m} \times 12.75 \text{ kN/m}^3 \times \frac{2.38 \text{ m}^2}{2.15 \text{ m}} = 0.226 \text{ kN/m}^2 \)

\( G_{ol} = 1.112 \text{ kN/m} \)
- The self-weight of the glass beam is \( G_1 = 0.20 \text{ m} \times 0.030 \text{ m} \times 25 \text{ kN/m}^3 = 0.15 \text{ kN/m} \)

So \( G_{total} = G + G_1 = 1.262 \text{ kN/m} \)

- The live load (persons, maintenance) is \( Q = 1 \text{ kN/m}^2 \)

(For simplicity reasons for the hand calculations, we assume that the maintenance and snow load can be taken as one load with the value 1 kN/m\(^2\) since the situation where there might be snow and people on the roof is considered highly unlikely.)

Therefore \( S = 1 \text{ kN/m}^2 \times 2.38 \text{ m}^2/2.15 \text{ m} = 1.11 \text{ kN/m} \)
Load combinations for the beam

**Design situation 1**

1.35*G + 1.30*0*S = 1.35*G = 1.35*1.262= 1.7037 kN/m

**Design situation 2**

**ULS**

1.20*G + 1.30*0*S = 1.20*G = 1.2*1.262= 1.51 kN/m

1.20*G + 1.30*S = 1.20*G + 1.3*S = 1.2*1.262+ 1.3*1.11= 2.95 kN/m (factor 1.3 instead of 1.5 for the glass calculations)

**SLS**

1*G + 1*0*S = 1*G =1.262 kN/m

1*G+ 1*S = 1.262+1.11 =2.37 kN/m

M= 1/8*q*l²=1/8*2.95*2.15²= 1.70 kNm

W=1/6*b*d² = 1/6*0.020*0.20²= 1.33*10⁻⁴ m³

σ = M/W= 12.75 MPa < 40MPa

μ=12.75/40=0.32<1 (32% utilization) √

δ = 5*q*l⁴/(384*I*E)= 5*2.804*2.15⁴/(384*1.33 * 10⁻⁵ *70*10⁹)=8.38*10⁻⁷ m =8.38*10⁻⁴ mm << l/250 = 8.6 mm

**Glass columns in the glass roof**

As it has been described in the architecture chapter, the homogeneity is one of the main principles in this design. Thus, all the vertical glass elements are made by glass bricks and all the horizontal glass elements by float glass. The glass column consists of glass bricks customized dimensions glued together with the DELO PHOTOBOND 4468 for the horizontal bonding and 4497 for the vertical bonding. The connection can be found in the next chapter.

**Loads for the column**

Since the type of the connections of the glass beam in the roof are not the same (one is fixed between the buttresses in the glass brick façade and the other is connected with steel plate with the glass column, the loads are not equally distributed. Assuming that the 2/3 of the loads are transferred to the glass columns and after to the concrete beam and only the 1/3 goes to the glass brick façade through
buttresses. Following this assumption, the load surface for each of the glass column in the roof is \( A = \frac{2}{3} \times 2.15 \times 1.3 = 1.86 \text{ m}^2 \). In the following drawing, the load surface for each column is illustrated.

![Figure 4.19: Load surfaces for the glass brick column in the roof](image)

- The self-weight of the glass panes (\( t=0.032\text{ m} \)) is \( G = 0.032 \text{ m} \times 25 \text{ kN/m}^3 \times 1.86 \text{ m}^2 + 0.016 \text{ m} \times 12.75 \text{ kN/m}^3 \times 1.86 \text{ m}^2 + 0.107 \text{ kN/m}^3 \times 1.5 \times 10^{-3} \times 1.86 \text{ m}^2 = 1.87 \text{ kN} \)
- The self-weight of the glass beam is \( G_1 = 0.20 \text{ m} \times 0.030 \text{ m} \times 25 \text{ kN/m}^3 \times (1.43 \text{ m} + 1.30 \text{ m}) = 0.41 \text{ kN} \)

So \( G_{\text{total}} = G + G_1 = 2.28 \text{ kN} \)

The live load (persons, maintenance) is \( Q = 1 \text{ kN/m}^2 \)  
*(For simplicity reasons, it is assumed that the maintenance and snow load can be taken as one load with the value 1 kN/m² since the situation where there might be snow and people on the roof is considered highly unlikely.)*

Therefore \( S = 1 \text{ kN/m}^2 \times 1.86 \text{ m}^2 = 1.86 \text{ kN} \)

**Load combinations for the column**

**Design situation 1**

\[ 1.35G + 1.30S = 1.35G = 1.35 \times 2.28 = 3.078 \text{ kN} \]

**Design situation 2**

\[ 1.20G + 1.30S = 1.20G = 1.2 \times 2.28 = 2.736 \text{ kN} \]

\[ 1.20G + 1.30W + 1.30S = 1.20G + 1.3S = 1.2 \times 2.28 + 1.3 \times 1.86 = 5.154 \text{ kN} \]

*(the factor 1.3 instead of 1.5 for the glass calculations)*
Therefore $N_{rd} = 5.154$ kN

Compression check

$N_{c,Rd} = A*f_y \geq N_{rd} = 5.154$

$A \geq 5.154 \times 10^3/40 = 125.75$ mm$^2$

$a^2 \geq 125.75$

$=> a = 11.21$ mm $= 0.012$ m

For construction reasons, due to the thickness of the glass beams, the dimension of the glass brick column should be bigger than 100 mm so the buckling check will be done for a column with side size $a=0.10$ m.

Buckling check

$k_c = \frac{1}{k + \sqrt{k^2 - \lambda_{rel}^2}}$

$\lambda_{rel} = \frac{\lambda}{\pi} \sqrt{\frac{f_c}{E}}$ (fc without factor)

$k = 0.5(1 + \beta(\lambda_{rel} - 0.3) + \lambda_{rel}^2)$

sawn timber: $\beta=0.2$, glulam and LVL: $\beta=0.1$

(for glass you can use 0.1, as the manufacturing quality and accuracy is large)

$\lambda = l_{buckling}/i$

$i = \frac{I}{A}$ (should be around 78.5mm for a hollow section of 200mm)

For the glass brick column calculation $\beta=0.2$ is taken since the column consists of lot of bricks that can have slightly differences in dimensions due to manufacturing process.

Requirement

$\sigma_{c,0,d} < k_c f_{c,0,d}$

Therefore,

$l = 1/12 \times a^4 = 8.33 \times 10^{-6}$ m$^4$

$A = a^2 = 0.01$ m$^2$

$i = (8.33 \times 10^{-6}/0.01)^{1/2} = 0.029$

$\lambda = 0.80/0.029 = 27.59$ m

$\lambda_{rel} = \lambda/\pi \times (f_c/E)^{1/2} = 27.59 /\pi \times (40/(70 \times 10^3))^{1/2} = 0.21$ m

$k = 0.5(1+\beta(\lambda_{rel} - 0.3) + \lambda_{rel}^2) = 0.513$

$k_c = 1/(k+(k^2 - \lambda_{rel}^2)^{1/2}) = 1.01 > 1 \Rightarrow k_c = 1$
Requirement

\[ k_c A f_y > N_{ed} \]
\[ 1 \times 0.01 \times 40 \times 10^3 = 400 > 5.03 \]

Thus, the dimension of the cross section of the glass brick column in the roof is: 0.10m X 0.10m.

Figure 4.20: Impression of the glass roof
Glass Brick Columns

Following the idea of using the same material as the façade in order to achieve the continuity, the glass columns are made of customized glass bricks and their lengths reach the 22 meters since they transfer the loads from the big concrete beam in the roof to the basement. A consistent and elegant design where the existing concrete structure will fit well with the new added glass structure leads to the choice of rectangular cross section of glass column as the concrete ones and not to the choice of tubular, IPE, cross etc.

For the predesign structural calculations the dimensions of the glass columns are the same as concrete (0.4 m X 0.4 m). The most critical calculation for such a slender column is buckling, thus apart from the structural calculation with the ANSYS software, a compression and buckling check in hand are necessary in order to ensure the stability of the columns.

Loads for the glass brick column

Stiffness depends upon material properties and geometry. The stiffness of a structural element of a given material is the product of the material's Young's modulus and the element's second moment of area. In a structure made up of multiple structural elements where the surface distributing the forces to the elements is rigid, the elements will carry loads in proportion to their relative stiffness - the stiffer an element, the more load it will attract. That means that most of the loads will go at the glass columns in the middle of the frame (figure 4.21). Being in the safety side, it has been considered that all the loads are being carried by the two glass columns only.

\[ EI \]
\[ 7/3 \, EI \]
\[ 7/3 \, EI \]
\[ EI \]

*Figure 4.21: Load path based on the stiffness of the elements*
Assuming that half of the concrete floor weight is distributed equally to the concrete beams and the 2/3 of the weights of the glass roof goes at the concrete beam the loads that the concrete beam carries and in consequence the glass columns (figure 4.22) are:

- **Glass panes**
  
  \[ G_{\text{panes}} = (0.032m \times 25\text{kN/m}^3 \times 15 \text{ (the number of panes)} \times 2.8\text{m}^2 \text{ (area of each pane)} + 0.016m \times 12.75\text{kN/m}^3 \times 15 \times 2.8\text{m}^2) / 20m = 2.10\text{kN/m} \]

- **Glass beams**
  
  \[ G_1 = (0.20m \times 0.03m \times 25\text{kN/m}^3) \times 16 \text{ (number of beams)} = 1.6\text{kN/m} \]
  
  \[ 1.6\text{kN/m} \times 2/3 \times 2.15m = 2.29\text{kN} \]
  
  \[ 2.29\text{kN} / 20\text{m} = 0.1145\text{kN/m} \]

  \[ G_2 = (0.20m \times 0.03m \times 25\text{kN/m}^3) \times 15 \text{ (number of beams)} = 2.25\text{kN/m} \]
  
  \[ 2.25\text{kN/m} \times 1.35m = 3.04\text{kN} \]
  
  \[ 3.04\text{kN} / 20\text{m} = 0.15\text{kN/m} \]

- **Glass columns**
  
  \[ G_{\text{columns}} = 0.80m \times 0.10m \times 0.10m \times 25\text{kN/m}^3 \times 16 \text{ (number of columns)} = 3.2\text{kN} \]
  
  \[ 3.2\text{KN/20m=0.16 kN/m} \]

- **Concrete floor**
  
  \[ G_{\text{floor}} = 0.15m \times 20m \times 3.28m \times 24\text{kN/m}^3 = 236.16\text{kN} \]
  
  \[ 236.16\text{kN/20m=11.81 kN/m} \]
- **Concrete beam**

  \[ G_{\text{beam}} = 0.45m \times 0.40m \times 24 \text{ kN/m}^3 = 4.32 \text{ kN/m} \]

  \[ G_{\text{total}} = 18.65 \text{ kN/m} \times 20m = 373.09 \text{ kN} \]

  The load is distributed equally to the two glass columns. Thus, \( G = 186.57 \text{ kN} \)

- **Snow**

  \( S = 1 \text{ kN/m}^2 \)

  The area that is exposed to the snow is \( 20 \times (3.28 + 1.4 - 0.35) = 86.6 \text{ m}^2 \) (figure 4.22)

  Thus, \( 86.6 \text{ m}^2 \times 1 \text{ kN/m}^2 = 86.6 \text{ kN} \)

  \( 86.6/2 = 43.3 \text{ kN} \) each glass column

  \( S = 43.3 \text{ kN} \)

*Load combination for the glass brick column*

\[ 1.20 \times G + 1.30 \times 0 \times W + 1.30 \times S = 1.20 \times G + 1.3 \times S = 1.2 \times 186.57 + 1.3 \times 43.3 = 280.174 \text{ kN} \]

\( N_{sd} = 280.174 \text{ kN} \)

*Compression check*

\[ N_{c,Rd} = A \times f_y \geq N_{sd} = 280.174 \text{ kN} \]

\[ A \geq 280.174 \times 10^3/40 = 7004 \text{ mm}^2 \]

\[ a^2 \geq 7004 \]

\[ \Rightarrow a = 84 \text{ mm} = 0.084 \text{ m} < 0.4 \text{ m} \]
Buckling check

\[
k_c = \frac{1}{k + \sqrt{k^2 - \lambda_{rel}^2}}
\]

\[
\lambda_{rel} = \frac{\lambda}{\pi} \sqrt{\frac{f_c}{E}} \quad (fc \text{ without factor})
\]

\[
k = 0.5(1 + \beta(\lambda_{rel} - 0.3) + \lambda_{rel}^2)
\]

sawn timber: \(\beta=0.2\), glulam and LVL: \(\beta=0.1\)

(for glass you can use 0.1, as the manufacturing quality and accuracy is large)

\[
\lambda = \text{buckling} / i
\]

\[
i = \sqrt{\frac{I}{A}} \quad (\text{should be around 78.5mm for a hollow section of 200mm})
\]

(For glass brick \(\beta=0.2\))

\[
I = 1/12*a^4 = 1/12 * 0.4^4 = 2.13*10^{-3} \text{ m}^4
\]

\[
\Lambda = a^2 = 0.16 \text{ m}^2
\]

\[
i = (2.13*10^{-3}/0.16)^{1/2} = 0.1154
\]

\[
\lambda = 22/0.1154 = 190.64 \text{ m}
\]

\[
\lambda_{rel} = \lambda/\pi * (f_y/E)^{1/2} = 190.64/\pi * (40/70*(10^3))^{1/2} = 1.45 \text{ m}
\]

\[
k = 0.5*(1+\beta*(\lambda_{rel} - 0.3) + \lambda_{rel}^2) = 1.67
\]

\[
k_c = 1/(k+(k^2 - \lambda_{rel}^2)^{1/2}) = 0.40 <1
\]

Requirement

\[
k_c * A * f_y > N_{sd}
\]

\[
0.40*0.16*40*10^{-3}= 2560 \text{ kN} > 280.174 \text{ kN}
\]

\[
\mu = 280.174/2560=0.11
\]

There is margin for smaller section but in favor of homogeneity, the section of the glass brick columns are kept the same as the concrete columns at the existing building (0.4m X 0.4m).
Since such a column structure with that pattern and size has not realized before, some safety measures should be taken into account. Unavoidably, there are differences in the dimensions of each of the glass brick due to the manufacturing process. These differences in a column with height 22m which is made by lot of glass bricks, can cause lot of problems in the connection between the concrete and glass structure. For that reason, an aluminum base is placed at the bottom and at the head of the column which compensate these height differences and assure the equally distribution of the forces from the building into the glass column through this connection type. A prototype of a bundled all glass column with that soft aluminum base at the bottom and head can be seen in the figure 4.23.

Moreover, some measures should be taken at the level of ground floor around the column, to protect it from accidently damage or break due to cleaning devices or other objects. Placing sofa around the column can be one good solution for this. The sofa can be made by glass in order to maintain the transparency of the column (figure 4.23).

![Prototype of a bundled all glass column (Louter, 2010) (left), glass sofa designed by FIAM (www.furniturefashion.com) (right)](image)

The final dimensions of the element are defined by not only the allowable stresses and deflections but by the construction and connection constraints. Undoubtedly, designing is not one way street and it is based on the personal aesthetics and belief of the designer.
Structural calculations with the use of ANSYS FEM software

In this chapter the steps followed for the simulation of the whole building in ANSYS software as well as the results and the optimization are elaborated.

ANSYS Software

ANSYS is an engineering simulation software (computer-aided engineering) developed in Pennsylvania, United States. ANSYS has lots of different Simulation Technologies such as Structural Mechanics, Multiphysics, Fluid Dynamics, Explicit Dynamics, Electromagnetics, Hydrodynamics (AQWA) The Workflow Technology of ANSYS is also different. There is the Ansys Workbench Platform, High-Performance Computing, Geometry Interfaces (GUI), Simulation Process & Data Management. The choice depends on the desired accuracy and available time one have.

ANSYS Multiphysics version 15.0.7. software was considered the most suitable for the utilization of the structural calculations for this design and Graphic Use Interface (GUI) for the workflow.

The model

Element type

The element types that are used to simulate the structure is BEAM 188 for all the columns and Shell 181 for all the slabs, walls and beams. The beams are simulated as shell and not as beam in order to achieve better accuracy and more elaborated results of the distribution of stresses along the cross section. The connection between the beams and slabs is implemented with two Keypoints instead of one.

The BEAM 188 is a linear (2-node) beam element in 3-D with six degrees of freedom at each node. The degrees of freedom at each node include translations in x, y, and z directions, and rotations about the x, y, and z directions. The beam elements are well-suited for linear, large rotation, and/or large strain nonlinear applications. This element is suitable for analyzing slender to moderately stubby/thick beam structures. It is based on Timoshenko beam theory. Shear deformation effects are included (mostreal.sk/html/elem_55/chapter4/ES4-188).

The SHELL 181 element is suitable for analyzing thin to moderately-thick shell structures. It is a four-noded element with six degrees of freedom at each node: translations in the x, y, and z directions, and rotations about the x, y, and z axes. It is well-suited for linear, large rotation, and/or large strain nonlinear applications (mostreal.sk/html/elem_55/chapter4/ES4-181).
Materials

<table>
<thead>
<tr>
<th>Material Properties</th>
<th>Material Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Concrete</td>
</tr>
<tr>
<td><strong>E (GPa)</strong></td>
<td>30</td>
</tr>
<tr>
<td><strong>v</strong></td>
<td>0.2</td>
</tr>
<tr>
<td><strong>ρ (kg/m³)</strong></td>
<td>2400</td>
</tr>
</tbody>
</table>

*Table 4.6: Material properties used in the Model*

Sections

<table>
<thead>
<tr>
<th>Element Type</th>
<th>Element</th>
<th>ID</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam</td>
<td>Concrete and Glass Brick Column</td>
<td>1</td>
<td>0.4m X 0.4m</td>
</tr>
<tr>
<td>Shell</td>
<td>Concrete Floor</td>
<td>2</td>
<td>t=0.15m</td>
</tr>
<tr>
<td>Shell</td>
<td>Glass Floor</td>
<td>3</td>
<td>t=0.0421m</td>
</tr>
<tr>
<td>Shell</td>
<td>Concrete Beam</td>
<td>4</td>
<td>t=0.40m</td>
</tr>
<tr>
<td>Shell</td>
<td>Glass Beam</td>
<td>5</td>
<td>t=0.036m</td>
</tr>
<tr>
<td>Shell</td>
<td>Glass Brick Façade</td>
<td>6</td>
<td>t=0.21m</td>
</tr>
<tr>
<td>Shell</td>
<td>Concrete Wall (in basement)</td>
<td>7</td>
<td>t=0.25m</td>
</tr>
<tr>
<td>Shell</td>
<td>Brick Masonry</td>
<td>8</td>
<td>t=0.20m</td>
</tr>
<tr>
<td>Shell</td>
<td>Glass Pane in Roof</td>
<td>9</td>
<td>t=0.032m</td>
</tr>
<tr>
<td>Beam</td>
<td>Glass Brick Column in Roof</td>
<td>10</td>
<td>0.1m X 0.1m</td>
</tr>
<tr>
<td>Shell</td>
<td>Glass Brick Buttresses</td>
<td>11</td>
<td>t=0.195m</td>
</tr>
<tr>
<td>Shell</td>
<td>Glass Beam in Roof</td>
<td>12</td>
<td>t=0.030m</td>
</tr>
</tbody>
</table>

*Table 4.7: Sections of the elements used in the Model*
**Geometry**

The geometry of the model has been created by setting Keypoints and drawing lines and areas.

![Figure 4.24: The model with lines (left) and areas (right) (ANSYS)](image)

As it can be seen in the figure 4.24, the X axe runs parallel to the width of the façade, the Y axe is perpendicular to the facades and the Z axe defines the height of the building.

The shafts where the staircases, the elevators and the building services are distributed vertically in each floor can be seen in the floor plan in figure 4.25.

Shaft 1: The main glass staircase with the glass elevator in the middle

Shaft 2: The emergency concrete staircase

Shaft 3: The staff elevator and the shaft with the pipes and ducts running vertically
Figure 4.25: Plan of the 1st floor (ANSYS)
Meshing

After giving the mesh attributes to each line and area, the size of the mesh division took place. Each of the element has been divided in element edge length approximately 0.2m.

Figure 4.26: Meshing (ANSYS)
Glass structure

Concrete Structure

Figure 4.27: Meshing (ANSYS)
**Boundary Conditions**

The building is adjacent with two other buildings in both sides. This is simulated with applying constraints to all the degree of freedom of the nodes in the connection between beam and column in each floor (figure 4.28). The bottom of each of the columns is constrained at the foundation (all DOFs = 0) (figure 4.29).

*Figure 4.28: Side view of the building showing the DOFs of the Keypoints in each column that has been constrained (Boundary Conditions) (ANSYS)*
Figure 4.29: Plan view of the floor in the basement showing the DOFs of the keypoints in each column that has been constrained (Boundary Conditions) (ANSYS)
Loads

The loads that were input in the program are the following:

Permanent loads

- The self-weight of the concrete and glass structure is calculated automatically by the program
- Concrete floor covering and services: $G_1 = 0.50 \text{ kN/m}^2$
- Concrete roof covering loads: $G_2 = 0.20 \text{ kN/m}^2$

Variable loads

- Live Load for concrete floors: $Q_1 = 4 \text{ kN/m}^2$
- Live Load for glass floors: $Q_2 = 5 \text{ kN/m}^2$
- Maintenance load for the concrete and glass roof: $Q = 1 \text{ kN/m}^2$

Snow and wind loads for Amsterdam, Netherlands

- Snow load for the concrete and glass roof:
  The snow load is $S=\mu_i*C_e*C_t*s_k$
  In Netherlands $s=0.7 \text{ kN/m}^2$
  For $\alpha=0$ (flat roof) $\mu_i=0.8$
  $C_e=1$ and $C=1$.
  So the snow load is $S=(0.8*1*1*0.7)=0.56 \text{ kN/m}^2$
  $S = 0.56 \text{ kN/m}^2$

- Wind load is applied on the facades and the roof:
  The wind load is $W_i=c_s*c_d*c_f*q_p(z_e)$
  The structural factor $c_s*c_d=1$ for regular low-rise buildings
  $z_e=h=20 \text{ m}$ so $q_p(z_e)=1.07 \text{ kN/m}^2$ (Amsterdam belongs to Urban area I among the wind regions in Netherlands)

  For $S-W$ wind orientation the windzone for flat roofs is G, so the $c_f=-1.2$
  So the wind load is $W_i=1*(-1.2)*1.07 = -1.284 \text{ kN/m}^2$
  $W_i = -1.284 \text{ kN/m}^2$

  The wind load for the façade is $W_i=c_s*c_d*c_f*q_p(z_e)$
  The structural factor $c_s*c_d=1$ for regular low-rise buildings.
  $b=20\text{m}$ $d=20\text{m}$ and $h= 20\text{ m}$ and $e=b=20\text{m}$ and $h/d=1$ so the wind zone for facades is D, so the $c_f=+0.8$
  So the wind load is $W_i=(1*(0.8)*1.07)) =0.856\text{kN/m}^2$
  $W_i = 0.856\text{kN/m}^2$
Snow and wind loads for **Tampere, Finland**

- Snow load for the concrete and glass roof:
  The snow load is $S = \mu \times C_e \times C_t \times S_k$

  Where for Finland the characteristic snow load on the ground is given by the formula:
  $S_k = 0.790 \times Z + 0.375 + A/336$,
  $A$ is the site altitude above Sea Level (m)
  $Z$ is the zone number given on the map
  For Tampere is $Z=2$ and $A=114$m (EN 1991-1-3)
  Thus, $S_k = 0.790 \times 2 + 0.375 + 114/336 = 2.29\text{kN/m}^2$
  For $\alpha=0$ (flat roof) $\mu=0.8$
  $C_e=1$ and $C=1$.
  So the snow load is $S = (0.8 \times 1 \times 1 \times 2.29) = 1.832\ \text{kN/m}^2$
  $S = 1.832\ \text{kN/m}^2$ (2 times more than for Netherlands-critical load)
Snow and wind loads for Valencia, Spain

- Snow load for the concrete and glass roof:
  The snow load is \( S = \mu_i C_e C_t S_k \)
  Where for Spain the characteristic snow load on the ground is given by the formula:
  \( S_k = (0.190Z - 0.095)(1 + (A/524)^2) \), (European Climatic Regions: Iberian Peninsula) (EN 1991-1-3)
  \( A \) is the site altitude above Sea Level (m)
  \( Z \) is the zone number given on the map
  For Valencia is \( Z = 2 \) and \( A = 23 \) m
  Thus, \( S_k = (0.190*2 - 0.095)(1 + (23/524)^2) = 0.285 \) kN/m²
  For \( \alpha = 0 \) (flat roof) \( \mu = 0.8 \)
  \( C_e = 1 \) and \( C_t = 1 \).
  So the snow load is \( S = 0.8*1*0.285 = 0.228 \) kN/m²
  \( S = 0.228 \) kN/m² (3 times less than for Netherlands - not critical)

The most critical load combination is the wind of Netherlands, the snow of Finland and the thermal load (sun) of Spain.
**Structural integrity**

Progressive collapse occurs when the collapse of a structural element gives rise to a chain reaction type failure of adjacent structural elements. Structures should be planned and designed so that they are not unreasonably susceptible to the effects of accidents. In particular, situations should be avoided where damage to small areas of a structure or failure of a single element may lead to collapse of major parts of a structure.

Robustness is fundamental when designing glass structure, since any glass can break. The question that should be answered though, is what will happen when it does. The goal is to achieve safe breakage and avoid collapse. Component failure should never be a threat to human life or endanger the overall stability of the whole structural system. The present design was followed this direction for the glass structure in three different levels (the material level, the component level and the structural level).

Each of the glass element is heat strengthened, laminated, reinforced and has been designed assumed that one layer is broken. These measures are good strategies in increasing robustness in the level of component. When it comes to the level of the glass structure, it is important to avoid the local stress concentrations. Glass requires more careful workmanship than other structures, since poor manufacturing and construction principles may lead to high stress concentrations.

Furthermore, it is really important for the designer to be able to identify the most possible exposures and unforeseen events that can happen. For example, a vehicle can crash to the glass brick façade or a vandalism action can happen. For this reason, impact and vandalism laboratory tests have been conducted. The level of the allowable breakage of the element depends on the importance and the function of this element. For instance there can be different consequences of failure of the glass beam or glass panes at the ground floor and the upper levels.

The consequences of failure that should be considered for the design are:
- Serviceability problems or cracking, which require replacement of panels
- Risk of glass falling, which can cause injuries
- Risk of someone is falling from height due to the failure of the glass structural element (beam or floor), which can cause fatality
- Progressive collapse of parts of the structure or the entire assembly

More details about the measures taken to increase redundancy in the glass structure can be found in the chapter “Glass Technology Analysis”.
Stability

When part of the existing building is to be demolished to create the atrium and to add the glass structural elements, it will be necessary to check carefully the structural behavior and the stability of the remaining structure. The pattern of loading, applied to members close to the demolished part, will change. It should be thoroughly studied the stability during the demolition process as well as any need of strengthening of the remaining structure. Before the construction of the glass bricks columns, the loads from the roof should be transferred safely to the foundation through a temporary metal structure.

The existing building is adjacent to both of the sides with two other buildings, leaving exposed to horizontal forces (wind load, earthquake) only the two facades. For buildings up to four storeys high, rigid frames may be used in which the multiple beam to column connections provide bending resistance and stiffness to resist horizontal loads. This is generally possible where the beams are relatively deep (400mm).

The vertical forces are transmitted from the slabs to the beam and to the frames. The floors are acting as simply supported slabs. The horizontal force is transmitted from the façade to the floor slab structure, and by diaphragm action to the frame structure.

The stability of the added glass structure is based on the glass brick buttresses that are built inwards the façade. The pattern that is followed in the design is different than the one used in the P.C. Hooftstraat in Amsterdam, where the buttresses are at the bottom of the façade and 5.5 tall (figure 4.31)
The high slenderness of the façade in the present design, demands stiffening in more parts along the height and length of the whole façade. Therefore, it was considered better solution to interlock in the façade some glass bricks in the level of the glass floor in each level along the whole length (figure 4.32)

![Figure 4.32: Places that the glass bricks buttresses are built](image)

Each of the glass beams then is wedged between the glass bricks in the buttresses. The dimensions of the bricks used for the buttresses as well as the number of rows of the bricks are customized and arranged in a way that cover the whole height of the glass beams, which differs from floor to floor. That way local torsional buckling and in consequence breakage of the uncovered part of the glass beam is avoided. At the bottom of the glass beam a glass console is fixed in order to keep the glass beam between the glass bricks without the risk of slippage in case of failure of the sealant between the bricks and the beam. Similarly, at the top, the glass panes of the floors cover the connection stabilizing the beams between the bricks. A detail of this connection can be seen in the following chapter. The width of the bricks that comes out from the façade is 105mm for all the floors and it is sufficient to provide stability, as the results of the simulations in ANSYS shows (figure 4.33).
The benefits of the glass brick buttresses built in that way are:

- Together with the glass beams, they reduce the out of plane buckling length of the glass brick façade
- Glass floors are not cantilevered, allowing to 6 meters span without the risk of failure, since the loads from the glass floors are distributed (not evenly due to the different kind of connection) between the concrete structure and the façade
- Stabilize the glass beams by preventing the torsional buckling

In conclusion, the stability is assured with the use of only glass elements and transparent silicone sealant, avoiding any metal component that could ruin the whole concept of this project. Besides, it does not distort the transparency of the façade, since first of all the level of the buttresses are too high to be reached by an eye from the pavement and second the width of these added glass bricks are small compared to the whole height of the façade, having the bigger at 16m high from the level of the street. Thus it does not add any negative aesthetic value in the façade. Some impressions of the effect in the transparency of these buttresses can be seen in the figure 4.34.
Since the analysis takes place in a 3d model of the structure, the stability of the whole structure under wind loading will be automatically taken into account in the stress calculation of all the elements and can be verified by displacement checks on the most unfavorable points. If the model just comprised of 2d models without connection with each other, then a separate stability check with the calculation of the centre of rotation of the structure would be necessary.
**Horizontal deflection**

The maximum horizontal deflection is calculated by the program for the wind load to Y direction. As expected, the largest horizontal deformation is found on the top of the building in the façade.

The horizontal deformation limit for the whole building is taken from the Dutch code for medium – high rise, non-industrial building as:

\[ \frac{1}{500} \times h_{\text{total}} = \frac{1}{500} \times 20 \text{ m} = 0.04 \text{ m} \]

For the Y direction the horizontal displacements in the façade parallel to the wind are shown in the figure 4.35.

\[ U_{\text{total}} = 0.002 \text{ m} < 0.04 \text{ m} \]
For the X direction the horizontal displacements of the building are limited, close to zero, proving the stability that the two adjacent buildings offer (figure 4.36).

Figure 4.36: Horizontal deflection (Ux) front façade (left) and back façade (right) for NL (ANSYS)

Vertical deflection

Deflection control is a central consideration in serviceability of mainly floor systems. A concrete floor should have adequate stiffness to prevent changes in deflection that would damage attached partitions or other construction elements likely to be damaged by large deflections. The deflection of a floor should not be noticeable by occupants such as to convey a sense of inadequacy or safety concerns. When for concrete slabs the vertical out of level sag limit is L/250, where L is the span of the floor and L/125 for cantilevers, the deflection limit for glass is slightly different, mostly due to the different human perception to glass.

The main problem with deflection is at the connections. If the deflections of the panels are too excessive and the joints cannot deform sufficiently, the bond can break. With regard to vertical glass planes generally 2 serviceability criteria should be ensured: appearance and comfort (i.e. feeling safe). To the former, the appearance criterion, there are no straightforward limits. The later, the comfort criterion is associated with vibrations. The limit should ensure that movements of the panels are not annoying to the occupants. Movements and deflections of large panels are often scary.
Beams, fins, cantilevers and columns are usually stress controlled and deflection limits are of less importance. For example, for glass beam is more important to take measures to avoid instability (e.g., lateral torsional buckling) than to limit the deflection. Floor, roof panes and stair treads are more deflection limit governed (Honfi & Overend, 2013).

There are different standards defining allowable deflections of glass. For this design, the allowable deflection defined by BS 6262 which wants the glass supported along four sides to be deflected along any glass edge less than 1/125 of the span of each edge for single glazing and 1/175 of the span of each edge for double glazing (Zhou).

The maximum vertical deflection is calculated by the program for the snow load to Z direction. As expected, the largest vertical deformation is found on the roof at the biggest beam (L=12m).

The maximum vertical deformation for the concrete floor, roof and beam due to permanent and variable actions according to the Dutch code is:

\[ w_{max} = \frac{L}{250} \]

The vertical displacements for the concrete structure are shown in the figures 4.37, 4.38.
Figure 4.37: Vertical deflection (Uz) of the concrete structure for NL (ANSYS)

\[ w_{\text{max}1} = \frac{6000}{250} = 24 \, \text{mm} \]
\[ w_{\text{max}2} = \frac{12000}{250} = 48 \, \text{mm} \]
\[ w_{\text{max}3} = \frac{6000}{250} = 24 \, \text{mm} \]

\[ w_1 = 15 \, \text{mm} < 24 \, \text{mm} \]
\[ w_2 = 20 \, \text{mm} < 48 \, \text{mm} \]
\[ w_3 = 10 \, \text{mm} < 24 \, \text{mm} \]
Figure 4.38: Vertical deflection ($U_z$) of the 4th floor 3-sided slab for NL (ANSYS)

$$w_{max_4} = \frac{1700}{125} = 13.6 \text{ mm}$$

$$w_4 = 15 \text{ m} > 13.6 \text{ mm} \quad \text{Need for bigger thickness of the slab at that part}$$
The maximum vertical deformation for the glass beam, floor and roof pane due to permanent and variable actions according to the BS 6262 regulation is:

\[ w_{\text{max, beam}} = \frac{L}{250} \]

\[ w_{\text{max, floor}} = \frac{L}{125} \]

\[ w_{\text{max, roof pane}} = \frac{L}{175} \]

As expected, the largest vertical deformation is found on the biggest glass beam at 4\textsuperscript{th} floor (L=6m).

The vertical displacements for the glass beams are shown in the figures 4.39.

![Figure 4.39: Vertical deflection (Uz) of the glass beam in 4\textsuperscript{th} floor (ANSYS)](image)

\[ w_{\text{max, beam}} = \frac{6000}{250} = 24 \text{ mm} \]

\[ w_{\text{beam}} = 7 \text{ mm} < 24 \text{ mm} \]
As expected, the largest vertical deformation is found on the biggest glass floor at 4th floor (6m X 2m). The vertical displacements for the glass floors are shown in the figures 4.40.

\[ w_{\text{max, floor}} = \frac{2000}{125} = 16 \text{ mm} \]

\[ w_{\text{floor}} = 12 \text{ mm} < 16 \text{ mm} \]

The big difference between this result and the result by the Timoshenko formula (2.6mm) is based on the fact that the in the hand calculation it was considered as a 4 sided equally supported glass pane, but in reality the glass beams are supported in one side at the glass bricks in façade and in the other side with the concrete structure, where at the 1st and 4th floor there is a cantilevered part of the slab, increasing the vertical deflection of the floors. The big deflection at the 3rd floor is due to the planted columns (figure 4.41).
Figure 4.41: Section of the building (2D AutoCAD)
As expected, the largest vertical deformation is found at the middle of the glass roof because of the large deflection of the 12m concrete beam the roof is supported by.

The vertical displacements for the glass roof are shown in the figures 4.42.

\[
\begin{align*}
\Delta_{\text{max}} &= \frac{2150}{175} = 12.29 \text{ mm} \\
\Delta_{\text{roof}} &= 10 \text{ mm} < 12.69 \text{ mm}
\end{align*}
\]

*Figure 4.42 Vertical deflections of the glass roof (elevation) (ANSYS)*
Stress checks

Tension stresses

The maximum tensile stresses for the heat strengthened glass with safety factor of 4 is:

\[ \sigma_{11,\text{max}} = \frac{40}{4} = 10 \text{ MPa} \]

The tensile forces for the glass floor are shown in the figures 4.43.

\[ \sigma_{11,\text{floor}} = 7 \text{ MPa} < 10 \text{ MPa} \]
The tensile forces for the glass beam and façade are shown in the figures 4.44.

\[ \sigma_{11}^{\text{beam}} = 2.1 \, \text{MPa} < 10 \, \text{MPa} \]

\[ \sigma_{11}^{\text{facade}} = 3 \, \text{MPa} < 5 \, \text{MPa} \]
The tensile forces for the glass beams in the glass roof are shown in the figures 4.45.

![Figure 4.45: Tensile stresses $\sigma_{11}$ for the glass beams in the roof (ANSYS)](image)

\[ \sigma_{11_{\text{beam}}} = 6.9 \text{ MPa} < 10 \text{ MPa} \]
The tensile forces for the glass roof pane are shown in the figures 4.46.

\[ \sigma_{11\text{roofpane}} = 6.8 \text{ MPa} < 10 \text{ MPa} \]
Compressive stresses

The maximum compressive stresses for the glass bricks according to the POESIA catalog 2013, with safety factor of 4 is:

\[ \sigma_{33,\text{max}} = \frac{397}{4} = 99 \text{ MPa} \]

The compressive forces for the glass brick façade are shown in the figures 4.47

\[ \sigma_{33,\text{façade}} = 20 \text{ MPa} < 99 \text{ MPa} \]
The compressive forces for the glass brick column are shown in the figures 4.48

\[
\sigma_{33}^{\text{column}} = 1.2 \text{ MPa} < 95 \text{ MPa}
\]
Optimization

From the above simulations, it was resulted that the only redesign should be in the 4th floor at the three sided concrete slab (small span 1700mm) which connects the glass beam of 6m with the concrete structure. The reasons for need to redesign is:

1. It deflects at the middle of the span in the range of 15mm which is above the permitted deflection
2. The connection detail is difficult and risky if the thickness of the concrete slab is 0.15m and the height of the glass beam 0.6m.

Therefore, a thicker thickness of the concrete slab in that part of the floor is necessary in order to satisfy both of the reasons. In the next simulation the thickness of the slab is 0.30m.

\[ w_4 = 9 < 13.6 \text{ mm} \]

The vertical deflection of the glass floor at the 4th level was reduced from 12mm to 10mm.
Tampere, Finland

The snow load is two times higher than the snow load for Netherlands, therefore, it was considered wise to check the tension stresses and the vertical deflection of the roof.

\[
\sigma_{11_{\text{roof pane}}} = 7 \text{ MPa} < 10 \text{ MPa}
\]

*Figure 4.50: Tensile stresses \( \sigma_{11} \) for the glass roof pane (ANSYS)*
Figure 4.50: Vertical deflection of the concrete structure for snow load for Tampere, Finland (ANSYS)

\[ w_{beam} = 38\text{mm} < 48\text{ mm} \]
Foundation

The glass brick façade weighs approximately 25% more than the conventional masonry façade of the same dimensions due to the higher density of glass compared to brick. This weight difference makes an imperative need the reinforcement of the foundation. The redesign of the foundation is not part of this research.

Earthquake

Safety measures against earthquake have not taken into account for this design, since all of the 3 countries that is designed for, there are not highly seismogenic area. Therefore, if a relevant structure like this one will be designed for a more seismogenic location, it is crucial to be assured that the whole structure can withstand the destructive forces of an earthquake. The measures regard the dimensioning of the load-bearing elements, the flexibility of the structure and the rigidity of the key connections.
Construction Order

First step

The first step of this renovation is to demolish the concrete part (floor, columns and beams) while carefully support with temporary structure the roof till the glass brick columns will be built. The glass elements will arrive at the site after all the debris will be removed, in order to avoid any accident that can cause flaws in the surface of the glass elements and in consequence reduce the strength. The extra reinforced concrete at 4th floor is also taken place in that step anchoring the steel reinforcement to the existing beams. The elevator and staircases in the middle are removed as well in order to replace them with glass ones.

Figure 4.51: Step 1 of the construction (3ds Max)
Second step

The second step is the construction of the glass brick columns that support the concrete roof and part of the glass roof that will be placed afterwards. The temporary structure is removed leaving space for the installation of the glass beams and floors. The glass elevator and staircases are built in this early stage to ease the movement of the people.

Figure 4.52: Step 2 of the construction (3ds Max)
The third step is the connection of the glass beams to the concrete structure with metal shoes. The other side of the beams is supported by a temporary structure until the glass brick façade will be built. Afterwards the glass panes of the floor is glued in a metallic channel which is placed along the top of the beams. The installation of the glass floor and the placement of the beams can happen at the same time for the different floors.

Figure 4.53: Step 3 of the construction (3ds Max)
Fourth step

The fourth step is the construction of the glass roof. The glass brick columns are built and at the top the three glass beams are stabilized with metal plate and with glued glass bricks on top (see next chapter for the detail of the connection). The other side of the glass beam in the roof is supported by temporary structure till the glass brick façade reaches that height. After the double glazing roof pane are glued with the same way as before with the glass beam. This process can take place before the installation of the glass beams and floors.

Figure 4.54: Step 4 of the construction (3ds Max)
Fifth step

The fifth step is the construction of the glass brick facade. The construction process has been explained in the chapter glass technology analysis. When the level of the bricks reach each of the floors, the beams are wedged and sealed with silicone between the buttresses. Right after the glass consoles is glued at the bottom of the beam to assure the stiffness of the connection.
For less time consuming construction that means to less total budget, some of the above processes can take place simultaneously. For example the glass brick facade can start when at the same time the glass beams and floors are installed.
Experimental settings

All the information and photos are taken from the paper “A Completely Transparent, Adhesively Bonded Soda-Lime Glass Block Masonry System” written by F. Oikonomopoulou and the paper “Innovative structural applications of adhesively bonded solid glass blocks” written by F. Oikonomopoulou.

One of the measures that enhance the structural integrity of the structure, in the scale of elements, as described in chapter Glass Technology Analysis, is the conduct of laboratory experiments where is possible. In this section experiments in the glass brick elements (façade and columns) will be mentioned since they are the most innovative structural elements and its structural and thermal behavior is still under investigation. The sizes of the specimens and the results of the tests are intended to cover the scale of a project such as Crystal House in Amsterdam. However, the good structural and thermal behavior of these elements proves as well the ability of this system to be implemented in a bigger scale such the present design.

In glass masonry structures, it is more important the properties of the whole structure as a unit rather than the properties of the glass and adhesive itself. Therefore, various mechanical tests were conducted on assembled prototypes in order to assure the integrity of the system defining the failure behavior and verifying the tolerances needed in the glass blocks for better performance. All the tests have been conducted by the TUDelft Glass and Transparency team. Each of the specimen of these prototypes are quite expensive, thus the number of the tests is limited. However, the date acquired were considered sufficient to meet the requirements for safe structural calculations as required by the local building codes.

Since most of the laboratory experiments have been utilized before the final sizes of the glass bricks arrived in the lab, some of the first tests were carried out using standard-sized Poesia bricks (53mmX116mmX246mm). The tests were conducted in various configurations to evaluate the degree in which uneven surfaces affect the structural performance of the assembly.

The experimental settings are:

- Compression tests
- Four-point bending tests
- Impact and Vandalism tests
Compression tests

Four columns made by different size and pattern of glass bricks were tested in a force controlled hydraulic compression machine to determine the compression strength of the glass block-adhesive structure as an assembly. The different configurations were chosen in order to study the relation between the latter with the strength of the element. The columns comprised standard Poesia blocks of 53 x 116 x 246 mm (specimens A and B) and of 53 x 116 x 121 mm (specimens C and D) that were adhesively bonded together in three different configurations (Figure 4.56).

![Figure 4.56: Illustration of the three different column configurations (F. Oikonomopoulou, 2015)](image)

Three series of blocks of the custom-made sizes were used for verifying the compression strength (65 x 210 x 105 mm, 65 x 210 x 157.5 mm and 65 x 210 x 210 mm). The maximum load capacity of the machine was 3 MN. For the first two series of tests, the glass blocks were placed directly on the metal plate of the device, while for the third series two 18mm each multiplex plates were placed between the glass and metal surfaces. For safety reasons, all specimens were wrapped in several layers of clear PET plastic foil and put in a steel safety cage with polycarbonate windows.

![Figure 4.57: Test set-up for the two first series of blocks (left), test set-up for the last series of blocks (right), (F. Oikonomopoulou, 2015)](image)
The compressions tests have shown that both the blocks and columns have sufficient compressive strength to meet the requirements of the design, although the values of the compression strength of the glass blocks are lower than the ones stated in literature. This can be due to the air bubbles that are created when such big thickness of glass is casted. In the following tables the resulting compressive stresses for the blocks and the columns are summarized.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Dimensions (mm)</th>
<th>Load where first crack became visible [kN]</th>
<th>Nominal stress where first crack became visible [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small brick</td>
<td>210x105x65</td>
<td>- (A)</td>
<td>- (A)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>500 (B)</td>
<td>22.7 (B)</td>
</tr>
<tr>
<td>Small brick with wood bases</td>
<td>210x105x65</td>
<td>2977 (C)</td>
<td>135 MPa (C)</td>
</tr>
<tr>
<td>Medium brick</td>
<td>210x157.5x65</td>
<td>999 (A)</td>
<td>30.2 (A)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>870 (B)</td>
<td>26.3 (B)</td>
</tr>
<tr>
<td>Medium brick with wood bases</td>
<td>210x157.5x65</td>
<td>&gt; 3000* (C)</td>
<td>&gt; xx (C)</td>
</tr>
<tr>
<td>Large brick</td>
<td>210x210x65</td>
<td>1248 (A)</td>
<td>28.3 (A)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>882 (B)</td>
<td>20 (B)</td>
</tr>
<tr>
<td>Large brick with wood bases</td>
<td>210x210x65</td>
<td>&gt; 3000* (C)</td>
<td>&gt; xx (C)</td>
</tr>
</tbody>
</table>

*Table 4.8: Results of glass blocks' compression tests (F. Oikonomopoulou, 2015)*

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Dimensions [mm]</th>
<th>Failure load [kN]</th>
<th>Nominal failure stress [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>232x106x492</td>
<td>2090</td>
<td>85</td>
</tr>
<tr>
<td>B</td>
<td>246x106x464</td>
<td>1296</td>
<td>49.7</td>
</tr>
<tr>
<td>C</td>
<td>116x121x484</td>
<td>1597</td>
<td>113.8</td>
</tr>
<tr>
<td>D</td>
<td>116x121x484</td>
<td>1484</td>
<td>105.7</td>
</tr>
</tbody>
</table>

*Table 4.9: Results of glass columns' compression tests (F. Oikonomopoulou, 2015)*

The effect of the existence of the multiplex between the glass and the metal can be seen through the different results in the tests. For the two first series (A, B) of compression tests if the blocks, where no multiplex was used, lot of obvious cracks were presented in a compressive stress of 20-30 MPa (remarkably less than the value stated in the literature) (figure 4.58). This can be explained because any unevenness in the contact surface of the two hard materials can induce local peak stresses resulting in a brittle material like glass in local cracks. For the third series of compression tests, between the glass and metal at the top and bottom of each glass block, a 18mm multiplex plate were placed (figure 4.57).

The results of these tests show that the glass blocks can withstand very high compressive loads. More particularly the smallest block, measuring 210 x 105 x 65 mm, presented its first crack at only 2980 kN load, a load five times as big as the complete dead load of the Crystal House facade, while the other two blocks did not crack until the compressive machine reached its force limit of 3000 kN.
Through these experiments, it becomes evident the importance of the good and detailed design of the connections when one has to cope with glass elements. Poor detailing or execution can result in high local stresses that significantly reduce the overall strength of the glass structure, while connections that provide a uniform load distribution will result in much higher failure loads. The crack patterns in all broken specimens demonstrate the absence of internal residual stresses in the glass blocks. In specific, no secondary crack branching – an effect of internal residual stress – was observed in any of the specimens, even under high compression loads (F. Oikonomopoulou, 2015).

![Figure 4.58: Typical initial crack pattern in specimen (F. Oikonomopoulou, 2015)](image)

The results of the compression tests of the four glass columns showed significant differences in strength. There are three reasons that can explain these remarkable differences in the results. Firstly, the different configuration of the glass blocks can lead to different strength of the specimen, secondly, the oblong shape of the specimen can create indirect local tensile stresses and thirdly the improper bonding between the glass bricks can definitely affect the strength. Indeed, prototypes A and B that presented non-homogeneous bonding demonstrated considerably less strength, up to 50%, than prototypes C and D that were homogeneously bonded. In particular, A and B were adhesively bonded on the largest faces of the standard-sized Poesia bricks. These faces present a convex plane of approximately 0.5 mm at the centre. Thus, the bonding layer is relatively thick and inhomogeneous resulting in a weak joint in the middle of each specimen. In contrast, specimens C and D use a different configuration, where the glass blocks are only bonded on their shorter and much more even surfaces. Accordingly, stronger adhesive bonds were formed and the columns showed a much more monolithic behavior, resulting in higher compressive strength. Although the samples’ size is limited to derive more general results, they indicate that the compressive strength of the structure is very dependent on the configuration of the blocks and the quality of the bonding surfaces (F. Oikonomopoulou, 2015).

![Figure 4.59: Compression experiments of the columns (F. Oikonomopoulou, 2015)](image)
Four-point bending tests

For the determination of the flexural strength of the glass masonry wall, three prototypes were tested in four-point bending until failure in a Zwick Z100 displacement controlled universal testing machine, using a specially fabricated test frame. The specimens had different dimensions and configurations. The initial prototypes, A and B were made using standard sized Poesia bricks (53 x 246 x 116 mm). The last prototype C was made using the final-sized bricks (65 x 210 x 210 mm). To determine both the in- and out-of-plane bending strength of the wall, the specimens were placed either standing or lying in the test frame. The dimensions, configuration and experimental set up of each specimen are summarized in figure 4.50. Prior to testing, all specimens were wrapped in several layers of clear PET plastic foil as a safety precaution.

**Specimen A**

**Test: In-plane bending**

Standing Position

Specimen Size:
Span: 123 cm  
Width: 5.3 cm  
Height: 34.8 cm

**Specimen B**

**Test: Out-of-plane bending**

Specimen Size:
Span: 123 cm  
Width: 34.8 cm  
Height: 5.3 cm

**Specimen C**

**Test: In-plane bending**

Specimen Size:
Span: 84 cm  
Width: 21 cm  
Height: 19.5 m

*Figure 4.60: Specimen and 4-point bending test configurations (F. Oikonomopoulou, 2015)*
The results of the four point bending tests in the three specimens can be seen in the following figure. For the specimens A and B the in-plane flexural strength is 7.85 MPa and for out-of-plane strength 9.13 MPa at failure. Normally the flexural strength of glass is higher than these values. This can be attributed to the sole horizontally bonded of the beam specimens which results to stress concentrations on the open vertical joints. In reality, the glass bricks are confined by the boundaries of the structure and thus the vertical joints of the wall are prevented from opening and the strength is expected to be higher.

The low flexural strength of the C specimen is caused from the fact that the series of the bricks that this specimen was built, presented considerable intolerances in flatness and height, exceeding many times the limit of 0.5mm resulting in improper bonded joints. These results emphasize the critical role of the accurate dimensioning of the glass blocks to the overall structural performance of the wall.

<table>
<thead>
<tr>
<th>Specimen A</th>
<th>Specimen B</th>
<th>Specimen C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block size: 53x116x246 mm</td>
<td>Block size: 53x116x246 mm</td>
<td>Block size: 65x210x210 mm</td>
</tr>
<tr>
<td>Adhesively bonded only in the 53x116 faces (horizontal joints)</td>
<td>Adhesively bonded in the 53x116 faces (vertical joints)</td>
<td>Adhesively bonded in the 210x210 faces (horizontal joints)</td>
</tr>
<tr>
<td>Failure load: 44800 N</td>
<td>Failure load: 11900 N</td>
<td>Failure load: 29500 N</td>
</tr>
<tr>
<td>$\sigma_{\text{flex}} = 7.85 \text{ MPa}$</td>
<td>$\sigma_{\text{flex}} = 9.13 \text{ MPa}$</td>
<td>$\sigma_{\text{flex}} = 3.05 \text{ MPa}$</td>
</tr>
</tbody>
</table>

*Figure 4.61: Results of four-point bending tests (F. Oikonomopoulou, 2015)*

*Figure 4.62: The failure pattern of the glass beams demonstrates the monolithic behavior of the system against loading (F. Oikonomopoulou, 2015)*
Impact and Vandalism test

Such a big scale glass façade located in a busy shopping street is exposed in accidental impact loads such as cars, bicycles, skateboards or even loads such as bottles, bricks, tools in case of vandalism or robbery. Therefore, it is imperative need to conduct rigid body impact and vandalism test in an experimental glass wall. The mock-up consisted of 22 glass blocks, each measuring 53 x 246 x 116 mm, which were adhesively bonded to form a wall (figure 4.62). In order to simulate the real boundary conditions of the glass wall, it was mounted into a wooden frame which was fixed to a rigid concrete wall.

First, a hard body impact test was conducted on the specimen. The test was carried out using a solid concrete brick of 65 x 102.5 x 215 mm, weighing 3.4 Kg. The concrete brick was placed in front of the façade, touching the target brick. At that position it was suspended with a hook from a 1.5 m long metal wire, hanging down from a wooden cantilever projecting above the mock-up (figure 4.63). The concrete brick, attached to the wire, was then swung outwards by a 45 degrees angle and released from there. The test was repeated two times from a 45 degrees angle, then another two from 90 degrees angle. Afterwards, a vandalism test was carried out on the same experimental wall using a 4 Kg sledgehammer until fracture (F. Oikonomopoulou, 2015).

The results of the impact test were satisfactory since only the concrete brick used as impactor was damaged, leaving all the glass bricks in the prototype uncracked. Thus, it is expected that any accidental impact load of objects such as bikes, bottles will not cause any damage to the glass brick façade.
The results of the vandalism test with a sledgehammer ensured that cracks occurred only in the aimed glass brick and not to any of the adjacent blocks. For better understanding of the crack pattern behavior, the adjacent block was hit by the same sledgehammer. As it can be seen in the figure 4.64 the same crack pattern was occurred. These results signify that an impact force can cause damage only in the aimed block and not to any of the adjacent structure and that the surface of this damaged brick maintain a smooth external surface, so people can touch it without getting hurt.

One important note that is implemented in the real project, is that the glass blocks in the façade will already be in high compression due to the self-weight of the structure. Thus, they are prone to fail under less load than the expected. However, this pre-compression of the blocks is not expected to significantly change the results.

![Figure 4.64: Results of the first vandalism test. The vandalism test was then repeated to an adjacent brick (right). Only the aimed block was damaged. (F. Oikonomopoulou, 2015)](image)

The replacement of the damaged brick should be possible and easy. Therefore, after the vandalism tests, a procedure of replacing the damaged bricks was developed. The first step is to take away the biggest piece of the damage block using mechanical tools. Then the adhesive is locally heated above 120°C with a hot air blower. This temperature is the limit where the adhesive starts to become viscoelastic and softer, allowing for easy mechanical removal of the last glass shards and of the adhesive layer itself, without damaging the adjacent blocks. Lastly, a new glass block, machined down by 0.1 mm in dimensions to slide easily into the empty slot, can be then inserted (figure 4.65 right). Adhesive can be injected into the surrounding seams, using a syringe.

![Figure 4.65: The prototype before replacement (left). The prototype after replacement of one of the damaged blocks (right) (F. Oikonomopoulou, 2015)](image)
Conclusions

The results of the structural simulations and the laboratory tastings proves that large glass masonry façade and glass brick columns of high slenderness can be realized.

The slender dimensions of the façade and the columns are plausible if the construction process will be followed with high precision by specialized staff in order to avoid mistakes which can lead to failure of the elements. Moreover, after a specific height of the façade, measures to reduce the buckling length should be taken into account. In the present design, glass bricks which are interlocked in the façade in every floor level work as buttresses and minimize the buckling length of the façade. However, other measures are possible, their choice depends on the size of the element, the desired architectural design etc.

Regarding the structural performance, preliminary structural simulations and the results of the laboratory compression test indicate that the structure should be able to withstand buckling. However, apart from static analysis in ANSYS, buckling mode analysis is also useful for that kind of structures.

In the present research, there is no earthquake resistance consideration, since it is located in three non-seismic countries. However, it can be critical load for that kind of structure and more measures should be taken into account for the design.

More experimental testing is needed for the bending of the glass floors, since their span is bigger than the usual for glass floors.

In every glass structure, the most crucial part of the design for assuring the structural integrity is the detailed design of the connections. Thereat, in the following chapter, the most crucial connection details are being illustrated and calculated.
References


- Bijan O Aalami, Delfection of concrete floor systems for serviceability


**Detailing**

“There are generally two approaches in glass design. There is the “Jiricna” approach where every connection and detail is celebrated and the MUMA approach where there are no visible metal connections.” Macfarlane says for the transformation of the existing light well of the Victoria and Albert Museum’s Medieval and Renaissance gallery in London.

When designing with glass, it is vital to avoid local stress peaks that may arise and cause brittle failure. The arrangement and placing of glass components governs the locations and magnitude of stresses. The use of glass in construction must be treated with the utmost attention, since it is due to wrong handling during the installation or not carefully designed details that the probability of failure from local stress peaks can be increased. Thus, when detailing glass connections, it is important to follow some design principles in order to assure that the connection will safely transfer the loads and join the pieces (Connor, 2011).

These design principles originate from the material’s special characteristics and mechanical behavior.

- No contact between glass and harder materials
- Avoidance of restraint stresses due to unintentional loads
- Choice of suitable geometry for the glass elements
- Specification of a suitable method of connection
- Ensuring a sufficient level of robustness of glass constructions
- Guarantee of serviceability
- Ensuring durability and weather resistance

Some general rules that should be followed when designing connections with glass elements are:

- Transfer the loads over an area that is large enough
- Tensile strength of glass is 1/10 of the compression strength
- Avoid multi axial loads
- Use the right materials to transfer the forces
- Avoid holes
- Choose the right adhesive system (optimum thickness, match and clean surfaces)
- Make certain the process is controlled from the beginning to the end (Fred Veer, connections in glass, lecture in TUDelft)

There are available various types of supports for glass depending on its intended use. The main categories of connections that is often met in glass structures are clamped, drilled and material bonded.

Bonded joints are those in which the glass may not detach from the connection. The connection is made by adhesion (attraction between similar molecules) and cohesion (intrinsic attraction of molecules of the same substance). It employs large contact faces for stress distribution via elastic adhesives. Forces are transferred perpendicular or parallel to the joint surfaces and are dependent on temperature and duration of the load. This kind of connection demonstrates improved thermal, sound and weather insulation. Gluing is the most common way of adhesive bonding and it can be applied in the whole surface, linearly or in discrete points. Structural silicone adhesives are more common for sealant glazing. Structural
Sealant glazing (SSG) is a type of construction in which glass is permanently connected to an adapter frame via a load bearing, waterproof silicone joint. Silicones can be black and transparent. The black silicone is made from polymer base plus chalk, silicic acid and soot filter whilst the transparent requires more expensive polymers such as resins.

The clamped and drilled connection, on the other hand, belong to the positive and non-positive connections which allow for subsequent detachment. Positive joints are held together by interlocking with the glass through various geometries, whilst non-positive joints are held together by applying a force via friction or contact that clamps the glass together. Within friction connections are clamping discs, which provide a point support (figure 5.2a), and clamping bars (figure 5.2b), which provide linear support. The intermediate bearing pads on the clamps can be made of soft metals, plastics, or other materials. If the clamps supporting the glass are weakened, or if moisture or other forces interact with the glass, then the panes could slip out of the fixing. In contact connections, the force-transfer mechanism is compression. Failure through this type of connection can occur by excessive compression or by the glass pane slipping out of the fixing when there is severe deformation.

The advantage of the drilled connections by means of screws or bolts is that they can be easily dismantled. However, the force transfer through drilled fixings cause high local stresses in the glass at the point of contact, make imperative need the use of laminated glass made from toughened safety glass, heat-
soaked toughened safety glass, or heat-strengthened glass. The drilling fixings may be either rigid or hinged depending on whether the point can accommodate any twist. For rigid point fixings, the glass pane can be held by two discs on elastic bearing pads which are connected to the support through a threaded rod. In order to dissipate the high stress peaks around the hole, a bearing between the shank of the fixing and the glass should always be designed. The materials that can be used for this purpose are prefabricated, tight-fit sleeves made from plastic or aluminum, two-part composite mortars, epoxy resin-based adhesives, or glazing compounds that can be mixed on-site (Weller, 2009).

Figure 5.3: Cylindrical-conical with undercut drilled fixing

One of the design principles is the glass to not come into contact with harder materials or actions that may cause cracks. To address this problem, various materials, such as synthetics, casting resins, or aluminum alloys can be used to place between glass and the connections so that they may absorb any deformations and ensure a maximum area for load transfer.

Each of the methods have its advantages and disadvantages (table 5.1) and the choice of the type of connection should be taken under taking into account lot of considerations.

<table>
<thead>
<tr>
<th>Type of fixing</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clamp Fixings</td>
<td>Loads transferred evenly to glass, reduces stress concentrations</td>
<td>Susceptible to panes slipping out of fixing</td>
</tr>
<tr>
<td>Drilled fixings</td>
<td>Easily dismantled</td>
<td>High local stresses</td>
</tr>
<tr>
<td>Bonded fixings</td>
<td>Improved insulation, greater transparency</td>
<td>Glue material often degradable</td>
</tr>
</tbody>
</table>

Table 5.1: Pros and Cons for the main types of fixings

For the present design, since one of the main design principles is the maximum transparency, the connections have to be designed as small as possible and preferably with the use of glass elements instead of metal, aluminum or steel which should be used only when needed. At the same time they should be able to withstand big loads and take up tolerances due to the assembly process. Moreover, the joints need to absorb any geometrical differences of the elements while also to ensure the protection of the glass components, especially of their edges, during their assembly on site. Finally, since it is a renovation project
and future changes are always possible, the joints should be easily dismantled without ruining the joining components.

Apart from these reasons though, the choice depends also on the elements type that need to be joined and on the type of load that need to be transferred. Undoubtedly there are lot of different ways of designing these connections. In the following section, the most feasible and effective in terms of structural and aesthetical, according to the writer, detail of each connection is illustrated giving the structural calculations and the characteristics of the materials used, where needed.
1. Glass Beam – Glass Floor
2. Glass Beam – Glass Brick Façade
3. Glass Beam – Concrete Beam
4. Glass Beam – Glass Roof Panes
5. Glass Beams – Glass Brick Column in the roof
6. Glass Brick Column – Louvres Mechanism in the roof
7. Glass Brick Column – Concrete Beam
8. Glass Pane for the cold draft – Glass Brick Facade

Figure 5.4: Location of the details presented in the following figures
The glass floor panes are two sided supported in the glass beams. In order to increase the transparency without risking the safety, metal substructure is glued with transparent silicone along the whole length of the top edge of the glass beam. The silicone setting strips should be glued to the steel substructure before the glass is set. The silicone should be a non-acidic clear silicone of 3-6 mm thickness. In order to protect the silicone and the metal structure from the top, the sacrificial glass layer of 4 mm is placed creating a protective cover.
The connection has been simulated in ANSYS software and the self-weight of the glass floors and the live loads are applied directly to the metal structure in order to assure that the stresses are allowable using a safety factor of 4.

The element type that is used for this simulation is SOLID187 which has a quadratic displacement behavior and it is well suited to modeling irregular meshes. The material properties are shown in the following table.

<table>
<thead>
<tr>
<th>Material Properties</th>
<th>Material Model</th>
<th>Steel</th>
<th>Soda Lime Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>E (GPa)</td>
<td>200</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>ν</td>
<td>0.3</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>ρ (kg/m³)</td>
<td>7800</td>
<td>2400</td>
<td></td>
</tr>
</tbody>
</table>

*Table 5.2: Characteristics of the Materials*

The first estimation of the dimensions of the metal structure is based on the rule of thumb that the length of the salient part for each side should be more than the 1.5 * h, where h is the total height of the glass.
floor panes. Thus, 1.5*41.14= 61.71mm ≈ 62mm. The trapezoidal shape of the cross section of the metal structure is cost-efficient design because it uses less material with the same results. The dimensions of the trapezoidal metal substructure are 62mm the biggest salient part (top), 40mm the smallest (bottom), 10mm the thickness).

The load combination for the glass floor is:

\[ 1.20G + 1.30Q = 1.20G + 1.3*Q = 1.2*1.053 +1.3*5 = 7.763 \, \text{kN/m}^2 \]

For each side of the metal in the glass beam is \( P = 7.763 \, \text{kN/m}^2 \times 1 \, \text{m} = 7.763 \, \text{kN/m} \)

For the surface of each side of the metal is \( q = 7.763 \, \text{kN/m} / 0.062m = 125.2 \, \text{kN/m}^2 \)

*Figure 5.6: Model of the glass beam with the steel substructure in ANSYS*
Figure 5.7: Tensile stresses of the steel substructure

\[ \sigma_{11} = 2.35 \text{ MPa} < 58.75\text{MPa} = \frac{235}{4} \text{ (for S235)} \]

Figure 5.8: Compressive stresses of the steel substructure

\[ \sigma_{33} = 1.28 \text{ MPa} \]
The connection between the glass beams and the glass brick façade should not violate the transparency of the masonry wall. Therefore, the loads should be transferred safely through only glass elements which are glued together with transparent silicone sealant. In order to achieve a safe connection between the
beams and the façade, glass bricks are interlocking in the façade in the level of the beams. The number of the rows of the bricks depends on the height of the beams. During the construction, the glass beams are temporarily supported in a substructure and are placed in a mold (e.g. transparent polycarbonate). After the glass bricks have been built, DELO glue is poured between the beams and the mold. Before the glue is cured and obtain its structural properties, the mold is removed. So, each of the glass beams is wedged between the glass bricks in the buttresses. That way local torsional buckling and in consequence breakage of the uncovered part of the glass beam is avoided.

In order to minimize the risk of slippage of the beams in case of failure of the glue (overheat etc.), a glass triangular console is glued vertically with the façade and horizontally with the bottom of the glass beam. The thickness of the console is the same as the thickness of the beam (36mm) and the length of the two vertical sides are 50% longer of the thickness of the buttresses (1.5*105mm ≈ 158mm). For the vertical bonding the DELO glue that has been used for the vertical sealing between the bricks is used, while for the horizontal connection between the float glasses (beams and console) silicone sealant is applied. Finally, the glass floor lie upon the buttresses stabilizing the beams between the bricks.
This connection is the link between the two structures, the existing and the new. It must assure that the wind loads from the façade are safely transferred through the glass beams to the concrete frame structure. The glass beams are supported on stainless steel shoes, which are set into the concrete beam of the existing building and the side return panels are fixed with bolts into a groove meticulously formed in the beam.

The steel shoe is closed at the bottom to ensure a safe support of the beam and open at the top so the metal substructure can take over all the loads from the glass floor. The gap between the steel shoe and the glass beam in all the three sides is filled with structural silicone (4mm).

The dimensions of the steel element are estimated with rule of thumbs and can be seen in the following figure. The amount of bolts needed and the distances between the bolts are different in each floor due to the different sizes of the glass structure. In the following the calculation for the third floor is given, where $h_{glassbeam}=450\text{mm}$.
Figure 5.11: Dimensions of the steel element dependent on the height of the glass beam

For the third floor is $H_{\text{glassbeam}} = 450\text{mm}$. The minimum and maximum distances of the bolts are:

\[
\begin{align*}
e_{1,\text{min}} &= 1.2 \times d_o = 21.6\text{mm} & \quad e_{1,\text{max}} &= 125\text{mm} \\
e_{2,\text{min}} &= 1.2 \times d_o = 21.6\text{mm} & \quad e_{2,\text{max}} &= 125\text{mm} \\
p_{1,\text{min}} &= 2.2 \times d_o = 39.6\text{mm} & \quad p_{1,\text{max}} &= 14 \times t = 140\text{mm} \\
p_{2,\text{min}} &= 2.4 \times d_o = 43.2\text{mm} & \quad p_{2,\text{max}} &= 14 \times t = 140\text{mm}
\end{align*}
\]

Thus, $e_1 = 100\text{mm}$, $p_1 = (450 - 100 \times 2)/2 = 125\text{mm}$

\[
e_2 = 50\text{mm}, \quad p_2 = (225 - 50 \times 2)/2 = 62.5\text{mm}
\]

The connection takes over the vertical loads from the glass floors and the glass beams and transferred to the bolts as shear forces, while the wind load is transferred to the bolts as tension force. Therefore, both the shear and tension strength of the bolted connection should be tested.
The vertical loads that are transferred to the bolts have been calculated in the Structure chapter:

\[ N_{sd} = 1.20 \times G + 1.30 \times Q = 1.20 \times 2.65 + 1.30 \times 5 = 9.68 \text{ kN/m}^2 \]

\[ 9.68 \times 2 = 19.36 \text{ kN/m} \]

\[ N_{sd} = 19.36 \times 2/3 \times 6 = 77.44 \text{ kN} \]

It is assumed 8.8 type of bolt \( f_{ub} = 800 \text{ N/mm}^2 \), and M16 \( d=16 \text{ mm} \), \( A_s = 157 \text{ mm}^2 \) and for the steel of the plate S275 \( f_u = 430 \text{ N/mm}^2 \) with \( t = 10 \text{ mm} \) (for \( d=16, 20, 24 \text{ mm} \) the thickness of the plate is between the values \( 10 \text{ mm} \leq t \leq 25 \text{ mm} \))

**Check of the plate**

\[ N_{pl,Rd} = A \times f_y \times \frac{225 + 275 \times 10^{-3}}{275} = 618.75 \text{ kN} > 77.44 \text{ kN} \]

(the weakened cross section apparently is sufficient as well)

**Design bearing resistance**

\[ F_{b,Ed} < F_{b,Rd} \]

\[ F_{b,Rd} = k_1 \times a_b \times f_u \times d \times t \times \frac{1}{Y_{M2}} \]
Where:

\[ f_u = 430 \text{ N/mm}^2 \]

\[ d = 16 \text{mm} \]

\[ t = 10 \text{ mm} \text{ (for } d=16, 20, 24\text{mm the thickness of the plate is between the values } 10\text{mm} \leq t \leq 25\text{mm}) \]

\[ f_{ub} = 800 \text{ N/mm}^2 \]

\[ a_b = \min \left( a_d, \frac{f_{ub}}{f_u}, 1.0 \right) = 1.0 \]

In the direction of the load:

For the last row of bolts: \[ a_d = \frac{e_1}{3do} = \frac{100}{3\times18} = 1.85 \]

For the internal bolts: \[ a_d = \frac{p_1}{3do} - \frac{1}{4} = \frac{125}{3\times18} - \frac{1}{4} = 3.22 \]

In the direction perpendicular to the load:

For the last row of bolts: \[ k_1 = \min \left( 2.8 \times \frac{e_2}{do} - 1.7 \text{ or } 2.5 \right) = \min \left( 2.8 \times \frac{50}{18} - 1.7 \right) = 6.08 \text{ or } 2.5 = 2.5 \]

For the internal bolts: \[ k_1 = \min \left( 1.4 \times \frac{p_2}{do} - 1.7 \text{ or } 2.5 \right) = \min \left( 1.4 \times \frac{62.5}{18} - 1.7 \right) = 3.16 \text{ or } 2.5 = 2.5 \]

\[ F_{b,Rd} = \frac{k_1 \times a_b \times f_u \times d \times t}{\gamma M_2} = \frac{2.5 \times 1 \times 800 \times 16 \times 10}{1.25} \times 10^{-3} = 256kN > 77.4/12 \]

**Design shear resistance per shear plane:**

\[ F_{v,Rd} = \frac{a_d \times f_{ub} \times A}{\gamma M_2} = \frac{0.6 \times 800 \times 157}{1.25} = 60kN > 77.4/12 \]
The connection between the glass roof panes and the glass beam is utilized with a very thin component (d=20-25mm) which enables a firm and distinctive connection. On the top of this connection an interlocking rubber seal is placed to achieve a homogenous joint between the roof panes. The thickness of the joint is 25mm. Almost invisible.
The type of the connection between the glass beams and the glass brick column in the roof is quite innovative and makes use of the glass bricks mass in order to stabilize the beams and avoid the local torsional buckling. The beams are connected with the use of a steel element which is glued at the top of the column. After adding the bolts in each element, customized glass bricks are glued at the four sides in order to cover the whole length of the beams. These bricks are not glued with the same adhesive as the rest of the bricks so they can be easily removed in case of maintenance or replacement of the elements. Finally, at the top of this structure, more glass bricks with different dimensions are glued with the rest of the elements stabilizing the beams and prevent them from slipping up due to the weight of the glass roof panes and snow.
Figure 5.15: Detail 5: Connection glass beam with glass brick column in the roof (fixed view)
At the top of the glass roof there is louvre system that operates automatically according to the natural ventilation schedule or when needed. The structure consists solely by glass elements apart from the small metal inserts that are drilled in the glass plate which is glued vertically on the glass brick column. The design offers rain and snow protection, since the upper glass pane overlaps part of the lower glass pane which are sealed with silicone sealant when they are closed. Except from the right inclination of the concrete roof with direction to the back façade, there is a glass square plate that has twofold role. It prevents water from entering the building and it functions as the stopper of the last glass pane with the silicone that has at the outside side.
Figure 5.16: Detail 6: Connection glass brick column with the louver system in the roof
Glass Brick Column – Concrete Beam

Figure 5.17: Detail 7: Connection glass brick column with concrete beam

This connection should be strong enough to transfer safely all the loads from the long concrete beam in the roof to the glass brick column and from there to the concrete slab in the basement while at the same
time it should be assembled easily and give the option of disassembling if needed without damaging the existing structure. Therefore, it was considered, that the most suitable connection between these two materials is a metal plate with bolts that are inserted in the concrete beam. The plate is one single piece with the aluminum base that is placed at the bottom and at the head of the column in order to compensate the height differences due to the manufacturing process of the glass brick.

The load combination for each of the glass brick column has been calculated in the previous chapter and it is:  
\[ N_{sd} = 280.174 \text{ kN} \]

The load is transmitted through tension of the bolts. The next figure gives the relation between the elongation of the bolt and the shortening of the plate assembly due to preloading. When an external tension force \( F_e \) is applied to the connection, the force in the bolt \( F_t \) will increase. At the same time the elongation of the bolt increases, and the shortening of the plate assembly decreases by the same amount. As a result, the force in the plate assembly decreases. In practice, the stiffness of the plate assembly is about 4 times the stiffness of the bolt.

\[ \text{Figure 5.18: Effect of external load (} F_e \text{) on the bolt force (} F_t \text{) and the contact force (} F_c \text{) in a HSFG bolted connection (ESDEP, chapter 11, Connection design: static loading)} \]
Check of the bolts

The amount and the quality of the bolts that are used in this connection will be defined by the tension resistance check of the section of thread:

$$F_{t,Ed} \leq F_{t,Rd}$$

where

$$F_{t,Rd} = \frac{k_2 \cdot f_{ub} \cdot A_s}{\gamma_{M2}}$$

It is assumed 8.8 type of bolt ($f_{ub} = 800 \text{ N/mm}^2$), and M20 (d=20mm, $A_s = 245\text{mm}^2$)

The factor of safety is $\gamma_{M2} = 1.25$ and $k_2 = 0.90$.

For safety reasons, it is assumed two rows of bolts in each side, leading to 8 bolts in total.

The tension strength of each of the bolt is

$$F_{t,Rd} = \frac{0.90 \cdot 800 \cdot 245}{1.25} = 141.12 \text{ kN} > 35.02 \text{ kN} = 280.174 / 8$$

Check of the plate

The length of the plate is estimated 400mm as the width (determined by the width of the concrete beam).

For d = 20mm the thickness of the metal plate should range between $10 \text{ mm} \leq t \leq 25 \text{ mm}$.

It is chosen $t = 10 \text{ mm}$. The steel quality: S275

Full section

$$N_{pl,Rd} = \frac{A \cdot f_y}{\gamma_{Mo}} = \frac{(10 \cdot 400 \cdot 275 \cdot 10^{-2})}{1} = 1100 \text{ kN} > 140.087 = 280.174 / 2 \text{ (there are plates at both sides)}$$

The weakened section is obviously sufficient as well.
Glass Pane for the cold draft – Glass Brick Façade

Figure 5.19: Detail 8: Connection glass pane for the cold draft with the glass brick facade
The large glazed facade and atria give people the opportunity, in cold regions, to perform their daily activities in a naturally lit environment away from the negative effects of a long and cold winter. The use of an atrium can create a thermally compact building where heat loss from the parent building is reduced and passive solar energy gained in the atrium is utilized. Furthermore, both the glazed facade and atria improve the usability of the daylight by allowing it to penetrate deep into the building in the adjacent rooms and thereby reduce the need for electrical lighting. In winter, however, such a large glazed facade is often the cause of thermal discomfort, partly due to cold radiation effects and partly due to downdraft problems caused by cold natural convective flows along the surface. For this facade, the most critical problem is downdraft, as the CFD simulation indicates (see next chapter, figure 6.56). In the middle the glass floors are not allowed this phenomena to happen, but in the atria the velocity of the air is more than 0.5 m/s² which cause discomfort for the people that stands close to the façade. It has to be mentioned though, that this problem can be only faced by the staff and only when they change the vitrine. However, this high velocity of the air can be enough to cause movement of the fabrics in the dolls in the vitrine.

Therefore solution to this problem should be investigated which not affect neither the transparency of the façade nor the energy balance in the building. An effective and not energy consumed solution can be to use the structural system of the glazed façade as an obstacle on the cold boundary layer flow. Depending on the width of the obstacle, different flow conditions can be expected to occur as it can be seen in figure 5.20. When the width of the obstacle is smaller than a critical width, the boundary layer flow reattaches to the surface after it has passed the obstacle. The velocity will, however, be reduced; therefore, smaller velocities and an improvement in the thermal comfort can be expected in the occupied zone compared with the situation with a plane surface. When the width of the obstacle is larger than a critical width, the boundary layer flow will separate from the surface after it has passed the obstacle and a new boundary layer flow will be established below the obstacle. The separated airflow will flow into the room probably acting like a cold air jet. In this way, a highly glazed facade can be expected to act as a combination of small individual parts on top of each other. The top parts supply cold air to the room above the occupied zone and the risk of downdraft in the occupied zone is only determined by the flow conditions at the lowest part of the facade.
Since the main principle that is followed during the whole design process is transparency, the obstacles that are used to prevent this draft are made of glass elements. The length of the atria in each of the side is 4m and the width of the glass pane should range between 0.30m and 0.50m. For safety reasons, it is chosen two glass panes 2m X 0.50m each. The reason of choosing two panes instead of one is the effect of the condensation behind the glass surfaced of the façade.

To prevent this, a 2% inclination outwards at the sides is applied to both panes so the water is gathered at the floor without destroying any of the products in the vitrine (figure 5.21).
The supporting structure consists of three hollow triangular glass elements, which in the vertical direction are glued in the glass brick façade with DELO Photo bond adhesive and in horizontal direction is glued with the glass pane along the whole width with silicone. The cross section is square 12cmX12cm.

This structure is placed 0.4m below the first floor level, so the distracted air will not cause air cold draft at the level of feet in the first floor. That way the air level is led to the top below the ceiling.

The glass panes are heat strengthened laminated with Sentryglass foil 1.52mm. The thickness of each pane is 4mm, which is enough to withstand the air pressure at that point, as the calculation demonstrates.
The glass panes are two sided supported as it can be seen in the figure 5.23. In the safe side it is assumed that the deflection is the same as it was cantilever. Therefore

\[ \delta = \frac{q \cdot L^4}{8 \cdot E \cdot I} = \frac{0.567 \cdot 0.5^4}{8 \cdot 70 \cdot 10^9 \cdot 8.53 \cdot 10^{-8}} = 0.007 \text{mm} \]

If it is considered as a simply supported beam with uniformly distributed load then then deflection is:

\[ \delta = \frac{5q\cdot L^4}{384\cdot E \cdot I} = \frac{5 \cdot 0.567 \cdot 2^4}{384 \cdot 70 \cdot 10^9 \cdot 8.53 \cdot 10^{-8}} = 0.02 \text{mm} \]

The maximum air pressure on the surface can be found from the CFD simulations and it is N=0.567 N/m².

The stresses and deflections of the glass structure can be seen in the following figures after simulating in ANSYS software. The first estimations of the dimensions of the elements are satisfied the checks.

Figure 5.23: Deformation and tensile stresses of the glass pane (2mX0.5m)
References


Thermal Performance

It is of great importance, except from determining and assuring the load bearing capacity of a façade made by glass bricks, to be assured the thermal performance of the shopping store, by both achieving the optimum climate comfort in the interior environment and by testifying that the structural performance of the glue is not affected under any possible weather conditions.

For the former, the type of the space should be defined and the temperature range that is accepted as thermal comfort by the staff of the shopping store and by the clients will be determined. Afterwards, the analytical geometry of the design, the material properties and the location data along with the external meteorological parameters are input into the Design Builder thermal simulation software for three different climate zones. The results of the different scenarios of the simulations are used in order to indicate the most optimum design that can provide the desired climate comfort with the least possible energy produced by mechanical systems. The performance of the adhesive as well as of the glass brick due to extreme weather conditions have been tested by conducting thermal shocks tests in the laboratory.

Thermal comfort model

Thermal comfort is hard to define and perhaps harder to measure. According to ASHRAE, thermal comfort is “the condition of mind that expresses satisfaction with the thermal environment” (Paliaga et al., 2013). Humans have been creating spaces to induce thermal comfort for eons. The long-established components of comfort include air temperature, mean radiant temperature, humidity, and air velocity within the space, along with the personal factors of clothing insulation and activity level. All these factors are independent but in combination can determine one’s thermal comfort.

There are lots of thermal comfort models, theoretical and empirical, developed by various researchers. One of the well-known is that of Fanger (1970). The model assumes an energy balance for people in a stationery situation, in which energy released by the body’s metabolism is equal to energy removed from the area. Fanger’s research led to the two models “Predicted Mean Vote” (PMV) and “Predicted Percentage Dissatisfied” (PPD), that give the numeric value of a comfort level for a given indoor climate valuation and the percentage of the dissatisfied people respectively.(Lee & Strand, 2001)
The “predicted mean vote” (PMV) calculation is based on the following equation:

\[ PMV = (0.303e^{-0.036M} + 0.028)(H - L) \]

where:
- \( H \) is the internal heat production rate of an occupant per unit area (= \( M - W \)), W/m\(^2\)
- \( L \) is all the modes of energy loss from body, W/m\(^2\)
- \( M \) is the metabolic rate per unit area, W/m\(^2\).

The resulting PMV value is evaluated on a seven-point scale where 0 represents relative comfort with the thermal surroundings, positive numbers indicate that an average person will feel warm, and negative numbers indicate cool to cold conditions.

The drawback of his model is that it is only applied within the comfort range and that means that it cannot give a valuation for the climate during a brief stay in a room or for activities that last only a short time (e.g. clients in a shopping mall).

Another theoretical model is the **“Pierce Two-Node Model”** by John B. Pierce. The model divides the human body into two major compartments. One represents the internal core, and the other represents the skin. To determine the thermal sensations of human body, passive heat conduction from the core to the skin and the deviations of the core and the skin temperature from their set points are considered. The effects of shivering are also taken into account. The thermal sensation (TSENS) of an average person is calculated using one of the following equations:

\[
\begin{align*}
TSENS &= 0.4685(T_b - T_{b,c}) \quad \text{if } T_b < T_{b,c} \text{ in a cold environment} \\
TSENS &= 4.7\eta_{ev}(T_b - T_{b,c})/(T_{b,h} - T_{b,c}) \quad \text{if } T_{b,c} < T_{b} < T_{b,h} \text{ in a warm environment} \\
TSENS &= 4.7\eta_{ev} + 0.4685(T_b - T_{b,h}) \quad \text{if } T_{b,c} <= T_b \text{ in a hot environment}
\end{align*}
\]

Where:
- \( T_b \) is the mean body temperature, C
- \( T_{b,c} \) is the mean body temperature, lower limit for evaporative regulation zone, C
- \( T_{b,h} \) is the mean body temperature, upper limit for evaporative regulation zone, C
- \( \eta_{ev} \) is the evaporative efficiency.
The thermal sensation parameter obtained from these equations is compared to a scale that is similar to the one used for the Fanger model PMV calculation. The model has been continually expanding since its first publication in 1970. The most recent version on the model appears in the 1986 ASHRAE Transactions.

The model for “Standard Effective Temperature” (SET) also uses skin temperature as part of its limiting conditions, but uses skin wetness (w) rather than sweat rate for the other limiting condition. SET relates the real conditions to the (effective) temperature in standard clothing and metabolic rate and 50% RH which would give the same physiological response. Effective temperature can then be related to subjective response.

The drawback of these two models is their complexity and the need to take lot of assumptions and average values. Moreover, all these models assume steady-state situations. The effect of the dynamic character of thermal conditions is omitted. They take into consideration only thermo-physiological factors to determine thermal sensations.

However, non-thermal factors also play role such as psychological and cultural. For example, occupants in buildings in which the windows can be opened, they can influence the indoor climate themselves. That means that the “comfort temperature” as stated by the occupants of the building is not the same as the “neutral thermal situation”, as defined by the PMV model. People can adjust to the outdoor conditions more easily in a natural ventilated than in a climate-controlled building.

The adoption of a more adaptive comfort model is significant for the world of green building. If greater swings in the temperature or humidity can be achieved, then less energy is needed to condition the air. The acceptance of an adaptive model could also result in buildings that keep more people comfortable more of the time—which might increase productivity, keep people healthier, and have other benefits.

The fundamental assumption of the adaptive approach is expressed by the adaptive principle: *If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort*. This principle links field surveys conducted in a wide range of environments and thus supports meta-analyses of comfort surveys such as those of Humphreys (1976, 1978), Auliciems and deDear (1986) and deDear and Brager (1998).

According to Humphreys “the adaptive approach notices that people use numerous strategies to achieve thermal comfort. They are not inert recipients of the environment, but interact with it to optimise their conditions.”

The most used adaptive model is given by ASHRAE (1998). The operative temperature is given by the formula:

\[ T_{co} = a \times T_{ext,ref} + b \]

The “a” and “b” parameters are for the distinction between building and climate types. Alpha is used for buildings in which the windows can be opened and where the users can influence the indoor thermal climate, while beta applies to buildings with sealed facades and centrally controlled air conditioning that users have no sense of control.
For a mechanically ventilated building:
\[ T_{co} = 0.31 \times T_{ext,ref} + 17.8 \]

For a naturally ventilated building:
\[ T_{co} = 0.11 \times T_{ext,ref} + 21.45 \]

The \( T_{ext,ref} \) is the outdoor referenced temperature which can be derived by the monthly temperature average. An offset of 2.5°C above and below the calculated Operative Temperature value indicates a temperature range that would result in less than 10% complaint rate.

An investment in defining the thermal comfort criteria for a building will provide long term value both in design and in maintaining low energy operations that also provide thermal comfort to occupants. The steps to create thermal comfort criteria according to Cindy Regnier in Laurence Berkeley National Laboratory are (Regnier, 2012):

**Steps to create thermal comfort criteria**

1. **Define spaces of distinct thermal comfort needs**
   - occupancy periods, non-occupied spaces, etc
   - different occupant exertion areas (areas where physical exercise occurs, etc.)

2. **Select wind and weather data source of the site**
   Identify the weather and wind data sources to be used as a basis for design and operations. Ideally this would be historic data collected on site, to capture localized weather and wind patterns, or if not available identify a suitable local weather and wind station, potentially with some guidance on adjustments to be made with collected data to more accurately reflect local conditions. Select a source with reliable, multi-year data available (ideally no less than 5 years’ worth of data) with an environmental condition as similar to the site as possible, including local wind patterns.

3. **Select reference thermal comfort standards as a baseline**
   (ASHRAE Standard 55 may be appropriate for most cases)

4. **Define the conditioning systems to be addressed with the thermal comfort criteria**
   - Natural ventilation
   - Mechanical ventilation
   - Mixed mode (current, changeover, zoned)

5. **Set interior environmental conditions for comfort**
   For each distinct thermal comfort case, and space conditioning system, define the temperature and humidity ranges acceptable for thermal comfort.
6. **Set an occupant clothing value**  
   For each distinct thermal comfort criteria case, state the assumption of the clothing level of the occupants. Clothing (clo) values are typically between 0.5 and 1.2. ASHRAE Standard 55 may be referenced for further information, including guidance in calculating clothing values on the basis of activity type and duration.

7. **Assess and define seasonal considerations**  
   Provide any direction on differences in clothing values appropriate for seasonal change, use changes of spaces that vary seasonally.

8. **Set occupant control standards**  
   Define what types of occupant control over thermal comfort are desired and are acceptable and any operational or design restrictions on these controls.

9. **Define minimum coverage of occupant controls**

10. **Include occupant education requirements**

11. **Set a thermal comfort acceptability standard**  
    For spaces following the ‘traditional’ thermal comfort criteria outline in ASHRAE Std 55, these criteria are developed for 80% occupant acceptability of thermal comfort. For spaces following the adaptive thermal comfort model in ASHRAE Std 55, two acceptability ranges are provided, 80% and 90% acceptability, where 80% is the typical recommendation, and the 90% criteria may apply for conditions where a tighter range of interior temperatures is desired.

12. **Set a number of acceptable allowable hours of exceedance**  
    In designing system options, the thermal comfort analysis may indicate that a system performs very well, except for a small range of hours, perhaps coinciding with an annual extreme weather event. A small percentage of hours out of the acceptability range may be permissible by the owner, e.g., 3-5% of working hours, and should be discussed. Consider also whether the exceedance hours should be set for only occupied hours, or if a separate standard could apply for unoccupied hours.

13. **Describe any design elements desired**  
    For each conditioning system, identify whether any level of controls or design elements is desired in the system to allow for flexibility in operations in future. Particularly for systems that will be new to the owner and operators, a certain level of controls flexibility, system switchover or redundancy, may be desired to help tune the system once in operation.

*Some of the steps will not be covered by this research for evident reasons.*
1. Defining space

Thermal environment surrounding a man could be classified into several layers according to the level of environmental control applied. The layers are: outdoor environment, semi-outdoor environment, indoor environment, occupied zone and personal/task zone.

In the outdoor environment people need to adjust themselves to the environment in order to achieve comfort, since no artificial adjustments can be made. The indoor environment is divided into two categories, the occupied zone and the personal/task zone, so more efficiency and higher quality can be achieved. Semi-outdoor environment acts as a thermal buffer space between indoor and outdoor for occupants walking in and out of the building to mitigate the sudden change in thermal environment. Transition process through a buffer space such as entrance halls and atria may be regarded as a series of environmental step changes through indoor, buffer space and outdoors.

Semi-outdoor conditions have significant role. As Gehl (1987) claimed in his book “Life Between Buildings”, the importance of environmental quality in semi-outdoor spaces in the attraction of people and their social activities within, lie in the same continuum with the outdoor spaces with the slight difference in the range of environmental control.

The expected level of comfort differs when comparing indoor, semi-outdoor and outdoor areas. Particularly, in semi-outdoor spaces occupants tend to tolerate a two to three times wider temperature range than the one determined based on standard thermal comfort models, as applied in indoor areas [Nakano and Tanabe, 2004]. The latter can be partially explained by the numerous differences that exist in occupancy conditions of semi-outdoor environments (e.g. occupants do not have to stay in semi-outdoor spaces for hours, and the main use can be a passage or agora where people are free to stay or leave at their will [Nakano, 2003]); and also to the psychological predisposition of the occupants, who tend to tolerate higher levels of discomfort when being in spaces that are not conceived by them as indoor areas [Hoppe, 2002]. As a result, thermal comfort conditions in semi-outdoor space should be investigated with regard to how the semi-outdoor architectural space is actually used, from the point of transition phase while walking through and the short-term occupancy phase for a period of less than an hour [Nakano, 2003].

The function of the building is a 5 storey one brand shopping store. In each floor there is different department (men, women, accessories etc.) of the same brand. There are no closed spaces, or any partitions that divide the space into multiple thermal zones. Even the glass partitions on the 5th floor which separate the offices of the owner and staff from the shopping area, do not reach the ceiling leaving a space for the air and temperature to mix with the rest of the room. However, the area behind the glass brick façade, it can be characterized as a transient thermal comfort space where one succeeds a short walk in a buffer space from outdoor to indoor climate. The range of the temperature behind the façade is wider than those in the existing concrete building as the first thermal simulations in Design Builder software shown. It was proven that the temperature in the glasshouse was risen dramatically compared to the rest of the building.

People experience a large step change of thermal environment when entering or leaving an architectural environment, especially in summer and winter when the temperature differences are large between indoor and outdoor. This effect of buffer space is even more intense in long warm to hot summers like in
Spain, where occupants sweat and wear a fewer amount of clothing. Semi-outdoor environments acting as thermal buffer spaces such as entrance halls and atriums are often built to mitigate these sudden environmental differences, besides aesthetic aspects. Although there exists no thermal environmental guideline for designing these buffer spaces, it is very likely that the thermal environment in the buffer space would have large effects on impression and thermal comfort in a succeeding environment.

![Figure 6.2: Conceptual figure of the effect of the buffer space (Nakano, 2003)](image)

From all the above reasons, the building can be divided into two different spaces. All the floors of the existing building can be characterized as indoor environment and the area behind the glass brick façade, the “glasshouse” as semi-outdoor environment. It should be mentioned that there are no real partitions that divide these two spaces, although some scenarios about placing glass partitions creating double skin façade will be elaborated in the following.

2. **Select wind and weather data source of the site**

Since the building that is renovated has been created for the purpose of the research, there is no real location and orientation of the building. However, it was considered the location and orientation of the project that the concept has been inspired by. Thus, the building is located in the PC hoofstraat 94-96, Museumkwartier in Amsterdam, (latitude 52.3667° N), Netherlands. The Netherlands have a temperate maritime climate influenced by the North Sea and Atlantic Ocean, with cool summers and moderate winters. Daytime temperatures varies from 2°C-6°C in the winter and 17°C-20°C in the summer. Rainfall is distributed throughout the year with a dryer period from April to September. Dutch weather can be called, therefore, moderate.

In this research, apart from the dutch climate data, they have been introduced two more senarios including more extreme weather conditions in Europe. Tampere in Finland is represented the Scandinavia, where the climate is subarctic with more humid continental, while Valencia is representing the Mediterranean countries, where the climate is more subtropical and the summers are hot. If the results of the analysis with these extreme weather conditions are permissible for the project, then it is easier to prove that this new technology of the glass brick self supporting wall can be appied in almost all the climates.

Nonethelss, in projects such as the Crystal House, it is not yet absolutely known how the glass bricks will act in different weather conditions. The sudden change of the weather and the abrupt rise or fall of the temperature in a short time of period ,typical of the dutch weather, can be proved that it can be more
critical for a facade made by glass bricks than being exposed in extreme conditions such as really low
temperatures, frozed days or sunny days for a longer period of time, typical for the weather in Finland or
Spain respectively.

The orientation has been kept the same for all these three different locations and it is South-East, as the
glass brick facade in PC Hooftstraat is orientated (figure 6..). This orientation is the least favourable for
such a big glass area to be exposed, since the solar radiation is higher than it is in North-West. Thus, the
thermal performance of such a design can be improved if it is applied in a new building where the
orientation of the facade can be opted.

![Figure 6.3: Google maps view of the building in P.C. Hooftstraat, Amsterdam](image)

For all these reasons, there are simulations for 3 different weather zones,

1. Central Europe: [Amsterdam, Netherlands] temperate maritime climate
2. Scandinavia: [Tampere, Finland] humid continental climate/subarctic climate
3. Mediterranean: [Valencia, Spain] warm-temperate subtropical climate

3. Select reference thermal comfort standards as a baseline

As it has been described above, the most used adaptive model is given by ASHRAE (1998). The operative
temperature is given by the formula: \( T_{co} = a \times T_{ext,ref} + b \)

4. Define the conditioning systems to be addressed with the thermal comfort criteria

The design of the new part has been directed by the need of utilizing passive strategies in order to enhance
the thermal comfort while minimizing the energy consumed. When applied only natural ventilation, the
air quality is enough to cover all the area of the building, but the cooling needs mechanical support as
well. Besides, there is no such a big shopping store of a luxury well know brand without mechanical
ventilation. Therefore, current mixed mode is used.
5. Set interior environmental conditions for comfort

The design concept of a ‘semi-outdoor space’ varies dramatically depending on the climate of the building location and the desired comfort level inside. Climate has a large influence on the amount of cooling or heating load of a semi-outdoor space, and the basic structure is chosen by the orientation of environmental control: heating or cooling, or both. The comfort level is largely divided into four categories: (a) canopy, (b) buffer, (c) tempered buffer and (d) full comfort [Nakano, 2003]. However, there is little literature about the actual target temperature value of these categories. Two empirically derived design criteria, one from UK and one from Japan are presented in figures 6.4 and 6.5 respectively. Although the winter climate is similar in both countries, Japan has a relatively more humid summer compared to UK, thus, the target summer temperature in Japan is generally lower.

<table>
<thead>
<tr>
<th>Atrium Type</th>
<th>Performance Level</th>
<th>Applications</th>
<th>Comfort Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canopy</td>
<td>Shelter, shade, No air containment.</td>
<td>Shopping precincts, Links between buildings, or alongside buildings.</td>
<td>Heating (Winter)</td>
</tr>
<tr>
<td></td>
<td>Winter air containment. Shelter, shade, summer natural ventilation</td>
<td>Conservatory link, Covered courtyard, Covered shopping center.</td>
<td>Ambient air temperature, No heating, No cooling.</td>
</tr>
<tr>
<td>Buffer</td>
<td>Winter air containment. Shelter, shade, summer natural ventilation</td>
<td>Office entrance halls, Enclosed shopping centers.</td>
<td>Air temperature heated to 10°C in occupancy zone.</td>
</tr>
<tr>
<td></td>
<td>Winter air containment. Shelter, shade, background heating, Summer natural ventilation</td>
<td>Office entrances and meeting halls, Enclosed shopping centers, Hotels, Restaurants, hospital, Glazed links.</td>
<td>Air temperature heated to 19°C in occupancy zone. Radiant heating to offset cold glazing.</td>
</tr>
<tr>
<td>Partial Comfort</td>
<td>Winter air containment. Shelter, shade, heating, Summer natural and/or mechanical ventilation</td>
<td>Office space, banking halls, Enclosed shopping centers, Prestige hotels, restaurants.</td>
<td>Winter design 19°C minimum.</td>
</tr>
<tr>
<td>Full Comfort</td>
<td>Winter air containment. Shelter, shade, heating, ventilation and mechanical cooling</td>
<td>Any. Design approach seeks to optimize solar gains during winter and maximize natural ventilation effects in summer.</td>
<td>Winter design up to 19°C as designed, Heating to supplement solar gains.</td>
</tr>
<tr>
<td>Passive Solar</td>
<td>Can be between buffer and full comfort according to design approach.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 6.4: Environmental criteria for Japanese atrium, (SHASE, 2002, modified by Nakano) [Nakano, 2003]
Each floor in the building has its own thermal zone but all the floors can fall under the definition of ‘partial comfort/full comfort’ category as it is considered as part of indoor space, where there is staff that is working during the whole time of occupancy schedule. The glasshouse falls under the definition of ‘partial comfort/tempered buffer’ category, as the occupancy of the space is too long to define it as a tempered buffer and too short to regard it as a full comfort space.

According to the weather data of the location of the building and according to the figure above, it can be derived that the target interior temperature for the building should lie between 22°C during winter and 26°C during summer (the stricter temperatures of this category). For the glasshouse the respectively values are 18°C and 28°C, with acceptable peak air temperature around 33°C.

This temperature range however, is required only when there are people inside the shelter and thermal comfort is essential. In non-visiting hours (between sunset and sunrise) the shopping store can undergo through wider temperature differences. Yet, during these hours, it is crucial that the temperature inside the store never drops below zero to prevent the formation of ice. It is also important that the interior temperature never rises above 40 °C since the SGP glass interlayer’s mechanical performance decreases in higher temperatures. Moreover, freezing or really high temperatures can damage and impair the quality of the products causing loss to the owner. Since the building is intended for luxury brand, the range of the temperatures in the interior can be tighter. In response to all the above, it can be estimated that during the non-occupancy hours the shopping store can present an interior temperature between 15 - 30 °C. The
maximum and the minimum temperature values according to the occupancy schedule are presented below, in table 6.1.

<table>
<thead>
<tr>
<th>Occupancy schedule</th>
<th>Zones</th>
<th>Summer</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occupancy hours</td>
<td>existing building</td>
<td>Max 26°C</td>
<td>Min 22°C</td>
</tr>
<tr>
<td></td>
<td>glasshouse</td>
<td>Max 28°C</td>
<td>Min 18°C</td>
</tr>
<tr>
<td>Non-occupancy hours</td>
<td>existing building</td>
<td>Max 33°C</td>
<td>Min 15°C</td>
</tr>
<tr>
<td></td>
<td>glasshouse</td>
<td>Max 33°C</td>
<td>Min 15°C</td>
</tr>
</tbody>
</table>

Table 6.1: Lower and higher temperature margins for the interior temperature of the building

However, these values are the general accepted temperature range throughout the year in order to achieve the desired comfort level, without taking into account some extreme weather situations during the winter and the summer. As mentioned in the previous section, the interior comfortable temperature should be dependent also on the exterior temperature. Hence, the adaptive model of ASHRAE will be applied for estimating the internal comfortable temperature range corresponding to the exterior conditions. Even though there is both natural and mechanical ventilation in the building, the formula that is used, is for naturally ventilated building. This is based on the fact that the windows are operable and easily adjustable by the users anytime during the day.

Thus, \( T_{co} = 0.11 \times T_{ext, \text{ref}} + 21.45 \)

Regarding that the main area that is used by the staff and the clients for longer period is the existing part of the building which has an indoor environment, the offset zone from the operative temperature of the ASHRAE model should be less than 2.5°C, which corresponds to a less than 10% complaint rate.

For the glasshouse, the range can be wider and equal to an offset of 5°C which corresponds to an approximately 30% complaint rate.

As a result, the previous table can be rewritten as follows:

<table>
<thead>
<tr>
<th>Occupancy schedule</th>
<th>Zones</th>
<th>Summer</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occupancy hours</td>
<td>existing building</td>
<td>( T_{co} -2.5°C ) to ( T_{co} +2.5°C )</td>
<td>Max 26°C</td>
</tr>
<tr>
<td></td>
<td>glasshouse</td>
<td>( T_{co} -5°C ) to ( T_{co} +5°C )</td>
<td>Max 28°C</td>
</tr>
<tr>
<td>Non-occupancy hours</td>
<td>existing building</td>
<td>Min Outside Temperature - Max 33°C</td>
<td>Min 15°C - Max Outside Temperature</td>
</tr>
<tr>
<td></td>
<td>glasshouse</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.2: Temperature values of the interior temperature of the shelter.

(\( T_{co} \) stands for the operative temperature as calculated according to the ASHRAE adaptive model for naturally ventilated buildings: \( T_{co} = 0.11 \times T_{ext, \text{ref}} + 21.45 \))

As a consequence, the temperature range for comfort, according to characteristic values of the exterior reference temperatures \( (T_{ext, \text{ref}}) \) for the existing part of the building and the glasshouse can be seen in the tables 6.3 and 6.4 respectively.
Table 6.3: Proposed temperature values for comfort during occupancy hours according to the Text, ref for the existing part.

<table>
<thead>
<tr>
<th>$T_{\text{ext, ref}}$</th>
<th>$T_{\text{co}}$</th>
<th>Temperature Range</th>
<th>Correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10</td>
<td>20.35</td>
<td>17.85-22.85</td>
<td>22-22.85</td>
</tr>
<tr>
<td>-5</td>
<td>20.9</td>
<td>18.4-23.4</td>
<td>22-23.4</td>
</tr>
<tr>
<td>0</td>
<td>21.45</td>
<td>18.95-23.95</td>
<td>22-23.95</td>
</tr>
<tr>
<td>5</td>
<td>22</td>
<td>19.5-24.5</td>
<td>22-24.5</td>
</tr>
<tr>
<td>10</td>
<td>22.55</td>
<td>20.05-25.05</td>
<td>22-25.05</td>
</tr>
<tr>
<td>15</td>
<td>23.1</td>
<td>20.6-25.6</td>
<td>22-25.6</td>
</tr>
<tr>
<td>20</td>
<td>23.65</td>
<td>21.15-26.15</td>
<td>22-26</td>
</tr>
<tr>
<td>25</td>
<td>24.2</td>
<td>21.7-26.7</td>
<td>22-26</td>
</tr>
<tr>
<td>30</td>
<td>24.75</td>
<td>22.25-27.25</td>
<td>22.25-26</td>
</tr>
<tr>
<td>35</td>
<td>25.3</td>
<td>22.8-27.8</td>
<td>22.8-26</td>
</tr>
<tr>
<td>40</td>
<td>25.85</td>
<td>23.35-28.35</td>
<td>23.35-26</td>
</tr>
</tbody>
</table>

Table 6.4: Proposed temperature values for comfort during occupancy hours according to the Text, ref for the glasshouse

The temperature range for the climate comfort for the other two locations, Spain and Finland, has opted to remain the same as in Netherlands. Despite the fact of the differences in the weather data between these three countries, it was considered wise to keep the same temperatures for the interior of the building in order to have better comparison between the results of the simulation for the three different climates. Moreover, in luxury well known fashion brand stores it is common to keep the same principles in every store around the world. It is known, that sometimes clients, entering a shopping store, feel the high difference in the temperature between the interior and outdoor climate. So, during summer days, even when the temperatures outside are $38^\circ$C, the temperature they feel when they enter the building can be in the range of $26^\circ$C.

The level of relative humidity hardly matters in terms of thermal comfort. An upper limit of $\phi = 70\%$, or a moisture content of $x = 12$ g/kg is often maintained. There is no lower limit from a comfort point of view.
Although often it is set at $\phi = 30\%$, as below this level there is an increased chance of static electricity occurring which causes dust to move around leading to the irritation of the mucous membranes. It is therefore a good idea to consider these values for relative humidity from a general comfort point of view (BouwPhysica, 2006). Of course, for each of the three location the level of the humidity in the exterior differs, which makes different acceptable ranges for the level of the humidity in the interior.

For example for Amsterdam, the relative humidity typically ranges from 56\% (mildly humid) to 97\% (very humid) over the course of the year, rarely dropping below 36\% (comfortable) and reaching as high as 100\% (very humid). The air is driest around May 15, at which time the relative humidity drops below 66\% (mildly humid) three days out of four; it is most humid around November 20, exceeding 94\% (very humid) three days out of four.

![Figure 6.6](image)

*Figure 6.6: The average daily high (blue) and low (brown) relative humidity with percentile bands in Amsterdam, Netherlands (www.weatherpark.com)*

For Valencia the relative humidity presents a more stable fluctuation through the year. It typically ranges from 38\% (comfortable) to 90\% (very humid) over the course of the year, rarely dropping below 22\% (dry) and reaching as high as 97\% (very humid). The air is driest around March 14, at which time the relative humidity drops below 46\% (comfortable) three days out of four; it is most humid around October 21, exceeding 87\% (very humid) three days out of four.
Finally, for Tampere in Finland, the relative humidity typically ranges from 41% (comfortable) to 98% (very humid) over the course of the year, rarely dropping below 26% (dry) and reaching as high as 100% (very humid). The air is driest around May 15, at which time the relative humidity drops below 48% (comfortable) three days out of four; it is most humid around November 16, exceeding 99% (very humid) three days out of four.

As a general rule for the acceptable level of humidity in the interior of the building can be:

$$30\% \leq \phi \leq 70\%$$

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6. Set an occupant clothing value

The human occupants of the building maintain their own energy balance with indoor climatic conditions, and the extent to which they rely on physiologic (as opposed to behavioural or engineering) responses to maintain that energy balance determines the magnitude of their thermal discomfort and attendant dissatisfaction. A key behavioural mechanism that attenuates thermal discomfort indoors is the adjustment of clothing insulation levels, but there are several factors, some of them psychological (cognitive, aesthetic, organisational, cultural, etc.) impinging on clothing decisions as well as the usual thermal variables (temperature, humidity, etc.). One of these is the clothing policy of the occupants’ employer. Corporate dress codes, as found in the present office environment study, all but extinguish clothing adaptive opportunity. The net result of such policies is to transfer responsibility for comfort thermoregulation away from the individual and towards a building’s facilities manager. However, another factor impinging on clothing decisions is outdoor weather, either directly experienced or perhaps forecast by the local meteorological service. Figure 13 attempts to draw this complexity together in the form of a conceptual model of clothing, building, climate and energy.

Figure 6.9: Conceptual model of the interactions between weather/climate, the built environment and clothing (Morgan & de Dear, 2003)

After lot of research and statistical association between daily mean clo values and outdoor temperatures in shopping mall and stores buildings the clothing value for winter and summer are the following:

In winter for female and male (average) → 1 clo
In summer for female and male (average) → 0.5 clo
7. **Set occupant control standards**

The staff of the shopping store can adjust the number and the area of the opening of the windows in the back façade and the louvres in the glass roof depending on the outdoor and indoor climate conditions. Moreover, they can turn out lights or adjust the level of the artificial luminosity.

8. **Include occupant education requirements**

The staff that can control the standards for the thermal comfort, should be able to understand the building and to operate it efficiently. This requires education.

9. **Set a number of acceptable allowable hours of exceedance**

The number of the hours of exceedance of the thermal conditions will be defined after the simulation with the Design Builder software. Provided that the shopping store is designed for a luxury brand, the hours of this exceedance would be limited and even only during the unoccupied period.
Passive strategies

According to the Government established Carbon Trust, the retail sector is responsible for 21 million tons of CO₂ emissions per annum. The biggest energy consumption for retails belongs to lighting, ventilation and cooling. Retailers demand good ventilation, lighting and thermal comfort for their staff and customers, especially for luxurious brands which have stricter requirements. These demands often exceed the minimum requirements specified by legislation, codes and standards, yet CO₂ emissions and energy use must satisfy the highest levels of environmental standard classification. Achieving these targets demands stringent controls on the efficiency of lighting, air conditioning and ventilation performance.

Figure 6.10: Electricity consumption for different function of buildings. Retail stands score the higher consumption. (Data Source: Itron California Commercial End-Use Survey 2007)

![Electricity consumption for different function of buildings](image)

Retail

Figure 6.11: The energy distribution which is used in a typical retail store. Interior and exterior lighting and HVAC account for almost 80% of energy use (Data Source: Itron California Commercial End-Use Survey 2007)

![Energy distribution in a typical retail store](image)

To minimize carbon emissions and ensure energy efficiency, there is a strong emphasis on using natural ventilation, daylighting and passive cooling in retail premises. Designers are therefore required to demonstrate that new designs and major refurbishments take full advantage of natural solutions. Even
for countries with cold climate, like Finland and Netherlands, where comfort cooling is used for short period of time can cost as much as a whole year’s heating. Moreover, reducing energy use makes perfect business sense; it saves money, enhances corporate reputation and helps everyone in the fight against climate change (Jesus, Almeida, & Almeida, 2007).

It is estimated that following passive strategies, energy savings of up to 20% (equivalent to more than 560 million euro) are possible. There is hence considerable attention on reducing these emissions with strong emphasis placed on the use of natural ventilation, daylighting and passive cooling. Passive climate systems focus on natural sources for the lighting and heating/cooling demands of the space by directly linking the outdoor climate with the interior of the building. More specifically, based on the local climate conditions, passive strategies aim to cover the lighting requirements via natural daylight, while the temperature in the interior is influenced by the physics of the form, the amount and location of the mass (thermal mass), the size and the orientation of the openings (stack ventilation), the shading, the material properties and the effect of passive systems [Nicol and Roaf, 2007]. These parameters can be used for optimizing the thermal conditions in the interior of the building through passive cooling/heating systems. The general principles of these parameters are analyzed in the following section.

Another measures that could be used in a design like this, is to use the thermal mass of materials with high thermal storage capacity. Thermal mass is the ability of building materials to absorb heat, store it, and at a later time release it. This thermal storage capacity of structural materials plays an effective role in attenuating and shifting the thermal load, particularly when the climatic parameters vary significantly. More precisely, thermal mass is greatly important for comfort in warm climates where summer temperatures are high and there is a large deviation between the daily average maximum and minimum temperatures. The fluctuations in temperatures are then considerably reduced and the peak temperatures are decreased due to thermal inertia. Fountains with water in the ground floor could lead to a decrease of 1°C of the interior temperature, especially for the Spain location.

Even today that lot of efforts have been made to achieve a totally passive building design, most of the times there are always some active systems that assist the passive. For example, heat recovery ventilation, solar thermal systems, ground source heat pumps and so on. Very broadly, where it is possible to do so, designers will aim to maximize the potential of passive measures, before introducing hybrid or active systems. This can reduce capital costs and should reduce the energy consumed by the building. However, whilst passive design should create buildings that consume less energy, they do not always produce buildings that might be considered sustainable as sustainability is dependent on a range of criteria, only one of which is energy usage. Measures like green roof or solar tubes etc., were considered not necessary to apply in this research because it would not be comparable the results of the existing situation with the renovated situation.
Natural ventilation

One important characteristic of large glazed spaces such as atrium is that the air temperature is not always homogeneous but can increase with the height of the atria. This phenomena is called **temperature stratification**. It occurs in atria in periods of high solar gains. The stratification is important for calculation of thermal comfort, and it is also critical for heat recovery systems that utilize the surplus heat under the ceiling. The stratification depends on the thermal condition, and particularly on the distribution of the solar and internal heat gains. The air movement in the atrium and between the outside or adjacent zones also have a significant influence on stratification. Depending on the thermal situation, it can be defined four main temperature distributions in large enclosures.

1. Constant in the height  
2. Increasing linearly  
3. No linear profile, increasing rapidly in the lower part  
4. No linear profile, increasing rapidly in the upper part

After the thermal performance and CFD simulations this temperature stratification can be distinctively seen. The temperature increases rapidly in the upper part, whilst on the horizontal direction the temperature of the air is always quite homogenous.

![Figure 6.12: Attached atrium (above) and attached atrium naturally ventilated (below) (Bryn & Schiefloe, 1996)](image)

The natural ventilation of the atri by opening vents at different levels will decrease the stratification depending on the efficiency of the piston flow (size of the openings, height difference between them and so on), which are described below.
Stack ventilation and cross ventilation

Apart from the temperature stratification, ventilation must be provided, under normal circumstances, for limiting the accumulation of pollutants and moisture, which could lead to mould growth and would otherwise become a hazard to the health of people in the building. The prescribed minimum rate for retail premises is 5lt/sec/person.

In the present design, stack and cross ventilation is possible due to the atriums that are formed behind the glass brick façade that lead the fresh air at each of the floor to the windows in the back façade (cross ventilation) and to the top in glass roof (stack ventilation). In order to move out the hot daytime air, convective cooling air streams should be created. For that purpose, cool air is drawn in from the bottom of the glass brick façade while at the same time hot air is released through openings at the top of the same façade and at the windows at the back façade.

The schedule of the natural ventilation can be either dependent on the difference of the indoor and outdoor temperatures, so the air will be supplied only when the outdoor temperature is at least 1°C lower than the indoor or the incoming air will be further cooled down or heated (in case of winter) through the use of earth ducts underneath the glass brick façade. The utilization of underground ventilation provides the temperature difference needed to ensure the stack effect throughout the year: during winter outdoor air is preheated through heat exchange with soil and during summer it is cooled down through the same principle. The stack effect is further enhanced due to the large height difference between the air inlet and outlet, which equals to 20 meters.

The effectiveness of the natural ventilation applied in this design is proved with the CFD simulations done by the Design Builder software. The results can be found in next section of this chapter.
Figure 6.13: Principle of stack and cross ventilation: Cool air is pulled in from the bottom of the glass brick façade and hot air is pushed out from the openings at the back façade and from the louvres at the glass roof.

At the top of the glass roof there is louvre system that operates automatically according to the natural ventilation schedule or when needed. The detail of this system can be seen in the figure 6.14. The structure consists solely by glass elements apart from the small metal inserts that are drilled in the glass plate which is glued vertically on the glass brick column. The design offers rain and snow protection, since the upper glass pane overlaps part of the lower glass pane which are sealed with silicone sealant when they are closed. Except from the right inclination of the concrete roof with direction to the back façade, there is a glass square plate that has twofold role. It prevents water from entering the building and it functions as the stopper of the last glass pane with the silicone that has at the outside side.
Another solution, apart from the earth duct and the openings at the bottom and top of the façade, is to apply the "windcatcher" design in the glass roof. Windcatchers satisfy ventilation and passive cooling needs by incorporating the top down natural ventilation technique. Any prevailing wind is encapsulated by the louvres on the windward side of the system and this air is turned through 90° to provide a continuous airflow down to the room below. Motorized volume control dampers, together with a sophisticated control system, can accurately control this airflow to provide the desired ventilation rate. Since the airflow is drawn from above the roof level, the air is generally much cleaner than it would be drawn through windows or low level intakes (as in the previous solution). By drawing air in from a high level, this avoids dust, dirt, and often traffic pollution that generally circulates at pedestrian level. Since the down flow of incoming air is generally much cooler and being wind driven, it has been proven through many years of testing that this airflow descends to floor level, similar to a displacement ventilations system, but without any energy costs.

Constant movement of air to floor level tends to slightly pressurize the room which the windcatcher serves, and this incoming air helps to displace the warm air that rises through the natural passive stack effect of the leeward side of the system. Warm air naturally rises to ceiling level in any room and since the air ducts are open to atmosphere “passive stack ventilation” is created ("The importance of Natural Ventilation and Daylight for Healthcare Applications Contents").
Cooling

Shopping centers dating from the mid twentieth century are defined as “acclimatized” spaces, where all areas are cooled or conditioned by mechanical systems. This mentality has been maintained since the seventies, reflecting the expansion in the marketplace of air conditioning, which sometimes was causing really low temperatures in the interior of the shopping stores that could cause health problems in the clients when entering for short time of period in such a big different climate condition compared to the high outdoor temperatures. However, this has been changed and the design of the building follows the passive or hybrid systems that reduces the dependence on HVAC. In addition to the advantages associated to the reduction of initial and operational costs, the passive cooling systems tend to increase indoor air quality and productivity, as well as decrease diseases if compared to mechanical systems. Due to these benefits, these new systems are being applied more and more to Shopping Centers.

First of all, the use of night ventilation in summer can decrease the interior temperatures remarkably without consuming any energy or causing discomfort to the occupants since it is during unoccupied period. Glass and concrete has high thermal storage capacity, saving lot of heat load during the day and release with the natural ventilation during the night. The thermal storage capacity of structural materials plays an effective role in attenuating and shifting the thermal load, especially for climate that the temperatures vary significantly between the day and night. For example, in Valencia, thermal mass is greatly important for comfort in warm climates where summer temperatures are high and there is a large deviation between the daily average maximum and minimum temperatures.

The thermal capacity of glass is 0.84 kJ/kg*K and concrete is 0.75 kJ/kg*K.
The solar protection through appropriated insulation and low $U_{\text{glassing}}$ values is one of the main passives measures that reduce the heat load in the building. Since the biggest glass surface area is the glass brick façade, from where the most solar radiation is absorbed, it would have been wise to apply some coatings or take measures in order to prevent that. However, the $U_{\text{value}}$ of the bricks are fixed from the factory and any other interventions will affect the visual effect of the façade. Therefore, the glazing performance have been focused in the rest of the glazing surfaces such as the glass roof and the windows in the back façade. In this section, the passive measures that have been taken for the glazing are analyzed. At the end of the chapter though, some interventions that are possible to make in the façade can be found, as well as some suggestions for future research.
Glazing performance

Successively, the energy performance of the glass panes influences parameters such as energy consumption, cost and comfort. The parameters that influence the thermal performance of a glazing is the U-value of the panes, the solar, reflection, absorption and transmittance factors, the applied coatings, the number of the glass panes and the existence of gas gap between the panes and so on (Roos, 2001).

Figure 6.17: Solar control glass controls solar radiation by managing reflectance, transmittance and absorptance (Pilkington, 2009)

Coatings can be applied for the self-cleaning of the glass (self-cleaning coatings) and the minimization of the reflections (anti-reflective coatings). Moreover, low-e and solar control coatings can regulate the amount of light and heat infiltrating into the space, turning glass into an important component for a building’s energy consumption.

Reflective coatings are applied in the outer surface of the glazing in the roof and the windows, reducing in this way heat gain and loss. Apart from minimizing the solar heat gain coefficient (SHGC), a high reflective glass also reduce glare. The drawback of this reflective coating, though, is the mirroring effect due to the thin metallic layers that compose the coating and the great reduction of the glazing’s visible and light transmittance. However, this coating is only applied on the roof glazing and this mirror appearance is not so visible from underneath. Besides the surface of the glass roof is small compared to the façade, so the amount of the natural light coming into the building does not present any difference.

Low-e coatings are applied on the inner surface of the outer pane of the glazing in the roof and windows for the warm climates (Spain and Netherlands), and at the inner surface of the inner pane of the glazing for the colder climates (Finland). In this way, the coating is not exposed to cleaning or discoloring and is condensation resistant. This coat can reduce the heat flow through the glazing and thus drastically improve the thermal insulation properties of the glass. More practically, the low-e coating decreases the $U_{value}$ of the glazing.

However, the improved energy performance depends not only on the properties of the glazing, but also on the prevailing climate conditions and the type of building. More significantly, in locations such as Spain where cooling demands are higher and more critical than heating demands, measures that will reduce the
risk of overheating should be the first priority, whilst locations such as Finland where lower temperatures are taken place, measures to increase the heat loads during the winter should be taken into account.

The **geometry of the glass pane** in the roof and in the windows in the back façade can be seen in the figure 6.18. Double glazing is preferred over single glazing, since thermal isolation is important. The upper part consists of 2 glass panes of 8mm each, heat strengthened laminated with 1.52mm Sentryglass foil *Pilkington Optifloat*, which reduces the glare and offers a degree of solar control performance, whilst the lower part consists of 2 glass panes 8mm each, heat strengthened laminated with 1.52mm Sentryglass foil *Pilkington Optilam*, which provides both impact resistance and security. At the air gap, argon gas 16mm is preferred for better thermal insulation.

![Figure 6.18: Cross section of the roof and windows glazing](image)

The Pilkington Company offers lot of different glazing types for different purposes (solar control, insulation, fire protection, noise control, self-cleaning, decoration etc). For this design, since both safety and high thermal performance is important, the Optifloat and Optilam glazing has been chosen.

The geometry of the glazing in the louvres at the glass roof is different from the rest of the windows due to the feasibility of the function of the louvre mechanism. Thus, triple glazing is applied without gas gap, where the middle layer has metal sockets that enter a glass plate which is glued in the glass brick column. Through this distinctive mechanism the louvres can be opened when it is needed, preserving the transparency of the glass elements.

![Figure 6.19: Cross section of the louvres glazing in the roof](image)
Another important measure is the **window shading** during the times that the solar radiation is high. Blinds with high reflectivity slats are placed inside the windows in the back facade (figure 6.22) being controlled by the amount of the solar radiation, which is set to 120 W/m². The operation schedule of the shading in the windows is confined to the months with the highest radiation (May-August) and for the hours between 10:00-17:00. For the rest of the period, the heat load from the solar is needed to decrease the heating demands.
Figure 6.21: Blinds inside the windows (www.hunterdouglascomponents.com)
The reduction of the solar gain is achieved by fritting the outer glass pane in the roof. Fritted glass creates an effective UV shield that helps to control solar gain and glare and it helps in diffusing the light in the interior. Fritted glass is produced after an enamel image is fired into the surface of the glass. This firing process is usually done during the toughening process of the glass. There are lot of variations of the forms and textures available in the market, giving an easy tool to the architects to design interesting and attractive facades. Some examples of fritted pattern can be seen in the figures 6.23, 6.24.
For the present design though, the fritting process is only applicable in the glass roof pane, since such a process is difficult or at least has never applied before in glass brick surface. The surface of the glass roof is only a small part of the total exterior glazing of the design, hence after applying fritting in the design builder model, the differences in the results of the simulations are small. The pattern that has been chosen for the glass roof is simple and consist of dots which are uniformly distributed on the whole surface. The dots are white so they can reflect better the light and not absorb it.

As a recommendation for further research on the possibilities of applying the fritting process in the glass bricks, thermal simulations with fritting the upper half part of the glass brick façade (the most exposed to the sun) can be found in following section.
Finally, one of the most common passive measures for both commercial and residential building is the green roof. Green roof has lot of purposes for a building, one of them is to cool down the interior by evaporating the water. Another solution is to create “cool roof”, by applying bright colors or other materials which deliver high solar reflectance, infrared and ultraviolet wavelengths of the sun, reducing heat transfer to the surface. Furthermore, solar thermal collector or solar panels are always sustainable ideas to produce energy. However, none of these measures have been applied in the present design because it would deviate from the initial scope of the research.
Lighting

The new design with the big glass façade and the glass floors allows the natural light to come into the interior, decreasing the electricity demand. More specifically, the simulations of the daylight in the third floor of the concrete part of the building and the in the glasshouse zone can be seen in the figures 6.26 and 6.27 respectively. The first photo shows the daylight of the building with the conventional façade and the traditional windows in both of the facades, whilst the second photo displays the daylight of the building with the glass brick façade and the traditional windows in the other façade.

*Figure 6.26: Daylight simulation in the third floor of a building with conventional brick façade (top) and glass brick façade (bottom)*
The increase of the Lux for the third floor reaches the 19%, while the reduction in the electricity for lighting, in combination with lighting control and sensors, reaches 12% (as it has been calculated through the fuel breakdowns data from the two different simulations in Design Builder).

Undoubtedly, there are more measures that can be applied to make a building more sustainable. However, the purpose of this research is based on the effect of the replacement of the conventional façade with glass brick façade. So any other measure will affect and mislead this goal. Summing up, a table is being presented summarizing the passive measures that are implemented in the present design and also some other measures that, although not implemented in this case, could serve as an important reference for future shopping centers.
<table>
<thead>
<tr>
<th>Measures</th>
<th>Applied</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ventilation</strong></td>
<td></td>
</tr>
<tr>
<td>Passive</td>
<td></td>
</tr>
<tr>
<td>Create stack and cross ventilation</td>
<td>✓</td>
</tr>
<tr>
<td>Apply earth duct</td>
<td>✓</td>
</tr>
<tr>
<td>Active</td>
<td>✓</td>
</tr>
<tr>
<td>Use of mechanical devices to supply or extract the air</td>
<td></td>
</tr>
<tr>
<td><strong>Cooling</strong></td>
<td></td>
</tr>
<tr>
<td>Passive</td>
<td></td>
</tr>
<tr>
<td>Prevention measures and solar protection through appropriated insulation and building shape</td>
<td>✓</td>
</tr>
<tr>
<td>Use of night ventilation in summer.</td>
<td>✓</td>
</tr>
<tr>
<td>Ground cooling (direct and indirect contact)</td>
<td>✓</td>
</tr>
<tr>
<td>Associate similar activities to obtain larger advantages in building orientation and storage of similar cooling needs</td>
<td>✓</td>
</tr>
<tr>
<td>Use of technical areas as air chambers</td>
<td></td>
</tr>
<tr>
<td>Reduce the paved areas to decrease the heat storage around the building</td>
<td></td>
</tr>
<tr>
<td>Consider the use of green roofs to increase thermal insulation</td>
<td></td>
</tr>
<tr>
<td>Use of renewable energies, such as the solar thermal systems (thermal energy) and photovoltaic modules (electrical energy).</td>
<td></td>
</tr>
<tr>
<td>The solar photovoltaic energy can be more cost effectiveness through BIPV (Building Integrated Photovoltaic)</td>
<td>✓</td>
</tr>
<tr>
<td>Use of centralized technical management</td>
<td></td>
</tr>
<tr>
<td>Active</td>
<td></td>
</tr>
<tr>
<td>Use of thermal energy storage, known as ice bank</td>
<td>✓</td>
</tr>
<tr>
<td>Use of Cogeneration / Tri generation - Cogeneration saves 15 to 30% through combined heat (thermal) and power (elect.) production, reducing costs in 40%. Tri generation means combined production of power, heat and cold</td>
<td>✓</td>
</tr>
<tr>
<td>Selection of high efficiency equipment, operating on a bi-modal function (for total or partial loads)</td>
<td>✓</td>
</tr>
<tr>
<td><strong>Daylighting</strong></td>
<td></td>
</tr>
<tr>
<td>Passive</td>
<td></td>
</tr>
<tr>
<td>Maximization of southern exposure and glazing properties</td>
<td>✓</td>
</tr>
<tr>
<td>Establishment of lighting levels considering the occupant needs</td>
<td></td>
</tr>
<tr>
<td>Use of top lighting strategies (skylights, glass roof)</td>
<td>✓</td>
</tr>
<tr>
<td>Verification of the shape of the building considering the daylighting and thermal control</td>
<td>✓</td>
</tr>
<tr>
<td>For indoor space, selection of light colored surface materials and ideal ceiling heights (minimum 6 meters), to increase reflection index and thermal comfort.</td>
<td>✓</td>
</tr>
<tr>
<td>Consider exterior shading techniques for solar control (mainly movable shading), based on glazing height and latitude.</td>
<td>✓</td>
</tr>
<tr>
<td>Active</td>
<td></td>
</tr>
<tr>
<td>Choice of efficient low consuming lamps</td>
<td>✓</td>
</tr>
<tr>
<td>Use of Leds, which consume 12% less energy than a normal lamp, with a life expectation of 80 years.</td>
<td>✓</td>
</tr>
<tr>
<td>The reduction of energy demand through the control of the electric lighting system in response to daylighting.</td>
<td>✓</td>
</tr>
<tr>
<td>Lighting management establishing timetables for each zone.</td>
<td></td>
</tr>
<tr>
<td>Adjust efficient lighting (Lumens/W) and lamps to optimize the optical control (maintaining desire illumination levels on the required space)</td>
<td></td>
</tr>
<tr>
<td>Use of electronic ballasts and occupancy sensors to better control and save effective lighting costs</td>
<td></td>
</tr>
</tbody>
</table>

*Table 6.5: Passive and active measures*
Thermal calculations

For the thermal calculations of the building, the Energy software Design Builder has been utilized. Design Builder software is the “user friendly” graphical interface mode of the Energy Plus simulation program. Design Builder has been specifically developed around Energy Plus allowing most of the Energy Plus fabric and glazing data to be input. Databases of building materials, constructions, window panes, window gas, glazing units and blinds are provided. The model introduced to the software is quite complex and consists of lot of climate zones and materials. Before input the data to the software some hand calculations were made in order to estimate the natural ventilation rate inside the building, as well as the operation schedule of the windows and shading. After defining the geometry, materials, weather data into the Design Builder, the results of the different simulations are examined in order to achieve the optimum thermal performance of the building consuming the least possible energy.

Input data in Design Builder

The architectural design of the renovated building has been directed by the need of ensuring the good and sustainable thermal performance of the building.

Geometry

The geometry of the model is quite complex and it consists of lot of construction materials, different climate zones and variant operation schedules. In this section a brief description of the geometry is given.

![Figure 6.28: The model in Design Builder (front and back façade)](image-url)
Figure 6.29: The rendered model in Design Builder

Figure 6.30: The zones of the model
Figure 6.31: The elements in each zone
Figure 6.32: The construction materials and the openings of each of the zone
The arrows in the following figure indicates the zones of openings for natural ventilation. The area of these openings have been determined after the natural ventilation rate calculations (see next section).

Figure 6.33: External Vents at the bottom and at the top of the glasshouse zone
The openings in the back façade of the building can be seen in the figure 6.34. The size and the pattern of the windows is based on the traditional brickwork facades in Amsterdam. The dimensions of the window is 2mX1m, while the glazing area that can be opened has been set to 10%, based on the desired ventilation rate.

Figure 6.34: The rendered view of the back façade of the building in Design Builder
Adjacency

The building is in both sides adjacent to the neighbor buildings (same or higher height). It is considered, thus, that the heat is not transferred across in these walls. The adjacency of these two walls is set to **Adiabatic**. In Design Builder software, adiabatic surfaces are frequently used in thermal modeling to represent surfaces which are between two zones at substantially similar conditions. They are often used, therefore, for modeling the boundary between the actual building model and any adjacent buildings which are not to be modeled. Another way would be to draw component blocks as the neighbor buildings. For the present research, it was chosen the first way.

For both of the facades and the other construction elements (floors, ceilings etc.) the adjacency is set to **Auto**. This means that the adjacency of the surface is determined automatically by the software based on its position. The ground floor and all the side walls in the basement are set to **Adjacent to Ground**.

Airtightness

For the scheduled natural ventilation the airtightness is set as **0.5ac/h constant rate**, while when the calculated natural ventilation is active, the airtightness is defined by the chosen crack template. In the present design, it is opted the medium template, since the existing concrete building is dated some years ago.

![Crack template](image)

*Figure 6.35: The chosen crack template for the calculated natural ventilation*

Schedules

The schedules for all the countries are the same, since such a luxury brand of shopping stores follows the same regulations. Moreover, in that way, the comparison of the thermal performance of the building would be easier and more unbiased. All the schedules input in the software can be found in the Appendix D.
Construction Materials

All the construction and glazing materials that have been used in the model are given in tables analytically in the Appendix D. The properties of all the glazing used in the design can be seen in the following table.

<table>
<thead>
<tr>
<th>glass element</th>
<th>outer pane</th>
<th>cavity / mid pane</th>
<th>inner pane</th>
<th>Fritting</th>
<th>SHGC/Total Solar Transmission</th>
<th>Direct solar Transmission</th>
<th>Light Transmission</th>
<th>U-value (W·m⁻²K)</th>
<th>Shading</th>
</tr>
</thead>
<tbody>
<tr>
<td>glass roof pane</td>
<td>Pilkington Optifloat 16mm</td>
<td>Argon 16mm</td>
<td>Pilkington Optifloat 16mm</td>
<td>90%</td>
<td>0.569</td>
<td>0.428</td>
<td>0.693</td>
<td>1.065</td>
<td>-</td>
</tr>
<tr>
<td>windows in the façade</td>
<td>Pilkington Optifloat 16mm</td>
<td>Argon 16mm</td>
<td>Pilkington Optifloat 16mm</td>
<td>-</td>
<td>0.569</td>
<td>0.428</td>
<td>0.693</td>
<td>1.065</td>
<td>inside blinds with high reflectivity slats</td>
</tr>
<tr>
<td>glass pane in louvres</td>
<td>Pilkington Optifloat 6mm</td>
<td>Pilkington Optifloat 6mm</td>
<td>Pilkington Optifloat 6mm</td>
<td>90%</td>
<td>0.636</td>
<td>0.519</td>
<td>0.702</td>
<td>5.286</td>
<td>-</td>
</tr>
<tr>
<td>glass floor</td>
<td>Generic Clear 4mm</td>
<td>Pilkington Optifloat 12.7mm</td>
<td>Pilkington Optifloat 12.7mm</td>
<td>anti-slip texture</td>
<td>0.438</td>
<td>0.305</td>
<td>0.565</td>
<td>2.86</td>
<td>anti-slip texture</td>
</tr>
<tr>
<td>glass bricks in the façade</td>
<td>float glass 210mm</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.475</td>
<td>0.313</td>
<td>0.483</td>
<td>1.354</td>
<td>-</td>
</tr>
</tbody>
</table>

*Table 6.6: Properties of the glazing as calculated by Design Builder software*
Natural ventilation rate

The shape and the design of the building helps in the utilization of stack and cross ventilation effect. The big height difference between the air inlet at the bottom of the glass brick façade and the air outlet at the top of the glass floor (equal to 20 m) enhances the efficiency of the thermal-driven air flow.

The ventilation rate is equal to \( n = \frac{Q}{V} \)

Where \( Q \) is the amount of air in \( m^3/h \) and \( V \) represents the volume of the whole building, since the air occupies the existing building as well, due to the windows at the back façade that activate the cross ventilation.

It can be deducted from the formula \( Q = C_p * A * \sqrt{\frac{2 \Delta P}{\rho}} \), where \( \Delta P \) is the pressure difference between the air inlet and outlet. It is calculated from the formula \( \Delta P = g * h * \frac{P_R}{R} * \left( \frac{1}{T_{out}} - \frac{1}{T_{in}} \right) \)

The following values are applied to the calculations:

- \( C_p = 0.6 \)
- \( g = 9.81 \text{ m/s}^2 \)
- \( R = 287 \text{ J/kg*K} \)
- \( h = 20 \text{ m (differences in height between the two openings (in the glasshouse)}) \)
- \( A = 2 * 4.8 \text{ m}^2 = 9.6 \text{ m}^2 \) (total surface of the openings (first estimation))
- \( V = 20 * 20 * 20 = 8000 \text{ m}^3 \)
- \( h_1 = -2 \text{ m (altitude above sea level for Amsterdam)} \)

The air pressure above sea level is \( P = 101325 * (1 - 2.25577 * 10^{-5} * h_1)^{5.25588} = 101349 \text{ Pa} \)

Earth duct

Earth duct is an innovative and sustainable way to supply fresh air to a building making use of the thermal mass of the soil. The expected energy savings over conventional air-conditioning systems are quite considerable. If a typical fan-coil air-conditioning system can consume about 225kWh/m² a year for heating, ventilating and mechanical cooling for a specific project, it is believed that the earth duct approach could bring the energy down to 45kWh/m² annually. And if phase two is fitted with thermal wheels, energy consumption could perhaps drop to 28kWh/m².

Despite the fact that earth ducts are not common found in shopping stores, in order to achieve a more sustainable design and to enhance the natural ventilation function in the present design, an earth duct can be used that controls the temperature range of the incoming air through the air ducts at the bottom of the glass brick façade. Earth duct can be buried about a meter underground and bring the ventilation air into contact with the thermal mass of the earth. The best material of the duct for this purpose is prefabricated concrete pipe which provide excellent thermal mass in themselves and are non-corroding while can be sealed against water ingress using proprietary gaskets. The supply air is injected into the
building and the design air volumes range from about 1.0 air changes per hour in winter to about 4 in peak summer conditions (see the calculations).

Some of the general criteria to design an earth tube are (Building Sustainable Design):

- At a soil depth of 2m, the ground temperature is stable at about 13°C throughout the year
- Air drawn through large ducts (of 600-700mm diameter) at a low velocity (below 2m/s) is optimal for heat transfer
- The earth tubes need to be about 100m long for significant heat transfer to occur
- Creating and maintaining turbulent airflow along the duct length can increase heat transfer by between 3-8°C for an incoming air temperature range of -1°C to 5°C (and the earth tubes could be made shorter)
- Ribbed-steel drainage ducts offer a high surface area, but sealing against water ingress may be difficult
- The porous nature of a concrete drain section could help to control the humidity of the supply air, and sealing may also be easier

There are lot of research on simulating the earth duct model based on the heat transfer balance, taking into account changes in the soil temperature, physical properties of the soil, tube material and fluid nature and time. However, the accurate modelling of the earth tube is beyond the scope of this work. Thus, it was assumed that, according to (Pen, 2008), the outlet temperature of the earth tube is 4°C less than the outdoor air temperature during summer and 2°C more during winter.

It has been chosen the two most extreme cases for the climate of Netherlands regarding the temperature difference. So, a really warm day during the summer can reach the 28°C (because few days have temperatures higher than this value according to the weather data for Amsterdam) and a really cold day during the winter can reach the -4°C (because few days and hours during the occupied period have temperatures lower than this value according to the weather data for Amsterdam).

If no other cooling device will be utilized, then the air temperature in the glass roof can reach the 40°C. Therefore, a mixed mode ventilation has been used in order to reach the thermal comfort values. The
reason earth duct is used, is to minimize the capacity of the mechanical support. Having this mechanical support, the air temperature at the glass roof reaches the 30°C.

<table>
<thead>
<tr>
<th></th>
<th>$T_{\text{air, outside}}$</th>
<th>$T_{\text{air, indoor}}$</th>
<th>$T_{\text{air, inlet}}$</th>
<th>$T_{\text{air, outlet}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Summer</strong></td>
<td>28°C</td>
<td>28°C</td>
<td>24°C</td>
<td>30°C</td>
</tr>
<tr>
<td><strong>Winter</strong></td>
<td>-4°C</td>
<td>18°C</td>
<td>-2°C</td>
<td>18°C</td>
</tr>
</tbody>
</table>

Table 6.7: The inlet and outlet temperatures of the earth duct

During the summer:

\[
\Delta P = g \cdot h \cdot \frac{P}{R} \cdot \left( \frac{1}{T_{\text{out}}} - \frac{1}{T_{\text{in}}} \right) = 9.81 \cdot 20 \cdot \frac{101349}{287} \cdot \left( \frac{1}{(30+273)} - \frac{1}{(24+273)} \right) = -4.6 \text{ Pa}
\]

\[
Q_{\text{summer}} = C_P \cdot A \cdot \sqrt{\frac{2 \Delta P}{\rho}} = 0.6 \cdot 9.6 \cdot \sqrt{\frac{2 \cdot 4.6}{1.2}} \cdot 3600 = 57415 \text{ m}^3/\text{h}
\]

\[
n_{\text{summer}} = \frac{57415}{8000} = 7.18 \text{ h}^{-1} = n_{\text{max}}
\]

During the winter:

\[
\Delta P = g \cdot h \cdot \frac{P}{R} \cdot \left( \frac{1}{T_{\text{out}}} - \frac{1}{T_{\text{in}}} \right) = 9.81 \cdot 20 \cdot \frac{101349}{287} \cdot \left( \frac{1}{(-2+273)} - \frac{1}{(18+273)} \right) = 17.57 \text{ Pa}
\]

\[
Q_{\text{summer}} = C_P \cdot A \cdot \sqrt{\frac{2 \Delta P}{\rho}} = 0.6 \cdot 9.6 \cdot \sqrt{\frac{2 \cdot 17.57}{1.2}} \cdot 3600 = 112211 \text{ m}^3/\text{h}
\]

\[
n_{\text{winter}} = \frac{112211}{8000} = 14 \text{ h}^{-1} = n_{\text{max}}
\]

These rates are the maximum that can be achieved given the opening surface. Yet, the airflow speed should not be more than 0.5m/sec, because otherwise drafts will produce discomfort to the occupants. The minimum required ventilation rate is based on the maximum human occupancy inside the building. The human occupancy in the building is set to 0.1 people/m$^2$. It was selected this value, since in luxuries brands shopping stores it is not common to be overcrowded like in shopping malls or less expensive brands. Hence, the maximum number of people in the building is 0.1 people/m$^2$ * 1688m$^2$ (the gross internal area) = 168.8 ≈ 170 people. So, the total airflow rate is equal to 170 people * 35m$^3$/h = 5950 m$^3$/h.

The minimum ventilation rate demanded is $n_{\text{min}} = \frac{5950}{8000} = 0.74 \text{ h}^{-1}$

\[0.74 < n < 14 \text{ (h$^{-1}$)}\]

The ventilation rate can be adjusted, between the above values, depending on the outdoor and indoor conditions. For example, during the summer a higher ventilation rate, equal to 4 h$^{-1}$ would increase the comfort level inside the building due to the breeze feeling. On the other hand, during a cold day in the winter, the rate can be limited to the minimum required 0.74 h$^{-1}$. This adjustment on the rate is
feasible by regulating the tube’s outlet and the openings according to weather conditions and number of people so as to adjust the rate throughout the year. Yet, when the air temperature is really low outside the ventilation is achieved only by the mechanical equipment.

The maximum required size of the opening is calculated, when the pressure difference between the air inlet and outlet is the minimum. Assuming a minimum temperature difference equal to 1°C (T_{air, inlet} = 25°C and T_{air, indoor} = 26°C), the pressure difference is ΔP = -0.78 Pa.

The openings minimum total surface for increasing the comfort during the peak hot days in the summer is calculated as follows:

\[ n = 4 \text{ h}^{-1} \rightarrow Q = n \times V = 4 \times 8000 = 32000 \frac{m^3}{h} = 8.89 \frac{m^3}{sec} \]

\[ A = \frac{n \times V}{0.6 \times 3600} \times \sqrt{\frac{1.2}{2 \times \Delta P}} = \frac{4 \times 8000}{0.6 \times 3600} \times \sqrt{\frac{1.2}{2 \times 0.78}} = 13 m^2 \]

\[ \frac{1}{A_{eff}^2} = \frac{1}{A_{inlet}^2} + \frac{1}{A_{outlet}^2} \Rightarrow \frac{1}{13^2} = \frac{2}{A^2} \Rightarrow A = 18.38 m^2 \Rightarrow A_{inlet} = A_{outlet} = 18.38 m^2 \]

This is the maximum area of the earth duct (A_{inlet}) and the total area of the louvres in the glass roof and the windows in the back façade that can be opened (A_{outlet}). In each floor the maximum number of people differs, since each floor has different gross area. Assuming, however, the maximum floor area in the ground floor A = 400m² and the maximum human occupancy in this floor people = 0.1 *400 = 40 people, \( Q = 40 \times 35=1400 m^3/h \times 0.39 m^2/sec \). Thus, the total opening area of the windows in the back façade in the ground floor is A_{min} = 0.39/0.3=1.2m² (u=0.3m/sec so there is no draft problem). The number of the windows in each floor is 6 and the area of each of the windows is A_{window} = 2*1=2m². Hence, each of the window opens maximum 10%.

The area of the opening in the louvres at the top of the glass roof can be calculated as follows:

\[ A_{louvres, outlet} = 18.38 m^2 - 1.2 \times 5 = 12.38 m^2 \sim 12.4 m^2 \]

The height of the glass louvres is 0.80m, thus the length of the openable area is 12.4/0.8 =15.5m
Figure 6.37: Stack effect and cross ventilation (the directions and the “gradient” of the arrows have been guided by the CFD calculations)

The schedule of the natural ventilation that is input in the software for the simulations can be seen in the table 6.8. These rates are more than enough to cover the occupancy demands and to offer better thermal comfort during the warm days of summer.

<table>
<thead>
<tr>
<th>Schedule</th>
<th>7:00</th>
<th>8:00</th>
<th>9:00</th>
<th>12:00</th>
<th>14:00</th>
<th>17:00</th>
<th>18:00</th>
<th>19:00</th>
<th>0:00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>1</td>
<td>1.5</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td>Winter</td>
<td>0</td>
<td>0.5</td>
<td>1</td>
<td>1.5</td>
<td>2</td>
<td>1.5</td>
<td>1</td>
<td>0.5</td>
<td>0</td>
</tr>
</tbody>
</table>

*Table 6.8: Ventilation scheme according to the opening hours of the shop. In the winter during the non-occupancy hours, the openings are closed and sealed so the solar gain is kept in the interior*
Figure 6.38: The compact schedule of the natural ventilation (Design Builder)
To realize the effect of the interventions in the physics of the building, the simulation of a model with conventional clay brick façade has been utilized keeping the rest of the criteria and materials the same. The comparisons in the interior temperatures during summer and winter when applying only passive measures (natural ventilation, shading, low-e coatings and fritted glass), as well as the heating and cooling loads can be seen in the figures 6.40-6.44.
Figure 6.40: The conventional clay brick façade (left) and the glass brick façade (right) (Design Builder)

Figure 6.41: Comparisons of the average interior temperatures at 15 July without applying any mechanical system for the two designs
From the above figures it is entailed that replacing the clay brick façade with glass brick façade the interior temperature is getting higher throughout the year. While for the winter, this is a big advantage since it reduces the heating load (as it can be seen in the figure 6.43), for the summer it causes overheating problems which leads to high cooling demands (figure 6.44). The biggest impact of this change is for the summer days, since it presents higher difference in the interior temperature (6°C higher), whilst for the winter is only 2°C higher. This is reasonable, since glass bricks absorb the solar radiation much more than the clay bricks.
The total heating load of the building with the conventional brick façade is 530 kW, while for the renovated building with the glass brick façade is 310 kW. The difference is quite big (220 kW), giving a 41% reduction of the energy consumed for heating the building.

On the other hand, since the interior temperature, after this renovation, are getting higher, the cooling demand in the summer presents an increase of 31%. As a conclusion, such an intervention in a building can offer lot of advantages during the winter, such as increasing the heat loads and the natural light that can come in. However, it can cause lot overheating especially in warm climates where the outdoor temperatures and the solar gain is really high.

The results of the simulations, that are followed, show a variety of temperatures between the zones (floors) and especially between the ground floor where the air inlet is and at the top of the glass roof where the warm air is going out through the louvres. The difference between the zones in the existing concrete building and the zones in the added glass part (glasshouse zones) is explained also due to the different comfort range that has been set and input in the software (see previous section). For brevity reasons, though, it will be presented the average thermal conditions of the whole building and the thermal conditions at the glasshouse 5 (glass roof) only.
Thermal simulation without utilizing any passive or active system

In order to assess the effect of the application of the passive measures that have been described in the previous section, the results of the simulation of the building without applying any active or passive measures are presented in the figure 6.45.

The range of the temperatures through the whole year is close to the desired temperature range during the non-occupancy hours. The maximum operative temperature reaches 35°C few hours per year, whilst the minimum operative barely falls below 15°C. That means that the design does not need extra energy consumed for retaining the required climate conditions in the interior during the hours that the store is closed, even when the temperature outside drops below zero or reaches 33°C.

The maximum operative temperature in the glasshouse reaches 48°C, few hours during the hottest days of the summer (when it is 33°C outside). As the graph in figure 6.46 depicts, for most of the hours during the year the temperature in the area behind the façade ranges in high values (30°C-48°C). Accordingly, the temperature in the area behind the façade for every floor presents higher values than the temperature in the respective floors. Therefore, cold air driven from the bottom to the top of the façade (stack effect) can mitigate this overheating.

The temperature distribution for all the hours though a year in the zone of the third floor can be seen in the two figures 6.47.
Figure 6.47: Temperature distribution for the third floor shows the number of hours at or below the 22°C limit (blue color) and the number of hours at or above the 26°C limit (red color)

It seems that the cooling demand is higher than the heating in order to preserve the interior temperatures according to the desired thermal comfort conditions.

**Thermal simulation by the sole utilization of passive systems**

The maximum operative temperature in the building reaches 34°C few days during the summer. From the figure 6.43 it can be seen that through the exclusive use of passive systems the temperature never falls below 15°C, which is the lowest limit of the temperature for the interior during the non-occupancy hours, even when the temperature outside drops to -6°C. Moreover, it rarely exceeds the upper limit of the non-occupancy hours (33°C). Consequently, there is no imperative need of the application of mechanical systems to keep the range of the desired temperatures when the store is closed. The graph in figure 6.48 demonstrates the operative temperature (green color) in hourly intervals throughout the year. The lighter zones define the temperature range for the non-occupancy hours.

Figure 6.48: Annual graph of the operative temperature (green color) inside the building in hourly intervals

As it was expected the radiant temperature in the glasshouse 5 is higher than in the rest of the building and it reaches even the 50°C few hours during the warm days in the summer. However, the operative temperature exceeds the 40°C only few hours throughout the whole year. As the lighter zones indicate in the figure 6.49, there is only need for cooling the space (and not the entire building) for few hours when the store is closed, so the temperature will not exceed the 33°C.
In the figure 6.50 the drops of the temperatures due to the application of the passive measures at a summer day for different spaces in the building can be seen. The decrease varies between 3°C and 8°C, with the biggest difference in the glasshouses zones, where the stack ventilation occurs.

From the simulation of the weather file, it is deducted that the building’s interior is always warmer or has the same temperature with the exterior space. Furthermore, from the above figures, it can be clearly seen that there is no big fluctuation of the operative temperature throughout the whole year. This indicates that the schedule and the operation as well as the airflow rate of the natural ventilation work with the most optimum way for this design and for this weather data.

This fact is confirmed as well through the CFD simulation after importing the climate data from the hourly simulation of the 15th of July (hottest day in the summer) as CFD boundary conditions. The results about the velocity of the air and the temperature distribution in the interior can be seen in the figures 6.51-6.56.
Figure 6.51: Temperature contour of 15\textsuperscript{th} of July by the sole utilization of passive measures

Figure 6.52: Air velocity at the glass roof, the warm air comes out from the louvres
Figure 6.53: The arrows illustrates the movement of the air, the size of the arrows the magnitude of the velocity of the air

Figure 6.54: View of the temperatures and air from the front facade
Figure 6.55: The turbulence of the air in the main shaft. The velocity is below 0.2m/sec, so there is no inconvenience to the occupants that use the staircase or the elevator.

Figure 6.56: The high velocity at the two sides of the façade illustrates the cold draft phenomenon.
In winter, such a large glazed façade is often the cause of thermal discomfort, partly due to cold radiation effects and partly due to downdraft problems caused by cold natural convective flows along the surface. For this facade, the most critical problem is downdraft, as the CFD simulation indicates (figure 6.56). In the occupied zone the air velocity should not exceed 0.2m/s. In the middle the glass floors are not allowed this phenomena to happen, but in the atria the velocity of the air is more than 0.5 m/s² which cause discomfort for the people that stands close to the façade. It has to be mentioned though, that this problem can be only faced by the staff and only when they change the vitrine. However, this high velocity of the air can be enough to cause movement of the fabrics in the dolls in the vitrine.

Therefore solution to this problem should be investigated which not affect neither the transparency of the façade nor the energy balance in the building. An effective and not energy consumed solution can be to use the structural system of the glazed façade as an obstacle on the cold boundary layer flow. Depending on the width of the obstacle, different flow conditions can be expected to occur as it can be seen in figure 6.57. When the width of the obstacle is smaller than a critical width, the boundary layer flow reattaches to the surface after it has passed the obstacle. The velocity will, however, be reduced; therefore, smaller velocities and an improvement in the thermal comfort can be expected in the occupied zone compared with the situation with a plane surface. When the width of the obstacle is larger than a critical width, the boundary layer flow will separate from the surface after it has passed the obstacle and a new boundary layer flow will be established below the obstacle. The separated airflow will flow into the room probably acting like a cold air jet. In this way, a highly glazed facade can be expected to act as a combination of small individual parts on top of each other. The top parts supply cold air to the room above the occupied zone and the risk of downdraft in the occupied zone is only determined by the flow conditions at the lowest part of the facade.

![Figure 6.57: Principle of flow conditions at a cold vertical wall with different sizes of obstacles (Heiselberg, 1996)](image_url)
Since the main principle that is followed during the whole design process is transparency, the obstacles that are used to prevent this draft are made of glass elements. The length of the atria in each of the side is 4m and the width of the glass pane should range between 0.30m and 0.50m. For safety reasons, it is chosen two glass panes 2m X 0.50m each. The reason of choosing two panes instead of one is the effect of the condensation behind the glass surface of the façade. Because of the condensation of the façade, the water could be gathered on the glass panes and with the high velocity of the air, drops can be dispensed at the area of the vitrine and ruin the garments of the dolls.

To prevent this, each of the glass pane has a slight diagonally inclination at the outer side (2%), so the water is gathered at the floor without destroying any of the products in the vitrine (figure 6.59).

Figure 6.58: Impression of the glass structure for protection of the vitrine from the cold draft behind the façade

Figure 6.59: Impression of the glass structure for protection of the vitrine from the cold draft behind the façade (the blue lines indicates the water path)
The supporting structure consists of three hollow triangular glass elements, which in the vertical direction are glued in the glass brick façade and in horizontal direction is glued with the glass pane along the whole width. The cross section is square 12cmX12cm. This structure is placed 0.4m below the first floor level, so the distracted air will not cause air cold draft at the level of feet in the first floor. That way the air level is led to the top below the ceiling.

The glass panes are heat strengthened laminated with Sentryglass foil 1.52mm. The thickness of each pane is 4mm, which is enough to withstand the air pressure at that point, as the calculation demonstrates. The structural calculation can be found in the chapter of Detailing.

Figure 6.60: Glass panes for preventing the draft behind the façade

The temperature distribution for all the hours though a year in the zone of the third floor can be seen in the two figures 6.61.

Figure 6.61: Temperature distribution for the third floor shows the number of hours at or below the 22°C limit (blue color) and the number of hours at or above the 26°C limit (red color)

After applying the passive systems, the overheating problem has been reduced dramatically (58%). Only 568 hours through the whole year presents 26°C or higher temperature, with some of them occurring at the non-occupancy hours. Moreover, due to the earth duct utilization which controls the temperature of the inlet air using the thermal storage of the soil, the hours below 22°C have been decreased as well (32%).
The temperatures of the inside surface of the glass bricks in the façade in the glasshouse 1 and 4, and the temperatures of the inside surface of the windows in the conventional façade at the third and fourth floor, as well as the heat gains from these glazing can be seen in the following figures.

It can be seen that the temperature of the inside surface of the glass brick can reach the 60°C when applying the passive measures, while the respectively temperature of the back window barely reaches the 40°C.
However, the desired comfort level for the hours when the shopping store is open, has not yet been achieved. The lighter zones in the figure 6.63 depicts the part that mechanical heating and cooling support is needed.

Figure 6.62: Surface temperatures of the glazing and heat gains in the glasshouses zones and 4th and 3rd floor

Figure 6.63: Annual graph of the operative temperature (green color) inside the glasshouses in hourly intervals
Supplementary Mechanical Unit

There are a lot of the options offered in the market about the mechanical unit used in shopping stores for heating, cooling and air condition. Normally when the required amount and quality of air is achieved completely through the natural ventilation (temperatures controlled by earth duct), the best option for cooling and heating the building is by radiation using climate ceiling through a closed water pipes circuit system. However, since it is more common in such a big and luxury shopping store to have mechanical ventilation either as a backup when the outdoor temperatures are extreme (below 0°C, or above 40°C) or as a mixed ventilation, induction units or fan coil units in the ceiling are preferred. Induction units have less capacity compared to the fan coil units, but the advantage of the former over the latter is that it does not produce noise and it is more suitable for installations in the interior of a shopping store.

For this design, a combination of a heat pump supplying active chilled beams through a closed water circuit was opted as the best proposal. This system is based on a remote unit of heat pump (approximately 2.5 meters by 3.5 meters) that provides heating and cooling through water pipes. For a more sustainable design, ground-source heat pump has been utilized for all the three locations. Ground-source heat pumps or geothermal heat pumps (GHPs) use the constant temperature of the earth as the exchange medium instead of the outside air temperature. This allows the system to reach fairly high efficiencies (300% to 600%) on the coldest winter nights, compared to 175% to 250% for air-source heat pumps on cool days (energy.gov). Depending on latitude, ground temperatures range from 7°C to 21°C. Like a cave, this ground temperature is warmer than the air above it during the winter and cooler than the air in the summer. The GHP takes advantage of this by exchanging heat with the earth through a ground heat exchanger. There are four basic types of ground loop systems. Three of these, horizontal, vertical, and pond/lake, are closed-loop systems. The fourth type of system is the open-loop option. Which one of these is best depends on the climate, soil conditions, available land, and local installation costs at the site. All of these approaches can be used for the shopping store.
The choice of using the same system for all the three locations is to have a better comparison in the simulations results based on the different climates and not in the different mechanical systems.

The chilled beams are mounted flush into the ceiling and they are able to ventilate rooms with large thermal loads without creating draughts. Flush ceiling installation is an aerodynamic necessity for certain types of discharge. The horizontal air flow requires the ceiling to maintain the horizontal direction so that it does not just “fall” into the occupied zone with a correspondingly low temperature in the direct vicinity of the active chilled beam. This can lead to draught problems in the occupied zone. Active chilled beams supply fresh air to the space from a central plant room to maintain indoor air quality whilst providing cooling and heating using heat exchangers. The fresh air is discharged into the beam mixing chamber via
nozzles. As a result of this secondary air is induced via an inlet grille and then passes through heat exchangers into the mixing chamber. Then, it is mixed with the fresh air and the total supply air is discharged horizontally into the space through integral slot diffusers.

The horizontal discharge into the space results in a “mixed flow” air distribution. The slot diffuser discharge velocity is selected such that the supply air penetrates into the occupied zone to maintain the air quality in the space without creating draughts. Due to induction of room air into the supply air stream in the space, the temperature differential in the air stream reduces and its velocity decreases. In the occupied zone the air velocity should not exceed 0.2m/sec. This will be assured after the CFD simulation with boundary conditions these devices (suppliers and diffusers). The number and the size of the modules will be determined through the calculation of the heating and cooling demand of the building which will be defined later through simulation in Design Builder.
There is no need to take any special action to supply the air since the ceiling height is up to 3.8m, so the air can reach the occupied zone.

The chilled beams can be arranged parallel or perpendicular to the façade. The layout has considerable influence on the horizontal air discharge in the space and should be taken into account at the early design stage.

**Figure 6.67: Ceiling arrangement of the chilled beams (TROX TECHNIK design manual)**

Parallel to the façade

The air discharges towards the façades, since no internal walls exists, apart from the 5th floor where the offices are separated from the rest of the space with glass partitions. The discharge towards the façade brings thermal advantages. On the one hand the window surface is kept at a moderate temperature, on the other the air velocity and its temperature difference reduce outside the occupied zone. Any infiltration through the façade is mainly dealt with by the supply air stream thus reducing the risk of draught and condensate forming at the heat exchanger. An active chilled beam for each module allows a room division with high degree of flexibility during initial use and layout changes in the future.

Perpendicular to the façade

The perpendicular arrangement possibly leads to a reduced number of active chilled beams and thus lower costs. The effects on the horizontal air discharge, the air distribution across the modules, and the resulting flexibility, however, need to be considered. If the length of the active chilled beams is related to the room depth, a better horizontal air discharge can be achieved. On the basis of the air flow rates and thermal performance one active chilled beam suffices for three to five modules. However, flexibility is reduced. An active chilled beam for each module results in an insufficient ventilation of the space. The distance between two beams is less than the minimum recommended, resulting in too high an air velocity entering the occupied zone. In practice, one beam should supply at least two modules. The air movement in the space runs parallel to the façade. Infiltration may come into the space perpendicular to the face of the glazing and cause draughts in this area and condensate forming at the heat exchanger.
After considering all the above, the modules will be placed parallel to the façade in order to deal with the draught and the condensation problem and to give flexibility in future redesign.

The ventilation is set in change-over mode (Same space, different times). So the building “changes-over” between natural ventilation and air-conditioning on a seasonal or even daily basis. The building automation system may determine the mode of operating based on outdoor temperature, an occupancy sensor, a window (open or closed) sensor, or based on operator commands. The louvers at the top of the façade can open automatically to provide natural ventilation when the HVAC system is in economizer mode and then close when the system is in cooling or heating mode. Following the same principle, the windows are opened and closed when needed.

Size of the mechanical unit

As a result, the power demand that should be supplemented by the mechanical unit reaches a maximum of 180 kW for heating and 270 kW for cooling. The heat pump unit is calculated with the coefficient of performance equal to CoP=2.5. Thus, a mechanical unit equal to 270/2.5 = 108 Kw. However, since only 0.2% of the total hours around the year the cooling demand exceeds the 250kW, a heat pump of 100kW input power would ensure the maintenance of the temperature inside the building between the limits that has been set in previous section.

In order to design the mechanical plan with the configuration of the chilled beams in each floor, some design principles should be taken into account such as the distances between each of the modules and between the internal or external walls. In order to cover 270kW for the peak hours of the year, a module type DID300B by TROX TECHNIC with the maximum cooling capacity (1800W).
Figure 6.69: Type of chilled beam used for heating/cooling/ventilation

The plan of the second floor with the distribution of the chilled beams can be seen in the figure 6.70. The red line represents the hot water pipe, the blue line the cold water pipe and the grey the air duct.
Finally, what reflects the performance of the passive systems is the total amount of hours that demand supplementary cooling or heating. The output data of the simulation of the annual weather file suggest that in total 1422 hours per year (16.22%) demand supplementary cooling and 859 hours per (9.8%) supplementary heating. These estimations were made by exporting the fuel breakdown file into Excel, in order to obtain the total hours that the mechanical system should operate for cooling and heating. The sum of the hours per year with fuel consumption above 0 were calculated.
Some alternatives in the design that could improve the thermal performance are presented below. Application of glass partitions in 1.80m below the façade, so it would work as a double skin facade

The partitions are in each floor, apart from the ground floor, since clients when entry the building should face an open place rather than a glass big surface. There are two alternatives in the configuration of the glass partitions (figures 6.72, 6.73). In the first one (figure 6.72) the glass partitions are for all the floors at the same distance behind the façade, so extra structural calculations are needed, while in the second configuration (figure 6.73), the partitions are different for each floor and they separate the room from the atrium. The last is different to implement it because of the irregularity of the floors. Moreover, applying with this arrangement the glass partitions it will have as a result to block the air exchange between the floors, hindering both the stack and cross ventilation. Therefore, the first arrangement was chosen for this design.
Figure 6.72: Plan of the second floor. The red line depicts the location of the glass partitions. (*Configuration 1*)

Figure 6.73: Plan of the second floor. The red line depicts the location of the glass partitions. (*Configuration 2*)
The function of the glass partitions would be to block the large solar gains from the façade to enter the rest of the building, reducing the energy needed. On the other hand, this would block as well the air driven by the cross ventilation for each floor, increasing the ventilation and cooling demand in the existing part of the building. The balance between reducing and increasing the cooling demand and in general the effect of this intervention can be seen in the following figures after simulating the new model.

![Graph](image1)

*Figure 6.74: Annual graph of the operative temperature (green color) inside the building in hourly intervals. The lighter zones indicates the area of the graph where active cooling and heating are demanded for retaining the temperature between 15°C-33°C during the non-occupancy hours.*

![Graph](image2)

*Figure 6.75: Annual graph of the operative temperature (green color) inside the building in hourly intervals. The lighter zones indicates the area of the graph where active cooling and heating are demanded for retaining the temperature between 22°C-26°C during the occupancy hours.*

From the graphs above, and comparing them with the figures 6.43-6.44, the temperatures seem to have been decreased, especially during the winter. The drop is quite significant and ranges between 1°C-8°C. During the winter, the temperatures are stabilized between 15°C and 20°C (5°C less than before without the glass partitions). This can be explained from the fact that the glass partitions block all the solar heat gained from the façade. Although this is a disadvantage for the winter months, it works advantageously for the summer months. Most of the temperatures during the summer are below 26 °C, decreasing significantly the cooling demand.
Figure 6.75: Annual graph of the operative temperature (green color) inside the glasshouse in hourly intervals. The lighter zones indicate the area of the graph where active cooling and heating are demanded for retaining the temperature between $22^\circ C - 26^\circ C$ during the occupancy hours.

As it was expected, the temperature range in the “glasshouse” zones gets wider, since the glass partitions form an area that functions as the space in the double skin facades. Thus, high temperatures will be occurred during summer days and low during winter. The difference with the previous result before the partitions is approximately 5°C lower for the winter and 28°C higher for the summer!!

Some of the CFD calculations can be seen in the following figures. The airflow is different due to the glass partitions “obstacles” that lead the air directly to the glass roof and it is not distributed in the rest of the floors. The air that goes through the atrium behind the partitions comes from the windows in the back façade.
The 10% operable part of the windows in the facade - in the first floor finish air comes in. The velocity of the air is below 0.5 m/s, so it does not cause problems to the occupants.

The air coming through the louvre system:

The air comes out from the lovere system in the roof:
The surface temperatures as well as the heat gains for some of the zones in the glasshouse can be seen in the following figures. It can be clearly seen that temperatures are getting higher at the top and lower at the bottom of the façade.
The benefits but also the drawbacks of this intervention can be seen in the total hours that mechanical cooling and heating is needed.

The hours that cooling is needed has been reduced 66%! While the hours that heating is needed has been increased 237%! (Compared to the temperature distribution of the same zone (3rd floor) when only passive measures utilized in the building without the glass partitions).

From all the above, it is concluded, that this system can work beneficially throughout the year only if the partitions are operable and adjustable to the weather conditions. So, during the summer, the partitions will be closed forming double skin façade and blocking the solar gains, while during the winter, they will be open letting the solar radiation comes into the building.
Application of fritted glass bricks at the 1/3 top of the facade

One measure that could reduce significantly the solar gains and as a consequence the cooling demand, is to frit the outside surface of the glass bricks. Since this would ruin the aesthetical part of the design (full transparency is the main principle), fritted bricks would be applied only at the top of the façade where there is the most of the solar gain and it will not be visible from the ground level. Furthermore, a low-E coating can be placed on top of the frit in order to reduce long-wave radiative heat gains. Such a process in the glass brick manufacturing has not been realized before, so this measure is for further investigation and represents mostly a suggestion in future production of fritted glass bricks modules.

Figure 6.79: Fritted glass bricks at the 1/3 of the facade at the top
The difference in the annual temperatures is significant. The radiant drops 10°C compared to the simulation with the façade without fritted glass bricks. For the winter, there is no big difference, stabilizing the range between the desired values.

Both the glass partitions and the fritted glass bricks in the façade offers remarkable benefits in warmer climates with really hot summers.
Hollow glass bricks instead of solid glass bricks in the façade

As it has been described in the “Glass Technology Analysis” chapter, the glass bricks can be hollow which offer different characteristics in the structural and thermal performance of the building. Since the air in the gap in the hollow bricks has lower thermal conductivity ($\lambda=0.03 \text{ W/(m*K)}$) than the soda lime glass ($\lambda=0.7 \text{ W/(m*K)}$), the total U-value of the wall will be less ($U_{\text{hollow}} = 1.167 \text{ W/(m}^2\text{K)}$ and $U_{\text{solid}} = 1.354 \text{ W/(m}^2\text{K)}$) resulting in better thermal insulation for the interior of the building. Therefore, it was considered wise to study the thermal performance of the building for this case as well.

Figure 6.82: Solid glass brick used in the original project (left), hollow glass brick used for the following thermal simulations (right)

Figure 6.83: Annual graph of the operative temperature (green color) inside the building in hourly intervals.

Figure 6.84: Annual graph of the operative temperature (green color) inside the glasshouse 5 in hourly intervals.
From the graphs above, and comparing them with the figures 6.43-6.44, the temperatures seem to have not been changed a lot. However, the inside temperatures of the glass bricks in the façade have been decreased, as it can be seen in the following figures.
This decrease in the surface temperatures can be beneficial because it minimizes the thermal expansion of the wall and the possibility of the thermal shocks in case of sudden rain (see the last section of this chapter with the experimental tests).

Moreover, comparing the above graphs with the graphs in the figures 6.62 it can be noticed that although the surface temperatures have been decreased, the heat gain from the solar transmission has been increased. This can be explained from the fact that a solid massive glass brick has lower total solar transmission (SHGC) than a glass brick with air cavity. Specifically, the values of the SHGC, direct solar and light transmission can be seen in the next figures.
As it can be seen in the following figures, there is no big difference in the amount of hours that are above and below the desired temperature range between the two designs (solid and hollow glass bricks). The cooling load has slightly decreased while the heating load has been slightly increased.

Figure 6.87: Glazing data for the glass solid bricks (Design Builder)

Figure 6.88: Temperature distribution for the third floor shows the number of hours at or below the 22°C limit (blue color) and the number of hours at or above the 26°C limit (red color)
Conclusion for Netherlands

As a result, from the above simulations of all the passive measures applied in the design, a good scheduled natural ventilation, operable and adjustable glass partitions and proper shading of the glazing (fritting of the roof and local shading devices in the windows at the back façade) can improve the thermal performance of the building remarkably leading to a more sustainable design. A replacement of the solid glass bricks with hollow bricks would only create addition need for structural support without resulting in big improvement in the thermal performance of the building. Therefore, has not been chosen as an efficient passive measure for this design.
Figure 6.89: Impression of the building in Valencia, Spain
For Valencia, there is no need for active heating during the non-occupancy period, since all the hours during the winter months the temperature is above 15°C. On the other hand, during summer, the temperature reach even 40°C, making imperative need to activate the cooling system even when the store is closed.

The radiant temperature in the glasshouse5 reach even 56°C, while the operative varies between 24°C and 48°C.

From the temperature distributions throughout the whole year, it can be seen that there is serious overheating problem, compared to Netherlands. The hours that are above 26°C have been increased 205%, while the hours that heating is needed has been decreased 54%.
Figure 6.92: Temperature distribution for the third floor shows the number of hours at or below the 22°C limit (blue color) and the number of hours at or above the 26°C limit (red color).

Figure 6.93: Power demand [kW] for preserving the temperature between 22°C-26°C during the occupancy hours throughout the year.

The power demand that should be supplemented by the mechanical unit reaches a maximum of **220 kW for heating and 400 kW for cooling**. The heat pump unit is calculated with the coefficient of performance equal to CoP=2.5. Thus, a mechanical unit equal to 400/2.5 = 160 kW.
Application of glass partitions in 1.80m below the façade, so it would work as a double skin facade

The results of the simulations when applying the glass partitions behind the façade for this location can be seen in the following figures.

![Figure 6.94: Annual graph of the operative temperature (green color) inside the building in hourly intervals.](image1)

![Figure 6.95: Annual graph of the operative temperature (green color) inside the glasshouse in hourly intervals.](image2)

From the graphs above, and comparing them with the figures 6.90-6.91, the temperatures seem to have been increased, especially during the summer. As it was expected, the temperature range in the “glasshouse” zones gets wider, since the glass partitions form an area that functions as the space in the double skin facades. Thus, high temperatures will be occurred during summer days and low during winter. The difference with the previous result before the partitions is approximately 7°C lower for the winter and 27°C higher for the summer!!

The surface temperatures as well as the heat gains for some of the zones in the glasshouse can be seen in the following figures. It can be clearly seen that temperatures are getting higher at the top and lower at the bottom of the façade.
The benefits but also the drawbacks of this intervention can be seen in the total hours that mechanical cooling and heating is needed.
The hours that cooling is needed has been reduced 7%. While the hours that heating is needed has been increased 200%! (Compared to the temperature distribution of the same zone (3rd floor) when only passive measures utilized in the building without the glass partitions).

From all the above, it is concluded, that this system can work beneficially throughout the year only if the partitions are operable and adjustable to the weather conditions. So, during the summer, the partitions will be closed forming double skin façade and blocking the solar gains, while during the winter, they will be open letting the solar radiation comes into the building.
Figure 6.98: Impression of the building in Tampere, Finland
For Tampere, the cycle of the temperature is more stable throughout the year than in Valencia and Amsterdam, due to the stability of the climatological conditions (6 months day, 6 months night). Only few hours during the summer the temperature is more than 33°C.

From the temperature distributions it can be seen that the building has big heating demand, more than in Netherlands and Valencia. Therefore, measures like glass partitions or fritting are not recommended for this climate.
Figure 6.101: Temperature distribution for the third floor shows the number of hours at or below the 22°C limit (blue color) and the number of hours at or above the 26°C limit (red color).

Figure 6.102: Power demand (kW) for preserving the temperature between 22°C-26°C during the occupancy hours throughout the year.

The power demand that should be supplemented by the mechanical unit reaches a maximum of **500 kW for heating and 100 kW for cooling**. The heat pump unit is calculated with the coefficient of performance equal to CoP=3.5. Thus, a mechanical unit equal to 500/3.5 = 143 kW (2 heat pumps of 75kW each).
Application of glass partitions in 1.80m below the façade, so it would work as a double skin façade

The results of the simulations when applying the glass partitions behind the façade for this location can be seen in the following figures.

From the graphs above, and comparing them with the figures 6.90-6.91, the temperatures seem to have been increased, especially during the summer. As it was expected, the temperature range in the “glasshouse” zones gets wider, since the glass partitions form an area that functions as the space in the double skin facades. Thus, high temperatures will be occurred during summer days and low during winter. The difference with the previous result before the partitions is approximately 8°C lower for the winter and 30°C higher for the summer!!

The surface temperatures as well as the heat gains for some of the zones in the glasshouse can be seen in the following figures. It can be clearly seen that temperatures are getting higher at the top and lower at the bottom of the façade.
The benefits but also the drawbacks of this intervention can be seen in the total hours that mechanical cooling and heating is needed.

The hours that cooling is needed has been reduced 38%. While the hours that heating is needed has been increased 37%! (Compared to the temperature distribution of the same zone (3rd floor) when only passive measures utilized in the building without the glass partitions).

From all the above, it is concluded, that this system can work beneficially throughout the year only if the partitions are operable and adjustable to the weather conditions. So, during the summer, the partitions will be closed forming double skin façade and blocking the solar gains, while during the winter, they will be open letting the solar radiation comes into the building.
Thermal shock laboratory tests

On a warm, sunny day the glass blocks can heat up significantly. In the event of rain on the same day, the warmed glass blocks will come into contact with the colder rainwater and limited thermal shock can occur. The shock intensity is related to the temperature difference between the material and the environment and the rate of heat flow from the glass. In that context, a hot-cold thermal shock is more harmful to glass than a cold-hot thermal shock, because it generates tensile stresses on the rapidly cooled surface. These stresses may be sufficient to activate pre-existing micro-cracks and lead to fracture. Therefore, to evaluate the performance of the glass blocks under peak temperature fluctuations, specimens were heated for four hours in a furnace with a constant temperature of 80°C. The temperature has been defined with two ways.

One by the hand calculations:

$$T_{sol} = T_{exterior} + (\alpha * q_{sun}) / \alpha_c$$

where $\alpha = 0.95$

$q_{sun} = 1000 \, \text{W/m}^2$

$\alpha_c = 20 \, \text{W/m}^2 \, \text{K}$ (assuming there is no wind)

$$\Delta T_n = (R_n / R_1) \Delta T$$

$T_{brick} = 80°C$

And the second by the simulation of the hottest day of the summer in Design Builder. Afterwards, the maximum inside temperature that the glass brick in façade develops is the requested temperature for the test.

Then, they were cooled down by being immediately immersed into 2.5mm deep tap water (20°C) and by spraying tap water in their surfaces. No cracks were noticed with a naked eye, as it can be seen in the following figures.
Figure 6.108: The glass bricks are placed in the oven

Figure 6.109: Pictures taken right after the placement at the basins after taking them out from the oven
Conclusions

The thermal performance of a building depends on lots of factors and can be improved with various passive measures. When designing a new building, the orientation of the glazing and facades is the first factor that one can take into account. In order to reduce the cooling load, big surfaces of glazing (facades, big windows) should be orientated North West. Moreover, green roof, insulated walls and glazing according to the energy national regulations, thermal storage materials, and phase change materials are some of the passive measures that one can take into account when designing a new building.

However, when there is renovation in an existing building, only some of the above measures can be applied. In the present design, the orientation of the building, as it has been mentioned in the relative section of this chapter, has been chosen the same as the orientation of the building in the P.C. Hooftstraat in Amsterdam. Thus, the glass brick façade faces the south-east orientation, consulting in higher solar gains and as a consequence higher cooling demand. Moreover, the wind velocity from this orientation is lower which does not facilitate the natural ventilation. Despite these drawbacks, the passive measures that have been applied to the present design prove, through the simulations with the Design Builder software that it is possible to achieve acceptable thermal performance of such a design with low cooling and heating demand even in countries with extreme weather conditions.

In general, a good scheduled natural ventilation, an effective shading system (fritted glass in the roof and inside shading devices in the windows at the back façade), operable and adjustable to the weather conditions glass partitions which are placed 1.80 m behind the façade would lead to a more acceptable design in terms of sustainability. In the following table, a brief indication of the results of all the simulations for each of the countries can be seen.

<table>
<thead>
<tr>
<th>Passive Measure</th>
<th>Netherlands</th>
<th>Spain</th>
<th>Finland</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controllable Natural Ventilation</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Adjustable Shading Devices</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Glass Partitions (Double Skin)</td>
<td>++*</td>
<td>++*</td>
<td>++*</td>
</tr>
<tr>
<td>Fritting of the top part of the façade</td>
<td>+</td>
<td>++</td>
<td>-</td>
</tr>
<tr>
<td>Hollow glass bricks</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* *only when they can be adjusted to the climate conditions (summer close, winter open)

++ highly
++ advisable
+ advisable
- not advisable

The replacement of the solid glass bricks with hollow it is not advised as a measure, because it offers no benefits in thermal and structural terms. Hollow bricks, as described in the first chapter, need reinforcement to withstand the vertical and lateral loads while increase slightly the interior temperatures due to the higher solar transmission factor.

It is important to mention that for better understanding of the thermal performance of such a structure and as a consequence for choosing the most efficient and sustainable mechanical system, the thermal conditions of each of the zones, especially the zones in the glasshouse, shall be studied and taken into
account. For example, in some of the above simulations when using only passive measures, the temperatures in the roof can reach the 120°C. This is the transition temperature where the adhesive starts to become viscoelastic and softer, resulting in a possible failure of the top part of the glass brick façade. Therefore, a more detailed approach is required for designing the mechanical system of this building.
References


Conclusions and Recommendations

The main conclusions of all the principles of the present research have been mentioned at the end of each chapter. Nevertheless, in this final chapter some general conclusions for the overall of the design and recommendations for future research will be labeled.

Architectural Design

There are lot of different clay brick patterns that can be tested in the case of the glass bricks. Forming the name of the brand by the sole use of glass bricks and adhesive can be one of the use of this façade patterns. For example, the logo of Coco Chanel can be formed with the right angle and orientation of the glass brick such as the numbers are illustrated in the figure 7.2.

The problem, of course of an action like this, is the weakness of reversibility. If the owner or the function of the building alters in the future, changes like these will cost a lot and maybe even destroy the design. Thus, interventions like this need more detailed research.

Figure 7.1: Different facade patterns
A configuration of glass bricks such as in figure 7.3, can result in interesting reflections and refractions of the natural light. But more structural challenges arise.
Furthermore, the use of LED lights behind the facade or inside hollow glass bricks can have impressive results, as well as the colored glass bricks.
Structural Design

The simulation of the structural system of the present design has been done assuming that the two side walls are adjacent to the walls of the neighbor buildings which are the same or higher height.

A future recommendation for research can be the structural study of a building with all four sides free supported and either all the walls are made by glass bricks or only two or three of them and the rest of them by the conventional way of facades. Measures to ensure the stability will need to be taken.

Furthermore, a study of this design in a high seismogenic country such as in Japan or in a country with lot of hurricanes can be the next step for the structural part.

Instead of using horizontal buttresses, another solution can be to use vertical buttresses which will be form the shape of a half pyramid with more bricks at the bottom and less at the top of the façade.

![Figure 7.6: Glass brick vertical Buttresses](image)

Moreover, some of the façade patterns that have been described above, function as a reinforcement for the façade increasing the lateral strength.
Thermal Performance

There are lot of measures that one can consider when there is need for improvement of the thermal performance of the building. Some of the sustainable measures that can be applied in similar projects in the future are:

- Rainwater capture from the roof and glass brick façade (combine the gutter with using the water for flushing the toilets)
- Green roof
- Roof with glass solar tiles

![Figure 7.7: Glass solar tiles (www.earthtechling.com)](/content)

Traditional roof tiles are either mined from the ground or set from concrete or clay. Once installed, they exist to simply protect a building from the elements despite the fact that they spend a large portion of the day absorbing energy from the sun. Unlike most solar units which are fixed on top of existing roofing, solar tiles are fully integrated into the building, protecting it from the weather and generating power for its inhabitants.

Finally, a study about the thermal performance in even more extreme climate conditions (outside of Europe) can be part of a future research.
Logistics

The elevation of 20m by 20m façade employs more than 20000 cast glass bricks, each of them cost only for its production approximately 15 euro. That means that only for the purchasing of the glass bricks for solely the façade the amount reaches the 300000 euro, makes it a really extravagant project.

As a counterbalance to this extravagant project, is the big impact that will have to the city, since it will easily become one of the landmarks and the attraction spots. Especially in streets like P.C. Hooftstraat in Amsterdam, where the Crystal House is being built the time that this report is written, it can result to increase in the income of the owners of the shops in that area, since some tourists and locals will visit the street to see this innovative design.

Final Conclusion

We can see that everything can be made of glass with great potentials, enhancing aesthetics and create the best open and clear space, full of light in a safety way. It is proven in that project that one can do everything with glass like the other materials and glass should be treated like that and no with the fear of risking safety and integrity of the structure.

By applying a combination of passive and active measures from the initial orientation of the building till the glazing coatings properties, it is possible to achieve a limited energy consumption building according to the energy national regulations despite the large glass surfaces.

Furthermore, by conducting more experiments on big specimens made by glass bricks and adhesive and extending the structural calculations to thermal and buckling analysis mode, it is feasible to achieve safe but yet impressive innovative glass structures.

Finally, this can set the basis for exploring the advantages and limitations of an adhesively bonded glass block system as a solution for all glass structures and will provide insights for possible future developments that can generate further innovative solid glass block applications.

The future of this technology is brilliant and is rising.
Appendix A
Materials
<table>
<thead>
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<th>Property</th>
<th>Symbol</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>$\rho$</td>
<td>Kg/m$^3$</td>
<td>2500</td>
</tr>
<tr>
<td>Hardness (Knoop)</td>
<td>HK$_{0.1/20}$</td>
<td>Gpa</td>
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<tr>
<td>Young's Modulus</td>
<td>$E$</td>
<td>Gpa</td>
<td>70</td>
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<tr>
<td>Poisson's ratio</td>
<td>$\nu$</td>
<td>-</td>
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<tr>
<td>Tensile bending strength</td>
<td>$f_t$</td>
<td>Mpa</td>
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</tr>
<tr>
<td>Specific thermal capacity</td>
<td>$c_p$</td>
<td>J*kg$^{-1}$*K$^{-1}$</td>
<td>720</td>
</tr>
<tr>
<td>Thermal expansion coefficient (between 20 and 300° C)</td>
<td>$\alpha$</td>
<td>K$^{-1}$</td>
<td>9*10$^{-6}$</td>
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<td>Thermal conductivity</td>
<td>$\lambda$</td>
<td>W*m$^{-1}$*K$^{-1}$</td>
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<tr>
<td>Mean reflective index to visible radiation (380 to 780mm)</td>
<td>$N$</td>
<td>-</td>
<td>1.5</td>
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*Table 1: Properties of annealed soda-lime silicate glass according to [EN 572-1:2004]*

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
<th>Unit</th>
<th>DELO-PHOTOBOND</th>
<th>SentryGlass®</th>
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<tr>
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<td>$\rho$</td>
<td>Kg/dm$^3$</td>
<td>GB368</td>
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<tr>
<td>Tensile Strength</td>
<td>$F$</td>
<td>Mpa</td>
<td>4468</td>
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<tr>
<td>Elastic modulus</td>
<td>$E$</td>
<td>Mpa</td>
<td>4497</td>
<td>900</td>
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<tr>
<td>Glass-Glass shear strength</td>
<td>$f_{g}$</td>
<td>Mpa</td>
<td>23</td>
<td>22</td>
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<tr>
<td>Glass-aluminum shear strength</td>
<td>$f_{ga}$</td>
<td>Mpa</td>
<td>23</td>
<td>24</td>
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<tr>
<td>Glass transition temperature</td>
<td>°C</td>
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<td>102</td>
<td>74</td>
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<tr>
<td>Elongation at fracture</td>
<td>%</td>
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<td>17</td>
<td>200</td>
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*Table 2: Indicative properties of the DELO adhesives and the SG interlayer according to [DELO, 2009; DuPont, 2009]*

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<th>Property</th>
<th>Symbol</th>
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<th>Value</th>
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<tr>
<td>Density</td>
<td>$\rho$</td>
<td>Kg/dm$^3$</td>
<td>7.9</td>
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<tr>
<td>Modulus of Elasticity at 20°C</td>
<td>$E$</td>
<td>GPa</td>
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<tr>
<td>Yield strength 0.2% proof</td>
<td>$F_{y,0.2%}$</td>
<td>MPA</td>
<td>210-230</td>
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<tr>
<td>Ultimate tensile strength</td>
<td>$f_t$</td>
<td>MPA</td>
<td>520-750</td>
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<tr>
<td>Elongation at fracture</td>
<td>$\varepsilon_r$</td>
<td>%</td>
<td>45</td>
</tr>
<tr>
<td>Mean coefficient of thermal expansion (20°C - 100°C)</td>
<td>$\alpha$</td>
<td>10$^6$K$^{-1}$</td>
<td>16</td>
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<tr>
<td>Thermal conductivity at 20°C</td>
<td>$k$</td>
<td>W/m*K</td>
<td>15</td>
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<tr>
<td>Specific thermal capacity at 20°C</td>
<td>$C$</td>
<td>J/kg*K</td>
<td>500</td>
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<td>Electrical resistivity at 20°C</td>
<td>$R$</td>
<td>$\Omega$*mm$^2$/m</td>
<td>0.73</td>
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<tr>
<td>Magnetizable</td>
<td>-</td>
<td>-</td>
<td>no</td>
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*Table 3: Properties of austenitic stainless steel type AISI 304 according to [EN 10088-1:2005; EN 10088-2:2005]*
<table>
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<th>Characteristic</th>
<th>Standard</th>
<th>Result</th>
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<tr>
<td>Average compression resistance</td>
<td>UNI EN 772-1</td>
<td>397 N/mm²</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>UNI 10077-1</td>
<td>0,974± 0,036 W (m K)</td>
</tr>
<tr>
<td>Linear thermal dilatation coefficient (10-6 °C-1)</td>
<td>UNI EN ISO 10545 - 8</td>
<td>10,2 – 10,6</td>
</tr>
<tr>
<td>Mohs hardness (Artiko Color excepted)</td>
<td>UNI EN 101 (92)</td>
<td>3</td>
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<tr>
<td>Vickers hardness (Artiko Color excepted)</td>
<td></td>
<td>520 Hv₀.₅</td>
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<tr>
<td>Armored bullet proof</td>
<td>UNI EN 1063 (2001)</td>
<td>cal. 357 Magnum armored bullet</td>
</tr>
<tr>
<td>Fire resistance</td>
<td>Circular letter n° 91 - 14/09/1961 of the Italian Department of the Interior</td>
<td>REI 60 by standard pose with cement mortar</td>
</tr>
</tbody>
</table>

*Table 4: Technical specification of the glass bricks used in the façade and in the columns according to [Catalog Poesia 2013]*
Appendix B
Architectural Design
2D Drawings

Figure 1: Plan of the basement
Figure 2: Plan of the ground floor
Figure 3: Plan of the first floor
Figure 4: Plan of the second floor
Figure 5: Plan of the third floor
Figure 6: Plan of the fourth floor
Figure 7: Elevation of the roof
Figure 8: Section across the facades
Alternative design maximizing the transparency but arises different and more structural challenges both for the façade (high buckling length) and the glass floors (cantilevers).

Figure 8: Section across the facades of an alternative design
Appendix C

Structure
Figure 1: Areas of the ground floor slab
Figure 2: Areas of the first floor slab
Figure 3: Areas of the second floor slab
Figure 4: Areas of the third floor slab
Figure 5: Areas of the fourth floor slab
Figure 6: Areas of the roof concrete slab and glass panes
Appendix D
Thermal Performance
## Construction materials

<table>
<thead>
<tr>
<th>glass element</th>
<th>outer pane</th>
<th>cavity / mid pane</th>
<th>inner pane</th>
<th>Fritting</th>
<th>SHGC/Total Solar Transmission</th>
<th>Direct solar Transmission</th>
<th>Light Transmission</th>
<th>U-value (W/(\text{m}^2)K)</th>
<th>Shading</th>
</tr>
</thead>
<tbody>
<tr>
<td>glass roof pane</td>
<td>Pilkington Optifloat 16mm</td>
<td>Argon 16mm</td>
<td>Pilkington Optifloat 16mm</td>
<td>90%</td>
<td>0.569</td>
<td>0.428</td>
<td>0.693</td>
<td>1.065</td>
<td>-</td>
</tr>
<tr>
<td>windows in the façade</td>
<td>Pilkington Optifloat 16mm</td>
<td>Argon 16mm</td>
<td>Pilkington Optifloat 16mm</td>
<td>-</td>
<td>0.569</td>
<td>0.428</td>
<td>0.693</td>
<td>1.065</td>
<td>inside blinds with high reflectivity slats</td>
</tr>
<tr>
<td>glass pane in louvres</td>
<td>Pilkington Optifloat 6mm</td>
<td>Pilkington Optifloat 6mm</td>
<td>Pilkington Optifloat 6mm</td>
<td>90%</td>
<td>0.636</td>
<td>0.519</td>
<td>0.702</td>
<td>5.286</td>
<td>-</td>
</tr>
<tr>
<td>glass floor</td>
<td>Generic Clear 4mm</td>
<td>Pilkington Optifloat 12.7mm</td>
<td>Pilkington Optifloat 12.7mm</td>
<td>anti-slip texture</td>
<td>0.438</td>
<td>0.305</td>
<td>0.565</td>
<td>2.86</td>
<td>anti-slip texture</td>
</tr>
<tr>
<td>glass bricks in the façade</td>
<td>float glass 210mm</td>
<td></td>
<td></td>
<td></td>
<td>0.475</td>
<td>0.313</td>
<td>0.483</td>
<td>1.354</td>
<td>-</td>
</tr>
</tbody>
</table>

**Table 1: Properties of the glazing as calculated by Design Builder software**

<table>
<thead>
<tr>
<th>Level</th>
<th>Construction Element</th>
<th>Layers</th>
<th>Total Thickness (m)</th>
<th>(U_\text{value} \ (\text{W/m}^2\text{K}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor</td>
<td></td>
<td></td>
<td>0.278</td>
<td>0.325</td>
</tr>
<tr>
<td>Basement</td>
<td>Ceiling</td>
<td></td>
<td>0.220</td>
<td>1.626</td>
</tr>
<tr>
<td></td>
<td>Side external walls</td>
<td></td>
<td>0.120</td>
<td>0.374</td>
</tr>
</tbody>
</table>

**Table 2: Properties of the construction materials in the basement as calculated by Design Builder software**
Table 3: Properties of the construction materials in the ground floor as calculated by Design Builder software

<table>
<thead>
<tr>
<th>Level</th>
<th>Construction Element</th>
<th>Layers</th>
<th>Total Thickness (m)</th>
<th>U\text{value} (W/m}^2\text{K})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor</td>
<td></td>
<td></td>
<td>0.278</td>
<td>0.325</td>
</tr>
<tr>
<td>Ceiling</td>
<td></td>
<td></td>
<td>0.220</td>
<td>1.626</td>
</tr>
<tr>
<td>Side external walls</td>
<td></td>
<td></td>
<td>0.476</td>
<td>0.254</td>
</tr>
<tr>
<td>Back Façade</td>
<td></td>
<td></td>
<td>0.476</td>
<td>0.259</td>
</tr>
<tr>
<td>Level</td>
<td>Construction Element</td>
<td>Layers</td>
<td>Total Thickness (m)</td>
<td>U_{\text{value}} (W/m²*K)</td>
</tr>
<tr>
<td>---------------</td>
<td>----------------------</td>
<td>------------------------------------------------------------------------</td>
<td>---------------------</td>
<td>---------------------------</td>
</tr>
<tr>
<td>1st,2nd,3rd</td>
<td>Floor</td>
<td>Inner surface: 10.00mm: Crystal House, 79 in. Plywood/wood panel.</td>
<td>0.208</td>
<td>0.984</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Outer surface: 150.00mm: Crystal House/Cast Concrete.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st,2nd,3rd</td>
<td>Ceiling</td>
<td>Inner surface: 200.00mm: Crystal House/Air gap 200mm (downwards)</td>
<td>0.220</td>
<td>1.626</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Outer surface:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st,2nd,3rd</td>
<td>Side external walls</td>
<td>Outer surface: 190.00mm: Brick and blockwork, masonry for external wall.</td>
<td>0.476</td>
<td>0.254</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Inner surface: 70.00mm: Insulating material 1, external wall.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st,2nd,3rd</td>
<td>Back Façade</td>
<td>Outer surface: 120.00mm: Brick and blockwork, Outer Leaf (not to scale)</td>
<td>0.476</td>
<td>0.259</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Inner surface: 70.00mm: Insulating material 1, external wall.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Table 4: Properties of the construction materials in the 1st, 2nd, and 3rd floor as calculated by Design Builder software*
<table>
<thead>
<tr>
<th>Level</th>
<th>Construction Element</th>
<th>Layers</th>
<th>Total Thickness (m)</th>
<th>U-value (W/m²*K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor</td>
<td></td>
<td></td>
<td>0.208</td>
<td>0.984</td>
</tr>
<tr>
<td>Ceiling/Roof</td>
<td></td>
<td></td>
<td>0.522</td>
<td>0.228</td>
</tr>
<tr>
<td>4th Floor</td>
<td>Side external walls</td>
<td></td>
<td>0.476</td>
<td>0.254</td>
</tr>
<tr>
<td></td>
<td>Back Façade</td>
<td></td>
<td>0.476</td>
<td>0.259</td>
</tr>
</tbody>
</table>

Table 5: Properties of the construction materials in the 4th floor as calculated by Design Builder software
Schedules

Crystal House

![Schedules Data](image)

*Figure 1: 1-7/12 schedule type for the occupancy*
**Crystal House/equipment**

![Schedules Data](image)

**Figure 2:** 1-7/12 schedule type for the computers and office equipment
Crystal House/ventilation

![Schedules Data]

**Figure 3:** Compact schedule type for the natural ventilation operation
Figure 4: Compact schedule type for the cooling design
Crystal House/heating design

Figure 5: Compact schedule type for the heating design
Table 6: Input data for the internal gains

<table>
<thead>
<tr>
<th></th>
<th>W/m²</th>
<th>Radiant Fraction</th>
<th>Visible Fraction</th>
<th>Schedule</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lighting</td>
<td>30</td>
<td>0.42</td>
<td>0.18</td>
<td>Crystal</td>
</tr>
<tr>
<td>Computers</td>
<td>5</td>
<td>0.2</td>
<td>-</td>
<td>House/equipment</td>
</tr>
<tr>
<td>Office Equipment</td>
<td>5</td>
<td>0.2</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

*Table 6: Input data for the internal gains*
Thermal graphs

In this section, more analytical and representative graphs about the thermal conditions (temperatures, ventilation rates, humidity range, heat balance) for the warmest (03-05 August) and coldest days (10-12 February) throughout the year for all the three locations (weather data are given) are going to be presented. The simulation graphs that are given are referred to the initial design and not in the alternatives due to the restriction of the pages of this report.

Amsterdam, Netherlands

Figure 6: Weather data throughout the year for Amsterdam
Only passive measures

Figure 7: Operative temperature (green color) in the building (top) and the percent of the relative humidity (bottom) at 10/02

Figure 8: Heat balance in the building (top) and ventilation rate (bottom) at 10/02
Figure 9: Operative temperature (green color) in the building (top) and the percent of the relative humidity (bottom) at 11/02

Figure 10: Heat balance in the building (top) and ventilation rate (bottom) at 11/02
Figure 11: Operative temperature (green color) in the building (top) and the percent of the relative humidity (bottom) at 12/02

Figure 12: Heat balance in the building (top) and ventilation rate (bottom) at 12/02
Figure 13: Operative temperature (green color) in the building (top) and the percent of the relative humidity (bottom) at 03/08 (Saturday)

Figure 14: Heat balance in the building (top) and ventilation rate (bottom) at 03/08 (Saturday)
Figure 15: Operative temperature (green color) in the building (top) and the percent of the relative humidity (bottom) at 04/08 (Sunday).

Figure 16: Heat balance in the building (top) and ventilation rate (bottom) at 04/08 (Sunday). It can be seen that between 11 am and 5pm where the outside air temperature is higher than the inside, the natural ventilation is not active and the rate is only due to infiltration (0.5-1.5 h⁻¹).
Figure 17: Operative temperature (green color) in the building (top) and the percent of the relative humidity (bottom) at 05/08 (Monday).

Figure 18: Heat balance in the building (top) and ventilation rate (bottom) at 05/08 (Monday). During the night the rate gets high in order to cool down the interior, while for the occupancy hours gets higher in order to cover the occupancy required rate as well.
Passive and active measures

Figure 19: Thermal simulation with the utilization of passive and mechanical systems. Hourly data for 10-12/02. During the occupancy hours it can be observed that the operative temperature is approximately 22 °C, while the exterior dry-bulb temperature ranges from -2 to 3 °C.

Figure 20: Heat balance in the building (top) and ventilation rate (bottom) for 10-12/02. During the non-occupancy hours the only ventilation is due to the infiltration.
Figure 21: Internal and Solar gains (kW) for 10-12/02

Figure 22: Thermal simulation with the utilization of passive and mechanical systems. Hourly data for 03-05/08. During the occupancy hours it can be observed that the operative temperature is below 26 °C, while the exterior dry-bulb temperature ranges from 18 to 30 °C
Figure 23: Heat balance in the building (top) and ventilation rate (bottom) for 03-05/08. During the non-occupancy hours the ventilation rate decreases.

Figure 24: Internal and Solar gains (kW) for 03-05/08.
Valencia, Spain

Figure 25: Weather data throughout the year for Valencia

Only passive measures

Figure 26: Operative temperature (green color) in the building (top) and the percent of the relative humidity (bottom) for 10-12/02. During the occupancy hours the operative temperature is between 22°C-26°C, makes no need for heating the space.
Figure 27: Heat balance in the building (top) and ventilation rate (bottom) for 10-12/02. The natural ventilation is active only when the shopping store is open, while for the rest of the hours the openings are closed so the heat gain is stored inside the building.

Figure 28: Operative temperature (green color) in the building (top) and the percent of the relative humidity (bottom) for 03-05/08
Passive and active measures

Figure 29: Heat balance in the building (top) and ventilation rate (bottom) for 03-05/08

Figure 30: Thermal simulation with the utilization of passive and mechanical systems. Hourly data for 10-12/02. During the occupancy hours it can be observed that the operative temperature is between 22 °C and 24°C, while the exterior dry-bulb temperature ranges from 10 to 14 °C.
Figure 31: Heat balance in the building (top) and ventilation rate (bottom) for 10-12/02. During the night the ventilation is closed, so the heat gain is stored in the interior of the building.

Figure 32: Internal and Solar gains (kW) for 10-12/02. The majority of the heat gain is due to the lighting during the occupancy hours.
Figure 33: Thermal simulation with the utilization of passive and mechanical systems. Hourly data for 03-05/08.

Figure 34: Heat balance in the building (top) and ventilation rate (bottom) for 03-05/08.
Figure 35: Internal and Solar gains (kW) for 03-05/08
Tampere, Finland

Figure 36: Weather data throughout the year for Tampere

Only passive measures

Figure 37: Operative temperature (green color) in the building (top) and the percent of the relative humidity (bottom) for 10-12/02. During the occupancy hours the operative temperature is between 13°C-17°C, makes imperative need for heating
Figure 38: Heat balance in the building (top) and ventilation rate (bottom) for 10-12/02. The natural ventilation is active only when the shopping store is open, while for the rest of the hours the openings are closed so the heat gain is stored inside the building.

<table>
<thead>
<tr>
<th>Time/Date</th>
<th>Glazing (kW)</th>
<th>Walls (kW)</th>
<th>Ceilings (inH) (kW)</th>
<th>Floors (inH) (kW)</th>
<th>Ground Floors (kW)</th>
<th>Partitions (inH) (kW)</th>
<th>Roofs (kW)</th>
<th>Internal Natural vent (kW)</th>
<th>External Air (kW)</th>
<th>Mech Vent + Nat Vent + Infiltration (achh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11 Mon</td>
<td>-3.14</td>
<td>-0.58</td>
<td>-1.39</td>
<td>-4.42</td>
<td>-3.52</td>
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<td>-5.03</td>
<td>-4.82</td>
<td>-5.50</td>
<td>-5.65</td>
</tr>
<tr>
<td>12 Tue</td>
<td>-2.75</td>
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<td>2.72</td>
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<tr>
<td>13 Wed</td>
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<td>-7.27</td>
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<tr>
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</tr>
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</tr>
<tr>
<td>-2.51</td>
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<td>-0.35</td>
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<td>-47.61</td>
<td>-21.77</td>
<td>-3.16</td>
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<td>-75.96</td>
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</tr>
<tr>
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<td>0.17</td>
<td>0.11</td>
<td>0.27</td>
<td>1.67</td>
<td>1.23</td>
<td>0.36</td>
<td>0.38</td>
<td>2.44</td>
<td>0.35</td>
<td></td>
</tr>
</tbody>
</table>

Figure 39: Operative temperature (green color) in the building (top) and the percent of the relative humidity (bottom) for 03-05/08
Passive and active measures

Figure 40: Heat balance in the building (top) and ventilation rate (bottom) for 03-05/08

Figure 41: Thermal simulation with the utilization of passive and mechanical systems. Hourly data for 10-12/02. During the occupancy hours it can be observed that the operative temperature is between 22 °C and 24°C, while the exterior dry-bulb temperature ranges from 10 to 14 °C.
Figure 42: Heat balance in the building (top) and ventilation rate (bottom) for 10-12/02. During the night the ventilation is closed, so the heat gain is stored in the interior of the building.

Figure 43: Internal and Solar gains (kW) for 10-12/02. The majority of the heat gain is due to the lighting during the occupancy hours.
Figure 44: Thermal simulation with the utilization of passive and mechanical systems. Hourly data for 03-05/08. The operative temperature (green) is slightly higher than 26°C.

Figure 45: Heat balance in the building (top) and ventilation rate (bottom) for 03-05/08. During the occupancy hours the ventilation rate is higher in order to reach the desired temperature with the least mechanical energy consumption.
Figure 46: Internal and Solar gains (kW) for 03-05/08. There is no cooling, lighting, equipment and occupancy load during Sunday, when the shopping store is closed.