Resilient Facade Design: Innovation Amidst Earthquakes

Automation of the structural analysis of a suspended facade under earthquakes and development of a bracket connection using FEM Models.

Master Thesis

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MSc Architecture, Urbanism & Building Sciences

Technical University of Delft

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Building Technology Graduation Project
MSc in architecture, Urbanism and Building Sciences

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Abstract

Curtain-wall systems have become increasingly common in present-day architecture. They can be produced with high-efficiency qualities selected by the architect or façade engineer, the most essential of which are excellent strength-to-weight ratio, functionality requirements, component material recyclability, transparency, and comprehensive aesthetic attributes.(Baniotopoulos et al., 2016) Over the last decade, much research has been conducted to produce performance-based earthquake resilient structures and façades. This research aims to explore the integration of timber and aluminium suspended façade systems within environments characterized by these extreme conditions. On the first part of the research thesis, the focus will be on developing a comprehensive understanding of the performance of this façade system under wind, earthquake forces and implementing automation techniques to streamline the calculations by creating a smart grid in Grassshopper and Python. Additionally, once structural integrity has been met, an optimal structural design of the bracket using steel and glass as a material is presented by using advanced finite-element analysis schemes and structural design criteria.

Contents

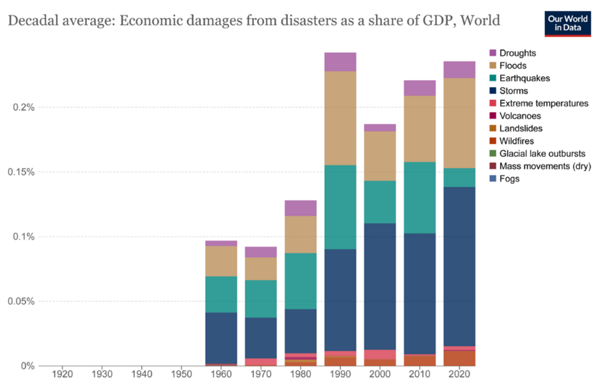
Contents

Introduction

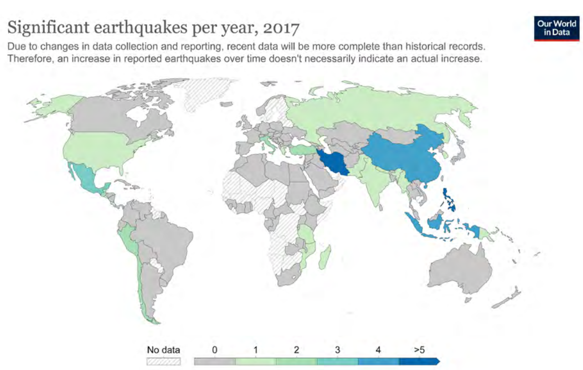
Disasters, as defined by the United Nations, encompass a spectrum of events ranging from rapid-onset occurrences like wind-storms, earthquakes, and sudden floods, to slow-onset phenomena such as prolonged droughts, encroaching salt-water, and expanding desertification.(Vereinte Nationen, 2022) Earthquakes fall into the category of rapid-onset disasters and stand as some of the most catastrophic natural occurrences affecting human civilization. Globally, over a million earthquakes strike each year, translating to an average of roughly two earthquakes per minute. Between 1998 and 2017, earthquakes accounted for over 750,000 fatalities worldwide, constituting more than half of all-natural catastrophe-related deaths. During this period, earthquakes affected over 125 million individuals, leading to injuries, displacement, homelessness, and emergency evacuations.

This study explores the potential of curtain-wall systems, particularly in the modular construction approach, as a means to enhance structural resilience in the face of such natural disasters. In this way of construction, factory-made volumetric units are delivered, assembled, and connected on-site to create functional structures. With up to 70–95% of the work taking place in factory conditions (Peng & Hou, 2023) , modular construction offers several advantages, including faster construction, superior quality control, better work safety, it can enhance the natural lighting, the economies of scale, and lower environmental impacts(Baniotopoulos et al., 2016; Lawson et al., 2014).

In the context of severe natural occurrences, such as earthquakes, the structural performance of curtain-wall systems must be rigorously examined and built to meet structural criteria. While considerable research has been dedicated to examining the structural aspects of buildings under extreme conditions, particularly seismic events, there remains a significant dearth in scholarly investigations focused on suspended façade systems within this domain. The core objective of this thesis revolves around assessing the susceptibility of the building's exterior to damage and financial consequences when subjected to earthquake forces. Aspects of curtain walls with series of metrics to quantify potential envelope damages, associated the failure of the non-structural and structural elements as well as the probability of water and air ingress. (Ouyang & Spence, 2021)



Picture 01 Source: EM-DAT, UCLouvain



Picture 02 Source: National Geophysical Data center

Introduction

The thesis proposes a departure from conventional structural engineering methodologies by firstly automating the process of calculating the seismic forces each panel has to withstand using algorithms, whilst reimagining the interaction between a building's main structure and its outer veneer. Rather than merely seeking to minimize or eliminate this interaction, the thesis advocates for leveraging it to dissipate energy during seismic events. This paradigm shift introduces the concept of advanced connections, engineered to exhibit superior ductility and damping properties. These connections serve as crucial links between the main structure and the cladding, effectively channelling and absorbing energy to mitigate the overall response of the building's core framework.

Central to this approach is the development and implementation of innovative cladding connections that push the boundaries of structural engineering. These connections are meticulously designed to withstand dynamic stresses during seismic events, ensuring optimal energy dissipation while preserving structural integrity. By dispersing energy dissipation across the building's height and minimizing stress concentrations, these connections offer a comprehensive strategy for enhancing seismic resilience. Moreover, their design aims to prevent the transfer of forces into the cladding panels, thereby safeguarding the structural integrity of both the core structure and the outer cladding.

Introduction

Diagram 01: Timetable Author's own work.

1 Research Framework

Background of study

Background of study

Suspended façades

Architects and designers select facade typologies based on factors like the building's use, environmental conditions, cultural context, sustainability goals, and desired aesthetics' to create visually appealing, functional, and contextually relevant exteriors for buildings. The structural system of a building's out skirt normally involves the selection of the lightest elements constructed for the most efficient configuration that is suited to the expected loads.(Baniotopoulos et al., 2016). This can also depend on the finishing of the structural element, the functionality of space the light needs as well as the overall aesthetic of the building. The façade structure typologies are the load bearing façade, the plinth, double skin façades and the suspended façade otherwise known as curtain wall system. (Galli, n.d.)

The term curtain wall indicates a type of perimeter wall or enclosure that differs from a regular and "customary" one in that it is not loadbearing for the levels above, nor is it supported or anchored by the floor or beam underneath. On the other hand, it refers to a perimeter enclosed wall that is totally outside the structure and has no connection to the structural system, namely to the beams or floors.

Curtain-wall system is a non-structural element in buildings, and it can be a utilized system or a stick system.(Galli, n.d.)

Types of curtain walls:

1. Stick-built curtain walls: These are assembled on-site, piece by piece, and installed one component at a time. They consist of aluminium frames that are filled with glass or other materials. The installation process involves erecting the vertical mullions first, followed by the horizontal transoms, and then installing the glass or panels.(Herzog et al., 2004)
2. Unitized curtain walls: Unlike stick-built walls, unitized curtain walls are pre-assembled in factory-controlled conditions. Large sections of the curtain wall, including the framing, glass, and sometimes insulation or other components, are assembled as complete panels. These panels are transported to the construction site and connected to the building's structure.(Herzog et al., 2004)

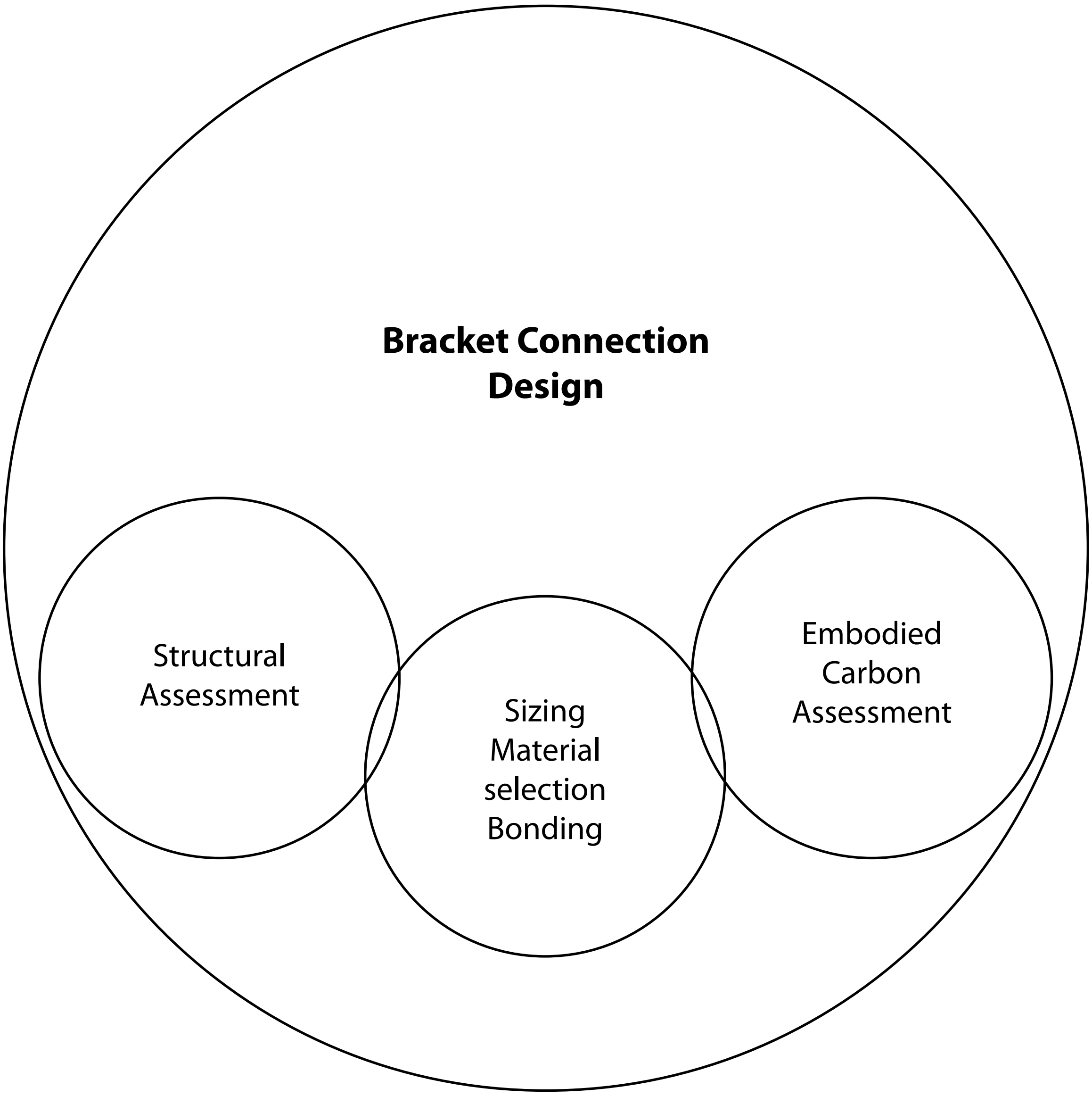
Statement of the problem

The façade of a building serves as its primary visual representation, encapsulating its architectural identity while simultaneously functioning as a protective barrier against external weather conditions. The comprehension of diverse structural systems and their inherent capacities equips designers with the ability to forge innovative designs while prioritizing occupant safety. However, the prevalence of earthquakes poses major challenges. These adversities disproportionately affect developing countries, resulting in substantial casualties and significant economic burdens for building owners. Consequently, forced relocations become inevitable, accompanied by tragic loss of life.

To mitigate these risks, the integration of automation in engineering processes offers an avenue for expedited comprehension of critical factors affecting building displacement and the requisite resistance of suspended façades against seismic forces. Moreover, employing finite element analysis presents a viable pathway towards developing cost-effective solutions utilizing sustainable materials—such as glass composites—derived from alternatives to traditional steel. This thesis aims to explore the combination of automation techniques and finite element analysis to propose innovative, economically viable, and environmentally sustainable strategies for fortifying building façades against adverse conditions.

Main research question

How can the integration of automation technologies in engineering processes, coupled with finite element analysis, facilitate the development of cost-effective and sustainable brackets to fortify the building's suspended facade against seismic activities?



Sub-Questions

How can the structural analysis of a façade become less challenging for architects, civil engineers', façade advisors?

How can a computational tool calculate the forces a suspended façade has to withstand from earthquakes and wind pressure?

How brackets withstand extreme conditions such as earthquakes?

Can we use structural glass as a bracket system and withstand seismic wind forces?

How can the efficiency of researching new materials for a façade system in extreme conditions be improved?

Objectives of the study

The primary objective of this thesis is to create an advanced computational tool with the capacity to autonomously calculate the forces sustained by the fixing system of the façade with a secondary aim the utilization of Finite Element Models (FEM) to design a cladding system, incorporating glass as a material.

Specifically, the investigation seeks to determine the subtle aspects of the bracket connection in response to extreme environmental conditions, analysing the forces sustained by the system, the resulting deflections, and the inherent limitations of a façade under the impactful conditions of earthquakes. To maintain research focus and clarity, this study confines its scope to suspended façades within buildings constructed from reinforced concrete with shear walls. By delving into these specifics, the research aspires to yield insights that are not only academically rigorous but also directly applicable to advancing the resilience and performance of façade systems in real-world scenarios.

Methodology, Limitations of Study

This thesis employs a mixed-methods approach to address research inquiries and accomplish primary objectives. The methodology comprises three distinct phases that serve as the framework for the research process: exploration, creation, and assessment.

1.4.1 Exploration

During the preliminary exploration phase, an extensive review of relevant literature is undertaken to acquire a nuanced understanding of the current research landscape. Key concepts, theories, and methodologies central to the research inquiries are carefully identified and scrutinized. The literature review employs a diverse set of search, screening, and selection methods to gather publications pertaining to the specified topics, encompassing suspended façades in earthquakes, automation, structural analysis, and bracket design. Five keywords are judiciously selected: Suspended façades, earthquakes, façade bracket, structural glass, and algorithm process. These keywords guide queries within reputable databases such as Scopus, Google Scholar, Academia, Research Gate, Science Direct, and Web of Science. Simultaneously, scheduled consultations with Façade Advisors and Structural Engineers from Gevel Advies contribute practical insights, ensuring alignment with industry requirements and the eventual applicability of the research.

The screening process involves a meticulous evaluation of titles and abstracts to pinpoint relevant papers for subsequent in-depth review. The literature review in this thesis is systematically organized into six distinct sections, each designed to address the sub-questions delineated in Chapter 1.2.2. The first section serves to establish a comprehensive understanding of suspended façades under extreme environmental conditions, notably earthquakes and wind-storms. Subsequently, the second section delves into Finite Element Analysis (FEA) and the material composition of elements within a wooden/aluminium curtain wall façade, with a particular emphasis on the meticulous construction of a dataset requisite for deploying FEA models. The third section critically evaluates structural analyses conducted under multi-hazard conditions, referencing both Eurocode guidelines and American standards. Sequentially, the fourth section scrutinizes site selection considerations and proposes architectural strategies tailored for wooden and aluminium façades. Moving forward, the fifth section centres on the development of an intelligent 3D model using Grasshopper, affording users the flexibility to customize dimensions for each façade fragment. The ensuing step involves the automation of structural calculations using Python, yielding the forces borne by brackets within each system across diverse building dimensions, heights, and floor numbers.

Concluding the literature review, the sixth section undertakes an in-depth exploration of bracket design. Employing inputs derived from the preceding sections and Finite Element Method Models, this section presents a range of design options aimed at optimizing the structural integrity of the brackets. Through this multifaceted approach, the literature review seeks to contribute a nuanced and comprehensive understanding of the intricacies surrounding suspended façades, fostering advancements in both theoretical knowledge and practical applications within the realm of architectural engineering.

Methodology, Limitations of Study

1.4.2 Creation phase

During the development phase, the research study implemented, a tool which calculates the forces taken by each façade fragment in seismic activities in different building dimensions, height, and weight of the fragment itself. The tool will also calculate the deflection off the part it is "hanged" from, the minimum shear force that the bracket must withstand and stay in the elastic region and not fail, according to the Eurocode standards. After the data is collected, the research continues with the finite element analysis of the bracket to create an energy-absorbing element, that will regulate the frequency of the suspended façade.

1.4.3 Assessment phase

After a series of test with the dimensions of the design, the outputs are discussed, and a final model will be presented. The condition for the selection is mass of the material, the CO2 emissions of the element, the cost and finally the time of assembling. The outcomes of the evaluation are meticulously reviewed and consolidated within a comprehensive report. This culminates in an in-depth discussion and conclusive findings addressing the primary research inquiry. Subsequently, the constraints of the research are deliberated upon, followed by the formulation of prospective avenues for future research proposals.

1.6 Limitations of the study

The selection of façade typologies, including plinth, curtain wall, and load-bearing systems, is inherently dictated by the architectural design of a building. Due to the constraints imposed by the time frame of my thesis project, I have intentionally focused my research efforts on exploring the intricacies of suspended façades and more specifically curtain wall system. The structural composition of the building primarily consists of reinforced concrete, featuring shear walls. This structural configuration significantly influences several key aspects of the building, including its natural frequency, overall mass, and the utilization of bracket connections. These factors are pertinent to my research due to the constrained time frame of the thesis project, thereby prompting a deliberate focus on understanding the implications of this structural setup on the performance and behaviour of suspended façades within this specific context.

Methodology, Limitations of Study

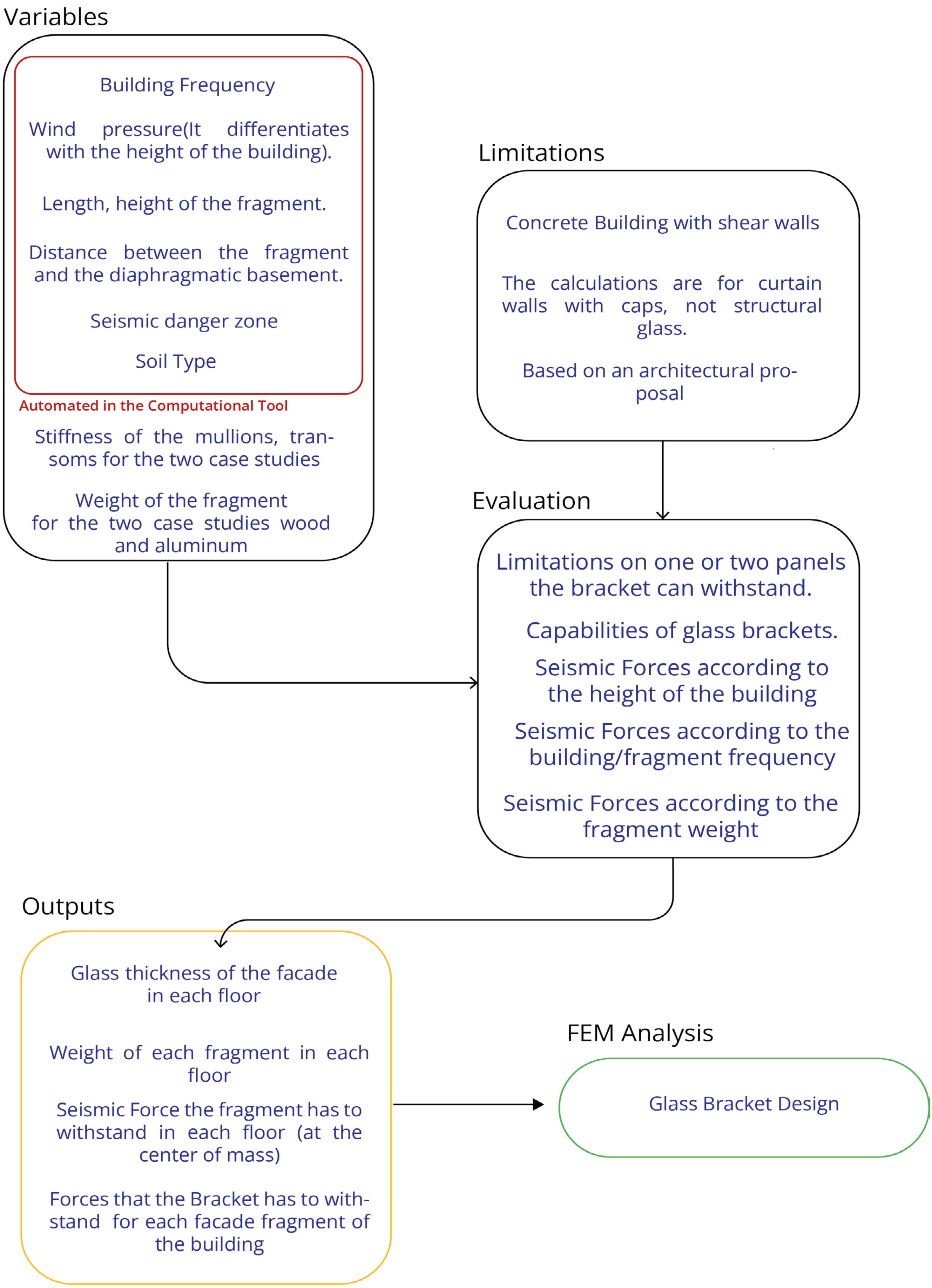


Diagram 03: Research Thesis Variables, Limitations, Evaluation, Outputs . Author's own work.

Methodology, Limitations of Study

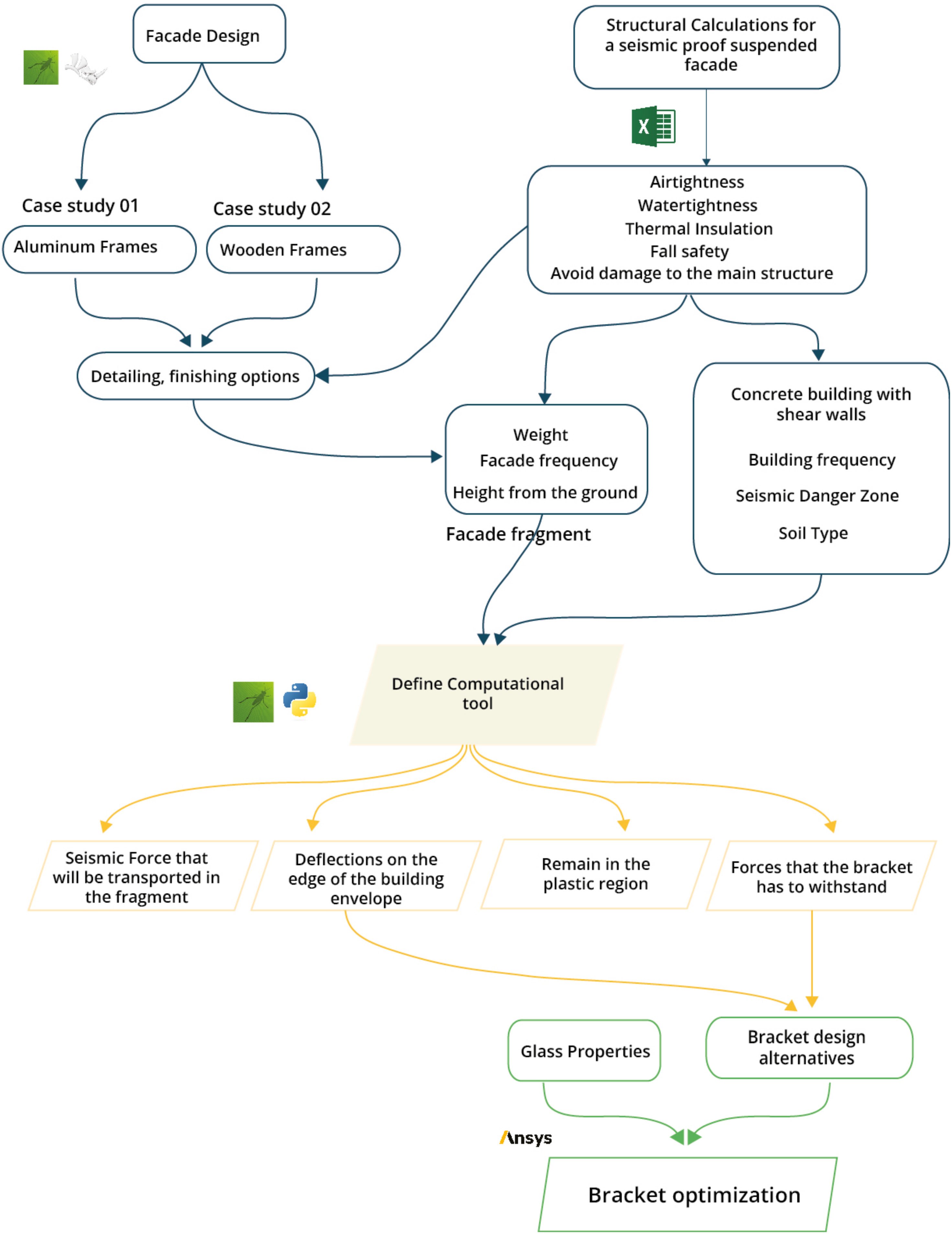


Diagram 02: Research Thesis Process Phases. Author's own work.

Design Vision

Design and develop a tool that will calculate the forces that a bracket must withstand in an extreme conditions (earthquakes), afterwards use Finite Element Method modelling and propose a new one made from glass.

Render 01: Interior of an office building. Author's own work.

2 Suspended Façades in extreme environmental conditions

2.1 Description of Aluminium and Timber Hanging Façades
2.2 Description of bracket connections
2.3 How earthquakes affect buildings
2.4 How the suspended facade is affected by these extreme conditions
2.5 The impacts associated with poor design
2.6 Critical parts of the suspended façade

Aluminium and Timber Hanging Façades

2.1 Description of Aluminium and Timber Hanging Façades

Curtain walls are a fundamental non-structural component of a building facade, with its main structural purpose aiming to insulate the interior from the outdoor environmental impacts. Within the construction discourse, we distinguish two fundamental façade typologies: loadbearing exterior façades and non-loadbearing façades. Non-loadbearing façades (curtain walls) stand independently in front of the building, forming an additional weatherproof envelope with glass and windows that are smoothly integrated. Experience has shown that the performance flaws of such structures frequently occur at floor-to-wall intersections. When considering curtain wall system, brackets lay a critical role supporting the façade fragments and connecting them to the main structure., Ensuring stability and functionality of the building envelope.(Herzog et al., 2004)

The façade's life cycle includes five stages: design, building, operation, repair, and destruction. Diagram 04 also depicts the important factors to consider throughout the façade design process. The façade design process is separated into two stages: concept design and detailed design. During the concept design stage, essential performance criteria such as thermal, acoustic, structural, fire, weather tightness, sustainability, security, and build ability are defined. To meet these objectives, architects investigate novel façade methods and materials that meet their aesthetic standards.
When choosing a façade material, consider mechanical and chemical qualities, technical properties, affordability, lifespan cost, and availability. Façade materials should operate effectively during their service life and in their intended purpose. The next phase in the façade design process is detailed design. To guarantee compliance with planning and construction standards, the performance criteria are revised and coordinated across many technical disciplines. Furthermore, the crucial elements of the facade interface are refined, and performance standards are set..(Fernando et al., 2023)

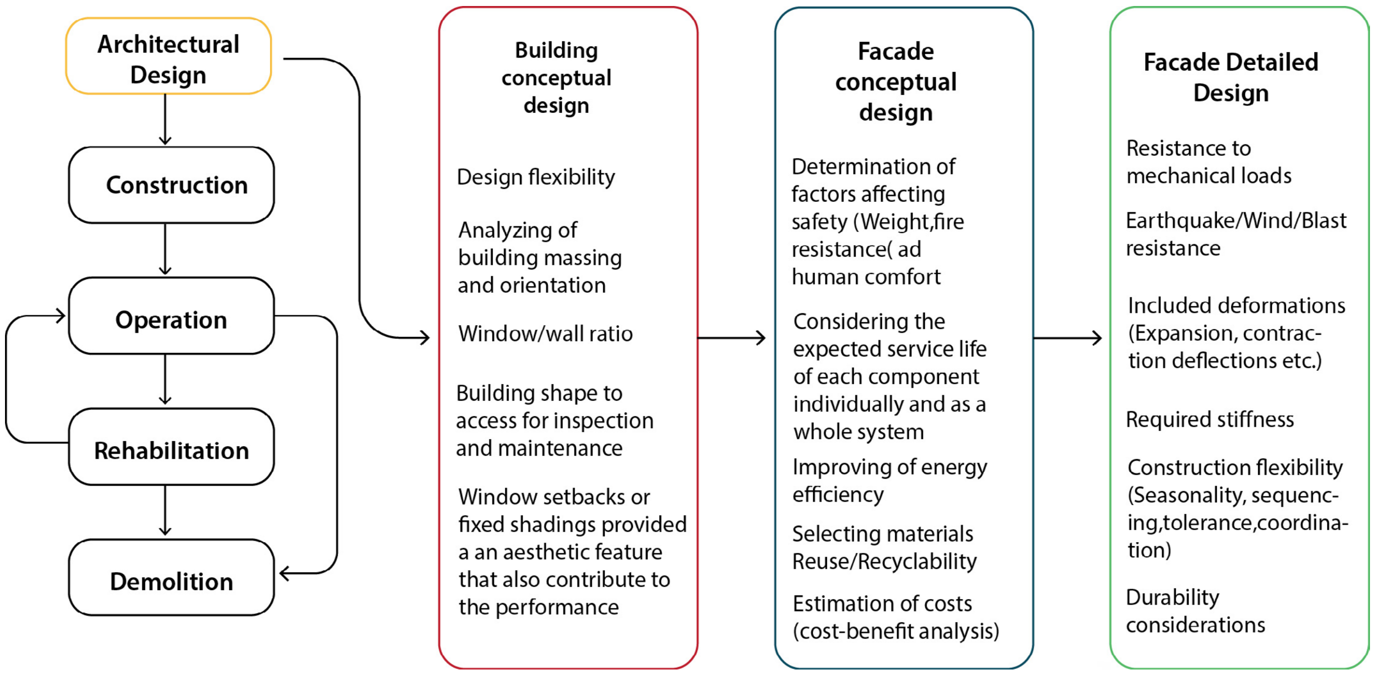


Diagram 04: Facade Cycles. (Fernando et al., 2023) Edited by author.

Aluminium and Timber Hanging Façades

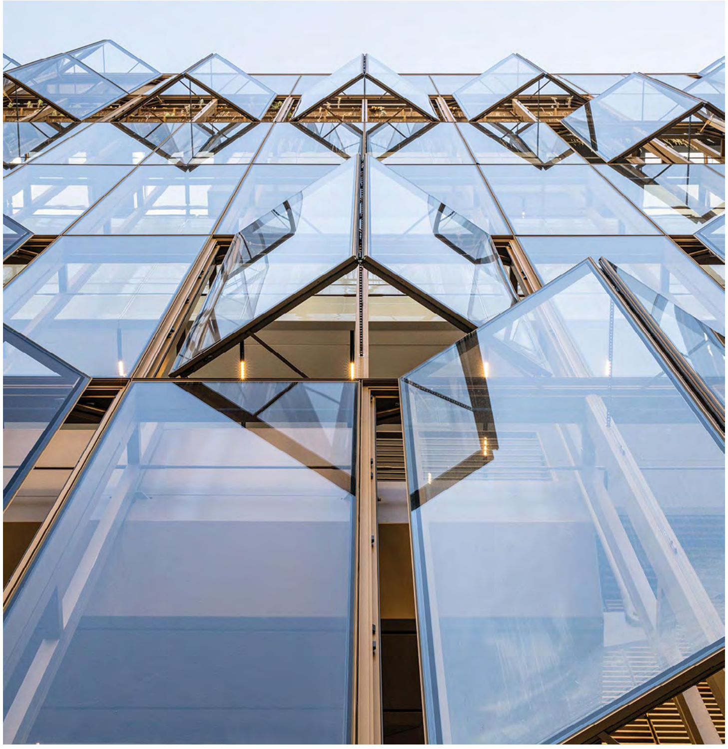
2.1 Description of Aluminium and Timber Hanging Façades

Suspended façades are separated in tree parts. The bearing structure, the climate zone and the finishing element.(See Diagrams 06,07,08). The bearing structure works as a beam that supports the infill frame. Bearing structure can be from a variety of materials as aluminium, steel, timber composites and structural glass. The main components of the curtain wall façades are the transoms, the mullions, the gaskets, the thermal block the infill(usually glass) and the finishing element that can be a cap or structural silicone. Transoms and mullions are designed very similarly, and their proportions are determined by the forces that they must bear. The distinction is that the mullions feature water channels that drain the water from the system. The mullions have channels, although they are much smaller. The design of the transoms and mullions influences the density of the seismic force as well as the absorption of vibration. To begin, the frequency of the element is determined by the stiffness of the mullions and transoms; another component influencing the frequency is its mass.

- Mullions are the vertical segments that hold the glass panels. They are meant to support the weight while also keeping the fragment water and airtight. When installing a curtain wall system, the mullions are installed first and fastened to the brackets before the glass panels and transoms are set up.
- Transoms are the curtain wall's horizontal caring parts. Transoms, like mullions, are meant to support the weight of the glass while also withstanding air pressure and blasts. In addition, they are designed for water and air tightness.
- Infill, Glass panel: The element that is placed inside the framing of the curtain wall façade is an infill, in most cases this is a glass plate, but it can also be made from stone, aluminium etc. The glass plate during an earthquake acts like a diaphragm (rigid element). More specifically the glass should be designed to never fail. All the forces must be transported to the mullions and the transoms, and that parts should either absorb and translate the force to movement and heat.(See diagram 00) (Murray, 2009)
- The Gaskets: The purpose of brackets is to allow the system to vibrate as well as assuring the airtightness and water tightness of the façade. This part is made from an elastomer material such as EPDM(ethylene propylene diene monomer)
- The thermal block in the centre of the element that limits the thermal bridge. Usually, this part is made from Polyurethane.
- The sealant between the glass panels Material: Silicone, Polyurethane): The aluminium cap. This part of the façade that transports the weight of the glass panels to the bolts and subsequently to the mullions and the transoms.
- Bolts are made from steel and are used for transporting forces from the glass plate to the mullions and transoms. They are also used in the bracket plates to transport the vertical, horizontal, and circular movements to the main building structure. The shape of the bolts differentiates depending on the directionality and the intensity of those forces.

Aluminium and Timber Hanging Façades

Uber Headquarters, San Francisco USA.
Architecture: SHoP Architects
Facade Advisor:Permasteelisas, Gartner

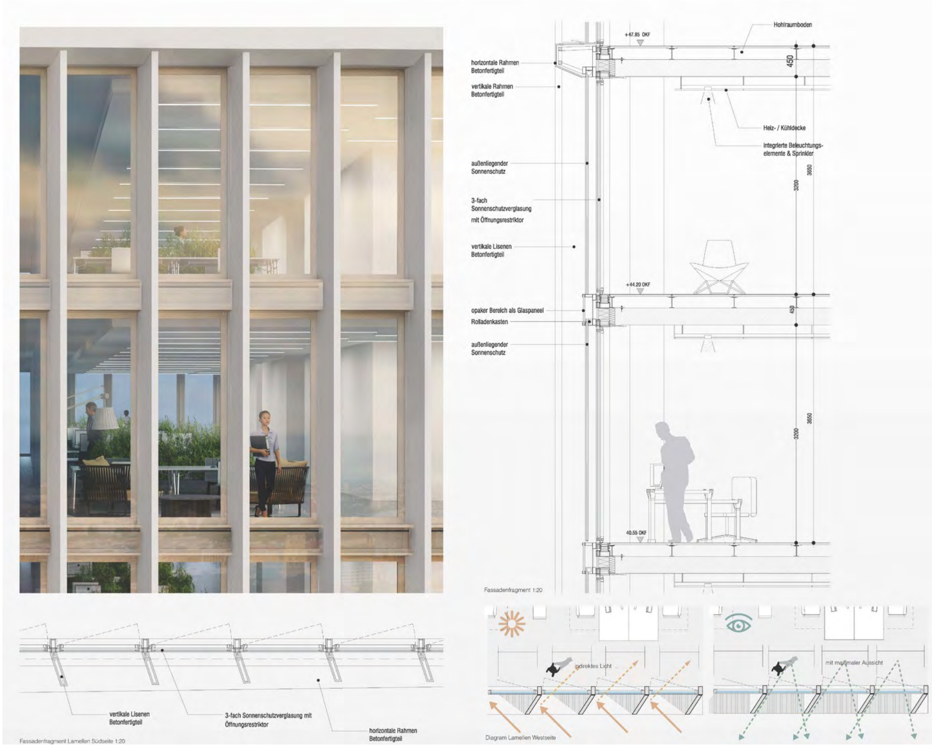


Picture 03 Source: www.architecturalrecord.com, SHoP Architects

Picture 05 Source: www.architecturalrecord.com, SHoP Architects

Aluminium and Timber Hanging Façades

Vertical Campus, Europaplatz
Architects: UN-Studio



Picture 04Source: UN Studio.com

Picture 06 Source: UN Studio.com

Aluminium and Timber Hanging Façades

Aluminum Frames

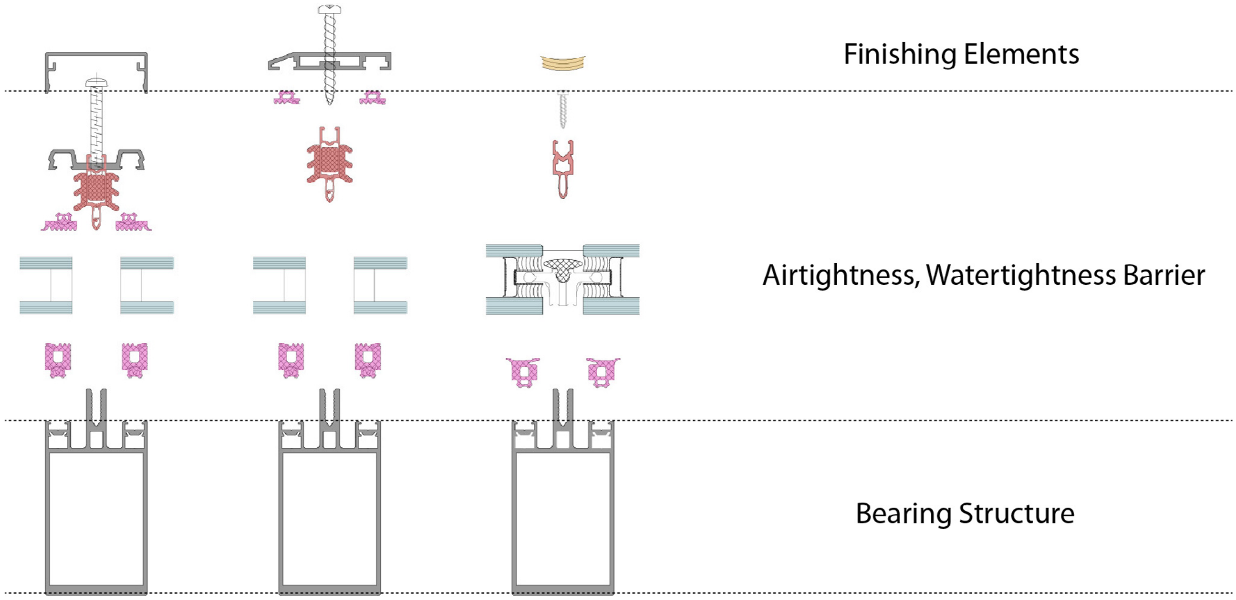


Diagram 05 Aluminuium Suspended Facade Zone Detailling, Detaill Source: Schuco, Model: FWS 50, Edited by Author

Timber Composite Frames

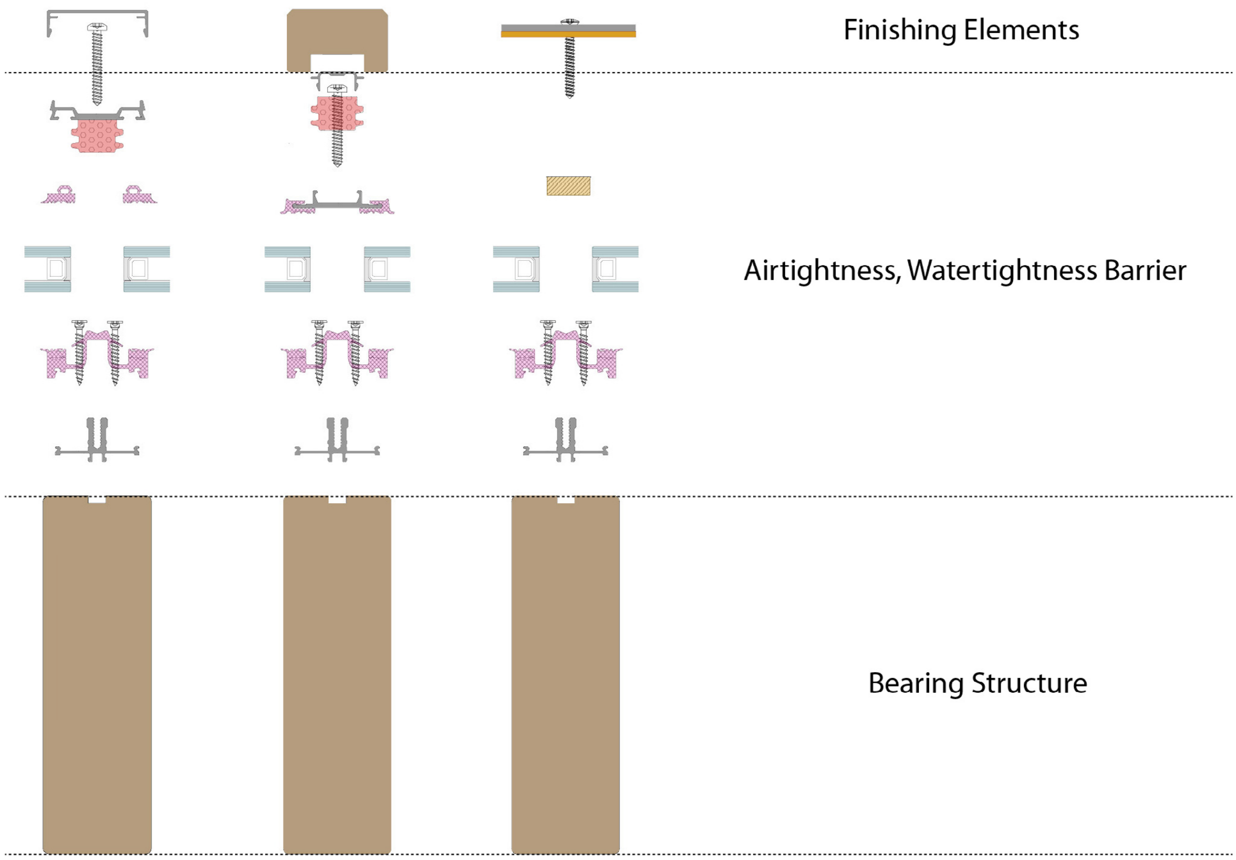


Diagram 06: Composite Timber Suspended Facade Zone Detailling, Detaill Source: Unicel Architectural, Model: Therm +56, Edited by Author

Aluminium and Timber Hanging Façades

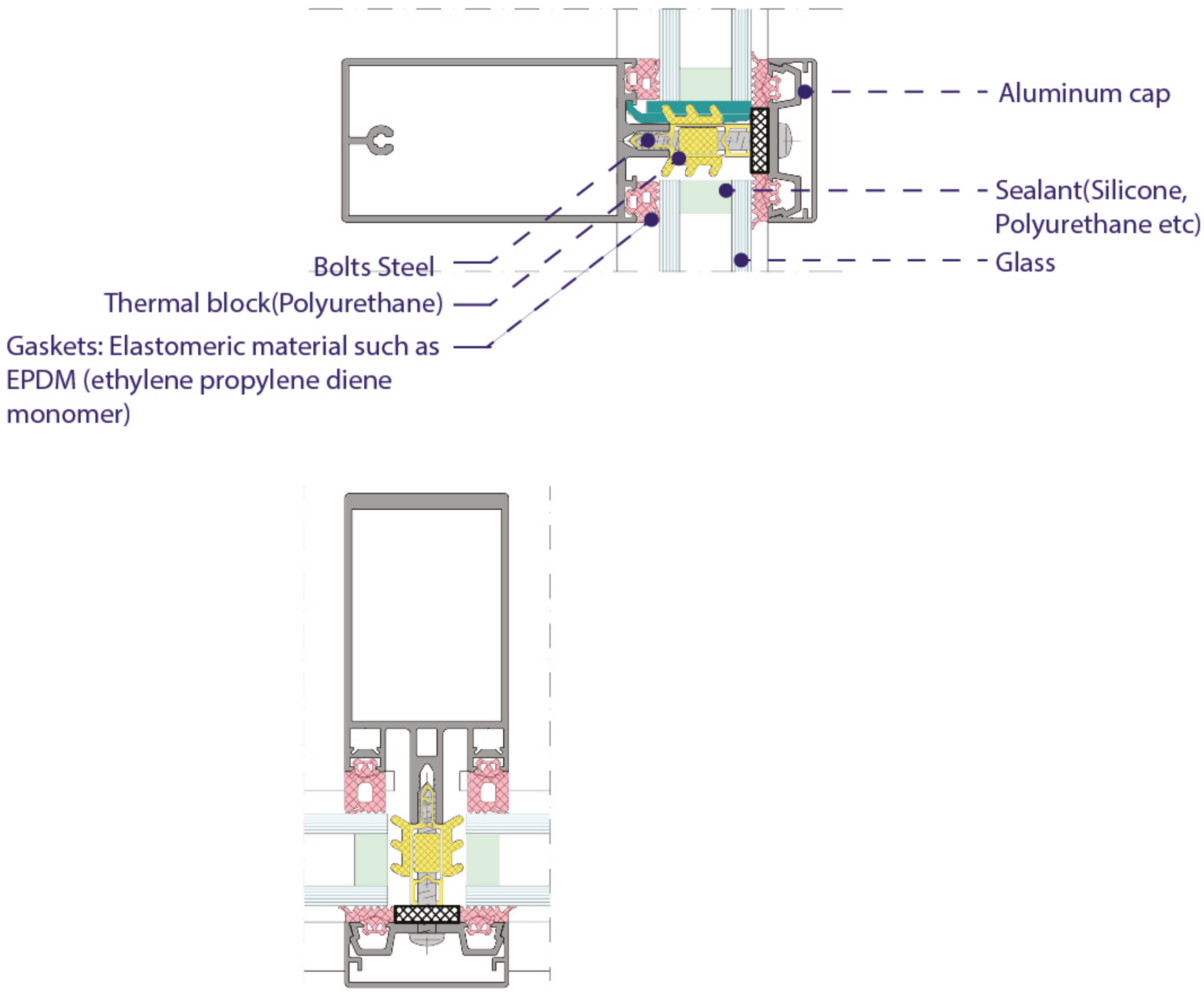


Diagram 07: Aluminuium Suspended Facade Components, Detaill Source: Schuco, Model: FWS 50, Edited by Author

Aluminium and Timber Hanging Façades

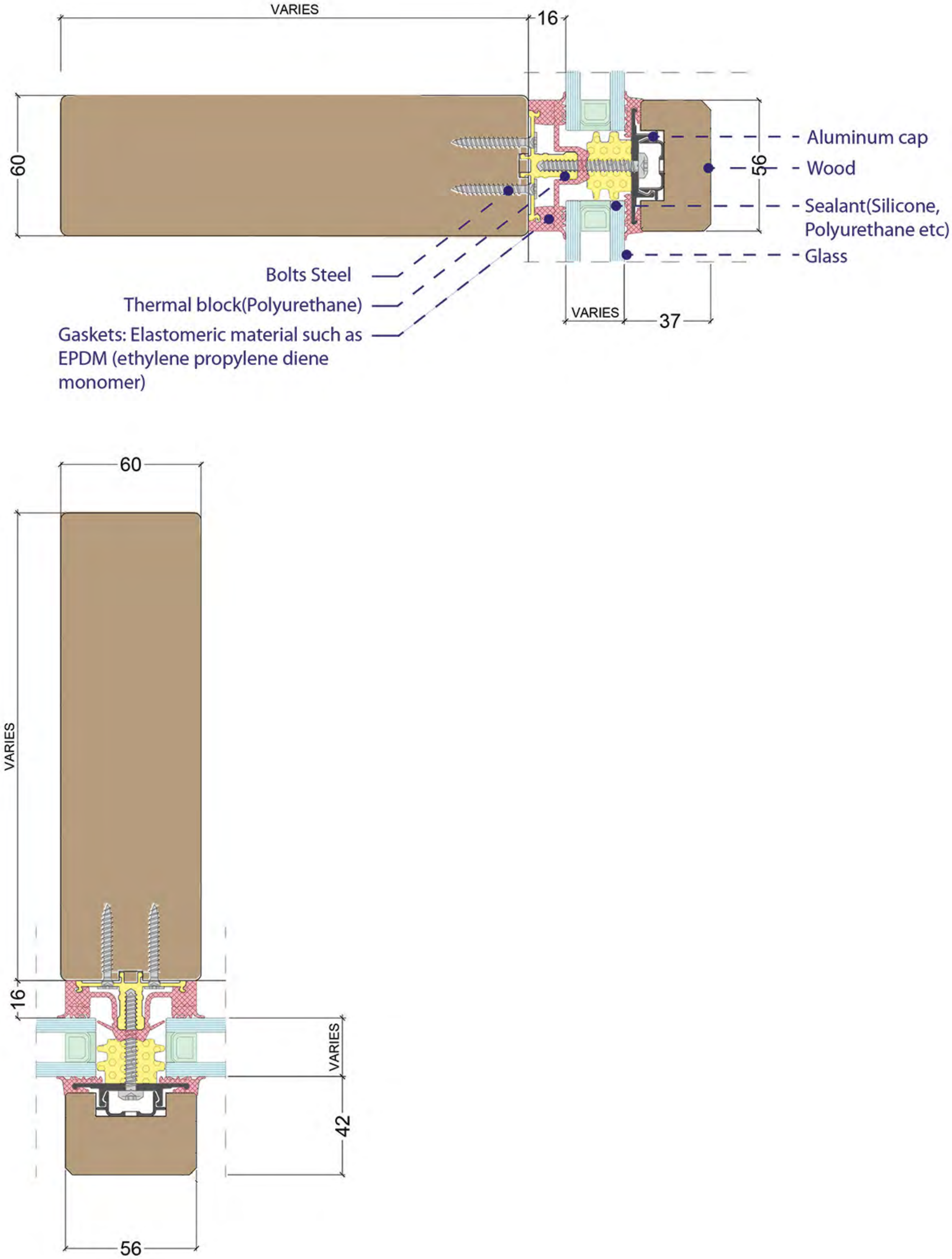


Diagram 08: Composite Timber Suspended Facade Components, , Detaill Source: Unicel Architectural, Model: Therm +56, Edited by Author

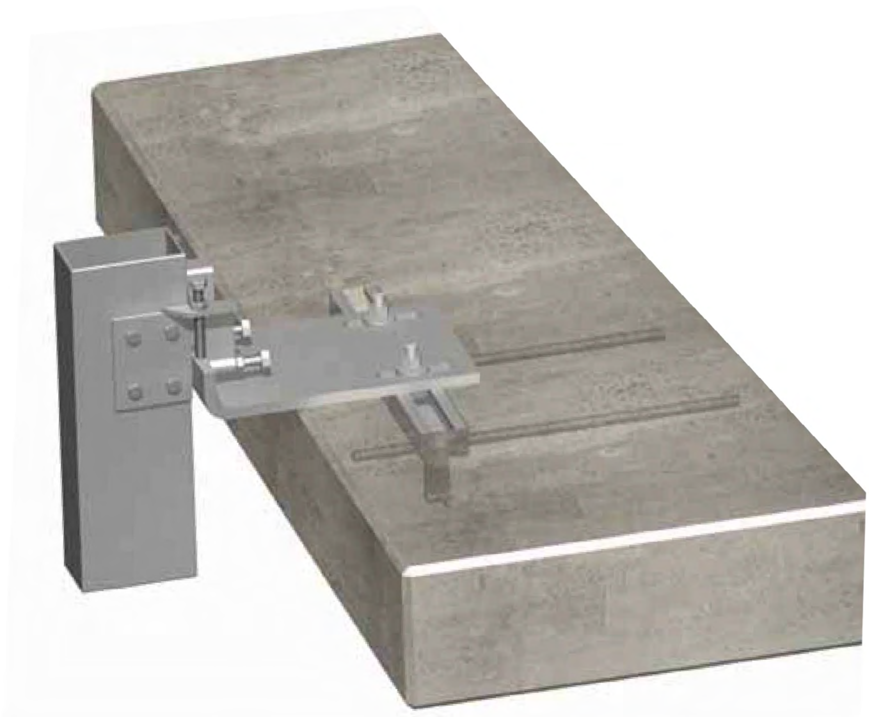
Bracket Connections

The anchorage system or bracket caries the loads from the curtain wall to the building's beams. Brackets vary in shape and size etherealness each system has two main features: a placed on top or on the side of the beam plate and an anchoring element made from steel with a hook for the easy assembly. The design of the system depends on the dimensions of the fragment, the wind load conditions, the seismic event and the outdoor conditions, also the design of each bracket must leave space for thermal tolerances and installation operations. During extreme wind loads and earthquake events, omnidirectional movements must be taken into consideration, and the anchorage system should be rigid and allow the circular movements of the system without failure. (Thai et al., 2020),(Enriquez, n.d.)

A bracket in a building façade is usually fastened at four points: two at the bottom and two at the top. In the United States, bottom connections are often bearing type connections, whereas top connections are typically tie-back connections. Although this configuration is simple, if the top connections fail, it can result in catastrophic collapse. (Enriquez, n.d.)

When considering the suitability of facade brackets for carrying horizontal and vertical loads in a top slab or edge slab application, both have their advantages and considerations:

The true balanced design approach permits to find a combination of glazing and framing that accomplishes the project specification request for both the façade elements by taking in account their dynamic interactions. However, other options could be pursued to find a successful design, in alternative to the upgrade of the glazing capacity.



PIcture 08: Top-Application Bracket by Halfen. Source: Halfen.com

Bracket Connections

Another possibility to modify the glazing-framing equilibrium consists of using a dissipative bracket instead of a rigid one. The dissipative bracket is a connection between the façade and the building structure that has a rigid behaviour under wind loading but collapses just above the maximum design wind load , allowing an overall movement of the façade and then an energy dissipation by means of inertial effect and permanent deformation of the crash absorbing material. In terms of resistance function of the overall bracket mechanism, one possible outcome is shown in the at the rights side, where the force versus displacement plot is taken from one experimental test conducted during the research and development process: the system should behave in elastic way beyond the maximum wind load (or other load combinations) with safety factor, while its plastic behaviour should be activated by means of a plateaus as much flat as possible within the acceptable plastic slip. (Lori et al., 2022)

For instance, aluminium tubes can buckle under several shape of deformation depending on the ratio of their length with respect to their thickness and their diameter with respect to the thickness. When the tube is relatively long, the Euler buckling governs the collapse, but this response is not the most suitable for the bracket design, as the resistance drops down in abrupt way. A rigid pin could be included to connect fixed and movable bracket part, in order to have redundancy with respect to the wind load resistance, if it is not considered safe enough to rely only on the crash absorbing components in elastic phase, because of resistance or allowable serviceability displacement reasons. During the movement the stresses on glazing and framing are likewise frozen and the beneficial effect can be included by an additional degree of freedom into the true balanced design chart. By applying a dissipative bracket, the balance of Fig. 6 can be transformed into the Fig. 9 chart, where the glass displacement results like translated at larger framing inertias, while the mullion displacement is translated to the smaller framing inertias.

Fixing of a curtain wall system using HCW-B2 Brackets connected to HTA-CE Cast-in channels

Fixing of a post and beam façade using HCW-ED Brackets on HTA-CE Cast-in channels

Fixing of a modular façade using HCW-ED Brackets on HTA-CE Cast-in channels

Typical curtain wall fixing with HTA-CE Cast-in channels

Picture 09, 10, 11, 12: Bracket Applications
Source: Halfen.com

Bracket Connections

1. Top Slab Application:
Advantages:
- Typically more accessible for installation and maintenance.
- Provides direct support from the top, distributing the load across the slab surface.
- Can better distribute vertical loads if the slab has sufficient strength and thickness to support the brackets.

Considerations:
- May necessitate reinforcement or specific structural design to support the concentrated loads at the top.
- The weight and distribution of the load should be carefully considered to avoid overloading the slab.

2. Edge Slab Application:
Advantages:
- Offers potential advantages in terms of lateral stability due to its position along the edge.
- May provide better support against lateral forces or wind loads if appropriately anchored to the building structure.
- Could potentially minimize the direct load on the top surface of the slab.

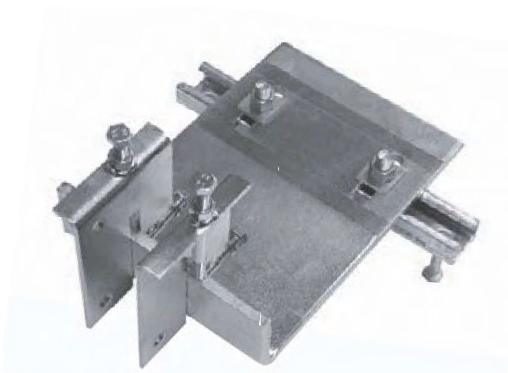
Considerations:
- Might require more complicated installation, especially if the edge detailing or structure isn't designed to bear additional loads.
- Structural integrity and safety measures are crucial to prevent potential failure or overloading of the edge slab.

Ultimately, the suitability of facade brackets in top or edge slab applications for carrying horizontal and vertical loads depends on various factors:

- Structural Design: Consideration of the building's structural design, load-bearing capacity, and intended use of the facade brackets.

- Load Distribution: How the loads are distributed and whether the slab can support these loads without compromising its integrity.

- **Installation and Maintenance:** Accessibility, ease of installation, and future maintenance requirements should also be factored in the decision-making process.(Halfen Curtain Wall Technical Information., n.d.)



Picture 13: Top-Slab Application
Source: Halfen.com

Picture 14: Edge-Slab Application
Source: Halfen.com

How earthquakes affect concrete buildings

Reinforced concrete structures featuring columns and shear walls are engineered to efficiently dissipate seismic energy. While columns provide vertical support, shear walls, strategically positioned throughout the building, counter lateral seismic forces. The mass and stiffness of a structure are pivotal factors influencing its behaviour during seismic events. When ground motion occurs, the building's bulk resists acceleration, with columns and shear walls aiding in transmitting lateral forces to the foundation, minimizing horizontal swaying, and maintaining the structure within its elastic range. Slabs and basements are integral components in seismic-resistant design, functioning as diaphragms crucial for distributing seismic forces and supporting the building during earthquakes. These horizontal elements link and reinforce the vertical elements, serving as the building's "floor" and "roof." During seismic events, these diaphragms aid in dispersing lateral forces across the structure, diminishing sway and deformation, thereby enhancing overall stability and preventing shearing of walls and structural elements. Well-designed diaphragms effectively absorb and distribute seismic energy, safeguarding both the structure and its occupants.(Alneyadi et al., n.d.)

Picture 15: Facade detachment after the earthquake in Samos, Greece in 2020
Source: cnn.com

How the suspended facade is affected by earthquakes

The curtain wall facade hangs from the building through a bracket system allowing for installation tolerances and accommodating the frequency of the structure. During moderate seismic events, the building may encounter significant ground basement acceleration. Consequently, the structural system, like other non-structural systems, follows a vibration path primarily dictated by the building's fundamental period. Seismic events create horizontal and sometimes minor vertical accelerations in the structure. The type of stress experienced depends on the building's structural system and materials. The Eurocode requires structural elements to be verified under static forces calculated after taking into consideration basement acceleration. To identify the worst load situation for non-structural systems, it is critical to assess their relevance, typology, fastening method, and location within the structure. Displacements, accelerations, and stresses.

Non-structural elements, while not vital for preventing building collapse, can absorb some energy acting on the building. Nonetheless, their failure must not endanger lives or impede the functionality of other systems, particularly life-safety systems like fire extinguishers. In seismic events, facade elements should remain functional, safe, and capable of delayed replacement if necessary. Thus, evaluating their behaviour during design is crucial to comprehend failure and collapse processes and implement preventive measures.

The failure mechanism of a non-structural element depends on its characteristics and the type of load it experiences—acceleration, displacement, or force. For curtain wall façades, like unitized and panellised systems, individual units are designed to withstand various actions and loads, especially wind pressure. Therefore, verifying glass, frame structure, and fastening system under wind loads also ensures compliance with seismic loads. Dynamic accelerations require a comprehensive understanding of the building's specific vibration characteristics in response to seismic actions. (Galli, n.d.)
Analysing the building's behaviour, obtaining its response to seismic and wind actions, and applying a time function acceleration to the facade unit are necessary. However, even with extensive analysis, the induced stress on components, primarily the fastening system, from this acceleration is significantly lower than that induced by wind loads at high elevations. Predictably, the relative displacement between adjacent stories poses the main risk to facade components. These components must withstand such displacements. Glass plates fixed by aluminium frames, while globally ductile, are vulnerable due to their rigid behaviour, potentially leading to contact-induced breaks and, in extreme cases, complete glass fallout.

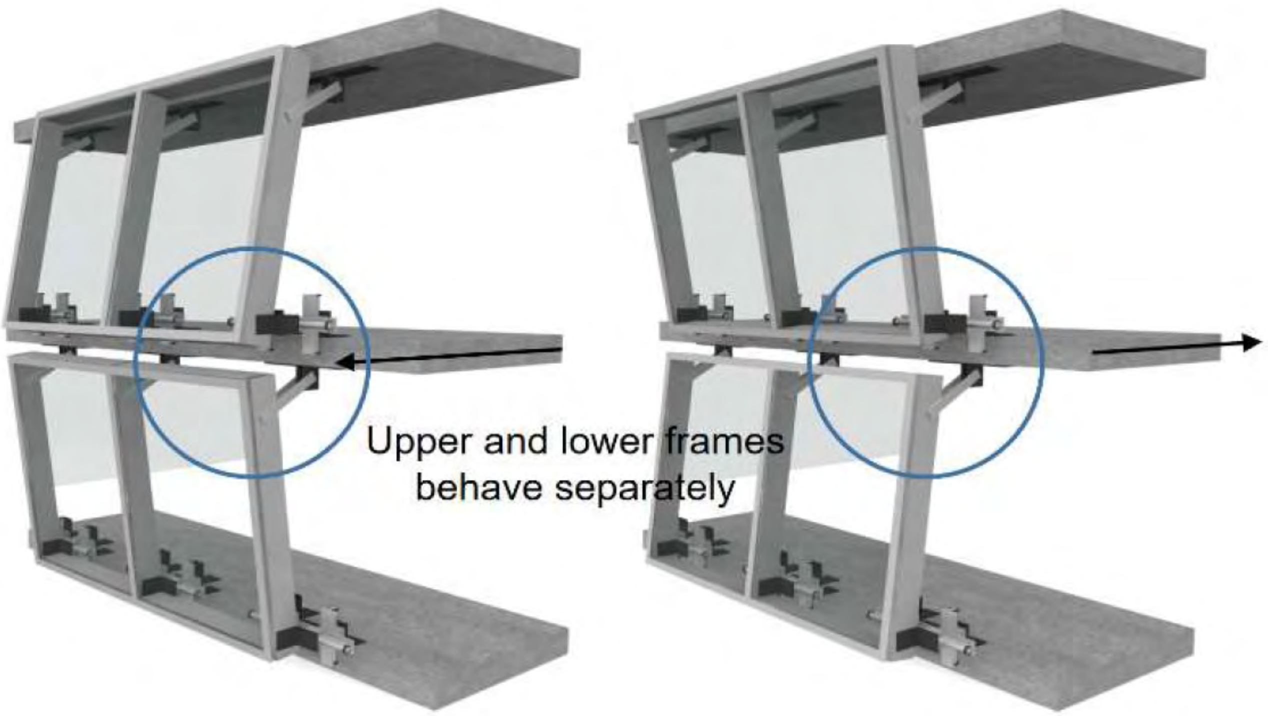
During an earthquake, the cladding's behaviour is determined by the cyclic interaction between the panels and the supporting primary structure, and the connections are generally subjected to three principal impacts at the same time:

- Inertia forces created by the panel's acceleration were transferred from the component to the main structure via connection shear loading.
- Horizontal inter-story movement is resisted by the panels, resulting in horizontal shear stresses in the connections.
- The gravity load of the panels is sustained by the bearing connections. (Galli, n.d.)

How the suspended facade is affected by earthquakes

2.5 The impacts and danger associated with poor design.

A poorly designed facade can lead to various issues related to thermal energy, structural integrity, and acoustics. While concerns like thermal comfort and noise insulation are important for occupant well-being and building durability, the structural aspect of facade design is paramount for life safety. Especially in tall buildings where wind pressure can be substantial, the loads exerted on the facade pose a significant risk to the safety of individuals both inside and outside the structure. Therefore, ensuring that the facade is structurally sound is essential to mitigate potential hazards and safeguard the lives of occupants and passers-by.(Galli, n.d.)



Picture 16: Seismic Reaction of a Suspended facade.
Source: Seismic and Energy Performance Evaluation of Large-Scale Curtain Walls Subjected to Displacement Control Fasteners. Authos: Lee, H.; Oh, M.; Seo, J. Kim, W.

How the suspended facade is affected by earthquakes

2.6 Critical parts of the suspended facade during multi-hazard events

As previously stated, a curtain wall facade is a non-structural element that is hung and connected to the building structure utilising a bracket system that secures it, allowing for installation tolerances and natural building motions. A seismic event, however, can cause a significant amount of ground basement acceleration in the building. The structural system, including all other non-structural systems, maintains its own vibration pattern that is primarily determined by the building's basic period. The intensity of the seismic force in the fragment depends on the building and the fragments structural properties as well as the site in which the project I placed. More specifically the soil type of the site, the seismic danger zone, the ductility class of the buildings structural system, the height, all affect its frequency and consequently the horizontal seismic force in the fragment. The geometry, the material of the mullion and transoms, the distance of each fragment from the diaphragmatic basement, as well as the weight of the suspended system affect the seismic force. These parameters also describe how the structure responds to excitations such as wind pressure.(Galli, n.d.)

A suspended façade during an earthquake poses little or no risk to the main building. The fragment nevertheless in the case of poor design can affect the residents in the indoors or the ones passing by. The important issues to be addressed are the maintenance of the original properties of the façade. These are the airtightness, the strong levels of water tightness, the thermal insulation, the fall safety as well as the avoidance of the damage to the main structure and the other non-structural elements of the building. Consequently, it is required to evaluate cautiously the behaviour of the suspended façade when subjected to the seismic forces to apprehend the intentional failures and make sure to prevent them and create a durable façade design.

Each part of the façade system is subjected to the vibrations created by the seismic force as well as the wind action. Air pressure in high rise buildings is the predominant load in which the design is based on. This horizontal force can be perpendicular as well as parallel to the system. This force is considered a continual load and it is not combined with the seismic load. The assumption is that a wind-storm and an earthquake cannot combine. Consequently the glass thickness, the mullions the mullions and the substructures in the system are defined firstly by the wind load and the seismic force can also be in that range of design.(Galli, n.d.)

The outcome of the building's acceleration and vibration, as well as the façade fragment, is thirst, which is transferred into strains in the bracket. The design of the bracket can influence the vibration of the façade and function as an energy-absorbing element, reducing the amount of energy delivered to the hanging piece. (Abtahi & Samali, 2014)

How the suspended facade is affected by earthquakes

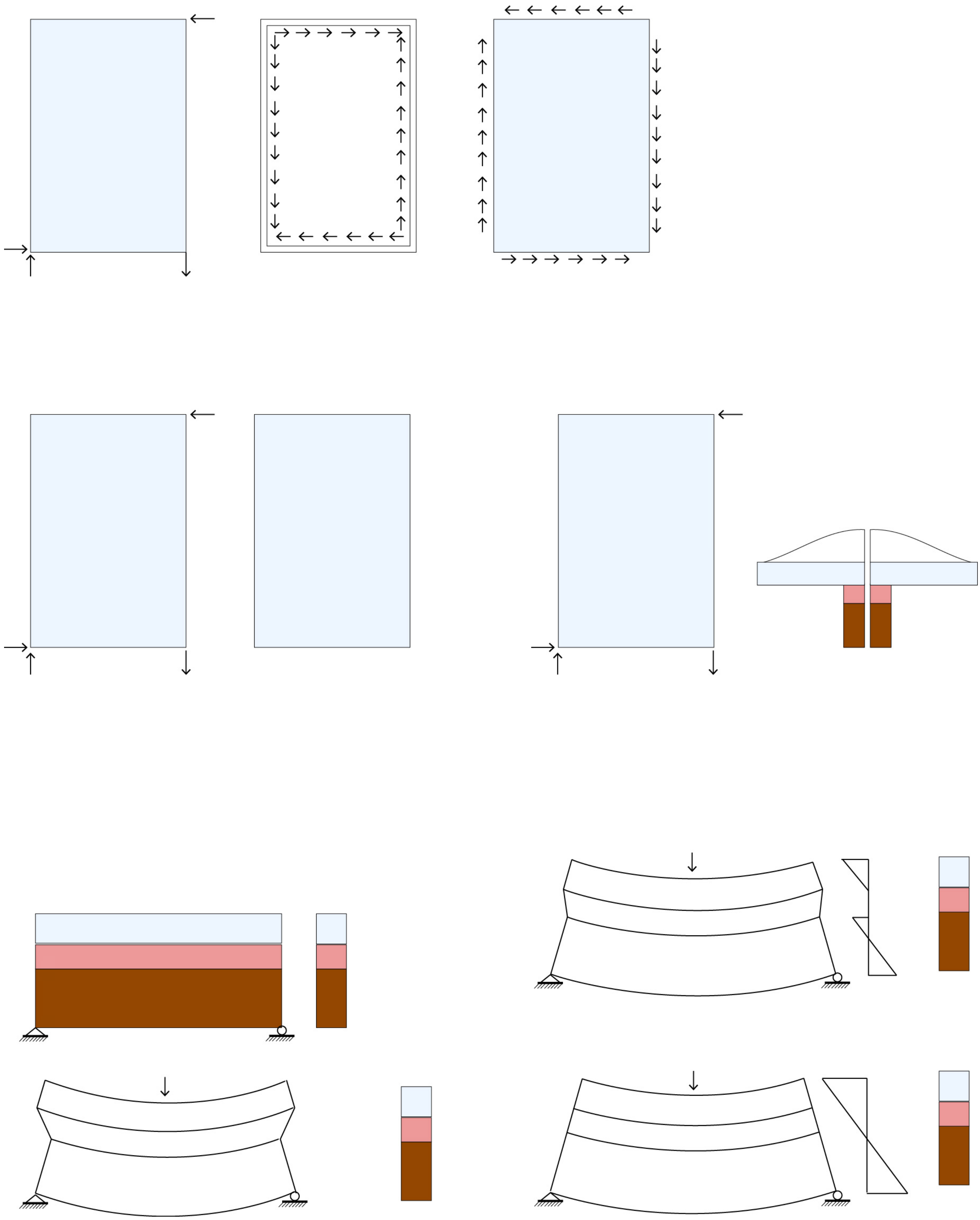


Diagram 09: Shear forces in the Facade Plane.
Source: Structural Principles of Timber- Glass composites. Modified by (Swedish wood, 2016

3 Finite element analysis and materials

Material Research, Aluminium

Aluminium Frames

Aluminium is the primary material used in the main structural supporting system of curtain walls. It serves as the material for anchors, brackets, and profiles of the suspended facade. The material exhibits high strength-to-weight ratios, resistance to torsion, and possess sustainable and recyclable properties. This lightweight design not only makes handling and shipping easier, but it also saves money and has a lower environmental effect. Furthermore, aluminium has excellent corrosion resistance due to the creation of a natural oxide layer when exposed to air. This layer serves as a protective barrier, therefore increasing the material's durability. Surface treatments such as anodizing improve aluminium's corrosion resistance, confirming its position as a popular choice for facade building. (Aung et al., 2023)
In addition to its corrosion resistance, aluminium has great thermal conductivity, allowing for efficient heat transmission. This characteristic is useful for managing inside temperatures and reducing energy consumption on building façades. However, aluminium's high thermal conductivity may cause problems in colder areas where heat retention is critical. Despite this, aluminium's lightweight nature, corrosion resistance, and thermal conductivity make it suitable for a wide range of façade applications. With a thorough grasp of these material qualities, architects, engineers, and researchers may make educated judgements on the use of aluminium in building façades.(Aung et al., 2023)

Ferrous alloys	Shear strength (GPA)	Young Modulus (GPa)	Density Kg/m3	Embodied carbon (Kg/Kg)
Medium carbon steel	77-85	200-220	7.80E+03	1.05-1.2
High carbon steel	77-85	200-220	7.80E+03	1.05-1.2
Low alloy steel	77-85	200-210	7.80E+03	1.05-1.2
Cast Iron, white	72-85	185-210	7.6E3-7.8E3	1.29-1.5
Coated steel, steel galvanized	79-84	200-215	7.8E3-7.9E3	1.71-2.01
Low carbon steel	79-84	200-220	7.8E3-7.82E3	1.05-1.2
Coated steel, stainless steel, terne coated	79-84	185-200	7.6E3-8.1E3	3.34-3.96
Wrought iron	75	185-195	7.4E3-7.8E3	1.23-1.44
Cast iron, nodular (sheroidal, ductile)	64-71	170-180	7.05E3-7.15E3	1.05-1.2
Cast iron, gray (flake grafite)	37-55	94-140	6.94E3-7.23E3	1.05-1.2

Non-ferrous alloys	Shear strength (GPA)	Young Modulus (GPa)	Density Kg/m3	Embodied carbon (Kg/Kg)
Aluminium alloy 96061, T4)	25.5-26.9	66.6-70	2.69E3-2.73E3	7.47-8.6
Aluminum, pure(1200, H4)	25-27	69-72	2.68E3-2.74	7.41-8.53
Brass	35-40	95-110	8.07E3-8.48E3	3.3-3.74
Bronze	38-49	97-130	8.05E3-8.7E3	3.93-4.45
Copper	44-50	120-140	8.94E+03	3.76-4.25
Lead alloys	4.3-6	14-17	1.05E4-1.13E4	1.61-1.92
Lead coated copper	45-54	112-148	8.93E3-8.94E3	3.25-3.68
Magnesium alloys	16-18	42-46	1.78E3-1.84E3	11.7-13.8
Nickel alloys	70-83	180-210	8E3-8.65E3	8.49-9.86
Tin	14-18	41-45	7.26E3-7.27E3	7.94-8.91
Titanium alloys	38-45	110-120	4.43E3-4.79E3	17.8-21.4
Tungsten alloys	120-140	310-370	1.69E4-1.86e4	27.2-31
Zinc alloys	26-40	75-96	5.71E3-7.16E3	3.27-3.67

Table 01: Non-Ferous Alloys Material Properties
Source: Ansys EduPack, Created by Author

Wood composite frames

While aluminium is a strong material, it lacks thermal resistance. To address this issue, thermal breaks are frequently built into aluminium frames to offer the necessary insulation. On the other hand, wood has greater thermal characteristics and is thought to be more sustainable. Facade fabricators are using innovative composite mullions to take use of the benefits of both materials. These mullions combine the structural strength of aluminium with the higher thermal performance and sustainability of wood. Mass wood products, such as Glulam and laminated veneer lumber (LVL), are highly valued for their strength and environmental friendliness. The paragraph also provides a list of appropriate wood materials for facade applications, which includes solid softwood or hardwood timber, finger-jointed solid wood, laminated beams, cross laminated timber, and LVL materials to achieve a balance between structural integrity and thermal efficiency.

Glulam or glued laminated timber

Glulam, or glued laminated lumber, is a structural material made up of several layers of finger-jointed boards bound together in the same direction. Glulam beams may be made in a variety of sizes and forms, with cross sections that are either uniform or have varying stresses. Some Glulam beams may have reinforced outer lamellas, resulting in linked Glulam. While glulam beams may not be as strong as solid beams, their strength distribution is more uniform across the element. Bending or shear forces are common causes of Glulam beam failure. Bending can produce tensile failure along the grain of the outer layers, whereas fractures along the grain can reduce shear capacity, usually owing to drying effects. Overall, Glulam's design versatility and constant strength distribution make it a popular choice for a wide range of structural applications.

Laminated veneer lumber (LVL)

Laminated Veneer Lumber (LVL) is a product composed of many layers of thin veneers, each approximately 3mm thick, with grain direction always lengthwise. To put together hot glue is placed in between layers until firm. It can manufacture beams up to 15 metres long, 1 metre wide, and 300mm thick. According to reports, LVL possesses high bending, tension, compression, and shear strengths, as well as a moderate elastic modulus. (Pantaleo, Roma, & Pellerano, 2012)

Material Research, Timber Composites

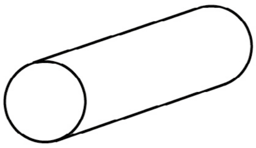
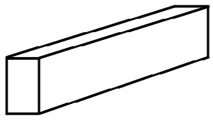
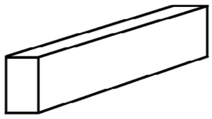
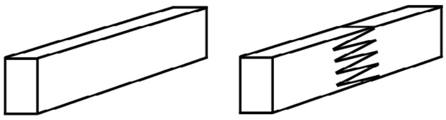
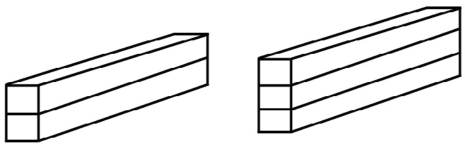
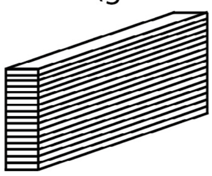
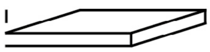
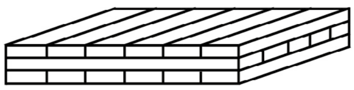
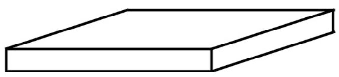
Components	Timber	Wood types
Solid Wood 	Solid Softwood Timber 	Spruce, Fir, Pine Larch, Douglas fir
	Solid hardwood Timber 	Beech, Oak, Poplar(not widley used), Maple, Alder, Birch Cedar, Ash
Finger-joined solid wood	Construction timber 	Spruce, Fir, Pine, Larch, Douglas fir
Laminated beams	Double triple laminated beams 	Spruce, Fir, Pine, Larch, Douglas fir Poplar
	Glulam (glue laminated beams) 	Spruce, Fir, Pine, Larch, Douglas fir Western Hemlock Cedar
Laminated planks 	CLT (Cross Laminated Timber) 	Spruce, Fir, Pine (not so widely used), Larch, Douglas fir
	LVL (Laminated venner lumber) 	Spruce, Beech, Pine, Douglas fir

Diagram 10: Types of Wood. Created by Author

SoftWood species	Shear strength (GPa)	Modulus of Elasticity (GPa)	Density Kg/m3	Embodied carbon (origin)
Spruce European	0.6 –0.74	14,3 – 17,4	460 - 560	N Europe
Spruce Sitka	0.71 – 0.87	10,7 – 13,1	400 – 490	UK
Fir Silver	0.61 – 0.75	10,8 – 13,2	400 – 490	C/ S Europe
Douglas Fir	0.87 – 1.06	12,2 – 14,9	480 – 590	N America
Pine Scots	0.83 – 1.01	11,8 – 14,4	480 - 580	UK
Pine Maritime	0.95	12	510	Europe
Pine Radiata	0.99 – 1.21	10,1 – 12,3	460 – 570	S Africa
Pine Southern	0.94 – 1.15	13,5 – 16,5	590 – 730	S America
Pine Corsican	1.02	13	510	Europe
Larch European	0.95 – 1.17	12,2 – 14,9	520 – 640	N Europe
Larch Siberian	0.99	10,6	560	N Europe
Cedar Lebanon	0.676	8,4	580	Europe
Hemlock	0.8 – 0.98	11,1 – 13,6	450 - 550	N America

Hardwood species	Shear strength (GPa)	Modulus of Elasticity (GPa)	Density Kg/m3	Embodied carbon (origin)
Oak	1.04	13,7	670 – 720	C/ N Europe
Teak	1.17 -1.43	10,6 – 12,9	610 – 750	S Asia
Keruing	1.28 – 1.57	14,1 – 17,3	770 – 940	SE Asia
Beech	0.9 – 1.1	14,2 – 17,3	680 – 830	UK
Poplar	0.57 – 0.69	9 – 11	430 – 530	Europe
Angelique	1.03 – 1.26	14,9 – 18,3	670 – 810	N America
Ekki / Azobe	1.23 – 1.51	18,1 – 22,1	960 – 1.180	W Africa
Meranti	0.94 – 1.15	10,6 – 12,9	510 – 630	SE Asia
Frake / Limba	0.87 – 1.07	6,9 – 8,4	420 – 520	W Africa
Padauk	1.22	13,5	640 - 850	W Africa

Table 02: Softwood, hardwood species Material Properties
Source: Ansys EduPack, Created by Author

Strength properties
$X_d = \Phi(k_{mod} * X_k)\ \gamma_m$
$X_d = X_k / \gamma_m$
kmod = modification factor for service class and load duration
Φ = multiple of relevant member and system modification factors
X_k = characteristic value of strength property
γ_m = material safety factor

K_{mod}. Only for structural timber. Source: (M.Y.H. Banglash, 2009)

Load duration classes	Accumulated duration	Service Class 1	Service Class 2	Service Class 3	Examples of loading
Permanent	>10 years	0.6	0.6	0.5	Self-weight
Long-term	6 months –10 year	0.7	0.7	0.55	Storage
Medium-term	1 week – 6 months	0.8	0.8	0.65	Snow load
Short-term	< 1 week	0.9	0.9	0.7	Wind load
Instantaneous		1.1	1.1	0.9	Accidental load

Material	γ_m
Structural imber	1.3
Glued laminated timber	1.25
CLT	1.3
LVL, plywood, OSB	1.2
Wood connections	1.3
Punched plate connect	1.25

Material Research, Timber Composites

Mass timber product for e Glulam, LVL and solid structural timber		Modulus of Elasticity (GPa)	Density Kg/m3
Europian Spruce	Structural timber	2,8 – 3,41	5.940 – 7.228
	Glulam	2,88 – 3,55	6.178 – 7.517
	LVL	3 – 3,7	6.435 – 7.830
Beech	Structural timber	4,15 – 5,08	5.898 – 7.186
	Glulam	4,32 – 5,28	6.134 – 7.473
	LVL	4,5 – 5,5	6.390 – 7.785

Table 03: Mass Timber product Material Properties
Source: Ansys EduPack, Created by Author

How timber façades react to earthquakes

The comprehensive assessment of vertical structural elements within light-frame wood construction under seismic conditions necessitates a meticulous consideration of performance criteria encompassing immediate occupancy, life safety, and collapse prevention. These distinct performance levels hold paramount importance in ensuring the structural integrity and safety of the building during and after seismic events. Immediate occupancy standards address the need for the structure to remain functional post-earthquake, facilitating safe and swift evacuation.

Concurrently, life safety requisites aim to safeguard occupants' lives by maintaining structural stability during seismic disturbances. Furthermore, collapse prevention criteria emphasize the structural robustness required to prevent catastrophic failure, emphasizing the resilience of the building against seismic lateral drifts. Hence, meticulous calculations accounting for these performance levels become imperative to evaluate the capability of vertical structural elements in light-frame wood construction to endure seismic effects, particularly concerning transient lateral drifts induced by seismic activity. (Ellingwood et al., 2004)

Material Research, Structural Glass

Structural Glass

In this chapter, we embark upon an exploration of the intricate design considerations inherent in incorporating structural glass elements within architectural frameworks. These elements serve dual roles, bearing direct loads as primary components such as columns, staircases, balustrades, and beams, while also enduring the nuanced forces imposed by wind, thermal fluctuations, self-weight, and variable actions.

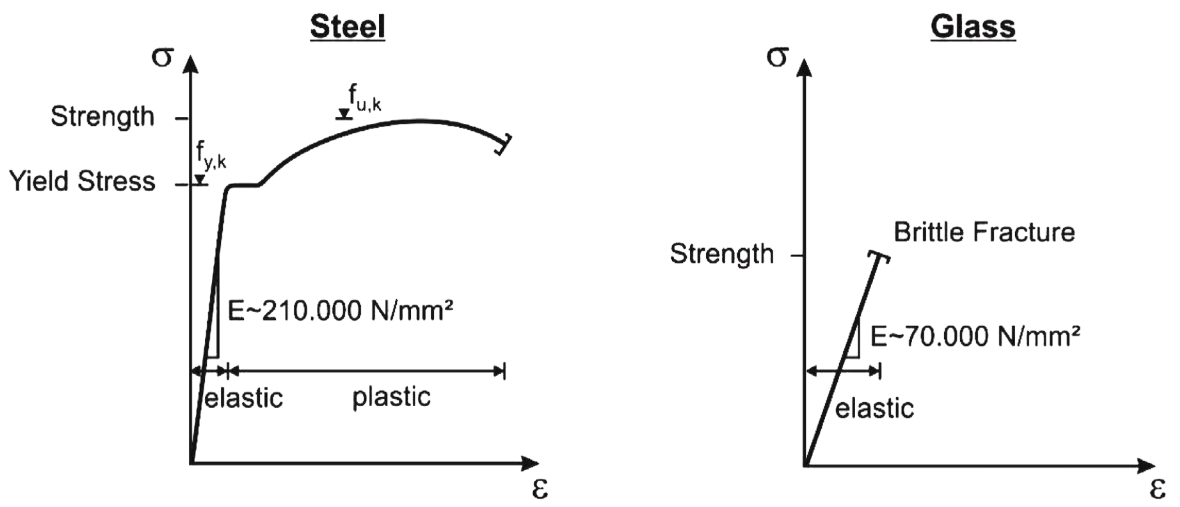
Structural Glass Material Properties

When compared to traditional structural materials like steel or aluminium, glass displays unique mechanical behaviour. Glass, unlike its equivalents, lacks ductility and is a brittle material that fractures under force without yielding. As a result, anticipating its failure is difficult due to its proclivity for rapid and unexpected fracture patterns. Figure 2.1 depicts the empirical data that define the failure characteristics discovered during testing of 6mm thick basic annealed glass.(C O'Regan, 2014)

Glass Types

The principal glass typologies that can be found in a curtain wall, or, more broadly, in a building façade, are mentioned below:

- Annealed float glass is carefully cooled after being formed in a molten tin bath. The gradual, homogeneous cooling to ambient temperature creates a reasonably stress-free material that may be cut, drilled, edge worked, and so on.
- Heat-strengthened (HS) glass is twice as robust to wind stresses as regular annealed glass. It is created similarly to FT glass, as described below.
- Fully tempered (FT) glass is four times more durable than annealed glass.



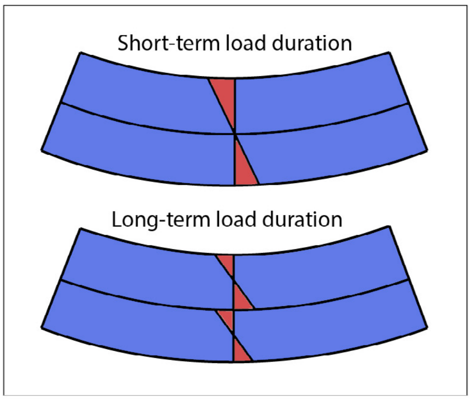
Picture 17: Stress to strain diagram for Steel and Glass
Source: (Matthias Haldimann, 2006)

Material Research, Structural Glass

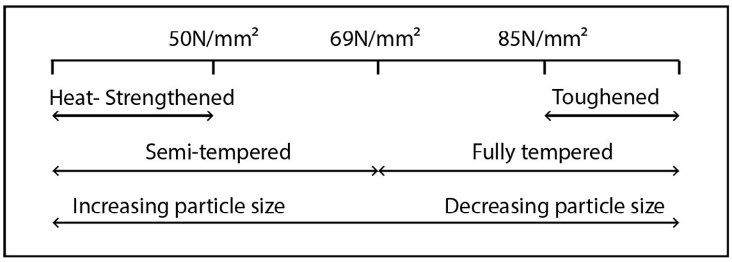
The thermal processing techniques for HS and FT entail heating the glass till it softens, then evenly chilling it on both sides with strong air blasts to quickly cool and harden the outer surface. The innermost layer of the glass subsequently cools off, shrinks, and compresses the skin, causing an equal and opposite tensile stress in the virtually faultless central core of the glass thickness. HS glass has a gentler quench process compared to FT glass, resulting in reduced compressive stress on external surfaces. Because glass breaks primarily under tensile stress, any wind load causing bending must first overcome the heat treatment process's built-in compressive stress, making heat-treated glass significantly stronger than annealed glass, which has virtually no built-in surface compressive stress. Because heat-treated glass (HS and FT) has had its temperature elevated to the point where the glass becomes soft, it will not be as flat as annealed glass and will frequently show some noticeable distortion, especially in reflected pictures when viewed at greater distances. When shattered, HS glass breaks into relatively big fragments, comparable to annealed glass, but FT glass shatters into countless cubes, each roughly the size of the glass thickness.(C O'Regan, 2014)

Before performing any heat treatment, HS or FT, or chemical tempering, the annealed glass piece must undergo edge working, bevelling, hole drilling, vee grooving, sand blasting, and so on. Surface treatment of any kind that penetrates the compressive skin of a heat-treated object may only diminish its strength, generally by an unknown amount, and must thus be avoided.

Laminated glass is created by enclosing multiple layers of equal or varying thicknesses of glass with a transparent adhesive layer. This interlayer, often polyvinyl butyral (PVB) or epoxy between two plies of glass, has roughly the same strength and rigidity as monolithic glass under short-term stresses, but behaves as a "safety glass" when shattered, staying in the frame and providing high penetration resistance. The uniform load resistance is difficult to calculate precisely. The plastic bridging materials are rigid under short-term stresses, particularly at room temperatures and below, causing the glass to behave monolithically under short-duration loads. For long-term loads or high temperatures, a more cautious option is to adopt a layered approach, which assumes that each ply takes half the load (assuming they are of equal thickness) with no shear stress resistance given by the interlayer.(C O'Regan, 2014)



Picture 18: Short and Long-term loading stress distribution. Source: Matthias Haldimann, 2006



Picture 19: Chart of glass types comparing their strength and particle size following failure. Source: (Matthias Haldimann, 2006)

Material Research, Structural Glass

The main argument for using laminated glass is to shield the building envelope from exposure; hence, the essential variable becomes the load resistance of the interlayer material itself after the glass plies have shattered. If necessary full-scale testing is the best way to achieve this number. As a result, and considering on the varied type of glass we study, impacted by how it has been formed and manufactured, the consequences of its failure might truly vary.(Galli, n.d.)

The primary concern to life safety, particularly for someone walking next or below a façade, is glass fragments coming down. The annealed variety is perhaps the worst since it breaks into huge and wide shards and cannot stay in the frame once shattered, posing a significant threat to anybody walking underneath. The heat-strengthened behaves in a similar manner, except for the greater levels of load resistance.(Galli, n.d.)

Fully tempered glass, on the other hand, behaves differently due to the uniformly high compressive stress condition. In actuality, the glass breaks into minute shards, about the width of a plate, which are far smaller and hence less harmful than those caused by annealed glass rupture. Furthermore, it is interesting how the glass panel, when broken vertically, does not fall out of the frame unless it is subjected to a strong horizontal stress. Finally, the laminated glass has the added benefit of remaining in the frame even after it has ruptured, thanks to the PVB keeping the fragments locked in their original location. For the above reason, its selection might be advised or even mandated by the codes and standard local regulations for sloping glazing or even vertical glazing of the façade in cases of significant horizontal stresses (for example, earthquake or wind loads).(Galli, n.d.)

Connections in Glass

Traditionally, the integration of connections within glass structures has required a deliberate strategy, which frequently included the interposition of resilient materials such as plastic, rubber, and wood between strong components. This deliberate choice helps distribute the applied forces throughout the structure while accommodating possible flaws or faults in the glass itself. Despite the multiplicity of connection designs, their underlying goal remains consistent: to reduce localised pressure points and improve the structural integrity of the assembly. This method is applicable to anything from simple continuous connectors with silicone spacers in direct touch with the glass to bolted connections with a hard-plastic bush against the glass. Recent developments in sealants have enabled glass to be bonded directly to glass, eliminating the requirement for an intermediate material between supporting pieces. There are worries concerning the longevity of adhesives used instead of mechanical fastening, as well as their reintroduction if the glue fails.(C O'Regan, 2014)

As mentioned by C. O'Regan in his book Structural use of glass in buildings there are four types of glass connections: Continuous linear supports, clap fixing, bolted fixings and Adhesives.

Continuous linear supports are the fundamental method for supporting glass panes in architectural assemblies, and they create the foundation of many cladding systems. These supports, typically are commonly made of aluminium, steel, plastic, or wood frames, offer structural reinforcement for the margins of glass panes. Out-of-plane loads are handled by gaskets or structural sealants, while in-plane loads are directed by setting blocks. By slightly surpassing the pane's size, the frame may support lateral loads with materials such as EPDM rubber or silicone. This guarantees that lateral loads are efficiently transmitted from the glass pane to the supporting frame. Furthermore, continuous linear supports can transfer stresses from diaphragm motion, demanding precise glass-frame alignment.(C O'Regan, 2014)

Instead of continuous linear supports, isolated clamps attached to a sub-frame support structure provide an option for cladding systems that require a visually elegant glazed surface with the supporting frame hidden behind the glass panes. These clamps, which may control solely out-of-plane weights or combined out-of-plane and in-plane loads, consist of microscopic metal components fortified with neoprene, EPDM rubber, or other materials that ensure even load distribution. Setting blocks are deliberately placed to assist in-plane weight transmission and provide necessary vertical support for the glass pane. Isolated clamp systems, like continuous linear supports, require special consideration for glass panes sensitive to diaphragm movement. Friction grip connections, which are made up of steel plates held together with bolts that run through enlarged boltholes, can be used to avoid direct contact with the glass. Pads made of softer materials than the clamp are put around the bolthole to uniformly distribute clamping force and create the necessary friction with both the glass and the clamp.(C O'Regan, 2014)

Material Research, Structural Glass

Bolted fixes are an increasingly common connection technique for glass elements, valued for their discreet size, which improves structural aesthetics. However, their compact design results in a reduced contact surface with the glass, which causes increased local tensions. Toughened glass is frequently selected because it is more resistant to such forces than ordinary annealed glass. Stress distribution around bolt fixings is seldom uniform; when pressures operate on the glass pane, non-uniform expansion or deflection occurs, resulting in significant differences in stress concentrations.

To overcome this issue, solutions such as allowing for localised bolt yielding by sandwiching materials that have a reduced modulus of elasticity among the glass and the bolt or employing articulated connections known as 'bushes' are used. Common bush materials include soft aluminium, polymers, and resins. However, bolt fixings are prone to loosening caused by vibration, especially in façades subjected to wind-induced load direction variations. Solutions to vibrational effects, such as spring washers or lock nuts, must be incorporated into bolt connection designs.

Detailing concerns include edge distances, glass pane thickness, isolating material between bolt and glass, and bolt fit. Countersunk fixes, although allowing for in-plane movement, need elaborate glass preparation and are more expensive due to greater complexity and poorer tolerances. Despite these constraints, bolted fixes remain adaptable, capable of providing in-plane restraint while also tolerating thermal expansion or support movement.(C O'Regan, 2014)

Glass constructions use two types of adhesives: soft elastics such as structural silicone and stiff adhesives such as epoxy or polyester resins. Structural silicone links glass panes to supporting frames and other glass components, resulting in visually pleasing connections, particularly when transparent. These adhesives are available in one- or two-part formulations, with curing time-frames influencing design concerns, perhaps demanding temporary initial restriction for slower-drying adhesives.

Adhesive bonding outperform mechanical fixes by equally dispersing loads over glass panes due to their homogeneous connection. Silicone-based adhesives perform well in tension but suffer with shear stresses and long-term durability. Stiff adhesives, while less frequent in structural glass, may provide composite action but need rigorous surface preparation and curing considerations to reduce stress concentrations and gaps. Stiff adhesive failure usually leads in plucking of the glass surface, requiring the entire structure to be replaced. To avoid excessive collapse, design concerns include creep effects, redundancy, and alternate load routes, which frequently necessitate auxiliary support structures.(C O'Regan, 2014)

Material Research, Structural Glass

Limitation Of material

In the design of glass structures, it is critical to recognise and solve the limitations imposed by the material's fundamental qualities, manufacturing constraints, and transportation and installation challenges. These limits frequently become critical elements in determining the design planning.
Glass's brittleness and inability to bend under stress make it prone to unexpected failure, especially at support points. In contrast to conventional materials like steel or concrete, where peak stresses control design, glass design is significantly impacted by local stresses, emphasising the importance of rigorous support evaluation and modelling.

Manufacturing restrictions influence the thickness and size of the glass panels offered for construction projects. Thicker glass necessitates changes to the manufacturing process, and customised thicknesses may be required for certain applications. Furthermore, the maximum diameters of glass panes are determined by manufacturing facility capacity, with greater sizes necessitating specific equipment. Edge treatment, such as chamfered arises and radii on interior corners, is critical for reducing stress concentrations, particularly around fasteners. Because of the risk of shattering after toughening, drilling holes is only allowed on pre-toughened glass.(C O'Regan, 2014)

Transportation limits demand conventional glass pane lengths of up to 6m or 8m, with non-standard vehicles necessary for greater spans. Installation tolerance is crucial, since variations might cause secondary forces that jeopardise glass integrity. For adhesive applications on glass-supported structures, stricter tolerance thresholds and stringent quality control are required. Furthermore, simplicity of replacement is critical for maintenance and safety purposes, thus designers must include systems for rapid and safe element replacement.(C O'Regan, 2014)

To summarise, understanding and overcoming the inherent limits of glass constructions is critical for guaranteeing structural integrity, lifespan, and safety during the design, production, shipping, and installation stages.

Design criteria for seismic loading.

Glass structures require designs that endure torsional movement during earthquake activity. Engineers must account for this movement to ensure that seismic activity does not harm glass integrity. Horizontal and vertical momentum forces acting on glass structures ought to be included in static load combinations alongside conventional loads, with the necessary safety factors applied.

Laminated basic annealed panes are less likely to separate than single-pane sheets. Silicone bonding emerges as the favoured attaching method, providing the flexibility required to handle racking movement without displacing panels. Silicone joints aid in the absorption of impact energy, an important feature for dynamic loads. Clearances between glass panels and frame components in curtain wall cladding systems must be designed to allow for movement during seismic occurrences.

Additional steps are required in high-risk seismic zones to reduce seismic stresses. Examples include using separate base supports to sustain glass structures and incorporating dampening systems at the glass-to-primary structure connection interface.(C O'Regan, 2014)

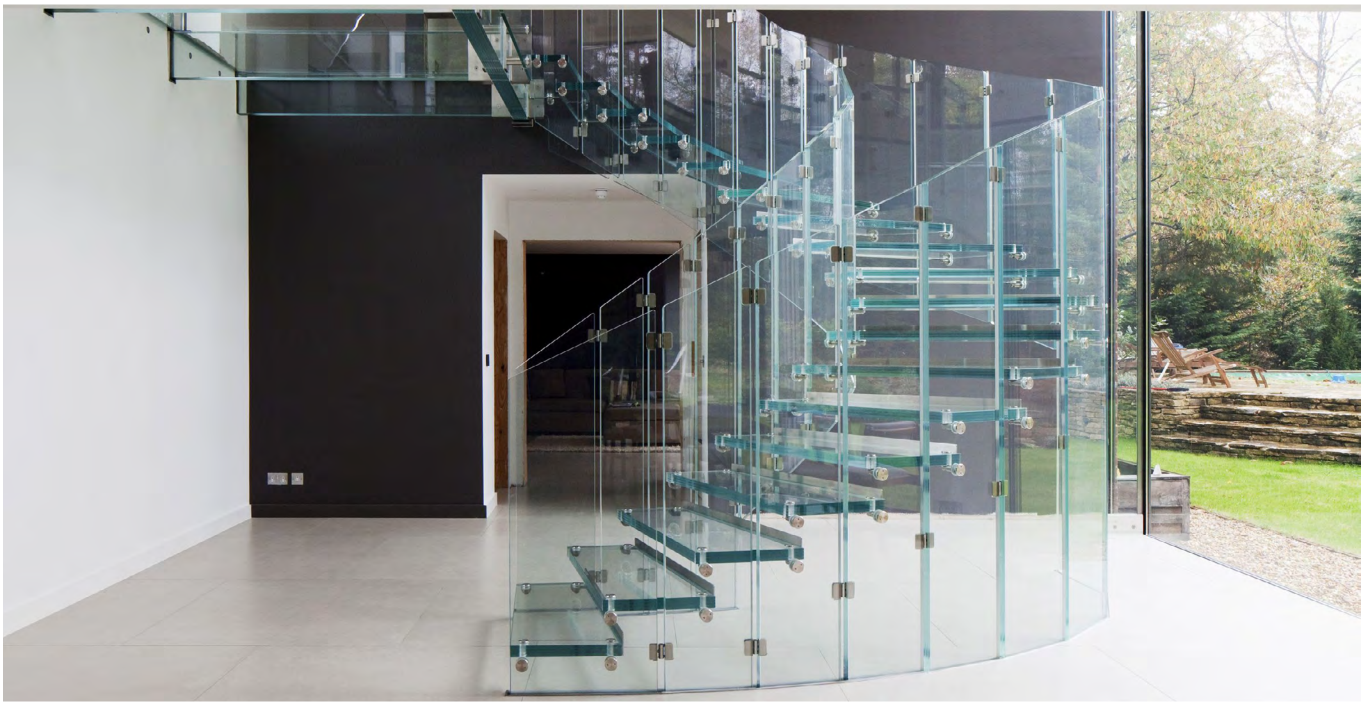
Material Research, Structural Glass

Glass balustrades, Glass floors, glass walls, glass beams

Glass rails or balustrades act as partial-height barriers, which are critical for protecting people from falling between floors within a structure. The balustrade height and design actions are determined by elements such as building usage, barrier position, and probable fall distance. Glass can either form part of the barrier by filling a structural frame or act as the barrier itself. Calculations for glass balustrades must consider four design actions: evenly distributed action, concentrated activity, line load at a specific height, and vertical action. Furthermore, any additional motions caused by air movement or wind must be incorporated into the design process.

Picture 20 represent situations in which glass is incorporated into the railing, demonstrating the wide range of uses and combinations possible in glass balustrade design.(C O'Regan, 2014)

Glass floors have two functions: they are both walking surfaces and supporting structures for other glass features like walls or balustrades. The length of applied actions has a considerable influence on the design strength of the glass; shorter durations correspond to greater estimated design strengths. Floor plates are subjected to various actions that can last either short or long periods of time, with permanent acts being essentially long-term.



Picture 20: Structural Glass Staircase
Source: stairs-siller.com

Glass wall design

Glass walls are available in a variety of formats, ranging from internal barriers and glazing to expansive parts within fully glass enclosures, such as retail units in shopping malls. Fully glazed enclosures are the most complex design difficulties owing to the multiplicity of pressures they must endure. These forces include lateral, axial, and diaphragmatic motions, since glass walls are frequently used as integrated components of enclosure lateral stability systems. During disproportionate collapse evaluations, the walls are closely examined for redundancy in the case of a breakdown in one or more glass plies.

The challenge of designing glass walls is to ensure their structural integrity under a wide range of loading circumstances while preserving aesthetic appeal and functional needs. Implementing strong design techniques and thorough testing processes is critical for reducing the dangers associated with glass wall systems. Glass walls, whether single pane, laminated, or double glazed, experience lateral forces similar to floor panels but with specific concerns. While they may have fewer supported edges, often simply the top and bottom, they must deal with axial forces caused by self-weight and supported parts, necessitating buckling analysis. Vertical movements necessitate precise attention to load transfer systems to reduce excessive local stresses, as glass's unwillingness to give makes it prone to fracture. The compression capacity of multi-glazed units, such as those with inner and outer panes, varies according to load distribution, which is influenced by construction tolerances.

Support circumstances for wall panels, such as fixed, pinned, or loose connections at the top and bottom, influence their capacity to sustain out-of-plane or in-plane loads, Stability circumstances, including cantilever scenarios, are examined in terms of rotational fixity and the requirement for appropriate strength, stiffness, and stability. The study of axial forces in glass walls supported at two edges follows column design principles, but those supported at three or more edges follow plate buckling mechanics, needing finite element analysis for precise findings. Shear forces, which occur when walls contribute to lateral stability, necessitate respect to beam design specifications. Although glass has a larger compressive capacity than tension, short squat walls may not be able to bear considerable compressive pressures due to tension failure along shear lines. As a result, detailed examination is critical, with analogies to concrete cube failures. To achieve best performance and safety, glass walls must be designed with a sophisticated understanding of their distinctive structural behaviour, taking into consideration varied loading circumstances and support configurations.(C O'Regan, 2014)

Picture 21: Structural Glass Walls
Source: apple.com.cn/retail/kunming/

Glass beams

Glass beams are indeed load-bearing sections that can withstand both bending and shear pressures. They are often positioned horizontally but may be oriented in a variety of ways to support floors, roofs, and other structural components. Vertical fins, similar to cantilevering beams, offer lateral support for walls while resisting wind and lateral stresses. Glass beams are often laminated for redundancy and structural stability, and may accommodate a variety of interlayer and glass kinds.

Length restrictions, which might range from 4 to 7 metres or even 15 metres, are determined by supplier capabilities and site logistics. Because of geometric limits, splicing glass beams is only done on rare occasions, necessitating friction-grip connections to reduce localised tensions. Gasket materials, such as 1mm vulcanised fibre or soft aluminium, are carefully designed to provide stress distribution and thermal compatibility.

Manufacturing tolerances and alignment are crucial, which are solved by drilling larger holes in glass for bearing connections or using adhesive-based splicing. Bearing connections, which outperform friction connections, are pre-assembled for precise alignment. Adhesive-based connections, albeit rare, rely on laminating or direct glueing and are limited by plastic interlayer creep and stress concentrations.

Shear connections using conventional bolts and high-density nylon bushes enable longer beam lengths, necessitating a careful assessment of local stresses. Overlapping glass sheets reduce bolt shear, increasing structural integrity. Careful consideration of connection types, materials, and manufacturing procedures is required to provide the best performance and lifespan of glass beams in structural applications.(C O'Regan, 2014)

Picture 22: Structural Glass Columns, Beams
Source: rchello.com/product/load-bearing-glass-beam

Description of FEM Models

3.3 Description of FEM Models

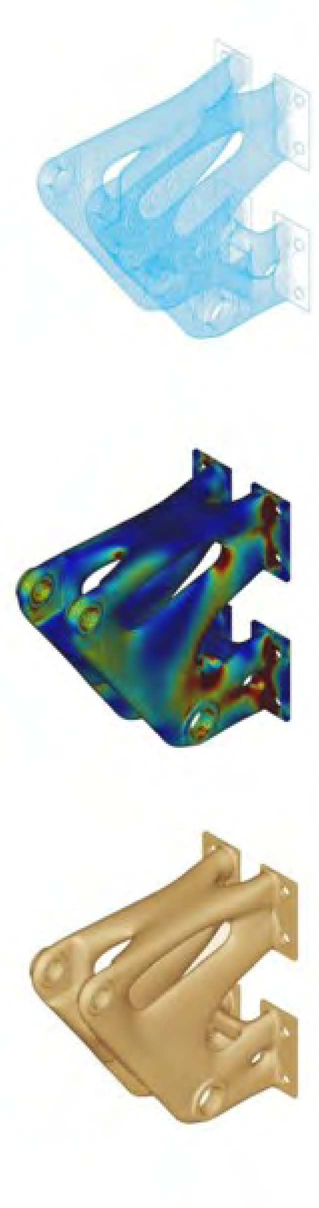
Finite Element Method is a computer approach for solving engineering problems with dispersed masses. FEM combines governing equations for numerous physical phenomena, such as displacement, temperature, and vibratory modes, and solves them with boundary conditions. The approach expresses these equations as a matrix, allowing numerous unknown variables to be determined at the same time. Overall, FEM is an effective method for studying complicated systems in engineering and physics. Any mass FEM study may reveal how materials deform, how heat spreads, and how they vibrate all in the same simulation.(Dugan Um, n.d.)

Within the framework of the Finite Element Method (FEM), there are two approaches: lumped mass and dispersed mass.

1. The Lumped Mass Approach reduces a rigid body to a set of springs, making Hooke's Law relevant. Hooke's law states that displacements are determined by external forces and spring constants (or elastic modulus).
2. Distributed Mass Approach: Here, complex geometries are decomposed into a network of interconnected springs called a "truss." Each spring's behaviour is governed by an equation derived from the linearly applied forces along its main member direction. These equations are then solved using Hooke's law to find displacements.(Dugan Um, n.d.)

The complex nature of today's engineering challenges requires automated calculations. Finite Element Analysis (FEA) is introduced as a useful approach for solving structural issues. However, it warns against depending entirely on computer models, emphasising the significance of theoretical knowledge and experimental investigation.(Dugan Um, n.d.)

Steps involved FEM:
1. Preprocessing: involves creating a model of the structure by separating it into distinct parts connected by nodes. This stage can take a long time, but commercial software with graphical preprocessors makes it easier.
2. Analysis: The finite element code uses the pre-processed dataset to generate and solve a system of linear or non-linear equations. The stiffness matrix creation and analysis approaches differ based on the issue type.
3. Post-processing: involves interpreting and visualising analytical results. Modern algorithms include graphical representations to help comprehend stress and strain distributions.
4. Validation: ensures accurate and reliable analytical results. Validation is critical because faults at any level of the analytic process might result in unanticipated inaccuracies in the results. (Dugan Um, n.d.)



Picture 23: Finite Element Analysis of a steel connection
Source: A parametric and physics-baseed aproach to structural weight estimation of the hybrid wing body aircraft. By Trevor Laughlin

Description of FEM Models

Inputs for Ansys Discovery

Material	Density (kg/m^3)	Modulus of Elasticity	Shear Modulus	Poisons Ratio
Steel 275	7850	200 GPa	79.3 Gpa	0.3
Toughtned Glass (Pernament Load duration 50 years)	2500	70 Gpa	30	0.22-0.23
Polyurethane Elatomer:Adiprene LFP	1200	25MPa	8 MPa	0.45

Material	Bulk Modulus	Tensile Yield Strength	Ultimate Tensile Strength
Steel 275	160 GPa	275 MPa	430-580 MPa
Toughtned Glass (Pernament Load duration 50 years)	36-37 Gpa	Brittle material, ot characterized by yield strength	30-90 Mpa
Polyurethane Elatomer:Adiprene LFP	2.7 Gpa	Elastomer, does not have a clear yield point	35 MPa

Table 04: Material properties for the materials used in FEM Analysis. Source: Ansys EduPack, Created by Author

Definitions:

Density is the mass per unit volume of a material. It is often denoted by the symbol ρ (rho) and is expressed in kilograms per cubic meter (kg/m^3).

Young's modulus, or the modulus of elasticity, measures a material's ability to resist deformation under tension or compression. It is defined as the ratio of tensile stress (force per unit area) to tensile strain (proportional deformation) and is expressed in Pascals (Pa).

Shear modulus, also known as the modulus of rigidity, measures a material's ability to resist shear deformation. It is defined as the ratio of shear stress to shear strain and is expressed in Pascals (Pa).

Description of FEM Models

Poisson's ratio is the ratio of the transverse strain to the axial strain in a material subjected to axial stress. It describes how a material deforms in directions perpendicular to the direction of loading and is a dimensionless quantity.

Bulk modulus measures a material's resistance to uniform compression. It is defined as the ratio of the change in pressure to the relative change in volume and is expressed in Pascals (Pa).

Tensile yield strength is the stress at which a material begins to deform plastically. Before reaching the yield point, the material will deform elastically and return to its original shape when the applied stress is removed.

Ultimate tensile strength (UTS) is the maximum stress that a material can withstand while being stretched or pulled before breaking. It is a critical property for determining the load a material can handle.

Sources: Ansys, Engineering Toolbox, Huntsman Corporation Technical Data Sheets , Britannica

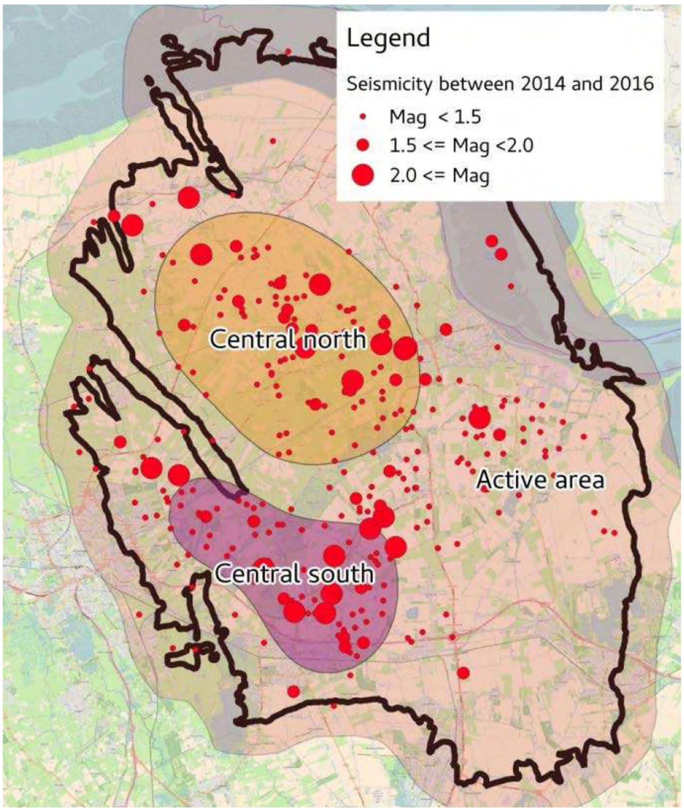
4 Site Selection, architectural Design of a facade

Site selection

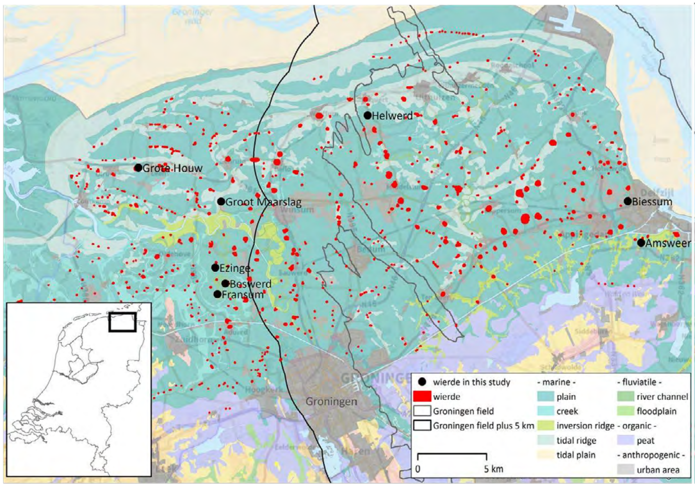
For the site selection of the multi-storey office building the selection of Groningen, Netherlands was made. Groningen is a vibrant town in the north of the Netherlands. It has a population of around 235,2871("Groningen," 2024) in December 2021, making it the Netherlands' sixth biggest city. Groningen's climate is sub-oceanic, with heavy rains all year, chilly, grey winters, and mild to pleasantly warm summers.(Groningen Climate: Weather Groningen & Temperature by Month, n.d.) The city has a long history of natural gas production, which has regrettably resulted in a series of earthquakes. Gas extraction at the Groningen field, located in the northern Netherlands, began in 1963. Since 1991, the compression of the sandstone deposit that houses the reservoir has resulted in induced seismic activity. The most important earthquake reported thus far was the Huizinge earthquake in August 2012, which measured ML 3.6. Following this incident, the field operator initiated a massive data collecting and modelling effort to quantify the resultant seismic hazard and risk. (Kruiver et al., 2022).

The seismic activity in the region originates from induced seismic, which includes earthquakes with magnitudes larger than 4.3 on the Richter scale. In 2014 and 2015, the activity rate, or yearly number of such events, remained consistent, ranging from 20 to 25 events each year. However, it fell to 13 events in 2016 and remained at 8 for the first part of 2017. The region is separated into zones, each with two parameters: activity rate and b-value (slope of the linear component of the frequency-magnitude curve). The seismic activity in the region is non-stationary, which means it varies over time. The geographical distribution of produced earthquakes in Groningen from 2014 to 2017 reveals a continuance of activity in the centre north and central south zones.(Spetzler, 2017)

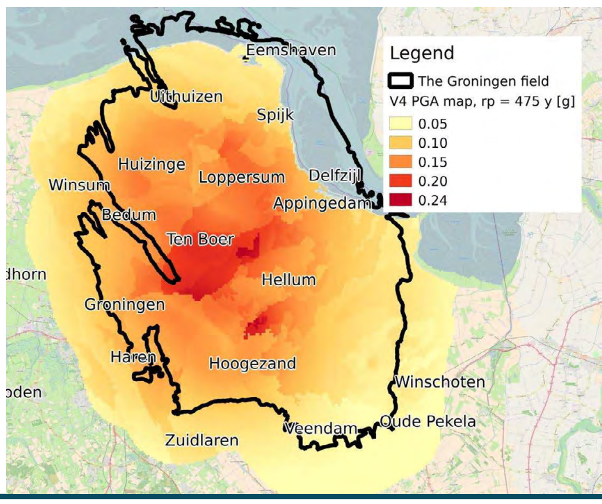
The Probabilistic Seismic Hazard Analysis (PSHA)(see map 01) is used to determine the seismic danger in the area. The Ground Motion Model (GMM) v4 was used to generate a new Peak Ground Acceleration (PGA) hazard map with a 475-year return time. The highest PGA value is 0.24g, or 2.4 m/s^2. The largest PGA values are found at Ten Boer and between Hoogezand and Hellum.(Spetzler, 2017)



Map 01: Earthquakes in Groningen Area. Source: Source: Jesper Spetzler and Bernard Dost 2017



Map 02: Earthquakes in Groningen Area. Source: Source: Jesper Spetzler and Bernard Dost 2017



Map 03(right): Probabilistic seismic hazard map for Groningen for the period T = 0.01 s. The return period is 475y according to Eurocode 8.
Source: Jesper Spetzler and Bernard Dost 2017

Architectural Proposal

Render 01: General Perspective of the Aluminium Facade proposal. Author's own work.

Architectural proposal

Render 02: General Perspective of the Aluminium Facade proposal. Author's own work.

Render 03: Aluminium Facade fragment. Author's own work.

Fragment typology 01

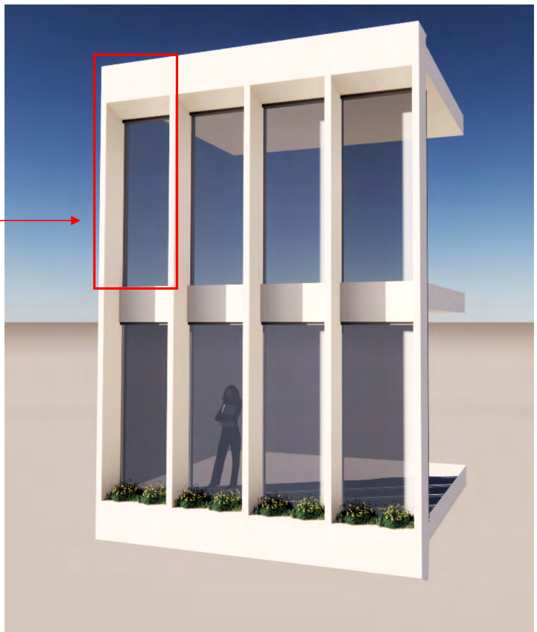
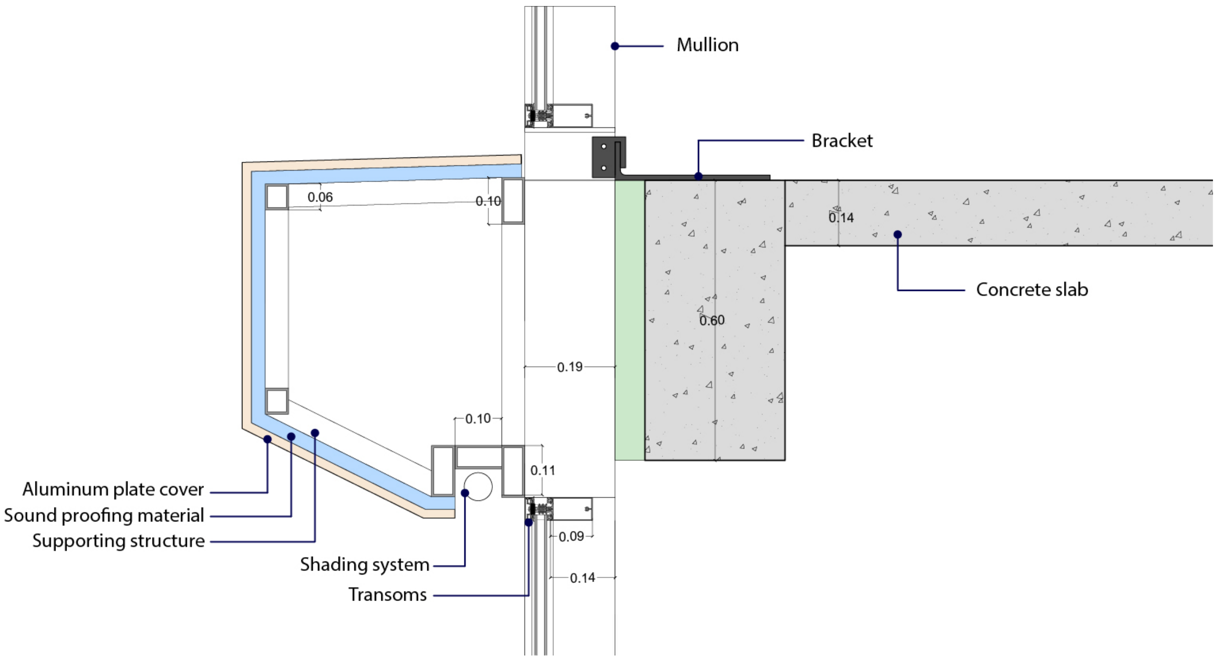


Diagram 11: Aluminium Suspended Facade Typology 01. Author's own work.



Detail 01: Aluminium Supended facade Detail Author's own work.

Architectural proposal

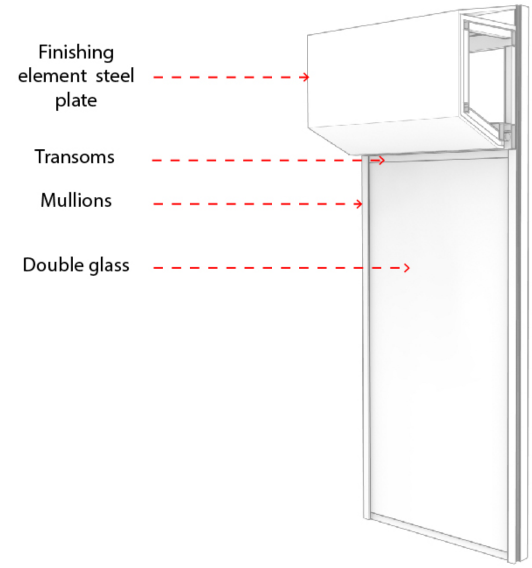


Diagram 12: Finishing Structure of Typology 01 for the aluminium suspended facade. Author's own work.

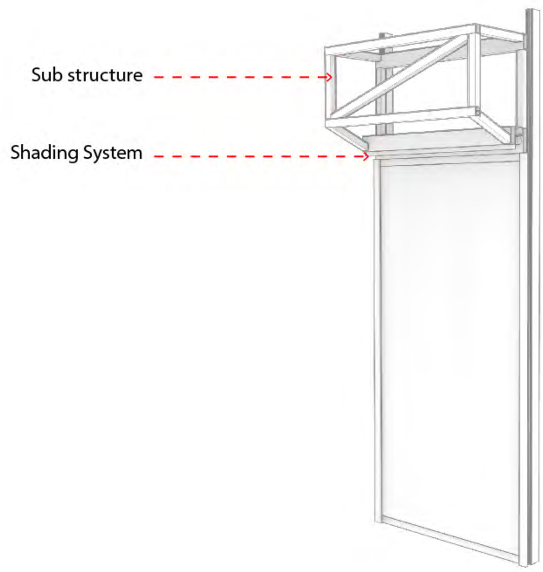


Diagram 13: Sub-Structure of Typology 01 for the aluminium suspended facade. Author's own work.

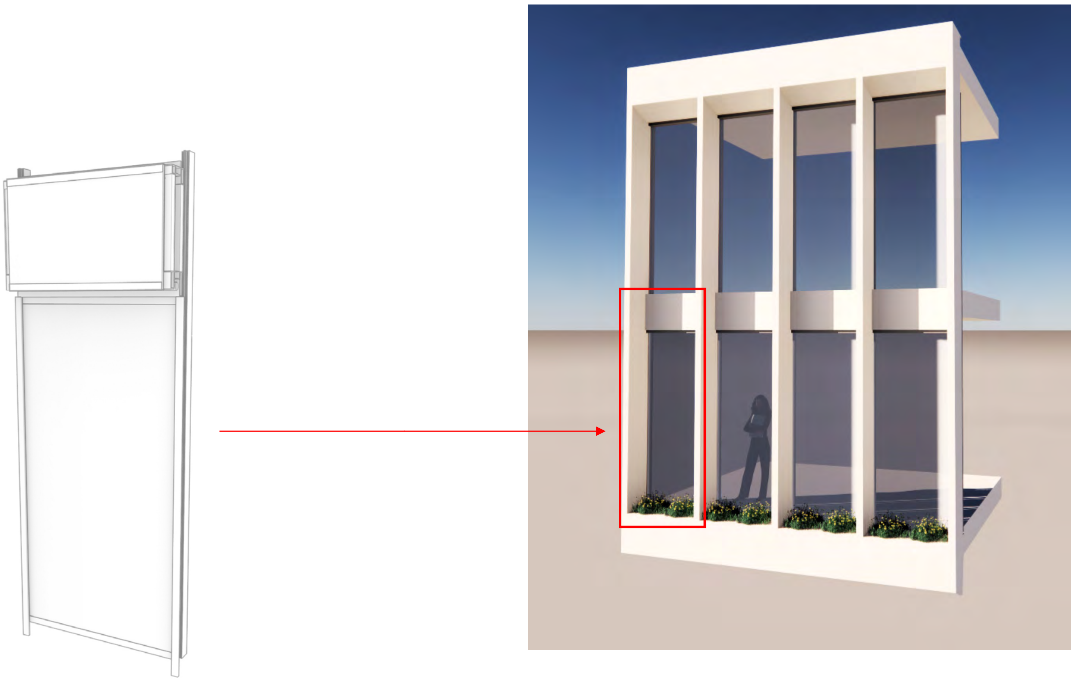
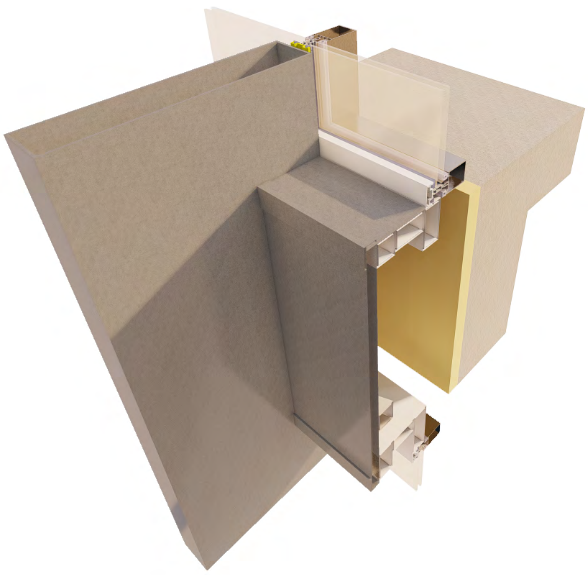


Diagram 14: Aluminium Suspended Facade Typology 02. Author's own work.



Render 08: Aluminium Suspended Detail Author's own work.

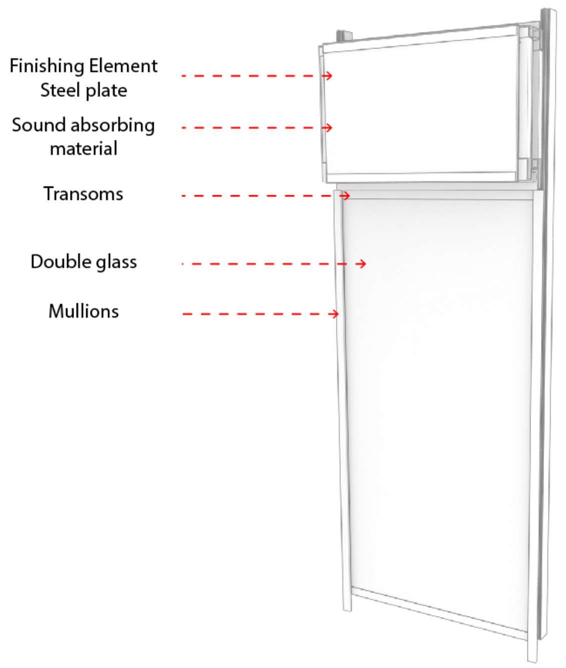


Diagram 16: Finishing Structure of Typology 02 for the aluminium suspended facade. Author's own work.

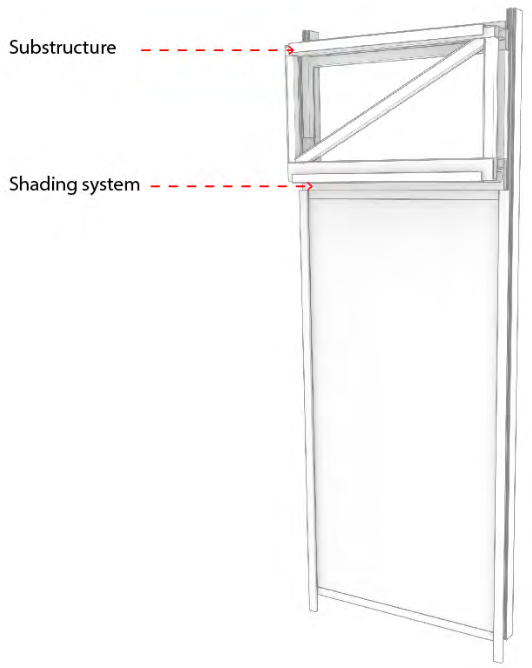


Diagram 17: Sub-Structure of Typology 02 for the aluminium suspended facade. Author's own work.

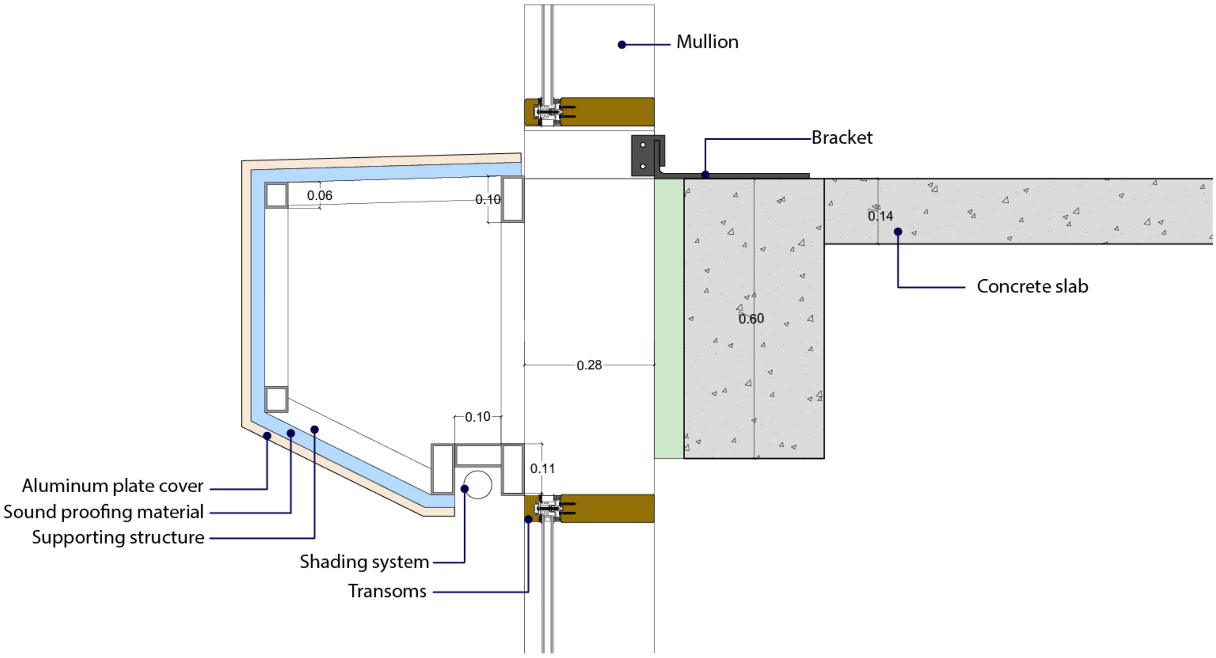
Architectural proposal

Render 10: General Perspective of the Composite Timber Facade proposal. Author's own work.

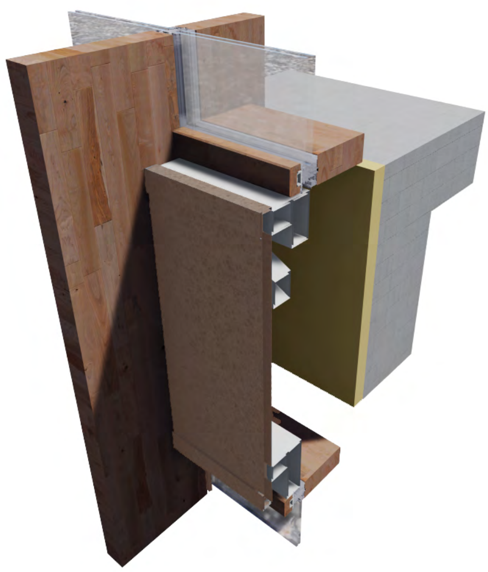
Render 11: Composite Timber Facade fragment. Author's own work.

Render 12: Close-up rende composite timber facade Author's own work.

Architectural proposal



Detail 02: Composite Timber Supended facade Detail



Render 13: Composite Timber Facade fragment detail. Author's own work.

Architectural proposal

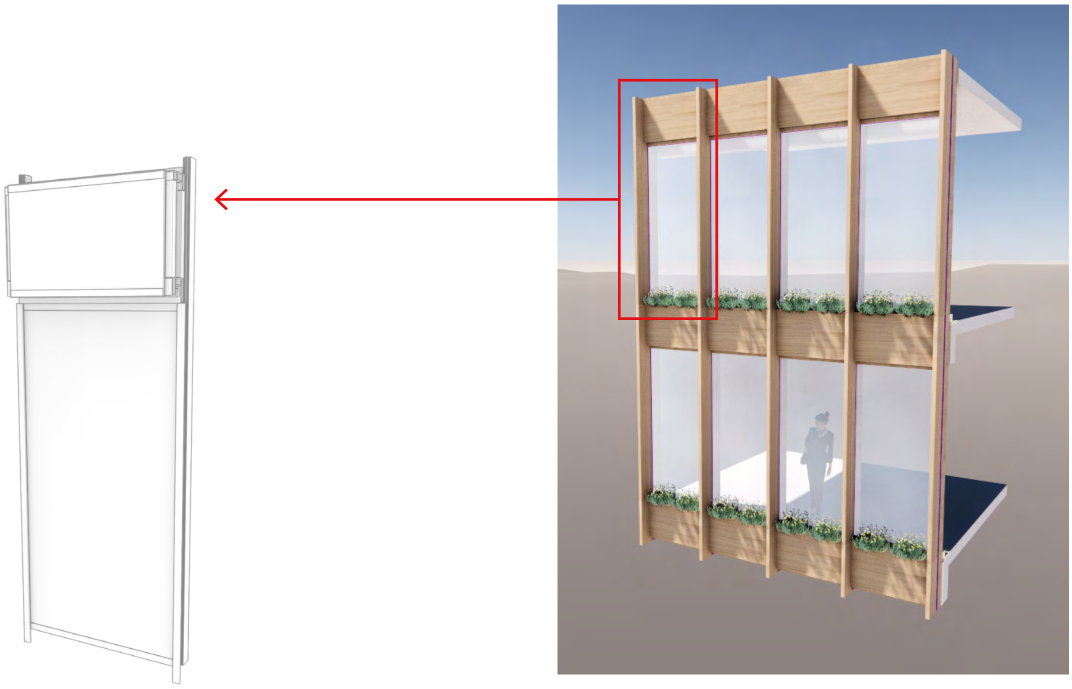


Diagram 18: Composite Timber Suspended Facade Typology. Author's own work.

5 Suspended Façades Structural Analysis

5.1 Building requirements according the Eurocode
5.2 Risk assessment, Performance based Engineering
5.3 Analysis of Aluminium and Timber Hanging Façades under normal conditions
5.4 Analysis of Aluminium and Timber Hanging Façades under earthquakes

Suspended Façades structural Analysis

Structural Analysis of a curtain wall

Curtain walls, as non-structural features, define the interior and outside spaces of a structure. Their major role is to transfer loads operating on the building's surface to the main structure while enhancing architectural aesthetics.(Herzog et al., 2004)

Types of Loads:
• Vertical loads consist of dead loads, snow loads, induced stresses (residents), and specific loads (such as sun shading).
• Horizontal loads encompass wind (pressure and suction) as well as applied loads (e.g., impacts, seismic occurrences).
• Restraint forces: Volume changes caused by temperature or moisture.(Herzog et al., 2004)

Causes of Structural Failure

Curtain wall structural failures are rare, but can be caused by:
- Negative air pressure.
- Component dislocation due to temperature variations.
- Anchor failure.
- Connection problems at high loads.(Herzog et al., 2004)

Wind Load Analysis

Lateral wind loads are a crucial consideration in curtain wall design. Wind load estimations are influenced by the building's location, size, orientation, surrounding environment, and past wind activity. Wind loads can be determined using building regulations, civil engineering standards, or wind tunnel testing.
European Building Standards
European standards include curtain walling and wind load evaluation, including:
- Product standards NEN - EN 13830.
- Performance criteria for wind load resistance NEN - EN 13116.
- Test methods for structural wind resistance NEN - EN 12179.
- Utilize ENV 1991-2-4 as a foundation for designing wind activities.

Wind loads function predominantly as out-of-plane loads on curtain walls. The structural parts of the facade should be able to deflect within acceptable limits before failing. Glass panes distribute wind pressure evenly to the supporting structure. Ductility of structural elements is required to withstand persistent deformations. Understanding the structural complexities and load dynamics of curtain walls is critical to assuring their durability and performance. Architects and engineers may construct curtain wall systems that balance aesthetics and structural strength by following to established standards and using strong design concepts.

Suspended Façades structural Analysis

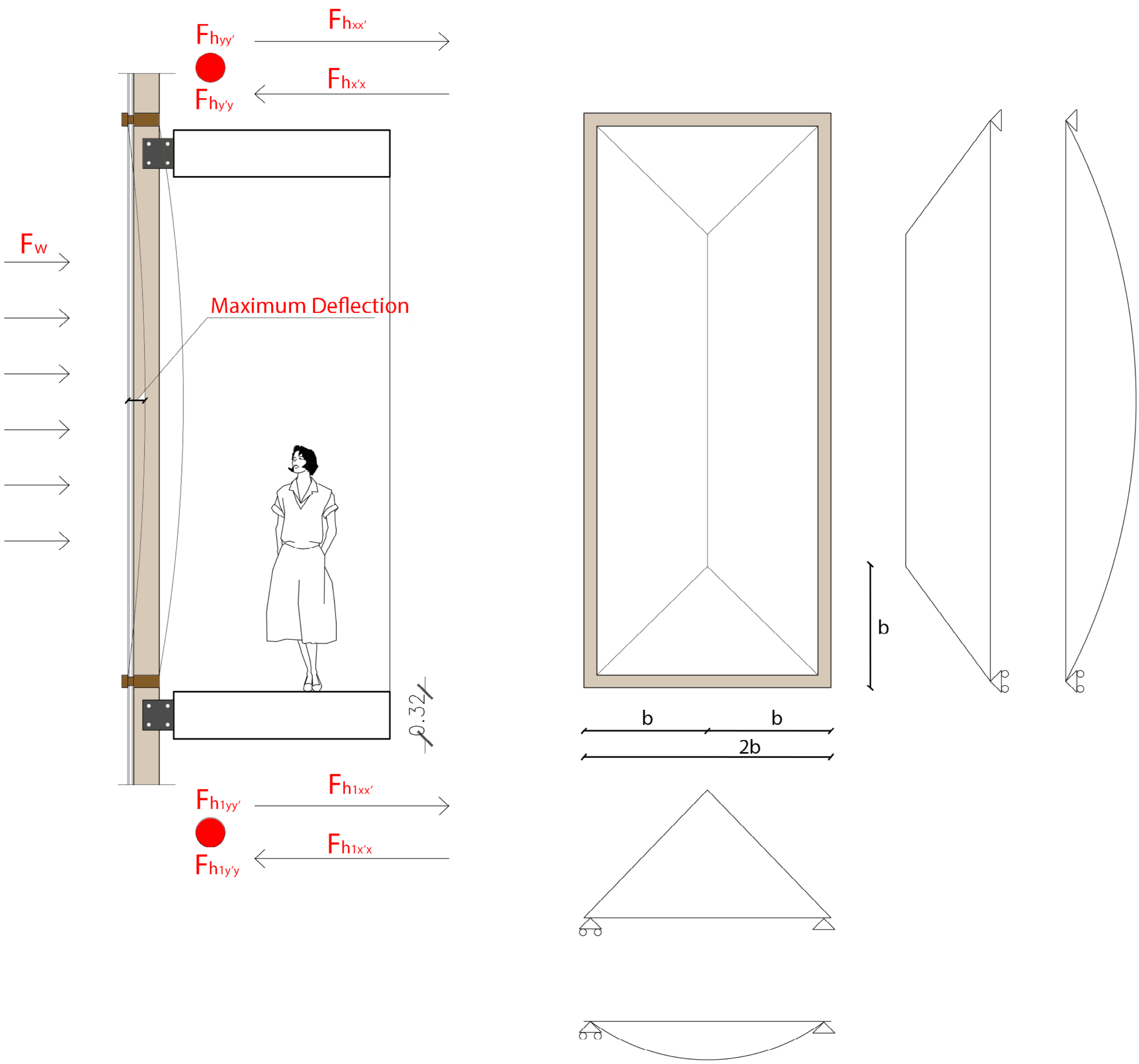


Diagram 19: Suspended facade forces distributions. Authors own work

Suspended Façades structural Analysis

Non-structural Elements under seismic loads

In Chapter 4.3 of the European standard [28], the focus is on structural analysis, specifically addressing the requirements for non-structural elements detailed in section 4.3.5 of Eurocode 8. These non-structural elements, termed "appendages," include parapets, gables, antennae, mechanical appendages, curtain walls, partitions, and railings. The crucial point highlighted by the standard is that these elements, along with their supports, must be able to withstand the designated seismic forces, emphasizing the vital role of their supporting and fastening systems, which significantly impact their failure mechanisms.

The standard emphasises that with regard to non-structural components with major relevance or risk, a complete seismic study based on a comprehensive model of the relevant structures should be conducted. This study makes use of suitable response spectra obtained from the supporting structural parts of the major seismic resisting system. However, in other circumstances, a simpler solution is suggested. This method involves verifying the resistance of the non-structural element against a static seismic horizontal force denoted as Fa. This simplified approach serves as a guideline for assessing the seismic performance of these elements under typical conditions, stressing the need to ensure their stability and safety within the broader structural framework.

$$F_a = \frac{S_a * W_a * \gamma_\alpha}{q_a}$$

Fa	horizontal seismic force, acting at the centre of mass of the non-structural element in the most unfavourable direction;
Wa	weight of the element
Sa	is the seismic coefficient applicable to non-structural elements, (see (3) of this subclause)
γa	is the importance factor of the element
qa	is the behaviour factor of the element

S_a Seismic coefficient applicable to non-structural elements

$$S_a = a * S * \left[\frac{3 * \left(1 + \frac{z}{H}\right)}{1 + \left(1 - \frac{T_a}{T_1}\right)^2} - 0.5 \right]$$

a	is the ratio of the design ground acceleration on type A ground, ag, to the acceleration of gravity g
S	is the soil factor
Ta	is the fundamental vibration period of the non-structural element
T1	is the fundamental vibration period of the building in the relevant direction
z	is the height of the non-structural element above the level of application of the seismic action (foundation or top of a rigid basement)
H	is the building height measured from the foundation or from the top of a rigid basement.

Importance factors γ_α

γ_α	1-1.5	anchorage elements of machinery and equipment required for life safety systems, tanks and vessels containing toxic or explosive substances considered to be hazardous to the safety of the general public
γ_α	1	any other case

Behaviour factors q_a

q_a	1	- Cantilevering parapets or ornamentations - Signs and billboards - Chimneys, masts, and tanks on legs acting as unbraced cantilevers along more than one half of their total height
q_a	2	- Exterior and interior walls - Partitions and facades - Chimneys, masts and tanks on legs acting as unbraced cantilevers along less than one half of their total height, or braced or guyed to the structure at or above their centre of mass. - Anchorage elements for permanent cabinets and book stacks supported by the floor.

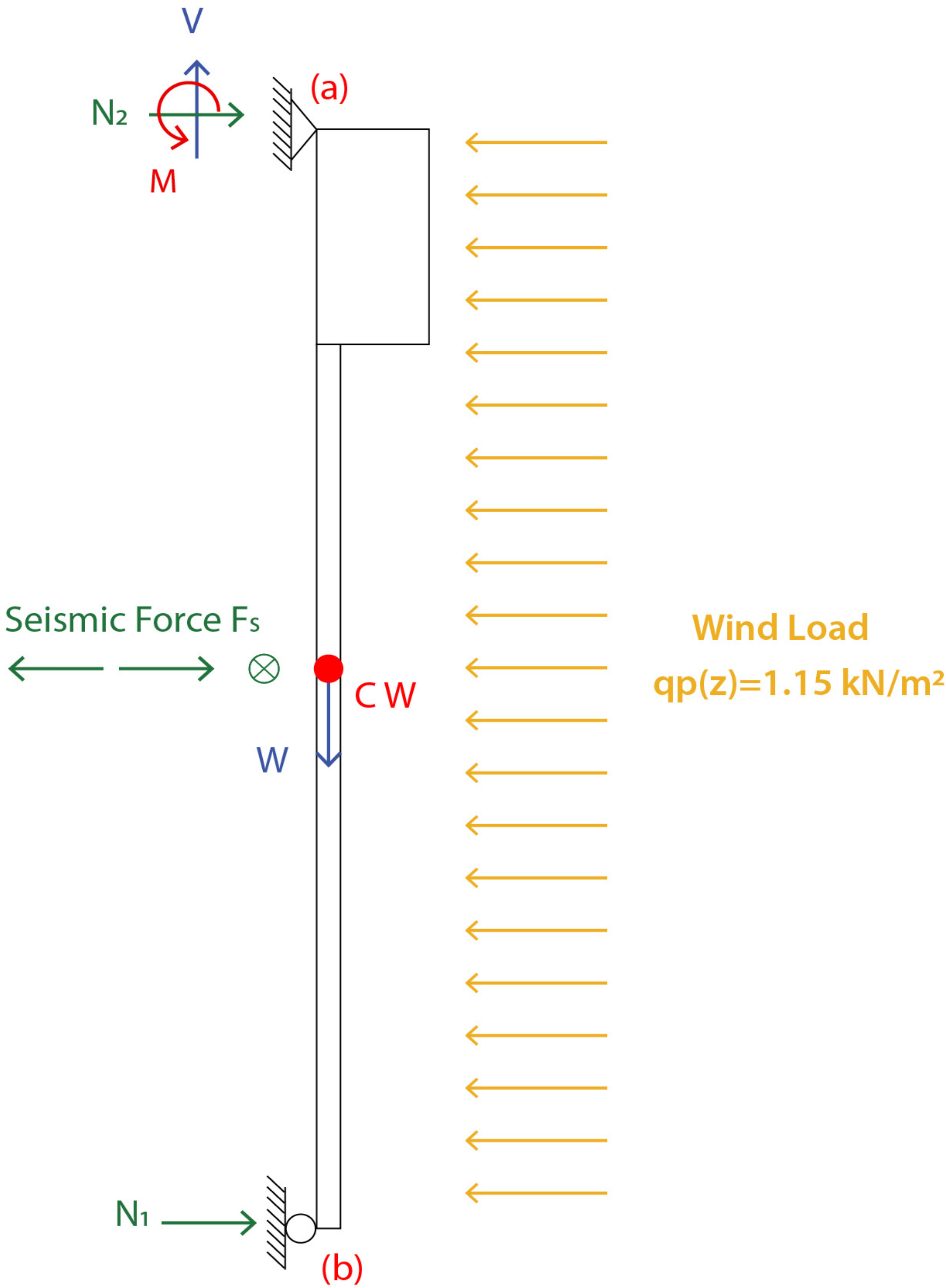


Diagram 20: Free-form diagram. Authors own work

Suspended Façades structural Analysis

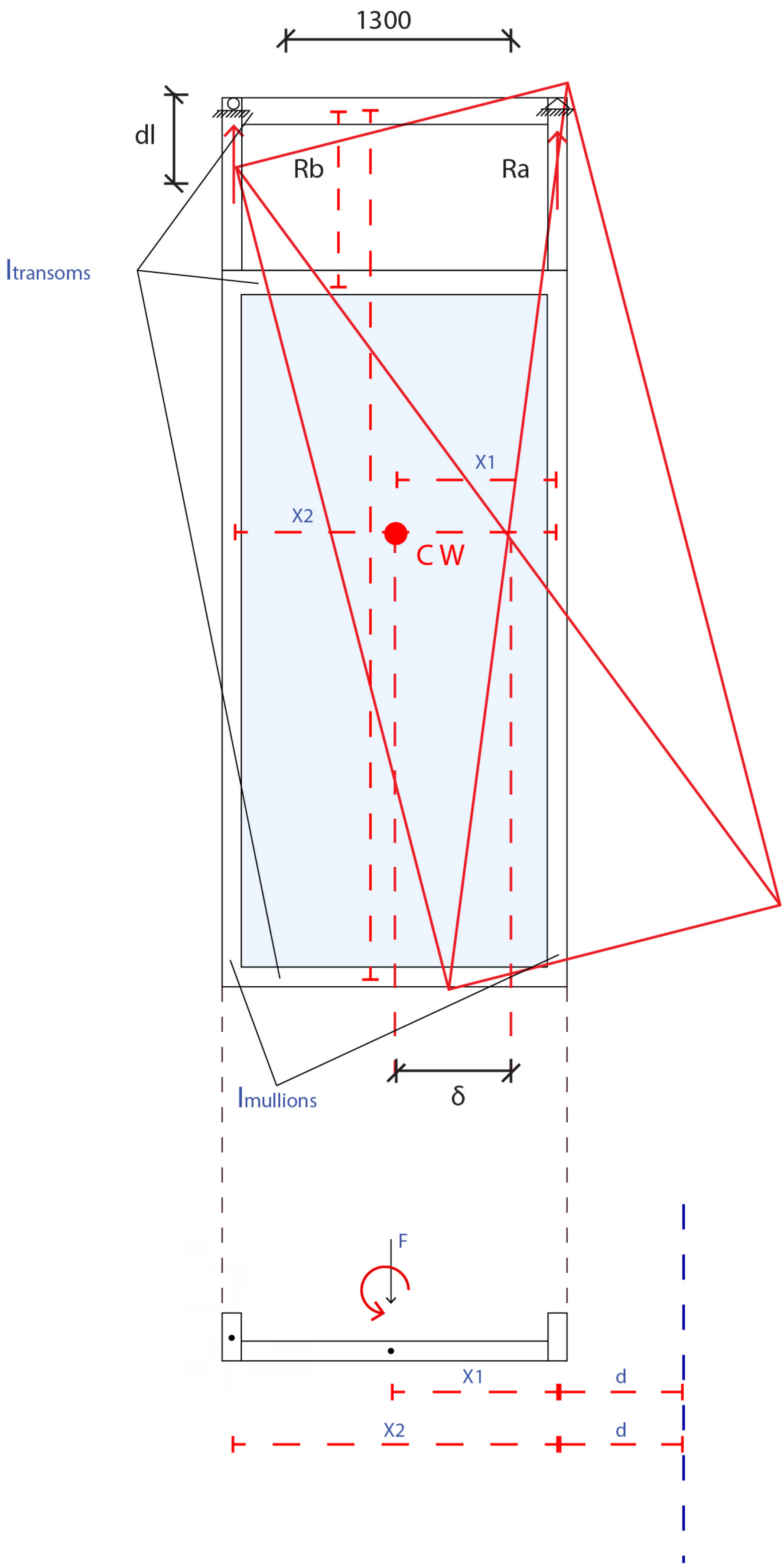


Diagram 21: Deliberate movements in the facade system. Authors own work

Suspended Façades structural Analysis

1. **Vertical Adjustments**
2. **Structural Node a fixed support**
3. **Structural Node b sliding support**
4. **Steel plate**
5. **Horizontal Adjustments**
6. **Structural node c sliding support**
7. **Structural node d sliding support**
8. **Channel taking horizontal loads**

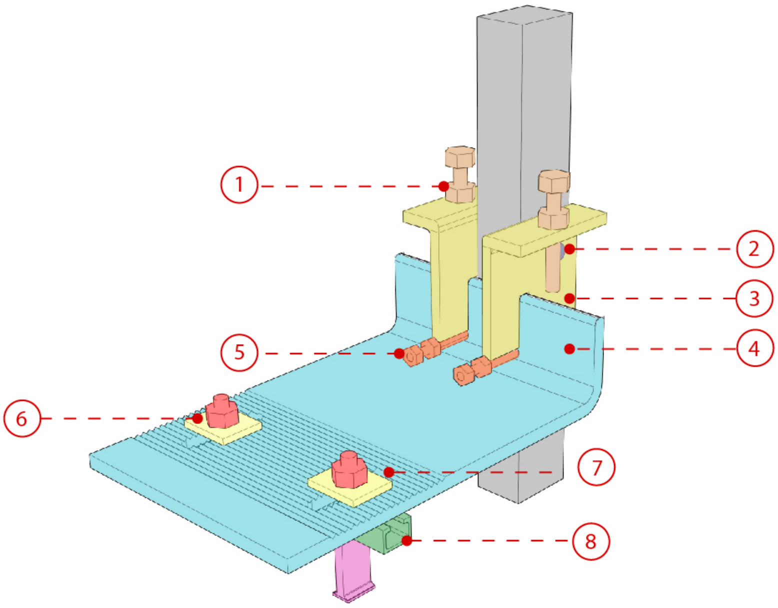


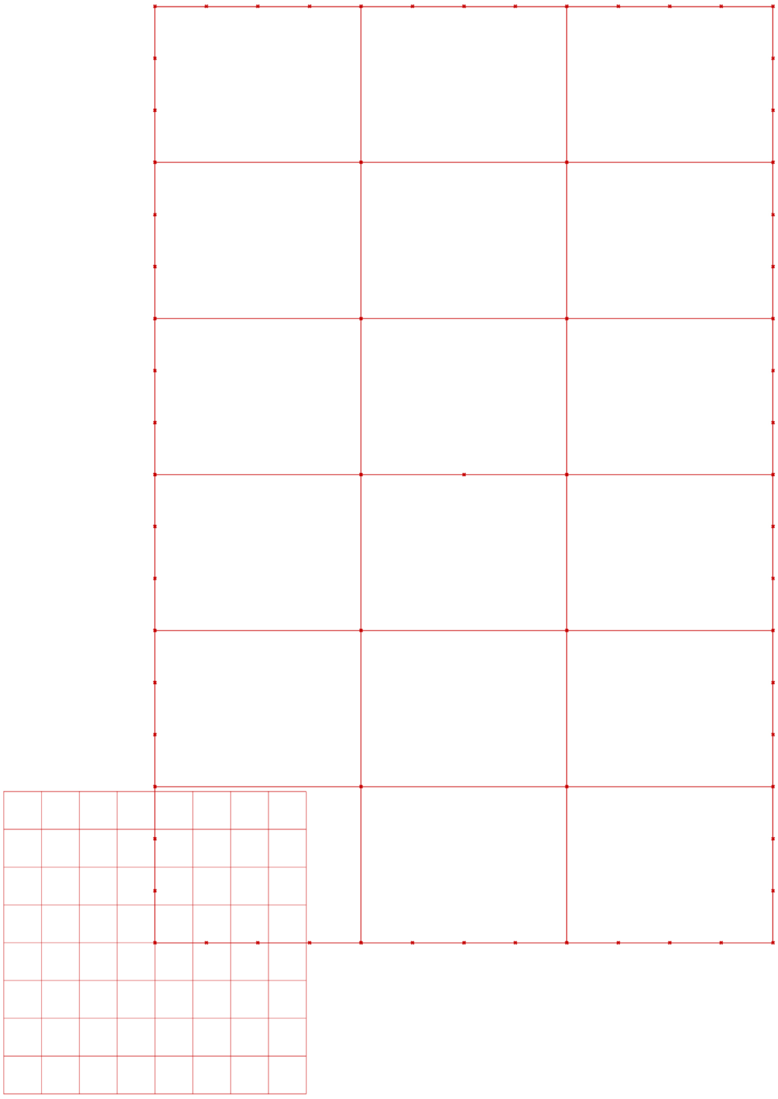
Diagram 22: Nodes of th Halfen bracket system.

6 Automation of the Structural Analysis

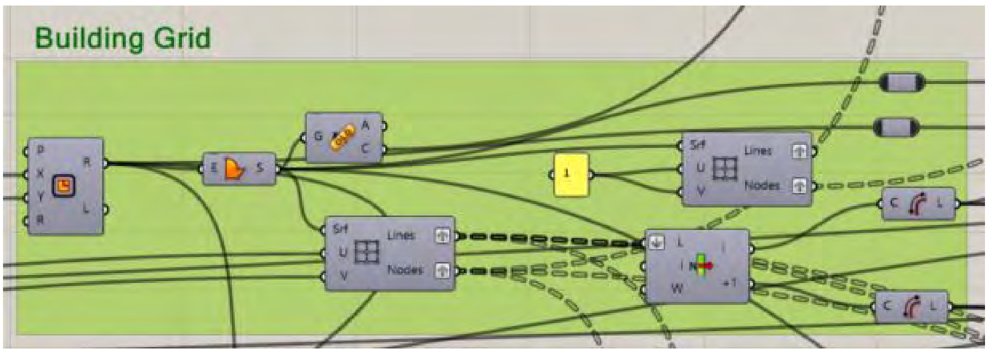
6.1 Development of the automation process
6.2 Implementation of the automation process
6.3 Testing and validation of the automation process

6.1 Development of the automation process

Grasshopper model

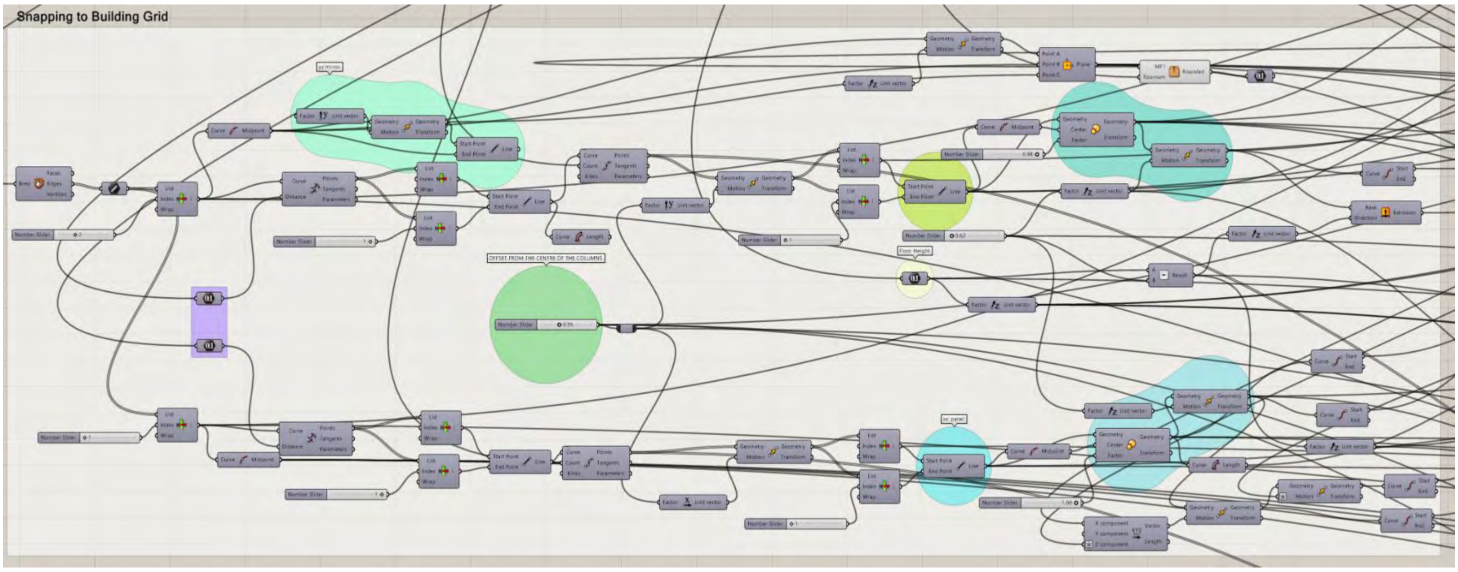


Picture 20: Smart Grid as shown in Rhino. Authors own work.

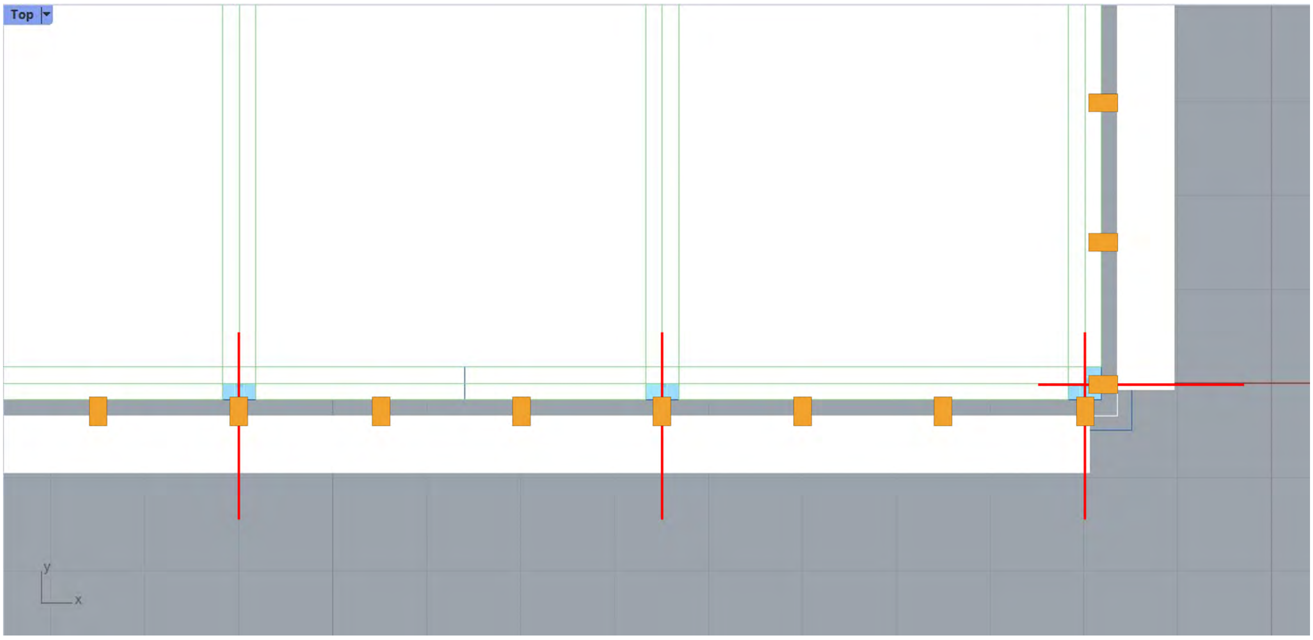


Picture 25: Grasshopper script for a smart Grid. Authors own work.

6.1 Development of the automation process

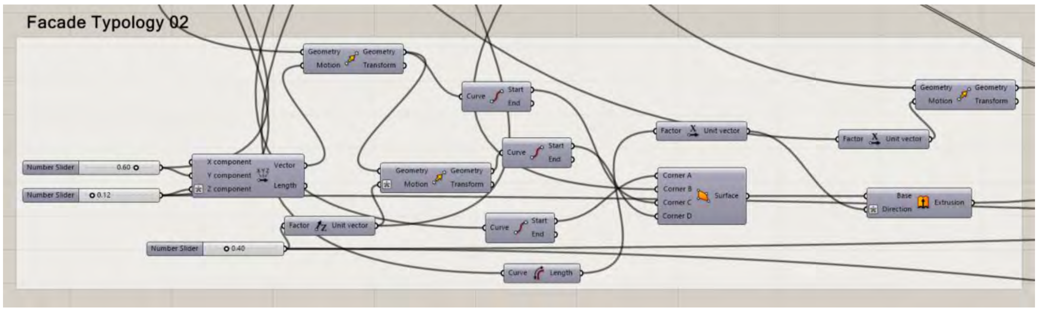


Picture 26: Distributing the suspended facade's weight on the beams in any grid, Grasshopper script. Authors own work.

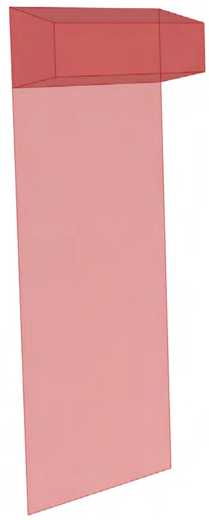


Picture 27: Distributing the supended facade's weight on the beams in any grid. Authors own work.

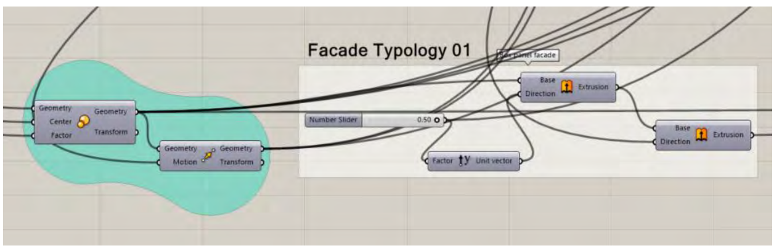
6.1 Development of the automation process



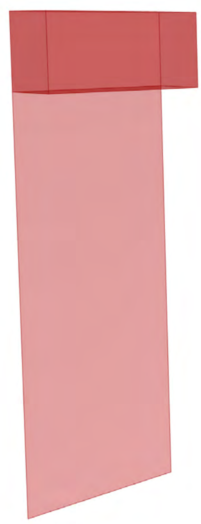
Picture 28: Grasshopper script for a smart 3D of the suspended facade typology 02. Authors own work.



Picture 29: Suspended facade typology 02. Authors own work.

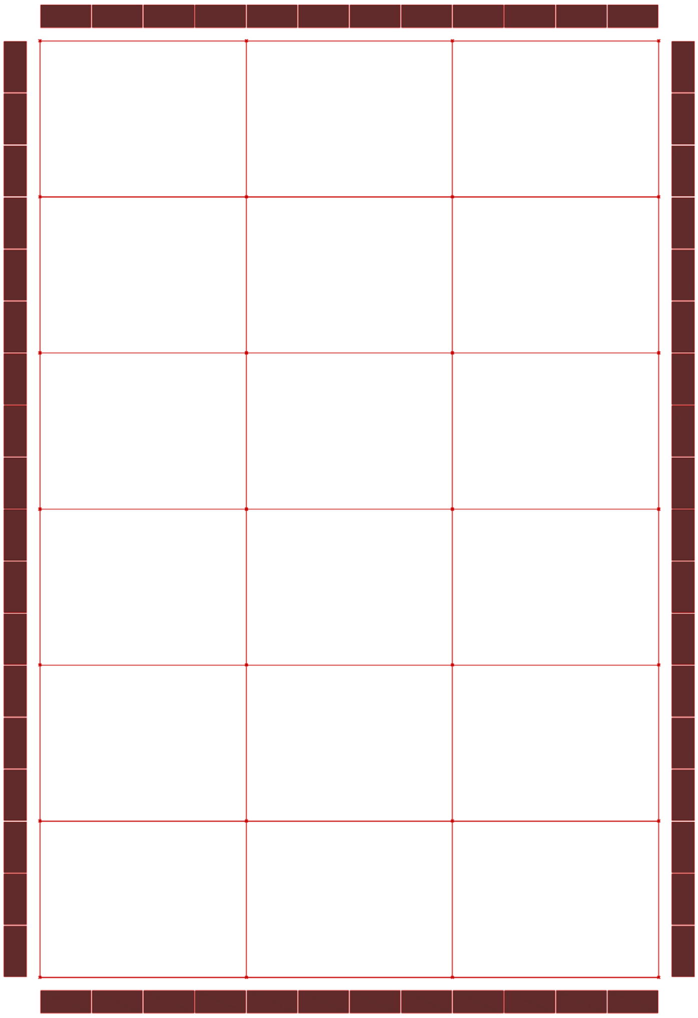


Picture 30: Grasshopper script for a smart 3D of the suspended facade typology 01. Authors own work.

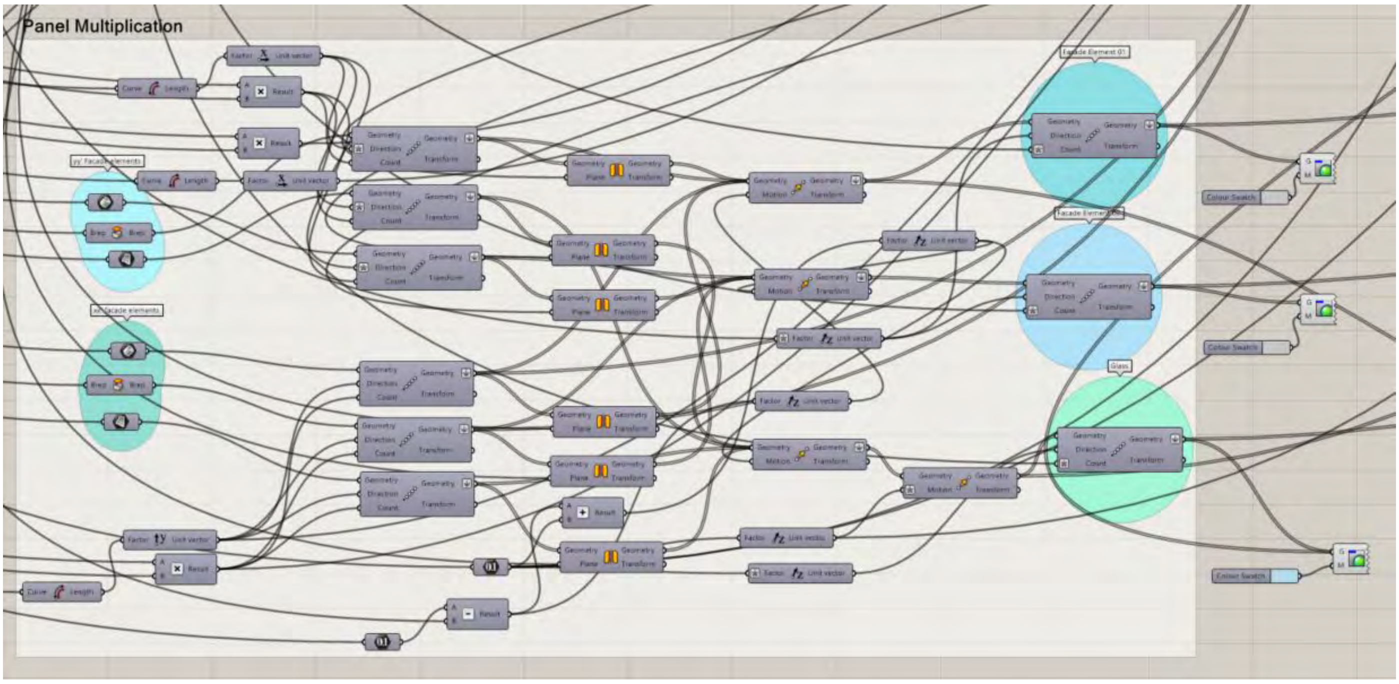


Picture 31: Suspended facade typology 01. Authors own work.

6.1 Development of the automation process

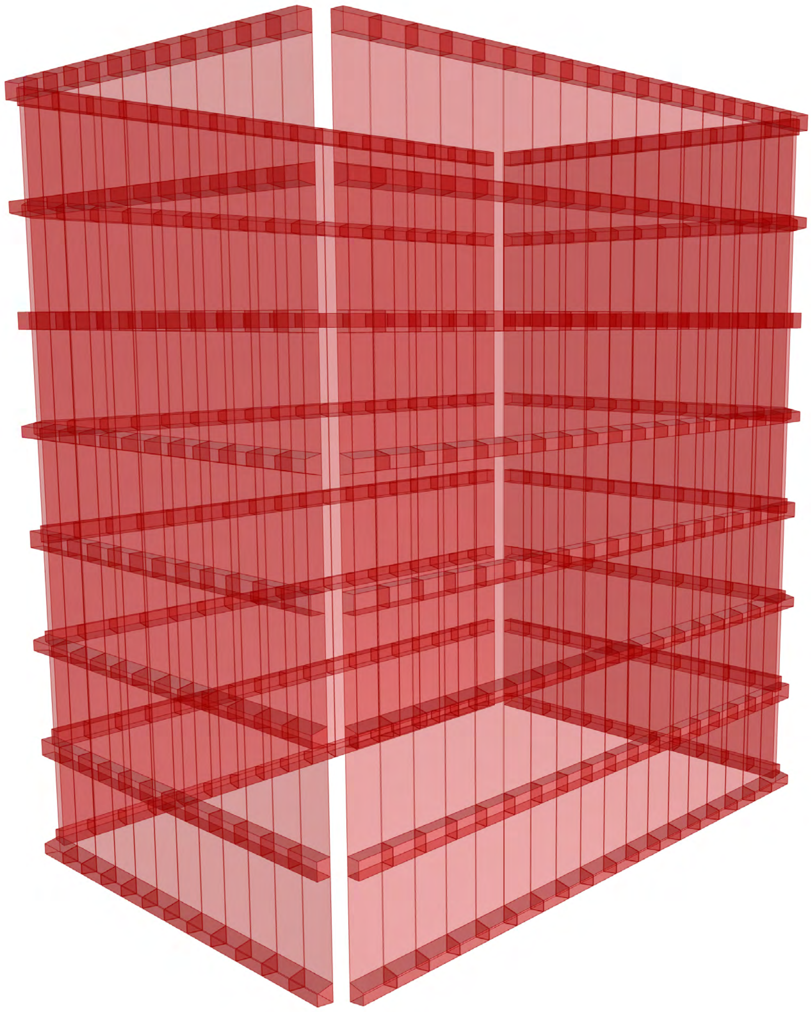


Picture 32: Panel multiplication, offset from Grid. Authors own work.

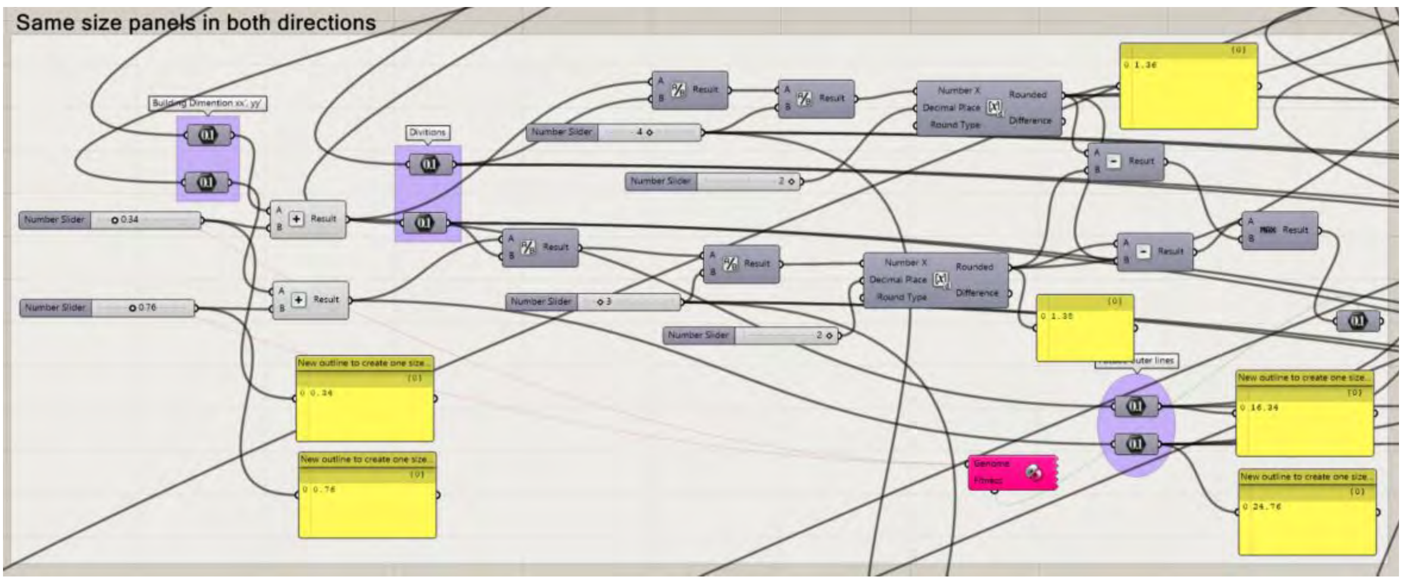


Picture 33: Panel multiplication, offset from Grid, Grasshopper script. Authors own work.

6.1 Development of the automation process

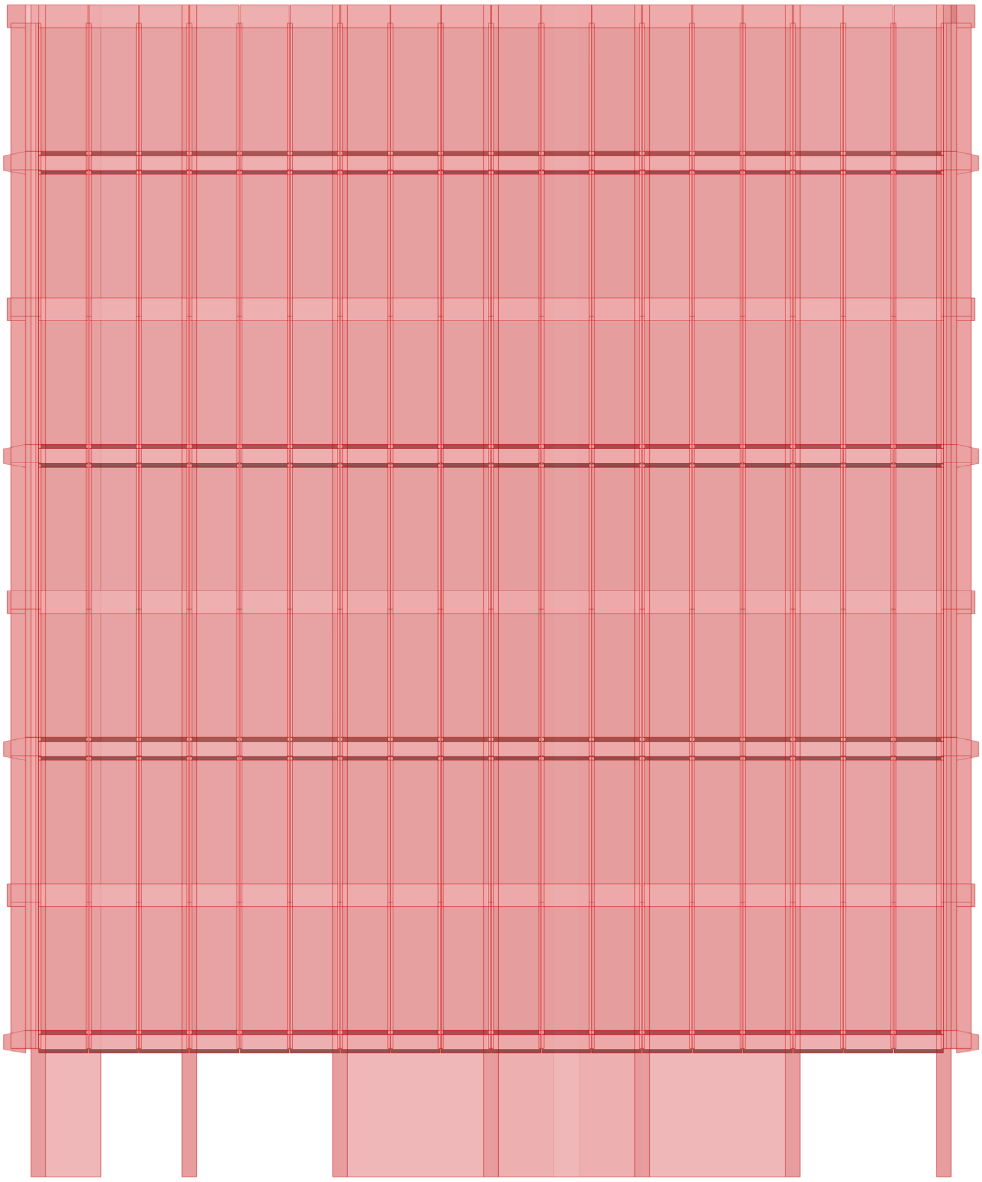


Picture 34: Multiplication in the z direction.Authors own work.

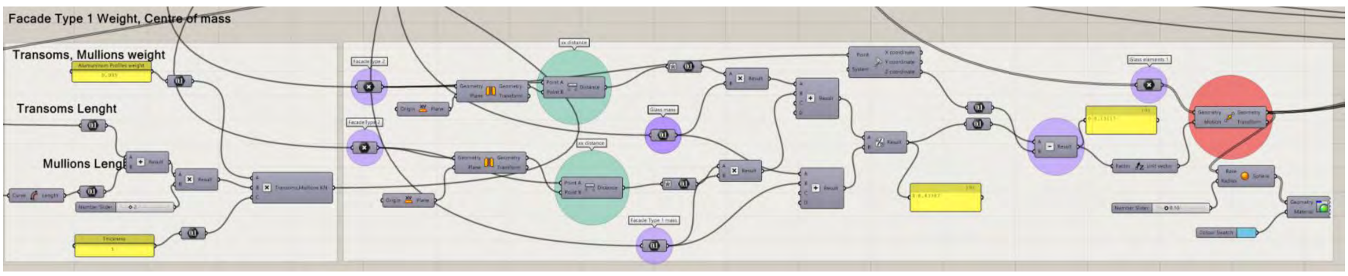


Picture 35: Panel multiplication, offset from Grid, Grasshopper script. Authors own work.

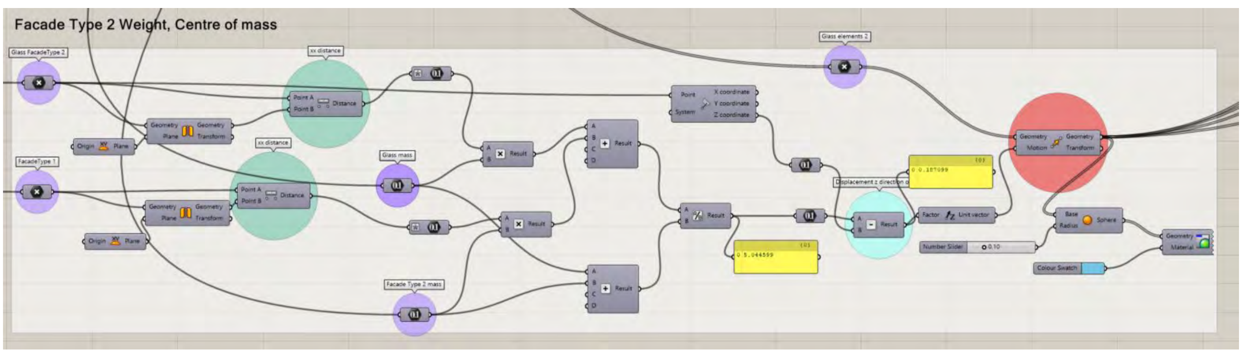
6.1 Development of the automation process



Picture 36: Elevation. Authors own work.

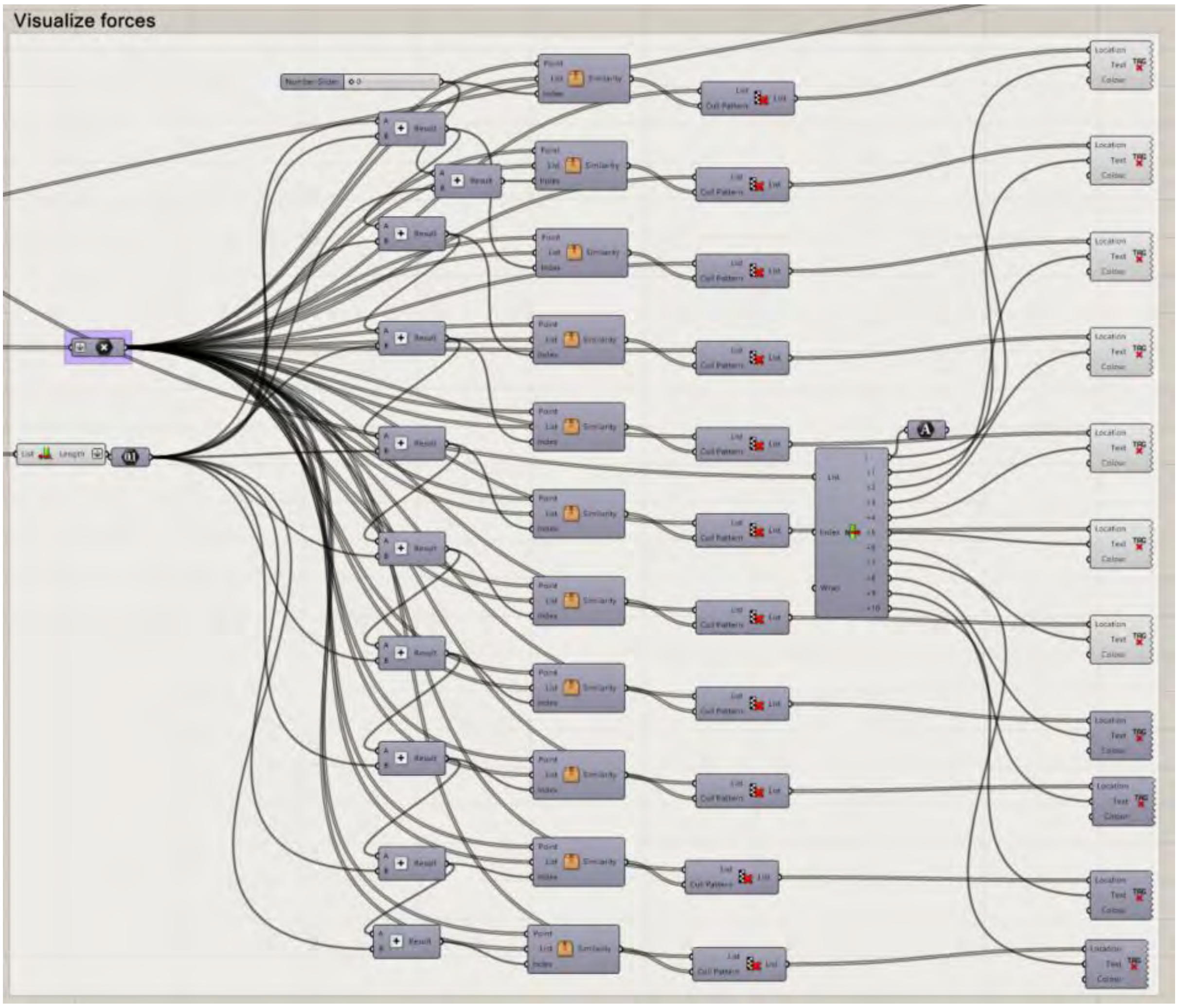


Picture 37: Centre of mass, weight calculation for facade typology 01 Grasshopper script. Authors own work.



Picture 38: Centre of mass, weight calculation for facade typology 02, Grasshopper script. Authors own work.

6.1 Development of the automation process



Picture 39: Showcasing the forces in Rhino, Grasshopper script. Authors own work.

6.1 Development of the automation process

Python Script

```python
xx_count = int(xx)
yy_count = int(yy)
fl_count = int(floors)
SDZ_count = int(SDZ)
b_count = int(b)
hght_cnt = int(hght)
bhlf = b * 0.5
flrnum= int(floors)
SDZ_count = int(SDZ)
m=int(mass)
mf1=int(mfa1)
mf2=int(mfa2)
gridsizex = int(gridx)
gridsizey = int(gridy)

SType_c=ord(SType)

x=xx_count/gridsizex
y=yy_count/gridsizey
d=0.2

y1=int(y)
x1=int(x)
x_step = xx_count // gridsizex
y_step= yy_count // gridsizey
```

Picture 40: Intergration of the Variables from Grasshoer to Python script. Authors own work.

```python
if SDZ_count==1:
  a=0.05
elif SDZ_count == 2:
  a=0.1
elif SDZ_count == 3:
  a=0.15
elif SDZ_count == 4:
  a=0.20
elif SDZ_count == 5:
  a=0.25

Ag= a*g
print("Ag=",Ag)
print("a=",a)

if SType_c == ord('A'):
 T1=0.15
 T2=0.4
 T3=2.5
 S=1

elif SType_c == ord('B'):
 T1=0.15
 T2=0.5
 T3=2
 S=1.2

elif SType_c== ord('C'):
 T1=0.2
 T2=0.6
```

Picture 41: :Calculation of the Seismic Design Spectrume. Authors own work.

6.1 Development of the automation process

Python Script

```
    T3=2
    S=1.4

elif SType_c== ord('D'):
    T1=0.2
    T2=0.8
    T3=2
    S=1.6

    #shear wall area
l = 4 * b
Ac = l * b * (0.2 + l / hght) ** 2
Ct = 0.075 / math.sqrt(Ac)


#building imporatance !! gi=1
gi=1
th=1
bo=2.5
q=3.5

    #Calculate SDS
T= Ct*(H)**(3/4)


Sds = 0

if 0 < T < T1:
    Sds = S * a * (1 + (T / T1) * (1.5))
elif T1 < T < T2:
```

Picture 42: :Calculation of the Building's Frequency Authors own work.

6.1 Development of the automation process

Python Script

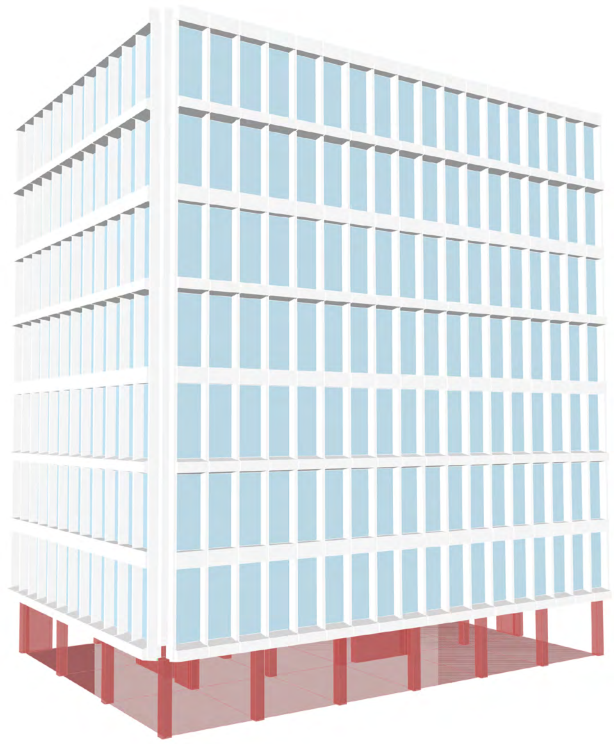
```python
Saf=0
Iy=7397673*10**-12
zf=3.5
E=210*10**9
lenght=fa1len

#facade frequency type 1
Km1 = (3 * E * Iy) / ((lenght)**3)
print('The facade stiffness is', Km1,'N/m')

Wf1m = mfa1*fa1len
print(Wf1m)
Taf = 2 * 3.14 * math.sqrt(Wf1m / Km1)
Tafr = round(Taf, 2)
print("The facade type 1 frequency is", Tafr)

```

Picture 43: Calculation of the facade's stiffness,Authors own work.

```python
mf1kn = 0
mf1kn = mfa1* 9.81
LIFF1=[]
a1=0
Zh=[]
ZH=hght

while a1 < floors :
    a1 = a1 + 1
    Saf = a * S * ((3 * (1 + (ZH / H))) / (1 + (1 - (Tafr / T)) ** 2 - 0.5))
    FF1 = Saf * mf1kn*0.001 * gaf / qaf
# from N to KN
    FF1_rounded = round(FF1, 2)
    ZH = ZH + hght
    LIFF1.append(FF1_rounded)
    Zh.append(ZH)


print('the seismic force per panel per floor is',LIFF1)

```

Picture 44: Calculation of the seismic force for everypanel for every floor. Authors own work.

6.2 Testing & validation of the automation process



Render 14: Model of a building office using the computational tool. Author's own work.

Building Information
Building Height 24m
Floor height=3.5m
Site Location Groningen Netherlands
Soil Type Soil Type D (Unstable ground)
Seismic Danger Zone 4, Ground Acceleration Ag=0.25g
Building Frequency
Case 01 Shear wall design T=0.48sec
Case 02 Simplified method T=0.05*H3/4 =0.6sec

Façade typology 01 information
Mass(m)= 306.78*1.35 Kg=414,153 Kg
Weight=414.153*9.81=4063N=4,1KN

Frequency
T=2π sqr(m/Ka)
Ka: Element Stiffness
K=(3*E*I)/L3

E: Modulus of Elasticity
Case 01: Aluminium frames E=70*109 N/m2 (Aluminium Alloy 96051)
Case 02: Wooden frames E=3.55*1012 N/m2 (Glula
T=2*3.14*sqr(346.39Kg/3157,34N/m)

Calculation of a section through a set of rectangles

TU Delft

Info: Calculation around the X axis (x)
Info facultatif on Y-axis (y)

Sketchup profile
inputfield

Inputdata

N°	width mm	Hiegth mm	bh mm2	bh^3/12 mm4	b^3h/12 mm4	dx mm	oppdx mm3	dy mm	oppdy mm3	oppdxx^2 mm4	oppdyy^2 mm4
1	50	4	200	267	41667	2	400	25	5000	2270146	225048
2	4	194	776	2433795	1035	101	78376	52	40352	44115	33237
3	50	2	100	33	20833	199	19900	79	7900	818305	41842
4	12	10	120	1000	1440	205	24600	110	13200	1116548	317719
5	4	15	60	1125	80	218	13050	118	7080	712339	212097
6			0	0	0	225	0	120	0	0	0
7			0	0	0	225	0	120	0	0	0
8			0	0	0	225	0	120	0	0	0
9			0	0	0	225	0	120	0	0	0
10			0	0	0	225	0	120	0	0	0

Results

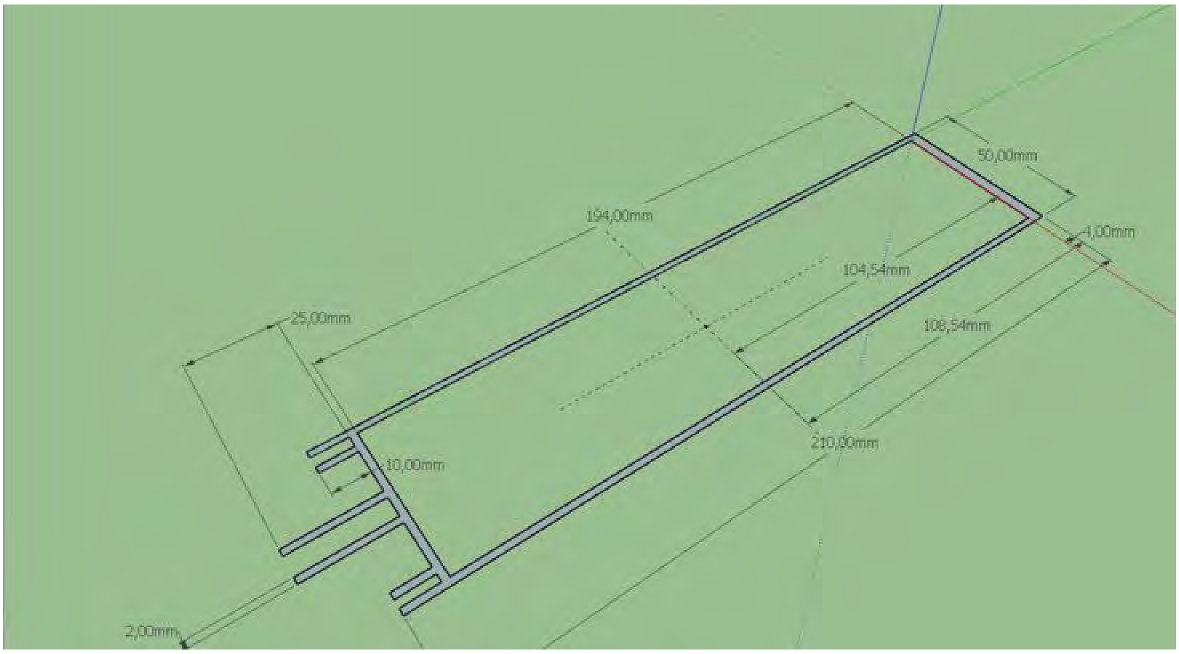
Surface 1256 mm^2

Inertia

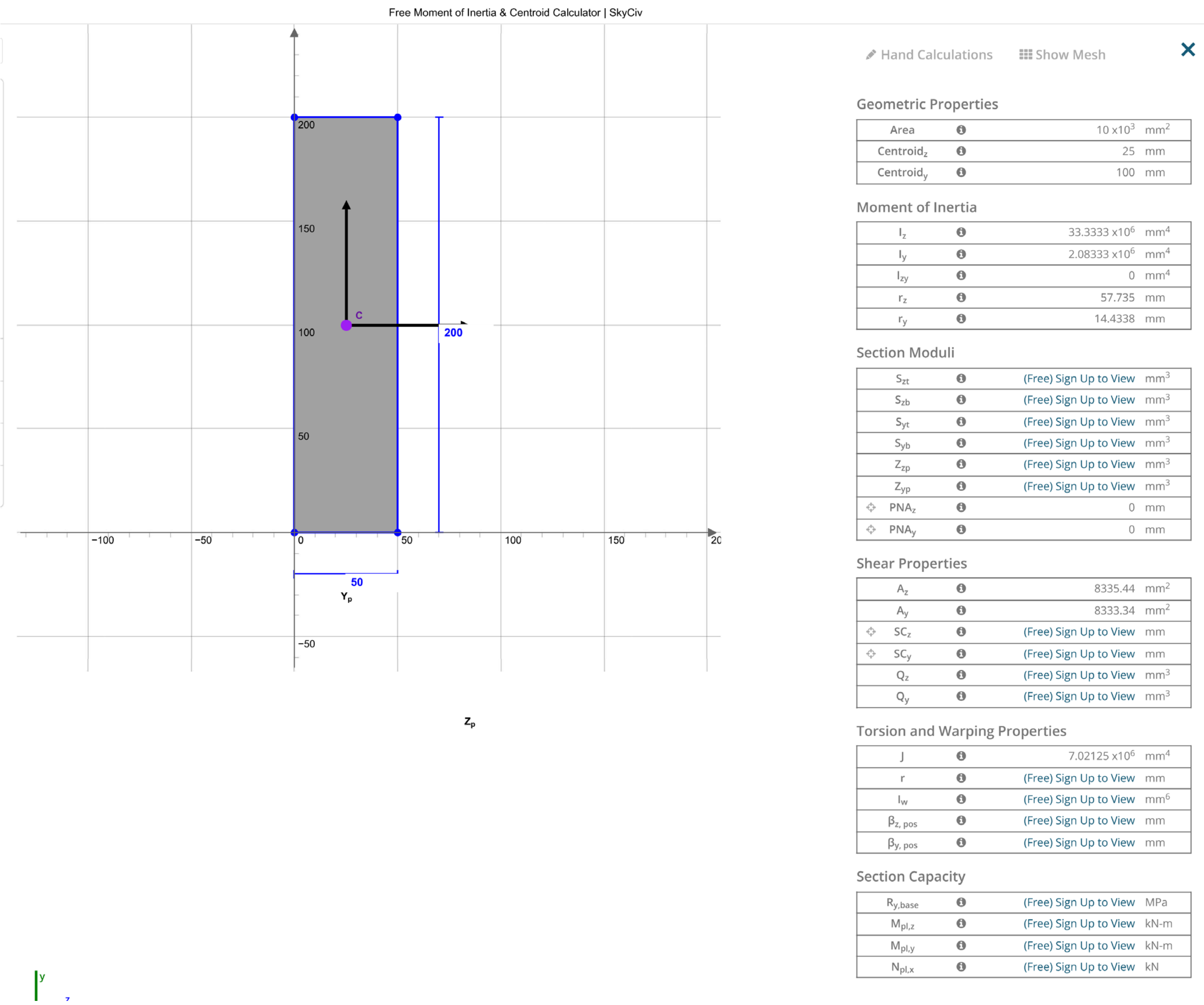
Ixx =	**7397673**	**mm^4**
Iyy =	*894998*	*mm^4*

ixx= 76.74547 mm

Zxtot:	**109**	mm
Zytot:	*59*	*mm*
Wxx1:	**68156**	mm^3
Wxx2:	**63521**	mm^3
Wyy1:	*15287*	*mm^3*
Wyy2:	*14563*	*mm^3*



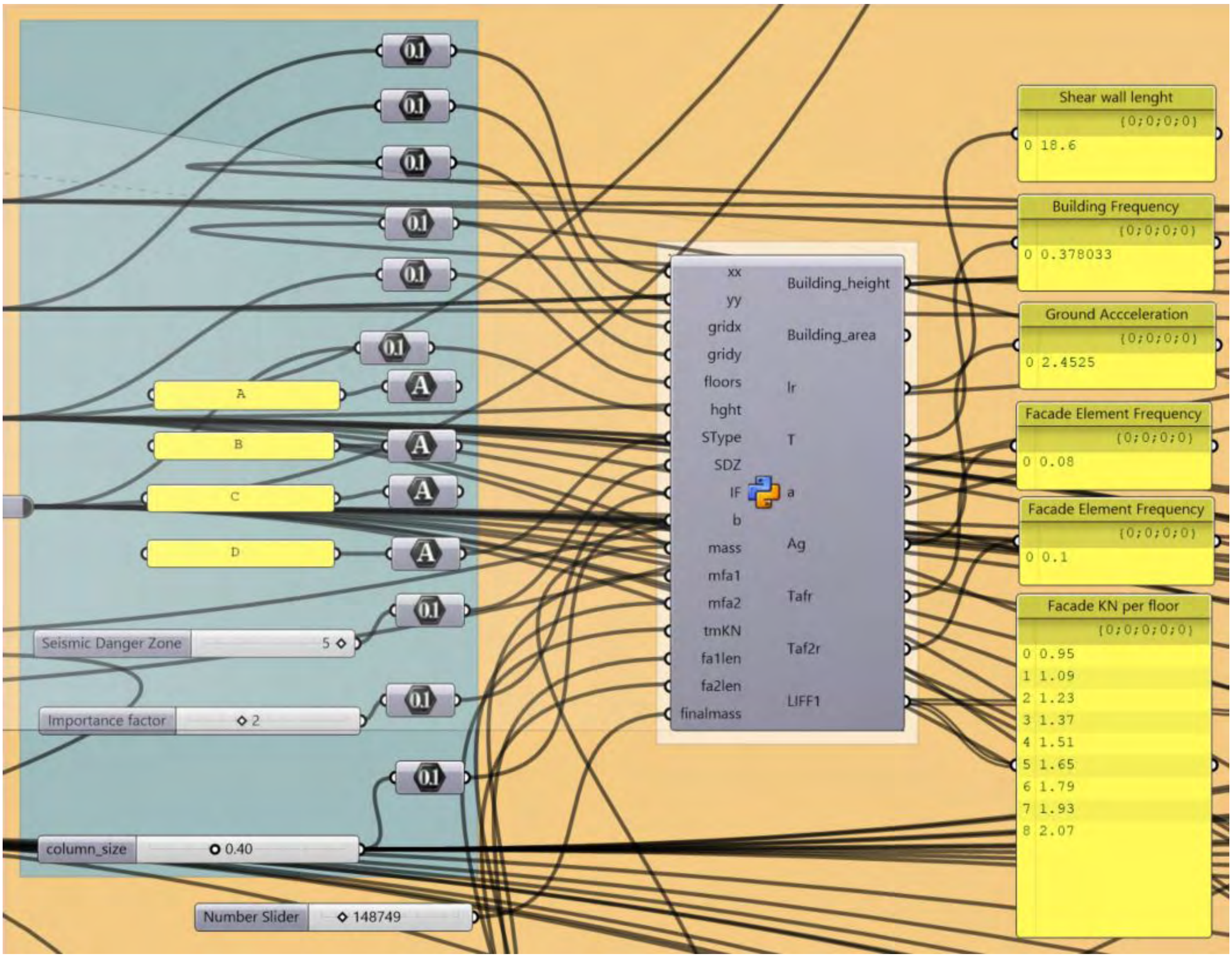
194,00mm
50,00mm
4,00mm
104,54mm
108,54mm
25,00mm
10,00mm
210,00mm
2,00mm



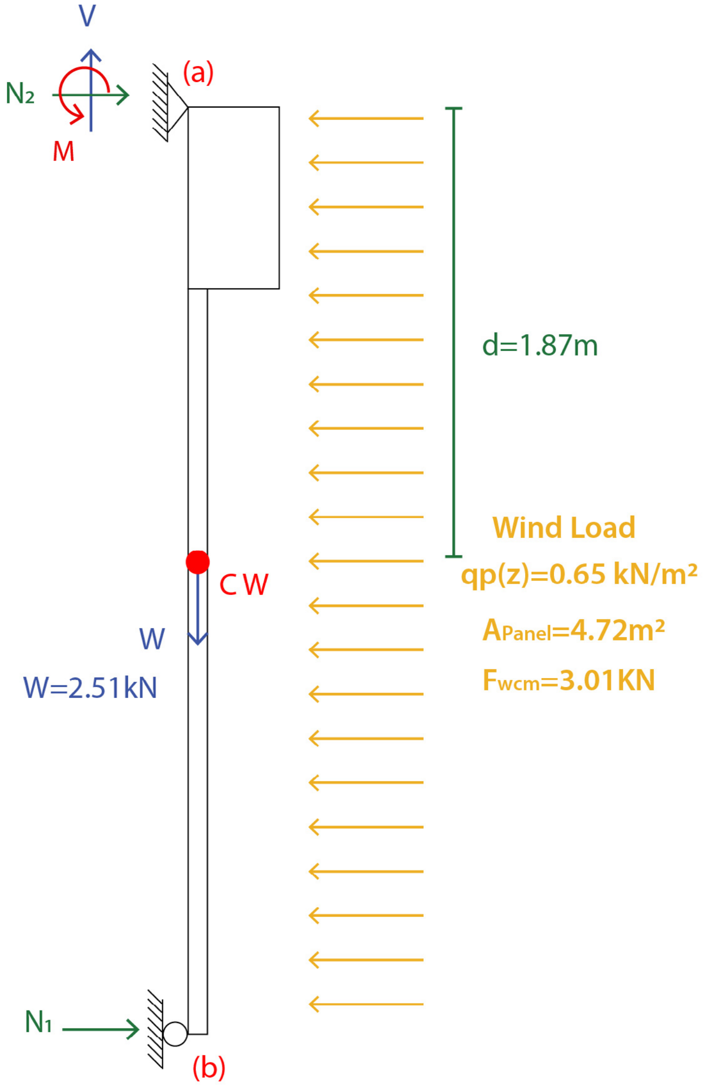
Free Moment of Inertia & Centroid Calculator | SkyCiv
Hand Calculations
Show Mesh
Geometric Properties
Area 10 x10^3 mm^2
Centroid_z 25 mm
Centroid_y 100 mm
Moment of Inertia
I_z 33.3333 x10^6 mm^4
I_y 2.08333 x10^6 mm^4
I_zy 0 mm^4
r_z 57.735 mm
r_y 14.4338 mm
Section Moduli
S_zt (Free) Sign Up to View mm^3
S_zb (Free) Sign Up to View mm^3
S_yt (Free) Sign Up to View mm^3
S_yb (Free) Sign Up to View mm^3
Z_zp (Free) Sign Up to View mm^3
Z_yp (Free) Sign Up to View mm^3
PNA_z 0 mm
PNA_y 0 mm
Shear Properties
A_z 8335.44 mm^2
A_y 8333.34 mm^2
SC_z (Free) Sign Up to View mm
SC_y (Free) Sign Up to View mm
Q_z (Free) Sign Up to View mm^3
Q_y (Free) Sign Up to View mm^3
Torsion and Warping Properties
J 7.02125 x10^6 mm^4
r (Free) Sign Up to View mm
I_w (Free) Sign Up to View mm^6
β_z, pos (Free) Sign Up to View mm
β_y, pos (Free) Sign Up to View mm
Section Capacity
R_y,base (Free) Sign Up to View MPa
M_pl,z (Free) Sign Up to View kN-m
M_pl,y (Free) Sign Up to View kN-m
N_pl,x (Free) Sign Up to View kN
200
50
Y_p
Z_p

6.2 Testing & validation of the automation process

T=2*3.14*sqr(306,8kg/1894237,25 N/m) =0.08sec **same as in the script**
F= Saf * mf1* gaf / qaf
Saf = a * S * ((3 * (1 + (ZH / H))) / (1 + (1 - (Tafr / T)) 2 - 0.5))= 0.25*1.6*((3*(1+(28/28)))/ (1+(1-(0.08/0.38)2-0.5))=1.38
Fsf=Saf*mf1* gaf / qaf=1.5*3.01kN*1/2=2.07kN **same as in the script**



Hand-calculations for th wind forces:



ΣF=0

ΣFz=0 <=> V-W=0<=>V=W=2.51kN

ΣFx=0 <=> $N_1+N_2-F_s$ =0<=>
N1+N2=3.01KN (1)

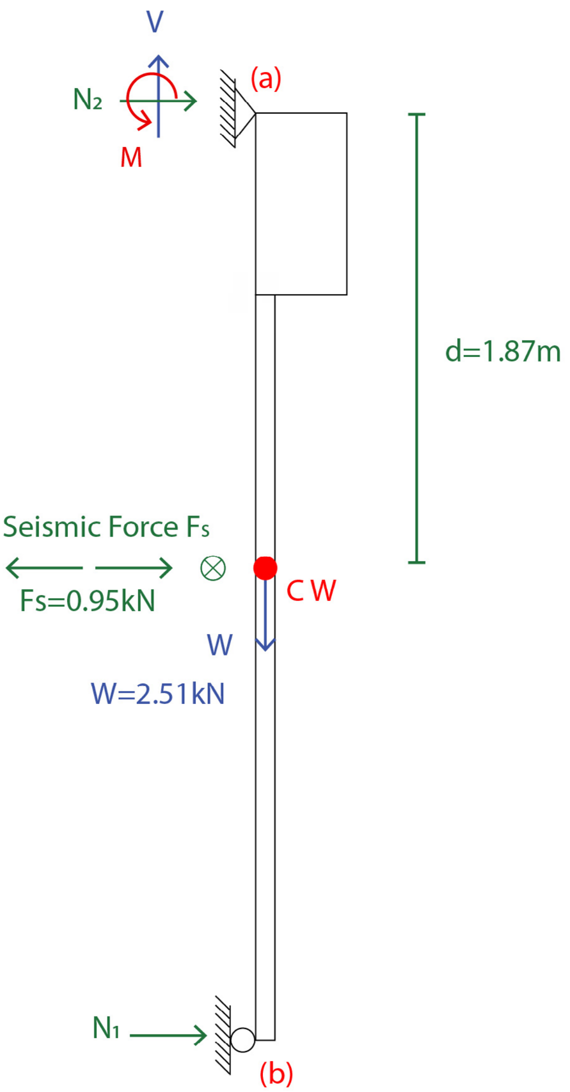
ΣM(a)=0 <=> N_1*3.5m-F_{wcm}*d=0 <=>
N_1= (3.01kN*1.87m)/3.5m=1.6kN

(1),(2) N2=3.01kN-1.6kN=1.41kN

ΣM(cw)=0 <=> -N_1*1.63m+M-N2*1.87=0
-1.41kN*1.63+M+1.6*1.87 <=>
M=+2.29-2.99=-0.7kN/m

Diagram 22: Free-form diagram, Calculations of Wind forces. Authors own work

Hand-calculations for the seismic forces(Fs):



SF=0

SFz=0 <=> V-W=0<=>V=W=2.51kN

SFx=0 <=> N_1+N_2-F_s =0<=>
N1+N2=0.95KN (1)

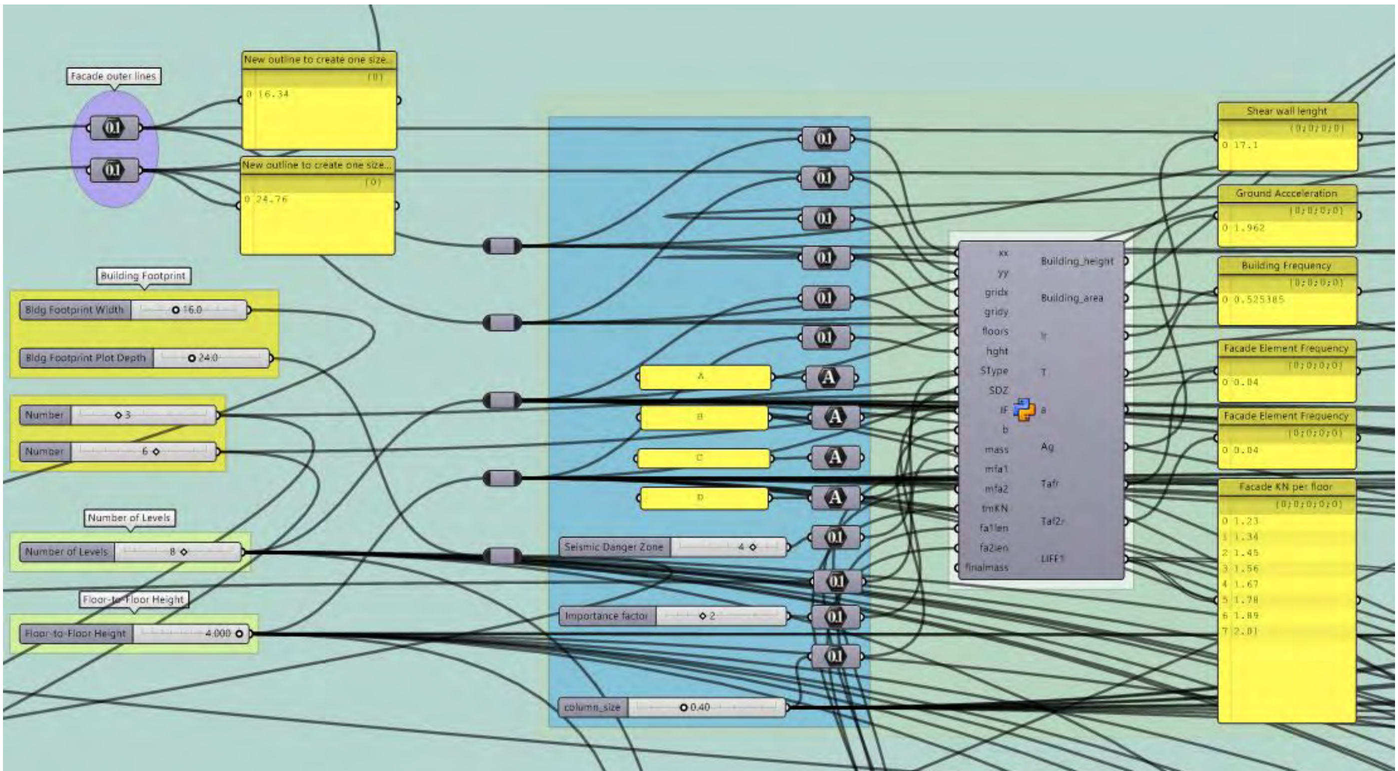
SM(a)=0 <=> N_1*3.5m-F_s*d=0 <=>
N_1= (0.95kN*1.87m)/3.5m=0.5kN

(1),(2) N2=0.95kN-0.5kN=0.45kN

SM(cw)=0 <=> -N_1*1.63m+M-N2*1.87=0
-0.5kN*1.63+M+0.45*1.87 <=>
M=0.81-0.84=-0.03kN/m

Diagram 23: Free-form diagram, Calculations of Seismic forces. Authors own work

6.1 Development of the automation process

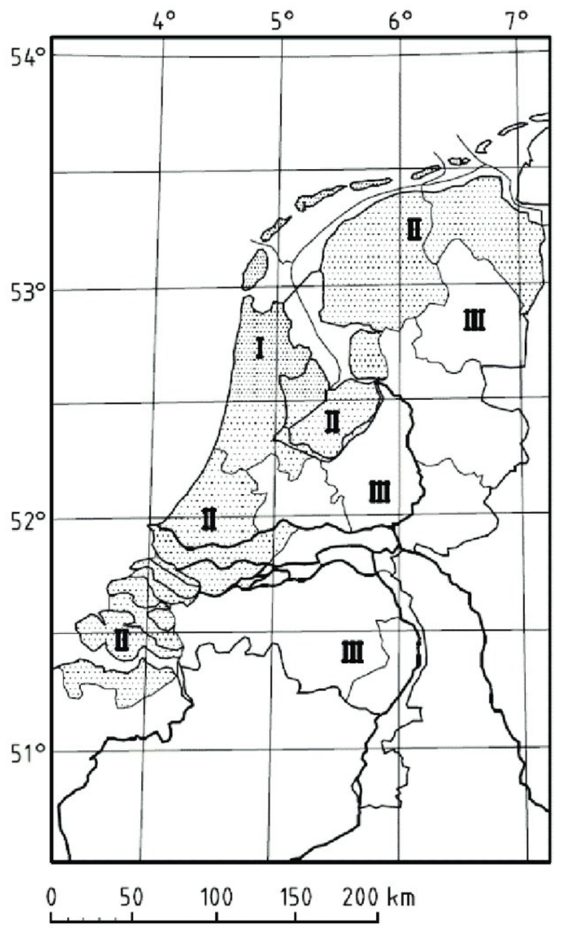


Picture 45: Outputs of the computational tool. Authors own work.

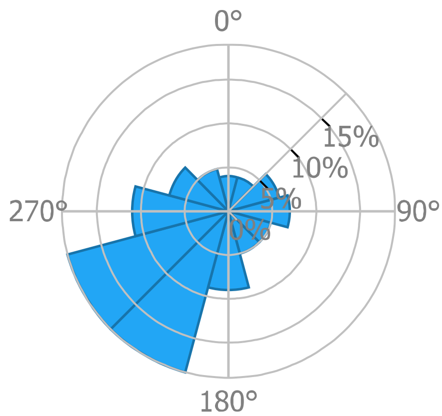
6.1 Wind forces Data processing

The diagram presented visualizes the variation of wind force with height for different zones and area types. This comprehensive graph provides insights into how wind forces impact structures at varying heights across different environmental conditions.

Key Elements of the Map 01:
Zone 1: Represented by lines indicating wind forces at different heights for coastal, underdeveloped, and developed areas.
Zone 2: Represented by lines indicating wind forces at different heights for coastal, underdeveloped, and developed areas.
Zone 3: Represented by lines indicating wind forces at different heights for underdeveloped and developed areas (no data for coastal areas).
Area Types:
Coast: Areas located near the coastline, typically experiencing higher wind forces due to less obstruction and higher wind speeds.
Underdeveloped: Areas with sparse development, where wind forces are influenced by limited structures.
Developed: Urban or densely populated areas, where wind forces are moderated by numerous buildings and other structures.



Map 04: Classification of the Netherlands in wind areas Source:NEN, 2011



Picture 46: Wind Directionality
Source: dlubal.com

6.1 Wind forces Data processing

Interpretation of the Data:

The x-axis represents the height of the building (in meters), ranging from 1 meter to 100 meters.

The y-axis represents the wind force (in kN/m^2) experienced at different heights.

Each line in the diagram corresponds to a specific combination of zone and area type, with different colors and markers distinguishing them.

Observations:

Coastal areas in Zone 1 exhibit the highest wind forces across all heights, peaking at around 2.38 kN/m^2 at 100 meters. Underdeveloped and developed areas show similar wind force patterns, with slightly lower values compared to coastal areas. Coastal areas in Zone 2 also show significant wind forces, but slightly lower than Zone 1. Wind forces in underdeveloped and developed areas are lower than coastal areas, following a similar trend as in Zone 1.

Zone 3 data is available only for underdeveloped and developed areas. Wind forces in these areas are generally lower than Zones 1 and 2. Developed areas in Zone 3 show the lowest wind forces among all zones, reflecting the moderating effect of dense urban structures.

The diagrams effectively illustrate the impact of height, zone, and area type on wind forces. It highlights the variations in wind forces experienced by buildings in different environmental conditions. Coastal areas consistently experience higher wind forces, while developed areas show lower forces due to the shielding effect of urban structures. This information is crucial for architects, engineers, and urban planners to design buildings that can withstand wind forces specific to their location and height.

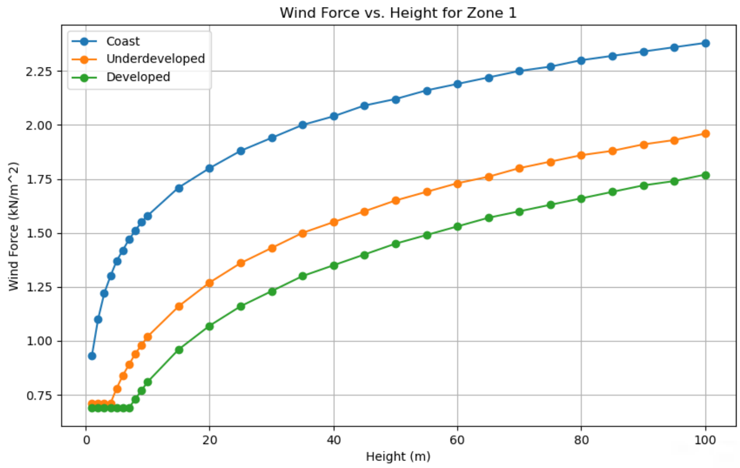


Diagram 05: Wind load in Wind Zone I,Coastline, Developed and Underdeveloped

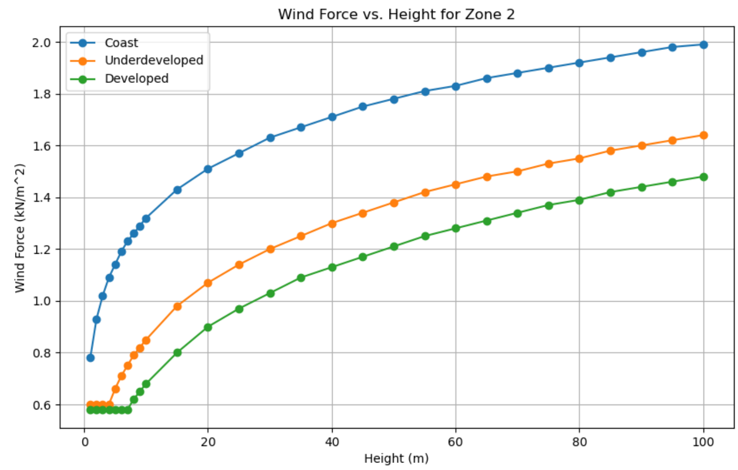


Diagram 06: Wind load in Wind Zone II,Coastline, Developed and Underdeveloped

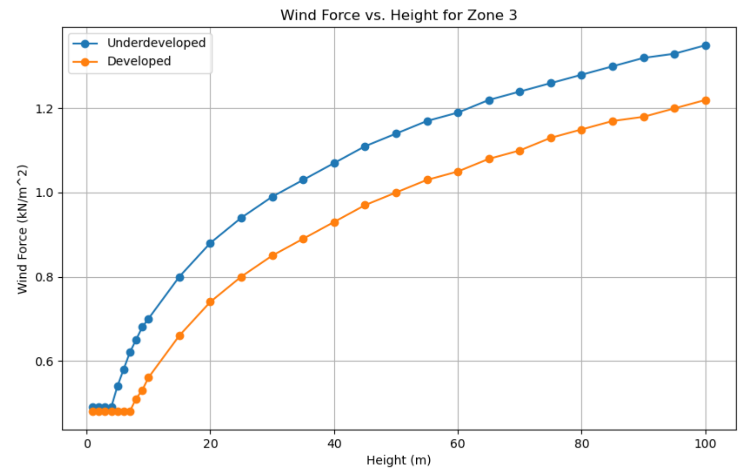


Diagram 07: Wind load in Wind Zone III,Developed and Underdeveloped

6.1 Seismic forces Data processing

The four diagrams produced visualize the seismic forces experienced by facade fragments at different floor heights across various seismic danger zones and soil types.

These comprehensive graphs provide insights into how seismic forces impact structures at varying heights in different environmental conditions. Each diagram focuses on a specific soil type and compares the seismic forces across multiple seismic danger zones.

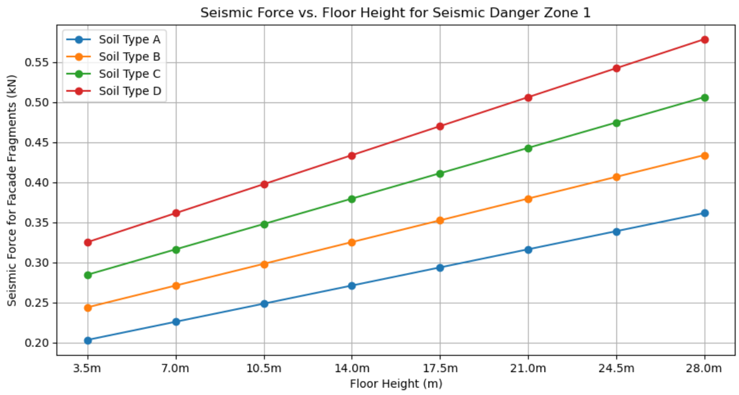


Diagram 08: Seismic Force per panel, per floor,soil Type,Seimic Danger Zone 1 Authors own work

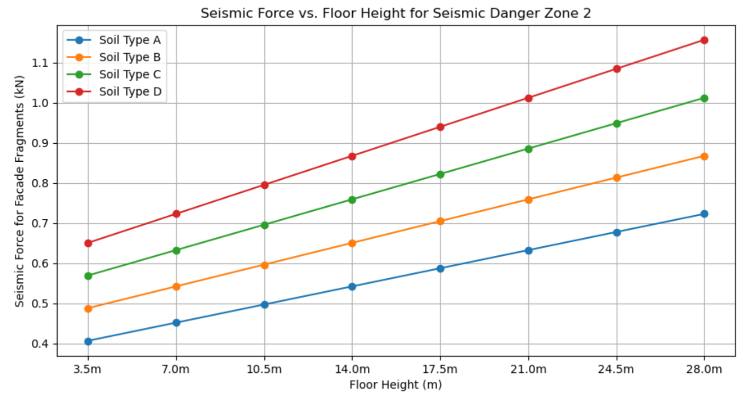


Diagram 09: Seismic Force per panel, per floor,soil Type,Seimic Danger Zone 2 Authors own work

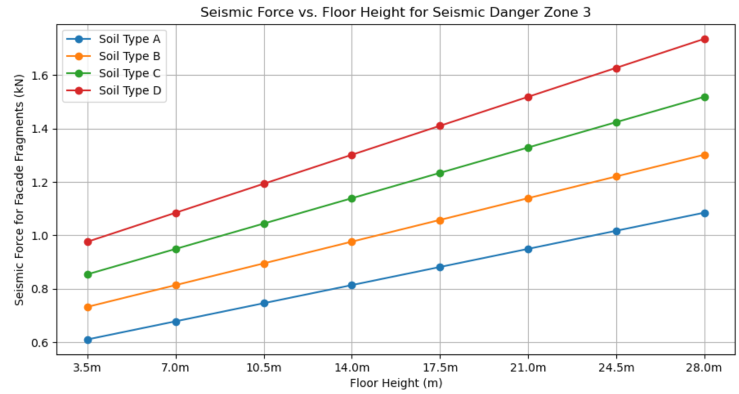


Diagram 10: Seismic Force per panel, per floor,soil Type,Seimic Danger Zone 3 Authors own work

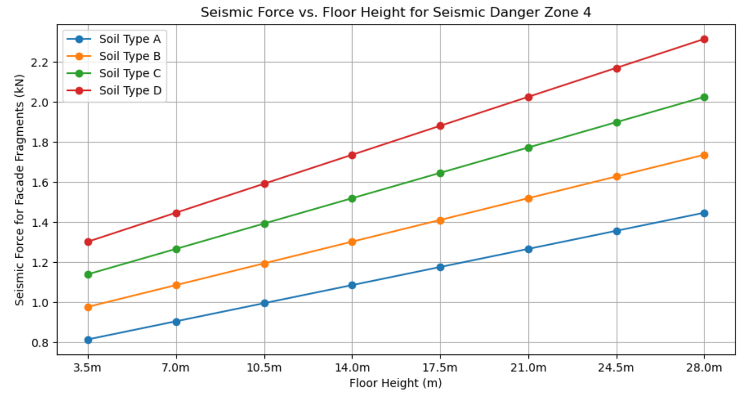


Diagram 11: Seismic Force per panel, per floor,soil Type,Seimic Danger Zone 4 Authors own work

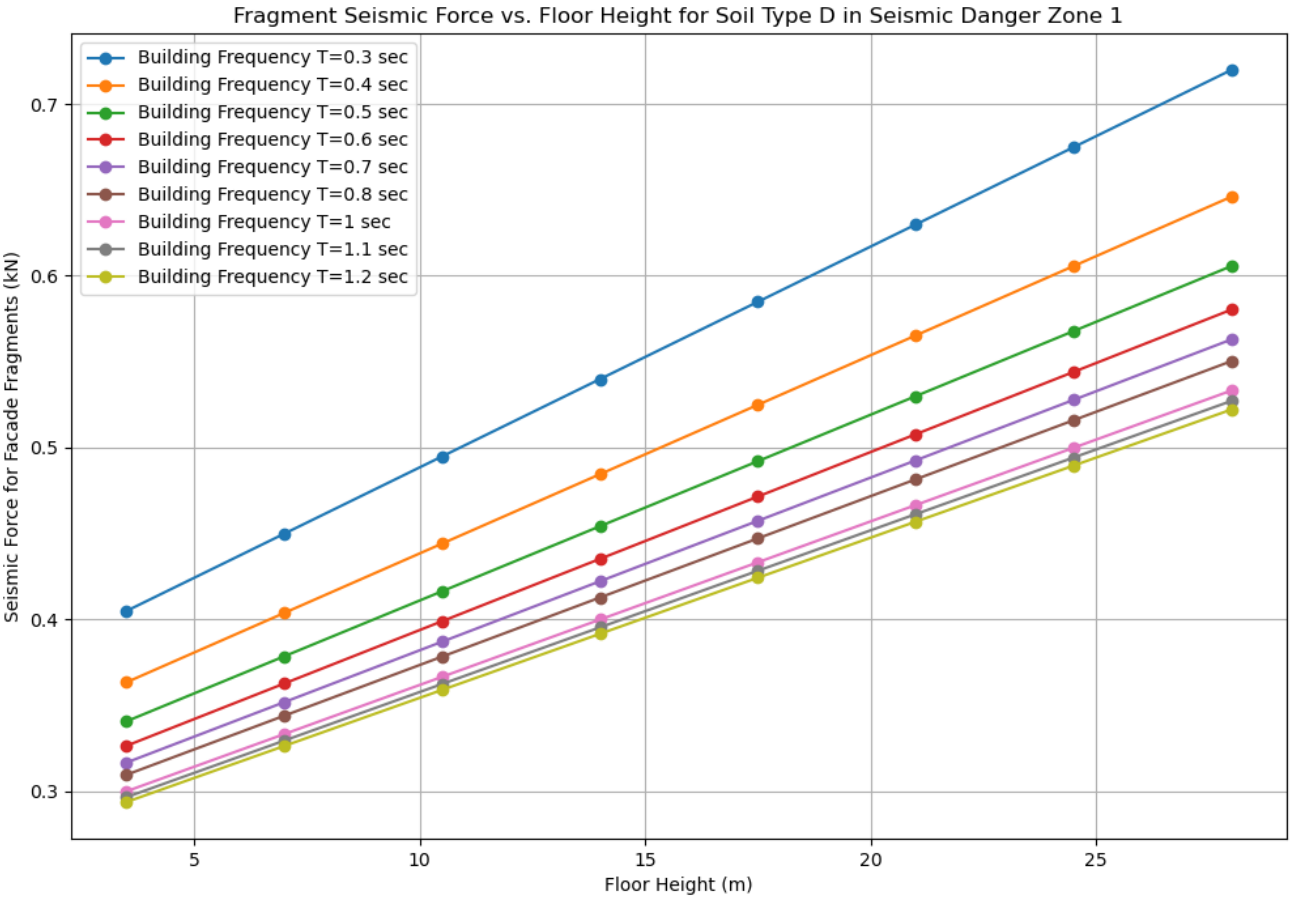


Diagram 12: Seismic Force per panel, per floor,soil Type D,Seimic Danger Zone 1 with different building frequencies, Authors own work

Each of the following diagrams illustrate the relationship between the seismic force acting on façade fragments and the floor height for buildings of various buildingfrequencies (0.3sec<T<1.2sec) within distinct seismic danger zones (SDZ 1 through SDZ 5). The analysis focuses on Soil Type D, which is the typical soil condition in Groningen, Netherlands.

Seismic Danger Zone 1 (SDZ 1)
The seismic forces range from approximately in 28m 0.51 kN to 0.73 kN(percentage increase: ≈43%).
There is a clear linear relationship between floor height and seismic force for each building frequency.
Buildings with lower natural frequencies (e.g., T = 0.3 sec) experience higher seismic forces compared to those with higher natural frequencies (e.g., T = 1.2 sec).
The linearity suggests a proportional relationship between the height of the building and the induced seismic forces on façade fragments.
Lower frequency buildings (indicating stiffer structures) are more susceptible to higher seismic forces at given heights.

6.1 Seismic forces Data processing

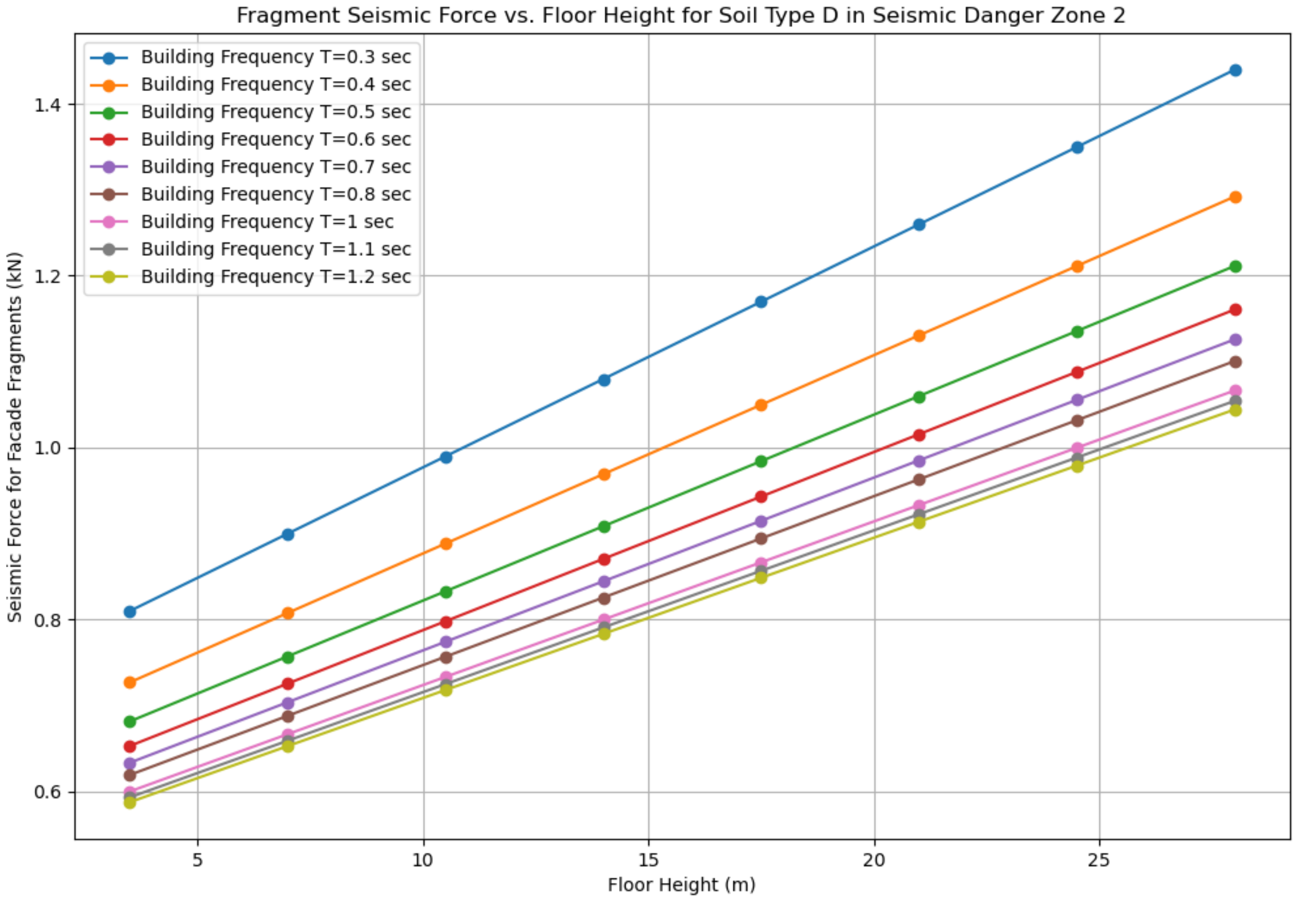


Diagram 13: Seismic Force per panel, per floor,soil Type D,Seimic Danger Zone 2 with different building frequencies, Authors own work

Seismic Danger Zone 2 (SDZ 2)
Seismic forces increase as the building;s frequency drops, for example at 28m ranging from approximately 1.05 kN to 1.45 kN.(percentage increase: ≈38%).
The proportional relationship between floor height and seismic force remains consistent.
The escalation in seismic force values from SDZ 1 to SDZ 2 highlights the increased seismic risk associated with the higher danger zone. The consistent trend across building frequencies emphasizes the importance of frequency considerations in seismic design, as stiffer buildings continue to exhibit higher forces.

6.1 Seismic forces Data processing

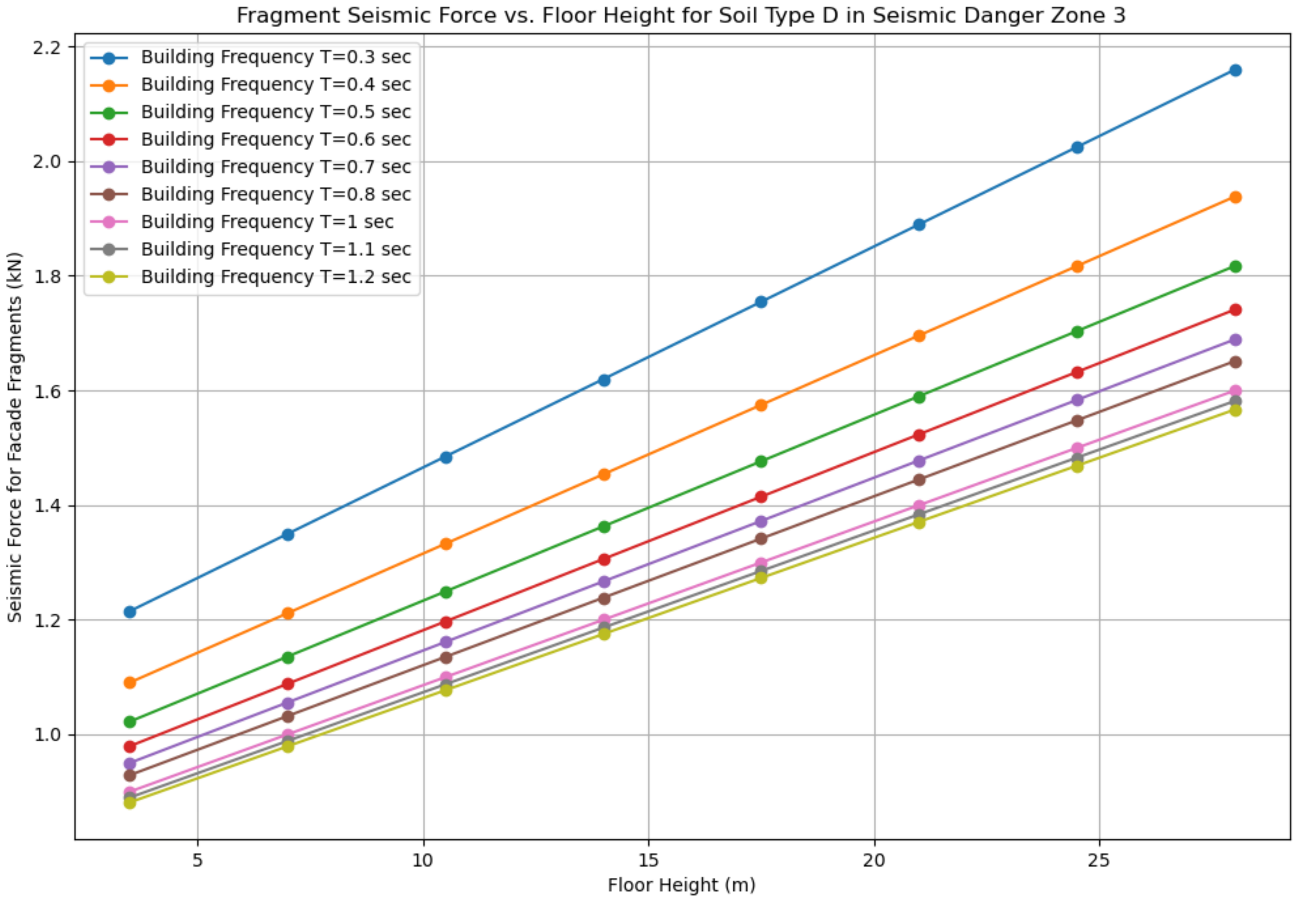


Diagram 14: Seismic Force per panel, per floor,soil Type D,Seimic Danger Zone 3 with different building frequencies, Authors own work

Seismic Danger Zone 3 (SDZ 3)
The seismic forces range from approximately 1.5kN to 2.18 kN(percentage increase: ≈45%).

6.1 Seismic forces Data processing

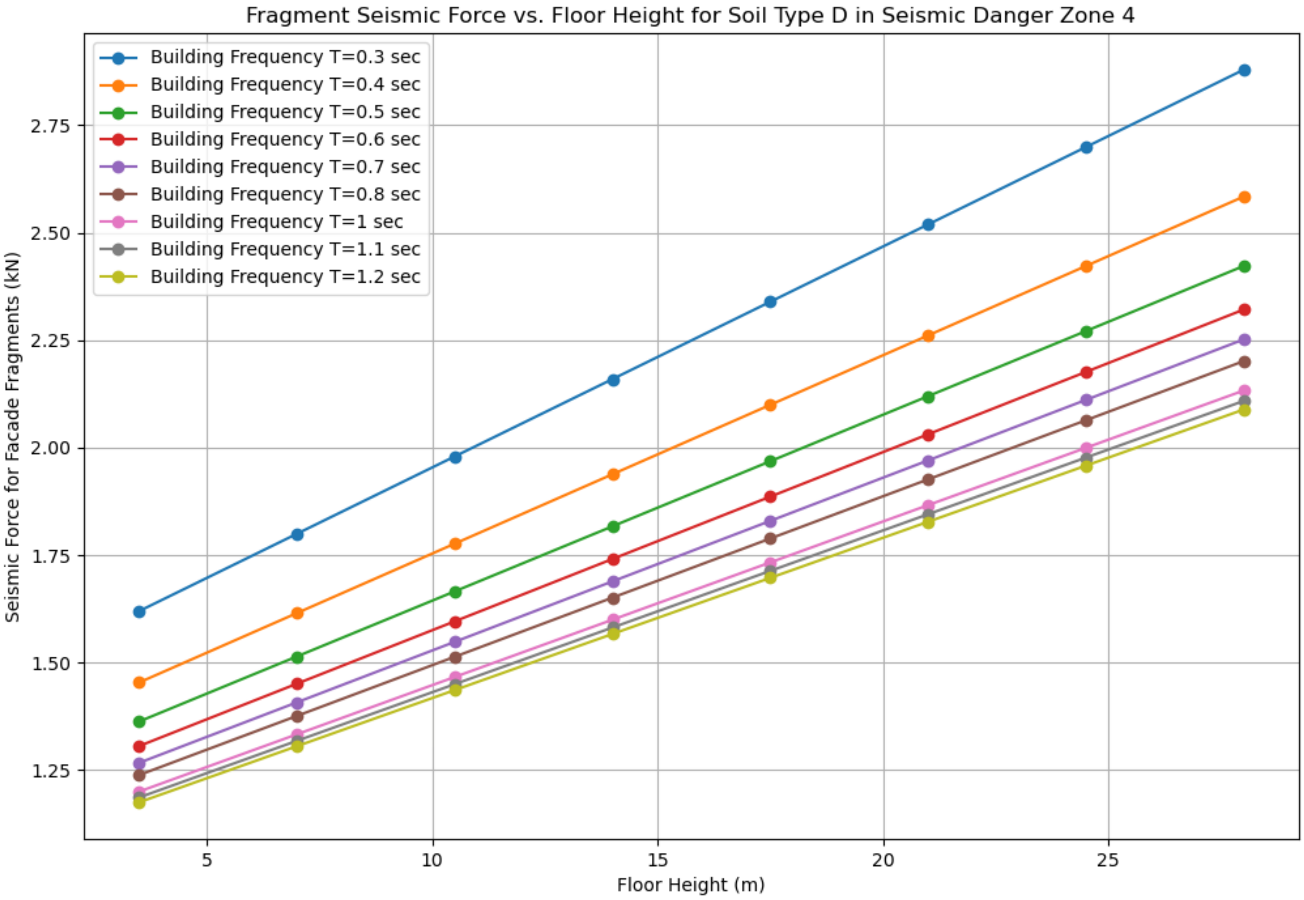


Diagram 15: Seismic Force per panel, per floor,soil Type D,Seimic Danger Zone 4 with different building frequencies, Authors own work

Seismic Danger Zone 4 (SDZ 4)
The seismic forces range from approximately 2.08kN to 2.85kN.(percentange 37%)
The linear relationship continues, with a steeper gradient compared to previous zones.

6.1 Seismic forces Data processing

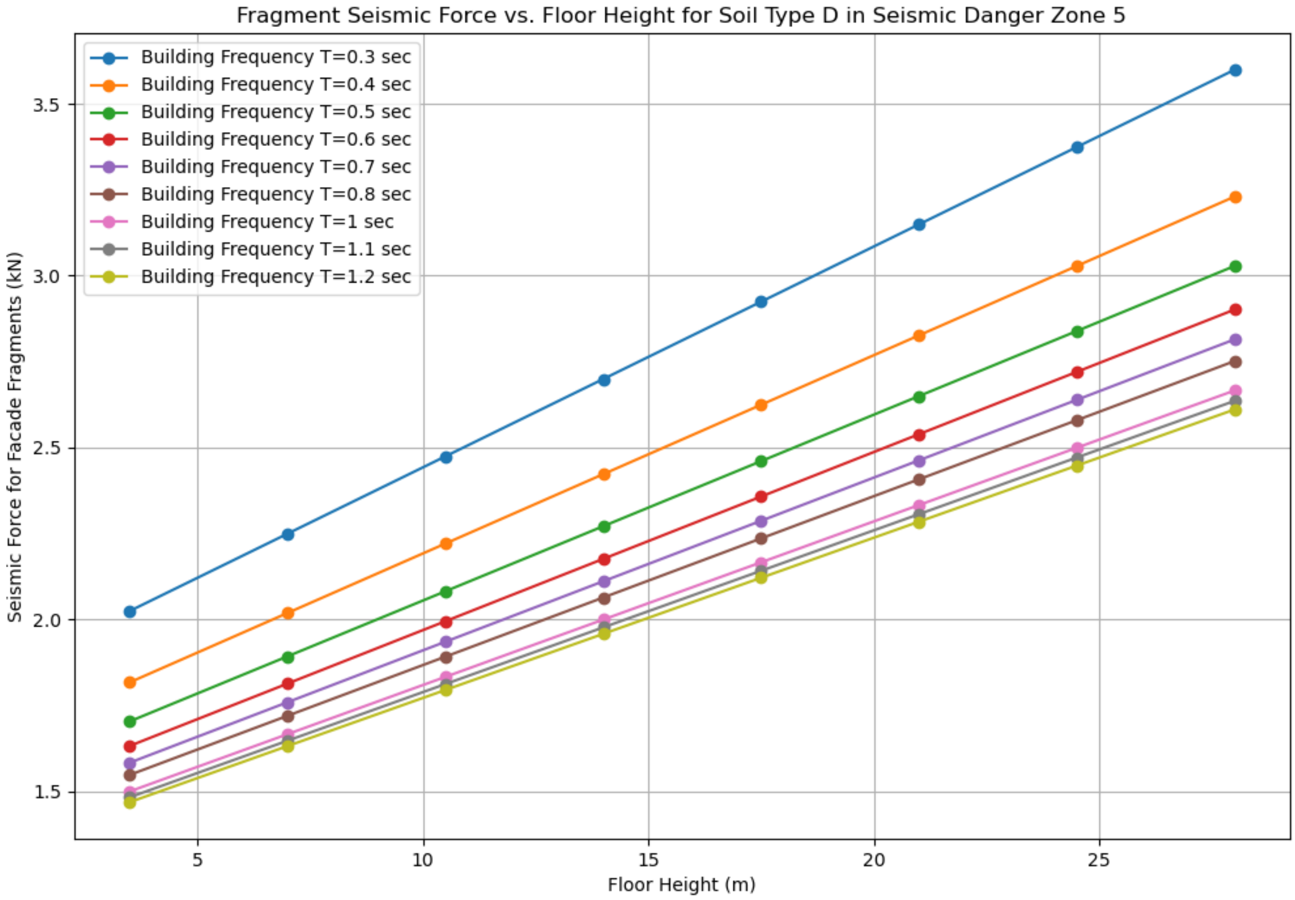


Diagram 16: Seismic Force per panel, per floor,soil Type D,Seimic Danger Zone 5 with different building frequencies, Authors own work

Seismic Danger Zone 5 (SDZ 5)
The seismic forces at 28m range from approximately 1.5kN to 2.3kN(percentage increase: ≈53%). This trend reinforces the necessity for enhanced structural integrity and façade design in higher seismic zones.

General Observations:
Seismic forces consistently increase with both floor height and decreasing building frequency across all seismic danger zones.
The rate of increase in seismic forces is higher in zones with greater seismic danger.
Design Implications:
Low-Frequency Buildings: Need robust seismic design to handle higher forces.
High-Risk Zones: Advanced engineering solutions and materials are essential.
Predictive Modeling: Reliable linear trends allow for effective use of height and frequency in predicting seismic forces.

By incorporating these detailed descriptions and analyses, we gain a comprehensive understanding of the seismic forces at play and the critical factors influencing their magnitudes. This data-driven approach aids in making informed decisions for safer building designs in varying seismic environments.

6.1 Seismic forces Data processing

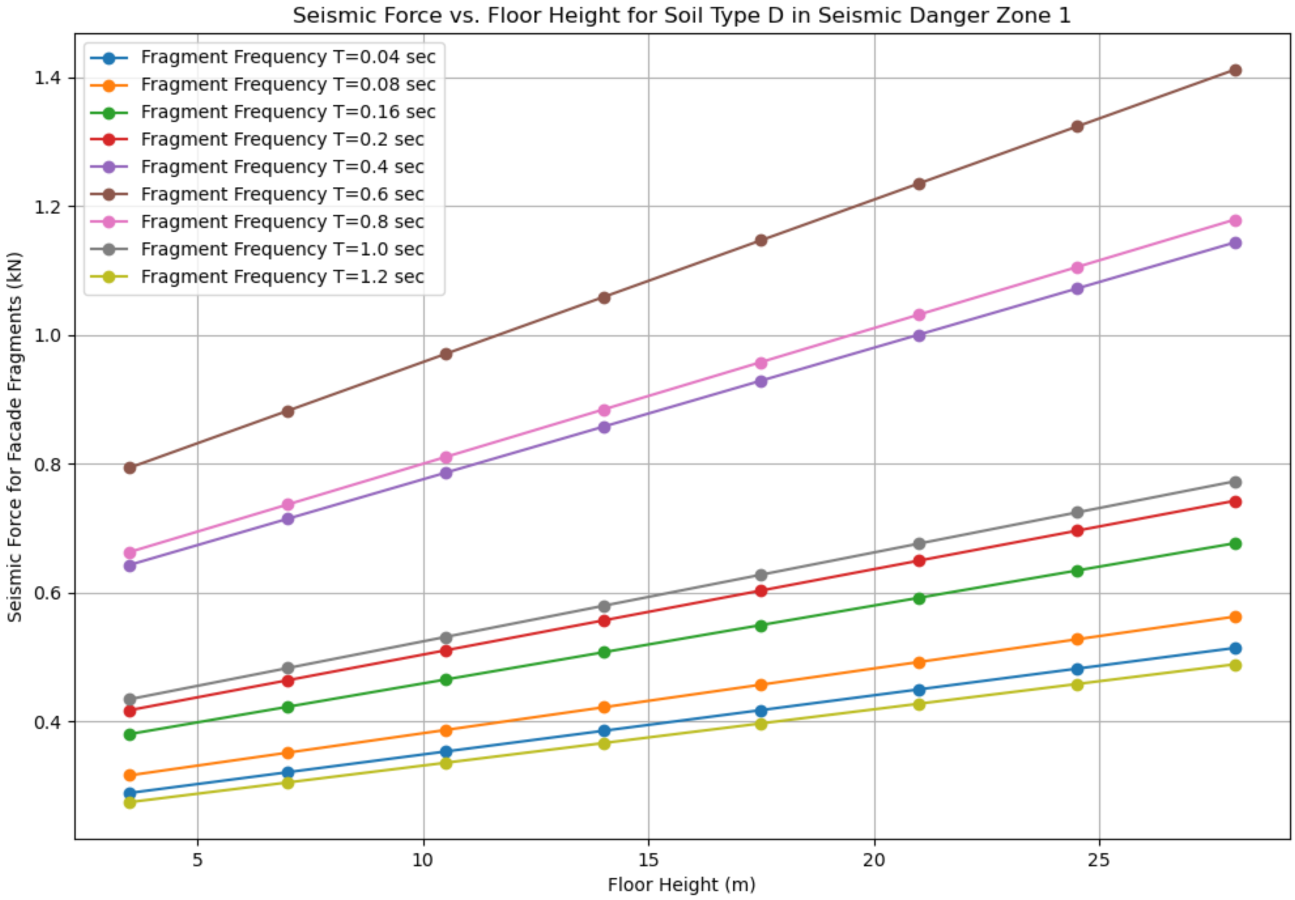


Diagram 17: Seismic Force per panel, per floor,soil Type D,Seimic Danger Zone 1 with different facade frequencies, Authors own work

This diagram presents the seismic force (in kN) experienced by façade fragments as a function of floor height (in meters) in Seismic Danger Zone 1.

Frequencies range from T=0.04 seconds to T=1.2 seconds. The seismic force exhibits a linear increase with floor height. This trend is consistent across all fragment frequencies. Lower frequencies (T=1.2 sec) result in similar seismic forces compared to higher frequencies (T=0.04 sec). When the fragment frequency matches the building's frequency the resonance effect takes place resulting the highest seismic force the fragments have to withstand(0.8kN to 1.4kN in the height of the building). The grater the difference from the renosance frequency the smaller the seismic force a fragment has to withstand. Engineers should focus on broading the building's natural period compared to the facades frequency to avoid resonance with predominant seismic frequencies. This can be achieved through structural stiffening and optimizing the distribution of mass of the fragment. In parallel materials with higher damping properties should be considered to dissipate seismic energy effectively.

Example: If the force at Tf=0.6 at 28m the sesmic force is 1.4 kN, then at Tf=0.04 it might be 0.5kN (180% decrease).

6.1 Seismic forces Data processing

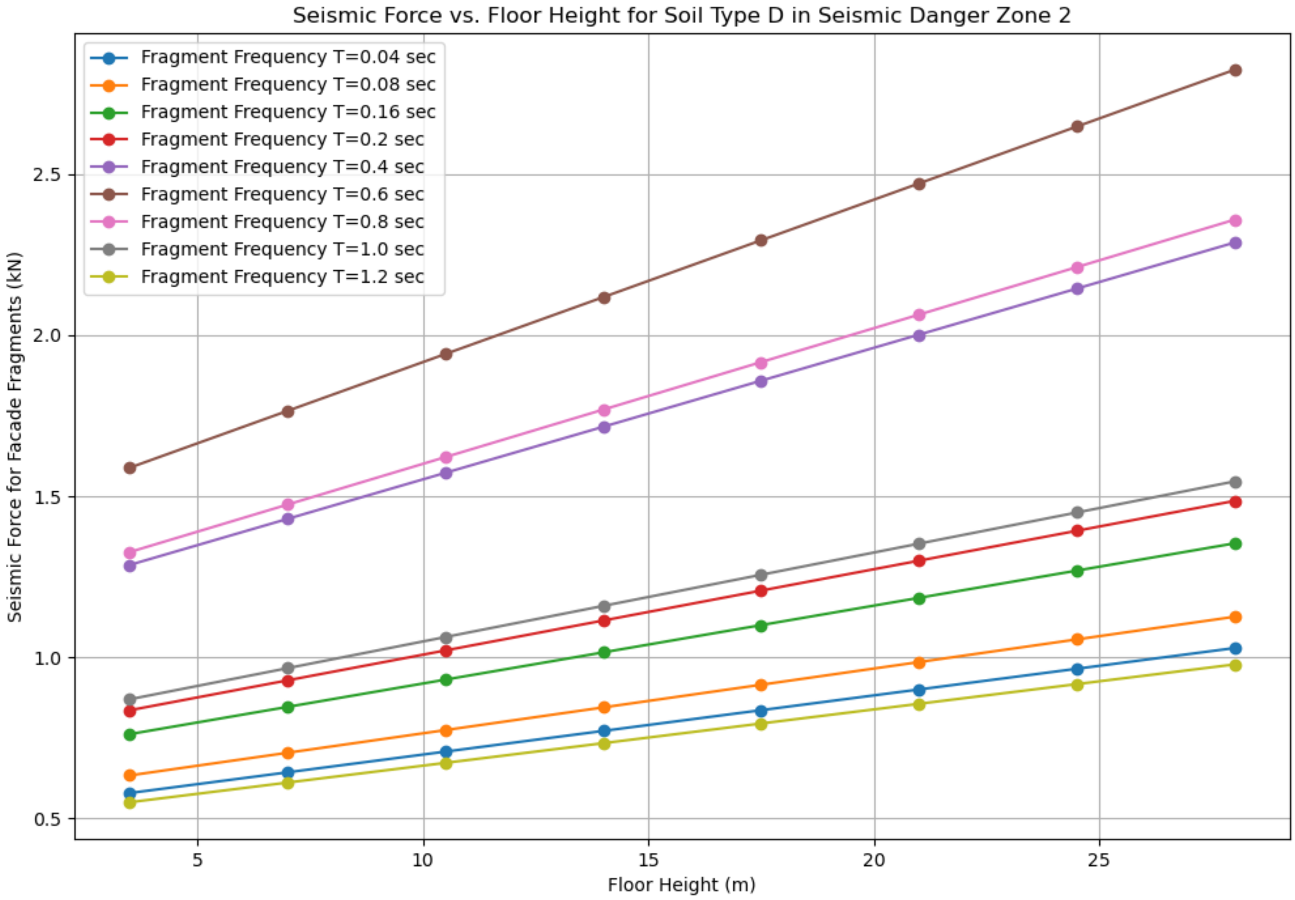


Diagram 18: Seismic Force per panel, per floor,soil Type D,Seimic Danger Zone 2 with different facade frequencies, Authors own work

This diagram presents the seismic force (in kN) experienced by façade fragments as a function of floor height (in meters) in Seismic Danger Zone 2.
The seismic force exhibits a linear increase with floor height. This trend is consistent across all fragment frequencies. As the frequency start getting closer to the building's frequency, the resonance effect becomes more pronounced, causing higher forces on the building façade.

Example: If the force at Tf=0.6 at 28m the sesmic force is 3kN, then at Tf=0.04sec or Tf=1,2sec it might be 1kN (200% decrease).

6.1 Seismic forces Data processing

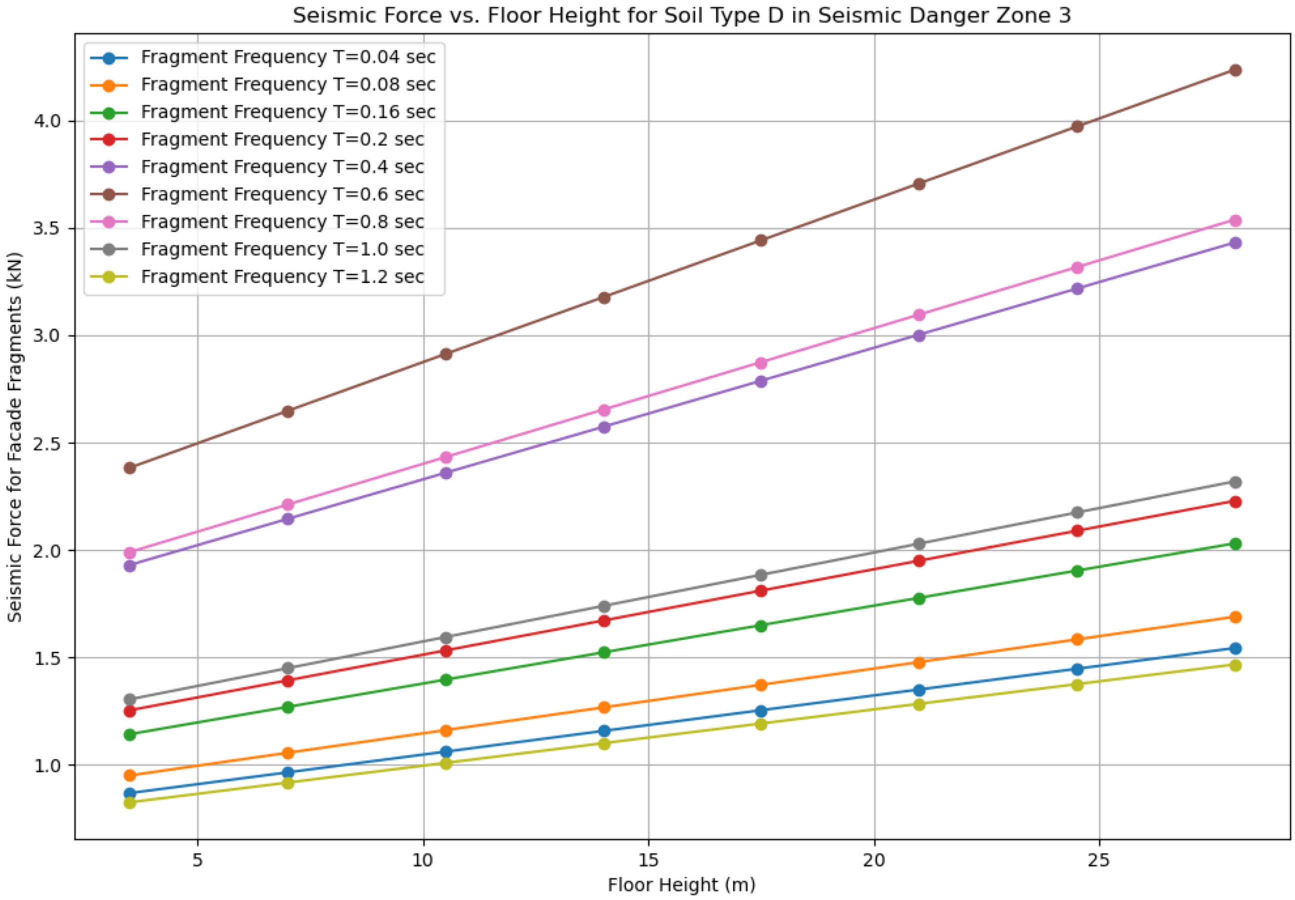


Diagram 19: Seismic Force per panel, per floor,soil Type D,Seimic Danger Zone 3 with different facade frequencies, Authors own work

This diagram presents the seismic force (in kN) experienced by façade fragments as a function of floor height (in meters) in Seismic Danger Zone 3.
The seismic force exhibits a linear increase with floor height. This trend is consistent across all fragment frequencies. As the frequency start getting closer to the building's frequency, the resonance effect becomes more pronounced, causing higher forces on the building façade.

Example: If the force at Tf=0.6 at 28m the sesmic force is 4.5kN, then at Tf=0.04sec or T=1.2sec it might be 1,5kN (150% decrease).

6.1 Seismic forces Data processing

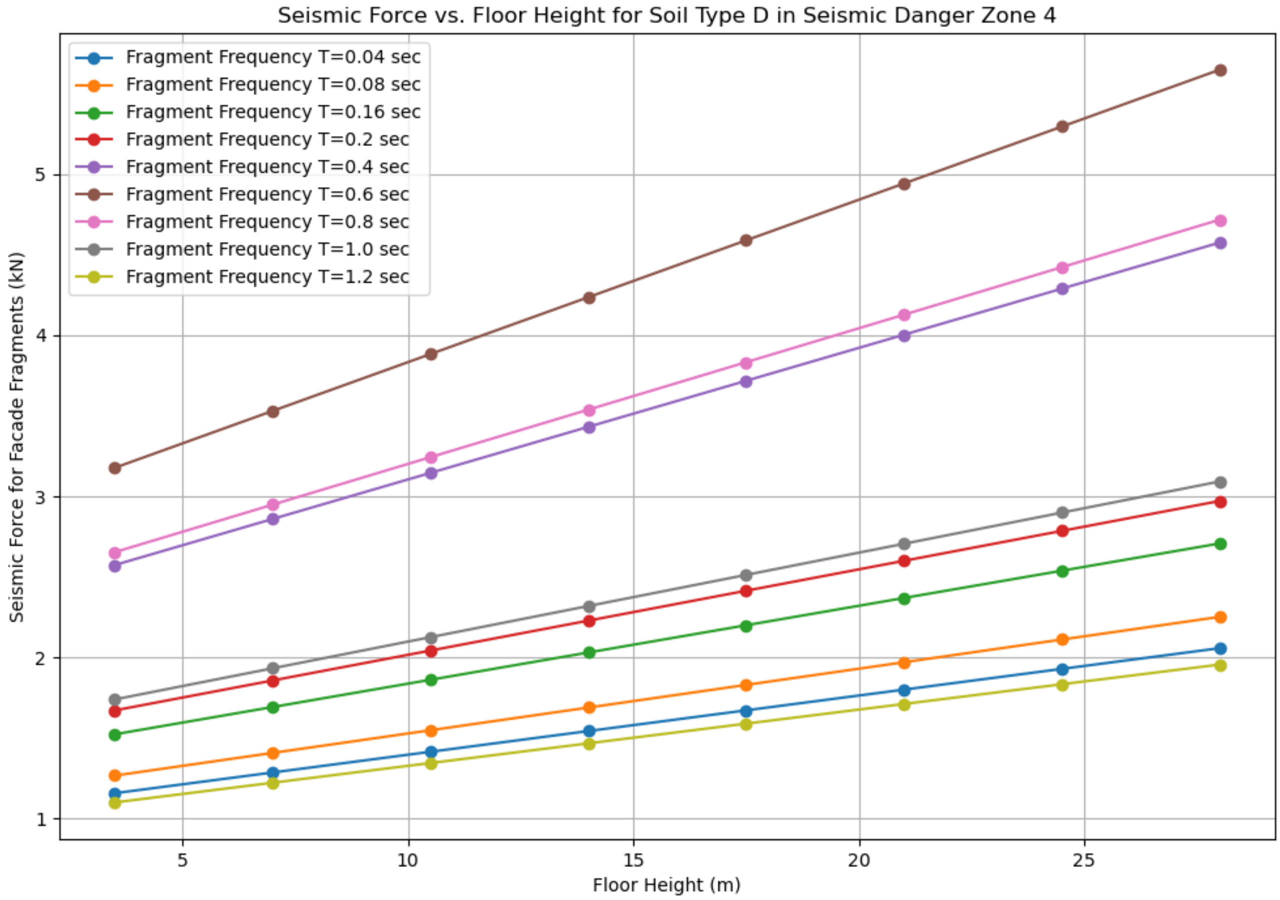


Diagram 20: Seismic Force per panel, per floor,soil Type D,Seimic Danger Zone 4 with different facade frequencies, Authors own work

This diagram presents the seismic force (in kN) experienced by façade fragments as a function of floor height (in meters) in Seismic Danger Zone 4.
The seismic force exhibits a linear increase with floor height. This trend is consistent across all fragment frequencies. As the frequency start getting closer to the building's frequency, the resonance effect becomes more pronounced, causing higher forces on the building façade.

Example: If the force at Tf=0.6 at 28m the sesmic force is 5,8kN, then at Tf=0.04sec or T=1.2sec it might be 2kN (140% decrease).

6.1 Seismic forces Data processing

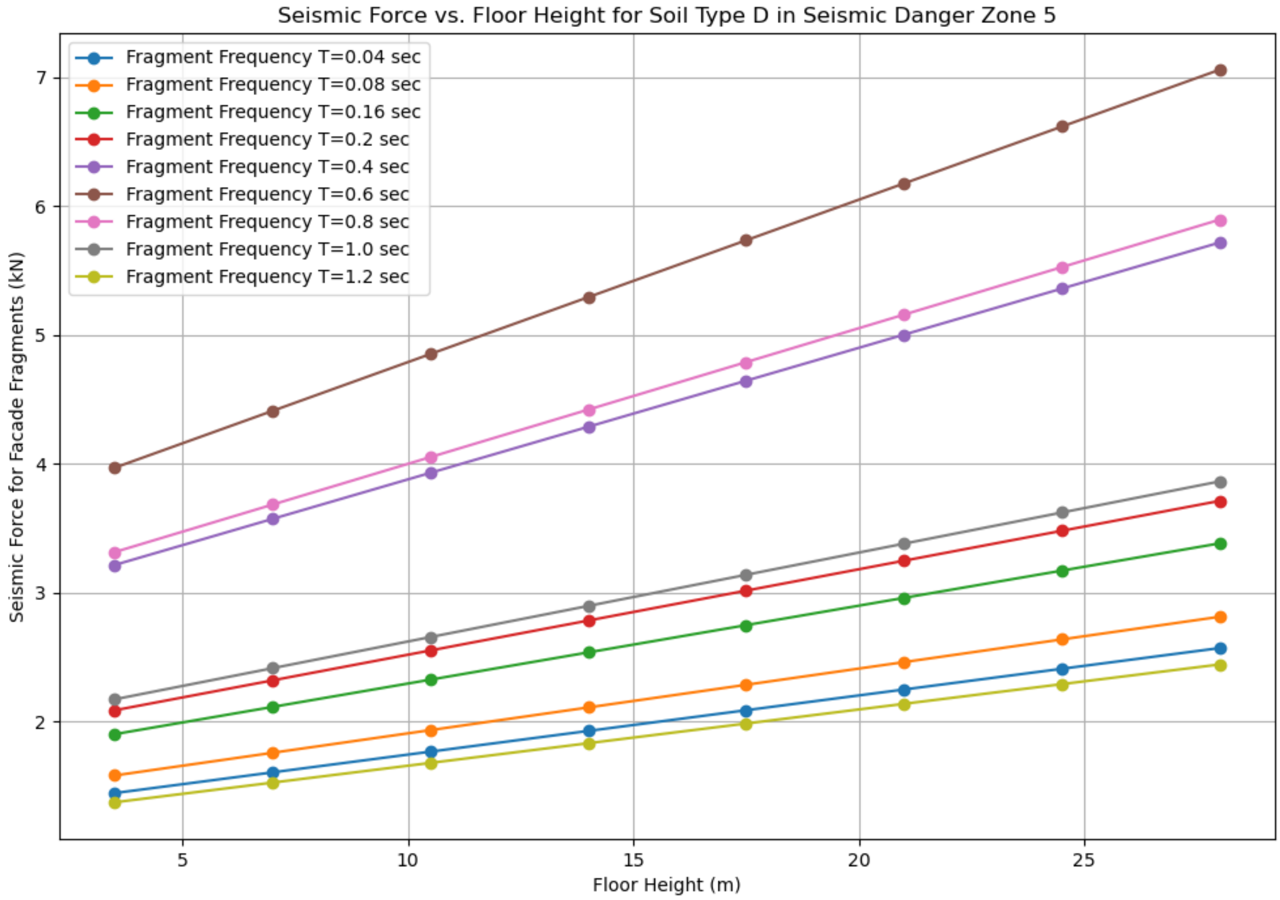


Diagram 21: Seismic Force per panel, per floor,soil Type D,Seimic Danger Zone 5 with different facade frequencies, Authors own work

This diagram presents the seismic force (in kN) experienced by façade fragments as a function of floor height (in meters) in Seismic Danger Zone 5.
The seismic force exhibits a linear increase with floor height. This trend is consistent across all fragment frequencies. As the frequency start getting closer to the building's frequency, the resonance effect becomes more pronounced, causing higher forces on the building façade.

Example: If the force at Tf=0.6 at 28m the sesmic force is 7kN, then at Tf=0.04sec or T=1.2sec it might be 2,5kN (180% decrease).

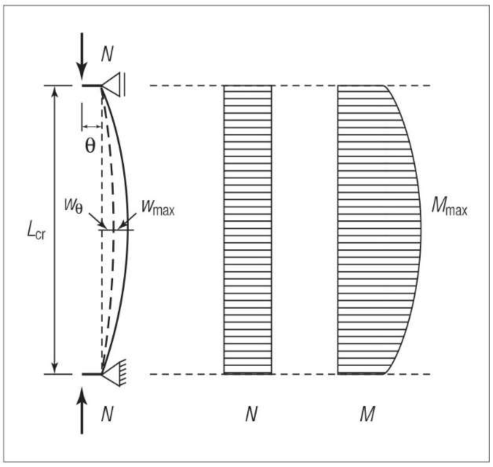
7 Development of a Bracket Connection

Development of a Bracket Connection

Glass wall hand calculations

A 350mm long glass bracket with a height of 120mm is supporting a design axial action of 2.51kN

Lcr	120	wall height
b	350	length
t	12	thickness
N	2.51	kN



Picture 47: Buckling model of a glass column
Source: (C O'Regan, 2014)

Pernament load action>50 years

kmod	0.29
k_{sp}	1
f_{gk}	45
fbk	120
k_v	1
γ_{MA}	1.6
γ_{Mv}	1.2

fgd 70.7 N/mm2 fgd = (kmod ·ksp ·fgk / γMA)+(kv ·(fbk-fgk)/γMv

Due to reduntacy requirement and the nature of the acion beeing pernament, the lamination cannot me considered to be composite and only one of the 12mm thick piles can be regarded tobe acting as a supporting element.

N_{cr} 828206 N $Ncr = (\pi^2 \cdot E \cdot I)/(Lcr^2)$

828.2 kN

Emod 70000 N/mm2

I (b*h^3)/12 17280

W 8400 mm3 $W = b \cdot t^2 /6$

w0 0.40 mm Wo = L/300

Wmax 0.40 mm Wmax = wo/(1-((N*10^3)/(Ncr*10^3)))

σ_{max} 0.72 N/mm2 σmax = (N*10^3)/(b*t)+((N*10^3)/W)*Wmax

Checking the combination between axial force and bending moment the following expression applies:

E 0.01 OK E=N/Ncr + σmax/fgd <1

Development of a Bracket Connection

Proposed Composite Bracket Glass, Steel Drawings

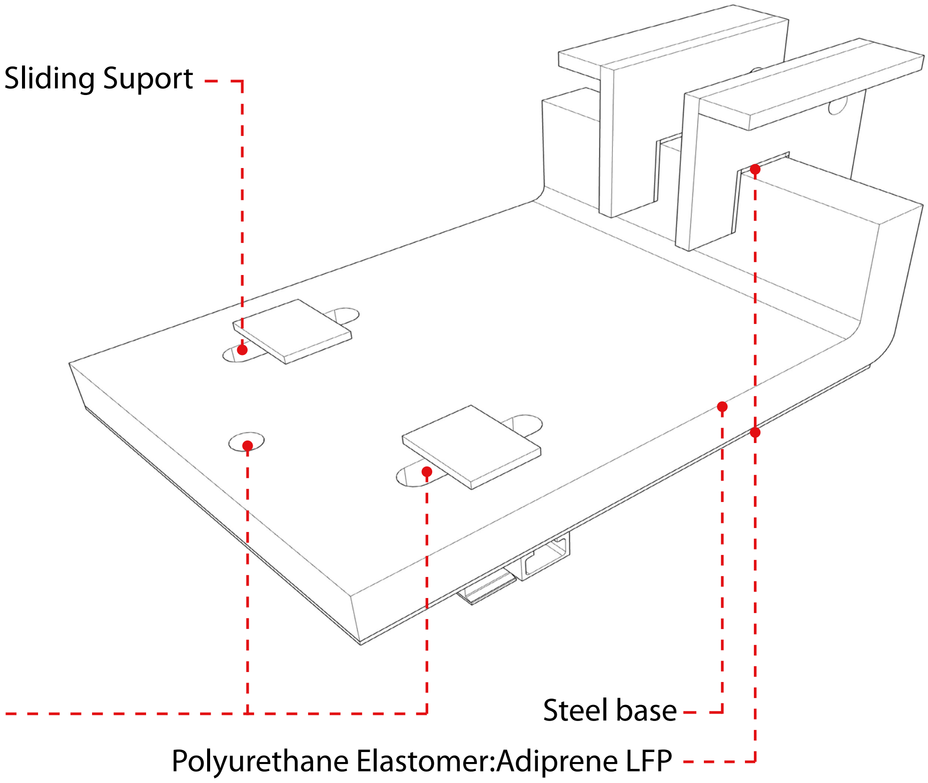


Diagram 24: Proposed composite bracket, materials, supports. Source: Author

To achieve the desirable movements (see diagramm 21, page 73) two sliding supports are placed on the bracket and one fixed support.

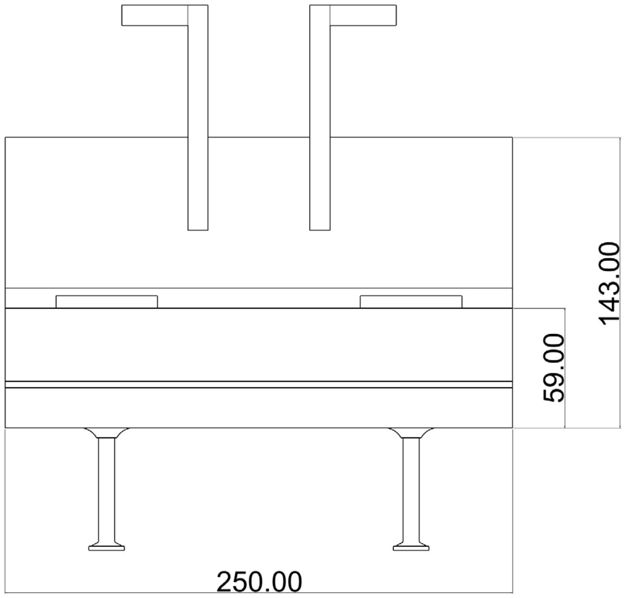
Forces applied	Perpedicular(yy')	Horizontal(xx')	Vertical(zz')	Momentum
Weight			3000N	
Wind first floor 0.65 kN/m^2		3000N		700N/m
Seismic Forces first floor	950N	950N		30N/m

Forces Combinations	Perpedicular(yy')	Horizontal(xx')(N)	Vertical(zz')(N)	Momentum(N/mm)
Weight+Wind		3000	3000N	700N/m
Weight+Seismic Force xx'		950	3000N	30N/m

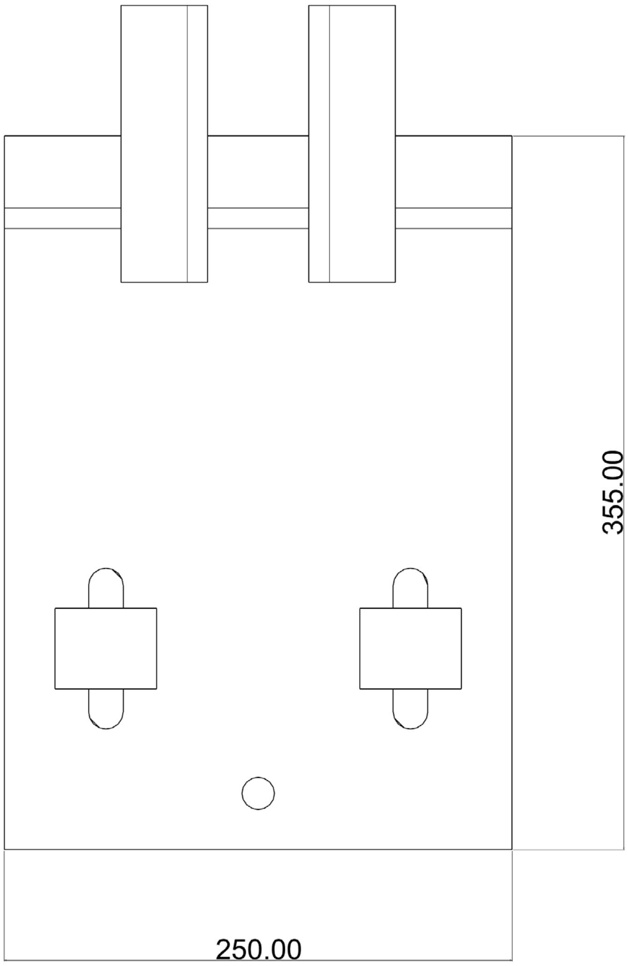
Table 05 : Forces applied, forces combination. Source: Author

Development of a Bracket Connection

Proposed Composite Bracket Glass, Steel Drawings



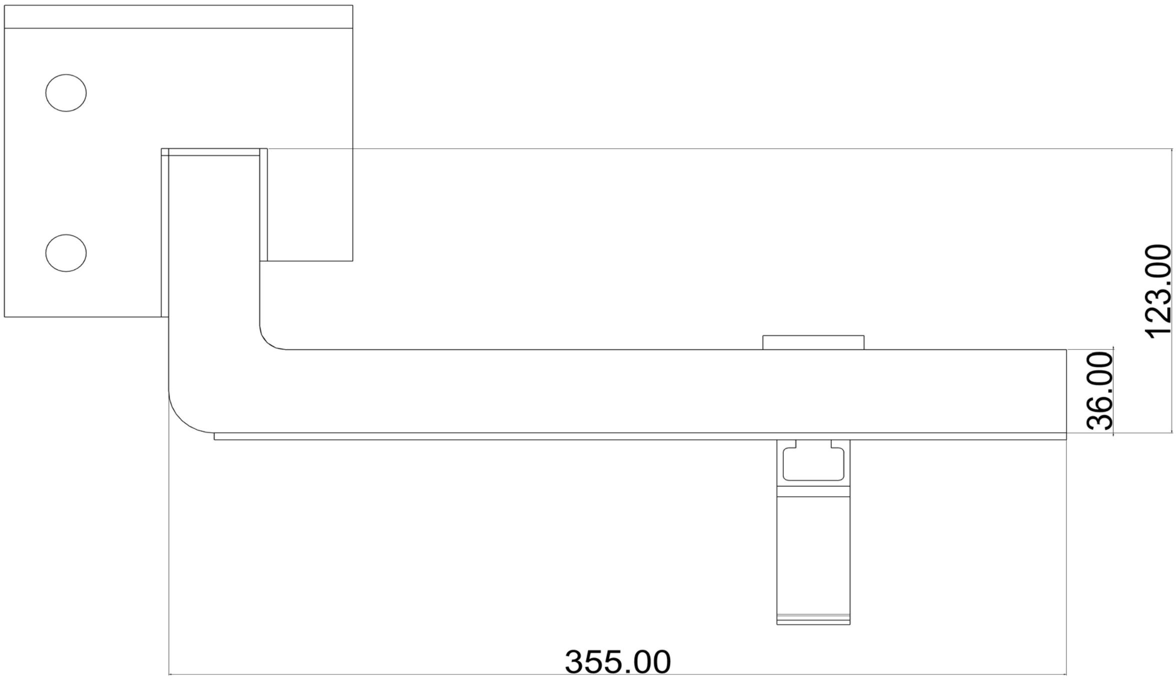
Drawing 05: Proposed Composite Bracket Front View.
Source: Author



Drawing 06: Proposed Composite Bracket Top View.
Source: Author

Development of a Bracket Connection

Proposed Composite Bracket Glass, Steel Drawings



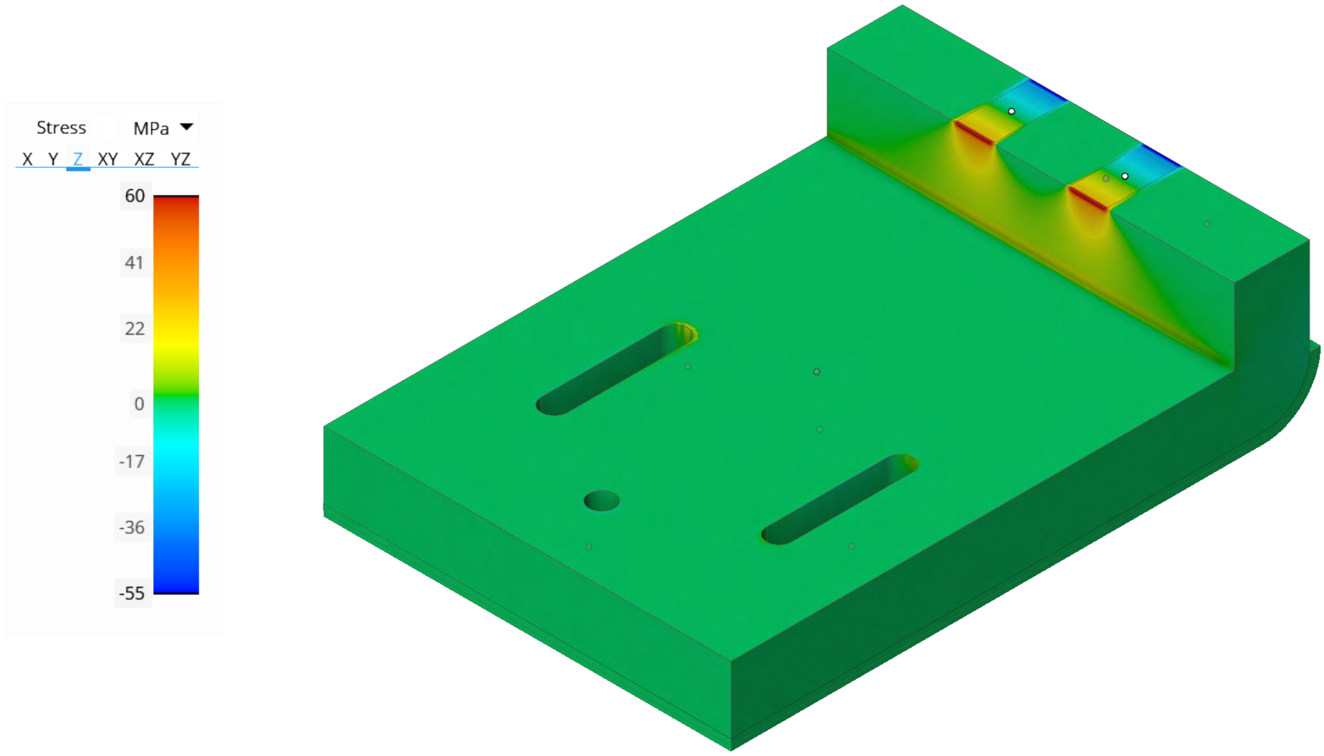
Drawing 06: Proposed Composite Bracket Side View.
Source: Author

FEM Analysis

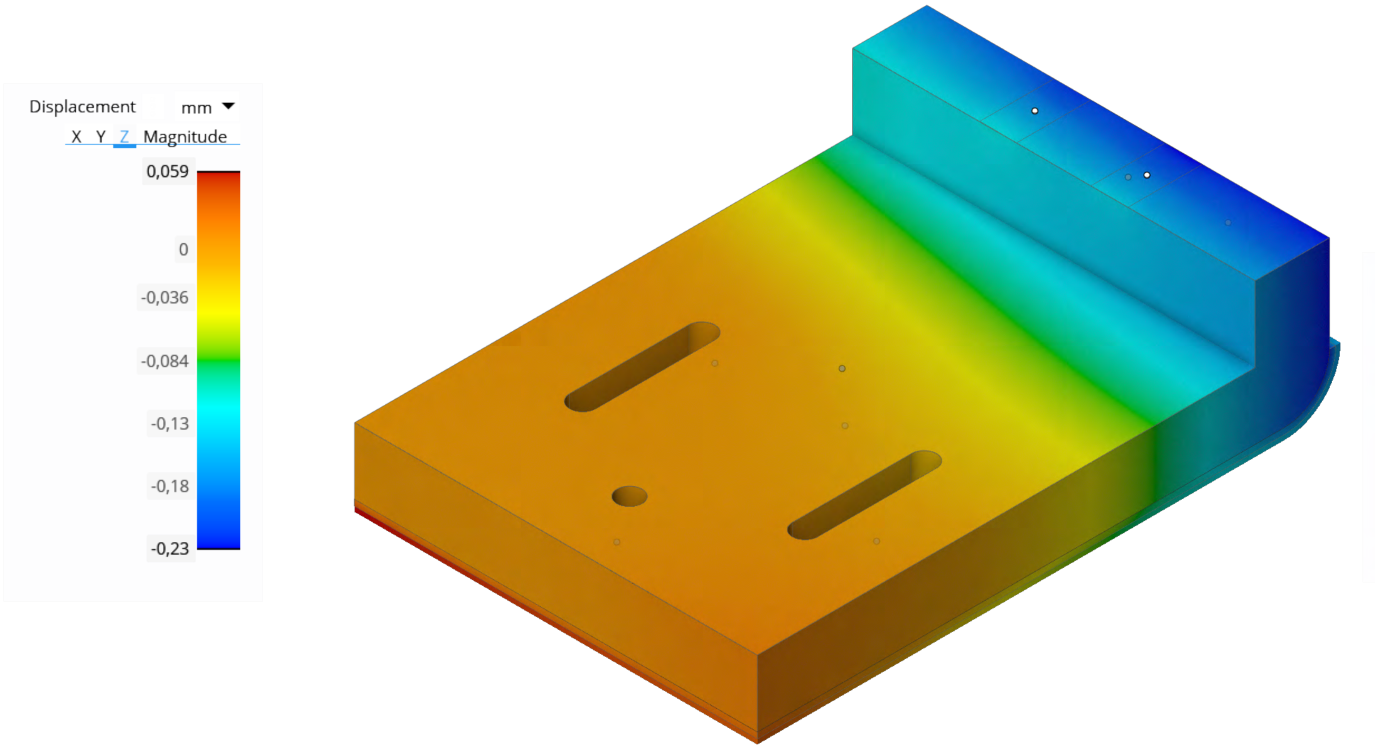
The Finite Element Method (FEM) analysis was conducted using Ansys Discovery. he analysis required careful consideration of various material characteristics as inputs. These inputs included density, modulus of elasticity, shear modulus, Poisson's ratio, bulk modulus, tensile yield strength, and ultimate tensile strength. Each of these properties plays a crucial role in accurately modelling the behaviour of materials under stress. The software does not state when the material fails, so according to the calculations in chapter 7.1 Development of a structural glass block. More specifically the maximum deflection for just one sheet to fail dmax=0.4mm, the ultimate stress is f_{gd} for a permanent load for taughtened d glass is 70.7MPa.

Development of a Bracket Connection

Only glass, applied forces: Wind forces, weight



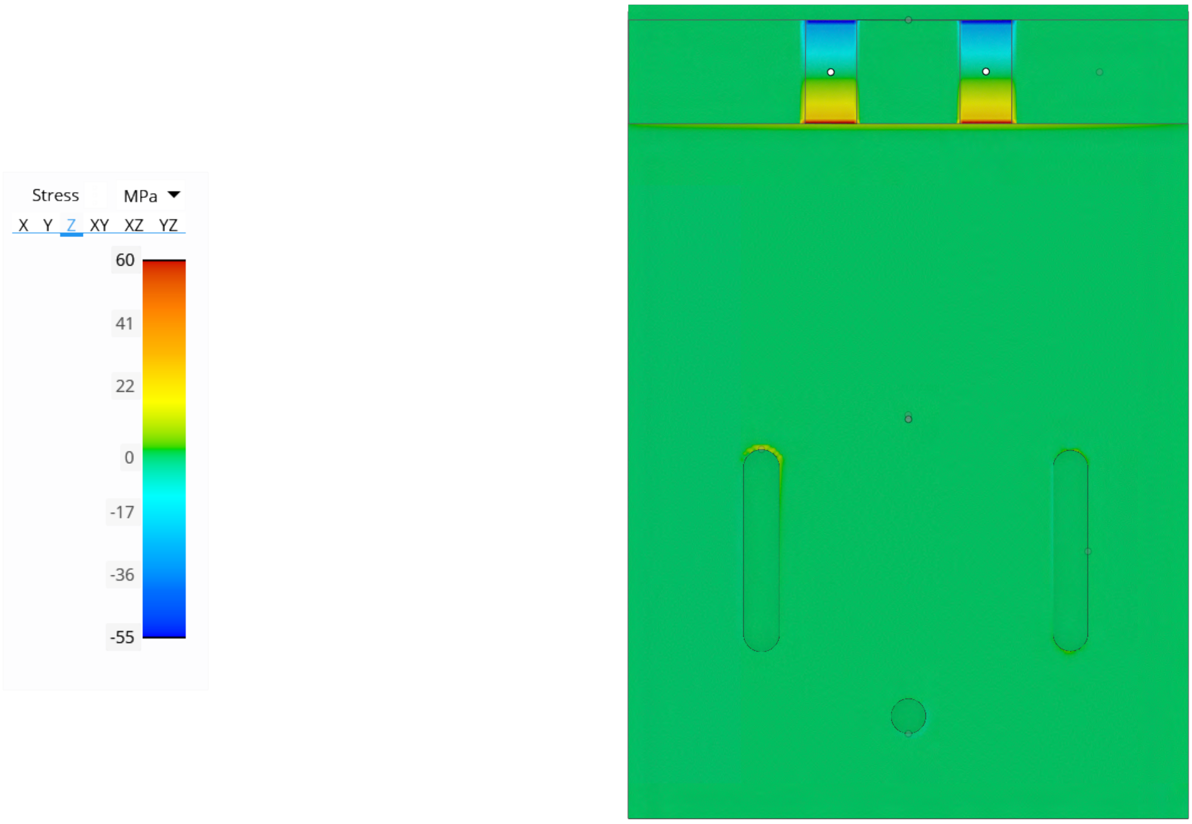
The maximum stress is concetrated in the siding and fixed supports of the bracket. The maximum value is 60MPa<f_{gd}.



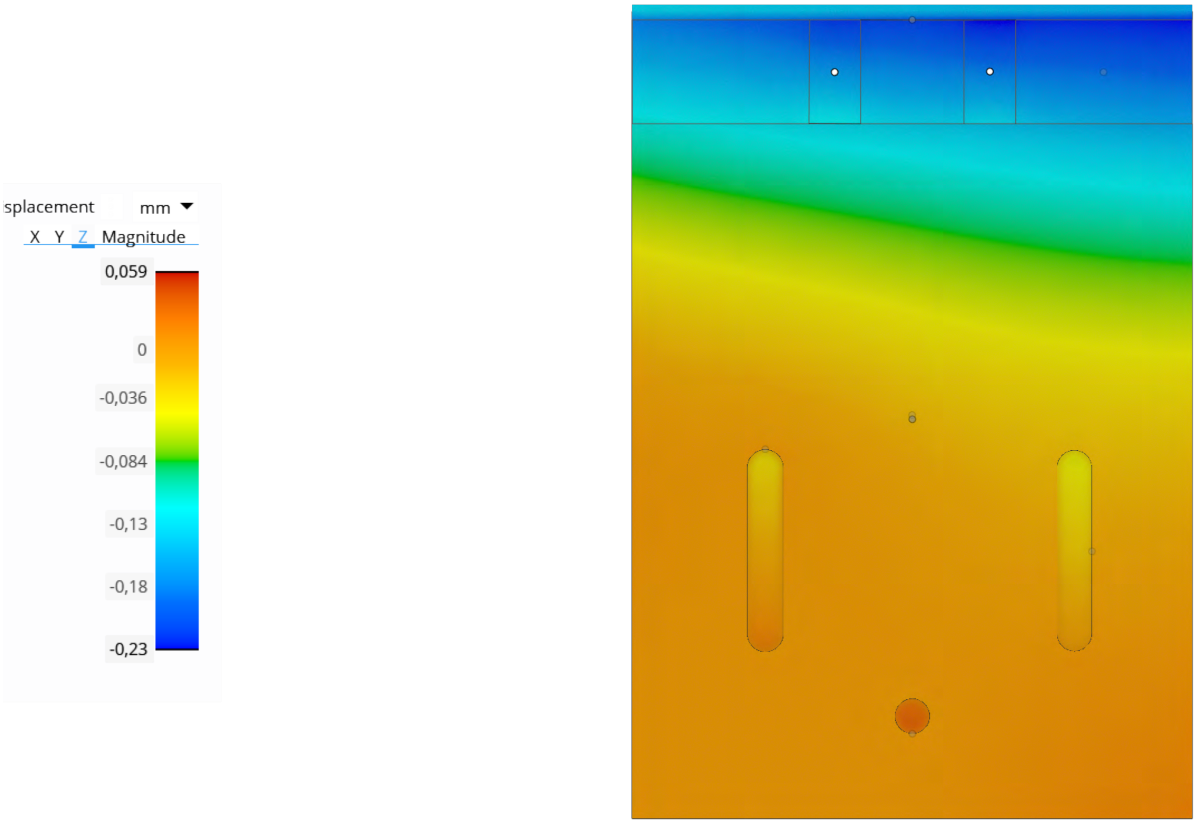
The maximum deflection is 0,23mm<dmax(0.4mm)

Development of a Bracket Connection

Only glass, applied forces: Wind forces, weight



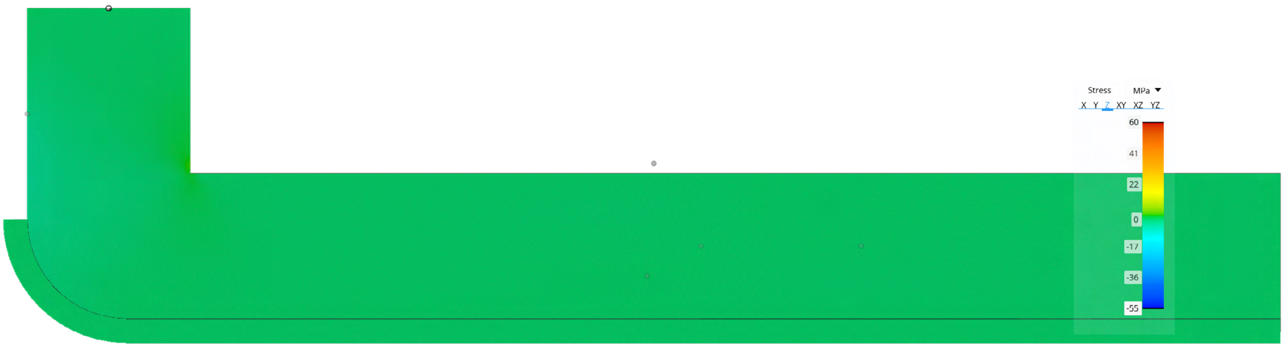
The maximum stress is concetrated in the siding and fixed supports of the bracket. The maximum value is 60MPa<f_{gd}.



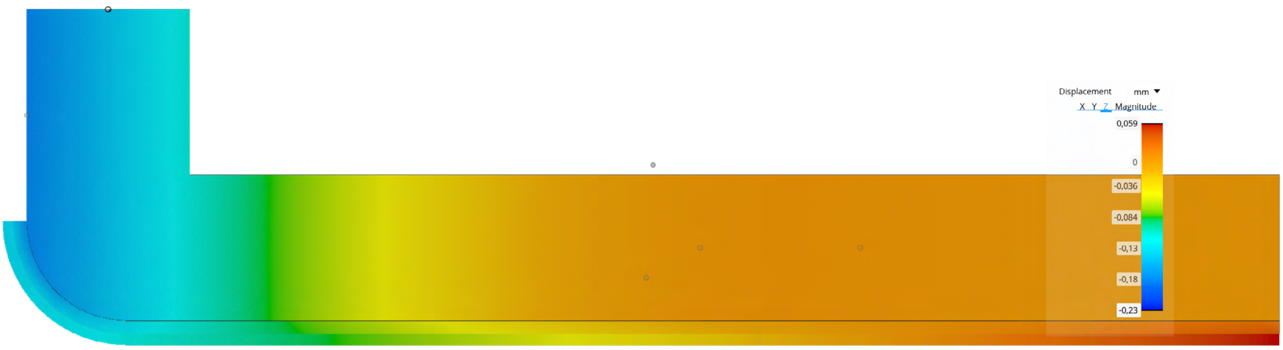
The maximum deflection is 0,23mm<dmax(0.4mm)

Development of a Bracket Connection

Only glass, applied forces: Wind forces, weight



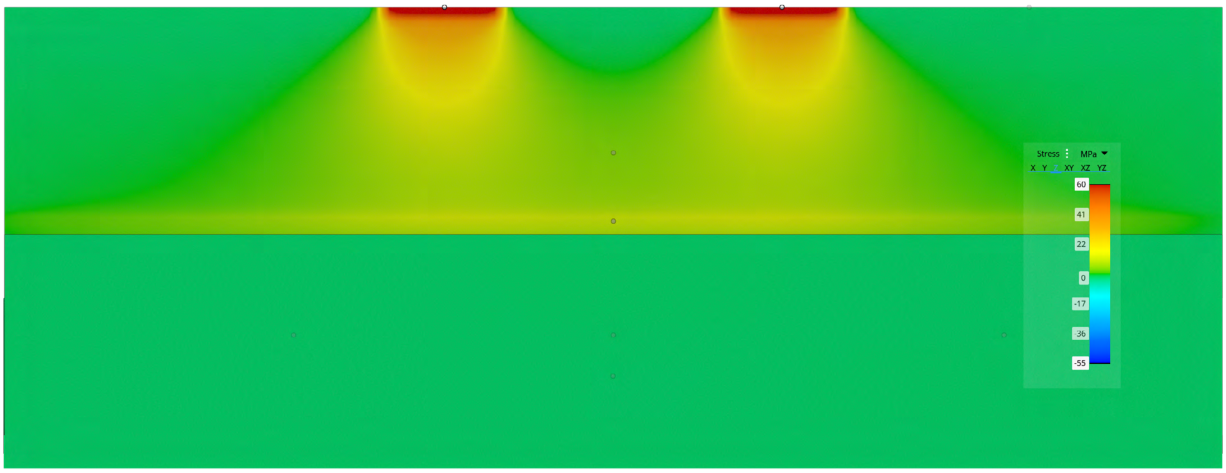
The maximum stress is concetrated in the siding and fixed supports of the bracket. The maximum value is 60MPa<f_{gd}.



The maximum deflection is 0,23mm<dmax(0.4mm)

Development of a Bracket Connection

Only glass, applied forces: Wind forces, weight

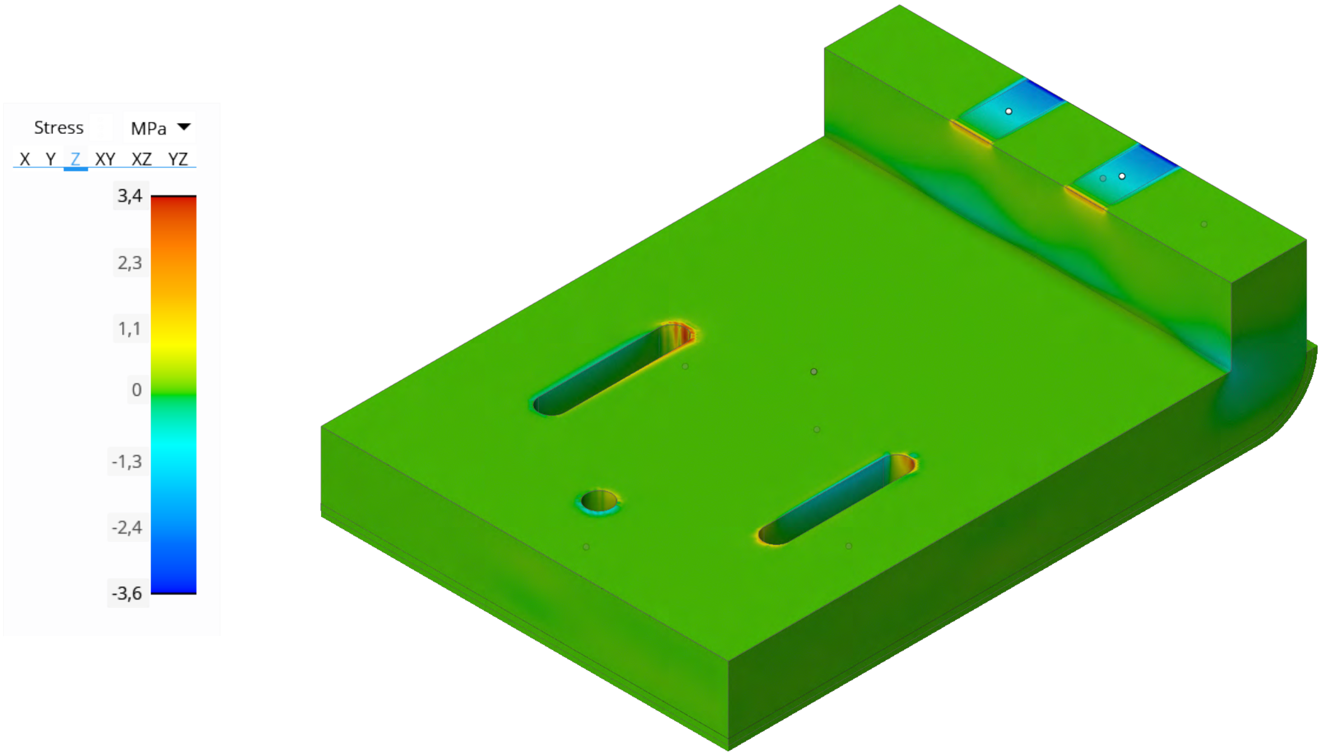


The maximum stress is concetrated in the siding and fixed supports of the bracket. The maximum value is 60MPa<f_{gd}.

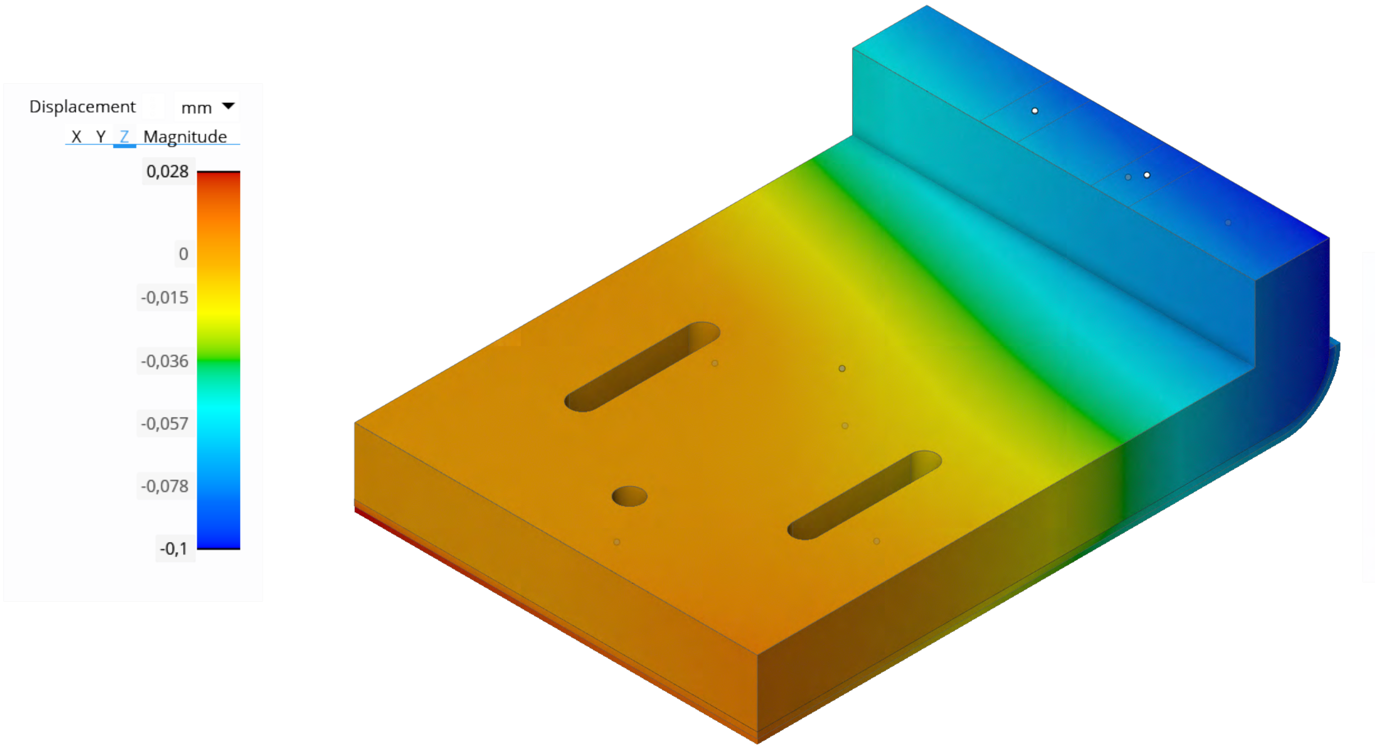
The maximum deflection is 0,23mm<dmax(0.4mm)

Development of a Bracket Connection

Only glass, applied forces: Seismic forces, weight

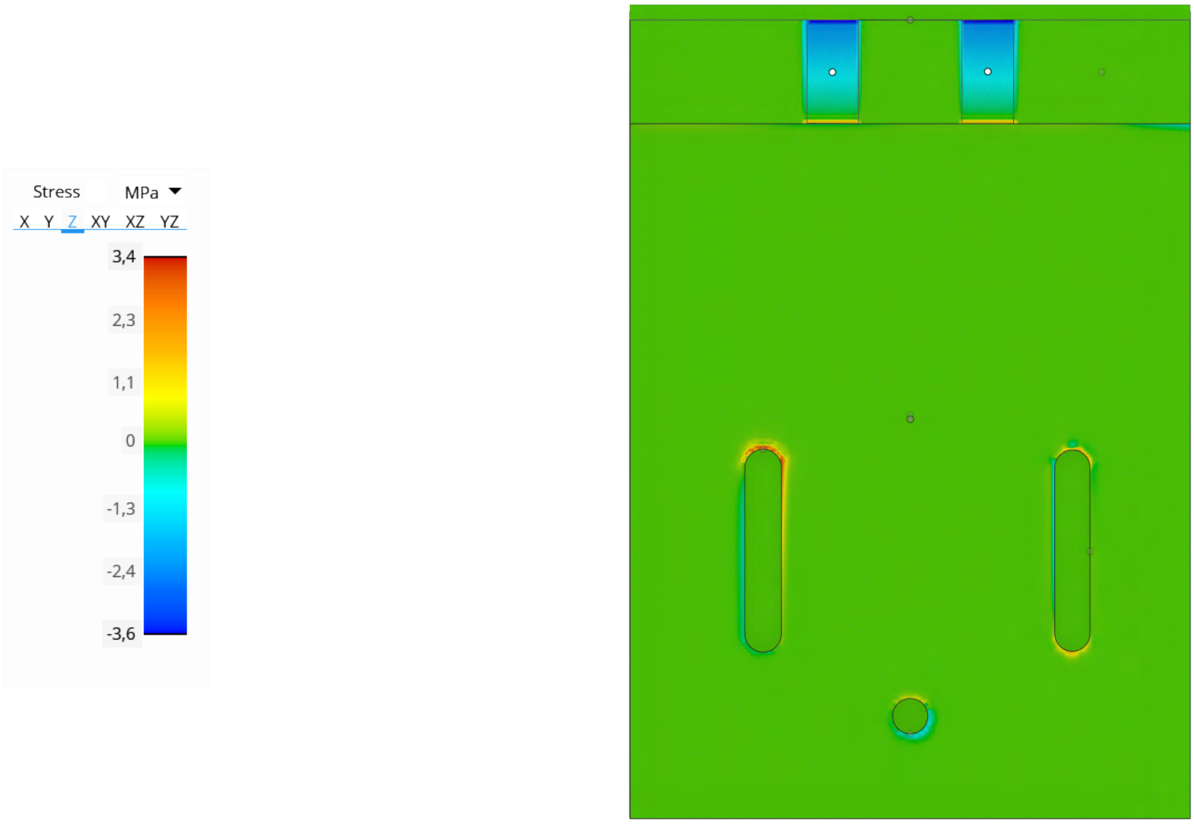


The maximum stress is concetrated in the siding and fixed supports of the bracket. The maximum value is 3.4MPa<f_{gd}.

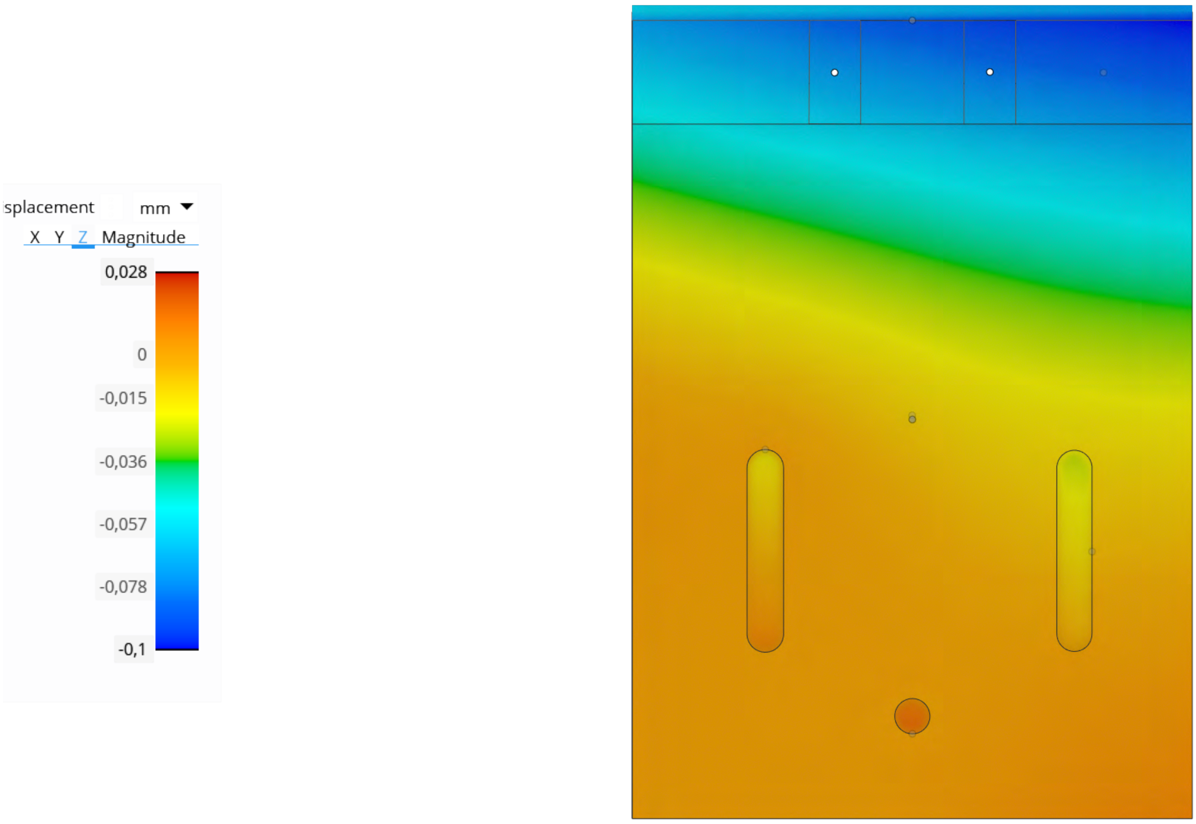


Development of a Bracket Connection

Only glass, applied forces: Seismic forces, weight



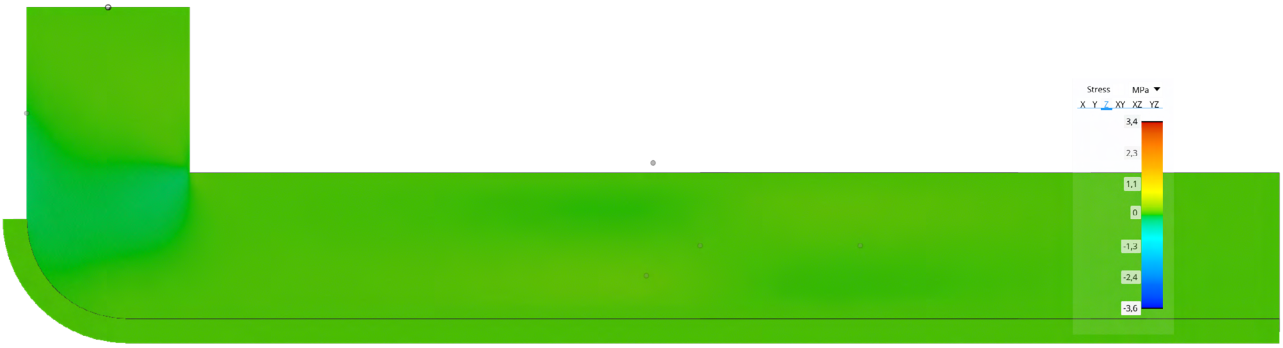
The maximum stress is concetrated in the siding and fixed supports of the bracket. The maximum value is 3.4MPa$<f_{gd}$.



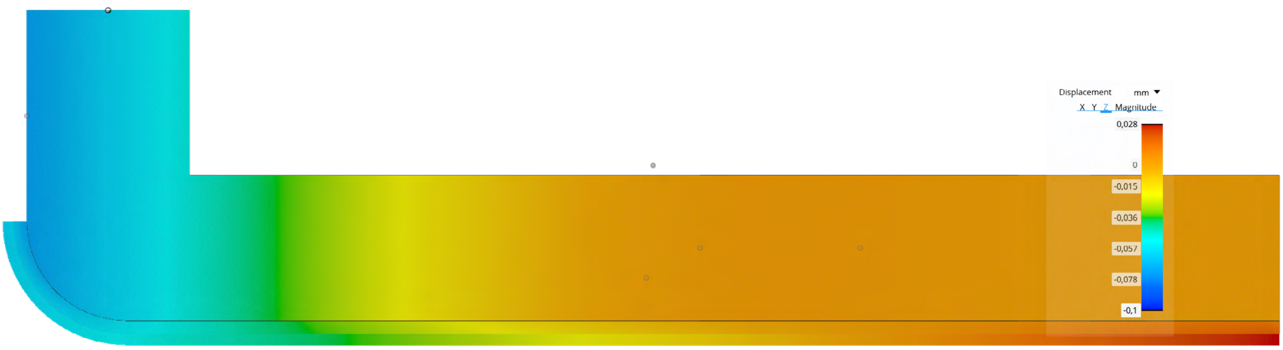
The maximum deflection is 0,23mm$<d_{max}$(0.4mm)

Development of a Bracket Connection

Only glass, applied forces: Seismicforces, weight



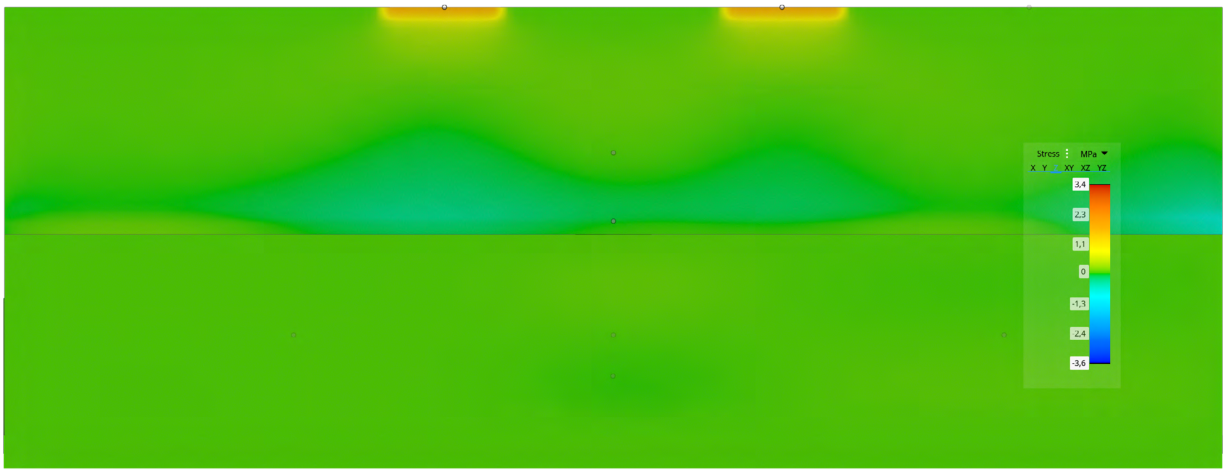
The maximum stress is concetrated in the siding and fixed supports of the bracket. The maximum value is 60MPa $< f_{gd}$.



The maximum deflection is 0,23mm<dmax(0.4mm)

Development of a Bracket Connection

Only glass, applied forces: Seismic forces, weight



The maximum stress is concetrated in the siding and fixed supports of the bracket. The maximum value is 60MPa<f_{gd}.

The maximum deflection is 0,23mm<dmax(0.4mm)

8 Conclusion

Discussion

This research thesis started with a vision to design and develop a tool that will calculate the forces that a bracket must withstand under seismic events, afterwards use Finite Element Method modelling a propose a new one made from glass and steel. In order to discuss the individual aspects, they are three sub-sections the automation of the calculations, Environmental Considerations for Façade Design in Groningen, Netherlands and the proposed structural materials-bracket design.

Automation of structural calculations.

The structural analysis of façade fragments involves numerous considerations to ensure safety and material efficiency, ultimately contributing to sustainability. However, traditional methods can be complex and time-consuming, requiring careful calculations to account for various forces and conditions. Typically, façade engineers focus on the least favourable fragment of the building, analysing the forces it must withstand to determine the appropriate glass thickness, mullion size, and bracket dimensions. This conservative approach, while necessary due to the complexity of the process, often results in over-engineering and increased material usage. Automation of structural calculations can streamline this process, making it more efficient and data driven. By leveraging advanced computational tools, engineers can perform precise and rapid analyses, optimizing material use and enhancing sustainability. The proposed automated model presented in this thesi integrates closely with traditional hand calculations and validation steps to ensure accuracy and reliability. This tool aids façade advisors by providing comprehensive, data-driven insights tailored to the specific building and site conditions. By reducing the complexity and time required for these analyses, the model enhances both safety and sustainability, ultimately contributing to more efficient and resilient building designs.

Environmental Considerations for Façade Design in Groningen, Netherlands

Groningen, Netherlands, is significantly affected by induced earthquakes due to gas extraction activities. The largest earthquake recorded in this region was 4.3 on the Richter scale. Understanding these seismic challenges is crucial for designing resilient architectural façades. Seismic Danger Zones and Peak Ground Acceleration (PGA): The seismic danger zones in Groningen, with a return period of 475 years, are classified by their Peak Ground Acceleration (PGA) reaching up to 0.24g.

Contrary to the relatively moderate seismic activity, wind forces in Groningen are very high. According to Dutch regulations, at a height of 30 meters, the wind loads are categorized by wind zones. In this case, the wind forces on each façade fragment are generally higher than those for seismic forces. However, seismic and wind forces affect façade fragments differently. Seismic forces occur with repeated frequency, causing the building and fragments to vibrate. In contrast, wind forces cause sustained pressure. As a result façade engineers must consider not only the structural integrity of the façade system but also its performance after seismic events. Components may fail, compromising watertightness and thermal efficiency. For example, water ingress and reduced U-value can occur post-earthquake, impacting the façade's overall functionality.

Discussion

Proposed structural materials, bracket design

This research thesis explores the innovative idea of using glass as a bearing structure for façade fragments. The goal is to create a visible structural element within the interior of buildings, challenging the conventional use of hidden structural supports. Glass is a brittle material with high strength, but it lacks ductility, fracturing under force without yielding. Unlike traditional structural materials like steel or aluminium, glass exhibits unique mechanical behavior. Its propensity for rapid and unexpected fracture patterns makes anticipating failure difficult, yet its strength warrants consideration as a structural element. To address the brittleness of glass, a composite bracket design is proposed. This bracket includes a steel channel and connections between the steel and glass parts with an intermediate layer of polyurethane. The polyurethane layer helps to distribute forces evenly across the glass, reducing the risk of fracture.

The proposed design was validated using finite element analysis (FEA). The results show that the composite bracket can withstand vertical, horizontal, and torsional forces that occur during an earthquake. This design leverages the strength of glass while mitigating its brittleness through careful material selection and engineering. Due to the inherent limitations of glass, it is not feasible to propose a glass bracket for all floors of a building. However, it can be effectively used on the first floor, where seismic and wind forces are minimal. In this scenario, the bracket primarily supports its own weight, making the use of glass both practical and innovative.

Conclusion

This research thesis aims to answer the following question: How can the integration of automation technologies in engineering processes, coupled with finite element analysis, facilitate the development of cost-effective and sustainable brackets to fortify the building's suspended facade against extreme environmental conditions like seismic activities? With the following sub questions present the outputs to conclude the main research question.

How brackets withstand extreme conditions such as earthquakes?

Brackets play a crucial role in transferring loads from curtain walls to the building's structural elements. Understanding their behaviour under extreme conditions, such as wind loads and earthquakes, is essential for ensuring building safety and integrity. The anchorage system, or bracket, carries the loads from the curtain wall to the building's beams. The design of this system depends on several factors, including the dimensions of the fragment, wind load conditions, seismic events, and outdoor conditions. Additionally, each bracket must accommodate thermal tolerances and installation operations. During extreme wind loads and earthquake events, multi-directional movements must be considered. The anchorage system should be robust yet flexible enough to accommodate these movements without failure. Specifically, brackets are designed to endure the rotational and lateral forces generated during an earthquake. Channels within the system withstand longitudinal forces, while the brackets themselves resist perpendicular forces. In conclusion the design of brackets for curtain walls must consider various forces from wind and seismic activities. Ensuring these systems can endure multi-directional movements is vital for maintaining structural integrity during extreme conditions.

How can a computational tool calculate the forces a suspended façade has to withstand from earthquakes and wind pressure?

With the increasing complexity of modern architectural designs, the need for precise and efficient structural analysis tools has never been greater. Computational tools play a critical role in calculating the forces that façades must withstand due to environmental factors like earthquakes and wind pressure.
Automation in structural engineering is a growing trend in the field. Many software programs can rapidly calculate the thickness of glass according to wind pressure and the thermal properties of profiles. However, there are currently no comprehensive tools that calculate both the seismic forces a façade fragment must withstand during an earthquake and the wind loads based on building height and pressure zones.

This research employs high-level programming using Python and the visual programming language Grasshopper. By combining 3D generation of the façade with automated calculations, we have developed a tool that outputs the seismic forces per façade fragment on each floor. The program accounts for various parameters, including building frequency, wind pressure (which varies by floor), wind zone (as detailed in Chapter 04), fragment dimensions, distance from the rigid basement, seismic danger zone, and soil type. While some variables are automated, others such as the stiffness, modulus of elasticity of the mullions and transoms, and the weight of substructures must be manually input.

The outputs of the tool include:

- Weight of the façade fragment
- Building Frequency
- Frequency of the fragment
- Seismic force acting on the fragment's centre of weight
- Vertical, horizontal, and perpendicular forces
- Moments (M) in each direction

Conclusion

How can the structural analysis of a façade become less challenging for architects, civil engineers', façade advisors?

The structural analysis of building façades has traditionally been a complex task, requiring precise calculations and consideration of numerous factors. However, advancements in high-level and visual programming tools have significantly streamlined this process.
Today, with the use of advanced programming languages and visual programming tools, the process of calculating the structural requirements of a façade fragment has become more efficient and less challenging. High-level programs like Python, and visual programming tools like Grasshopper, enable the extraction and manipulation of data such as the coordinates of each façade element. This data extraction facilitates the calculation of crucial parameters, including the centre of mass and the distance from the ground floor to the rigid basement.

Visual representation of these elements allows architects to make informed decisions that balance aesthetics with structural efficiency. For example, using Grasshopper, an architect can visually adjust the design of a façade to optimize the use of structural materials while ensuring the desired aesthetic outcome. This streamlined approach not only saves time but also enhances collaboration between architects, civil engineers, and façade advisors by providing a clear and interactive representation of the design.

By leveraging advanced software, the structural analysis of façades becomes significantly less challenging for professionals in the field. These tools facilitate precise and efficient calculations, ultimately leading to designs that are both aesthetically pleasing and structurally sound. This integration of technology into the design process represents a significant step forward in the field of architectural engineering.

Can we use structural glass as a bracket system and withstand seismic wind forces?

The use of structural glass in bracket systems presents unique challenges due to its brittle nature and lack of ductility. Glass fractures under force without yielding, making it difficult to predict and manage failure. Despite these challenges, with proper design considerations, structural glass can potentially withstand seismic and wind forces.

Glass structures require designs that can endure torsional movements during earthquake activity. Engineers must account for these movements to ensure that seismic activity does not compromise the integrity of the glass. Horizontal and vertical momentum forces acting on glass structures must be included in static load combinations alongside conventional loads, with necessary safety factors applied. This approach helps mitigate the risk of unexpected fractures by distributing the forces more evenly across the glass surfaces.

Similarly, wind forces acting on structural glass need to be carefully considered. Wind-induced stresses can cause significant strain on glass brackets, necessitating the incorporation of safety factors in the design process. By understanding the specific load combinations and environmental conditions, engineers can create designs that enhance the durability and resilience of glass brackets.
While structural glass is inherently brittle and poses challenges in terms of predictability and failure, careful design and appropriate safety measures can make it a viable option for bracket systems in seismic and wind-prone areas. Incorporating comprehensive load analysis and rigorous safety factors ensures that glass brackets can perform effectively under these extreme conditions.

Conclusion

How can the efficiency of researching new materials for a façade system in extreme conditions be improved?

Researching new materials for façade systems in extreme conditions is a complex and crucial task. It involves numerous variables and changing site-specific limits, particularly in areas prone to high-intensity earthquakes. The structural analysis of materials that must withstand circular forces, such as those generated by earthquakes, adds further complexity to the process.

Traditional façade systems, such as non-load-bearing clay bricks with insulation and plaster on interior and exterior faces, are often sufficient to create safe structures. However, these methods are time-consuming and prone to errors during on-site implementation. Additionally, they are not suitable for high-rise buildings due to the high load-bearing requirements. These limitations hinder the adoption of innovative materials and designs in earthquake-prone zones.

To improve the efficiency of researching new materials for façade systems in extreme conditions, several steps can be taken:

1. Advanced Computational Tools: Utilizing high-level programming languages and visual programming tools can streamline the analysis process. These tools can handle the complex variables and changing limits associated with extreme conditions, providing more accurate and faster results.
2. Simulation and Modelling: Implementing advanced simulation and modelling techniques can predict the behaviour of new materials under extreme conditions. This allows researchers to identify potential issues and optimize designs before physical testing.
3. Collaboration and Data Sharing: Encouraging collaboration between architects, engineers, material scientists, and industry experts can lead to the development of innovative solutions. Sharing data and research findings can accelerate the discovery and implementation of new materials.
4. Automated Testing and Prototyping: Integrating automated testing and prototyping into the research process can reduce time and human error. Automated systems can conduct repetitive and complex tests more efficiently than manual methods.

By adopting advanced computational tools, simulation and modelling techniques, collaborative research approaches, and automated testing methods, the efficiency of developing new façade materials for extreme conditions can be significantly improved. These advancements will lead to safer, more efficient building designs that can better withstand the challenges posed by high-intensity earthquakes and other extreme conditions.

Limitations

This study aimed to explore the use of structural glass as a bracket in a suspended facade. However, several limitations must be acknowledged to provide a comprehensive understanding of the study scope and constraints. Five primary limitations are identified: the constraints of the building structure, the architectural proposal, the building site, the typology of the façade, and the limitations of structural glass.

Building structure

The building structure significantly affects the frequency of the façade fragment that is suspended from the beams. This study assumed the use of concrete shear walls, commonly used in earthquake-prone areas. However, a building made from steel frames would have different frequency characteristics, necessitating adjustments in the computational tool. The proposed tool utilizes a grid based on one-dimensional parameters for each side of the building. In cases where the grid differs, a new script must be developed. For existing buildings, the tool can still be used, but the building's frequency must be manually in-putted.

Architectural proposal

The architectural fragments proposed for both the aluminium and timber façade options are based on specific drawings. New designs would require adjustments to the script, limiting the tool's flexibility to change the height and the width of the fragment. Each new architectural proposal might involve unique design elements that need bespoke computational adjustments.

Building site

This tool was designed specifically for the site in Groningen, Netherlands. If applied to a different location, adjustments must be made to accommodate regional codes and seismic danger zones. The seismic data and regulations vary by region, affecting the tool's accuracy and relevance.

Suspended façade

The choice of suspended façades was made due to their excellent strength-to-weight ratio, functionality, recyclability of materials, transparency, and aesthetic attributes. While the tool can be applied to similar curtain walls, different façade systems might require significant modifications to the computational approach.

Structural Glass

The fundamental qualities of structural glass impose several limitations, such as brittleness and sensitivity to local stresses. These characteristics make glass prone to unexpected failure, especially at support points. Unlike materials like steel or concrete, where peak stresses dictate design, glass design is significantly impacted by local stresses. This emphasizes the need for rigorous support evaluation and modelling. Overcoming these inherent limitations is critical for ensuring the structural integrity, longevity, and safety of glass constructions.

In conclusion, while the proposed computational tool and design methodologies offer significant advantages, they are constrained by the specific conditions and materials considered in this study. Addressing these limitations in future research could enhance the robustness and applicability of the proposed design tools, ensuring they can be effectively adapted to a wider range of building structures, sites, and façade systems.

Recommendations for future research

Future research is essential to enhance the capabilities and applicability of the proposed computational tool for façade design. The following recommendations highlight potential areas for improvement and expansion:

Building Structure:

Future research should explore creating building structures based on points instead of a fixed grid size. Incorporating structures with different ductility classes would also improve the tool's flexibility and accuracy. This would allow for better adaptation to various structural designs and material properties.

Façade Typology:

Investigate different façade typologies as new case studies. This includes load-bearing façades and plinths, and the specific seismic forces each fragment must withstand. Such studies would expand the tool's applicability across a broader range of architectural designs.

Building Site:

Currently, the computational tool is limited to the site of Groningen, Netherlands. Future developments should incorporate building regulations from other regions. This will make the tool adaptable to global standards and increase its utility in diverse geographic contexts.

Façade Components:

Research should extend to other elements of façade fragments in earthquake scenarios, such as gaskets, thermal blocks, and glass. Understanding how vibrations affect these components is crucial. While aluminium or timber mullions and transoms can handle structural loads, vibrations may compromise their ability to prevent water ingress and maintain airtightness.

Multi-objective solutions under extreme conditions:

The choice of using Grasshopper was driven by its ability to offer multi-objective solutions. Future developments should incorporate light and glare analysis into the tool. This would provide a more comprehensive assessment of façade performance, enhancing both structural and environmental considerations.

Wind Directionality:

Wind directionality data should be included in future versions of the tool. This will assist designers in orienting buildings to optimize for wind forces, thereby improving the structural performance of façade fragments and brackets.

Extreme Events:

Consider incorporating other extreme events, such as wind-storms, heat waves, and floods, into the tool. This will allow for a more holistic assessment of building resilience and help in designing structures that can withstand multiple environmental stresses.

9 Reflections

8.1 Graduation Process
8.2 Social impact

Reflections

Catastrophes, coupled with the effects of climate change, possess the capacity to weaken the fundamental aspects of sustainable development across its three core dimensions: social, environmental, and economic aspects. Disasters not only hinder the progress of development but also play a critical role in generating unstable societies. This includes actions such as excessive exploitation of natural resources and the development of cities and critical infrastructure that lack resilience to possible calamities. Over the next 25 years, an estimated $94 trillion will be invested globally in infrastructure development to support economic growth (Global Infrastructure Hub, 2021). This underscores the urgent need for a collective approach that integrates risk considerations when designing building façades.

Although several scholars have explored certain features of curtain walls, few have incorporated current seismic actions. This research seeks to address this gap by examining the behavior and performance of timber and aluminum façades under seismic activities. Furthermore, the study aims to revolutionize the field by automating the calculation processes involved in designing such façade systems and developing improved connections with the building envelope to bolster structural robustness (Baniotopoulos et al., 2016).

For optimally designed buildings, considering non-structural elements is crucial. Their failure can directly endanger individuals, disrupt functionality in other systems, render the building inoperable for extended periods, and incur substantial costs and environmental impact. Well-designed non-structural elements that withstand seismic and wind forces not only reduce immediate dangers but also minimize economic and environmental repercussions. This highlights the significance of meticulous design for safety and sustainability. Non-structural elements firmly attached to the structure must accommodate displacements induced by seismic activity or extreme wind loads to prevent threats to life and damage to other building elements.

While glass as a structural element has limitations, particularly at higher floors, this research demonstrates its potential for use at lower levels. By integrating advanced materials and careful design, glass can be successfully incorporated into structural systems, offering new possibilities for architectural innovation and interior aesthetics. The insights gained from this research will guide future endeavors in creating more sustainable, resilient, and aesthetically pleasing building designs.

Positioning my research within an ethical and cultural framework, I considered the implications of building safety in the face of natural disasters and climate change. Ensuring that infrastructure development incorporates resilience to such events is crucial for protecting communities and advancing sustainable development. This focus aligns with the historical and philosophical commitment of architecture to safeguard human life and promote societal stability.

In conclusion, this research emphasizes the critical need to incorporate seismic and wind load considerations into the design of building façades to enhance structural integrity and sustainability. By addressing these challenges through advanced computational tools and innovative design solutions, we can create safer and more resilient built environments. The findings of this study contribute to the broader professional, scientific, and ethical discourse on sustainable architecture and infrastructure development.

Reflections, Graduation Process

How does your graduation topic fit within the master track of building technologies?

In the course of the Master's program in Architecture, Urbanism, and Building Sciences, with a specialization in Building Technologies, I have obtained a diverse knowledge base that has laid the foundation for my research thesis. More specifically this program has equipped me with a comprehensive understanding of contemporary construction systems and methodologies essential for approaching new projects. Within the Master's track of Building Technologies, the curriculum has provided me with a robust foundation in creating sustainable structures. This encompasses considerations such as embodied carbon in proposed designs, harmonizing with the climate, the existing architecture, the demountability, and leveraging pre-existing elements in design solutions. These aspects align seamlessly with the overarching goal of advancing architectural design and building sciences.

The relevance of my graduation topic, focused on integrating automation technologies and finite element analysis to develop cost-effective and sustainable brackets for fortifying building suspended façades against earthquake events, aligns cohesively with the ethos of the Master's program. Specifically, within the Architectural Design and Building Sciences section, there exists a profound emphasis on fostering a more sustainable and aesthetically refined architectural landscape. Moreover, the intersection of architectural design and civil engineering, as emphasized in my thesis, represents a pivotal point in bridging disciplinary gaps. By establishing a symbiotic connection between these domains, the result is anticipated to be the realization of structures that are not only more sustainable and economical but also aesthetically pleasing.

What is the relevance of your graduation work in the larger social, professional, and scientific framework?

Earthquakes are classified as rapid-onset disasters and represent some of the most devastating natural events impacting human societies. Annually, over a million earthquakes occur globally, averaging approximately two per minute. Between 1998 and 2017, earthquakes were responsible for more than 750,000 deaths worldwide, constituting over half of all fatalities due to natural disasters. During this period, earthquakes affected over 125 million people, causing injuries, displacement, homelessness, and emergency evacuations. Concurrently, wind-storms, including hurricanes and cyclones, have severely impacted numerous regions, leading to significant destruction of infrastructure, communities, and livelihoods. These events frequently result in extensive damage, displacement, and necessitate urgent emergency responses, profoundly affecting the affected populations.

This study investigates the potential of curtain-wall systems, particularly within a modular construction framework, to enhance structural resilience against such natural disasters. In modular construction, factory-made volumetric units are delivered, assembled, and connected on-site to form functional structures. With 70–95% of the work conducted under controlled factory conditions, modular construction offers several benefits, including faster build times, superior quality control, improved work safety, enhanced natural lighting, economies of scale, and reduced environmental impact. This construction method can substantially diminish the environmental footprint of building activities.

Reflections, Graduation Process

How does the project affect architecture/the built environment?

Ensuring the safety of buildings in earthquake-prone regions is a critical concern for architects and façade engineers. This project addresses the challenges of structural calculations and proposes innovative solutions to enhance building safety and efficiency. The need to construct safe buildings for people affected by earthquakes is a pressing issue. Architects and façade engineers must ensure that buildings can withstand seismic events to protect residents and reduce the risk of damage. The structural calculations required for earthquake-resilient buildings are complex and time-consuming.

In developing countries, these calculations are often not performed correctly, leading to unsafe buildings that pose significant risks to residents. In many developing countries, inadequate structural calculations result in buildings that are not earthquake-resistant. Residents in these regions are often forced to relocate or live in temporary shelters, such as tents, following an earthquake. This project aims to address these challenges by providing tools and methodologies that streamline the calculation process and ensure the safety of façade systems.

This research thesis showcases how suspended brackets are affected by earthquakes and proposes a new design for brackets made from glass. By speeding up the structural calculation process, the project helps architects and engineers design safer and more efficient façade systems. The use of innovative materials, such as glass, not only enhances structural integrity but also offers aesthetic and functional benefits. By streamlining structural calculations and proposing resilient design solutions, this project has the potential to transform architectural practices and improve building safety in earthquake-prone areas. The adoption of these innovations can lead to safer living environments and better protection for residents, particularly in developing countries where building safety is a critical concern.

What did you learn from your thesis?

Through my thesis research, I enhanced my skills as a computational architect and façade engineer by carefully considering and critically evaluating various design and structural challenges. I learned the importance of using advanced computational tools and visual programming languages, such as Grasshopper, to automate complex calculations. This approach not only improved efficiency but also ensured precision in the design process.

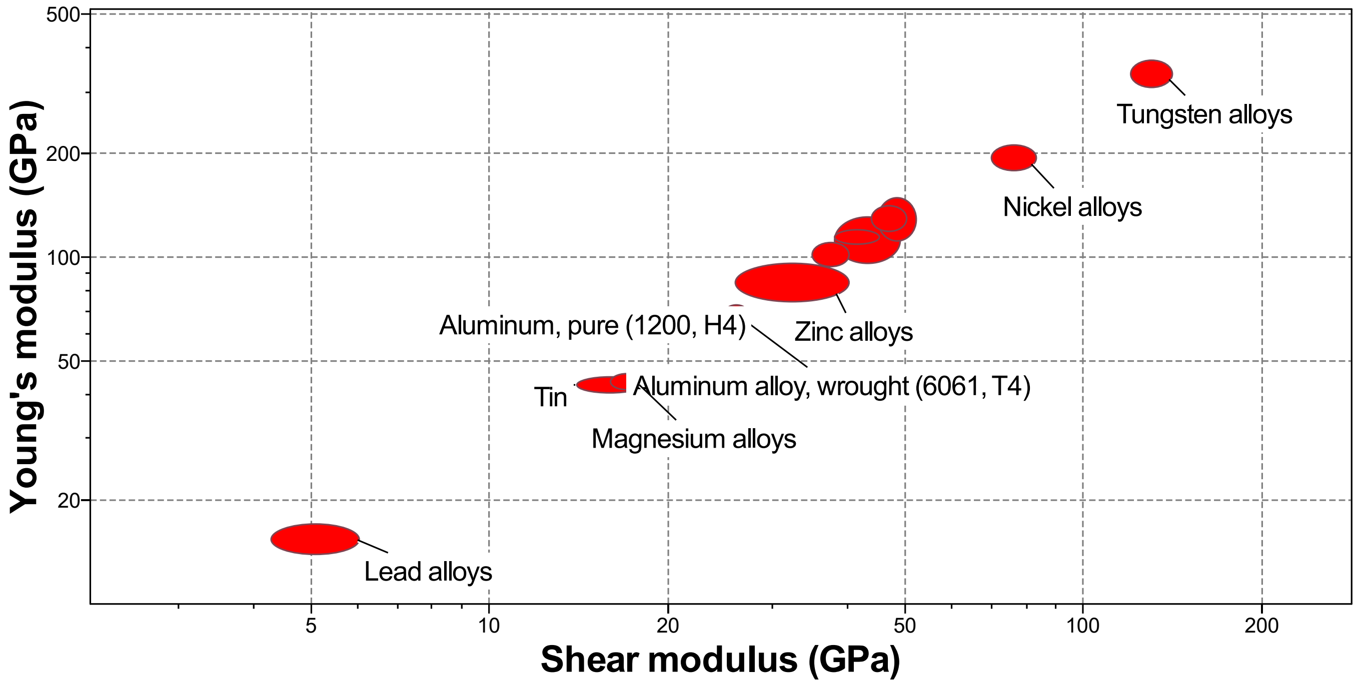
I observed the behavior of suspended façades under seismic forces and compared different materials and design strategies. This included analyzing how brackets withstand circular forces and how façade fragments maintain their structural, thermal, and water-resistant properties during seismic events. My evaluations revealed crucial insights into the relationship between a building's frequency and the frequency of its façade fragments, highlighting the impact of weight, stiffness, and design on seismic resilience.

Reflecting on my personal way of working, I realized the value of integrating computational tools into traditional engineering practices. This reflection extended to positioning my work within a broader professional and scientific context. I recognized the potential of my research to influence sustainable and resilient design practices, particularly in earthquake-prone regions. By addressing the limitations of structural glass, such as its brittleness and lack of ductility, I underscored the need for careful connection design and the importance of finite element analysis in understanding material properties. The process of making decisions throughout my research, from selecting materials to developing computational models, has been deeply instructive. I have become more adept at valuing different aspects of façade design and positioning them in relation to each other and the broader architectural context. This experience has strengthened my ability to think thoroughly and critically about design challenges and solutions.

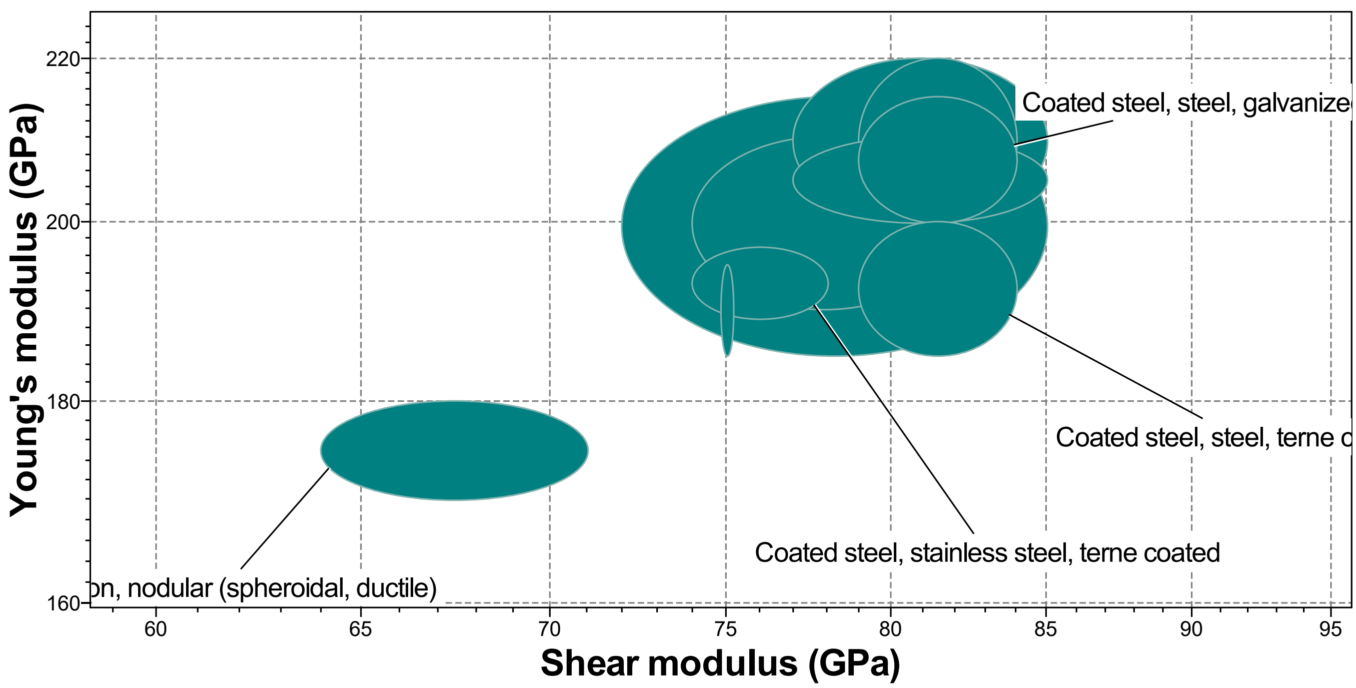
Reflections, Graduation Process

Positioning my research within an ethical and cultural framework, I considered the implications of building safety in developing countries, where inadequate structural calculations often lead to unsafe living conditions. My work aims to contribute to safer architectural practices by providing tools that ensure the integrity of building façades in extreme conditions. This focus on ethical responsibility aligns with the historical and philosophical commitment of architecture to protect and enhance human life.

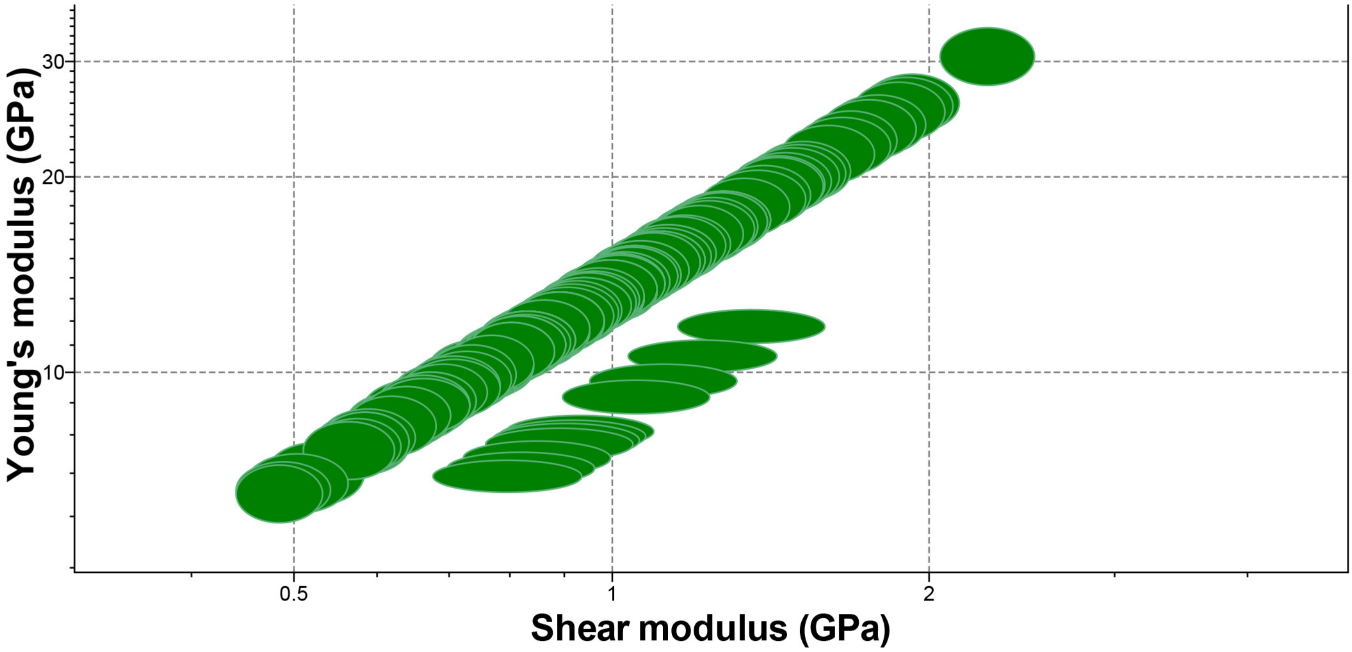
In conclusion, my thesis research has been a comprehensive learning experience that has deepened my understanding of computational architecture and façade engineering. By reflecting on various scales and considering the broader professional, scientific, ethical, and cultural context, I have developed a more holistic approach to design and research. The insights gained from this work will guide my future endeavors in creating more sustainable, resilient, and ethically responsible building designs.

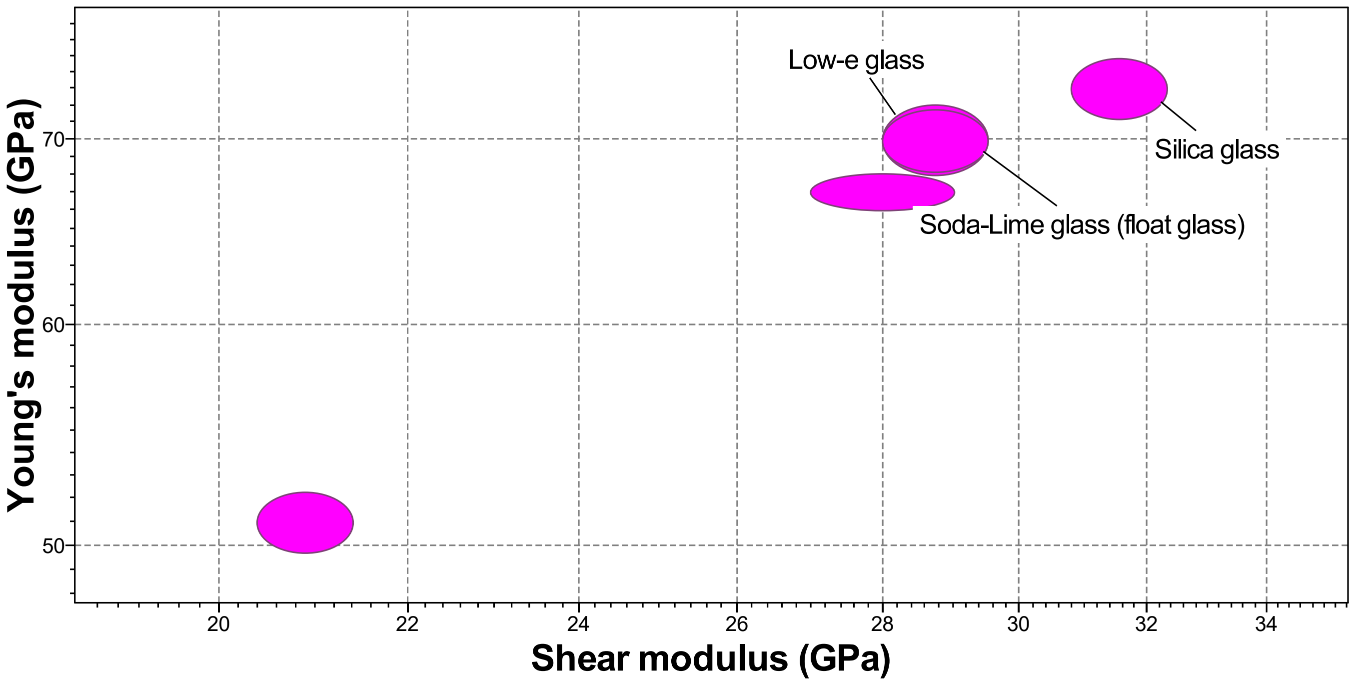


Young's modulus (GPa)
500
200
100
50
20
Tungsten alloys
Nickel alloys
Zinc alloys
Aluminum, pure (1200, H4)
Aluminum alloy, wrought (6061, T4)
Tin
Magnesium alloys
Lead alloys
5
10
20
50
100
200
Shear modulus (GPa)



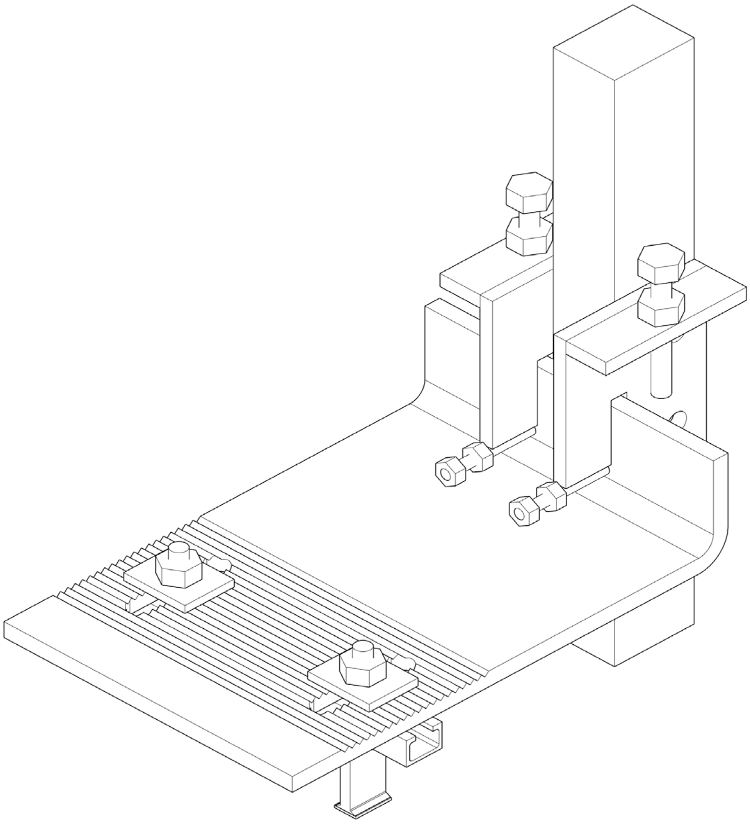
Young's modulus (GPa)
220
200
180
160
Coated steel, steel, galvanize
Coated steel, steel, terne c
Coated steel, stainless steel, terne coated
on, nodular (spheroidal, ductile)
60
65
70
75
80
85
90
95
Shear modulus (GPa)


Young's modulus (GPa)
30
20
10
0.5
1
2
Shear modulus (GPa)


Low-e glass
Silica glass
Soda-Lime glass (float glass)
Young's modulus (GPa)
70
60
50
20
22
24
26
28
30
32
34
Shear modulus (GPa)

Appendix

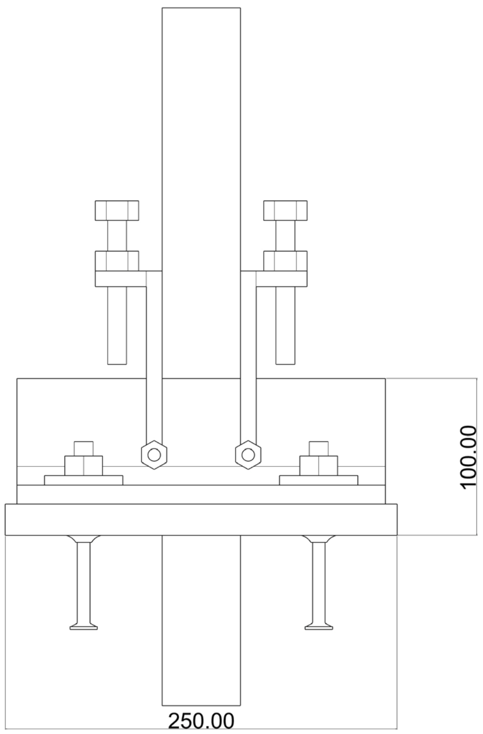
Halfen top-lab application bracket drawings



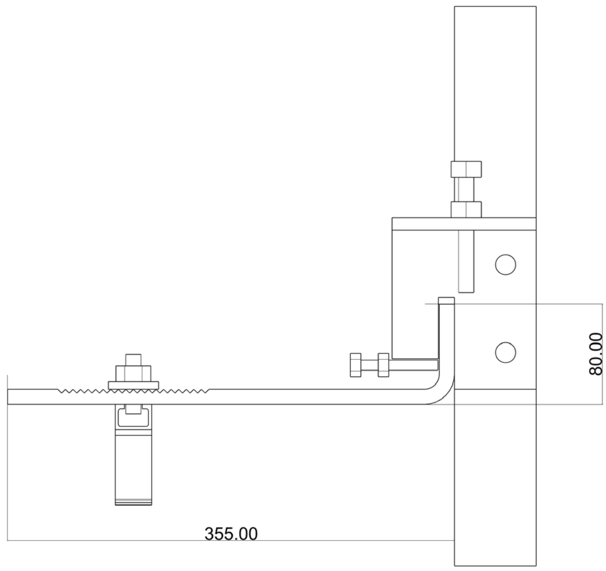
Drawing 04: Halfen Bracket Perspective View.
Source: Halfen, Author

Appendix

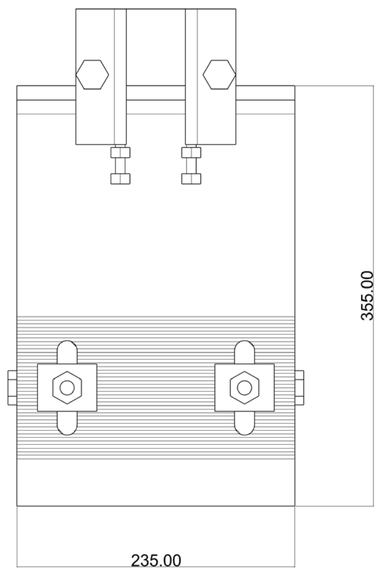
Halfen top-lab application bracket drawings



Drawing 01: Halfen Bracket Front View.
Source: Halfen, Author



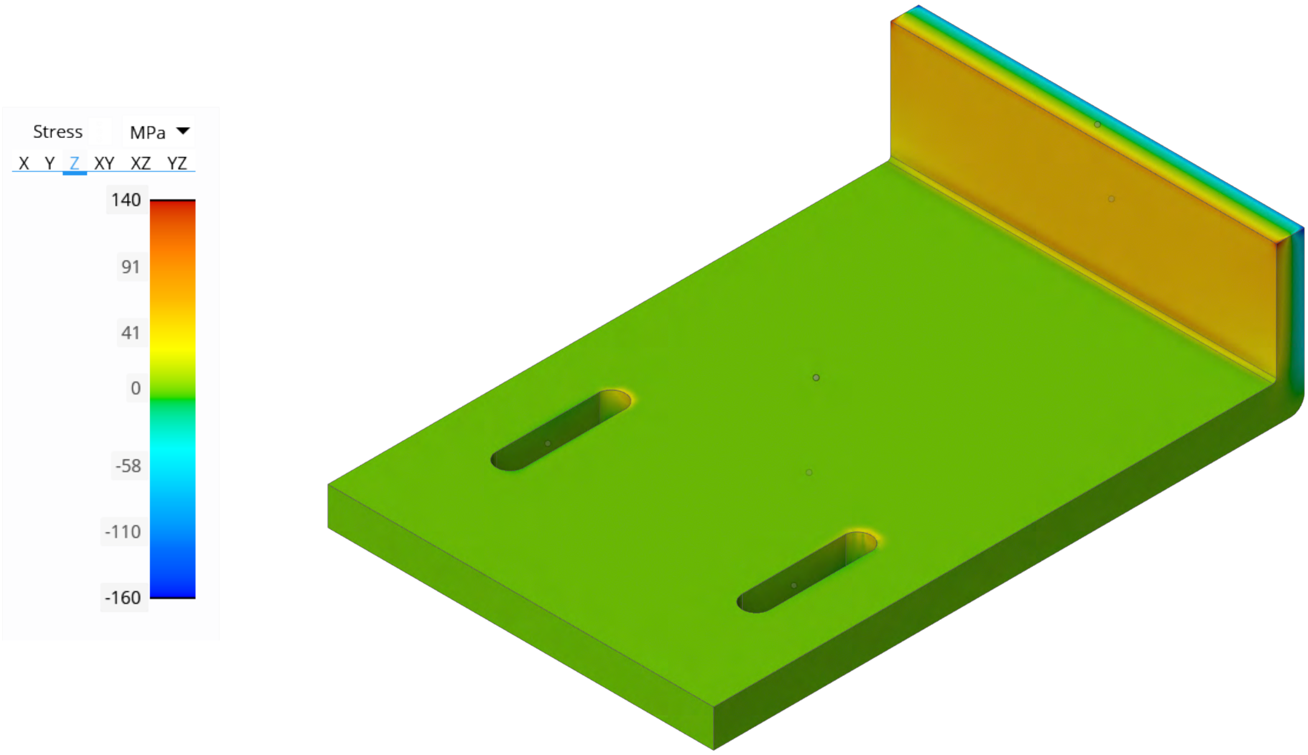
Drawing 02: Halfen Bracket Side View.
Source: Halfen, Author



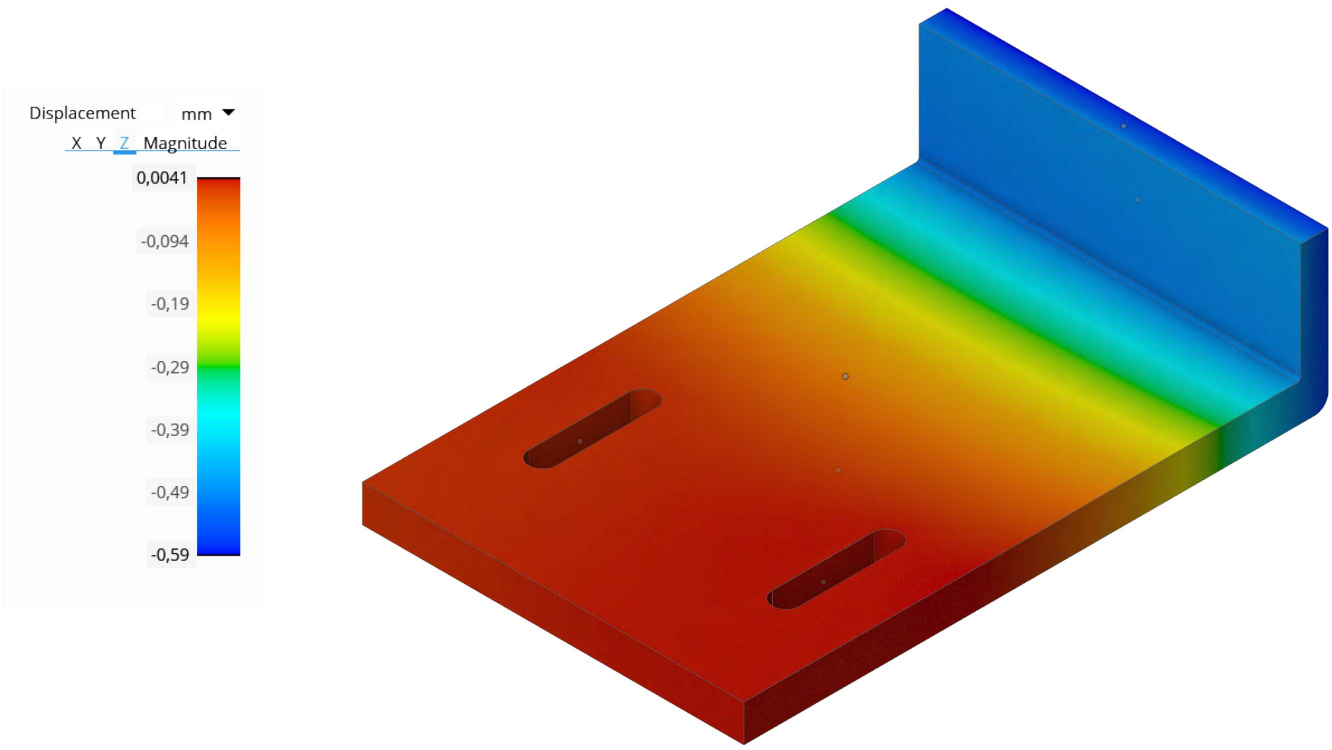
Drawing 03: Halfen Bracket Top View.
Source: Halfen, Author

Appendix

Halfen top-lab application FEM analysis under normail conditions (weight applied)



The maximum stress is concetrated in the siding and fixed supports of the bracket. The maximum value is 60MPa<f_{gd}.



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