

Fully Demountable glass connection for  
large-scale structural applications

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# Uni.Conn

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## Master Thesis

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## Abstract

The reuse of large-scale structural glass panels is significantly limited by existing connection systems. The existing connection methods either permanently alter the glass panel or leave residual damage upon disassembly, resulting in the disposal of structurally intact panels. This thesis investigates the feasibility of developing a fully demountable connection system for large-scale structural glass applications that addresses this gap.

The proposed system, uni.conn, introduces a mechanically controlled interlocking connection that meets the required structural performance benchmarks while allowing the connection to be attached, repositioned, and removed without permanently modifying the glass panel. The system consists of three components: a glass module with a modified rebated edge profile, a three-part mechanical insert comprising a pin, link and sleeve, and a gasket that acts as the load-transferring interface between the insert and the glass. The interlocking and separation of the pin and link is controlled by an external magnetic field, enabling disassembly without mechanical intervention at the connection itself. The structural behaviour of the system is investigated through load path analysis and finite element analysis at a product level using ANSYS Workbench.

The results demonstrate that uni.conn enables glass panels to be reused across different structural configurations without being constrained by specific connection locations or damage upon disassembly. While developed at concept level, the findings contribute to the broader effort of improving circular practice in the glass industry.

### Keywords:

Structural glass, dry-assembly system, demountable connections, interlocking connections

## Acknowledgments

I began this thesis with a genuine curiosity about the topic. Initially, I did not consider it to be particularly niche, given the growing interest in circular construction and the ongoing pursuit of reusable solutions within the industry. However, the lack of studies, specifically addressing the complete reversibility of structural glass connections, always surprised me. Once I began my research, the design process quickly became overwhelming. The industry problem is real, but there is no single way to solve it. There could always be a better connection method that I had not yet come across. This uncertainty kept me searching, exploring, and trying to understand as many connection systems as possible. Eventually, however, I learned to narrow down the possibilities and commit to a specific direction. There may always be an unknown system that could solve the problem more effectively, but the best solution is ultimately the one that can be developed based on the information, knowledge, and time available. In many ways, this realization became one of the most valuable lessons of this thesis.

My interest in glass and its structural applications developed during the Q3 course Technoledge: Glass Structures, led by my primary mentor, Faidra Oikonomopoulou. Her energy and expertise have had a profound impact on me, not only throughout this thesis but during my entire two years of master's studies. Even during the most difficult phases of the project, she always ensured that I remained calm and found ways to move forward and improve the work. I would also like to thank my second mentor, Marcel Bilow, for his practical and innovative inputs throughout the design process. I truly enjoyed the brainstorming sessions with him regarding the various connections and mechanisms from different applications. His expertise and insights were crucial in shaping the design and improving its workability. Together, my mentors made this journey far richer and more enjoyable than I could have hoped for.

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This thesis, one of the works I am most proud of, is dedicated to my family.

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# Introduction

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## 1.1 Background

In contemporary architecture, structural glass has transcended its traditional role as a transparent infill to become a primary load-bearing material. As architectural ambitions scale toward larger dimensions and increasingly complex geometries, the performance of glass connections has become the critical aspect of facade engineering. While the fundamental purpose of any connection is the efficient transfer of loads, the brittle nature and surface sensitivity of glass make this a significant technical challenge. Historically, these connections have been designed for a single service life, with little regard for what happens when a building is renovated or decommissioned.

### *The Sustainability Gap*

Despite the widespread use of glass, the industry currently operates on a linear cradle-to-grave model. Glass panels are notoriously difficult to recycle into high-quality flat glass, often resulting in downcycling or disposal in landfills once their initial service life ends (Oikonomopoulou et al., 2023). This prevents the recovery of the material's full economic and environmental value, contributing significantly to construction waste (Hartwell & Overend, 2019). Given the carbon intensity of glass production, there is an urgent foundational and environmental requirement to shift towards a circular economy where glass components are treated as reusable assets rather than disposable panels.

### *The Evolution of Glass Connections*

The history of glass engineering is defined by a quest for transparency. This evolution began with the small-paned, heavily framed systems of the Crystal Palace (1851) and has culminated in the present-day era of “all-glass” envelopes and high-end retail stores. Each leap in glass size has necessitated a corresponding evolution in connection technology. The industry transitioned from “wet” bonding techniques, which provided high strength but resulted in irreversible joints, to the mechanical and embedded systems used today, which offer improved maintenance and partial demountability.



Figure 1: Crystal Palace, London (1851) | Source: gettyimages

This progress resulted in the modern connection systems, broadly categorized as **adhesive-based**, **bolted**, and **embedded laminate joints**.

However, all the categories fail to meet the demands of a truly circular building economy as per present day standards:

- Adhesive-based joints offer excellent load distribution and aesthetics but are notoriously difficult to reverse without damaging the glass or leaving chemical residues.
- Bolted connections allow for straightforward disassembly but require glass perforations. These holes create permanent stress concentrations and physical damage that limit the panel's potential for reuse in different configurations.
- Embedded laminated inserts provide high-performance load transfer without drilling, yet they remain permanently fused within the interlayer, making the connection an inseparable part of the laminate and restricting complete material recovery.



Figure 2: Adhesive based (Left), Bolted Connection (Middle) & Embedded Laminated Inserts (Right)

## 1.2 Research Question

These limitations create a fundamental obstacle for circularity in structural glass. When a glass panel retains its full structural integrity and load-bearing capacity at the end of a building’s service life, its potential for reuse is limited by the connection detail rather than the material itself. This gap between architectural transparency and circularity highlights the need for a connection system that provides true demountability: a solution that requires no permanent modification to the glass surface while simultaneously meeting the structural demands of large-scale applications. Currently, a significant gap exists in the industry, where no established solution provides a fully reversible interface capable of transferring all tension, compression and shear forces without compromising the future reusability of the glass.

Based on the limitations identified in current connection typologies, this study seeks to answer the following:

*How can a fully demountable connection system be developed for large-scale structural glass panels without modifying or damaging the glass, while still meeting the necessary structural and durability requirements?*

To answer the main research question, the investigation is structured around the following five targeted sub-questions:

### Q1. Performance Requirements

What structural and durability criteria must a demountable connection satisfy for use in large-scale structural glass applications?

### Q2. Limitations of Existing Systems

What are the specific limitations of current connection systems in terms of reversibility, reuse, and glass integrity?

### Q3. Design Principles

What design principles and material behaviors must be considered when developing a connection that transfers loads effectively without modifying or penetrating the glass?

### Q4. Potential Connection Mechanisms

How can different connection mechanisms (e.g., mechanical interlocking, clamping, surface bonding, hybrid systems) be explored for achieving full demountability, and what are their constraints?

### Q5. Prototyping and Evaluation

How can proposed connection concepts be prototyped and tested to evaluate their structural performance, reversibility, and long-term behavior?

## 1.3 Methodology

This research follows a systematic multi-stage methodology designed to address the research question through a detailed investigation of its sub-questions. The initial phase of literature review addresses Q2: Limitations of Existing Systems and Q3: Design principles. The literature review begins with a focused analysis of the three major types of glass connections in the current market: adhesive, bolted and laminated inserts. This would provide a detailed understanding of the strengths and weaknesses of each category, and how one performs against the other. Following this, the study briefly highlights a few upcoming technologies on structural connections for float glass to understand the current trends that are being explored.

The literature then moves on to exploring demountable connection strategies employed in other structural materials for similar large-scale applications to develop a comprehensive set of criteria essential for a fully demountable connection system, addressing the Q1: Performance Requirements. These criteria will serve as a framework, which would be used to evaluate the connections that have been discussed through literature, and the potential concepts for a demountable connection as well.

The third phase, addressing Q4: Feasible Connection Mechanisms and Q5: Prototyping and Evaluation, involves the iterative development and validation of novel connection concepts. This stage will rely on digital methods, including Finite Element Method (FEM) analysis on Ansys Workbench and computational modeling for further explorations. This digital exploration will enable rapid iteration and optimization of designs. Simultaneously, the developed connections will be tested for the workability by 3D printing the prototypes. The findings from these empirical tests will inform a final evaluation against the established criteria, leading to the most viable and ideal solution that fully addresses the primary research question.

### 1.3.1 Timeline

Task	Dec	Jan	Feb	Mar	Apr	May	Jun
Literature study	█	█	█				
Potential concept exploration		█	█				
Design development			█	█	█	█	
Digital simulations				█	█	█	
Physical prototyping				█	█	█	█
Versions for different loadcases					█	█	
Conclude the design						█	█

Table 1: Thesis timeline

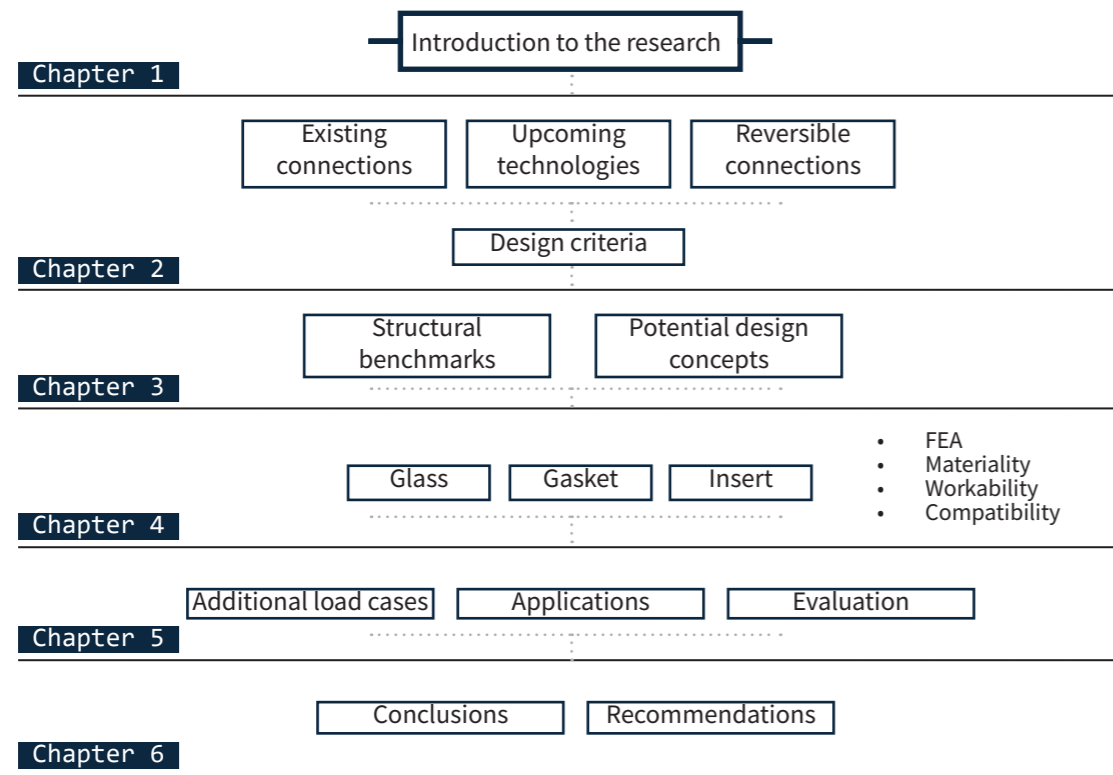


Figure 3: Structure of the Report | Source: Author

## 1.4 Relevance

This thesis proposes a fully demountable connection system for large-scale structural glass panels, addressing reversibility at the connection level without modifying the glass. Through a critical analysis of existing and emerging connection technologies, the research frames demountability as a key performance criterion for future structural glass systems.

In current glazing systems, glass panels are often discarded before the end of their potential structural life due to permanent alterations by the connection methods. Given the high energy intensive process of glass production, the inability to reuse structurally sound panels represents a significant material inefficiency. This research supports the reuse of glass components across various structural configurations by enabling reversible connections that return glass panels to their original state upon disassembly. This way, the proposed approach contributes to more circular construction practices and promotes more responsible use of glass as a structural material.

## 1.5 Scope

This research focuses on connection systems for large-scale structural applications using float glass panels. Other glass formats, such as cast glass or additively manufactured glass, are outside the scope of this study. Only glass panels suitable for load-bearing structural use are considered. For the purposes of this thesis, the investigation is limited to non-insulated glass panels. Design explorations and performance assessments are primarily conducted through digital simulations, enabling the evaluation of multiple design iterations within the available timeframe.

# 2.

## Literature

Glass Joinery	2.1
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Using glass as a structural material requires connection systems that perform beyond the basic functions of air and water tightness. In load-bearing applications, connections must reliably transfer structural loads while accounting for the brittle nature of glass and limiting stress concentrations within the material (Ramming, 2022). As a result, connection design plays a critical role in both the structural performance and durability of glass systems.

## 2.1 Glass Joinery

This section presents an overview of the principal typologies of structural glass connections currently employed in architectural applications. While these systems demonstrate significant advancements in load transfer and architectural integration, their mechanical behaviour, advantages, and limitations require careful evaluation.

### 2.1.1 Category 1: Adhesive connections

Adhesive bonding is one of the earliest and most widely adopted methods for connecting glass panels, relying on chemical and physical bonding between glass surfaces and adjacent structural elements. A key advantage of adhesive connections is their ability to distribute stresses uniformly across the joint, reducing local stress concentrations (O'Regan, 2014). Compared to bolted connections, adhesives enable the connection of thinner materials and offer superior aesthetic performance due to their minimal visual impact.



Figure 4: Steve Jobs theater | Source: fosterandpartners.com

Adhesive systems also accommodate dimensional tolerances and thermal movements, contributing to the joint performance. However, their mechanical properties degrade over time, particularly due to reduction in stiffness, which can compromise long-term structural performance (Lavko & Kvočák, 2020). The behaviour of adhesive joints varies significantly depending on the adhesive type, with commonly used systems including acrylates, epoxy resins, polyurethanes and structural silicones. The Guidance for European Structural Design of Glass Components (Feldmann et al., 2014) categorizes the adhesives based on

the flexibility. The silicones and polyurethanes are the flexible-elastic kind, with epoxy resins and acrylates as being rigid. These materials exhibit differing characteristics in terms of stiffness, UV resistance, transparency, and tensile and shear strength (Lavko & Kvočák, 2020). A key distinction between these categories lies in their mechanical behaviour: stiffer adhesives offer higher strength, but with limited elongation capacity, while the flexible adhesives allow for larger deformations at the expense of lower strength.

Feldmann et al. (2014), compare the 4 categories based on their properties:

	Strength	Stiffness	Ductility	Viscosity	Temperature resistance	Ageing behaviour	UV resistance	Transparency and color
Epoxy resin	+++	+++	+	+++	++	++	++	+
Polyurethane	++	+++	++	++	++	++	++	++
Acrylates	++	++	++	++	++	+++	+++	+++
Silicones	+	+	+++	+	+++	+++	+++	+

Table 2: Comparison of adhesives used | Source: Feldmann et al. (2014)

Ongoing developments in polymer chemistry have led to adhesives capable of resisting substantial structural loads while maintaining desirable aesthetic qualities through transparency or minimal visible presence. However, these advancements do not eliminate the inherent challenges related to long-term durability and reversibility. Moreover, the reliability of adhesive connections is highly dependent on the execution conditions, where a few types requiring controlled environments to ensure consistent curing.

### 2.1.2 Category 2: Bolted Connections

Bolted connections represent a fundamental mechanical approach to structural glass joinery, allowing for direct mechanical fastening of glass panels to a supporting structure or to each other. This method involves creating precisely drilled holes through the glass, through which bolts, typically accompanied by bushings, washers, and gaskets, are inserted to create a secure, point-fixed connection.



Figure 5: Bolted Connections, Seattle-Tacoma International Airport | Source: novumstructures.com

In bolted systems, glass panels are rigidly connected to the supporting structure, resulting in localized peak stresses around the bolt holes (Lavko & Kvočák, 2020). Compared to nominally identical adhesive joints, bolted connections generally exhibit inferior structural performance due to these stress concentrations (Overend et al., 2013).



Figure 6: Glass beams, University of Glasgow (left) | Source: thermospan.co.uk

Figure 7: Glass fins, Chicago (right) | Source: booking.com

There is no universally accepted rule for positioning or the dimensioning of the hole, however, it is preferable to have the hole diameter at least twice of the glass thickness (Eliasova, 2015). The design and choice of these connection is often strongly influenced by aesthetic considerations. Nevertheless, their use of standardized components and straightforward installation procedures makes them widely adopted in practice. Different material combinations and profiles demand different holes configurations in the glass panel (fig. 8). In the applications involving heavier loads, steel splices are used in the connection system to increase the contact area for better load spread.

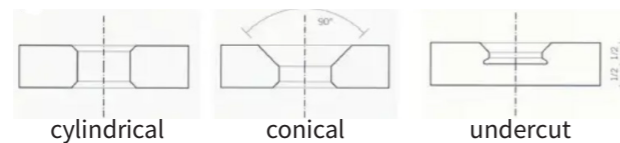


Figure 8: Typical hole shapes | Source: Eliasova, 2015

Multiple factors such as form of loading; geometry of the panel; relative size and position of the hole in the panel; closeness of fit; friction at the interface between bolt and panel; bushing used; and profile of the hole influence the stresses around the hole in the glass panel (Overend et al., 2013). The necessity of perforating the glass is intrinsic to bolted connections and represents a critical limitation, as holes inherently introduce stress concentrations at their edges. Research has explored alternative hole-making techniques aimed at reducing local stresses and improving load-bearing capacity. However, Sanders et al. (2021) demonstrate that conventional drilling methods continue to outperform alternatives such as waterjet cutting in terms of ultimate load capacity, stress distribution, and hole-edge uniformity.

### 2.1.3 Category 3: Laminated inserts

Laminated inserts, also known as Embedded laminates, represent a more recent innovation in structural glass joinery. This technique involves encasing metal inserts (typically stainless steel) directly within the interlayer (Bajtek et al., 2020) during the lamination process of two or more glass panels. As noted by O'Callaghan and Bostick (2012), inserts used in this context must exhibit high tensile strength, a suitable Young's modulus, sufficient deformation capacity, and minimal thickness, criteria that make stainless steel a common choice.



Figure 9: Apple Omotesando, Tokyo | Source: eocengineers.com

The core principle is to transfer loads from the glass to the structural frame or adjacent panels via these embedded elements, avoiding the need for through-holes or surface-applied adhesives. The external part of the insert often protrudes from the laminated glass edge, providing a connection point that can then be bolted or otherwise mechanically attached to the supporting structure.

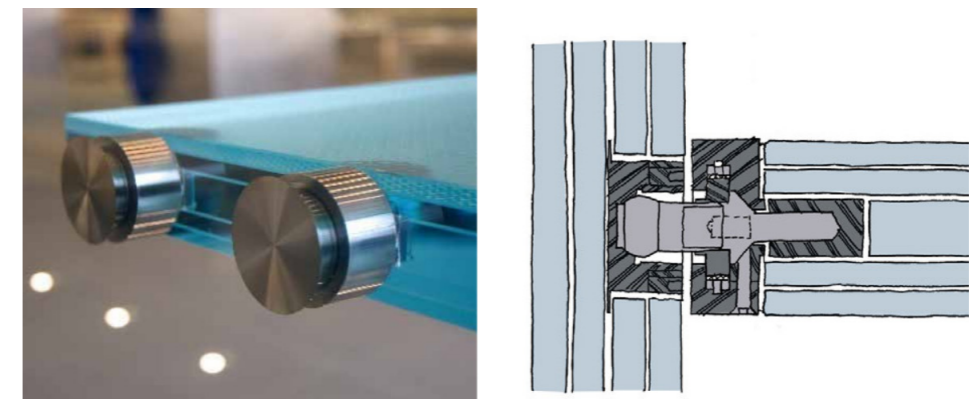


Figure 10: Laminated point fitting, Apple Hamburg | Source: Ramming, 2022

This method was developed to address the limitations of both adhesive and bolted systems, aiming to combine the aesthetic advantages of minimal visible hardware with improved structural performance by avoiding perforations in the glass. However, the embedded insert is permanently integrated within the laminated glass and cannot be removed without damaging the panel. As a result, while the glass module itself may be reusable, its reuse is limited to similar applications with the same connection locations, limiting flexibility across different structural configurations.

### 2.1.4 Summary of Glass Joinery (existing technologies)

Connection Type	Benefits	Shortcomings
<b>Adhesive bonds</b>	<ul style="list-style-type: none"> <li>Uniform load distribution.</li> <li>High transparency and minimal visual intrusion.</li> <li>Vibration damping due to elastic behaviour.</li> <li>Mature and well-established technology.</li> </ul>	<ul style="list-style-type: none"> <li>Non-demountable and largely irreversible.</li> <li>Damage of glass during removal.</li> <li>Limited reuse potential.</li> <li>Aging and UV-related degradation.</li> <li>Require specific environmental conditions during application.</li> </ul>
<b>Bolted Connections</b>	<ul style="list-style-type: none"> <li>Reliable and predictable mechanical performance.</li> <li>Straightforward demountability.</li> <li>Standardized and widely available components.</li> </ul>	<ul style="list-style-type: none"> <li>Stress concentrations at drilled holes.</li> <li>Permanent geometric modification of glass.</li> <li>Limited reuse flexibility.</li> <li>Visible hardware impacts transparency.</li> </ul>
<b>Laminated inserts</b>	<ul style="list-style-type: none"> <li>No through-holes in glass.</li> <li>Improved structural integrity over bolted systems.</li> <li>Reusable within similar configurations.</li> </ul>	<ul style="list-style-type: none"> <li>Inserts permanently bonded to glass.</li> <li>Restricted adaptability to new layouts.</li> <li>Difficult material separation reduces circularity.</li> </ul>

Table 3: Summary of existing glass connections

## 2.2 Upcoming Technologies

It is widely acknowledged that the industry of glass connections is constantly innovating. However, the motivation for these innovations varies. Most often, the need for achieving maximum transparency or improving recyclability becomes the primary criteria for innovation.

This section discusses a few upcoming innovations in the industry with motivation varying from developing a monolithic connection that achieves better recyclability, achieving maximum transparency and developing a connection that supports reusability better. While these examples do not provide an exhaustive overview of all ongoing innovations in structural glass connections, they illustrate key trends and highlight the diversity of approaches currently being explored. The following methods are discussed below:

1. Heat Bonding
2. Additive Manufacturing
3. Interlocking profiles

### 2.2.1 Heat Bonding

Innovations in the industry of glass connections with heat bonding usually revolve around two methods. Ideally, heat bonding requires melting glass to connect with glass or other materials. Melting glass is done at both micro and macro level, with completely different methods and purposes:

#### Micro-Level Glass Connection: Ultrashort Pulse (USP) Laser Welding

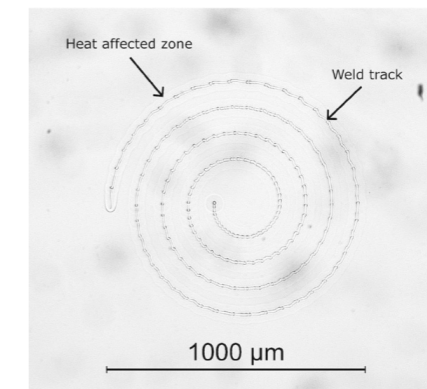


Figure 11: Ultrashort Pulse Laser Weld | Source: van Abeelen et al., 2025

Ultrashort pulse (USP) laser welding offers a precise method of joining glass at the micro-scale by locally modifying its optical properties. Unlike conventional light, which passes through glass without absorption, the high-intensity USP laser induces a temporary opaque state in the material, allowing energy to be absorbed and concentrated heating and melting to occur within a highly localized zone. This process creates strong, transparent bonds with minimal heat-affected zones and without disturbing the glass surface at room temperature (Cvecek et al., 2019).

Van Abeelen et al. (2025) demonstrate the technique’s application in vacuum insulating glass, where USP welding is used to attach glass pillars, replacing traditional metal spacers. This approach maintains material uniformity, avoids adhesives, and enhances recyclability while improving transparency.

However, despite these advantages, USP laser welding inherently results in permanent joints that cannot be demounted or reversed, limiting its applicability in systems requiring disassembly. Additionally, concerns about crack formation and inevitable surface impurities remain challenges that require further research (Cvecek et al., 2019; Utsumi et al., 2007).

Macro-Level Glass Connection: Glass Welding and Glass Fusion:



Figure 12: Welded Glass (Left) & Fused Glass (Right) | Source: Eskes, 2018

At a macro scale, Rammig (2022) and Eskes (2018) provide extensive detail regarding bonding using glass fusion and glass welding, for creating monolithic glass connection. Both techniques eliminate the need for adhesives or mechanical fasteners by bonding glass elements directly through controlled heating processes.

The table below summarizes their key characteristics, advantages, and limitations relevant to structural applications.

Criterion	Glass Welding	Glass Fusion
Heating method	Local heating after global preheating (~500 °C)	Global heating in kiln (up to ~765 °C) with the help of a cast.
Joint appearance	Fully transparent, monolithic	Translucent with visible seam/groove
Structural performance	Higher strength, better interface control	Lower strength, limited geometric control
Residual stresses	Higher than fusion	Lower than welding
Dimensional accuracy	Moderate inaccuracies (bending, shortening)	Significant deformation and thickness variation
Skill requirement	High	Moderate
Cost	High	Lower
Scalability	Limited by skilled labour and thermal control	Limited by kiln sizes
Demountability	Permanent bonding	Permanent bonding

Table 4: Comparison between glass welding and glass fusion

2.2.2 Additive Manufacturing

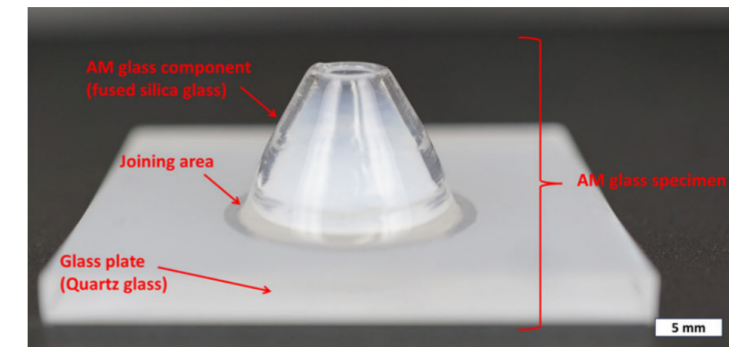


Figure 13: 3D printed silica glass fibers onto quartz glass | Source: Chhadeh et al., 2025)

Chhadeh et al. (2025) investigate Laser Glass Deposition (LGD) as an additive manufacturing technique to create monolithic glass-to-glass point fixings for facade applications. This approach aims to replace traditional metal fasteners, which often compromise aesthetics and introduce durability risks due to thermal expansion mismatches.

The process involves 3D printing fused silica glass fibers (0.4 mm diameter) onto quartz glass substrates (as shown in Figure 7), chosen for their low thermal expansion and ability to be printed without a heated chamber. One promising future application is the printing of stiffeners onto large flat glass sheets due to its significant contribution in increasing the moment of inertia, potentially reducing deflections and enabling significant material savings in construction. The geometry of the 3D printed profile has a significant impact on the structural integrity of the module. Even though the printed profile cannot be removed from the glass panel, the entire module can be designed for reuse.

2.2.3 Interlocking systems

Interlocking systems are designed to enable straightforward assembly and disassembly, with end-of-life scenarios typically following the reverse sequence of installation. Bouwmeester (2023) and Motedayen (2025) explore such systems through their master's theses, focusing on the development of glass profiles that facilitate easier connection and disconnection. These systems rely on predefined geometries that facilitate controlled mounting and demounting, making them suitable for modular construction approaches.



Figure 14: Interlocking glass profiles | Source: Bouwmeester (2023) (left) & Motedayen (2025) (right)

However, interlocking strategies often require permanent geometric modification of glass panels, limiting their applicability and reuse to specific configurations. In addition, scalability remains a key challenge, as the structural performance of interlocking profiles does not scale linearly; variations in profile geometry can significantly affect load-bearing behaviour at larger dimensions.

### 2.2.4 Summary

Connection Type	Benefits	Shortcomings
<b>Heat Bonding</b>	<ul style="list-style-type: none"> <li>Transparent bonds</li> <li>Uniform material-monolithic structures</li> <li>Ability to create precise bonds</li> </ul>	<ul style="list-style-type: none"> <li>Non-demountable and irreversible</li> <li>Requirement of skilled labour</li> <li>Limited scalability</li> <li>Limited knowledge of demountability at precise bonds</li> </ul>
<b>Additive Manufacturing</b>	<ul style="list-style-type: none"> <li>Strong, monolithic bonds</li> <li>Precise control of the printing profiles</li> <li>Stronger bonds, depending on the shape of the profile</li> </ul>	<ul style="list-style-type: none"> <li>Non-demountable and irreversible</li> <li>Limited knowledge of glass panel's performance upon demountability</li> <li>Limited scalability</li> <li>Requires specific equipment</li> </ul>
<b>Interlocking profiles</b>	<ul style="list-style-type: none"> <li>Reusable panels</li> <li>Reversible joints</li> <li>Modular elements</li> </ul>	<ul style="list-style-type: none"> <li>Permanent modifications to glass panels</li> <li>Limited scalability</li> <li>Reusability is limited to the same/ similar application</li> </ul>

Table 5: Summary of upcoming technologies for glass connection

## 2.3 Reversible joinery in construction

As part of the investigation into demountable connection strategies for structural glass applications, this research extends its scope to demountable connection systems developed for other construction materials. Materials such as steel, timber and concrete are examined due to their established use in structural and reversible constructions. These case studies are used to identify design principles, performance criteria, and recurring challenges that may inform the development of demountable connection concepts for glass.

### 2.3.1 Steel

Demountable steel connections can be categorized into two primary mechanical groups: bolted connections, which involve through-fastening often requiring material modification, and clamped connections, which utilize non-invasive pressure to join components. Even though welded connections are commonly practiced in steel structures, they are ignored in this research due to their lack of demountability (Cabaleiro et al., 2023).

#### Bolted Connections:

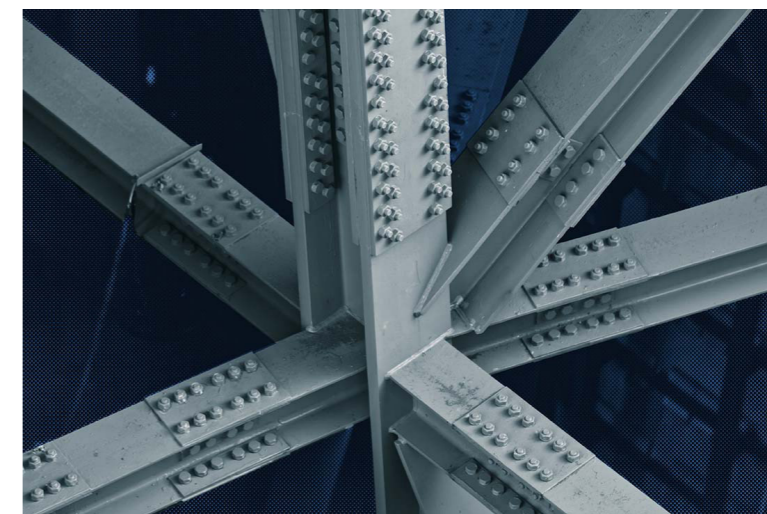


Figure 15: Bolted steel profiles | Source: Inasolutions.com

Bolted connections are the most common form of removable joint in the industry. These joints typically use high-strength bolts, sometimes in the form of blind bolts (fastened from one side) or bolted shear connectors. The strength of the connection is derived from the bolt's resistance to shear or tension through pre-made perforations.

However, bolted connections have significant shortcomings regarding long-term sustainability. While they allow for disassembly, their reconfigurability is often limited because the structural elements usually require pre-drilled holes, which are specific to the use case (Cabaleiro et al., 2023). Furthermore, these connections alter the structural capacity of the steel; the requirement for multiple bolt holes means material is removed from the element, creating perforations that can weaken the profile and reduce its load-bearing capacity (Cavalheiro et al., 2025).

### Clamped Connections:

Clamped connections are a superior alternative for reconfigurability because they do not require holes, drilling, or welding, thereby preserving the total material integrity of the steel profile. These systems operate on a lever mechanism principle: tightening a central bolt redistributes force to generate mechanical pressure, securing the steel components without permanent modifications (Cabaleiro et al., 2023).

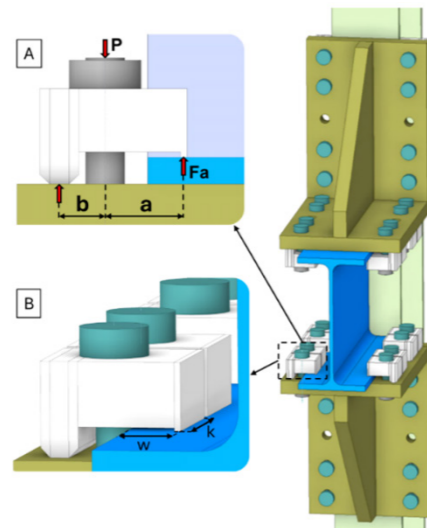


Figure 16: Clamped connection | Source: Cabaleiro et al. (2023)

Because they preserve the steel in its original state, clamped connections are ideal for highly dynamic industrial environments, where production layouts are frequently reconfigured every 7 to 10 years. They are widely applied in modular industrial shelving, temporary support structures, and maintenance platforms (Cavalheiro et al., 2025). This method ensures that profiles can be moved to any position or reused in entirely different structures without the need for reinforcement or reworking, aligning perfectly with the goal of maximizing the lifespan of structural components.

Despite these advantages, the application of clamped connections remains limited. Their structural stiffness is generally lower than that of conventional connections, and their cost is significantly higher. Furthermore, the lack of extensive large-scale structural research restricts their adoption beyond specific industrial use cases (Cabaleiro et al., 2023).

### 2.3.2 Concrete

It is more practical to discuss precast concrete instead of cast-in-site concrete because the latter is generally a permanent system and cannot be demounted without being destroyed through demolition (Heuver, 2024). Precast concrete structures are composed of standardized elements that are cast in controlled environments and then assembled on-site, offering significant advantages for circularity and reuse.

In parallel, demountability is also being explored within steel–concrete composite systems. Kavoura and Veljkovic (2023) highlight the potential of such systems to reduce construction waste and enhance the reuse of structural components, while also emphasizing the role of design guidelines in enabling reusability. Their work focuses

on connection strategies between steel–concrete composite panels and steel framing systems, which predominantly rely on bolted connections to enable disassembly.

### Bolted Steel Interfaces for Demountability

Industry research, such as that conducted by Peikko (Yrjölä, 2022 and Junes, 2025), demonstrates that demountability is achieved almost entirely through bolted steel interfaces rather than changes to the concrete itself. Standard bolted column–foundation and beam–column connections, utilizing components like column shoes and anchor bolts, are designed to be reversible and can be opened for reuse. For these systems to be successful, they must be detailed with clear access to hardware, proper tolerances, and designated lifting points from the initial design phase (Junes, 2025).



Figure 17: Demountable Concrete column detail | Source: Yrjölä (2022)

### Challenges

A primary challenge in deconstruction is access and sequence, as connections often cluster at corners and are frequently hidden behind interior or exterior finishes (McMullin et al., 2012). Successful reuse relies on the ability to reach these bolts and original lifting hardware without the need for destructive stripping of the elements (Yrjölä, 2022). If the removal process is not planned to minimize damage, the reclamation of materials becomes economically unviable.

Finally, standardization is essential for the industry to adopt large-scale reuse. Reclaimed elements are far easier to integrate into new structures when connectors and structural grids are standardized (Heuver, 2024). In the cases, where many precast products are project-specific rather than standardized, a uniform connection system that can adapt to varying dimensions is necessary to improve the reuse of existing concrete elements (Heuver, 2024).

### 2.3.3 Timber

Structures designed using timber and engineered wood constitute most buildings developed for disassembly, highlighting the material's significance in understanding demountable connection strategies currently practiced in the industry (Ostapska et al., 2024). The same study emphasizes the reliance on bolts and screws as primary enablers of component demountability in modern-day structures. It is also important to note that reducing the required tasks to mount and demount significantly improve the reusability (Al Shamaa & Saleh, 2021).



Figure 18: MOD-it system | Source: 3dmbc.com

Li et al., 2024 further explore the integration of interlocking connections using CLT panels with metal connections, as a single module. This study highlights the concept of sequences designed to mount and demount for retaining the reusability of the modules. One such example is the MOD-it system.

The MOD-it system enables rapid and reversible timber construction by allowing components to be separated without cutting or denailing. Connections are surface-mounted, compatible with a range of timber panel types, and can be pre-installed in factory settings, supporting standardization and efficient on-site assembly. Structural deformations are accommodated within the connection itself, preserving the integrity of the timber elements.

However, while the system supports reuse by avoiding permanent damage, timber members may still experience degradation in mechanical performance over time due to creep and fatigue. As a result, the authors emphasize the need for non-destructive testing methods to reliably assess the continued usability of reclaimed elements.

### 2.3.4 Aluminum scaffolding couplers

Scaffolding couplers are among the most successful examples of standardized mechanical connections in the construction industry. The connection is independent of the overall geometry of the structure, making them truly versatile. Common type of couplers, including right-angle, swivel, sleeve, etc., can be repeatedly used to create a wide variety of structural configurations without modifying the primary structural members.



Figure 19: Swivel coupler | Source: rombouts.nl

The couplers function based on frictional clamping and restraining mechanically. As a result, they remain unaltered during multiple cycles of assembly and disassembly. The connection can be removed, replaced, or repositioned without affecting the integrity of the connected members. One such commonly used coupler is the swivel coupler, which allows for connecting two elements at any angle. This makes it ideal for scaffolding structures requiring multiple members at different angles.

In the design of a coupler, the rate of assembly and disassembly plays as big of a role as their structural performance. The industry is constantly exploring ways to improve this speed, while maintaining the required strength. The simplicity in the design of a coupler and its straight-forward sequences of mounting and demounting improve the versatility and scalability of the design.

## 2.4 Criteria

The review of demountable connection systems in steel, concrete, and timber highlights that effective reversibility is achieved primarily through connection design rather than material modification. It is evident that the demountable connection systems avoid invasive operations, like cutting, welding or permanent bonding, to retain a high reuse potential. At the same time, they reveal the recurring challenges related to structural performance, accessibility, durability and widespread applicability.

These observations help in developing the following criteria, that become the guidelines for design development and evaluation of glass connection systems (both existing and designed):

### 1. Reusable module

The module of glass panel and the connection must be completely reusable, for a different use case.

### 2. Fully demountable connection

The connection must enable complete disassembly and true material separation, returning the glass panel to its original state.

### 3. Structural Capacity

The system must safely transfer required structural loads while limiting stress concentrations in the glass

### 4. Maintenance and accessibility

Connections should allow straightforward installation, inspection, maintenance, and disassembly through clear access and sequencing

### 5. Visually minimally intrusive

The connection should minimize visual impact on the glass surface, assessed through comparative analysis with existing systems.

### 6. Durability

The connection must maintain mechanical performance over its service life.

### 7. Scalability

The system (including the mounting and demounting sequence) should be adaptable to large number applications and compatible with standardized glass panels.

### 8. Ease of assembly and disassembly

The sequence of assembly and disassembly must be straightforward and easy to execute on site.

## Evaluation

Previously discussed glass joinery methods, along with the ones mentioned in the upcoming technologies are evaluated against the established criteria.

Legend:

- Poor
- ++ Better
- # Cannot be gauged with existing information
- + Good
- +++ Excellent

Design Criteria	Adhesive connections	Bolted connections	Laminated inserts	Heat Bonded joinery	Additive manufacturing	Interlocking systems
Modular reusability	-	+++	+++	-	-	+++
Demountability (reversible connection)	-	-	-	-	-	-
Structural performance	+++	+++	+++	#	#	#
Maintenance and accessibility	-	++	++	-	-	+++
Minimal visual intrusion	+++	-	++	+++	+++	+
Durability	++	+++	+++	+++	++	+++
Scalability	+++	+++	+++	+	-	+
Ease of assembly & disassembly	+	++	+++	-	-	+++

Table 6: Evaluation of glass connection systems based on design criteria

### 2.5 Discussion

Based on the reviewed literature and examples, this section explores potential solutions for the three existing connection categories, envisioning how an ideal system might meet the established criteria.

#### Adhesive based:

One innovative approach could involve structural adhesives that maintain strong bonding during service but can be “switched off” on demand via triggers such as heat, light, electrical current, or chemicals. For example, a thin release layer within the adhesive could be selectively dissolved by a mild solvent delivered through microchannels, enabling controlled debonding. However, such concepts are beyond the scope of this study due to the requirement of expertise in advanced material engineering.

A more practical mechanical alternative is to design composite joints combining adhesive and mechanical elements, where the mechanical component carries the full structural load, and the adhesive serves mainly for sealing and vibration damping. During disassembly, the adhesive can be safely removed without compromising structural integrity. However, this is the working principle in current bolted and laminated systems that use weatherproof sealants.

#### Bolted connections:

A potential solution for bolted connections is to refill drilled holes with glass pieces from the same panel, aiming for a seamless, homogeneous joint that is visually indistinguishable. Research by Eskes (2018) and Ramming (2022) on glass-to-glass welding explores this possibility. However, as the studies suggest, the existing technology does not achieve the required homogeneity, both structurally and visually.

#### Laminated inserts:

Laminated inserts generally offer better reusability compared to adhesives and bolted connections, but their main limitation lies in the permanent fusion with the glass interlayer, which prevents separation or relocation of the insert on the panel. To address this, new concepts propose designing inserts that are demountable rather than fused. One approach is to clamp the metal insert internally along a channel integrated into the edge of the glass panel, allowing the insert to be repositioned along the panel’s perimeter as needed.

Additionally, the USP laser method could be explored to connect metal and glass at select points, permitting minor, non-structural surface alterations. Because the heat-affected zone in USP laser welding is minimal, these alterations might be negligible and allow separation without damaging the glass. However, current literature lacks information on the feasibility of reversible separation using this technique.

# 3.

## Design preparation

Structural benchmarks	3.1
Design initiation	3.2
Potential Concepts	3.3

## 3.1 Structural benchmarks

To assist the design development of the connection system, an iconic structure, built in Glass, is chosen for the purpose of case study and design implementation. A prominent junction in the structure is chosen for the design development of the connection system, and later, the whole structure is re-imagined with the developed system.

### 3.1.1 The Apple Cube, Fifth Avenue

The Apple Fifth Avenue Cube in New York City (designed by Bohlin Cywinski Jackson with structural engineering by Eckersley O'Callaghan) is widely considered as a significant milestone in the evolution of Glass structures. It played a major role in shifting the perception of glass from being a passive cladding to an active, primary load-bearing system.

#### Mark I (version 1):

The original cube was completed in 2006 and was composed of a complex grid of 109 glass panels (a total of 164 glass units, including fin columns and beams) (O'Callaghan & Bostick, 2012). The version 1 of the cube utilized 18 panels per side (6x3 units), each measuring approximately 1.66m wide x 3.33m high. The roof consisted of 36 units of 1.66m x 1.66m, supported by glass beams underneath. At the time, this design stretched the limits of glass processing technology, showcasing the possibility of fully load-bearing structures entirely made of glass.



Figure 20: Apple Fifth Avenue Mark I | Source: Wikipedia

#### Mark II (version 2):

Driven by Steve Jobs' desire for more 'Crystal Clear' structure, the cube was redesigned and rebuilt in 2011. This version utilized massive panels to dramatically increase transparency, reducing the total number of glass units to just 35, over 75% reduction from the initial design (O'Callaghan & Bostick, 2012). It reduced the side panels from 18 to just 3 units. The sizing change was primarily driven by the development of larger manufacturing equipment. By 2010, the fabrication firm seele sedak had developed autoclaves capable of laminating and tempering panels up to 15m x 3.6m, allowing for the single-span height seen in Version 2.0.

The newer 'jumbo' panels, used in facade and roof, in this version are 10.3m high x 3.3m wide. To cater to the newer spans of the glass panels, the thickness for the layers has been increased to three panels of 12mm units. The facade panels are supported by 2 glass fins, per each face. Similarly, the roof structure was streamlined to two primary 10-meter glass beams braced by seven secondary beams.

The version 2.0 uses embedded laminated inserts to connect the glass panels. This allowed for the glass panels to be joined with no hardware protrusions from the surface. The technique of embedding the inserts within glass panels contributed in reducing the number of connections to just three per vertical joint.



Figure 21: Apple Fifth Avenue Mark II | Source: eocengineers.com

### 3. Design preparation

#### 3.1.2 Load Cases

A few critical junctions, along with typical loading systems have been used as a base for developing the connection system. These conditions are studied for load paths and the effect on the connection system. These load cases are calculated to achieve the load acting on the connection. In few cases, the structures are digitally modeled and analyzed on Grasshopper+Karamba to accurately achieve the loads acting at a specific point of interest. The chosen load cases are as follows:

##### 1. Facade: Panel-to-panel horizontal connection

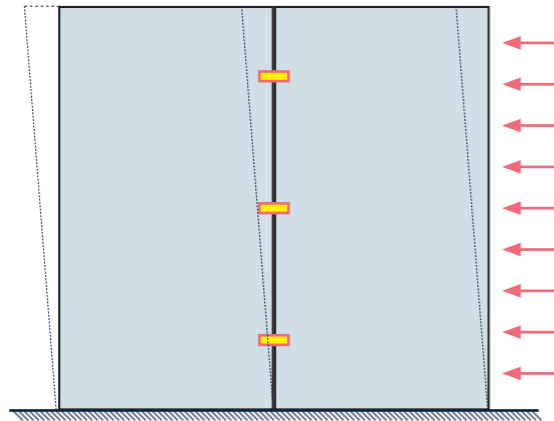


Figure 22: Load case: facade-to-facade panels | Source: Author

##### Geometry & Support:

Two adjacent facade panels, connected along vertical edge. Supported at the bottom.

**Load condition:** Wind load acting on the perpendicular facade.

**Critical requirement from the connection:** As the panels try to shear off the contact edge, the connection between the panels would be experiencing a tilting, coupling load. The insert region of the connection within the glass panels would be under coupling load, with two perpendicularly opposite forces acting within the panels.

**Note:** Thermal expansion and seismic racking would be introducing pushing/ pulling effects on the connection, but are negligible compared to the wind loads. Hence, they will be ignored for further explorations.

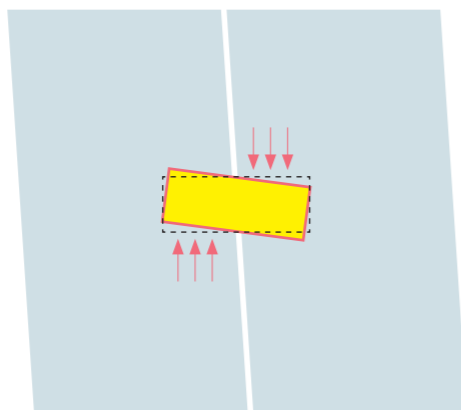


Figure 23: Coupling load at the connection interface | Source: Author

### 3. Design preparation

#### Load values

Wind load =  $1.5 \text{ kN/m}^2$   
Safety factor = 1.5

Load acting on the edge from the perpendicular facade:  
UDL =  $11.6 \text{ kN/m}$

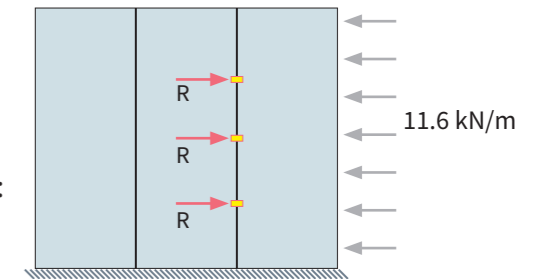


Figure 24: Load analysis | Source: Author

Considering the same number of connections (three) as the ones in Apple fifth avenue- Mark II,

Reaction force at the connection:

$$R = 40 \text{ kN}$$

This reaction force of 40kN acts as a coupling moment load equally towards both the ends of the connection.

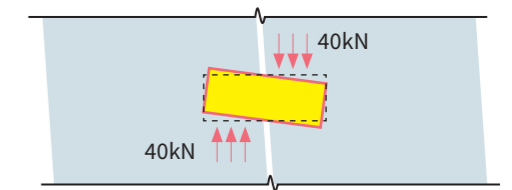


Figure 25: Load analysis | Source: Author

For design explorations and due to its wide application, this initial load case of interaction between two adjacent panels in a facade system will be used as a base. This provides constraints for developing for the connection, and once the design performs for this load case, further versions of it will be developed for the remaining load cases.

##### 2. Facade panels-to-vertical fin connection

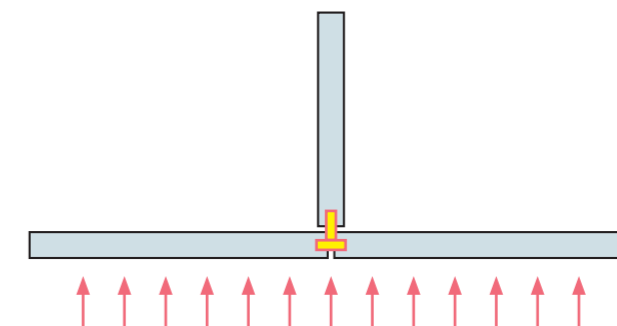


Figure 26: Load case: Facade panels-to-vertical fin | Source: Author

##### Geometry & Support:

Two adjacent panels in the facade are supported by a vertical fin against wind loads.

##### Load condition:

Wind load perpendicular to the face of the facade panels.

##### Critical requirement from the connection:

The connection needs to be integrated to all the three panels, in a T-junction, to efficiently transfer the loads

3. Roof panels-to-vertical beam connection

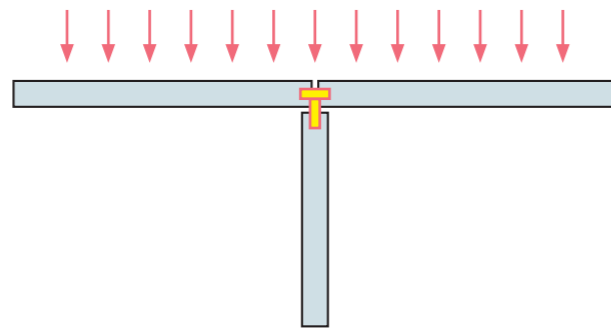


Figure 27: Load case: Roof panels-to-vertical beam | Source: Author

**Geometry & Support:**

Two roof panels are supported on a beam, under their contact edge.

**Load condition:**

Vertical loading on the roof, like snow or maintenance loads + Self weight of roof panels.

**Critical requirement from the connection:**

Critical requirement from the connection: The connection needs to be integrated to all the three panels, in a T-junction, to efficiently transfer the loads. It should be able to not only transfer the imposed loads, but also the self-weight of the roof panels.

**Load values**

(Detailed analysis can be found in Appendix 2)

Snow load (for New York City) = 0.96kN/m<sup>2</sup>

Safety factor = 1.5

Considered roof panel size: 9.6m x 3.2m

Spacing of supports: 0.8m

Reaction force at the connection:

$$R_{max} = 4.45kN$$

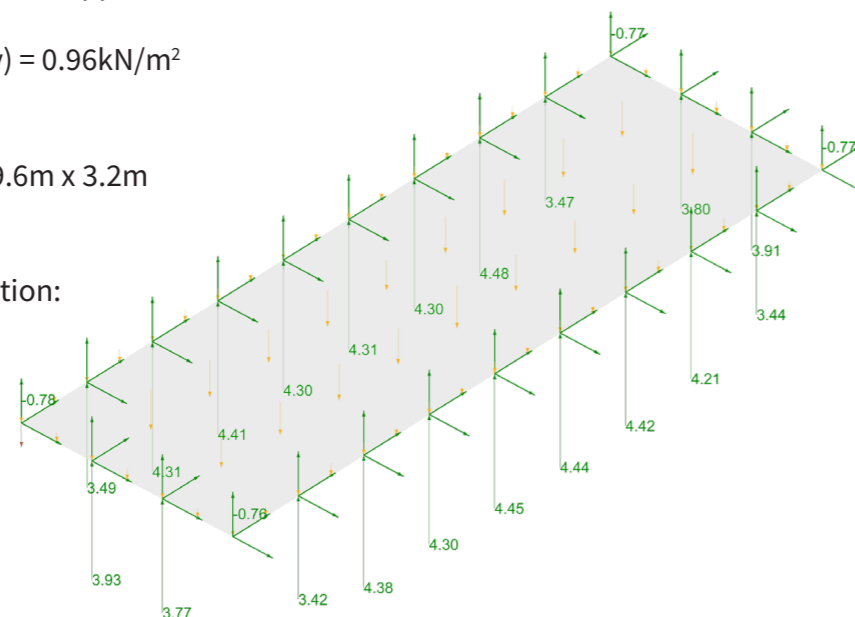


Figure 28: Load analysis using Karamba | Source: Author

4. Beam-to-beam

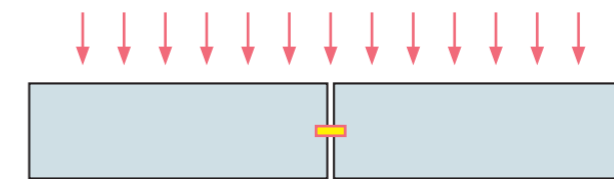


Figure 29: Load case: Beam-to-beam | Source: Author

**Geometry & Support:**

Two panels of glass are connected in continuation to form a longer spanning beam, while being supported at the other end.

**Load condition:**

Vertically downwards load from the roof panels and self-weight.

**Critical requirement from the connection:**

Due to the load condition, the panels are in bending. Therefore, the connection system must be supporting the glass panels, while holding them together.

5. Grid of 3x3 panels

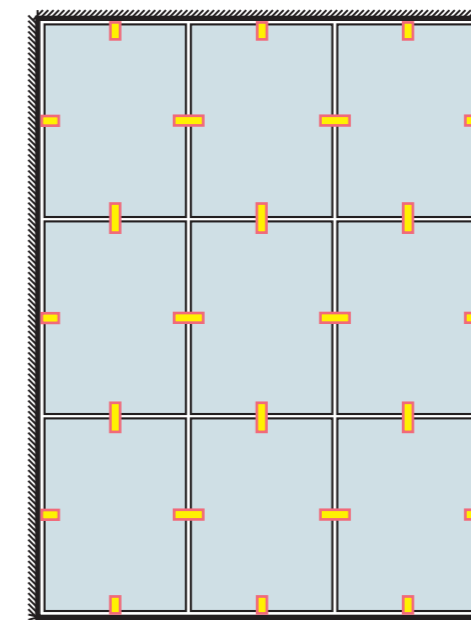


Figure 30: Grid of 3x3 panels | Source: Author

**Geometry & Support:**

The aim is to build a curtain wall system with the designed connection method, while being supported on all four sides.

**Critical requirement from the connection:**

A planned assembly order is essential for the connection to perform as required. The designed connection system must allow for assembling the panels in a typical facade. This exploration acts as a versatility test for the connection being developed, with a scope of testing its scalability.

### 3.2 Design initiation

The connection developed in this thesis begins the current technology of laminated inserts, by trying to improve the demountability of the connection. The treatment of the glass panel is initially explored, followed by connection between the interface of the inserts and the glass panels.

A successful demountable connection involves two key interfaces: **the connection between panels (joinery between modules)**, and **the connection between the panel and its individual connection element**.

Both must be reversible to ensure full demountability. However, disassembly does not have to occur simultaneously at both levels; these can happen separately and at different times depending on need and disassembly sequence.

Hereby, the design distinguishes between both modes of connection as following:

Glass panel + connection = **Module**  
 Module + Module = **System**

The system must be dismantled on-site for maintenance or end-of-use scenarios. However, module disassembly can take place either on-site or off-site (e.g., at a factory). Off-site disassembly requires additional transportation but can be optimized through effective logistics planning. This thesis explores the connection within the module, as the existing connections are already demountable at a system-level (example: Laminated inserts).

#### Modification to glass panel:

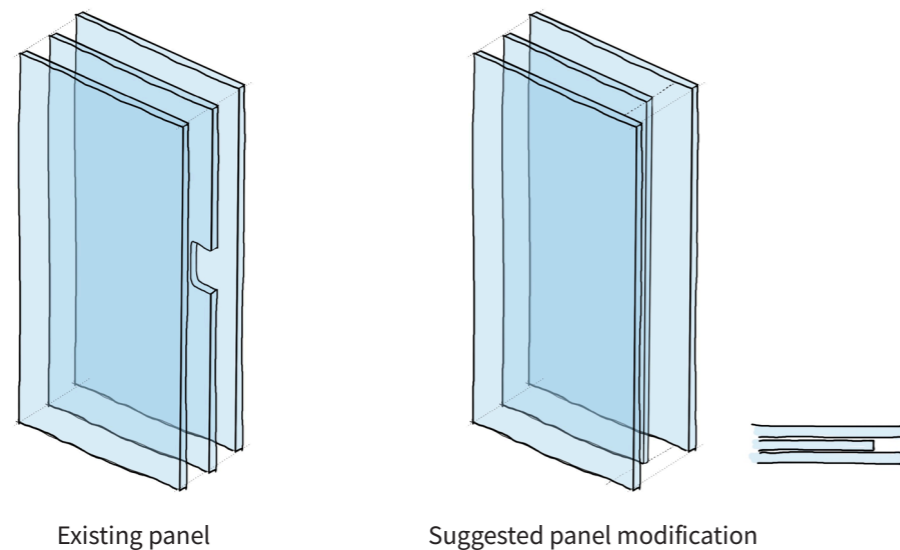


Figure 31: Panel modification | Source: Author

A typical glass panel with laminated inserts has the insert bonded with the glass panels at desired location. Moreover, the glass panel needs to be cut to make space for the insert. This not only makes the module difficult to demount but also make it a permanent

modification to the panels. The design in this thesis begins with re-imagining the design of a standard laminated float glass panel.

The central float glass layers in a typical laminated glass panel are smaller than the peripheral ones, and therefore, are inset by a certain length from the edge. This creates a channel along the edge, on all four sides of the panel. This will be further used to connect with the insert.

### 3.3 Potential Concepts

Primary concepts arrive from the treatment of glass, connection mechanism and ease of operations. Based on the upcoming technology and the existing connections, this section explores a few potential ideas for this thesis.

Different methods of enabling the glass panels for the connections are initially explored, followed by the method of connection. Based on each kind, the connection within the module could either happen at site or at the factory.

#### 3.3.1 Glass Panel Treatment

##### 1. Surface sanding

The surface of glass panels in the created channel is roughened by sanding. This provides enough friction for the insert to grip to the insides of the glass panels. Due to the whole surface being treated the same way, it is possible to relocate the connection along the length of the whole edge. The glass panels need to be over-dimensioned to have enough sacrificial layer along the edge to allow for sanding.

However, it is important to note that the surface treatment might wear-off after repeated usage in the same location. This means, the panel might need frequent checks and re-treatment after a couple of uses.

The main drawback for sanding the surface of glass panels are the irregularities, such as microcracks, that introduce peak stresses. Moreover, this method might be difficult to execute in a controlled manner, and therefore, might be invasive to the glass panels.

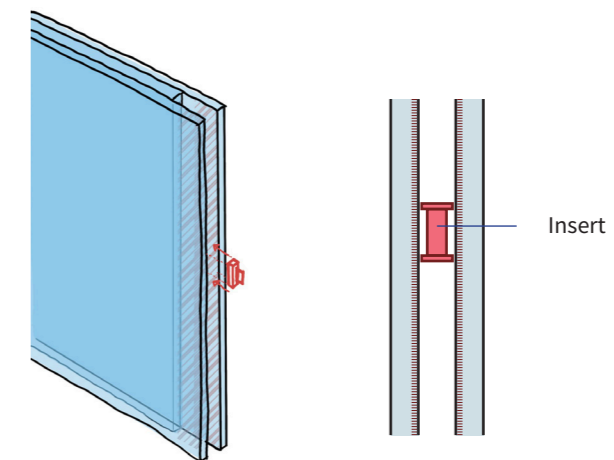


Figure 32: Surface sanding | Source: Author

2. Laser ablation (Ultra-short pulsed laser)

Using the method of USP, high-intensity lasers can be used to add grooves (surface pattern) on the glass edge for the insert to grip onto. This method addresses one of the drawbacks of the sanding method by being able to qualitatively assess the condition of the panel and execute in a controlled manner. Similar to the previous case, the glass panels are to be over-dimensioned to account for the grooves introduced.

Potential explorations with laser ablation would be to test and experiment with the profiles being created on the glass panel, while monitoring the peak stresses. However, the primary drawback of adding surface irregularities to glass panels remains. The process of USP might be difficult to execute to an industrial scale for the jumbo glass panels.

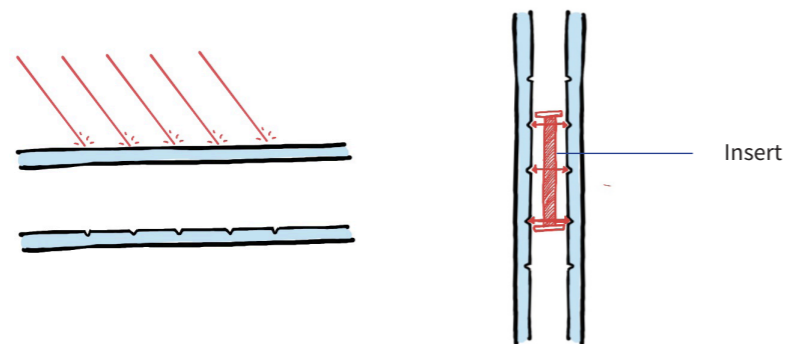


Figure 33: Laser ablation | Source: Author

3. Laser glass deposition

The process of laser glass deposition requires 3D printing layers of glass on the surface of the panels. This creates smaller profiles/ needles on the surface for insert to grip onto. This would be a pattern along the edge of the glass panels, allowing for different possibilities to place the insert. Unlike the previous methods, this method does not involve removal of material from the glass panels, and therefore, lowering the risk of introducing surface irregularities.

The insert can grip onto the profiles created, or alternatively, it could be bonded with the profiles depending on the chosen method of connection. Since the profiles could be printed on the surface again, these profiles could also become the sacrificial layer at the time of disassembly. Different profiles for 3D printing onto the panels could be explored, to reduce the peak stresses while supporting the insert. However, due to the lack of current knowledge of the behaviour of the profiles while disassembly and their impact on the glass surface once removed, this method may damage the glass surface.

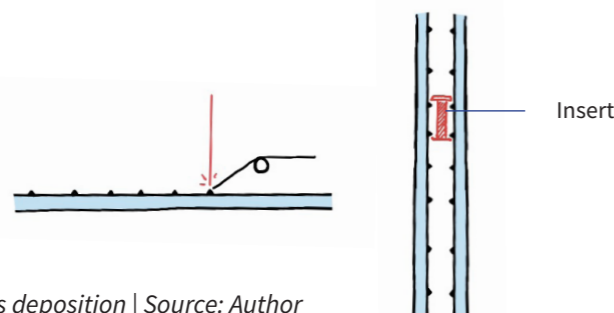


Figure 34: Laser glass deposition | Source: Author

4. Surface bending

The process of surface bending glass panels introduces grooves for the insert to connect. This could be done by using a laser to heat the specific location on the panel and load it evenly to achieve controlled deformations. Alternatively, the glass panel could be heat-pressed to achieve the required deformation. Surface bending of the panels could be executed at a larger-scale before the lamination process.

Unlike the other methods, this process is the least invasive, and most durable to the material.

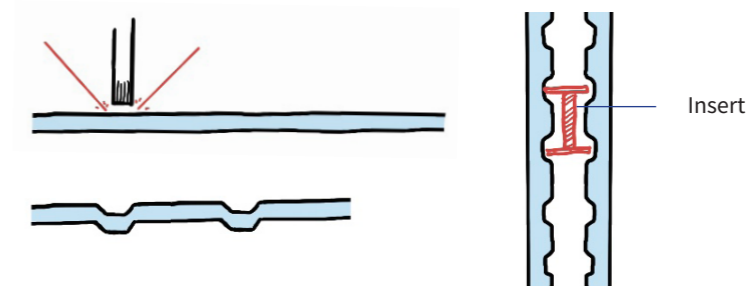


Figure 35: Surface bending | Source: Author

Summary

The following table summarizes the properties and impact of the mentioned design concepts at a qualitative level based on manufacturing and performance constraints.

	Surface sanding	Laser ablation	Laser glass deposition	Surface bending
<b>Structural grip</b>	Low	Moderate	Moderate	High
<b>Material invasiveness</b>	High	High	Moderate	Moderate
<b>Execution control</b>	Low	Moderate	High	High
<b>Scalability</b>	High	Moderate	Moderate	Moderate
<b>Durability &amp; Reusability</b>	Low	-	-	Moderate
<b>Cost</b>	Low	High	High	High

Table 7: Summary of potential glass treatment concepts.

However, it is not yet possible to draw conclusions among the treatment concepts, because it does not take into account regarding the potential connection methods. This will be elaborated in the subsequent section.

### 3.3.2 Connecting methods

This section explores the different methods the insert could be connected to the glass panels, within the channel created. Ease-of-use, durability, strength and assembly-disassembly methods play an important role in each of these methods.

#### 1. Frictional grip

The insert could simply be placed in location between the glass panels and activated on command to grip onto the interior surface.

#### 2. Interlocking grip

Using the surface pattern within the glass panel edge, the insert could interlock into the grooves created. This provides better control than the frictional methods of gripping.

#### 3. Micro welding (USP)

The process of USP could be used to selectively weld the insert with the glass layers. To reduce the risk of damaging the glass while disassembling, the glass could have a sacrificial layer that is welded to the insert. However, due to lack of information regarding the status of glass panels while demounting a welded connection, this process may pose a significant risk to the integrity of the panels.

#### 4. Clamping

Clamps are widely used in the construction industry at different scales. In glazing industry, clamps are already being used for balustrades and internal partitions. However, clamping the glass panels becomes difficult at a larger scale. As the size of the glass panels increases, the loads involved increase drastically. This requires larger clamps, that may be difficult to work with at site and become a visual hindrance.

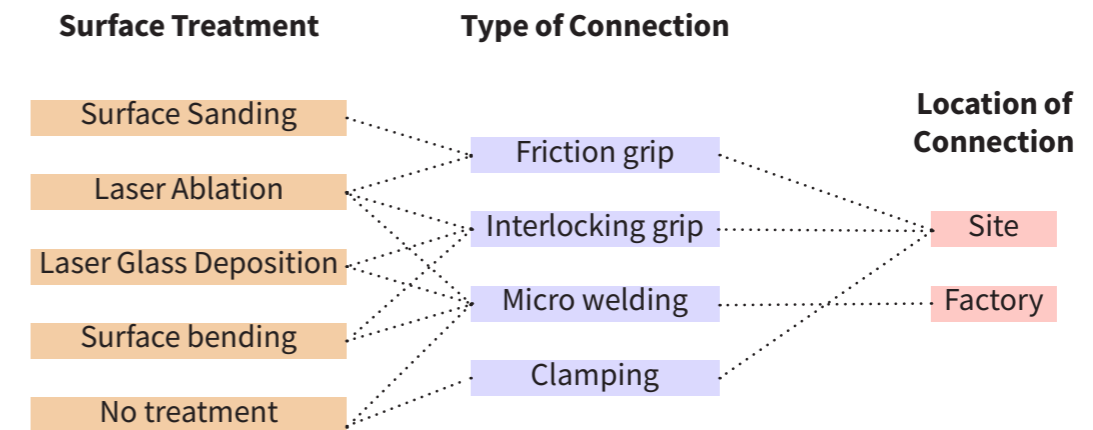
#### Summary

The potential connection methods are summarized as follows:

	Frictional grip	Interlocking grip	Micro-welding	Clamping
<b>Material invasiveness</b>	Moderate	Low	High(?)	Low
<b>Expertise to operate</b>	Low	Low	High	Low
<b>Visual impact</b>	Low	Moderate	Low	High
<b>Durability &amp; Reusability</b>	Low	-	-	Moderate
<b>Site vs Factory feasibility</b>	Site	Site	Factory	Site

Table 8: Summary of potential concepts for connection methods.

It is important to note that different methods of surface treatment are compatible with specific methods of connections. The following chart indicates this correlation between them, to assist in choosing the appropriate methods.

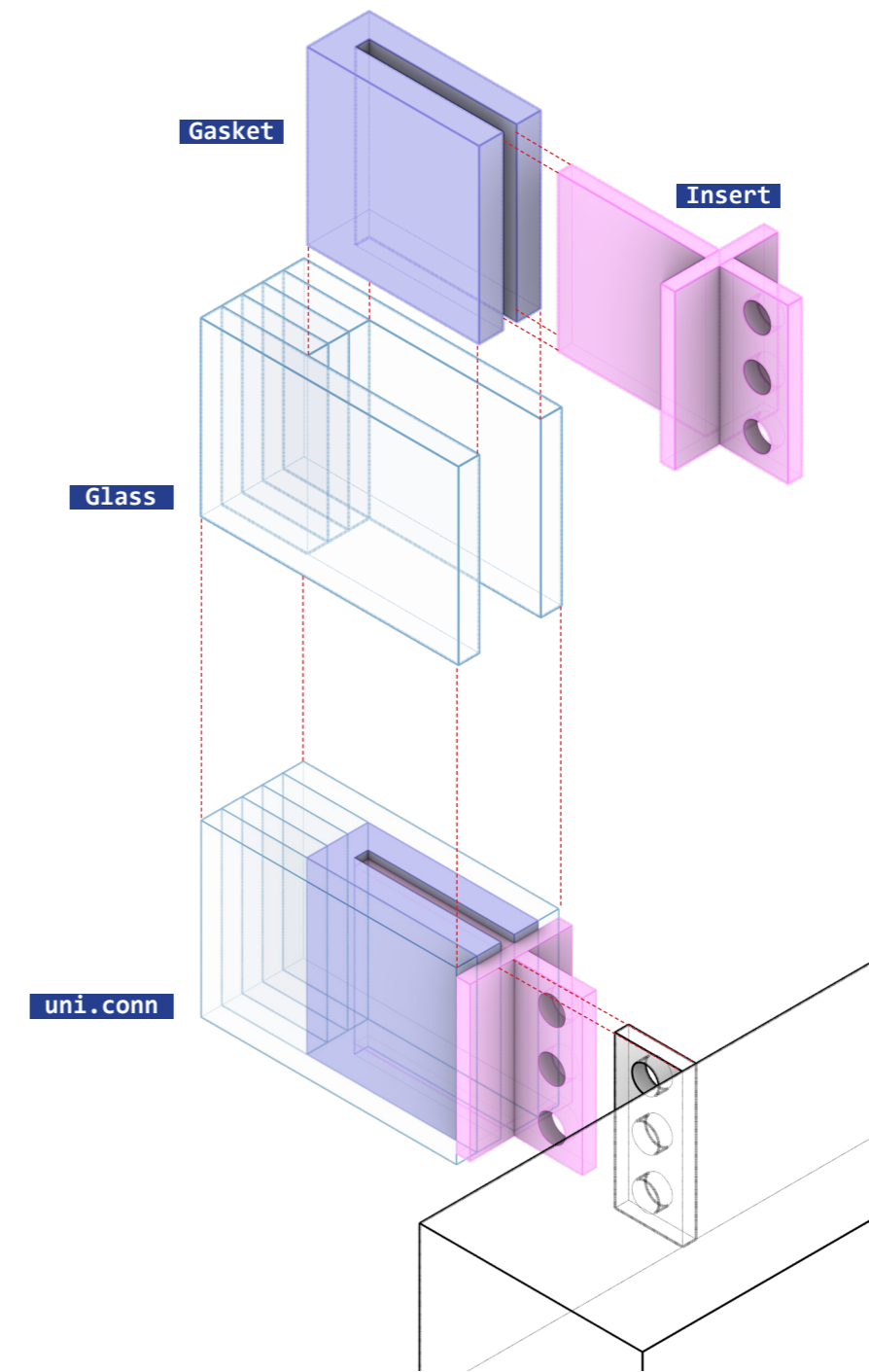


Among the potential concepts explored, the idea of utilizing interlocking mechanisms for the insert is chosen. To make the glass panel inter-lockable for the insert, the edge of the glass panel must be treated using surface bending. Due to the lower impact and better understanding of the structural performance of glass, heat pressing has been chosen as the method of surface treatment to proceed further.

The aim of this thesis is to find an alternative to the existing connection systems. As an analogy, the thesis compares this exploration to 'looking for a Unicorn', and therefore, is titled as **Uni.conn**. Henceforth, the connection system being developed will be referred as uni.conn in the subsequent sections.

The Uni.conn module primarily consists of three elements:

- Glass
- Insert
- Gasket



# 4.

## The Uni.conn

Glass	4.1	Materiality	4.6
Insert	4.2	Structural Performance	4.7
Gasket	4.3	Workability	4.8
Methodology	4.4	Technical Drawings	4.9
Design Iterations	4.5		

Figure 36: Components of the uni.conn | Source: Author

### 4.1 Glass

The profile of the glass within the channel allows for the insert to interlock. This profile created must withstand the loads and accommodate the connection system during different use cases of the panel.

The design exploration of the glass module is primarily guided by its structural performance. Soda-lime-silica float glass is considered in this thesis due to its widespread applicability. Glass panels are available in multiple thicknesses, typically ranging from 6-12mm. However, they can be produced for a wider range of 2-25mm, based on the requirement. Since 6mm thick glass is easier to produce, this thesis begins the exploration with laminated glass of 6mm thick layers. The panel thickness would be increased to the subsequent versions as per structural explorations.

The following physical properties of glass are used for structural explorations via Finite Element Analysis.

<b>Density</b>	2500 kgm <sup>-3</sup>
<b>Young's modulus</b>	70 - 74 GPa
<b>Poisson's ratio</b>	0.22 - 0.24
<b>Fracture toughness</b>	0.78 MPa.m <sup>1/2</sup>
<b>Knoop hardness</b>	6 GPa
<b>Annealing point</b>	10 <sup>13.5</sup> Pa.s (520 °C)
<b>Thermal Conductivity</b>	1 W.m <sup>-1</sup> .K <sup>-1</sup>
<b>Coefficient of thermal expansion</b>	7.7x10 <sup>-6</sup> K <sup>-1</sup> - 9x10 <sup>-6</sup> K <sup>-1</sup>

Table 10: Physical properties of soda-lime-silica glass | Source: SAMS datasheets

While EN 572-2 suggests the characteristic bending strength of a basic soda lime silicate float glass as 45MPa, the design considers the glass used in the design to be fully toughened for the ease of exploration, with Far-field and Edge strength as approximately 81MPa and 50MPa respectively (BS EN 12600). Since the design exploration of this thesis is primarily focused on the edge of the glass panel, 50MPa is considered as the maximum allowable principal stress.

Stress and load type	Approximate Strength (MPa)			
	Annealed glass		Fully toughened glass	
	Far-field	Edge	Far-field	Edge
Short term loads	18.5	8.5	93	57
Medium term loads	10.5	5	85	52.5
Long term loads (self-weight)	7	3	81	50

Table 9: Design strength of glass based on different type of loads | Source: SAMS datasheets

The profile developed must allow interlocking of the insert, while tackling forces as per the loading condition. As per the chosen load case of two adjacent facade panels in shear, the profiles developed must withstand 40kN of force acting vertically along the edge, within the glass profiles.

#### Profile development

The design uses a module of 5 layered laminated glass panel for better freedom in the explorations. The glass panel primarily consists of two parts:

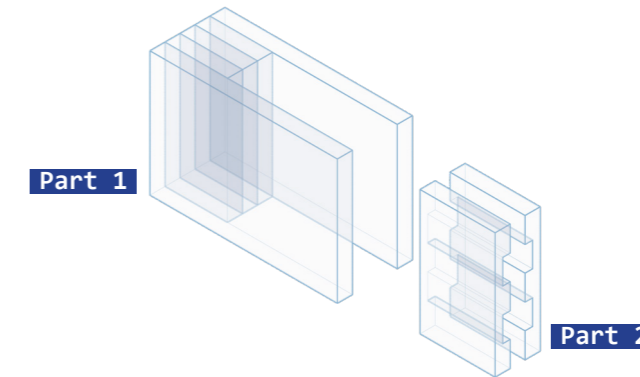


Figure 37: Components of the glass module | Source: Author

#### Part 1:

5 layered glass panel, with the 1st and the 5th panel longer than the central three panels, creating a 'U' profile along the edge of the panel.

#### Part 2:

Heat pressed glass elements with alternating thickness to create a rebated edge pattern. Part 2 is shorter than the length of the channel in Part 1, and is laminated within the channel, aligning with the outer edge.

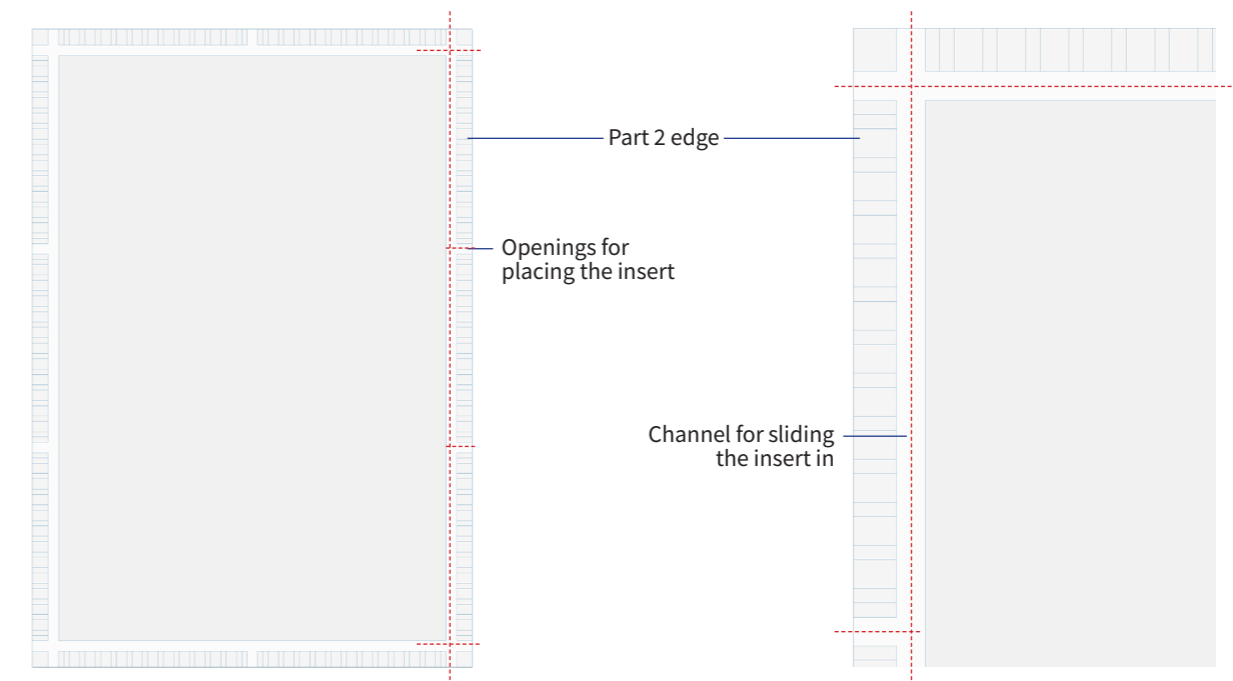


Figure 38: Openings in the rebated edge of uni.conn | Source: Author

## 4.2 Insert

The insert connects the glass panel with another panel or a frame. It interlocks with the glass module and must have a sequence of actions to assemble and disassemble. It is important for the insert to have the required structural performance and ease of access to allow for perfect demountability.

Workability, structural performance, demountability and durability are the major deciding factors in the design of an insert. The interlocking mechanism chosen for the insert design must have a strict sequence of assembly and disassembly. Preliminary explorations focus on the interaction between the link and the pin aspects of the connection.

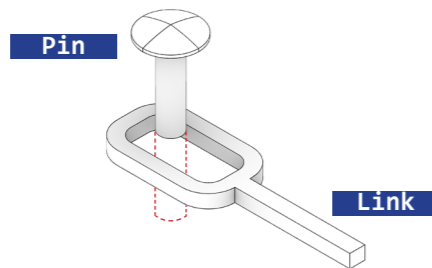


Figure 40: Pin-and-link principle | Source: Author

### Assembly

This thesis explores the idea of an interlocking system for the insert using the Link-and-Pin system.

The Link-and-Pin system operates on a straightforward two-part logic consisting of a female receptacle (the slot) and a male locking element (the pin or the key). When the two elements are brought into alignment, their matching geometries create a continuous, overlapping void. Dropping the rigid, independent pin through this void creates a mechanical obstruction that immediately restricts the movement along the primary axis of separation. Because the resistance is purely geometric and is held in position due to gravity, the connection does not require a continuous internal clamping force to function. This system and its subsequent evolutions are still being used as a coupling mechanism for trains.

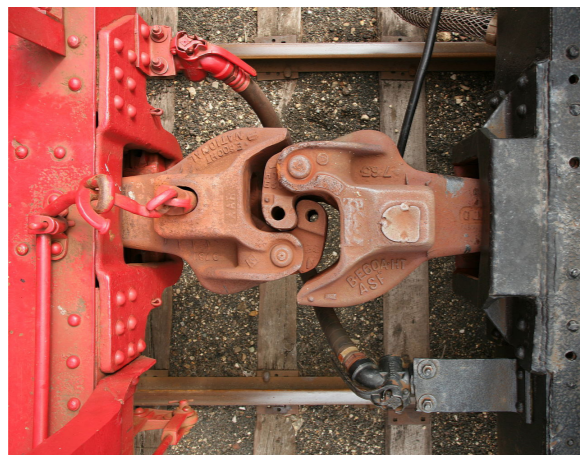


Figure 39: Janney train couplers | Source: Schwen, D. (2008), wikipedia

### Disassembly

In a link-and-pin system, disassembly involves vertically pulling the pin up to remove the link. Since the pin is inserted within the glass, it may not be possible to reach the pin, and could be only disassembled passively. As seen in the work of Dasopoulou (2020), usage of magnets to passively move profiles within glass seems to be one of the promising, durable solutions. Similarly, this thesis explores the usage of magnetic field to move the pin for unlocking the insert.

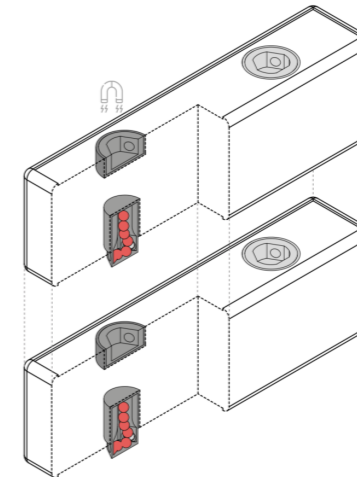


Figure 41: Disassembly of a conceptual cast glass structural system using magnets | Source: Dasopoulou (2020)

Geometries focusing on this mechanism are developed into multiple different versions for the insert. In most load cases, the link of the insert transfers loads directly to the glass module, while the primary role of the pin is to hold the link in position. The vertical movement of the pin must be constrained within strict boundaries. Hence, a sleeve is introduced around the pin. In all the prototypes, magnetic properties of the elements are replicated by using a 10x10mm magnet, either embedded within or attached to the pin.

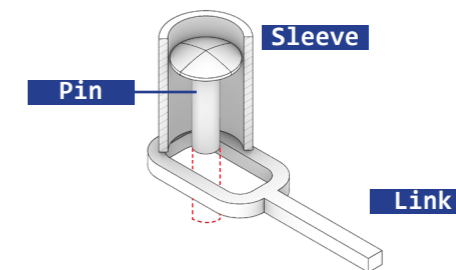


Figure 42: Introduction of sleeve | Source: Author

### Materiality

#### Link | Pin | Sleeve

In the combination of the three elements, along with their structural performance, their magnetic properties are quite essential. The pin must be magnetic, while the sleeve it is contained within must be non-magnetic for the pin to freely move.

Based on the widely used materials in the industry, Steel, Aluminum and Titanium will be explored for every iteration based on the loads experienced. The specific grade of the material will be explored help of Granta Edupack.

### 4.3 Gasket

The primary purpose of the gasket is to efficiently transfer the loads from the insert to the glass panels and vice versa. Due to the heavy loads experienced, the gasket must be rigid with low compression set. A clever design of the gasket can be used as an advantage to assist in the sequence of assembly or disassembly.

The design of gasket follows the design of the insert and the glass module. It must allow for the interlocking of insert, and efficiently distribute the forces to the glass around. Workability, structural performance and durability act as primary factors in designing the gasket. Mechanical properties such as compression set and frictional coefficient play a significant role due to the constant compressive forces acting on the gasket.

Compression set defines the permanent deformation in an *elastic material* once the compression forces are released. It is necessary for the gasket to be able maintain the shape to efficiently transfer the forces after repeated loading cycles.

To verify the workability, the developed prototypes are 3D printed at TU Delft's LAMA Lab using the Bambu TPU 95A-HF filament to replicate the materiality. Options with different rigidity were created by varying the infill percentage.

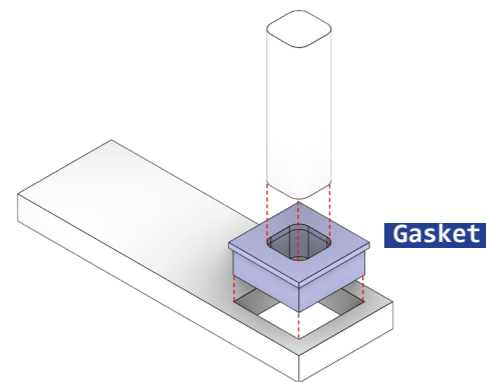


Figure 43: Introduction of gasket | Source: Author

#### Materiality

Initial explorations for the gasket in terms of materiality included the commonly used Silicone options, PMMA, Delrin and TPU. Using manufacturability, compression set, frictional coefficient and strength of the material, the selected options are filtered. Later, the specific grade of the material will be selected using Granta Edupack.

Good hardness and a high frictional coefficient are equally important properties for the gasket. However, in the industry, improving one of the property requires a compromise from the other. Surface treatment methods can be used to slightly improve the frictional coefficient values of materials. However, it is important to note that this thesis follows a material agnostic approach by primarily focusing on developing a gasket that allows for the workability and assembly-disassembly of the insert. Material and the specific grade

will be chosen based on the requirement of the specific load case in terms of compression strength, hardness (Shore A/D value), compression set and frictional coefficient values.

The following table consists of the range of properties the different grades of the specified materials exhibit:

	Silicone	POM (Delrin)	PMMA	TPU
<b>Density</b>	1400-3200 kgm <sup>-3</sup>	1290-1740 kgm <sup>-3</sup>	1110-1220 kgm <sup>-3</sup>	1180-1210 kgm <sup>-3</sup>
<b>Young's modulus</b>	0.002 - 0.05 GPa	1.31 - 12 GPa	1.6 - 3.6 GPa	0.01 - 0.03 GPa
<b>Poisson's ratio</b>	0.22 - 0.24	0.33 - 0.4	0.36 - 0.41	0.48 - 0.495
<b>Tensile yield strength</b>	1.69 - 12.1 MPa	35 - 160 MPa	38 - 72.4 MPa	35 - 49 MPa
<b>Compressive strength</b>	2.03 - 16.4 MPa	48 - 227 MPa	48 - 131 MPa	42 - 59.3 MPa
<b>Compression set (at 23 °C)</b>	5% - 10%	-	-	19.8% - 25.6%
<b>Hardness</b>	3 - 75 Shore A	58 - 90 Rockwell M*	35 - 100 Rockwell M*	65 - 92 Shore A
<b>Common manufacturing methods</b>	Injection moulding, extrusion	Injection moulding, extrusion	Injection moulding, extrusion, casting	Injection moulding, extrusion,

Table 11: Preliminary comparison of different material options for the gasket | Source: Granta Edupack

\*Rockwell scale is used for rigid, hard materials like metals and hard plastics, whereas Shore is used for soft, flexible materials like rubber and elastomers.

### 4.4 Methodology

The design and development of the uni.conn is an iterative process. At every stage, the module designed is weighed against the set criteria, with primary indicators being structural performance and workability. The learnings from this exercise become the starting point for subsequent explorations.

All three components of Uni.conn module, the glass module, gasket and the insert, influence each other and are explored simultaneously. At every stage, the designs are prototyped and physically printed at TU Delft's LAMA lab to test the sequences of assembly and disassembly. The same are also digitally tested on ANSYS Workbench for their structural performances.

### 4.5 Design Iterations

The Uni.conn has 7 significant iterations, indicating different stages of the design development process. At every level, each component is examined both at an individual and modular level. The learnings and successful versions are carried forward to the subsequent design iterations. Within a single iteration of uni.conn, all three components are developed simultaneously, resulting in multiple versions of the same components. The final version meets the initially set criteria and is further developed to cater to different loading scenarios.

The following table indicates the design iterations with the corresponding versions of glass panel, insert and the gasket.

Iterations	Glass Panel version	Insert version	Gasket version	Significant updates
Iteration 1	Version 1	-	G1 G2	Initial development of an interlocking system
Iteration 2	Version 1	I1 I2	G3	<b>Insert:</b> Adapted the slot-and-pin principle.
Iteration 3	Version 2	I3	G4	<b>Insert:</b> Combined the individual slots into a singular module with individual control <b>Glass:</b> Improved the structural performance with version 2.
Iteration 4	Version 2	I4	G4 G4.1	<b>Insert:</b> Redefined the 'slot' by reducing the number of moving elements.
Iteration 5	Version 2	I5	G5	<b>Insert:</b> 'Pin' is redesigned for better structural performance.
Iteration 6	Version 2	I6 I6.1	G5	<b>Insert:</b> Improved the workability of 'pin' by modifying the geometry.
Iteration 7	Version 3	I7 V I7 H	G6 V G6 H	<b>Glass:</b> Adopted 10mm thick layers for the laminated glass panel for better structural performance. <b>Insert:</b> Additional space in the channel was utilized to develop a better slot.

Table 12: Quick summary of Design Iterations of the uni.conn

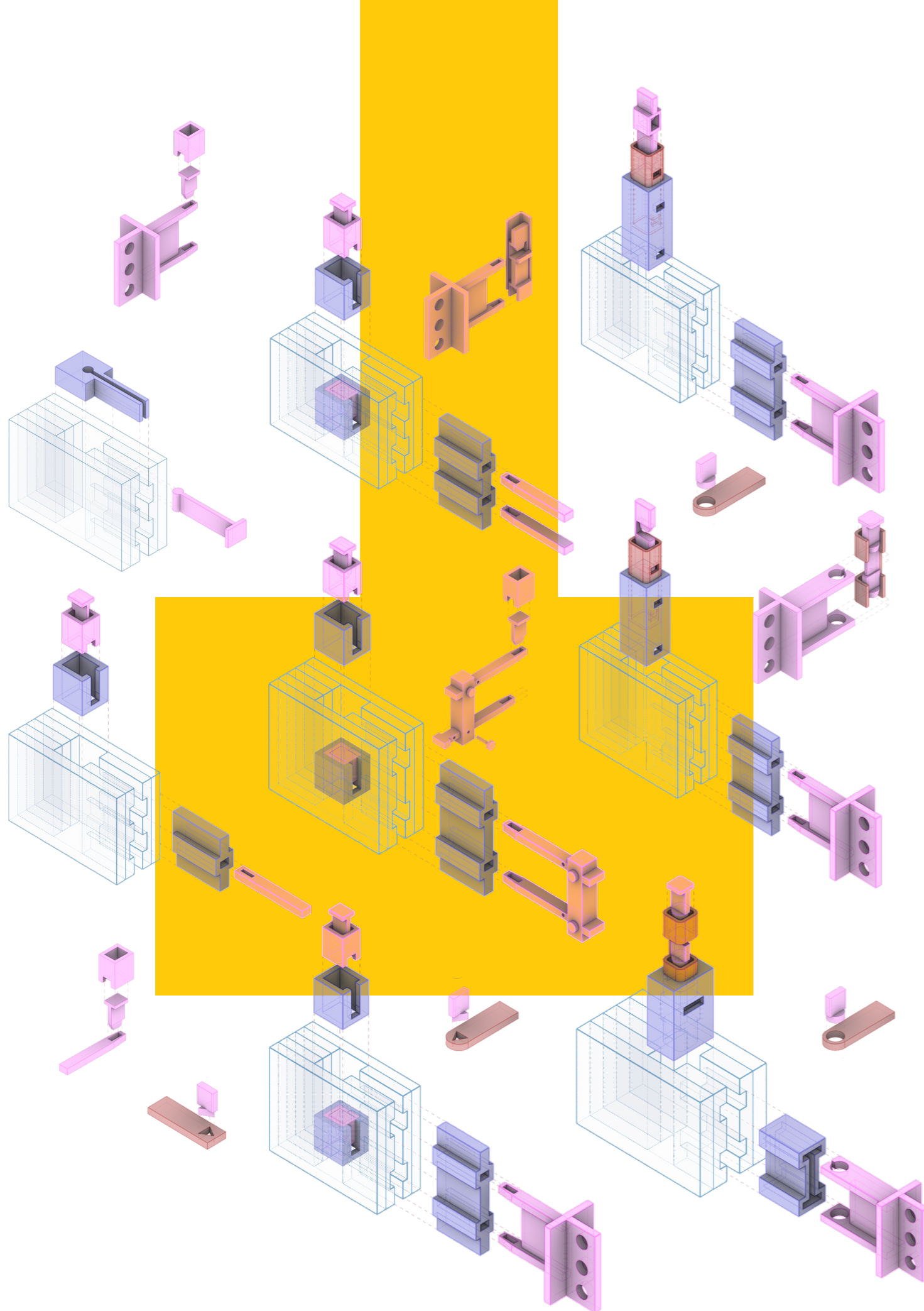


Figure 44: Illustration of all major design iterations | Source: Author

Design Iteration 1

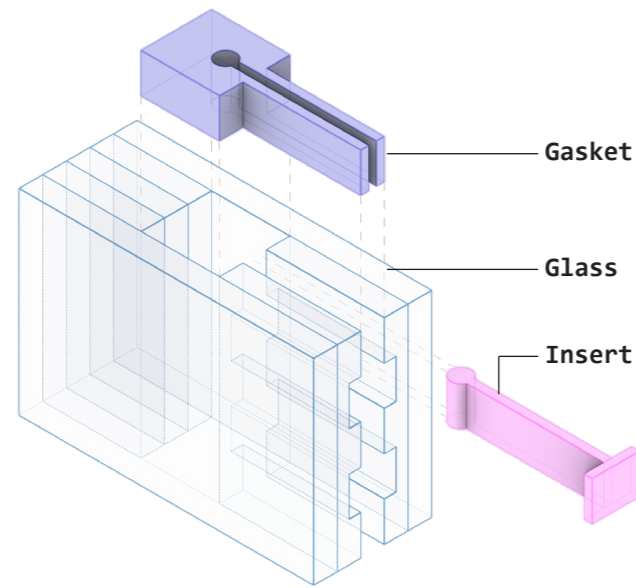


Figure 45: Design iteration 1 | Source: Author

The design exploration begins with the idea of developing a system that is held in position by pure geometrical configurations. The insert is conceptualized to have a linear profile, with a larger volume at the end to interlock within the glass channel. To support this, a gasket profile is developed around the insert, that is positioned within the rebated edge of the glass panel.

Since gasket plays a major role in holding the insert in-place throughout the application, it is necessary that it maintains the adequate rigidity and shape. However, the gasket must be able to deform slightly to push the insert through it. This requirement from the material demands a compromise on the rigidity aspect. Simultaneously, different profiles of gasket were explored to improve the load transfer from the insert to the glass edge, that assist the further explorations.

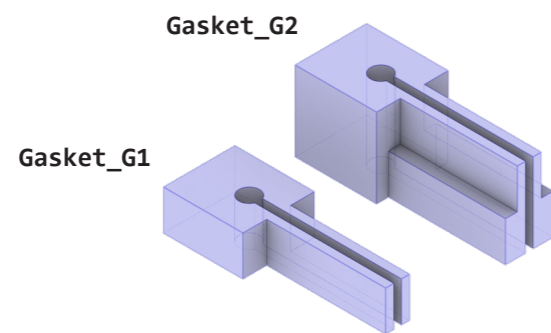


Figure 46: Gasket exploration- Design iteration 1 | Source: Author

The primary focus at this stage was to initiate the design process based on workability. However, no structural/ materiality tests were performed at this stage.

Design Iteration 2

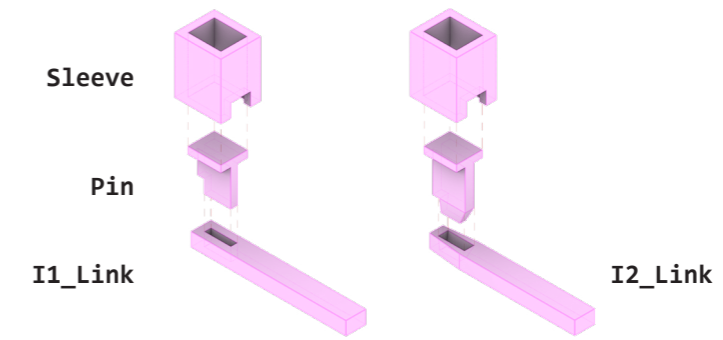


Figure 47: Insert exploration- Design iteration 2 | Source: Author

The second iteration realizes the drawbacks of relying purely on geometries and materiality of gasket for interlocking and begins with an exploration of the 'link-and-pin' principle. Initial tests and explorations involved the workability of the principle at a conceptual level. Prototypes were 3D printed and tested for ease-of-use at 1:1 scale. These prints revealed the difficulty in disassembly when the pin and the link slots were geometrically matched. The subsequent version, I2, was revised with a wedge-shaped slot, allowing for easy mounting and dismounting.

The gasket was developed around the sleeve and the link, and was split into two parts that act individually. The link, encased inside the gasket, is responsible for transferring load to the glass around. Given the sizing, it was evident that multiple pins must be used for transferring the load of 40kN as per the load case. Hence, further workability explorations involved two pins and their respective configurations.

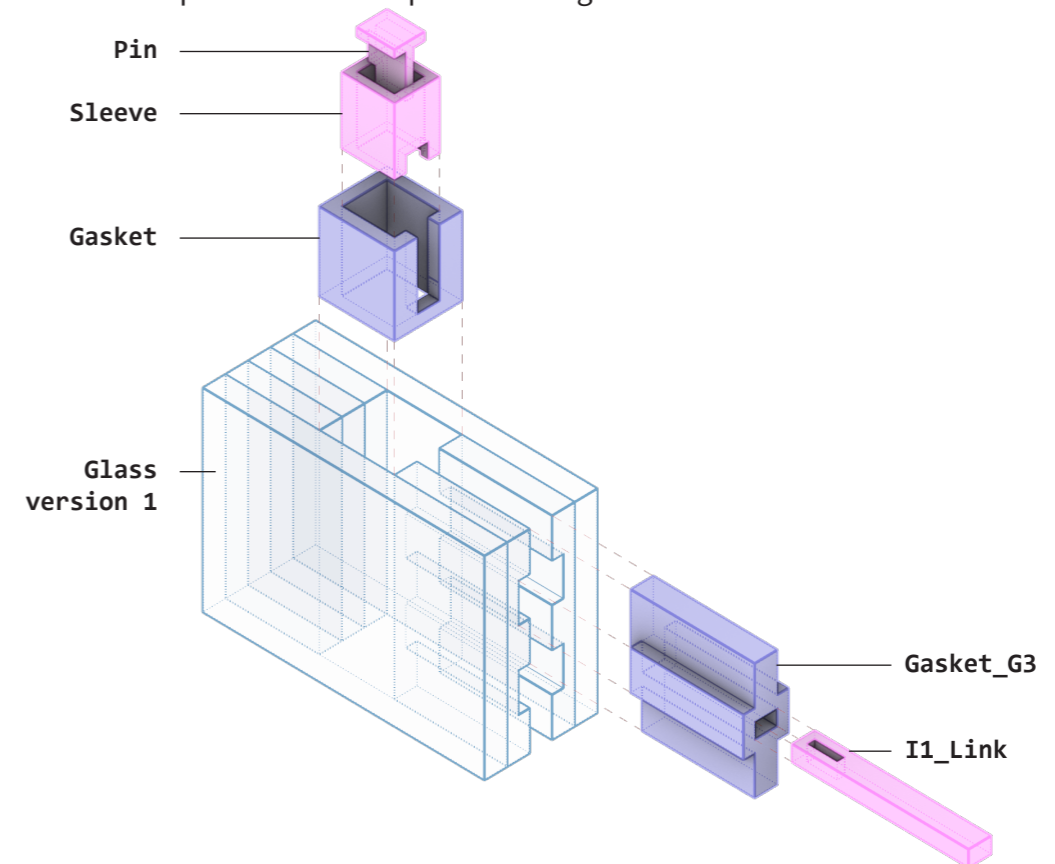


Figure 48: Design iteration 2 | Source: Author

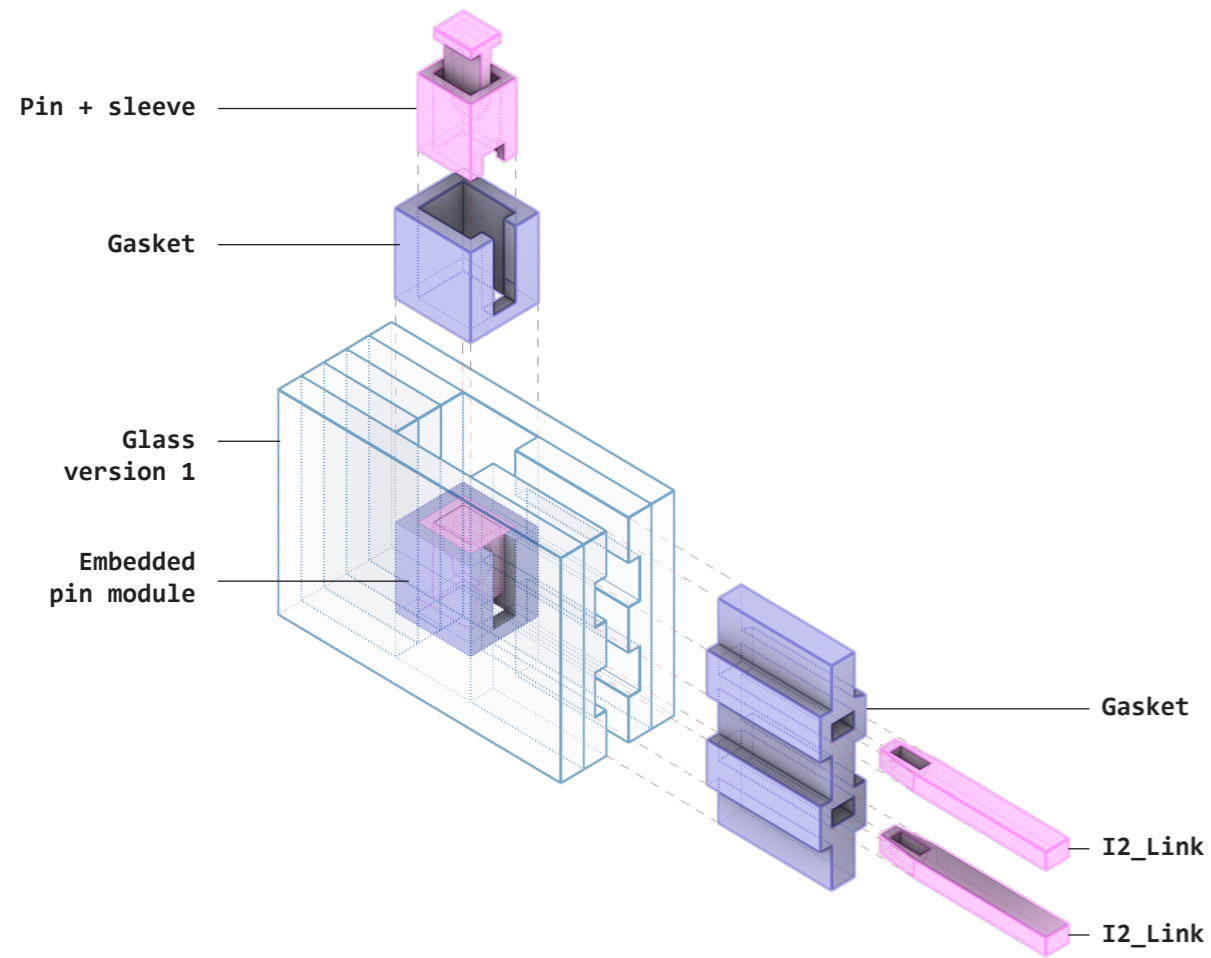


Figure 49: Further developed version of Design iteration 2 | Source: Author

The gasket was further developed to accommodate two I2 links. Each link has a corresponding pin, that act individually as well. The wedge shaped tip of the link allows for easier insertion through the gasket. Since both the links are required for an insert, further iterations explore methods of combining them.

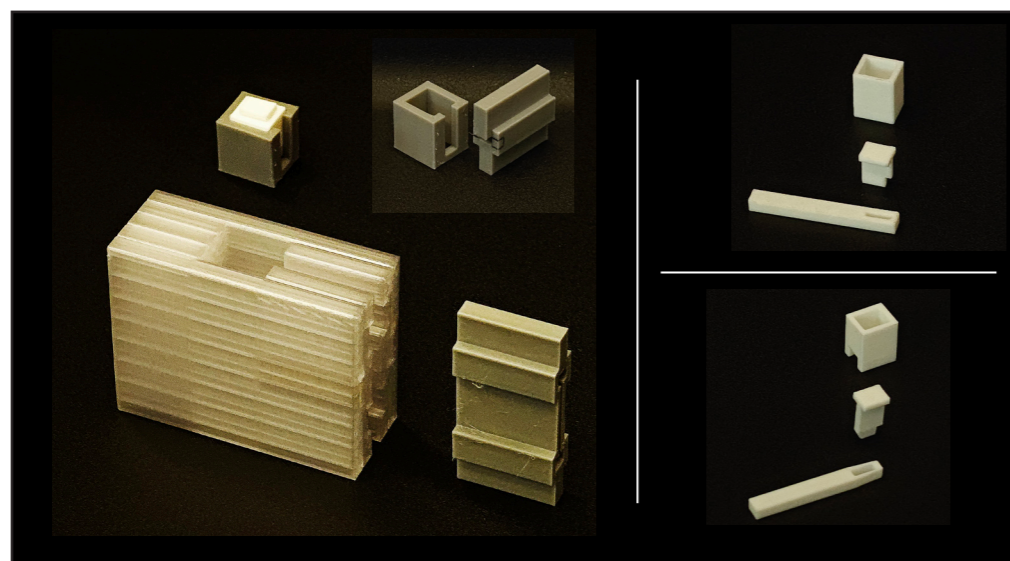


Figure 50: Physical prototypes of Design iteration 2 | Source: Author

Design Iteration 3

The developed glass module was subjected preliminary Finite Element Analysis using ANSYS Workbench. Initial loading of 40kN was applied vertically downwards on the horizontal surface of rebated edge. Results indicate a peak stress of 68MPa along the edge, which was expected due to the profile along the edge.

To improve the structural performance, the height of the 6mm thick glass was doubled, resulting in version 2 of the glass module. Upon performing similar structural analysis, the maximum peak stresses dropped to 53MPa. However, it should be noted that these initial Finite Element Analysis (FEA) results establish only a baseline understanding of the structural behaviour. An accurate estimation of structural performance will be possible once the specific geometry and material properties of both the insert and gasket are fully resolved. Hence, version 2 of glass module is considered for further design explorations.

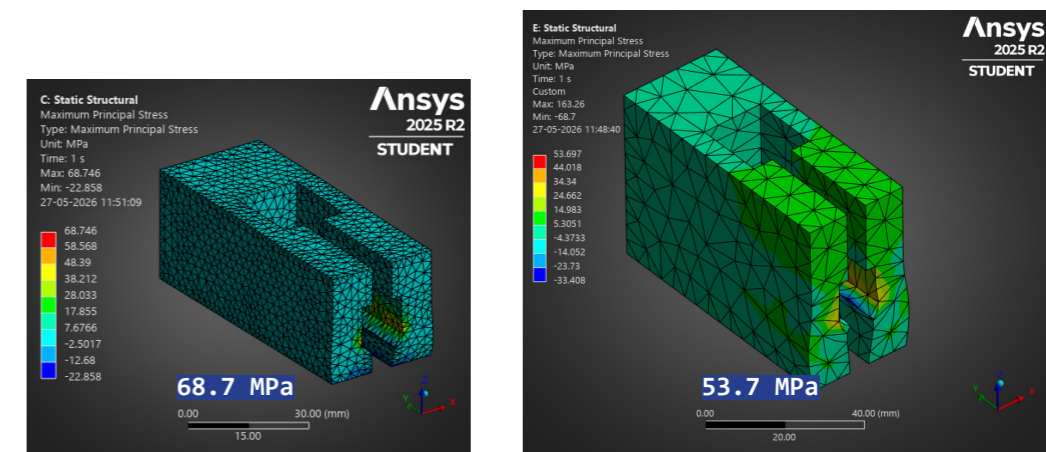


Figure 51: FEA of glass version 1 and version 2 (ANSYS Workbench) | Source: Author

Both gasket (G4) and the insert (I3) are developed for the version 2 of glass module. The I3 version of the insert is a system with two links combined into a singular module. Each link has a corresponding pin within the sleeve, embedded within the glass channel. Due to this configuration, both links require individual control for locking and unlocking.

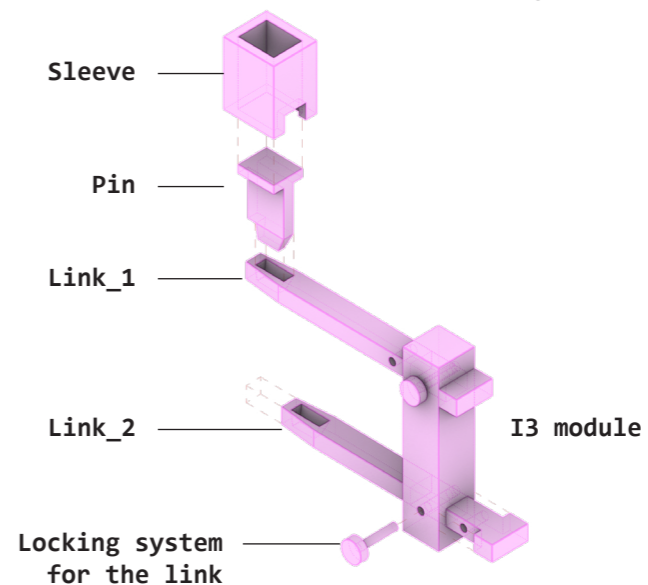


Figure 52: Insert exploration- Design iteration 3 | Source: Author

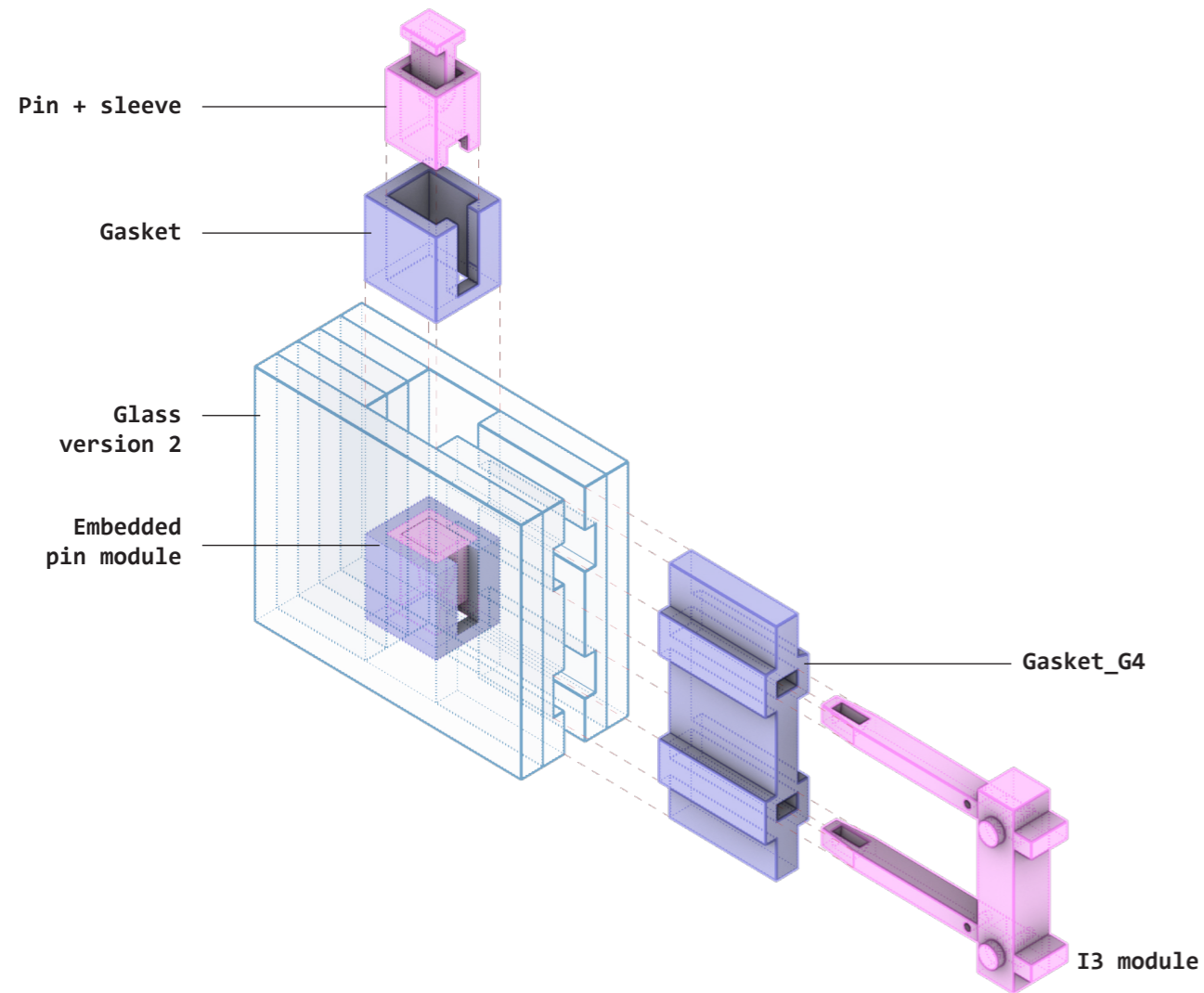


Figure 53: Design iteration 3 | Source: Author

The I3 version of the insert provided individual control for each of the links. However, given the size of the elements involved, this may pose a workability risk at site during assembly and disassembly processes. Due to the complex geometries involved, the scope of developing the extension to connect with external frame or another system is restricted.

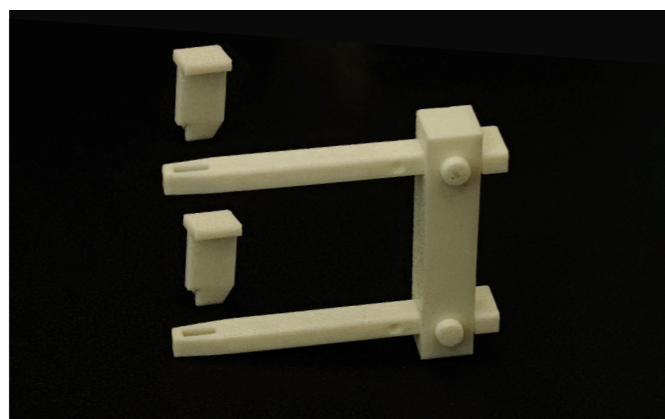


Figure 54: Physical prototype of insert I3- Design iteration 3 | Source: Author

Design Iteration 4

The I4 insert developed for the design iteration eliminates the individual control of the links to improve the on-site workability. A bracket has been accommodated within the insert to connect with external elements. This version still continues with the two pin system from the previous iterations. This makes it challenging to operate, considering that the link is a singular element.

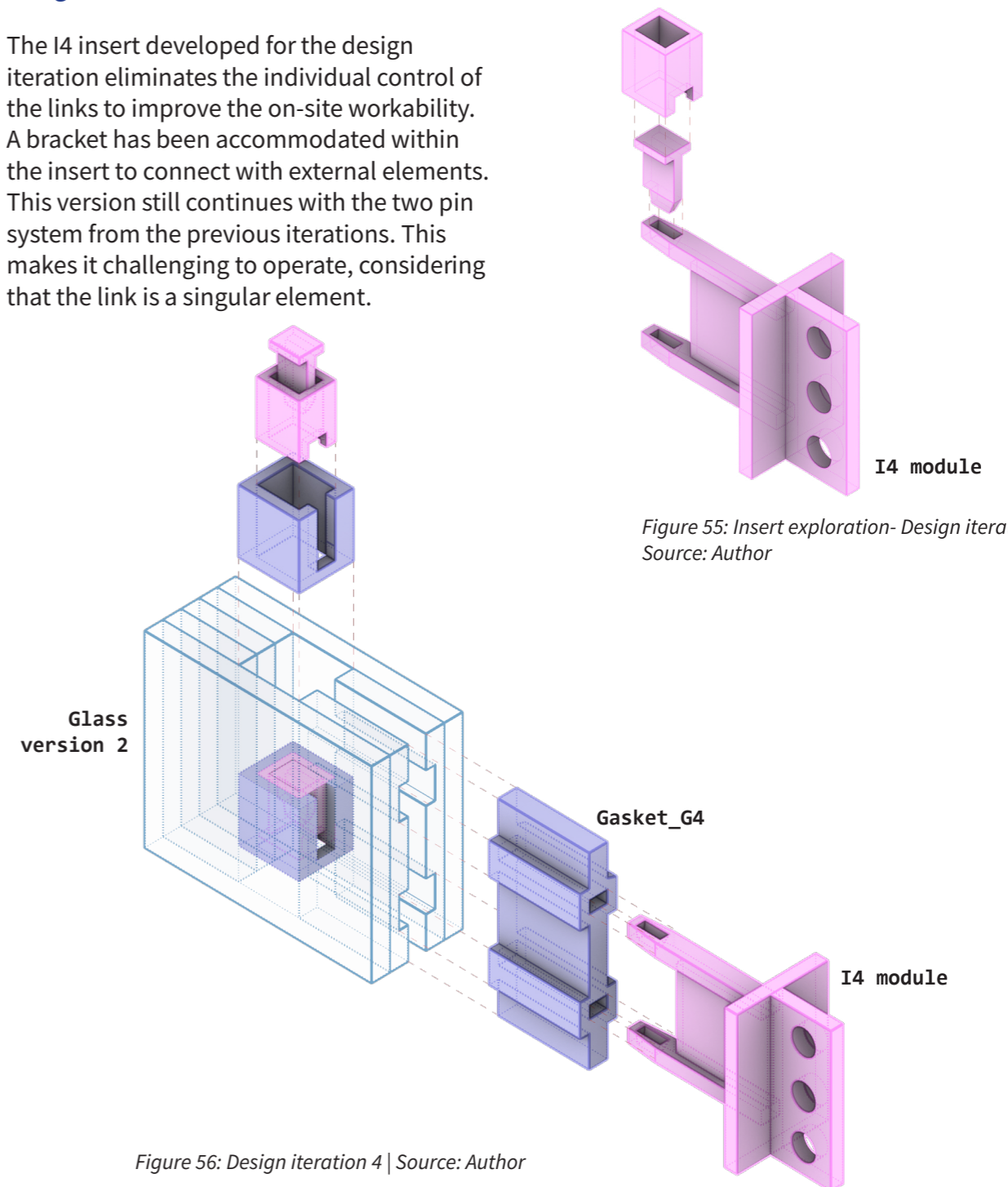


Figure 55: Insert exploration- Design iteration 4 | Source: Author

Figure 56: Design iteration 4 | Source: Author

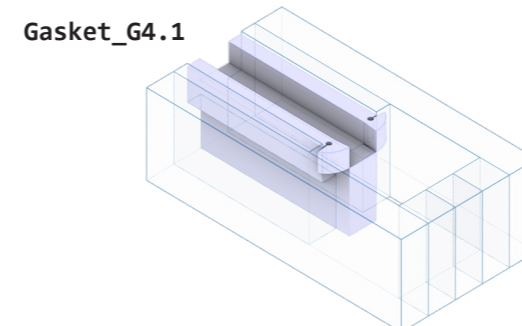


Figure 57: Gasket G4.1 | Source: Author

Inter-lockable profiles for the gasket were explored to restrict any unwanted movement within the system. Small, non-structural profiles were developed for the G4.1 version to ensure easy insertion of the gasket, with additional steps required for removal. However, once 3D printed, due to the tight space constraints, these smaller profiles made it significantly more difficult to remove. Hence, these profiles were omitted for subsequent versions, but scope to improve the workability remains.

**Design Iteration 5**

The iteration 5 focuses on combining the two individual pins into a linear element that moves vertically up and down to interlock with the link. This version, I5, has two geometric wedges that slot into the links, when placed in position. During the unlocked position, it allows for the link to be inserted exactly into the position, without any misalignment. However, the 3D printed profiles showed a difficulty in consistently aligning them due to the tight tolerances in the design. The I5 consists of an elongated sleeve that contains the pin to freely move along the vertical axis.

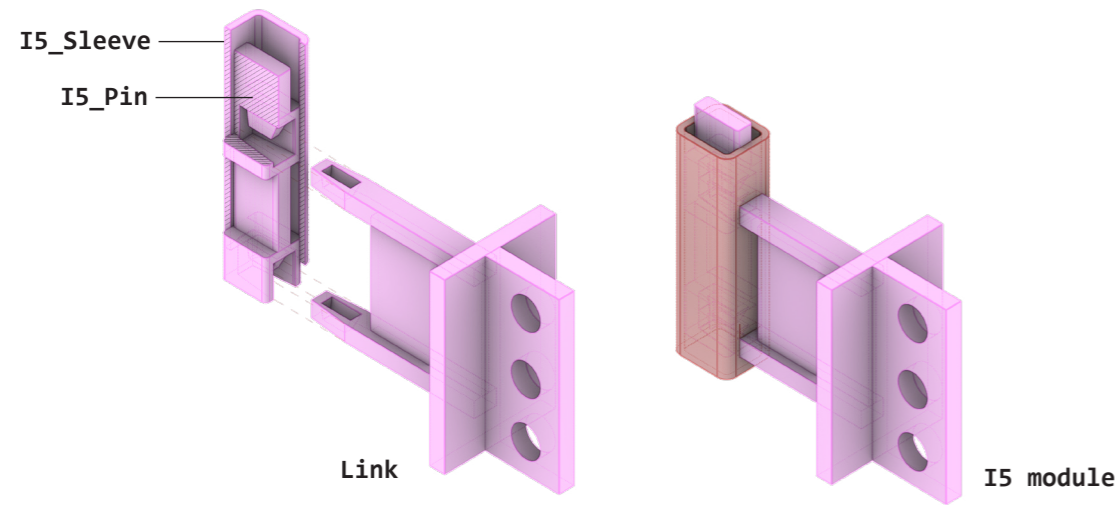


Figure 58: Insert exploration- Design iteration 5 | Source: Author

Initial structural analysis indicated major stress concentrations at the sharp edges of the pin, highlighting a major point of concern in the geometry. Moreover, it is important for the pin to maintain its geometry after multiple uses to ensure perfect workability.

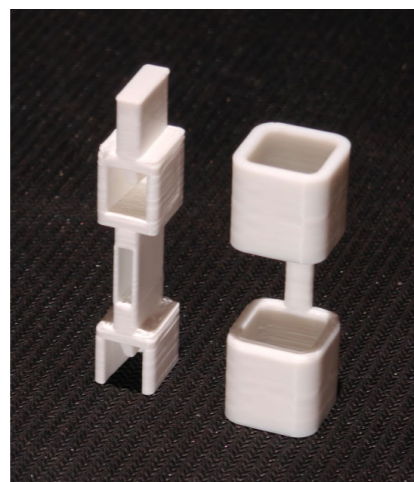


Figure 59: Insert I5 physical prototype | Source: Author

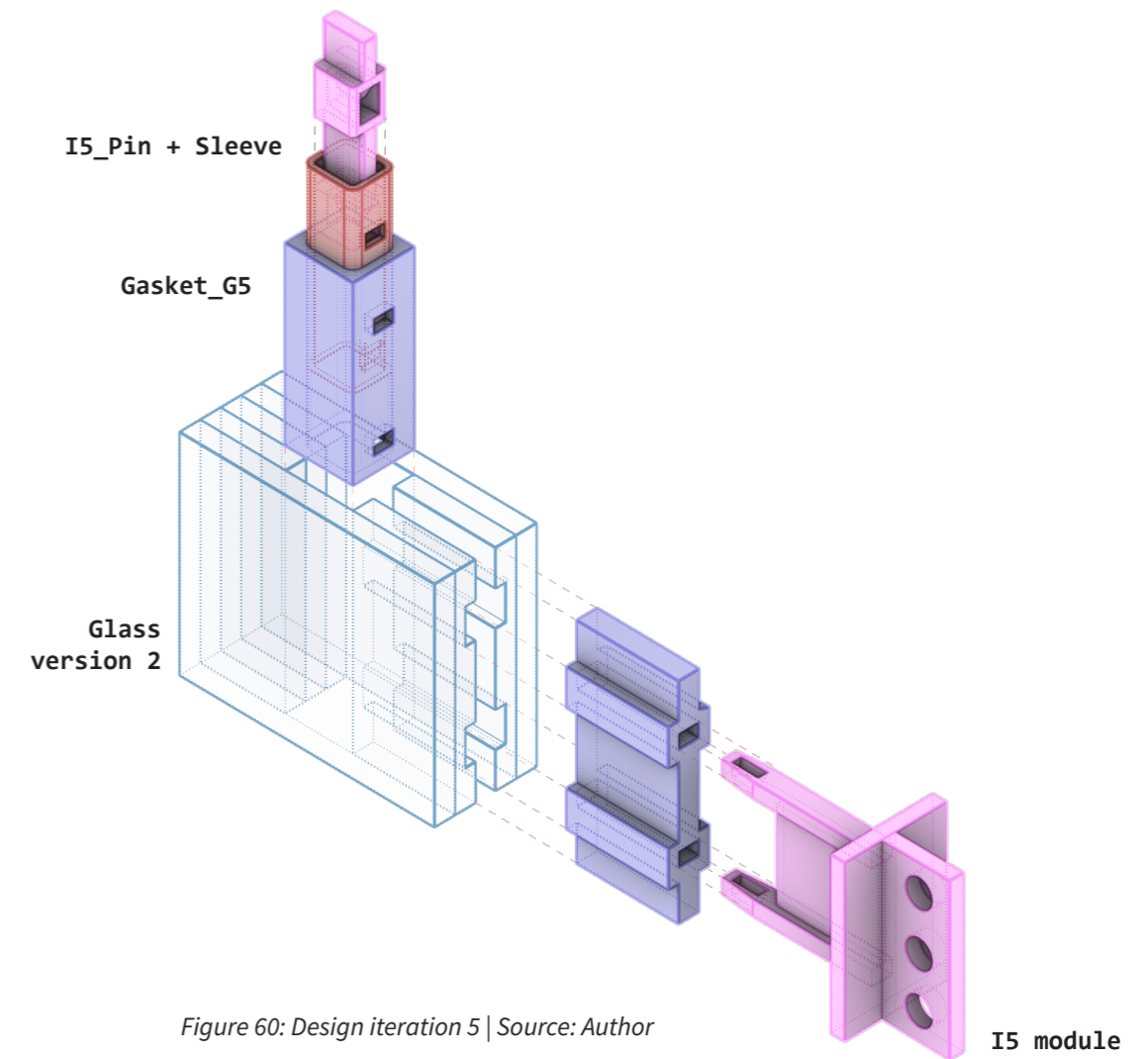


Figure 60: Design iteration 5 | Source: Author

**Design Iteration 6**

The insert version I6 revises the profile detail of the pin. The geometry has been simplified to allow for easy locking and interlocking of the link. This significantly improved the workability, ensuring that the components are easy to lock and unlock. The improvements in workability are further proven by the physical prototype, being locked and unlocked with the help of external magnets. The 3D printed prototype uses a 10x10mm magnet embedded within the profile to replicate the magnetic properties of a steel element.

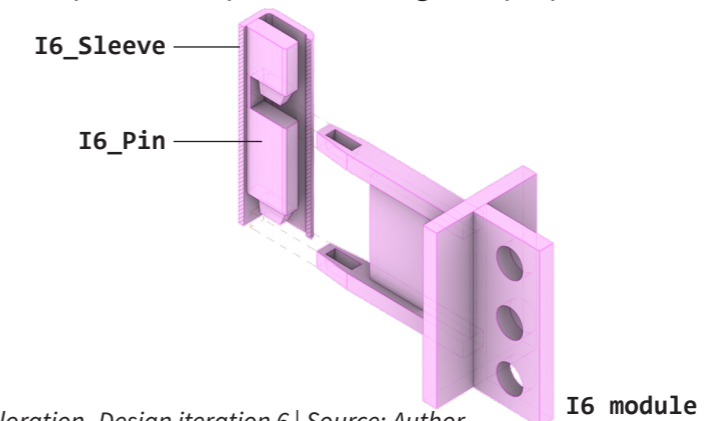


Figure 61: Insert exploration- Design iteration 6 | Source: Author

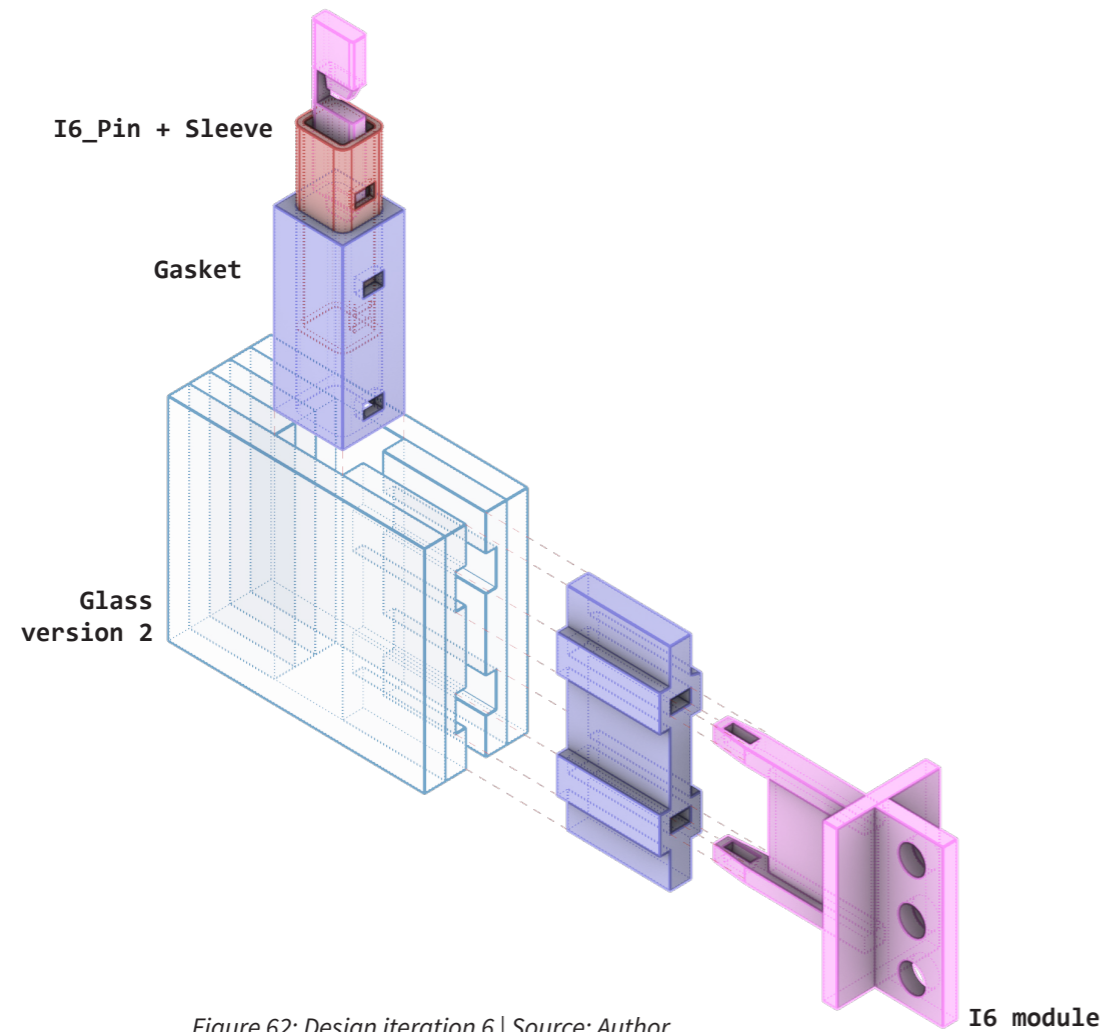


Figure 62: Design iteration 6 | Source: Author

This modification to the insert did not result in any significant improvements in terms structural performance. The 18x20mm opening of the channel within glass is currently housing the gasket, sleeve and the pin. Due to the space limitations, it is quite difficult to arrive at a design that meets the structural benchmarks. One potential solution would be the increase the number of connections beyond 3 (along the height of a facade panel at Apple, fifth avenue). But this thesis further explores the same number of connections with 10mm thick glass panels instead of 6mm.

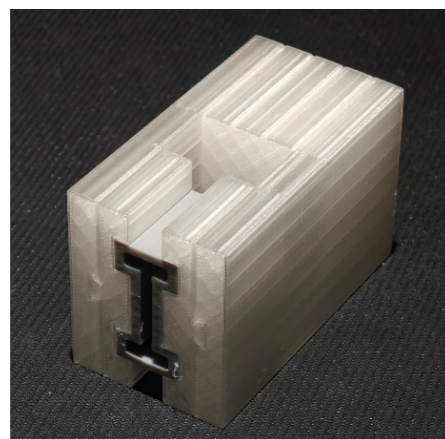


Figure 63: Glass module version 3 (Design iteration 7) | Source: Author

### Design Iteration 7

Once the glass layers are scaled to 10mm thick panels, the channel size increases to 30x20mm. This provides scope to improve both workability and the structural performance of all components. Larger size of the components helps in easy locking and unlocking, and better load transfer.

Additional space for components provides scope for testing different profiles and shapes that could not be tested for a tighter channel due to strict workability constraints. Hence, the following five different profiles for the link and pin were analyzed for their structural performance to reach at a version with least peak stresses (Refer to Appendix 1).

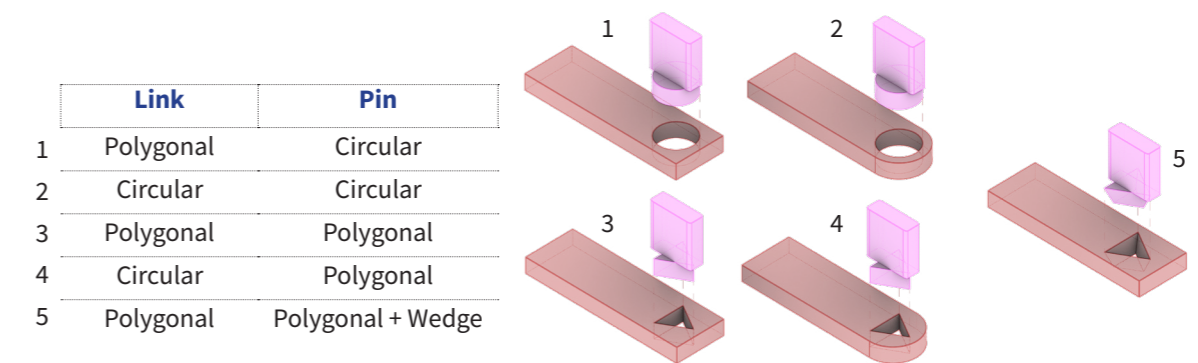


Figure 64: Various profiles of pin-and-link | Source: Author

Based on the structural analysis, a rectangular (polygonal) link with circular pin turned out to be the version with least peak stress. However, based on the previous explorations, it has been proved that wedge profiled (conical) pins perform way better in terms of ease-of-disassembly. Hence, a circular, conical pin with rectangular link has been adopted for I7.

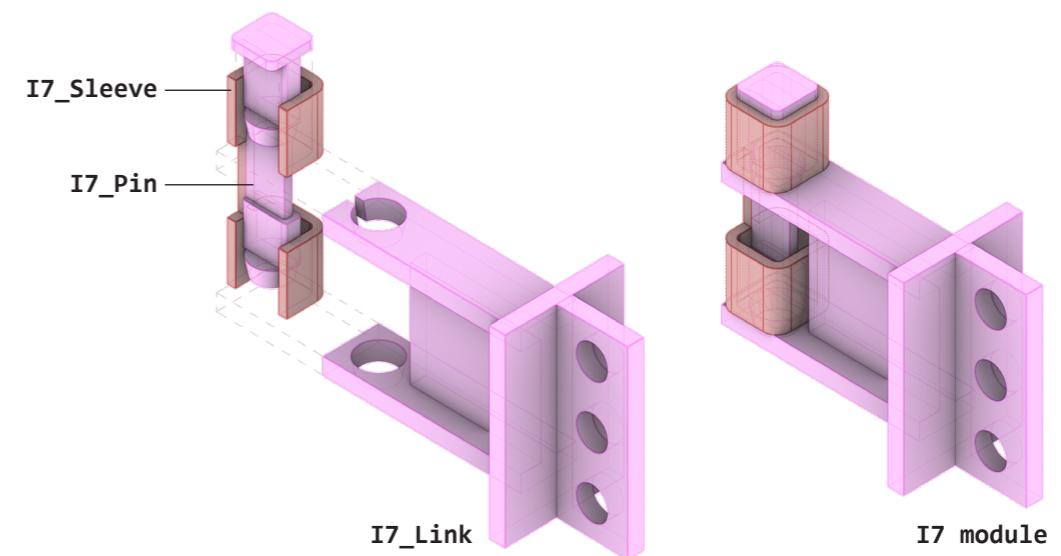


Figure 65: Insert exploration- Design iteration 7 | Source: Author

To cater to the newly developed link and pin system, the sleeve has been optimized as well. This version of sleeve provides ample room for placing the link in position. The version 3 of glass, with 10mm thick layers, offer better structural performance. The increased size of gaskets assist better in load transfer from the insert to the glass panels. The physical prototype confirmed the improved workability of the module.

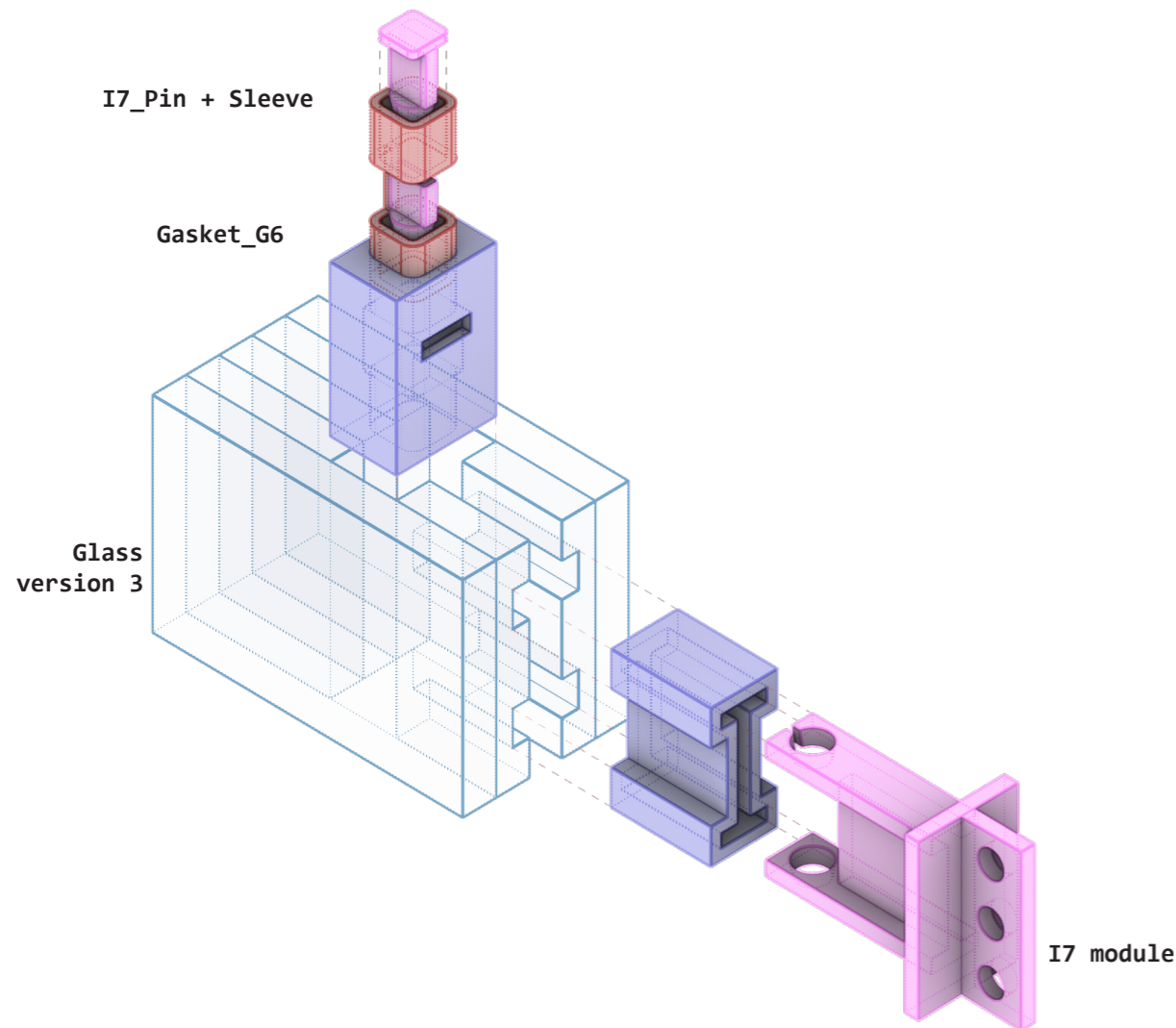


Figure 66: Design iteration 7 | Source: Author

The accurate dimensions of the components can be found in the section 4.9. It is important to note that the developed connection system is designed to work only in vertical alignments, i.e., when the pin is held in position due to gravity. It is applicable for any vertical load cases, where the pin can move vertical upwards and downwards for assembly and disassembly. However, for applications where the pin cannot be held in vertical position due to gravity (roof panels), another version of the connection has been developed, where the pin moves horizontally for assembly and disassembly. This distinction is shown in the nomenclature of the modules, where the version with vertically moving pin is I7 V; and the version with horizontally moving pin is I7 H. I7 H and its applications are further detailed in Chapter 5.

## 4.6 Materiality

While workability majorly depends on the geometric profiles, structural performance is heavily dependent on the chosen materials. The material and the specific grade is chosen using Granta Edupack.

### Insert

The insert is made of three components: Link, pin and the sleeve. In majority of the applications, the link transfers loads to the glass around as long as pin holds it in position. From the workability standpoint, it is important that the pin is magnetic and the sleeve is a non-magnetic material. While the link experiences most of the structural loads, the pin (and therefore, the sleeve) also experiences minute loads in case of any load eccentricities or thermal expansions.

<b>Link</b>	Steel S355 (AISI 1040, normalized)	Magnetic.
<b>Pin</b>	Steel S355 (AISI 1040, normalized)	One of the commonly used grades of steel in construction industry;
<b>Sleeve</b>	Aluminum 6063- T8 series	Non-magnetic; Commonly used in architectural applications; Easy to manufacture - hot/ cold forming, weld-ability

Table 13: Materiality options for link, pin and sleeve of the insert | Source: Granta Edupack

Using Granta Edupack, the following values of materials' mechanical properties are considered for further Finite Element Analysis:

Steel S355 (AISI 1040, normalized)		Aluminum 6063- T8 series	
Density	7850 kgm <sup>-3</sup>	Density	2730 kgm <sup>-3</sup>
Young's modulus	216 GPa	Young's modulus	71 GPa
Poisson's ratio	0.295	Poisson's ratio	0.33
Tensile Yield Strength	335 MPa	Tensile Yield Strength	280 MPa
Tensile Ultimate Strength	530 MPa	Tensile Ultimate Strength	305 MPa

Table 14: Mechanical properties of selected grades of Steel and Aluminum | Source: Granta Edupack

### Gasket

Out of the different materials considered for the gasket, Polyester urethane TPU of grades Shore A70 and Shore A85 are considered for their elasticity and the compressive strength. The following mechanical property values from Granta Edupack are used for further Finite Element Analysis.

TPU Ester, Shore A85		TPU Ester, Shore A70	
Density	1210 kgm <sup>-3</sup>	Density	1190 kgm <sup>-3</sup>
Young's modulus	0.0398 GPa	Young's modulus	0.0141 GPa
Poisson's ratio	0.495	Poisson's ratio	0.495
Tensile Yield Strength	49.4 MPa	Tensile Yield Strength	40.1 MPa
Compressive Yield Strength	59.3 MPa	Compressive Yield Strength	48.1 MPa

Table 15: Mechanical properties of selected grades of TPU | Source: Granta Edupack

### 4.7 Structural Performance

A complete module, with accurate materiality, was set up in ANSYS Workbench for structural analysis as per the Load Case 1.

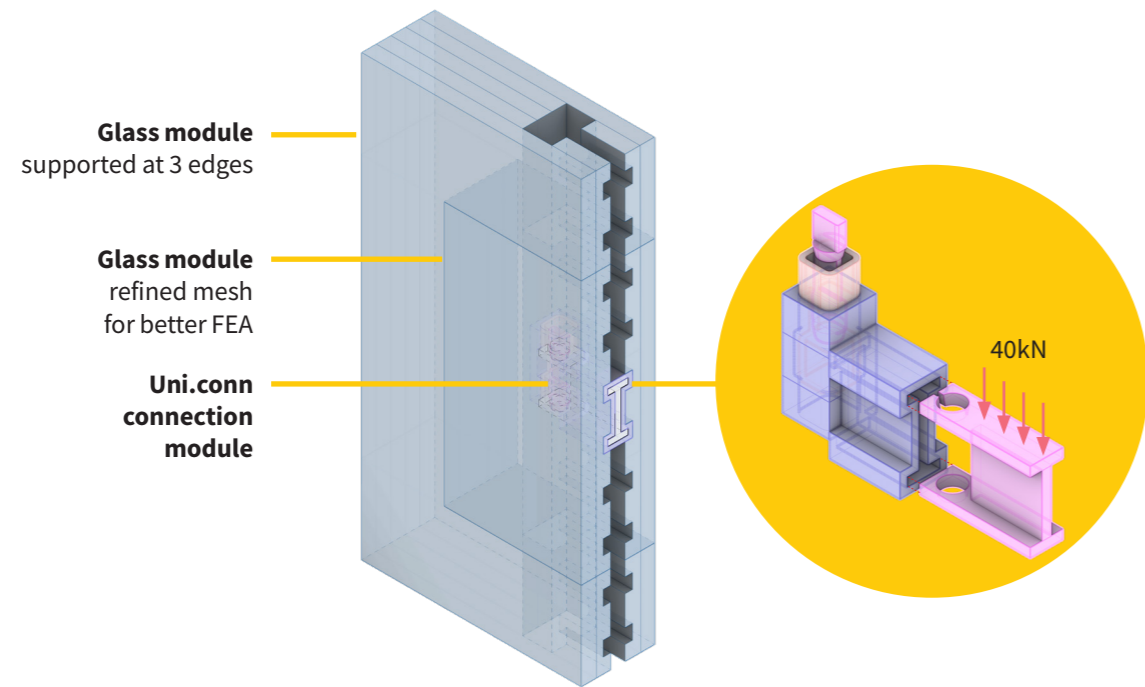
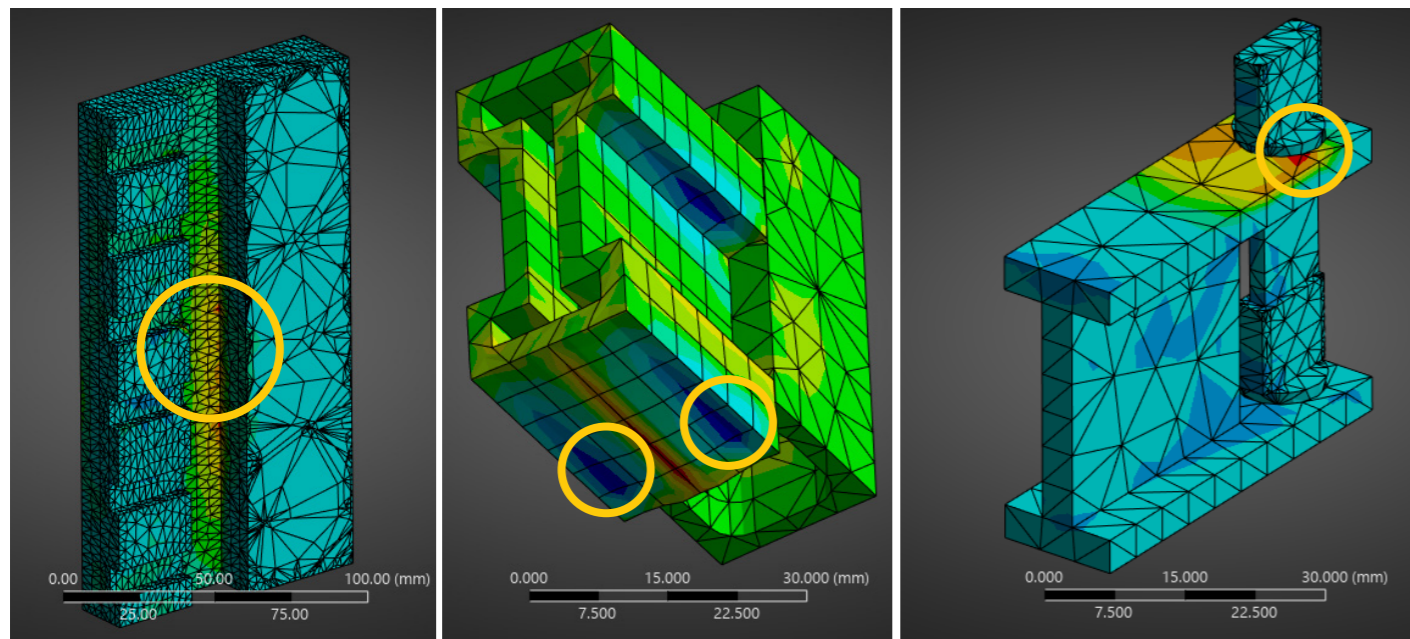


Figure 67: Uni.conn module setup for FEA (Load Case 1) | Source: Author



**Glass (in section)** Maximum Principle Stress: **8.03 MPa**  
**Gasket - TPU Shore A70** Maximum Principle Stress: **2.04 MPa** (Compressive forces)  
**Insert - Stainless steel S355** Maximum Principle Stress: **98.46 MPa**

Figure 68: FEA of uni.conn (Load Case 1) | Source: Author

The structural analysis confirms the stability of the module, well within the allowable limits. However, section 4.9 references the sizing of panels required to withstand the other load cases.

### 4.8 Workability

The pin, along with the gasket is placed in the channel with a tool and lowered into position. It is held in position due to friction between the gasket and the glass surface. Alternatively, it can also be held in position using an external magnet attached to the panel using suction clamps.

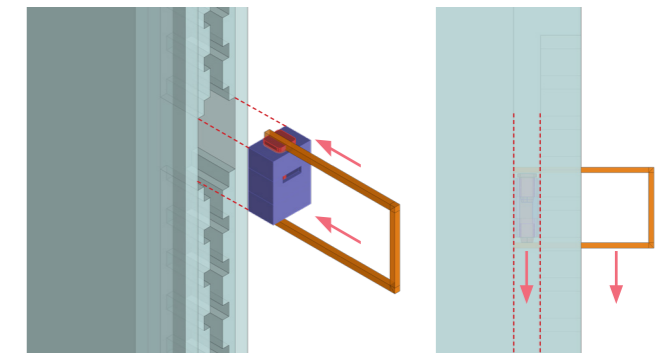


Figure 69: Placement of the insert | Source: Author

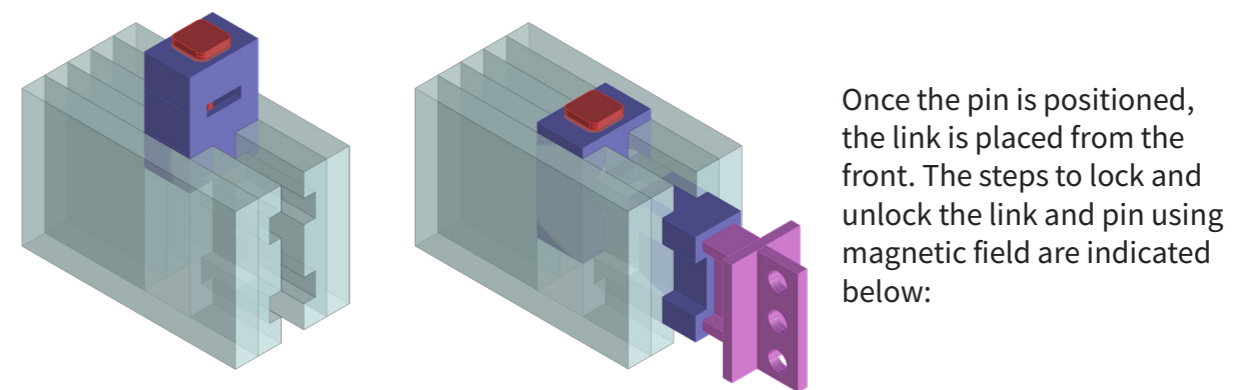
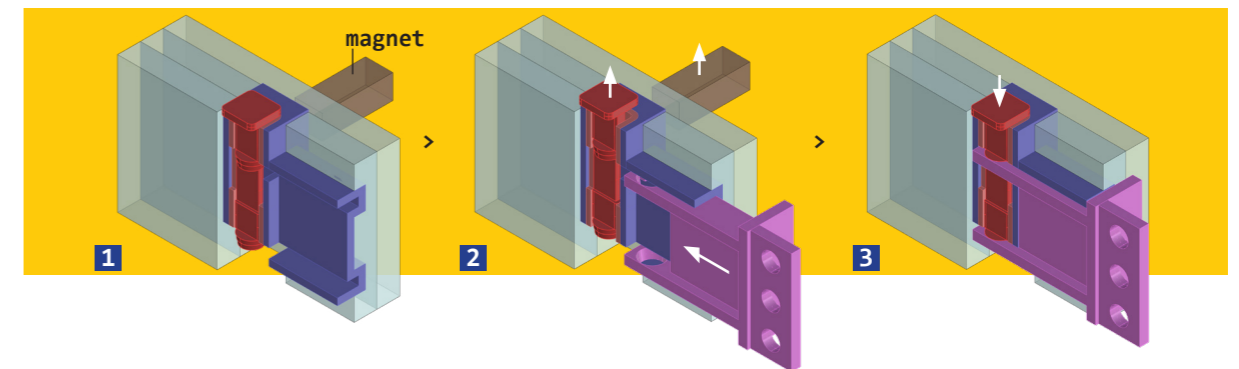


Figure 70: Sequence of insert assembly | Source: Author

Assembly >>



Disassembly >>

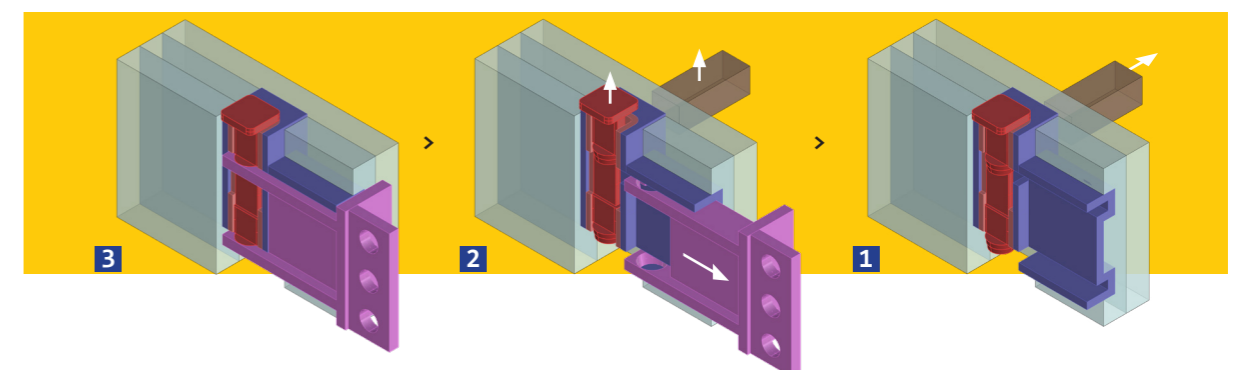


Figure 71: Sequence of assembly and disassembly of uni.conn | Source: Author

### 4.9 Technical drawings

Glass- version 3

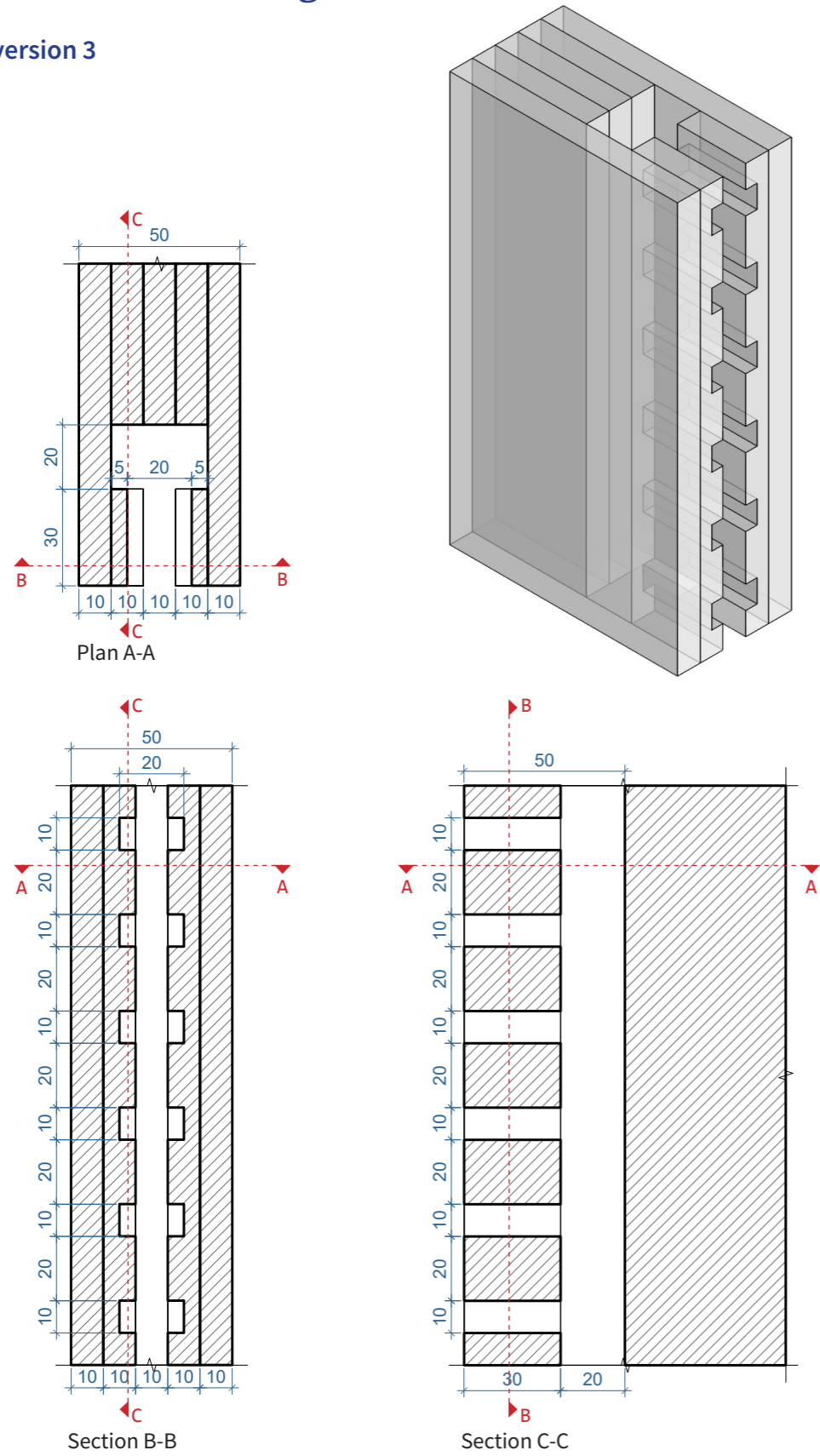


Figure 72: Technical drawings of Glass version 3- Uni.conn | Source: Author

Gasket- G6 V

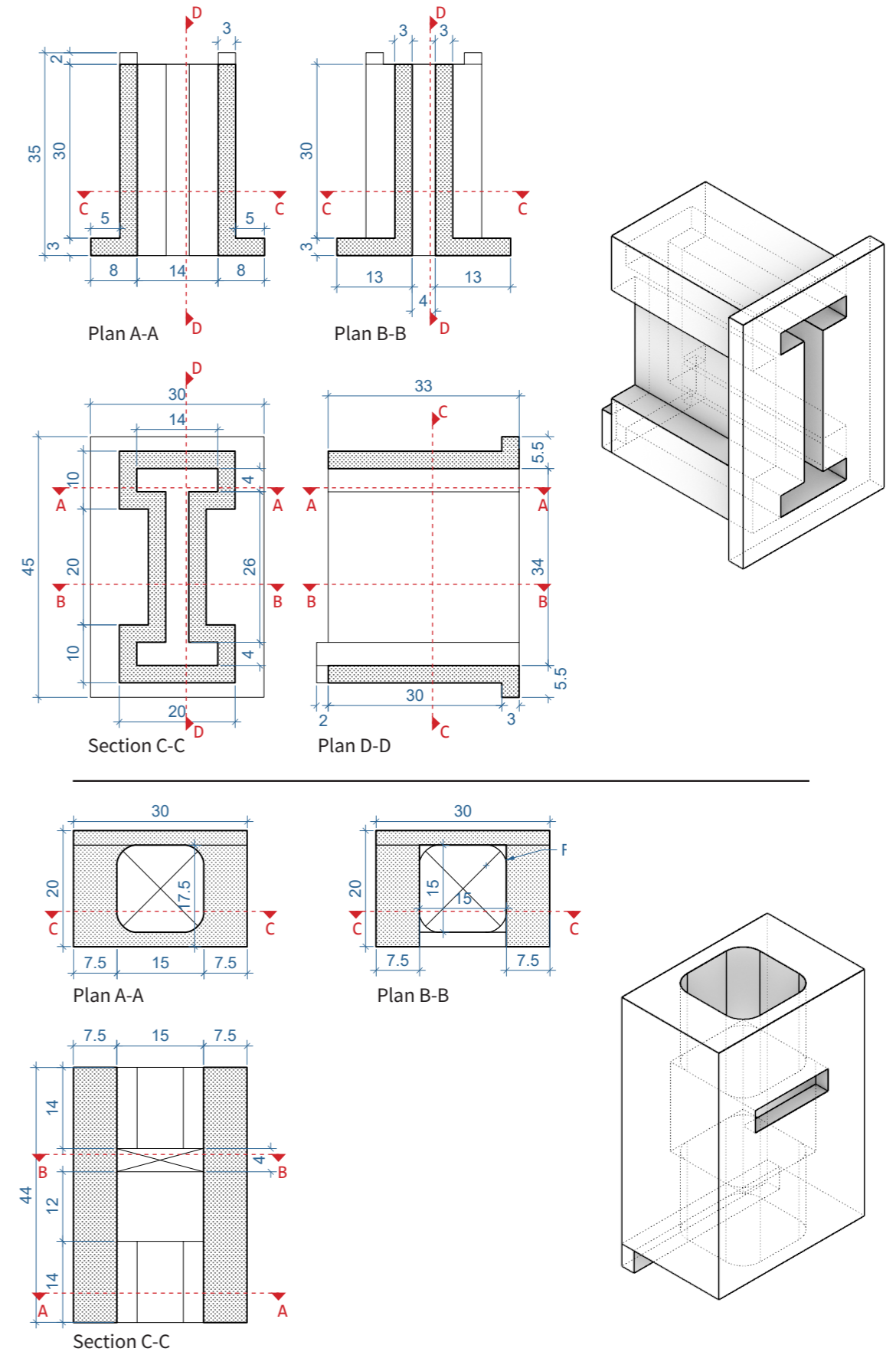
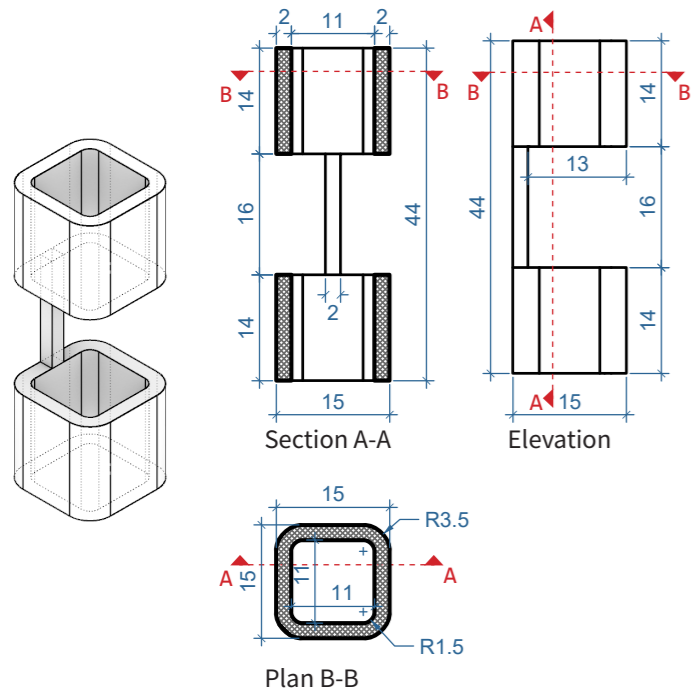


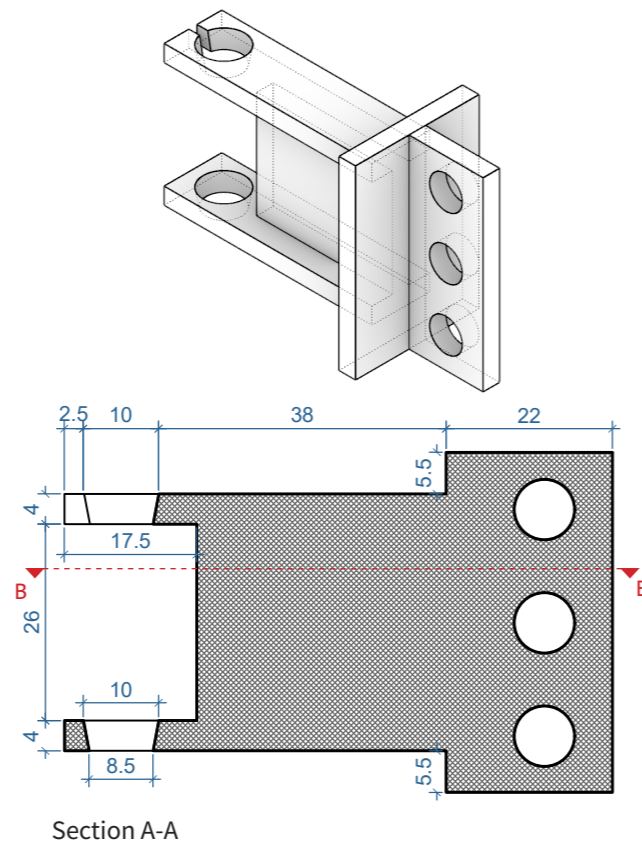
Figure 73: Technical drawings of Gasket G6 V- Uni.conn | Source: Author

Insert- I7 V

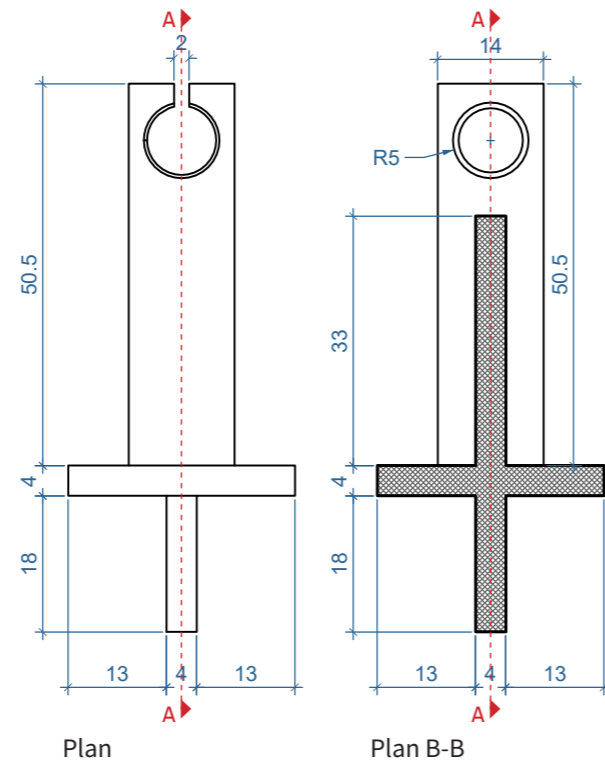
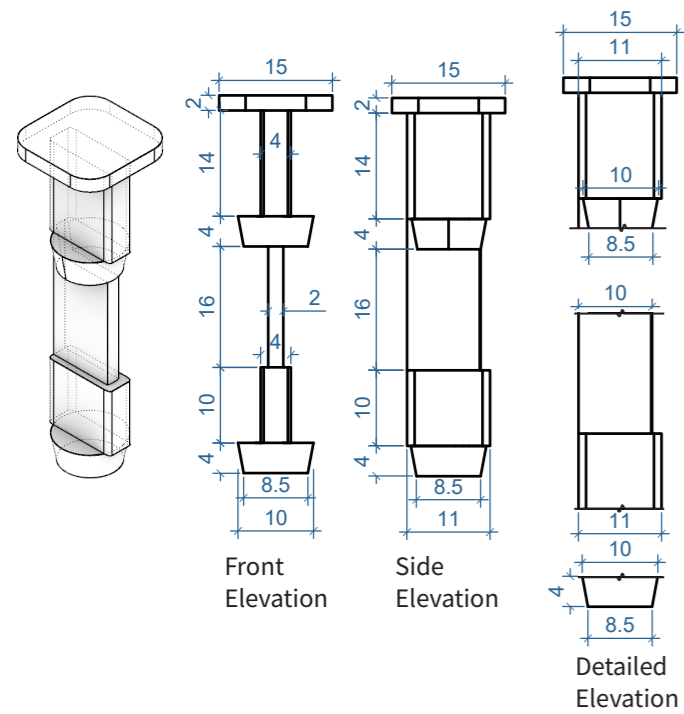
I7 V\_ Sleeve



I7 V\_ Link



I7 V\_ Pin



5.

# Design Applications

Load Cases	5.1
Apple Fifth Avenue, version 3.0	5.2
Evaluation	5.3

Figure 74: Technical drawings of Insert I7 V- Uni.conn | Source: Author

## 5.1 Load cases

### 5.1.1 Roof T junction

The roof panels resting on the 600mm deep roof beam, are connected at 13 locations, at a spacing of roughly 0.8m. A support block made of Delrin has been connected under the roof panels, at the support location to increase the contact area. This assists in transferring the load, reducing the load on the connection. The I7 H version is developed for such applications, where the pin moves horizontally, instead of vertically. Since the pin cannot be held in position due to gravity, an additional layer of locking system has been developed.

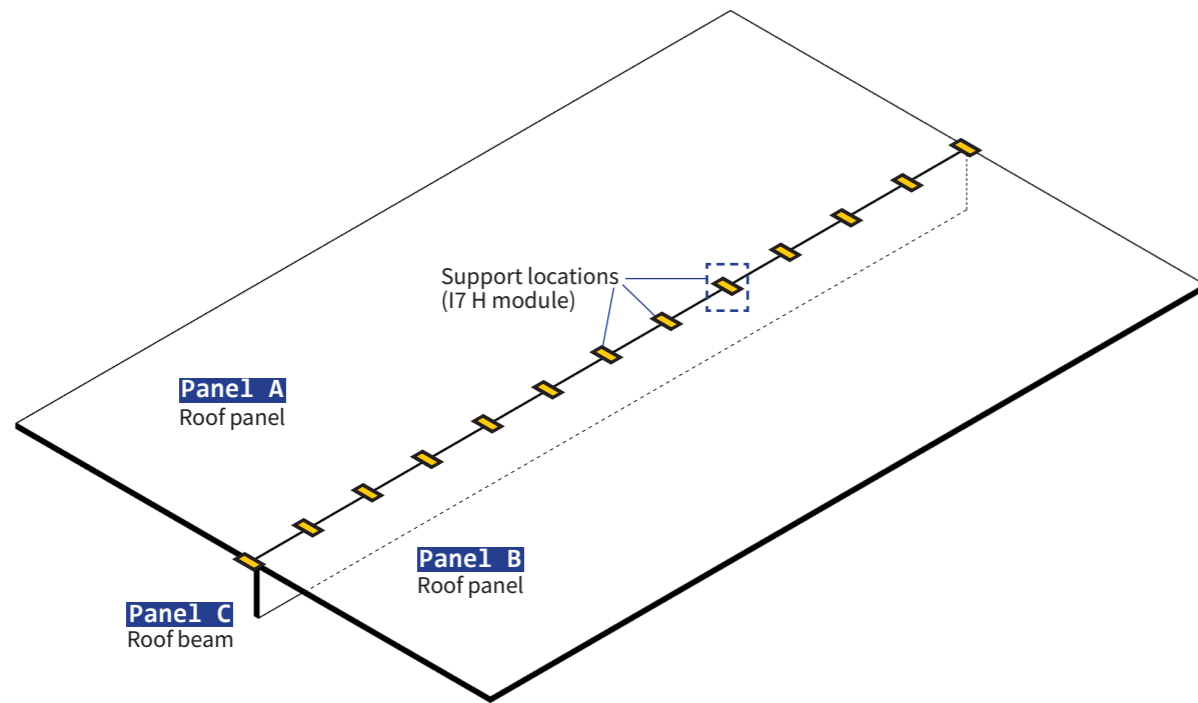


Figure 75: Location of connections- Roof T junction | Source: Author

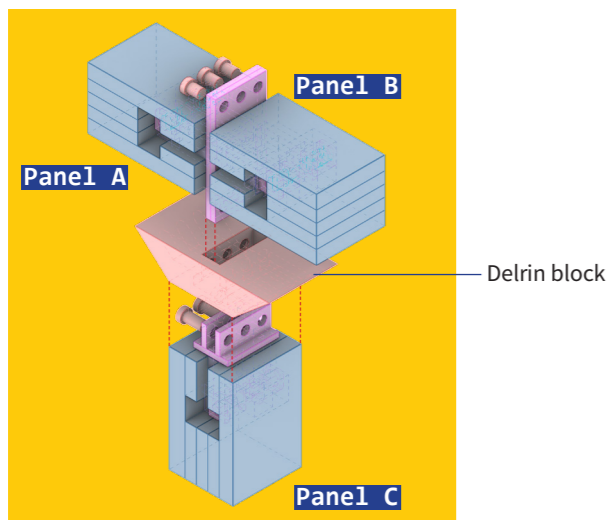


Figure 76: Connection detail- Roof T junction | Source: Author

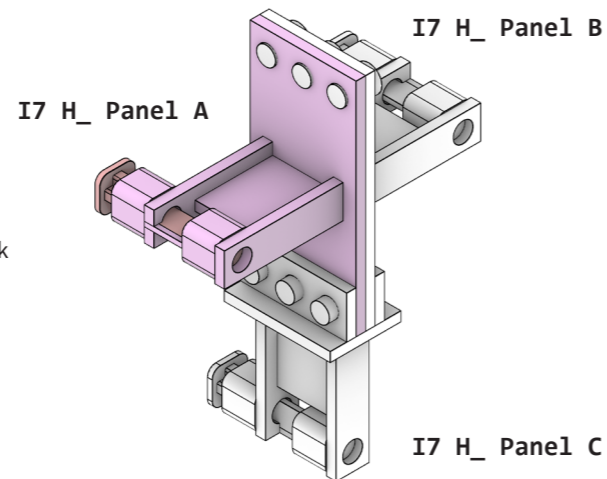


Figure 77: Insert detail (versions of I7 H)- Roof T junction | Source: Author

### Quick Connect Fitting

The locking system derives its inspiration from the principle of a *quick connect fitting* where a metal ball is used to hold the equipment in position. To dismantle, the ball must be physically moved using a specific action. In the case of I7 H, a magnetic (stainless steel) ball of 2mm diameter is positioned between the modified pin and the sleeve. This ball allows for locking of the pin, but restricts it from being unlocked. A smaller magnet is required to uplift the ball, allowing for the pin to unlock.

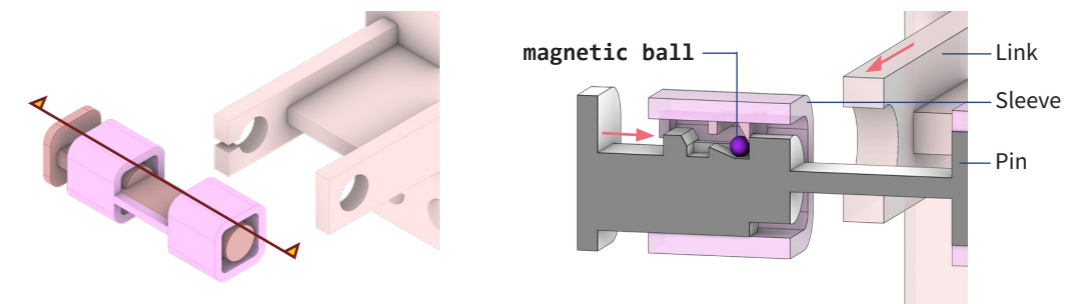
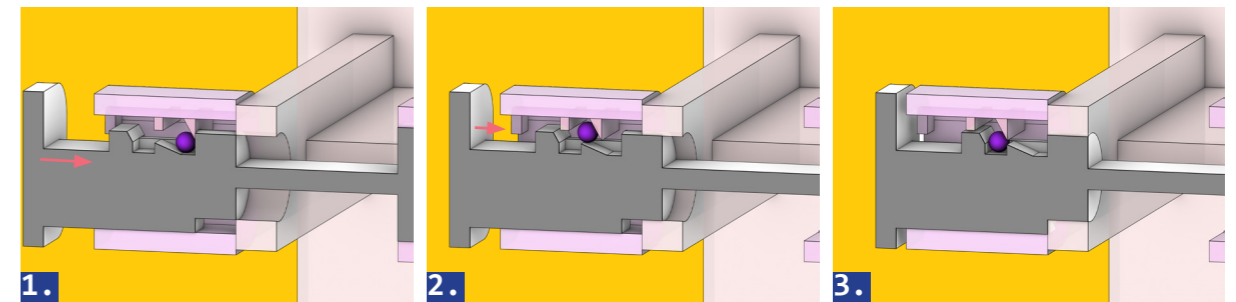


Figure 78: Incorporation of quick-connect fitting in I7 H | Source: Author

#### Assembly >>



#### Disassembly >>

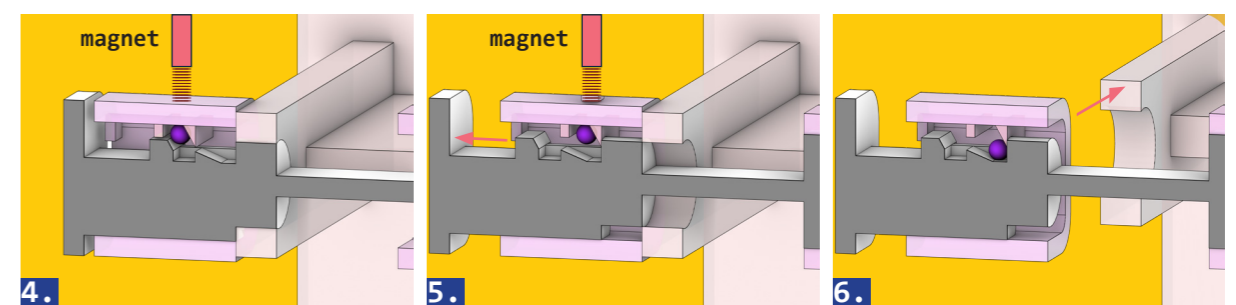
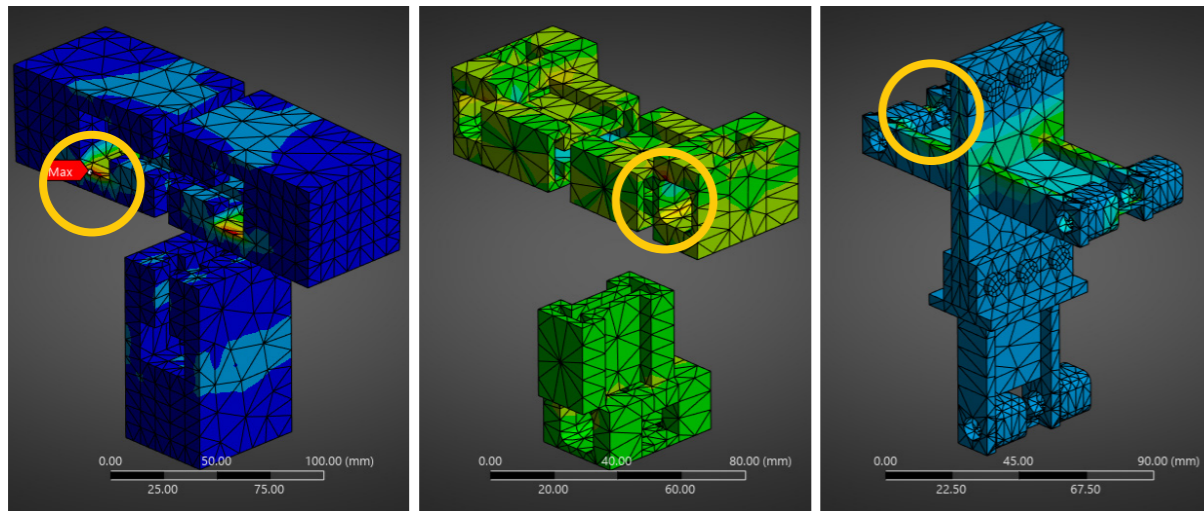


Figure 79: Sequence of assembly and disassembly of an I7 H insert | Source: Author

Structural analysis

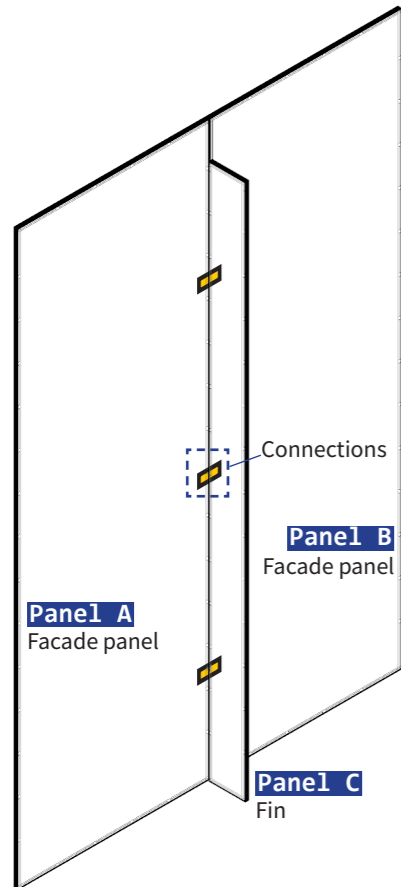


**^ Glass**  
50.1 MPa  
**^ Gasket**  
TPU (Shore A70) | 2.12 MPa  
**^ I7 H**  
180.47 MPa

Figure 80: FEA of the connection as per the defined load case (ANSYS Workbench) | Source: Author

The structural analysis confirms the stability of the module with a spacing of 0.8m. However, further analysis proved that the spacing could be increased to 1.06m if the two outer layers of glass were replaced to 12mm instead 10mm glass. More details regarding this simulation could be found in Appendix 2.

5.1.2 Facade T junction



The connection between facade panels and the vertical fin follows the same detail as I7 V. However, the bracket detail of the link, towards the end is modified to develop a different version that works for a T-junction.

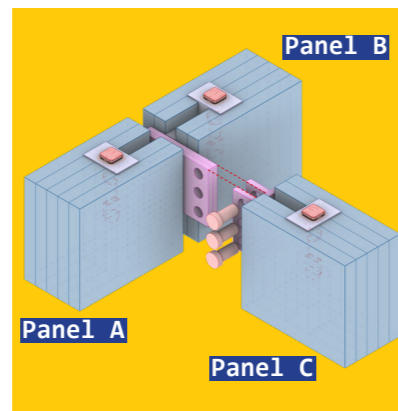


Figure 82: [Left] Connection detail- Facade T junction | Source: Author

Figure 83: [Below] Insert detail- Facade T junction | Source: Author

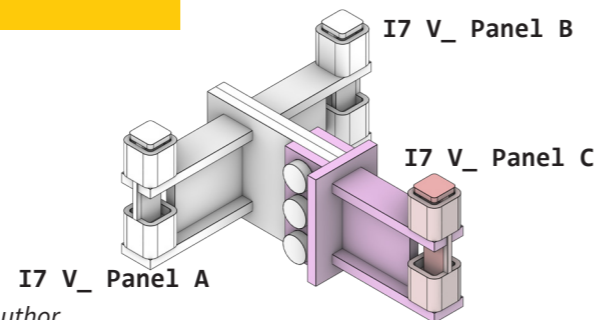


Figure 81: Location of connections- Facade T junction | Source: Author

5.1.3 Beam-to-Beam

The connection between beam-to-beam is similar to the connection between 2 facade panels. Two modules of I7 V are placed between the panels to rebated edge on the shorter side of each of the panel.

However, unlike the facade panels, the panels are not supported at the bottom. The horizontal forces that pull the connection outwards become more critical in this load case.

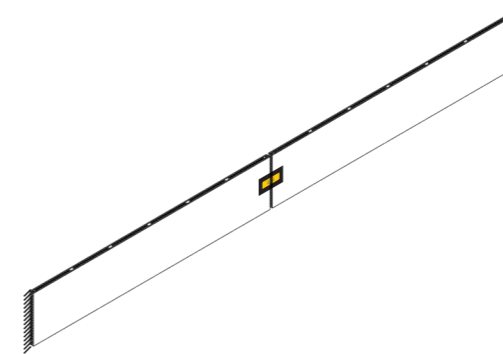


Figure 84: Location of connections- beam-to-beam | Source: Author

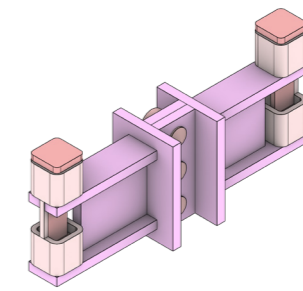


Figure 85: Insert detail- beam-to-beam connection | Source: Author

In such load cases, the channel within the rebated edge offers potential for developing composite structural systems. As explored by Louter (2011), the glass panels can be further strengthened by using a ductile member (stainless steel/ GFRP). In the case of uni.conn, there is an opportunity to embed such cables or rods in the lower channel to support the beams. This detail is crucial for the uni.conn system to function in a beam-to-beam connection.

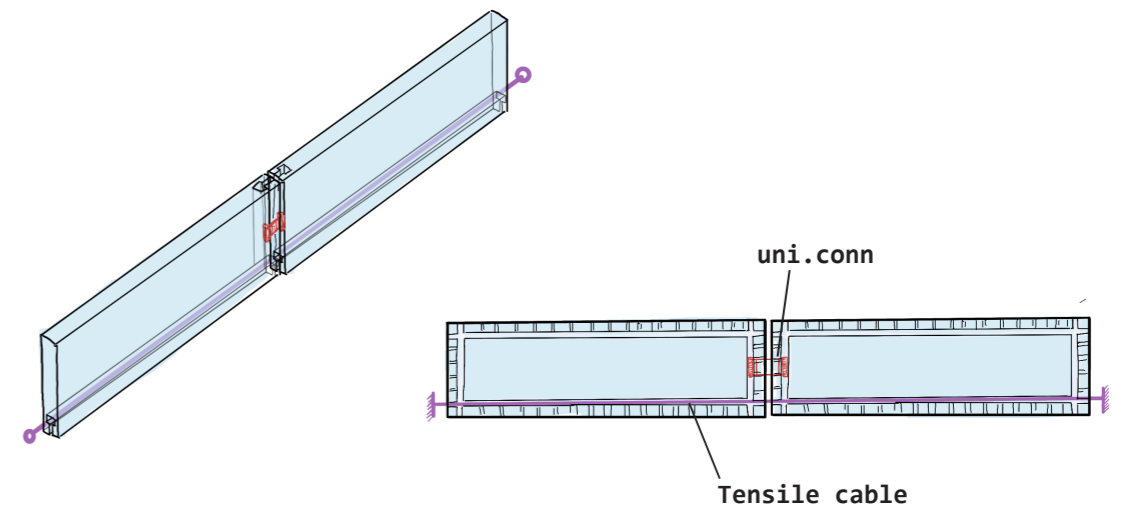
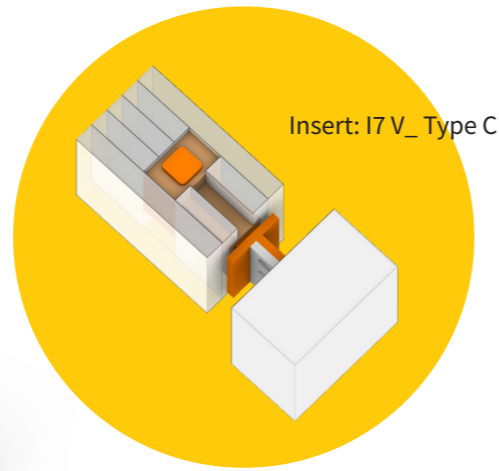
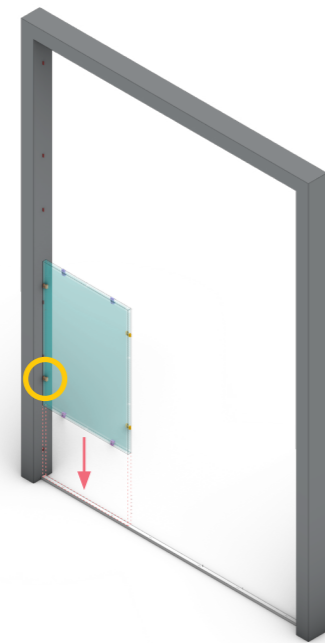


Figure 86: Conceptual designs for reinforcing the connection- beam-to-beam | Source: Author

5.1.4 Assembly of 3x3 facade panels



1. The first panel is to be slid into the slot and fixed at the bottom and the side support.

2.



Remaining panels in the first and second rows are slid in the same way to position them between the supports.

Different versions of uni.conn are used for the various connection systems.

3.

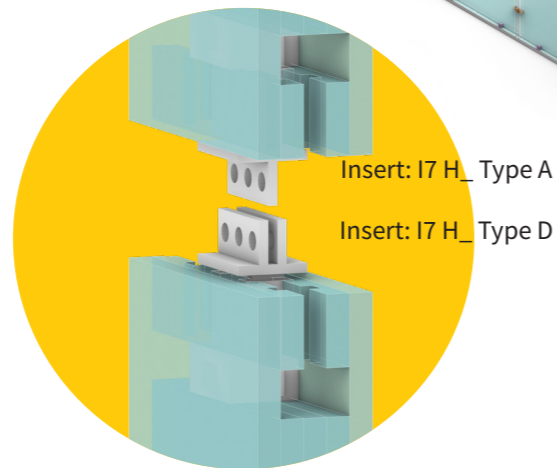
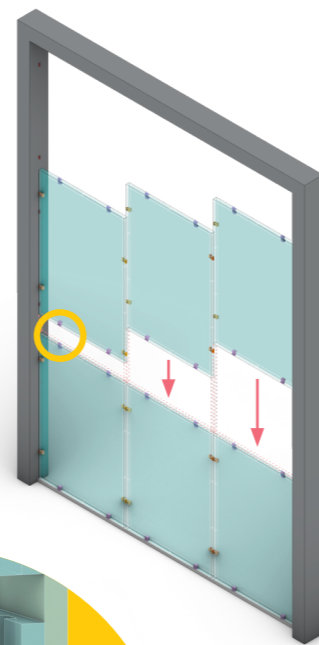
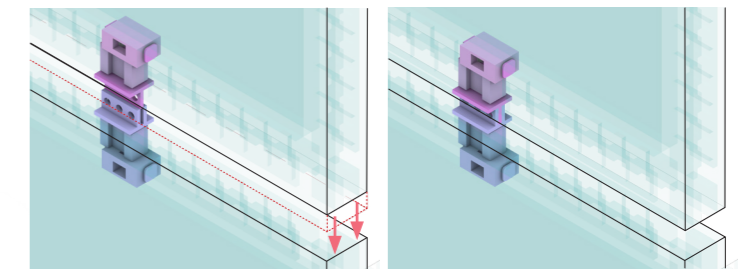
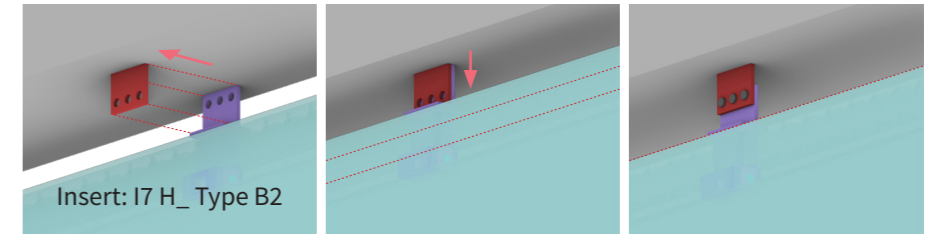
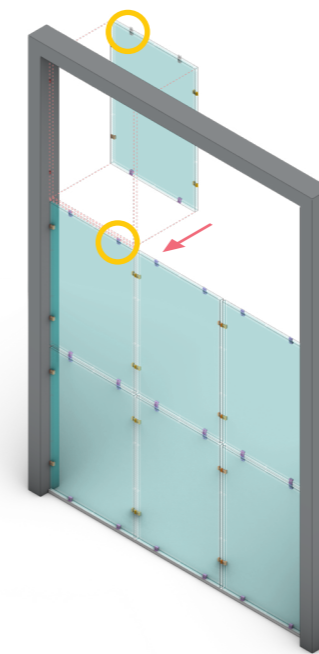


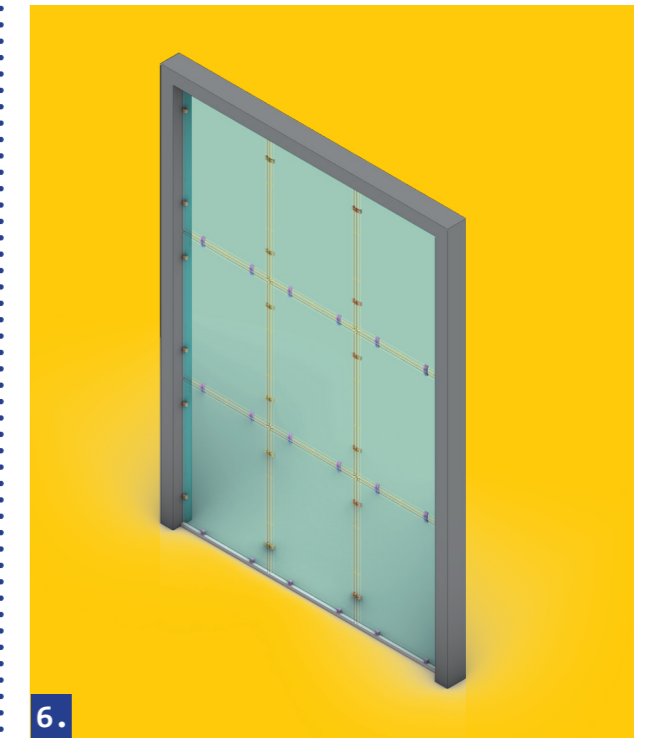
Figure 87: Assembly order of a 3x3 grid of uni.conn panels | Source: Author



The inserts at the top supports are longer than the rest. The panel is placed by aligning with the top support and slid down to insert it into position.

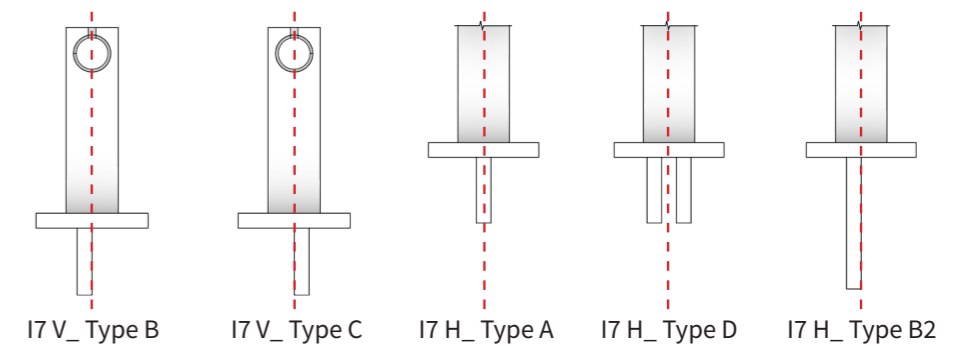
4.

5. The same continues for rest of the panels.



6.

Versions of inserts used in the Assembly of 3x3 panel system:



## 5.2 Apple fifth avenue, version 3.0

### 5.2.1 Building the cube

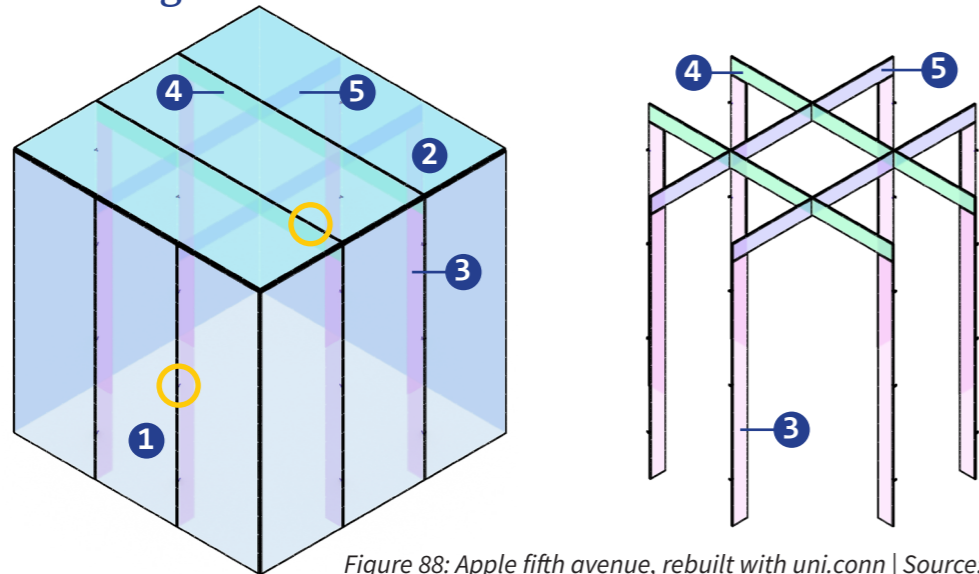


Figure 88: Apple fifth avenue, rebuilt with uni.conn | Source: Author

The Apple Cube version 3.0, built with uni.conn has 5 different sizes of glass panels. The dimensions of the cube are slightly modified due to the uni.conn system interface.

Panel no.	Sizing (m)	Location	Count
1	3.2 x 9.6	Facade panels	12
2	3.2 x 9.66	Roof panels	3
3	0.6 x 9	Facade fins	8
4	0.6 x 9.574	Longitudinal roof beam	2
5	0.6 X 3.11	Intermediate, secondary beams	6
<b>Total</b>			<b>29</b>

Table 16: Details of all the glass panels used in Apple fifth avenue- version 3.0

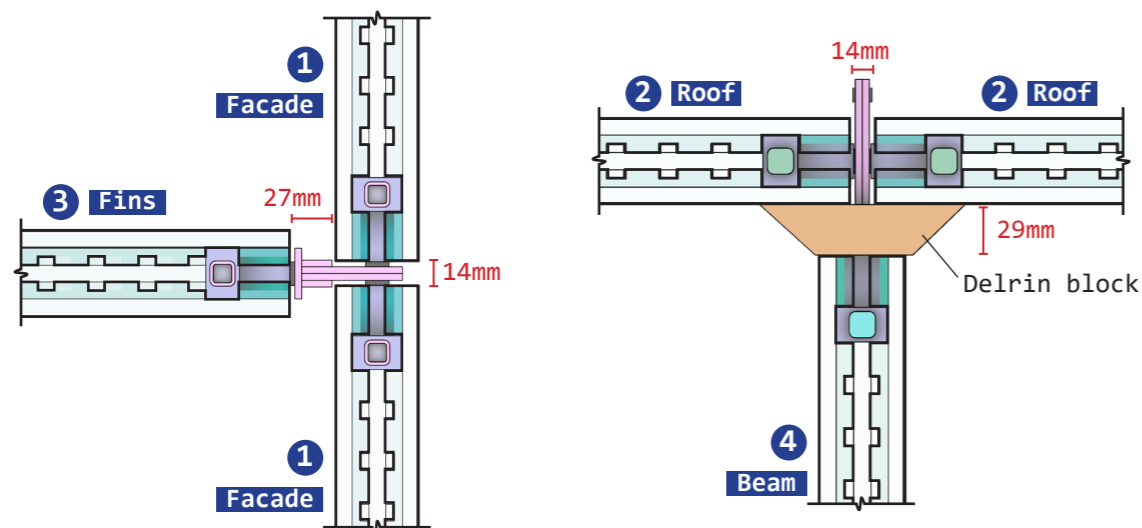


Figure 89: Facade panels- fin detail, Apple fifth avenue version 3.0 | Source: Author

Figure 90: Roof panels- beam detail, Apple fifth avenue version 3.0 | Source: Author

### 5.2.2 After the cube

This section adds to the primary goal of Uni.conn, achieving reusable structural glass panels. In a hypothetical situation where the Apple cube version 3.0 is dismantled, the glass panels could be reused in upcoming projects. If the logistics are planned accordingly, this system would not only be environmentally friendly, but also economically beneficial.

#### 1. One Manhattan West

Located just about 4km from the Apple fifth avenue, the One Manhattan West consists of three layers of 15feet high structural glass. However, if the panels from Apple cube 3.0 were utilized here,



Figure 91: [Above] One Manhattan West | Source: som.com



Figure 92: [Right] One Manhattan West with reused uni.conn panels | Adapted from: som.com

#### 2. Apple, Upper West

The Apple Upper West showroom in New York is one of the popular structures built with large glass panel. The glass panels from fifth avenue could be installed at the south facade (rectangular panels) of the Upper West store to spread the awareness of reusing the panels.

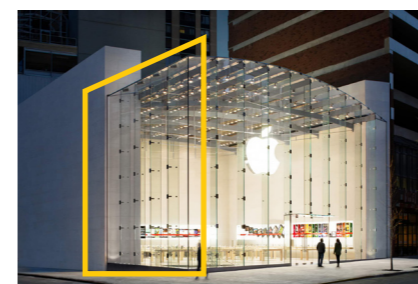


Figure 93: [Above] Apple, Upper West | Source: apple.com



Figure 94: [Right] Apple Upper West with reused uni.conn panels | Adapted from: apple.com

Academic explorations

With real-world projects that support and showcase the reusability of glass panels, the idea of reusing the glass panels from an existing project would also spread to academic explorations.

Below is one such academic project, re-imagined with the glass panels from Apple Fifth Avenue 3.0:



Figure 95: [Above] Khufu boat enclosure concept design | Source: Kalfa et al., 2025



Figure 96: [Right] Khufu boat enclosure concept design with reused uni.conn panels | Adapted from: Kalfa et al., 2025

Unboxing the cube

Beyond reusing the panels in upcoming constructions, the possibility of reusing gives scope for further, innovative design explorations.

The illustration below shows a conceptual design of an amphitheater space, made out of all the 29 glass panels from Apple Fifth Avenue 3.0.

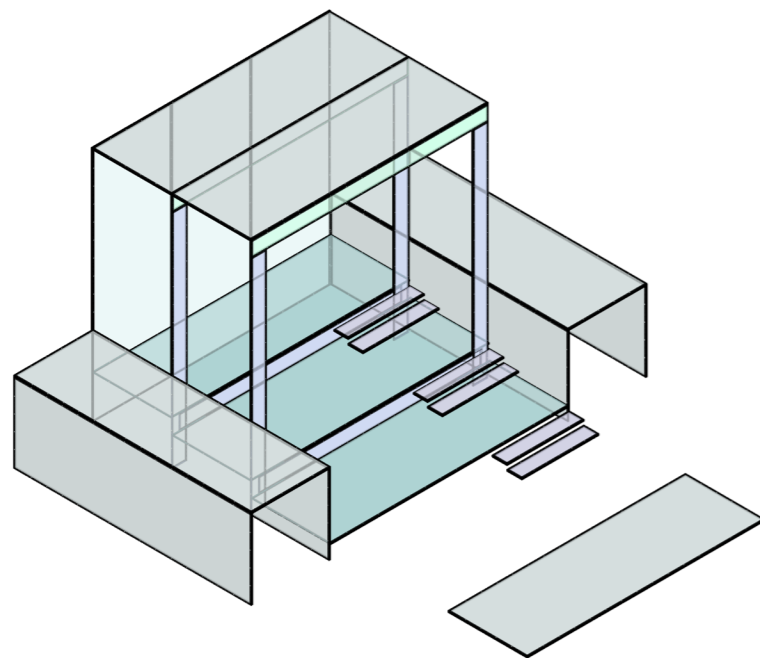
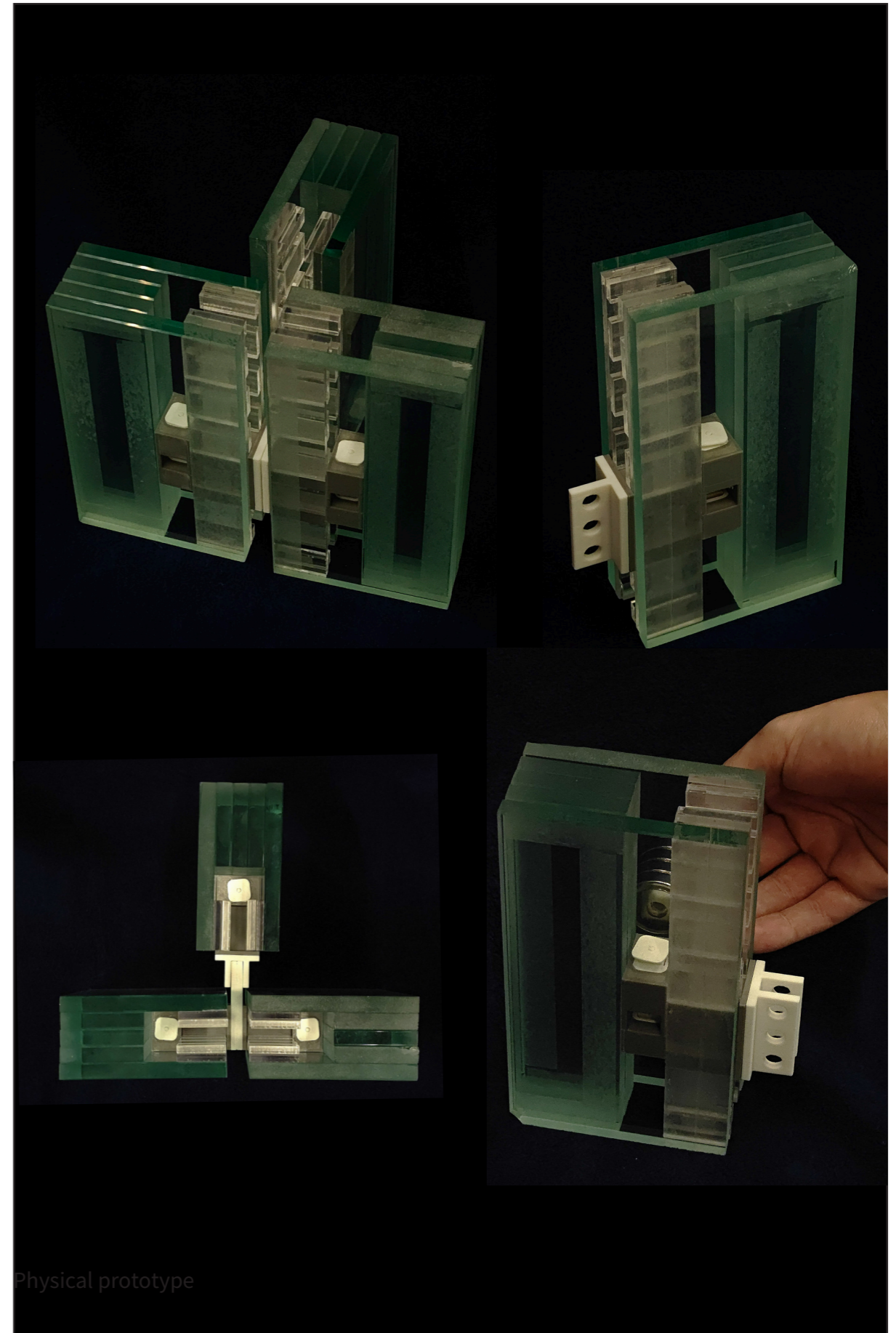


Figure 97: Concept design of panels from Apple fifth avenue 3.0 | Source: Author



Physical prototype

Figure 98: Physical prototype | Source: Author

### 5.3 Evaluation

At every stage, structural performance and demountability played a major role in iterating the design to achieve a functional connection system. However, it is important to evaluate the design against all the set criteria at once.

#### 1. Reusable module

Design of the connection system began from the existing knowledge of laminated inserts, which already enable the module of glass panel, along with its connection system to be reusable. At every stage, uni.conn ensured these values are transferred from laminated inserts to the different design iterations.

#### 2. Fully demountable connection

The primary drawback of laminated inserts, the inability to demount the insert from the glass panels, has been addressed by the uni.conn. A completely demountable connection system has been achieved with the design process.

#### 3. Structural Capacity

Uni.conn set the primary load case as a benchmark, and has been designed to match the existing standards. However, its drawback in scaling it up to different load cases (beam-to-beam) can be addressed by exploring a composite connection system, or by increasing the number of connections used.

#### 4. Maintenance and accessibility

The locking and unlocking mechanism of the uni.conn can be easily accessed externally, without requiring any laboratory-specific environment. Accessing the uni.conn within a structure is a non-invasive process, enabling easy maintenance and repairability.

#### 5. Visually minimally intrusive

Uni.conn requires rebated edge profiles along the glass panel edges. This adds to the visual noise compared to an adhesive connection with TSSA. The edge detail of the current uni.conn system has been restricted to 50mm from the edge, matching the typical laminated inserts. However, the uni.conn has a uniform profile along all the edges, making it visually consistent compared to a typical bolted connection.

#### 6. Durability

Durability played an important role in selecting the appropriate materials for the components of the uni.conn. Gaskets are more susceptible for natural degradation, but can be easily replaced with periodic inspections.

#### 7. Scalability

The primary load case considered is a common application in the industry. However, as seen in the different load cases addressed, versions of uni.conn can be explored further to improve its scalability.

#### 8. Ease of assembly and disassembly

Uni.conn requires minimal equipment, allowing for a straight-forward assembly and disassembly based on a sequence of actions.

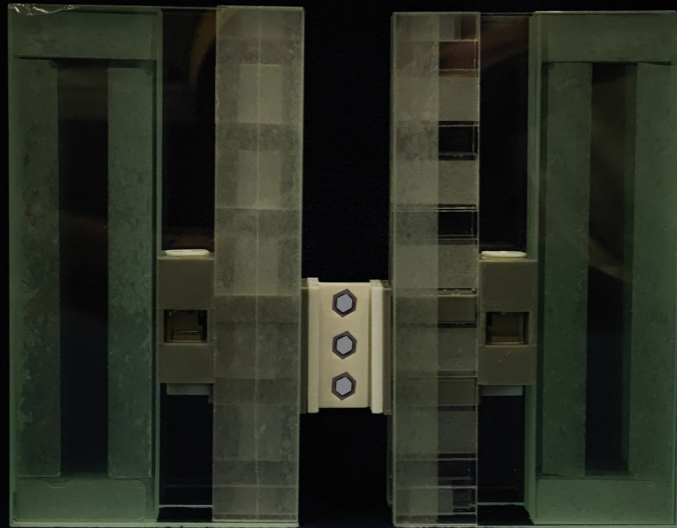


Figure 99: The Uni.conn | Source: Author

## 5. Design Applications

Previously evaluated glass joinery methods, along with the upcoming technologies are evaluated against the performance of Uni.conn based on the established criteria.

Legend:

- Poor
- ++ Better
- # Cannot be gauged with existing information
- + Good
- +++ Excellent

Design Criteria	Adhesive connections	Bolted connections	Laminated inserts	Heat Bonded joinery	Additive manufacturing	Interlocking systems	Uni.conn
Modular reusability	-	+++	+++	-	-	+++	+++
Demountability (reversible connection)	-	-	-	-	-	-	+++
Structural performance	+++	+++	+++	#	#	#	++
Maintenance and accessibility	-	++	++	-	-	+++	+++
Minimal visual intrusion	+++	-	++	+++	+++	+	+
Durability	++	+++	+++	+++	++	+++	++
Scalability	+++	+++	+++	+	-	+	++
Ease of assembly & disassembly	+	++	+++	-	-	+++	+++

# 6.

## Research Conclusion

Conclusion	6.1
Recommendations	6.2
Reflections	6.3
References	6.4

## 6.1 Conclusion

The thesis set out to investigate the possibilities of developing a fully demountable connection system for large-scale structural applications- the uni.conn. The connection system must make no permanent modifications to the glass panel, while meeting the necessary structural demands. The iterative and experimental design process resulted in a solution that addresses the primary concern of circularity in the glass industry.

This chapter provides the main conclusions and the results of this thesis by answering the primary problem statement and the sub-questions posed in the beginning. This provides an overall assessment, along with the main achievements of the connection system developed.

### 6.1.1 Research sub-questions

The primary research question was further broken down into five sub-questions. Addressing each of them, develops a solution for the research question. This section begins answering the sub-questions:

#### Q1. Performance Requirements

**What structural and durability criteria must a demountable connection satisfy for use in large-scale structural glass applications?**

This question consists of two parts, addressing the primary requirements in a large-scale structural glass application, and the required criteria that could make it demountable. The thesis picked one of the core examples to study and understand the common applications of a large-scale structural glass, the Apple showroom at fifth-avenue, New York. By deriving a few common load cases from the project, the thesis also targeted a few other common load cases to study the scalability aspect of the project. These 'other' load cases were chosen by studying the common demountable connections in the construction industry, which addresses the second aspect of the sub-question, developing the criteria to make a truly demountable connection.

Three primary load cases from the Apple, fifth avenue project were chosen to initiate the design of uni.conn: connection between 2 facade panels, T junction connection of facade panels and a supporting vertical fin and a similar T junction connection between the roof panels and a supporting beam underneath. Later, by studying the different applications of glass connections and demountable connections in the industry, two more applications: connecting two beam panels, and assembly of a grid of 3x3 panels. The primary load cases from the Apple project were structurally analyzed to set a structural benchmark for the uni.conn designs (Chapter 3.1).

Chapter 2.3 outlines the existing demountable connections, in commonly used structural materials in the construction industry: steel, timber and concrete, to derive a set of criteria for true demountability. However, scaffolding couplers made out of aluminum were also studied to understand in developing a truly versatile, scalable connection system. This established criteria, was later used to evaluate the existing glass connections, potential design concepts for the uni.conn, and finally, the uni.conn itself (Chapter 5.3).

### Q2. Limitations of Existing Systems

**What are the specific limitations of current connection systems in terms of reversibility, reuse, and glass integrity?**

The industry of glass architecture has evolved into three primary categories of connection: adhesive-based, bolted and embedded connections. In most cases, the primary driver for this exploration has been the need for minimal visual presence of the connection. Present-day adhesive connections are capable to handle massive structural loads and achieve better transparency. However, they permanently bond to the glass surface, making it quite challenging to separate it. Glass panels connected using adhesives are often discarded due to the permanent contamination from the adhesive. Although research continues to explore better methods to separate them, but scalability of such methods has always been a major limitation.

Bolted connections are mechanical connections that offer better serviceability compared to the adhesive connections. This system follows standardized components that improve its scalability. However, the bolted connection requires a hole to be drilled in the glass panel, and therefore, damaging its structural performance permanently. A panel demounted from a bolted connection system can be reused, but only within the same loading connection by matching the support locations. Embedded laminate connections allow for a reusing the module. But, the embedded laminate cannot be demounted from the glass panel, restricting the possible applications for reusing the glass modules. This system promotes reusability, but it is not reversible.

Reacting to the challenges in the industry, this thesis developed a novel connection system, uni.conn, that performs as per the required structural benchmarks and is completely demountable. After disassembly, the glass panel is left unaltered, enabling its usage in any further applications.

### Q3. Design principles

**What design principles and material behaviors must be considered when developing a connection that transfers loads effectively without modifying or penetrating the glass?**

The literature explores the impact of the connection on the glass under various systems. This provides a better understanding of the potential concepts to develop further. The existing demountable connections in other materials provide a base and form case studies for different connection mechanisms. The necessity of simple principles, like designing based on a sequence of assembly and disassembly orders, is highlighted by these case studies.

Drawbacks from the case studies also highlight important considerations that assist in better demountability. For example, as highlighted in the demountable connections in concrete structures, the access to the connection is frequently obstructed by subsequent finishing phases, complicating the demountability. The uni.conn addresses such constraint by relying on external access to assembly or disassembly the connection.

**Q4. Potential Connection Mechanisms**

How can different connection mechanisms (e.g., mechanical interlocking, clamping, surface bonding, hybrid systems) be explored for achieving full demountability, and what are their constraints?

Chapter 2.2 explores a few different upcoming trends in the glass industry, and their applicability in glass connections using existing literature and case studies. Based on these studies, potential schemes for connecting the glass panels were conceptualized. These connection mechanisms were compared and evaluated based on their compatibility with the corresponding connection methods and the established design criteria.

Primary factor in choosing the appropriate connection mechanism was the impact on glass surface. Different systems involved techniques that were not able to provide precise control and estimate of the glass surface and strength upon treatment. This may induce unforeseen peak stresses and would be difficult to replicate the results. Predicting the performance of a connection system is essential to analyze the structural capabilities and ability to assemble/ disassemble. The ability to scale up the number of connections without having to verify for structural performance is crucial for increasing the potential applications.

Finally, using heat-bent glass with interlocking mechanism for the insert was chosen as the method to develop the uni.conn further. The interlocking insert design developed in the uni.conn is independent from the adjacent conditions, making it easily scalable. In cases where the loads experienced are beyond the structural capabilities of a single unit, additional modules could be integrated seamlessly along the panel edge. This eliminates the need for repetitive, case-by-case structural re-verification of the glass module.

**Q5. Prototyping and Evaluation**

How can proposed connection concepts be prototyped and tested to evaluate their structural performance, reversibility, and long-term behavior?

Prototyping was always a part of the design iteration process. At every iteration, the modules were 3D printed at TU Delft's LAMA Lab to the geometries for their workability. Simultaneously, the same designs were checked for their structural performance using Finite Element Analysis (FEA) on ANSYS Workbench.

Workability check for rigid materials like glass and inserts could be easily done by replicating the geometries using PLA. However, the elasticity of different materials of gasket considered needs to be replicated similarly in the physical prototypes. This was achieved by exploring different infill patterns and profiles, and compared qualitatively on the basis of hardness levels. Even though this method was not completely accurate, it provided enough insights to evaluate the performance of the other components.

The magnetic properties of a stainless steel pin were replicated by attaching a 10mm x 10mm magnet onto the 3D printed PLA counterpart. Eventually, the iterations of the 3D printed pin were developed with the ability to embed the magnet within the material.

Unfortunately, the developed designs could not be physically tested for structural performance due to the complexity of machining the intricate geometries in different materials that were being explored.

**6.1.2 Research question**

*How can a fully demountable connection system be developed for large-scale structural glass panels without modifying or damaging the glass, while still meeting the necessary structural and durability requirements?*

The primary aim of this thesis was to investigate the feasibility of developing a fully demountable connection system for large-scale structural glass applications. Existing connection methods, including adhesive, bolted, and embedded insert systems, do not enable complete reversibility, as they permanently alter the glass panel or leave residual damage following disassembly. In adhesive-based systems, the bonding material itself deteriorates over time and may require replacement during the service life of the structure. However, the removal of aged adhesives often leaves residual material on the glass surface, making reuse difficult and frequently resulting in the disposal of otherwise intact glass panels. Consequently, in the other connection systems, the reuse of glass components remains limited to specific configurations, without the scope of complete reversibility.

The proposed Uni.conn system addresses this challenge by introducing a mechanically controlled interlocking connection that provides the required structural performance with complete demountability. Functioning similarly to an embedded insert, uni.conn provides an interface through which glass modules can be connected to external brackets or to other uni.conn modules. Unlike conventional insert-based solutions, however, the connection can be attached, repositioned, and removed without permanently modifying the glass panel.

The uni.conn system consists of three major components: the glass module, insert and the gasket. The glass module consists of a modified edge with rebated pattern, for the insert to grip onto. The insert is made of three components- pin, link and sleeve, that together, when assembled form the insert. The interlocking and separation of the pin with the link is controlled by an external magnetic field. The insert must be dismantled to disassemble the connection. Gasket is the interface between the insert and the glass. Its primary function is to transfer the loads evenly from one to the other. All the three components are equally explored in terms of geometry and materiality to result in the final version of uni.conn.

The system expands the potential for reuse beyond the original application by preserving the integrity of the glass panels. A glass panel employed as a vertical fin, for example, may subsequently be repurposed as a beam or incorporated into a different structural configuration without being constrained by pre-existing connection locations or damage. Furthermore, the channel within the uni.conn profile, provides opportunities for incorporating building services such as electrical conduits, sensors, or sprinkler systems. In this way, uni.conn demonstrates how its design can play a critical role in improving the adaptability, reusability, and functional integration different building systems.

## 6.2 Future Work

This thesis developed a fully demountable glass connection system for large-scale structural applications as an alternative to the existing structural glass connections. This endeavor proposes a magnetically controlled interlocking system that grips onto the glass panel and can be disengaged on-command. Based on the structural analysis on FEA software and the physical prototyping of the components, the proposed system appears to be very promising. However, some recommendations for further development are discussed in this section.

### Experimental validation

The current study focused on the conceptual development and numerical evaluation of the uni.conn system. While the simulation provide an initial understanding of its structural behaviour, physical testing is required to validate the assumptions made in the FEA models. Further research should therefor investigate the performance of prototypes with accurate materials under the specified load cases.

### Sealing the connections

The current system performs well structurally and in terms of demountability. However, when connected, the panels have gaps in between. Potential methods to seal the system by plugging in to the rebated edges could be explored further to make the design more practical.

### Optimization of the gasket

In the applications where uni.conn is combined with another system, such as, using cables to provide additional support, the gasket geometry and materiality could be explored to incorporate the cables running in the channel as well. The channel within the glass module provides scope to incorporate services like electrical conduits, sprinkler system, etc. However, the current design of the gasket leaves no room for such explorations. This could be done by exploring alternative elastomeric materials and optimize parameters such as hardness, friction coefficient, creep resistance, and durability. Experimental characterization of these materials would also improve the accuracy of numerical simulations.

### Scaling up the version of Uni.conn

This research considered the feasibility of the connection at the component level. Further investigations should evaluate its application within larger structural assemblies, including beams, fins, and space-frame systems. Such studies would help determine how the connection performs under varying load paths and different structural configurations. Beyond glass, this uni.conn could be explored in different systems such as cladding, dry-walls, timber construction, etc., with corresponding material explorations.

### Circularity assessment

Uni.conn was developed with reuse and demountability as primary objectives. However, the environmental benefits were not quantified within the scope of this study. Future research could assess the circularity potential of the system through LCA, material flow analysis, or embodied carbon calculations. This would provide a better quantitative comparison with the existing connection systems.

## 6.3 Reflections

### Academic relevance - Building Technology studio

This thesis is positioned within the two domains of Structural Design and Product Design within the Building Technology program. The thesis adopts a product-oriented approach through the development, prototyping, and evaluation of a novel connection system, supported by the facilities and resources available at the LAMA Lab.

The primary objective of the research was to develop a fully demountable connection for large-scale structural glass applications. Achieving this required an understanding of both the material behaviour of glass and the structural principles governing load transfer within the connection systems. The study adds to the existing knowledge and ongoing explorations towards circularity, adaptability and reuse in structural glass.

From a product design perspective, the research investigates how a connection can be developed as a reusable building component rather than a project-specific solution. The iterative process of concept generation, digital modeling, prototyping and structural evaluation reflects a product development methodology. The integration of material understanding, structural analysis and physical prototyping demonstrates the interdisciplinary explorations at Building Technology studio. This thesis combines both product development aspect and the material engineering, and therefore, contributes to the ongoing discussion on how structural glass systems can be designed for both performance and circularity.

### Thesis methodology

The methodology adopted in this thesis combined literature research, concept development, digital modeling, finite element analysis and physical prototyping. This multi-layered approach proved valuable because it allowed the research to move beyond a purely theoretical investigation and evaluate the feasibility of the proposed concept from both a structural and practical perspective. The iterative process of developing, testing and refining concepts resulted in design decisions throughout the project.

A limitation of the approach is that the structural performance of the proposed system was primarily assessed through numerical simulations and preliminary prototyping. While these methods provided valuable insights into the behaviour of the connection, full-scale experimental testing would be required to validate the assumptions and performance predictions made during the study. Although the Uni.conn system was developed specifically for structural glass applications, the primary principles of reversible assembly, non-destructive load transfer and separation of the structural element from the connection component can be applied to other building materials and connection systems.

### Societal and industrial relevance

Glass is an energy-intensive material. Considering the current environmental conditions, it is increasingly important that it is used consciously wherever it is applied. Yet it is equally fair to say that no other material currently available matches glass in its combination of aesthetic quality, durability and structural performance. This makes it difficult to argue for its replacement. Hence, it is important that glass is used responsibly.

In real-world applications today, glass panels are frequently discarded not because they have failed structurally, but because the connection systems used to fix them cause permanent damage, making them unusable. If we accept the environmental cost of producing glass, we cannot simultaneously accept connection methods that artificially shorten its usable life. It is the responsibility of the industry to consider end-of-life situation of the glass panels while designing them.

This thesis contributes to the ongoing effort of making the glass industry more circular. The system explored here addresses a specific connection scenarios and loading conditions, and generalizing it would require further research and industry collaboration. However, this thesis is a step in a direction towards circularity, where, starting the conversation now, over time, leads to something practical and widely applicable in the industry.

### The Uni.conn: Research vs Design

The research and design in this thesis did not follow a linear path. Each of them influenced the other continuously throughout the process. Understanding the load behaviour of glass connections informed what the design needed to achieve, and the limitations that emerged from each design iteration redirected where the research needed to go next. The development of the I7-H variant is a good example, where gravity cannot be used to hold the pin in position. Finally, a structural problem with an existing configuration led directly to a new design direction, much like how uni.conn itself originates as a response to the shortcomings of embedded laminate connections. In that sense, every concept in this thesis branches from the problem of another.

The research also drew inspirations from outside the immediate field. The pin-and-link system at the core of uni.conn was inspired by train couplers. If a single pin-and-link mechanism can transfer the loads involved in pulling a train, a scaled version of the same principle is worth exploring at an architectural level. Similarly, the locking mechanism developed for the I7-H was informed by quick-coupling systems used in pipe connections. This cross-industry observation became a consistent method of working throughout the thesis.

In terms of practical applicability, the results are at concept level. The connection has not been physically tested, and several aspects require further development before it could be considered for real application. However, the framework developed around load path behaviour and FEA methodology for glass connection models is directly applicable as a foundation for future work.

## 6.4 References

- ASCE 7 standard. (2003). American Society of Civil Engineers. <https://www.asce.org/publications-and-news/asce-7>
- Bajtek, J., Netušil, M., & Eliášová, M. (2020). Experimental Analysis of Laminated Embedded Steel Insert in Load Bearing Connections. *Challenging Glass Conference Proceedings*, 7. <https://doi.org/10.7480/cgc.7.4476>
- Belis, J., Louter, C., Nielsen, J. H., & Schneider, J. (2019). Architectural Glass. In J. D. Musgraves, J. Hu, & L. Calvez (Eds.), *Springer Handbook of Glass* (pp. 1781–1819). Springer International Publishing. [https://doi.org/10.1007/978-3-319-93728-1\\_52](https://doi.org/10.1007/978-3-319-93728-1_52)
- Bouwmeester, H. C. (2023). The glass Sashimono joint. Delft University of Technology.
- Bover, A., Martínez, À., & Guitart, N. (2023). Case of study: Glass façade of l'Oréal headquarters. *Glass Structures and Engineering*, 8(4), 513–525. <https://doi.org/10.1007/s40940-023-00242-z>
- Chhadeh, P. A., Sleiman, K., Hoffmann, H., Funke, N., Rettschlag, K., Jäschke, P., Baitinger, M., Knaack, U., Kaierle, S., & Seel, M. (2025). Design of additively manufactured glass components for glass point fixings. *Glass Structures & Engineering*, 10(1), 6. <https://doi.org/10.1007/s40940-024-00290-z>
- Cloutier, B., & Eskenazi, A. (2025). Port of Montreal Tower: Glass Cage. *Glass Structures & Engineering*, 10(2), 9. <https://doi.org/10.1007/s40940-025-00291-6>
- Covillault, P., Baldassini, N., & De Rycke, K. (2025). Epoxy adhesive for stainless-steel and glass assembly: Case study on the glass scaffolding “Réflexions.” *Glass Structures and Engineering*, 10(2). <https://doi.org/10.1007/s40940-025-00297-0>
- Cvecek, K., Dehmel, S., Miyamoto, I., & Schmidt, M. (2019). A review on glass welding by ultra-short laser pulses. *International Journal of Extreme Manufacturing*, 1. <https://doi.org/10.1088/2631-7990/ab55f6>
- Dasopoulou, G. (2020). Rolling in Transparency. <https://repository.tudelft.nl/record/uuid:908ca92b-daad-4d9f-9e23-632149667f95>
- Eliasova, M. (2015). Advanced Design of Glass Structures [Unpublished work].
- Eskes, A. (2018). Connecting Glass to Glass with Glass. <https://repository.tudelft.nl/record/uuid:73f48f2b-5da9-438f-86d0-52e3bcc70385>
- Feldmann, M., Kaspar, R., Abeln, B., Gessler, A., Langosch, K., Beyer, J., Schneider, J., Schula, S., Siebert, G., Haese, A., Wellershoff, F., Cruz, P., Belis, J., Colvin, J., Morgan, T., Ensslen, F., Eliasova, M., Šulcová, Z., Royer-Carfagni, G., ... Zarnic, R. (2014). Guidance for European Structural Design of Glass Components. JRC Publications Repository. <https://doi.org/10.2788/55303>

Fildhuth, T., Joos, P., Wüest, T., Haller, M., & Stevels, W. (2022). Development and behavior of a thin fitting connection for lamination with structural PVB. *Glass Structures & Engineering*, 7(3), 415–439. <https://doi.org/10.1007/s40940-022-00198-6>

Hartwell, R., & Overend, M. (2019). Unlocking the re-use potential of glass façade systems.

Hoekstra, R. (2025). Stiffening glass structures with laser-bending techniques [Delft University of Technology]. <https://repository.tudelft.nl/record/uuid:db01edae-a19d-434c-badd-561e7ba11837>

Kalfa, T., Leoudi, C., Myrtaki, E., & Venigalla, K. K. (2025). Khufu Boat Enclosure [Unpublished academic work]. Delft University of Technology.

Kassnel-Henneberg, B. (2016). Connections in Glass. Challenging Glass Conference Proceedings, 5, 489–496. <https://doi.org/10.7480/cgc.5.2273>

Kessel, E. C. van. (2025). Glass Unlocked. <https://repository.tudelft.nl/record/uuid:0e25e69e-edde-4caa-a557-a8e1e02b9709>

Lavko, M., & Kvočák, V. (2020). Comparison of Mechanical and Adhesive Joints for Structural Glass – A review. *IOP Conference Series: Materials Science and Engineering*, 867(1), 012027. <https://doi.org/10.1088/1757-899X/867/1/012027>

Lenk, P., & Lambert, H. (2012). Challenges in the design, fabrication and installation of glass structures comprising of super jumbo glass sheets. *Challenging Glass: Conf. Archit. Struct. Appl. Glass, CGC*, 101–110. <https://doi.org/10.3233/978-1-61499-061-1-101>

Louter, P. C. (2011). Fragile yet Ductile. <https://repository.tudelft.nl/record/uuid:15375137-d9f6-456d-a4de-df14d167a2d2>

Morgan, T. J., Thomas, P. G., & Hilton, J. (2017). Structural glass assemblies (United States Patent No. US9714509B2). [https://patents.google.com/patent/US9714509B2/en?q=\(glass+facade+connection+system\)&oq=glass+facade+connection+system](https://patents.google.com/patent/US9714509B2/en?q=(glass+facade+connection+system)&oq=glass+facade+connection+system)

Motedayen, M. (2025). Modular Float Glass Systems Designed for Reuse. <https://repository.tudelft.nl/record/uuid:b2e66bea-48c5-42f5-b53c-c463969a300c>

O’Callaghan, J., & Bostick, C. (2012). The Apple Glass Cube: Version 2.0. <https://doi.org/10.3233/978-1-61499-061-1-57>

O’Callaghan, J., & Coult, G. (2012). An All Glass Cube in New York City. 1–6. [https://doi.org/10.1061/41016\(314\)74](https://doi.org/10.1061/41016(314)74)

Oikonomopoulou, F., DeBrincat, G., & Fuhrmann, S. (2023). Glass and circularity. *Glass Structures & Engineering*, 8. <https://doi.org/10.1007/s40940-023-00230-3>

Oliveira, C., Teixeira, J. A., Oliveira, N., Ferreira, S., & Botelho, C. M. (2024). Microneedles’ Device: Design, Fabrication, and Applications. *Macromol*, 4(2), 320–355. <https://doi.org/10.1007/s40940-024-00230-3>

[org/10.3390/macromol4020019](https://doi.org/10.3390/macromol4020019)

O’Regan, C. (2014). *Structural Use of Glass in Buildings* (2nd Edition). Institution of Structural Engineers (ISTRUCTE). <https://app-knovel-com.tudelft.idm.oclc.org/kn/resources/kpSUGBE002/toc> (Original work published 2014)

Overend, M., Nhamoinesu, S., & Watson, J. (2013). Structural Performance of Bolted Connections and Adhesively Bonded Joints in Glass Structures. *Journal of Structural Engineering*, 139(12), 04013015. [https://doi.org/10.1061/\(ASCE\)ST.1943-541X.0000748](https://doi.org/10.1061/(ASCE)ST.1943-541X.0000748)

Pfarr, D., & Louter, C. (2023). Prototyping of digitally manufactured thin glass composite façade panels. *Architecture, Structures and Construction*, 3(2), 263–273. <https://doi.org/10.1007/s44150-022-00080-7>

Puller, K., & Sobek, W. (2012). Load-Carrying Behaviour of Metal Inserts Embedded in Laminated Glass. In *Challenging Glass 3* (pp. 307–314). IOS Press. <https://doi.org/10.3233/978-1-61499-061-1-307>

Ramming, L. (2022a). Advancing Transparency. <https://doi.org/10.7480/abe.2022.09>

Ramming, L. (2022b). The pursuit of transparency. In *Rethinking Building Skins* (pp. 89–115). Elsevier. <https://doi.org/10.1016/B978-0-12-822477-9.00033-4>

Sanders, K., Bos, F., ten Brincke, E., & Belis, J. (2021). Edge strength of core drilled and waterjet cut holes in architectural glass. *Glass Structures and Engineering*, 6(2), 131–145. <https://doi.org/10.1007/s40940-021-00146-w>

Santarsiero, M., Louter, C., & Nussbaumer, A. (2016). Laminated connections for structural glass applications under shear loading at different temperatures and strain rates. *Construction and Building Materials*, 128, 214–237. <https://doi.org/10.1016/j.conbuildmat.2016.10.045>

Santarsiero, M., Louter, C., & Nussbaumer, A. (2017). Laminated connections for structural glass components: A full-scale experimental study. *Glass Structures & Engineering*, 2(1), 79–101. <https://doi.org/10.1007/s40940-016-0033-2>

sbondadmin. (2013, January 6). Design Considerations for Solder Bonding. S-Bond. <https://s-bond.com/blog/design-considerations-for-solder-bonding/>

Stevels, W., Fildhuth, T., Wüest, T., Haller, M., & Schieber, R. (2022). Design Base for a Frameless Glass Structure Using Structural PVB Interlayers and Stainless-Steel Fittings. *Challenging Glass Conference Proceedings*, 8. <https://doi.org/10.47982/cgc.8.369>

The Strength of Glass. (2018). Saint-Gobain Building Glass UK.

Utsumi, A., Ooie, T., Yano, T., & Katsumura, M. (2007). Direct Bonding of Glass and Metal Using Short Pulsed Laser. *Journal of Laser Micro/Nanoengineering*, 2(2), 133–136. <https://doi.org/10.2961/jlmn.2007.02.0005>

## 6. Research Conclusion

van Abeelen, T., Mueller, L.-M., Ayvaz, I., Paschke, F., Dzipalski, A., Carter, R., Esser, M., Schwind, G., Seel, M., & Hand, D. (2025). Ultra-short pulsed laser welded-and-cut glass support pillars for vacuum insulating glass. *Glass Structures & Engineering*, 10. <https://doi.org/10.1007/s40940-025-00295-2>

Volakos, E., Davis, C., Teich, M., Lenk, P., & Overend, M. (2021). Structural performance of a novel liquid-laminated embedded connection for glass. *Glass Structures & Engineering*, 6(4), 487–510. <https://doi.org/10.1007/s40940-021-00162-w>

Volakos, E., Davis, C., Teich, M., Lenk, P., & Overend, M. (2023). Temperature effects on the behaviour of liquid-laminated embedded glass connections. *Engineering Structures*, 274. <https://doi.org/10.1016/j.engstruct.2022.115164>

Weller, B., & Schneider, J. (2021). *Engineered Transparency 2021: Glass in Architecture and Structural Engineering*. John Wiley & Sons.



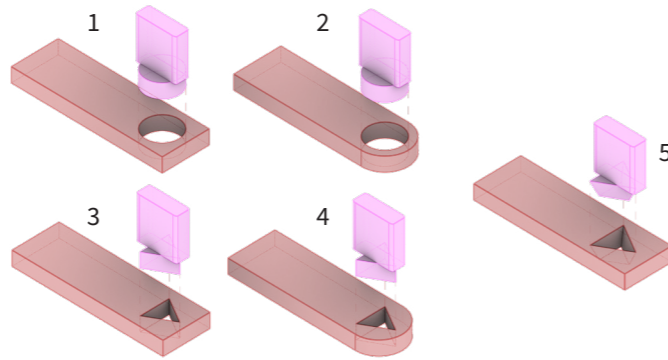
# Appendix

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Appendix 2	7.2
Appendix 3	7.3
Appendix 4	7.4
Appendix 5	7.5

Appendix 1

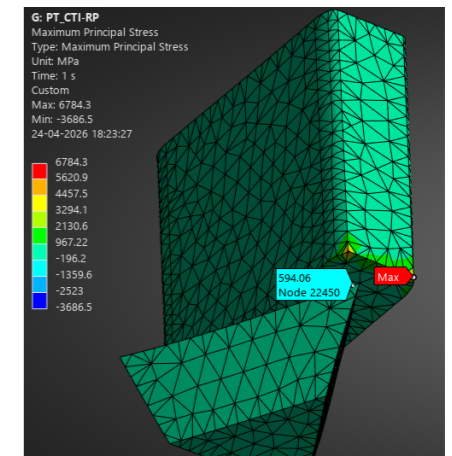
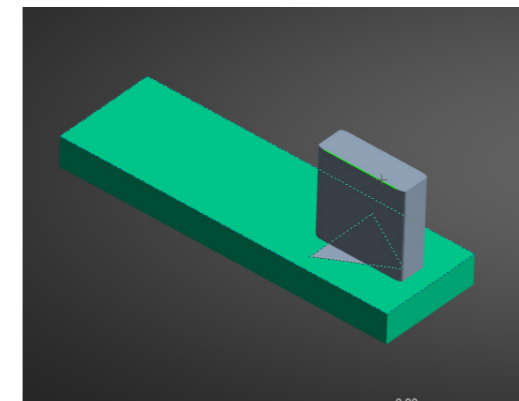
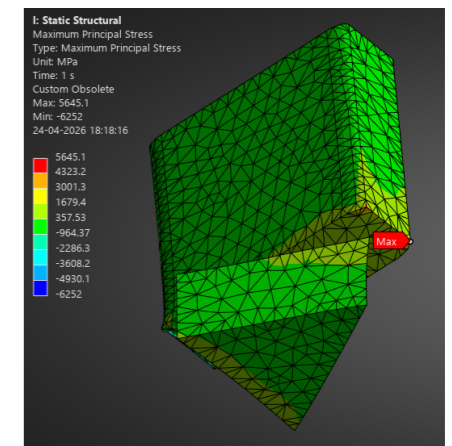
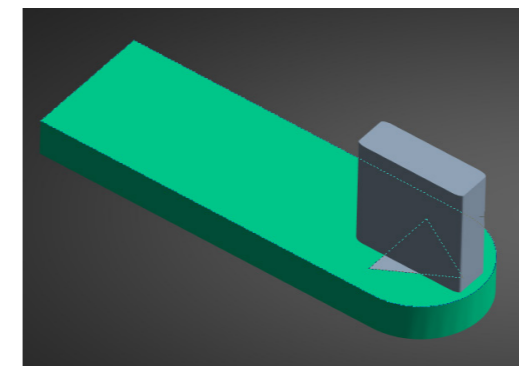
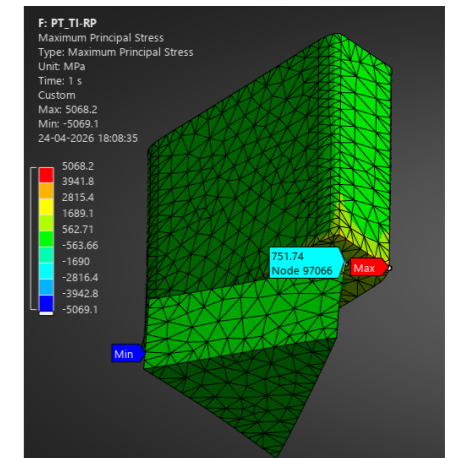
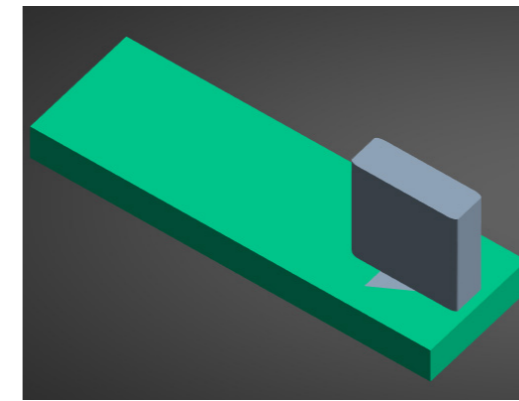
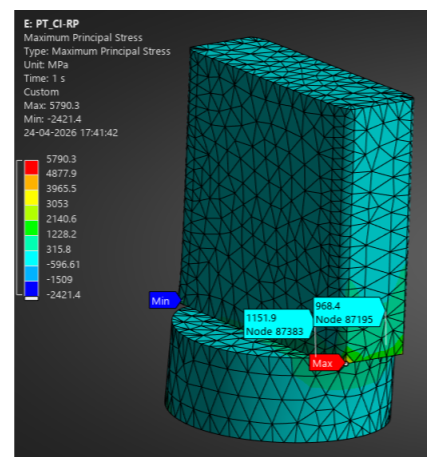
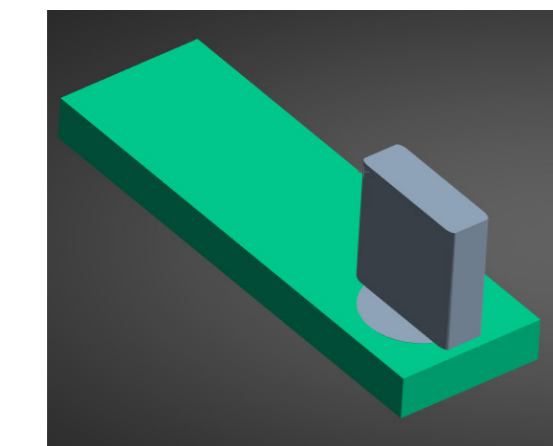
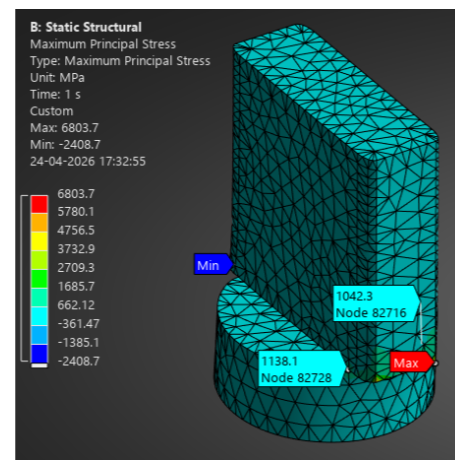
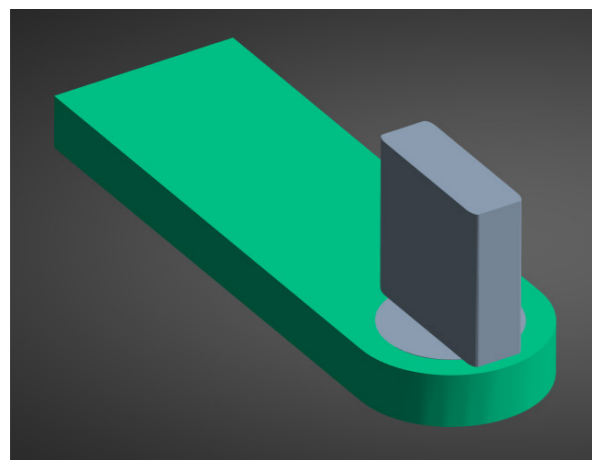
FEA of different configurations of pin and link for insert I7

	Link	Pin
1	Polygonal	Circular
2	Circular	Circular
3	Polygonal	Polygonal
4	Circular	Polygonal
5	Polygonal	Polygonal + Wedge



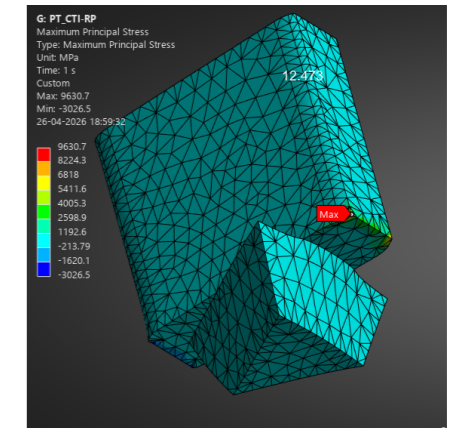
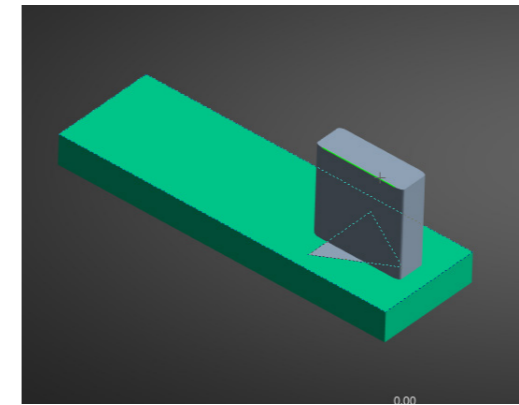
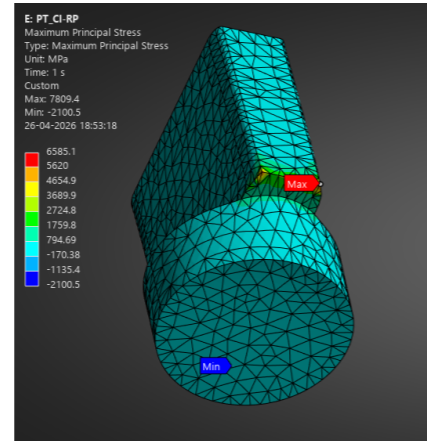
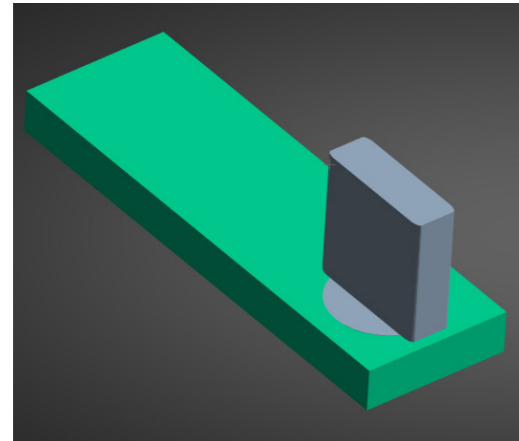
Pull-out (tension) simulations:

The same 40kN load was applied to eliminate the worst performing options

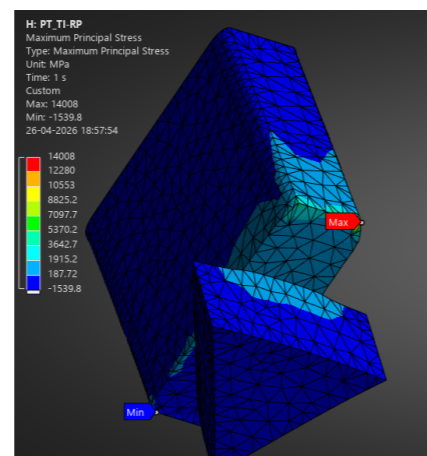
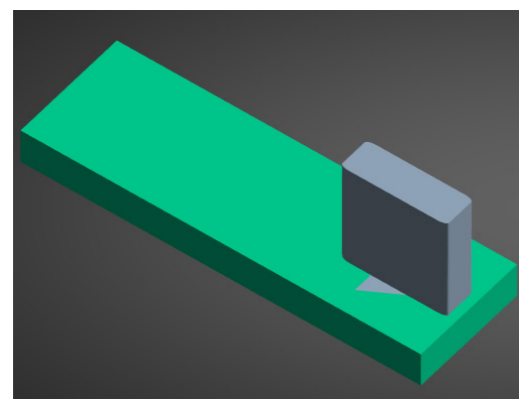
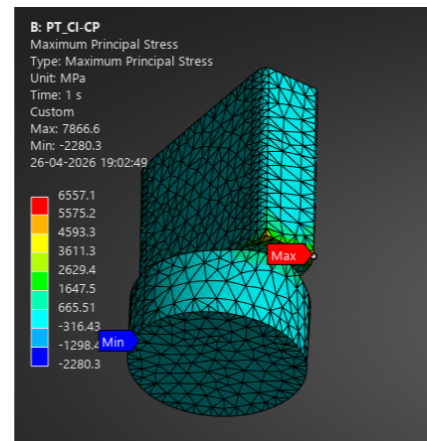
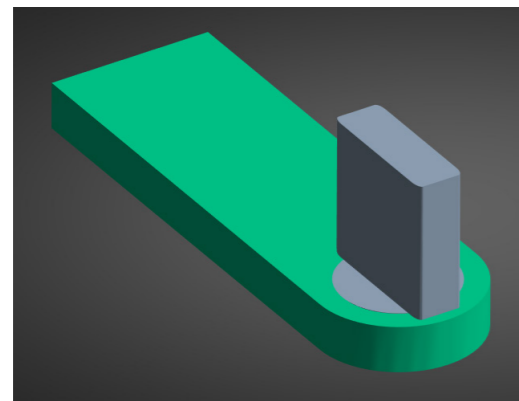


Polygonal pin with polygonal link performed better in pull-out loading. However, the insert experiences more chances of compression forces, rather than tensile. Compression forces are examined in the subsequent section.

Compression simulations:  
The same 40kN load was applied to eliminate the worst performing options



Polygonal link with circular pin performed better in compression loading. Since compressional loads are more likely to occur, the I7 insert proceeds with this configuration.

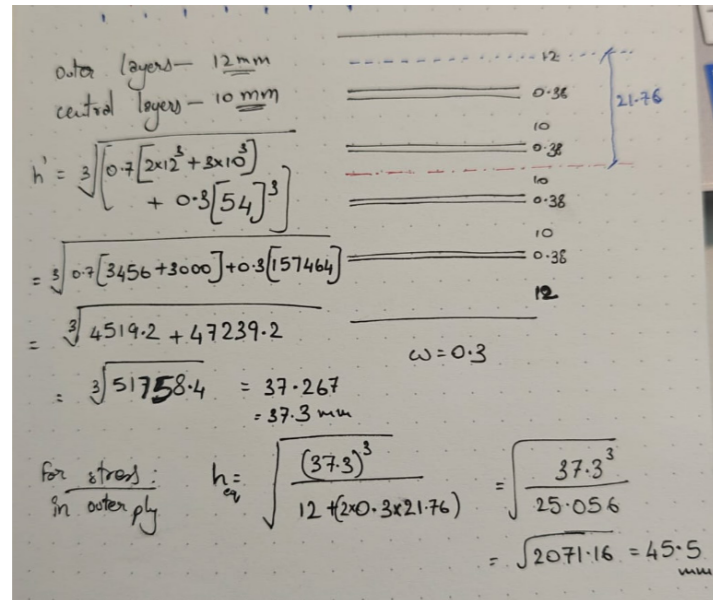


## Appendix 2

Load analysis of Roof panels + beam configuration with modified glass panel detail.

The glass module version 3, has been modified with 12mm thick panels on the outer edges instead 10, in an attempt to reduce the number of connections.

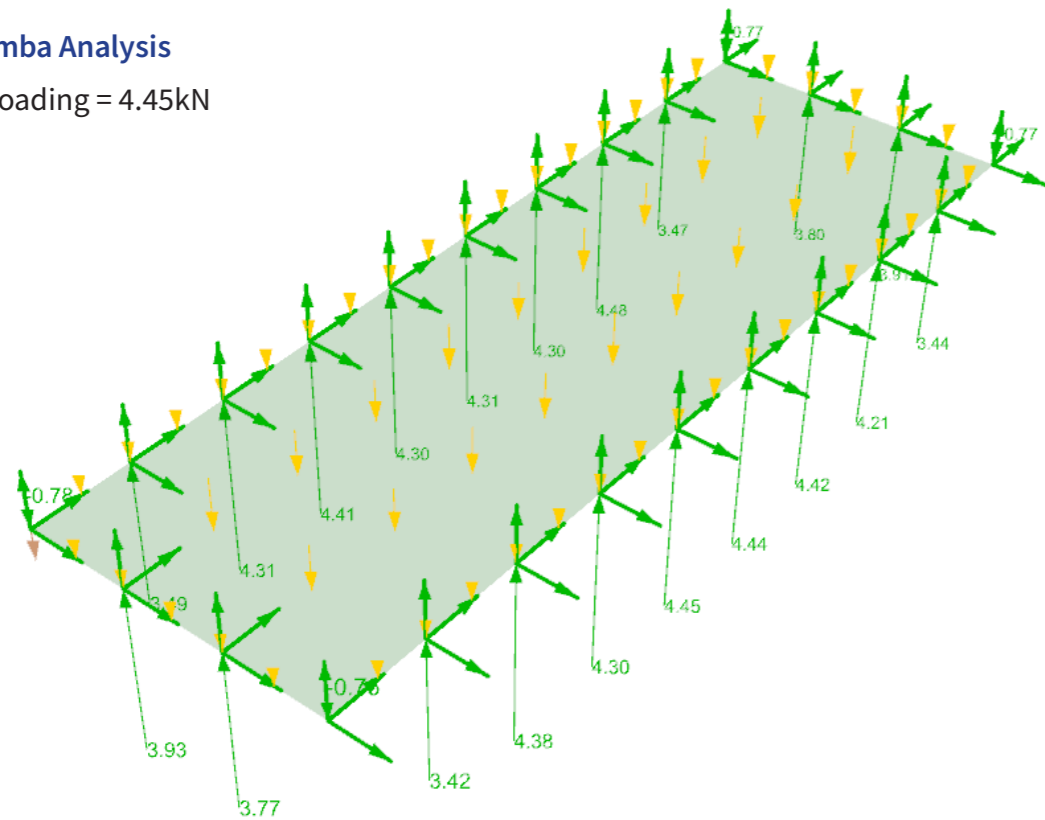
Equivalent monolithic glass thickness for karamba analysis:



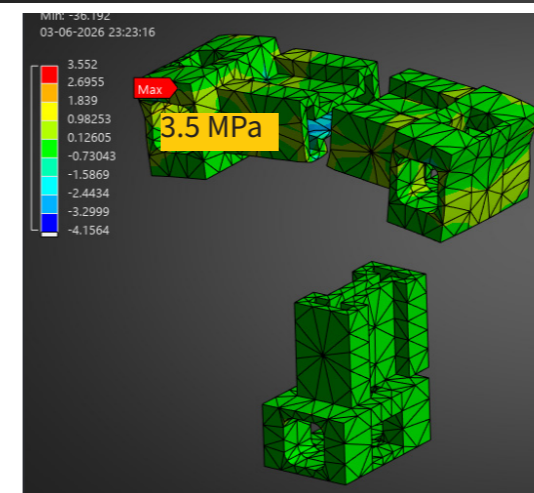
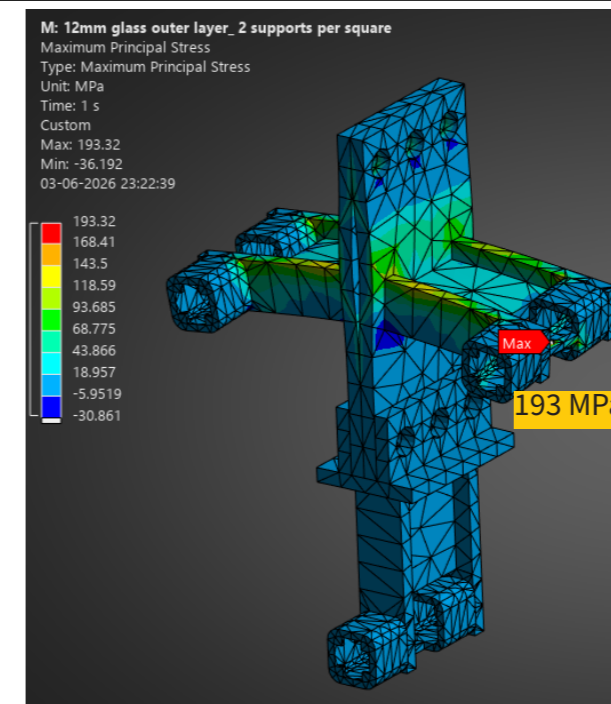
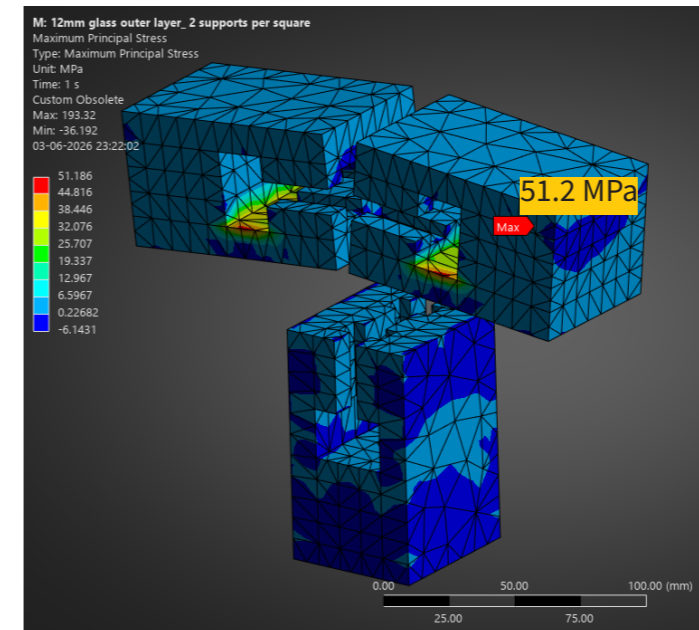
Glass thickness (equivalent) = 45.5mm

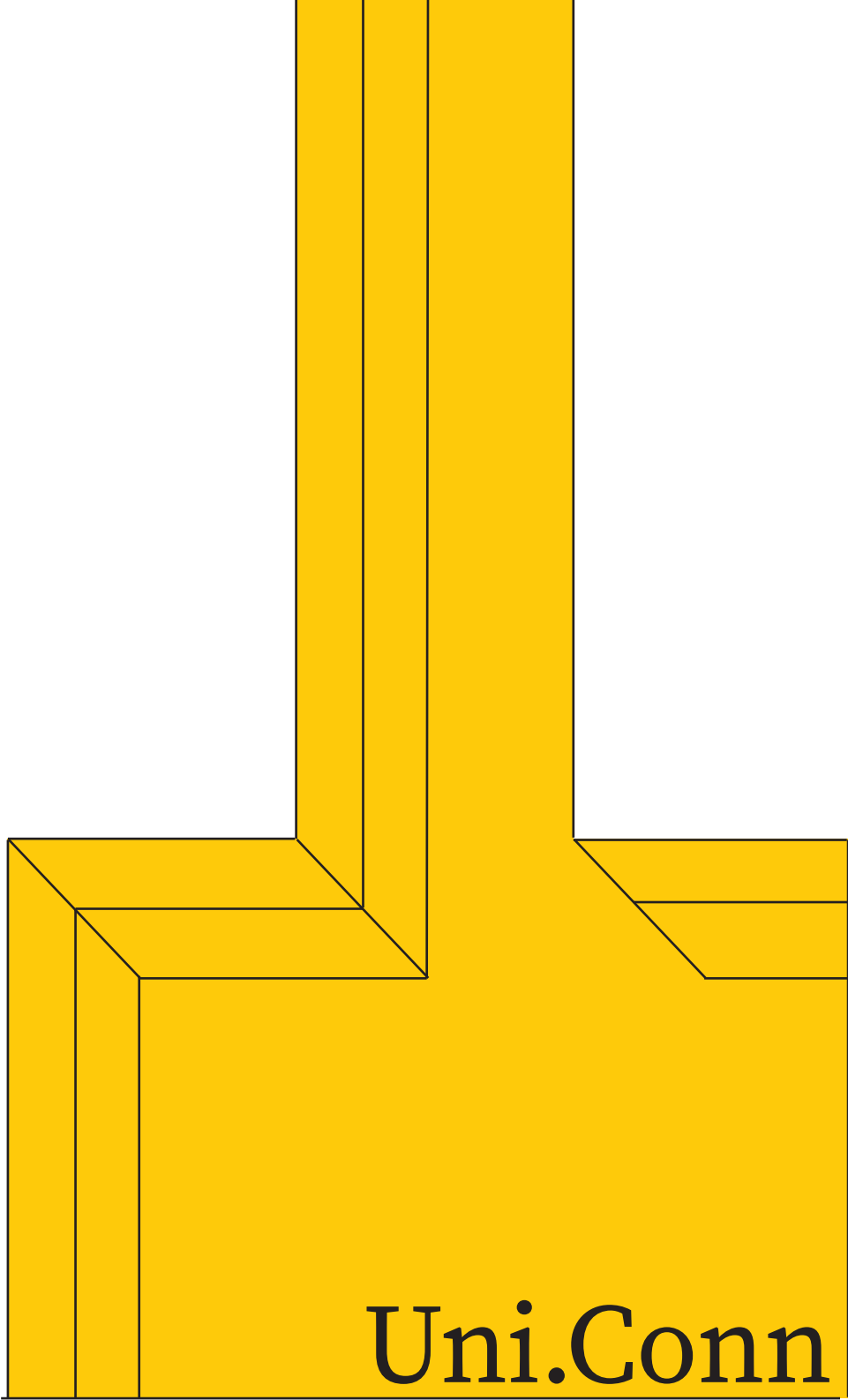
### Karamba Analysis

Max loading = 4.45kN



## FEA Analysis





Uni.Conn