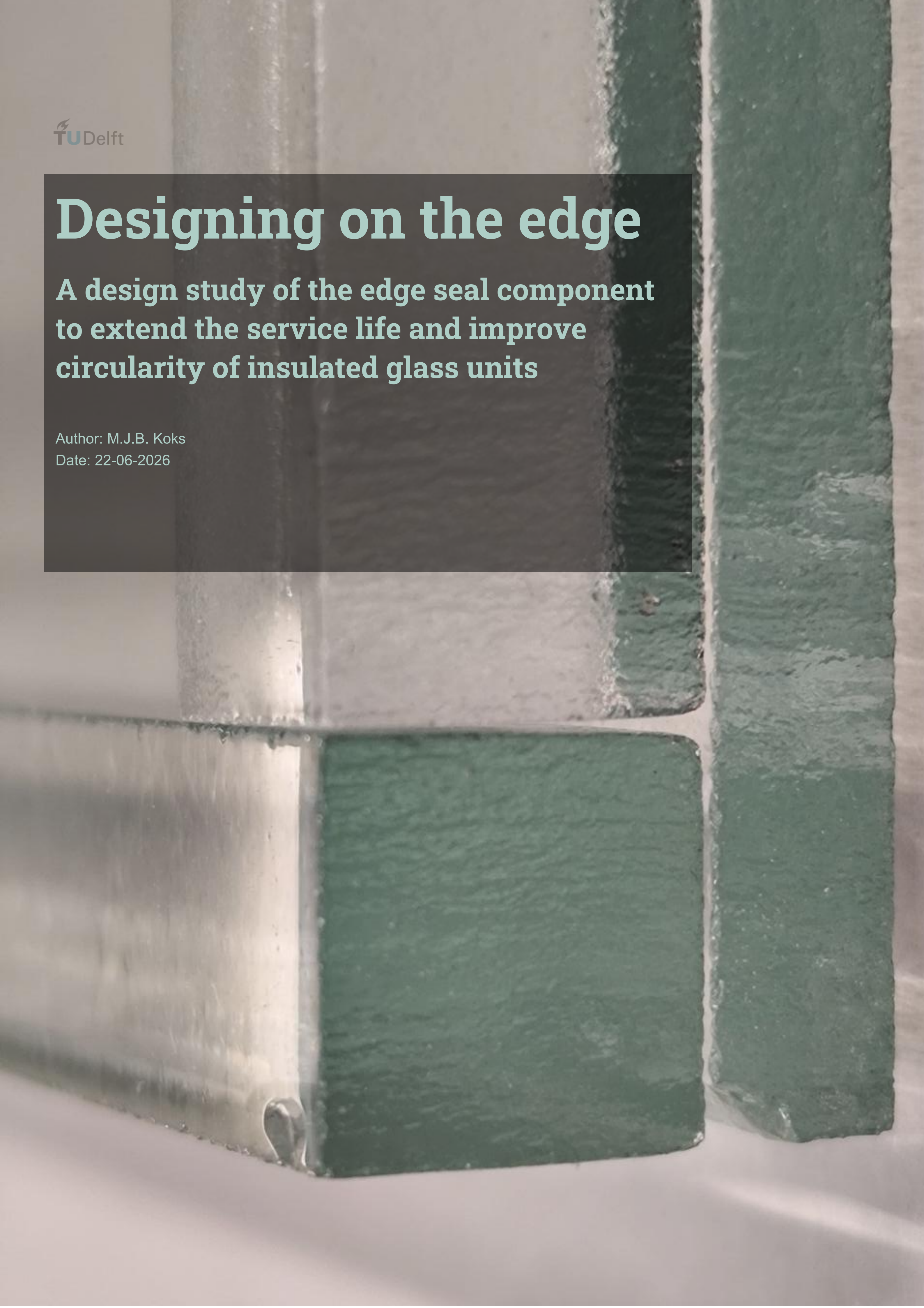


Designing on the edge

A design study of the edge seal component to extend the service life and improve circularity of insulated glass units

Author: M.J.B. Koks

Date: 22-06-2026

Designing on the edge

A design study of the edge seal component to extend the service life and improve circularity of insulated glass units

By

Marit J.B. Koks
5284740

22-06-2026

Master of Science
in Building Technology

at the Delft University of Technology,

Responsible supervisor	Dr. ir. Faidra Oikonomopoulou	TU Delft – BK-AET-S&M
Second supervisor	Dr. ing. Marcel Bilow	TU Delft – BK-AET- BD&T
External supervisor	Ir. Agnes van der Meij	TU Delft – BK-Arch

Acknowledgments

This master's thesis would not have been realised without the help and support of some people. Firstly, I would like to thank my two supervisors, Dr. ir. Faidra Oikonomopoulou and Dr. ing. Marcel Bilow for their enthusiastic support and guidance throughout the whole duration of my master's thesis. I am particularly grateful for Faidra and her guidance in helping me remain confident and interested in the project. For always supporting the goal and guiding me throughout the different steps of the research and for always giving me positive new energy to continue with the research.
I would also like to thank my second supervisor Marcel for his enthusiasm and guidance throughout my master's thesis. I specifically want to thank him for helping me realise the setup for the thermally debondable connection and for providing the materials needed.

This master's thesis includes a lot of experimental opportunities that were provided by the TU Delft and a lot of different enthusiastic professors that have dedicated their time and resources to this master's thesis research. I am particularly grateful for Dr. ir. Telesilla Bristogianni for providing us access to the Stevin II lab at civil engineering and her guidance and knowledge on glass and specifically on the use of the kilns and best way to approach the firing schedule.

I would also like to thank Hans van Ginhoven for providing the glass samples and for taking the time to waterjet cut the glass samples in the correct sizes.

Lastly, I would like to give an especially big appreciation to Dr. ing. Navid Vafa for investing a lot of time and effort into helping us realise the shear testing. Together with the help of TU Delft technician Ake Blom and my fellow student Pieter van der Werf I was able to build the test setup for the shear testing. But without the guidance and the time Navid put into performing and operating the tests, shear testing the glass samples would not have been possible. I would also like to thank Navid for processing the results of the test and for teaching me more about the principles of shear strength and stiffness.

Throughout the research process I was lucky enough to have come in contact with a lot of amazing people outside of the TU Delft that have taken the time to share their expertise with me and to help me guide my research in the right direction. Specifically, I would like to thank Valérie Hayez for her expertise in silicone and sealants, Christoph Rubel and Matthias Seel for their expertise in innovative spacer designs. I would also like to thank Ingrid Egtberts from GSF glasgroep for allowing me to visit their factory in Almere and for providing me with information.

Lastly, I would like to thank Cor Wittekoek from Vlakglas Recycling Nederland for providing me with post-consumer glass samples. Also, I would like to thank Cristian from team voordeligkunststof.nl for providing me with PETG samples.

Many thanks to my fellow students Emmanouela, Pieter, Krishna, Maja, Celia and more. Without you doing the master's thesis would not have been the same. I love that we supported each other and gave each other new positive energy to move forward. Sometimes just by telling someone everything was going to be all right. Or sometimes by sharing our troubles and struggles and helping each other out.
Special thanks to my supervisors for bringing us together as a group. This has really positively affected my experience in the master's thesis. Cause even though the master's thesis is an individual project and process. Being able to follow other people's feedback sessions allowed me to understand my own project better. And we were able to support each other and ask questions.

Lastly, I would like to thank the people closest in my life. I would like to thank all my friends and family. Special thanks to my boyfriend for being my rock for when times were harder and for always listening to my struggles. Thank you for giving me the balance, rest and distractions I needed.
My deepest gratitude goes to my mother, who has helped me not only during my master's thesis, but throughout my who life and in all school projects. Much love and thank you.

Thank you all sincerely. I could not have done this without you.

Abstract

Insulated glass units (IGUs) are essential components of contemporary energy-efficient building envelopes. The most conventional edge seal design in an IGU is the **dual-sealed metal spacer**. Although float glass is highly durable and recyclable, the **service life of an IGU is limited to 20-30 years** due to the degradation of sealants. UV exposure, thermal cycling, moisture ingress and mechanical stresses can compromise the durability leading to gas leakage, condensation within the cavity and reduced thermal performance. Furthermore, the permanent adhesion between glass panes, sealants and spacer prevents clean disassembly and often leads to contamination of glass cullet during recycling processes. As a result, most end-of-life IGUs are **downcycled**, mechanically crushed or disposed of as mixed construction waste rather than being reused or recycled into high-quality applications. Existing industry innovations have predominantly focused on improving thermal performance through warm-edge technologies, while the challenges of durability and circularity remain largely unresolved.

This research address the gap between thermal performance optimisation and the need for edge seal systems that simultaneously extend service life and support circular design strategies. Therefore, the objective of this master's thesis is to **redesign the edge seal component of insulated glass units (IGUs)** through material innovation and research-informed design, to **enhance durability and enable circularity**, while **maintaining the required performance** of IGUs and ensuring compatibility with standard façade systems.

Through literature-based exploration and systematic evaluation of the **current-state-of-the-art** and its limitations and by looking into the **requirements and regulations** according to the literature and the NEN norms and standards, a list of **design criteria**, to which a redesign of the IGU edge seal component should comply, was formed. These criteria included thermal, mechanical, moisture and gas resistance requirements, as well as additional criteria related to durability, demountability, contamination, and circularity.

The analyses demonstrate that the spacer and sealant components require fundamentally different material properties and therefore cannot be effectively replaced by a single material category. Material screening using the Granta EduPack database software combined with technical innovative literature-based connection research demonstrated that the most promising redesign strategy for the IGU edge seal system consists of combining a **heat-bonded glass spacer** connection with a flexible and preferably **thermally debondable polymer-based sealant** system. Experimental investigations demonstrated that glass fusion can create a durable and contamination-free connection. In addition, a thermally debondable connection using PETG showed potential as a reversible sealing strategy.

The resulting hybrid edge seal concept was **evaluated against predefined design criteria**. The results indicate that the concept can provide high thermal insulation, mechanical stability, environmental resistance, and air- and watertightness while significantly improving circularity. By limiting contamination to a single removable side and enabling future disassembly, the design facilitates reuse, remanufacturing, and high-quality recycling of glass panes. Furthermore, the replacement of conventional metal spacers reduces thermal bridging and contributes to improved thermal performance.

Although the concept remains at a **proof-of-concept** stage and requires further validation through accelerated ageing, durability testing, and full-scale prototyping, the findings demonstrate the potential of redesigning the IGU edge seal as a strategy to simultaneously improve durability and circularity. The research contributes to the growing field of circular façade design by shifting the focus from end-of-life management towards design-level interventions that address the root causes of premature IGU replacement. Demonstrating how material innovation and research-informed design can support the development of durable and more circular glazing systems.

Key words: ***Circular glass façade design; Insulating glass unit (IGU); Edge seal system; Glass fusing; Thermally debondable adhesives***

Contents

List of tables

List of figures

1. Introduction

From the 10th till the 21st of November 2025 delegates from more than 80 countries were present at the UN climate change conference in Belém, Brazil, at the edge of the Amazon forest. Here, they discussed if they are still on track to the climate goals set in the Paris Agreement (Harvey, 2025). The need for this climate conference was urgently pressed by the secretary general of the COP30 of Brazil, António Guterres. He stated that humanity has failed to limit global heating, which was set as a main goal in the Paris Agreement, to 1.5C above preindustrial levels (Harvey, 2025) Every country present must critically look at their Nationally Determined Contributions (NDCs) and make haste to update and deliver on their promises (Xipai & Watts, 2025).

In the front matter of this master's thesis a clear overview of the problem statement and the research questions is provided.

1.1 Background

Glass plays a **crucial role in the contemporary building envelop**, particularly in the form of transparent façade elements that balance daylight access, visual comfort and thermal performance (*Yeung, 2024*). As buildings become increasingly more energy efficient, the thermal performance of glazing systems has become a key factor in reducing operational energy consumption. Insulated glass units (IGUs) are therefore widely applied as standard transparent façade components in residential and commercial buildings.

An **insulated glass unit (IGU)** consists of two or more parallel panes of glass with a small space in between. They are separated by an aluminium spacer filled with desiccant and hermetically sealed at the edges to create a single unit. The cavity can be filled with air or an inert gas, like Argon, Xenon or Krypton, to improve the thermal insulation capacity of the transparent parts of the building envelope (*Glass Doctor, 2018*). A double glazed IGU can improve the U-value of glass from 5.2 W/m2K of a single glazed IGU to only 2.7 W/m2K (*Teich et al., 2024*). Whereas, triple glazing can even improve the U-value to only 0.5 W/m2K (*Saint-Gobain*, 2025).

Despite the performance benefits, IGUs are complex composite products composed of materials with very different lifespans. In practice, IGUs typically reach the **end-of-service-life after 20 – 30 years** (*Wolf, 1992*). The end-of-service-life for an IGU can be defined by the occurrence of condensation within the cavity or by a decline in thermal performance that no longer meets regulatory and functional requirements (*Likins-White et al., 2023*).

However, not all components of the IGU have reached their end-of life. Extensive research has shown that the **durability of IGUs** is not governed by the glass itself, but by the **quality and performance of the edge seal system** (*Nizich et al., 2022; Wang et al., 2024; Wolf, 1992*). The edge seal connects the glass panes and spacer into a sealed single unit and performs two critical functions: limiting water vapour ingress to prevent condensation and maintaining mechanical integrity under external and internal loads *(Nizich et al., 2022*). The majority of the IGUs are manufactured using a dual-edge system. The primary sealant, mostly Polyisobutylene (PIB), functions as the water vapour barrier and the secondary sealant is an elastic sealant that provides structural strength and elasticity (*Wolf, 1992*). The studies identify that environmental loads, such as temperature fluctuations, high humidity, mechanical stresses, Ultraviolet radiation and chemical exposure lead to ageing of the sealants (*Wang et al., 2024*). The water vapour diffusion of the primary sealant is the critical component to maintain long service life, but is dependent on the mechanical support and elastic recovery of the secondary sealant (*Wolf, 1992*).

The relatively short service life of the IGU has significant implications in the context of **sustainability and circularity**. While the soda-lime-silica float glass is highly durable and theoretically completely recyclable without loss of quality (*Elstner et al., 2024*), due to the presence of contaminations from sealants, coatings and spacers, reuse and high-quality recycling is almost never possible (*Oikonomopoulou et al., 2023*). Despite increasing emphasis on circular construction, practices, higher risks because of unknown quality *(Elstner et al., 2024*) and higher costs for safe removal, transportation and storage of the post-consumer IGUs restrain the circularity of IGU (*Reshamvala et al., 2024; Teich et al., 2024*). Consequently, most of the post-consumer flat glass from automotive or architectural industries ends up either downcycled or in landfill waste. Currently 75% of glass and 60% of construction and demolition waste are disposed in landfills (*Ferdous et al., 2021*). Only 21% glass is currently recycled globally *(Ferdous et al., 2021*). The rest is being downcycled to other practical products for glass, like container glass or glass insulation.

1.2 Problem statement

The current design of insulated glass units is constrained by organic edge seal systems that degrade significantly faster than the glass itself, leading to early end-of-life, loss of thermal performance, and limited opportunities for reuse or high-value recycling. Addressing the edge seal as the weakest component is therefore essential to extend IGU service life, improve durability and enable more circular end-of-life pathways for architectural glass.

Despite the proven circular potential of glass, its application in IGUs remains largely linear in practice. Peter et al. (*2024*) stated the general challenges that are faced when recycling materials, like the high costs and the higher risk with unknown quality. Multiple studies demonstrate that post-consumer float glass retains sufficient material quality for reuse, while reuse and remanufacturing strategies significantly reduce embodied energy and can meet modern energy requirements *(Cupać et al., 2024; Overend & Zammit, 2012; Reshamvala et al., 2024; Teich et al., 2024*).

1.3 Circular glass solutions

Several initiatives within the glass and façade industry aim to improve the circularity of insulated glass units (IGUs). These initiatives primarily focus on recycling, upcycling, reuse, and remanufacturing strategies to reduce waste generation, lower embodied carbon emissions, and extend the service life of glass products.

One notable recycling initiative is presented in the *Re-thinking the Life Cycle of Architectural Glass* report by Arup (*DeBrincat et al., 2018*). The aim of the report is to research the economic, technical, environmental and logistical viability of post-consumer construction flat glass closed-loop recycling, including a study of the regulatory drivers, opportunities and barriers. The report emphasizes that recycling glass into new glass products can significantly reduce energy consumption and CO_2 emissions while supporting the transition towards a circular economy. To stimulate industry-wide adoption, the report proposes incorporating glass recycling requirements into future façade refurbishment project specifications. The report further argues that designers and engineers should integrate circular economy principles and material selection considerations from the earliest stages of the design process, thereby influencing both material choices and client decision-making processes (*DeBrincat et al., n.d.*). However, further research and innovation are still required to develop materials and construction methods that enable the effective recycling of all major façade components.

In addition to recycling, upcycling approaches have emerged as an alternative strategy for valorising waste glass streams, like UPCAST Glass project. Conventional glass recycling processes often struggle to accommodate contamination and compositional variations present in post-consumer glass, resulting in large quantities of non-container glass being downcycled or landfilled at the end of its service life. UPCAST Glass addresses these limitations by developing a novel casting process for recycled glass that tolerates variations in composition and contamination from diverse waste streams (*Bristogianni & Oikonomopoulou, 2023*). Furthermore, the project investigates methods for assessing the influence of defects in recycled glass components and provides material property databases and design guidelines for transforming waste glass into high-value architectural products.

A third circular strategy focuses on the reuse and remanufacturing of existing IGUs. An example of this approach was observed during a factory visit to GSF Glasgroep B.V., where the company developed the isoMAX system, presented as the world's first circular IGU (*GSF Glasgroep B.V., n.d.)*. The remanufacturing process uses the HEGLA IG2Pieces system to separate post-consumer IGUs. Following disassembly, the recovered glass panes are inspected for quality, after which the contaminated edge regions are removed and the panes are resized according to new project requirements. The reclaimed glass is subsequently integrated into newly manufactured IGUs containing either 50% or 100% reused glass components. This approach demonstrates the potential of remanufacturing strategies to preserve material value and significantly reduce the environmental impact associated with new glass production.

1.4 Research gap

These approaches and research remain largely experimental and face persistent technical, economical and logistical challenges. This existing research focuses on end-of-life strategies, such as recycling, reuse or remanufacturing for conventional IGU configurations. **However, this still ignores the fundamental flaw in the IGU design: While glass is a material that is highly durable and recyclable, the design of the IGU enforces premature end-of-life. The edge seal component, rather than the glass itself, determines the service life and decreases the circular potential of the system.**

Kouvela *(2022)* approached this intrinsic design limitation of the IGU itself and proposed different redesign options for this connection. Kouvela *(2022)* initiated a design-driven exploration of alternative edge seal concepts, however the proposed solutions were not validated in terms of long-term performance or durability.

1.5 Objective

This master's thesis tries to continue the work of Kouvela *(2022)* by considering her redesign proposal and creating and validating new design options for future applications. That is why, the main objective of this research is to redesign the edge seal component of insulated glass units (IGUs) through a research-informed design approach, with the aim of extending their service life, improving durability, and enabling more circular use within façade systems.

1.6 Research questions

1.6.1 Main research question

How can the edge seal component of insulated glass units (IGUs) be redesigned through material innovation and research-informed design to enhance durability and enable circularity, while maintaining the required performance of IGUs and ensuring compatibility with standard façade systems?

1.6.2 Sub-questions

Phase 1: Literature review

SQ0 – Current-state-of-the-art
What is the current design of the IGU edge seal component and what currently happens at the end-of-service-life?

SQ1 – Design criteria
What functional, material, and environmental requirements must an IGU edge seal meet to comply with existing regulations, and what properties could be improved to extend the service life of an IGU and support circularity?

Phase 2: Material and technical research

SQ2 – Material level
Which alternative materials or material combinations can facilitate clean material separation and reduce contamination to the glass, thereby enabling recycling or reuse of individual materials at end of the IGU service life?

SQ3 – Component level
Which innovative connection techniques have the potential to replace conventional edge seal connections in insulated glass units (IGUs) while supporting durability, circularity and technical performance requirements?

Phase 3: Research-informed design

SQ4 –Engineering connection
How can experimentally developed alternative edge connection systems for insulated glass units be engineered to improve durability and circularity, while maintaining compliance with defined performance requirements?

1.7 Relevance

1.7.1 Relevance to master’s studio

The emphasis of the master’s Building Technology is on the design of innovative and sustainable building components and their integration into the built environment. This research directly aligns with the objectives of the master’s thesis studio in Building Technology by addressing the performance, durability and material behaviour of a critical building component at system level by looking into innovation technologies and sustainable material options.

1.7.2 Social relevance

The world is moving towards a circular economy that focuses on reducing wastes and keeping materials in use for the longest time possible. In the current linear economy, raw materials are taken from the earth to make products and to use them till their end-of-life. Afterwards we throw them away as landfill waste. The goal of a circular economy is to keep materials in circulation, through processes like maintenance, reuse, refurbishment, remanufacture and recycling and to stop producing more waste (*Ellen MacArthur Foundation, 2024*). The closer we stay by the user phase of the material, the less energy and therefor greenhouse gases (GHG) are emitted (*Ellen MacArthur Foundation, 2019*).

The building sector is a big contributor to the effects of climate change. The building construction sector consumes around two third of raw materials, like iron ores, silica and sand (*RVO, 2025*). Besides that, the building construction sector also uses a lot of intermediate products, like water and electronic equipment (*RVO, 2025*). The building construction sector is also responsible for 33% of the total generated waste in Europe (*RVO, 2025*). Within the EU, 85% of the current building stock predates 2001 and the majority of these existing buildings will still be in use in 2050 (*European Commission, 2020*). These existing buildings are generally not energy-efficient and rely on fossil fuels and are equipped with outdated technology. As a result, the building sector is responsible for about 40% of the EU’s total energy consumption (*European Commission, 2020*) and for one third of the total GHG emissions (*EEA, 2025*).

Evidence from the Dutch case shows that retrofitting existing buildings offers a promising solution to reduce construction and demolition waste (CDW) and reduces the energy demand for buildings (*Zhang et al., 2021*). This highlights the critical importance of improving the performance of the existing building stock to meet long-term climate goals. Within the refurbishment policy of the EU lies the opportunity to, instead of replacing, refurbish the insulation glass units (IGUs) found in these existing buildings.

IGUs are essential components of energy-efficient façades, yet their relatively short service life results in frequent replacement and substantial material waste, despite the durability of the glass itself. Insulated glass units are expected to have a service life of between 20 and 30 years (*Wolf, 1992*). Their service life is often limited by the failure of a specific component rather than by the glass itself. In the current linear economy, this will mean that a lot of that glass will end up in landfill waste and just a really small amount will be recycled (*Cupać et al., 2024*). Currently 75% of glass and 60% of CDW are disposed in landfills (*Ferdous et al., 2021*). Only 21% glass is currently recycled globally (*Ferdous et al., 2021*). However, glass itself is highly durable and is 100% recyclable (*Cupać et al., 2024*). Improving the longevity and circularity of IGUs therefore directly contributes to reducing embodied energy, construction waste, and greenhouse gas emissions.

By addressing the edge seal as the primary factor limiting the IGU service life, this research responds to the need for longer lasting and more circular façade systems. Extending the service life of IGUs has the potential to reduce replacement rates, lower embodied energy and decrease construction and demolition waste. Redesigning the edge seal may enable easier demountability for refurbishment, reuse and remanufacturing of IGUs, therefore contributing to more sustainable practices. Or the redesign may increase the expected service life of the IGU by making the edge seal component more durable.

Therefore, this research is relevant to architects, façade engineers, IGU and glass manufactures and policymakers seeking to transition the built environment toward circular construction.

1.7.3 Scientific relevance

While the social relevance of this research lies in reducing environmental impact and supporting circular construction, its scientific relevance lies in advancing design-oriented knowledge on IGU edge seal systems with respect to durability and circular potential.

From a scientific perspective, existing research on insulated glass units has predominantly focused on performance optimization, durability testing, and end-of-life strategies such as recycling and remanufacturing. While these studies demonstrate the technical feasibility of circular approaches, they largely assume conventional IGU configurations and treat edge seal failure as an unavoidable condition.

This research contributes to scientific knowledge by shifting the focus from end-of-life management to design-level intervention. By investigating alternative materials, assemblies, and design strategies for the edge seal, the research addresses a critical yet underexplored component that governs both durability and circular potential. Furthermore, the study contributes to research-informed design methodology by integrating material research, technical performance requirements and iterative prototyping. In doing so, it aims to bridge the gap between experimental research and scalable façade applications, offering new insights into how durability and circularity can be embedded into IGU design.

1.8 Scope

1.8.1 Context

The research focuses on the redesign of the edge seal component in the IGU in order to extend its service life. This study concentrates on exploring technical innovations for redesigning the edge seal component and includes material research to improve durability, while maintaining the thermal, optical and structural properties of the IGU.

The research is positioned within the broader transition towards circular construction and increasing interest in design-for-disassembly approaches in façade engineering. Within this context, the edge seal is identified as a critical component influencing the service life, reparability, and end-of-life processing of IGUs. The study therefore examines how material innovation and research-informed design methodologies can contribute to more circular glazing systems.

The scope of the research includes qualitative and comparative evaluations of functional performance requirements based on relevant Dutch NEN standards and façade engineering principles to assess the technical feasibility of redesigned edge seal concepts.

Within the circularity objectives of this study, priority is given to preserving the reuse and recyclability potential of the glass panes themselves. Consequently, the environmental value of enabling glass recovery is considered more significant than achieving full circularity of the edge seal materials.

1.8.2 Limitations

This research is limited to the conceptual redesign and experimental prototyping of alternative IGU edge seal connections. The study is conducted primarily at the component level and does not extend to full façade systems, complete window assemblies, or whole-building integration. Furthermore, the research does not consider the influence or redesign of window framing systems. The research does not include full-scale industrial prototyping, long-term durability validation, accelerated aging tests, or certification procedures required for commercial implementation. As a result, the proposed concepts cannot be considered market-ready or compliant with all regulatory performance requirements. Furthermore, the study does not evaluate industrial manufacturing feasibility, supply-chain integration, market adoption, or economic viability.

The experimental investigations are limited to preliminary material and connection testing intended to explore proof-of-concept feasibility rather than provide definitive lifetime performance predictions. In addition, the research does not include a complete life cycle assessment (LCA) or quantified environmental impact analysis.

This study is restricted to double-glazed IGU configurations and does not investigate triple-glazed systems. The research mainly focuses on conventional float glass applications and excludes extensive investigation into laminated glass, cast glass, or highly specialized glazing systems.

2. Methodology

The goal of this master's thesis is to research and design an edge seal component to extend the service life and the circularity of insulated glass units. In this methodology the structure of the master's thesis is explained according to the research parts and report chapters. Also, a timeline is presented to show the planned research approached over time.

2.1 Research methods

This master's thesis is structured into three consecutive phases: literature research, material and technical research and research-informed design. Each phase addresses specific sub-questions and builds cumulatively toward the redesign of the IGU edge seal component, with the main goal to find an answer to the main research question: *How can the edge seal component of insulated glass units (IGUs) be redesigned through material innovation and research-informed design to extend their service life, while maintaining the required performance of IGUs and ensuring compatibility with standard façade systems?*

The first phase consists of literature research aimed at defining functional, material, and environmental requirements for the IGU edge seal. Scientific literature on IGUs, edge seal durability and failure mechanisms is combined with a review of the relevant standards and regulations regarding the IGU performance requirements. This phase results in design criteria that form the basis for subsequent research and design decisions.

The second phase focuses on material and technical research at both the IGU edge seal component level and the material level. At material level, alternative materials and material combinations are explored and evaluated based on the performance requirements and circularity. The alternative materials are selected through an evaluation of the necessary material properties in the edge seal. At component level, the conventional IGU edge seal is analysed through functional decomposition to identify crucial technical functions. Alternative glass connections and edge seal configurations are investigated. The objective is to identify an alternative component configuration that can both extends the service life of IGU and enable demountability for reuse.

In the third and last phase, all the information from the literature and material and technical researched is combined to identify the most promising design approach. A research-informed design strategy is implemented to investigate the alternative edge seal designs. Sketching and prototyping is used to develop, evaluate, assess and refine the design options. The objective of this phase is to create a prototype of a demountable IGU edge seal that demonstrates potential to extend the service life of the whole IGU.

Phase 1	***Goal***	***Method***
SQ0 – Current-state-of-the-art *What are the opportunities and limitations of the existing IGU edge seal design and what currently happens at the end-of-life?*	Set a baseline for the research	**Literature research** • Investigate the current state-of-the-art of the IGU design and its sustainability and durability • through literature-based research using data and literature found on various databases online
SQ1 – Design criteria *What functional, material and environmental requirements must an IGU edge seal system meet to comply with existing regulations, and which performance properties should be improved to extend the service life and support circularity?*	Define requirements and boundary conditions Translate into design criteria	**Literature research** • Investigate IGU performance, durability and failure mechanisms • Review of relevant standards and regulations (e.g. IGU performance, durability, façade integration) • Analysis of circularity principles relevant to façade components

Phase 2	***Goal***	***Method***
SQ2 – Component level *Which innovative connection techniques have the potential to replace conventional edge seal connections in insulated glass units (IGUs) while supporting durability, circularity and technical performance requirements?*	Research component-level logic, durability, and demountability	**Literature research** • Literature-based functional decomposition of the conventional edge seal system • Literature-based comparative analysis of existing and alternative edge seal concepts • Literature-based technical assessment of demountable vs bonded assemblies • Literature-based qualitative performance assessment (thermal, mechanical, airtightness)
SQ3 – Material level *Which alternative materials or material combinations can enable recycling or reuse at the end-of-life by facilitating clean separation and reduce contamination within the IGU edge seal?*	Research materials on behaviour and circularity potential	**Database-supported analysis research** • Material screening (permeability, ageing, chemical compatibility) • Assessment of bonding vs non-bonding material strategies • Database-supported comparative eliminative research into material database Granta Edupack

Phase 3	***Goal***	***Method***
SQ4 – Experimental design *How can experimentally developed alternative edge connection systems for insulated glass units be engineered to improve durability and circularity, while maintaining compliance with defined performance requirements?*	Analyse and design synthesis and validation	**Research through design** • Iterative design process combining insights from SQ1–SQ3 using research through design approach • Sketching and detailing of alternative edge seal concepts **Experimental research** • Physical prototyping • Assembly–disassembly testing • Test design alternatives against design criteria

Table 1: Methodology

2.2 Timeline

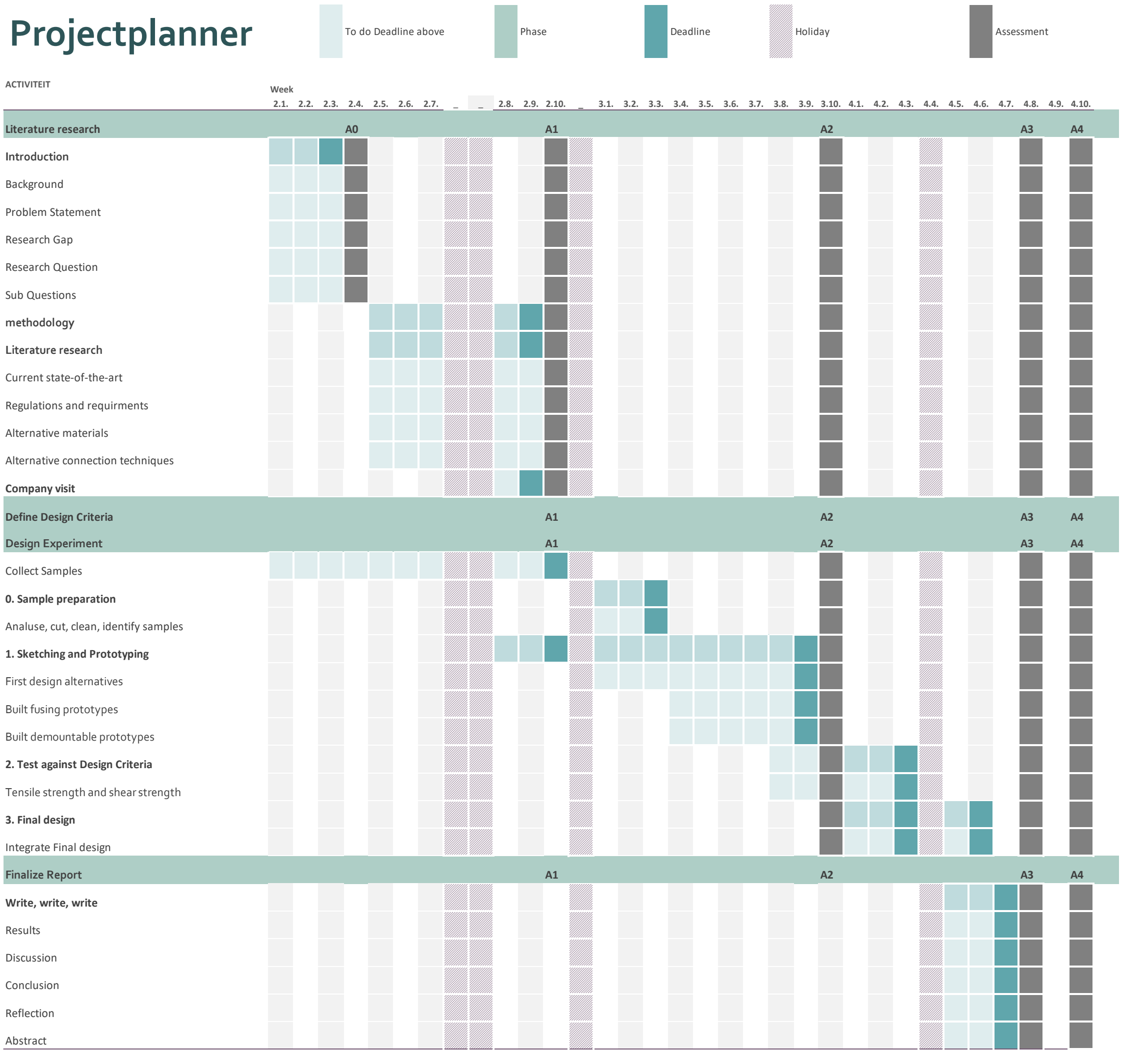


Figure 1: Timeline master's thesis planning (own image)

3. Literature research

This chapter presents a literature review of the most commonly used insulated glass unit (IGU) edge seal systems, existing alternative designs and the regulatory and performance requirements that govern their application. By analysing scientific literature, industry standards, and technical guidelines, the chapter provides an overview of the state of the art in IGU edge seal design and performance.

The goal of this chapter is to identify the functional, regulatory, and performance-driven constraints that define the design space of the IGU edge seal. Through the evaluation of existing systems, documented failure mechanisms and applicable standards related to thermal performance, durability, gas retention, and moisture resistance, the chapter establishes a set of design criteria and boundary conditions. These criteria form the foundation for the subsequent material and technical research and guide the development of alternative edge seal concepts with improved durability and circularity.

3.1 Current-state-of-the-art

The introduction has demonstrated that the edge seal component is identified as a critical determinant of the functional performance and durability of an IGU. In order to develop strategies for extending the service life it is necessary to first examine the existing alternatives for the edge seal component and learn from their performance limitations and improvements.

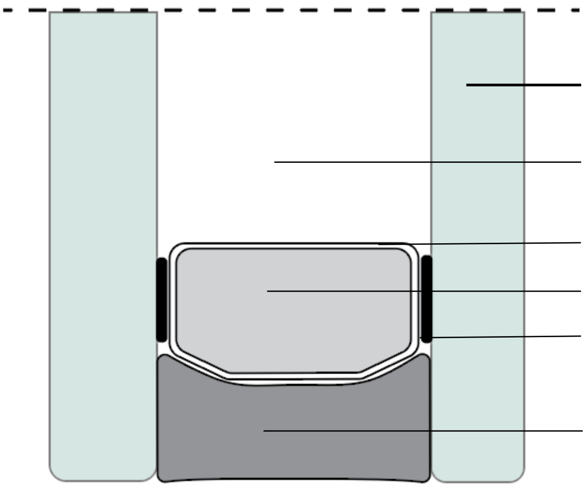
The dual-sealed metal spacer remains the standard of today's European market. However, alternative spacer materials and configurations have emerged in response to increasing thermal performance requirements. Table 2 shows an overview of the already existing edge seal designs currently available on the market.

3.1.1 Conventional edge seal

Figure 2 shows the conventional IGU commonly used in Europe, consisting of two or more parallel panes of glass with a small space in between, separated by metal standard dual edge seal *(Van Den Bergh et al., 2013*). This spacer is typically made from aluminium, galvanized or stainless steel filled with desiccant and sealed at the edges to create a single unit (*Wolf, 1992*). The cavity can be filled with air or an inert gas, like Argon, Xenon or Krypton, to improve the thermal insulation capacity of the transparent parts of the building envelope (*Glass Doctor, 2018*).

The spacers provide mechanical stability and keeps the glass panes at a specific distance from each other. It is usually filled with a desiccant to absorb moisture within the cavity and prevent fogging (*Glass Doctor, 2018*). A desiccant is a hygroscopic substance that attracts or absorbs moisture from the surrounding air to maintain dry air (*Greenberg, 2025*). The most commonly used desiccant in IGUs is silica gel (*Wolf, 1992*).

Together with the spacer, the secondary sealant provides the needed mechanical stability and keep the unit together. The secondary sealant is normally made from polysulphide, polymercaptan, polyurethane or silicone (*Nizich et al., 2022; Wang et al., 2024; Wolf, 1992*). It needs to manage external and internal loads and to allow for small movements to prevent stresses, but at the same time constrain for bigger deformations to prevent excessive extension from the primary sealant (*Nizich et al., 2022*). The primary sealant is normally made with polyisobutylene (PIB), with low water vapour and gas permeability (*Van Den Bergh et al., 2013*). Its main function is to prevent water vapour from entering the cavity and to prevent gas from escaping the cavity (*Wang et al., 2024*).



Component	Material	Main function
Float glass	- Annealed glass - Tempered glass - Laminated glass	- Transparency - Mechanical stability - Environmental resistance
Cavity	- Dry air - Inert gas: Argon, Krypton or Xenon	- Thermal insulation - Sound insulation
Spacer	- Aluminium - Galvanized steel - Stainless steel	- Mechanical stability - Moisture barrier
Desiccant	- Silica gel	- Water vapour absorption
Primary Sealant	- Polyisobutylene (PIB)	- Low water vapour permeability - Low gas permeability - Moisture and gas barrier
Secondary Sealant	- Polysulphide (PS) - Polymercaptan (PM) - Polyurethane (PU) - Silicone (S)	- Provide mechanical stability - Allow movements

Figure 2: IGU dual-sealed edge (own image)

Table 2: IGU dual-sealed edge components, materials and main function

3.1.2 Performance limitations of conventional edge seals

Although IGUs offer significant thermal advantages in façade applications, conventional metal spacers present several inherent performance limitations. The standard metal spacers create **thermal bridges**, due to their high thermal conductivity (*Van Den Bergh et al., 2013*). This results in significant temperature differences between the centre of the glass and the edge region of the IGU. The low temperatures in the edge of the glass increase the risk for condensation in the cavity.

The second performance limitation of the edge seal component influences the **durability** of the IGU. Even though glass is a durable material, the service life of the IGU is only 20-30 years (*Wolf, 1992*). The end-of-service-life for the IGU can be determined when the slipping and debonding of the primary edge seal, caused by temperature fluctuations or high humidity, resulting in condensation in the cavity and a lower thermal performance *(Likins-White et al., 2023; Wang et al., 2024*).

Lastly, the design of the conventional edge seal is not **circular** *(Peters et al., 2024; Teich et al., 2024*). Besides the economic, technical and logistical constraints of circular strategies, like the extra costs, higher risks and difficulty of safe removal and transport, the IGU is not demountable, which make reusing the different components before their end of life more difficult (*Rota et al., 2023*). Also the sealants used, cause contaminations on the glass, which make it harder to reuse and recycle the glass panes (*GSF Glasgroep B.V., n.d.*).

3.1.3 Improved edge seal

Thermal performance improves significantly when traditional metal spacers are replaced with improved metal spacers and non-metal spacers (*Van Den Bergh et al., 2013*). The main improvement is that these spacers have a **lower thermal conductivity** then the metal spacers or use techniques to break the thermal bridge. The technique that uses this principle is called **warm edge technology (WET)**. Warm edge spacers work by separating the glass panes using low conductivity materials, like plastic (*Swisspacer, 2026*). While these spacers typically have higher initial costs, these spacers improved thermal performance reduces heat loss through thermal bridges, resulting in lower energy consumption and therefore reduce costs long-term *(Technoform, n.d.*).

The first categories of improved spacer design are the **U-shaped** metal spacer and the **thermally broken aluminium** spacer. Even though these spacers still use metal as the main spacer material. Since the shape is interrupted, there is less thermal conductivity and therefore the thermal bridge is less significant (*Van Den Bergh et al., 2013*).

Hybrid spacers from the second category of improved designs. These spacers are considered hybrid because they combine low conductivity materials like polypropylene and thin metal. The metal section of the spacer, which wraps around its sides and back, gives the same durability and processability benefits as standard metal spacers (*Technoform, n.d.*). The presence of specially engineered polypropylene bridging the top significantly reduces its thermal conductivity. As a result, hybrid spacers achieves the warm edge performance of non-metal spacers, while maintaining the durability of standard metal spacer (*Technoform, n.d.*).

In the **non-metal spacers**, the mechanical stability normally provided by the metal spacer is achieved by (thermos)plastics or foam. These materials have a low conductivity and therefor also an improved thermal performance. However, the **composites** and **foam**s still need a corrugated structure of a thin metallized foil to perform as a water vapour and gas barrier (*Van Den Bergh et al., 2013*). The foam and the thermoplastic both contain desiccant to absorb moisture. Because the moisture resistance of the desiccated PIB is sufficient in the **thermoplastic** spacers, no metallized foil is required (*Van Den Bergh et al., 2013*).

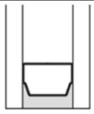
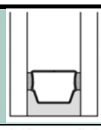
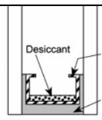
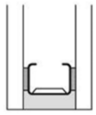
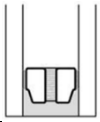
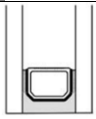
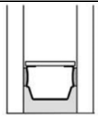
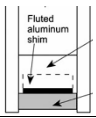
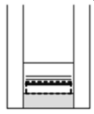
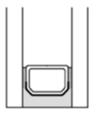
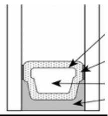
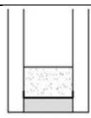
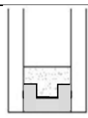
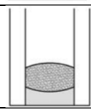
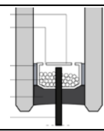
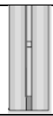
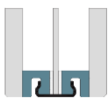
Metal spacers						
Standard	Aluminium Galvanized steel Stainless steel	Single sealed		Dual sealed		
Improved	U-shaped	Single sealed		Dual sealed		
	Thermally broken aluminium			Dual sealed		
	Hybrid spacer			Dual sealed		
Non-metal spacers *(with metallized foils)*						
Composites	Composite plastic + Corrugated metal Composite plastic + Corrugated aluminium Composite plastic + Corrugated plastic	Single sealed		Dual sealed		
	Composite plastic SAN + 35% glass fibres			Dual sealed		
Foam	Silicone foam EPDM foam	Normal shaped				
Thermoplastic	Synthetic rubber with desiccant PIB with desiccant			Dual sealed		
Other spacers						
Durable	Decompressed (*Weller et al., 2016*)			Dual sealed		
Vacuum	Micro-spacers (*Guardian Industries Holdings Site, 2026*)					
Demountable	Demountable spacer (*Kouvela, 2022*)					

Table 3: Overview of existing market standard conventional spacers. All images and spacer variants are from the research of Van den Bergh et al. (2013), unless written otherwise in the table.

3.1.4 Other spacers

While most alternative spacer designs focus on improving thermal performance, durability is generally maintained rather than fundamentally enhanced, and circularity is largely overlooked. Nevertheless, several additional edge seal concepts merit discussion and are mentioned in Table 3.

First, Weller et al. (*2016*) investigated an IGU design incorporating a pressure equalizer for use in harsh maritime environments. His design introduces a **pressure equalizer** in an otherwise conventional dual sealed IGU to reduce stresses caused by the environmental loads and increasing the durability. Initial findings suggest that this approach reduced stresses in the edge seal and therefore may extend the service life of the IGU. However, the research still has a lot of constraints and remaining uncertainties.

The second alternative is **vacuum insulated glass** (VIG). VIG consists of two or more panes of glass separated by a narrow vacuum space with an array of micro pillars that hold the two panes of glass apart and is hermetically sealed at the edges *(Guardian Industries Holdings Site, 2026; Van Den Bergh et al., 2013*). Therefore, the edge seal is separated. The mechanical stabilization by the micro pillars is divided in an array over the whole surface of the glass, while the edges only need to provide a hermetically water and airtight sealant. The VIG design still mainly improves the thermal performance, but is still an interesting innovation to learn from.

Finally, Kouvela (*2022*) proposes a **demountable** spacer concept aimed at improving circularity and transparency. The design uses a fused glass-to-glass connection to create a transparent bond without contaminating adhesives. This concept is combined with mechanical clamping to form temporary reversible connection. Low e-coating is incorporated into the design, but placed on an additional thin glass pane to reduce downcycling material.

3.1.5 Conclusion

This chapter has provided an overview of the current state-of-the-art in IGU edge seal design, from the most conventional dual-sealed metal spacer to the new and improved existing and experimental alternatives. Although the standard metal spacer exhibits inherent performance limitations like thermal bridges, premature condensation and minimal circularity, it remains the dominant market solution. The most important conclusions and limitations are visible in Table 4.

In response to these limitations, improved metal, hybrid and non-metal spacer designs and vacuum insulated glass have been introduced to the market. These innovations mainly focus on enhancing the thermal performance through warm edge technologies using low conductivity materials. While these innovations successfully enhance the thermal performance of the IGU, they only maintain the durability of the system and ignore the need to improve circularity.

Only more experimental research try to improve the durability and circularity of the IGU. Weller et al. (*2016*) introduces a new and improved durable design by adding a pressure equalizer to limit stresses on the edge seal. Kouvela (*2022)* improvement circular design of IGU gets rid of edge seal and contaminations by using glass fusion as a connection and improve demountability by using mechanical reversible clamping. However, this research mostly remain experimental and have not yet been converted to actual market ready performance IGUs. Therefore, the manufacturability and market maturity remains under investigated.

Overall, the state-of-the-art reveals a clear gap between thermal performance optimisation and the need for edge seal systems that simultaneously extend service life and support circular design strategies. This gap underscores the importance of defining regulatory requirements and performance criteria, which are addressed in the following chapters.

Spacer category	Typical materials	Thermal performance	Mechanical stability	Moisture & gas resistance	Manufacturability / market maturity	Durability	Circularity potential	Key limitations
Standard metal	Aluminium, galvanized steel, stainless steel	+ -	+ -	+ +	+ +	+ -	+ -	Thermal bridging, condensation risk, non-demountable, glass contamination
Improved metal	U-shaped or thermally broken aluminium	+	+ +	+ +	+ +	+ -	+ -	Thermal bridge reduced but not eliminated; still metal-based
Hybrid	Polymer + thin metal	+ +	+ +	+ +	+ +	+ -	-	Multi-material complexity, limited disassembly
Composite	Plastic composite + corrugated metal	+ +	+ -	+ +	+	+ -	-	Reliance on metallized foils; aging of polymers
Foam	Silicone or EPDM foam + foil	+ +	+ -	+ -	+	+ -	-	Long-term mechanical stability and permeability concerns
Thermoplastic	PIB or synthetic rubber with desiccant	+ +	+ -	+ +	+	+ -	-	Creep, aging, still adhesive-based
Pressure-equalized	Metal spacer with pressure equalizer	+ -	+	+ +	- -	+ +	+ -	Limited validation, no circular strategy
Vacuum glazing	Micro-spacers + hermetic edge seal	+ +	+ -	+ +	+ +	+ -	-	Complex manufacturing, different system logic
Demountable	Glass–glass fusion + mechanical clamping	?	?	?	- -	?	+ +	Lack of standardization, durability validation needed

Table 4: Overview of alternative spacer design with most important performance criteria and limitations

3.2 Requirements and regulations

In this chapter, the edge seal requirement of performance are investigated through literature research. (Van den Bergh). Also, the specific regulations on IGU performance and materials are investigated for NEN norms. *What functional, material, and environmental requirements must an IGU edge seal component meet to comply with existing regulations, and what properties could be improved to extend the service life of an IGU and support circularity?*

Requirements	*Norms*	*Regulations*
Thermal	*NEN-EN 1279:2018*	No thermal bridges Low thermal conductivity = 0.05 – 2.0 W/mK Low U-value = 1.0 – 2.0 W/m2K High thermal performance
Structural	*NEN-EN 1279:2018* *ASTM C1249*	Spacer: Mechanical stability High compressive strength Rigid Sealant: Allow movement High tensile strength Flexible Cohesive and adhesive bonding strength
Moisture and Gas	*NEN-EN 1279:2018*	High water vapour resistance & low permeability Available water absorption capacity of desiccant High gas transmission resistance & low permeability Gas leakage rate < 1% per year
Sound insulation	*NEN-EN 1279:2018* *EN ISO 10140*	No resonance Minimal sound insulation at different frequencies
Tolerances	*NEN-EN 1279:2018*	< 1.0 – 2.0 mm tolerances in all dimensions
Safety	*NEN-EN 1279:2018-5*	Mechanical-, fire-, impact-, explosion-, burglary-safety
Service life	*NEN-EN 1279:2018-2* *NEN-EN 1279:2018-3*	Economical reasonable working life = 20 – 30 years Accelerated aging tests
Productions and fabrication	*NEN-EN 1279:2018-6*	Factory production control systems to ensure reliability
End-of-life / circularity	*BENG* *BREEAM*	Material recovery, recyclability and life-cycle assessments

Table 5: Overview of requirement, relevant norms and regulations

3.2.1 Thermal requirements

Our windows make up a growing part of the building envelope. Most heat loss is still going through the transparent parts of the building envelope. Going to a more sustainable built environment. Less energy use for heating and cooling buildings.

The edge seal component should cause **no thermal bridge**. To prevent this as much as possible, the material of the edge seal should have **low thermal conductivity**. The lower the conductivity of the edge seal material, the lower the U-value of the window system. However, this relation is not linear, but has a logarithmic nature. Any thermal conductivity value between 0.05 and 0.25 W/mK will decrease the U-value significantly. While any thermal conductivity value between 0.25 and 2.0 will result in an acceptable U-value. If the thermal conductivity is higher than 2.0 W/mK, the U-value will not increase anymore.

The U-value of the IGU system will also depend on the amount of glass panes, the cavity fill, the coatings used and on the quality of the edge seal component. The **lower the U-value the better the thermal performance** of the window and the less heat is lost through the window. For a standard double-glazed window system, the U-value should be around 2,7 W/m2K. For a double-glazed window with argon fill and low-e coating the U-value can decrease to around 2,0 or 1,0 W/m2K, depending on the width of the cavity. Triple glazed windows systems the U-value should be around 0.5 W/m2K (*Saint-Gobain Building Glass UK, 2018*).

For **better thermal performance** of the edge seal a few interventions can be done besides choosing a material with a lower thermal conductivity. Increasing the thickness or length or decreasing the width of the edge seal component will result in better thermal performance. Lastly, in the current single or dual edge seal design, the material options for the secondary sealant all have a set thermal conductivity, therefore, decreasing the size of the secondary sealant needed for the structural performance will enhance the thermal performance.

3.2.2 Structural requirements

The window system is part of the building envelope and provides a transparent connection between interior and exterior, while protecting the inside from environmental elements. Most of the self- and gravitational loads of an IGU will be distributed through the glass panes, so this is a subordinate structural requirement for the edge seal. The edge seal however is responsible for the distribution of forces perpendicular to the glass. These forces can be created by wind pressure, temperature fluctuations and atmospheric pressure changes.

For the IGU under these compressive pressures distributed on the external glass surface, the sealant layers accommodate the required deformations. Their elastic behaviour **allows movement** and a certain rotation at the panels ends due to global bending *(Bedon & Amadio, 2020*). The secondary sealant is responsible for providing the necessary **tensile strength** since the spacer bar cannot actively contribute to prevent the separation of glass edges. Instead, the spacer bar will make sure that the panels remain at a minimum distance from each other and provide the necessary **mechanical stability**.

The materials of the edge seal need to have significant durable cohesive and adhesive bonding strength to the glass, the coating and the spacer material. The materials need to be UV and direct water resistant. The spacer material should specifically be **rigid and have high compression strength**. The rigidity or stiffness of the materials can be determined with the Young's modulus. The stiffer the material, the higher the Young's modulus. The sealants, however, should have a **high tensile strength and a low young's modulus**. The current main mechanical sealant silicone has a slightly lower tensile strength, typically ranging from **σ = 0.7 to 3.0 MPa**. It makes up for this with high elasticity and movement capability, making it better for seismic joints and thermal expansion. The alternative material in the redesign should be equal to or exceed the mechanical performance values of silicone.

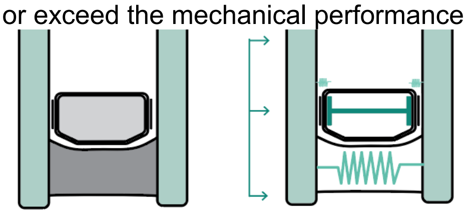
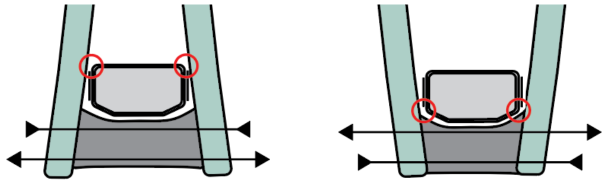


Figure 3: a. Schematic mechanical model of spacer connection under external design loads (own image, based on (Bedon & Amadio, 2020))



b. Exaggerated compression and decompression movement of the IGU edge seal, due to external forces perpendicular to the glass surface. Resulting in a tensile and bending strength in the secondary sealant and peak stresses in the spacer and primary sealant (own image)

3.2.3 Moisture and gas requirements

An IGU system is considered to have reached its end-of-service-life when condensation starts appearing in the cavity. This water vapour condensation is typically due to saturation of the desiccant. To prevent this from happening, the edge seal design needs to eliminate water vapour from entering the cavity.

Therefore, the edge seal component needs to have **high moisture vapour resistance** and the materials should have **low water vapour permeability**. The primary sealant made from PIB is the material with the lowest water vapour permeability. Therefore, the moisture resistance of the edge seal design is mostly dependent on the proper working of the primary sealant. However, the secondary seal must reduce the mechanical stress on the primary sealant to reduce the change of the primary sealant to fail. In case the moisture resistance of the edge seal fails and the water vapour does enter the cavity, the desiccant is able to absorb some amount of moisture during a reasonable economic lifetime of IGU. However, depending on the **available water absorption capacity** (AWAC) left in the desiccant, they will eventually reach their saturation and condensation will ultimately occur.

While the edge seal needs to keep water out of the system, it also needs to prevent the inert gases from evading the cavity and being replaced with air. The differential between the partial pressure of the gas within the cavity and the surrounding air causes gas to diffuse through the seal *(Van Den Bergh et al., 2013*). Therefore, the edge seal component needs to have **high gas transmission resistance** and the materials should have **low gas permeability**. Current regulations allow a **gas leakage rate** (L_i) of less than 1% per year (*Van Den Bergh et al., 2013*).

3.2.4 Additional requirements and regulations

The requirements listed above are the most important properties of the IGU. In addition to these core properties, several other important requirements should also be considered when redesigning the edge seal. However, these additional requirements are often dependent on the location of the building and the IGU withing the façade or the function of the building.

Sound insulation

The more panes of glass and the more cavities will result in better sound insulation. *EN ISO 10140-1* and *-2* define the laboratory measurement methods and provide the sound reduction index of a reference IGU 6/16/6 for all different frequencies. The specific requirements for sound insulation may vary depending on the location and the function of the building, but must be determined in accordance with *NEN-EN 1279:2018*.

Tolerances

The design of the IGU has to comply with tolerances as specified in *NEN-EN 1279:2018*. Compliance with dese tolerances is essential for proper installation, edge seal performance and durability. Dimensional tolerances for double or triple glazed IGU must comply with *NEN-EN 1279:2018*. Small IGU considered of 2 m2 and 6mm thickness may be allowed 2 mm tolerances. While bigger units of more than 5m2 and 12 mm thickness may be allowed up to 5 mm tolerances. The thickness of double glazing is allowed only 1 mm tolerance.

Safety regulations

IGU must comply with the safety requirements defined in *NEN-EN 1279:2018-5*. These include not only mechanical safety, but also extend to safety to fire, safety to impact, safety to explosion safety to burglary. Mechanical safety assures that the IGU will be resistant against extreme temperature changes or extreme wind and external loads. The applicability of these safety aspects depends on the building function and the position of the IGU within the façade system.

Service life requirements

The durability of the IGU should be demonstrated by a climate test. According to the regulations, the IGU must remain sealed and functional after the accelerated weathering test. Moisture penetration should be in accordance with *NEN-EN 1279:2018-2* and the gas leakage rate should be in accordance with *NEN-EN 1279:2018-3*. All results are accepted that are withing an economical reasonable working life. From the literature it can be concluded that the accepted typical service life of the IGU is 20-30 years (*Wolf, 1992*).

Factory and production requirements

All factories and related partners from incoming material inspections to the production and final product must comply with *NEN-EN 1279:2018-6*. IGUs must be manufactured in compliance with instruction from factory production control systems. Only tested and approved material combinations may be used. Each IGU or production batch must be traceable and demonstrate conformity with certifications. Production consistency and quality control is essential for long-term IGU reliability.

3.2.5 End-of-life and circularity considerations

NEN-EN 1279:2018 is a product performance standard that focuses on the performance, durability and safety related requirements of IGUs during their service life. It does not include end-of-life scenarios, circularity or sustainability standards.

Therefore, end-of-life and circularity must be justified using other sustainability frameworks that are not IGU standards. Relevant frameworks that could be considered are EU circular economy action plan or *BREEAM* standards. These frameworks provide guidance on material recovery, recyclability and life-cycle assessments. Both encourage designs that enable the circular economy strategies of reuse, recycling and remanufacturing with the goal to keep resources in use for as long as possible and reduce waste.

3.2.6 Conclusion

This chapter has established the requirements for the performance of the edge seal component and materials, based on literature and applicable *NEN-EN* standards.

In conclusion, the edge seal system must provide sufficient mechanical stability and durable adhesive and cohesive strength and at the same time allow movement, to retain integrity of the edge seal system exposed to environmental and mechanical loads during the economically reasonable working life of IGU. Low thermal conductivity and optimized geometry are essential to limit heat loss and prevent thermal bridging. From a durability perspective, resistance to moisture ingress into and loss of filling gas from IGU cavity determines the IGU service life.

In addition to these core performance requirements compliance with safety, sound insulation, UV resistance and service life testing standards further determine the edge seal design. Lastly, the norms do not address regulations for end-of-life or circularity strategies, so these are design criteria that can be further explored to improve the circularity of the edge seal component, next to extending its service life.

3.3 Design criteria

From all the literature research about the current state-of-the-art and their performance limitations and about the regulations and requirements, it can be concluded that the following design criteria should be considered when finding alternative materials and connections.

3.3.1 Material level

The materials that connect the two glass panes should comply with the following design criteria. All these design criteria are all hard criteria.

Compatibility	The materials that connect the two glass panes should be compatible with glass. Materials should maintain stable contact without degradation, chemical reaction, or loss of performance	*Adequate adhesion, dimensional stability, and long-term durability under environmental exposure*
Low thermal conductivity	The materials that connect the two glass panes should have a low thermal conductivity to avoid thermal bridges from appearing	*Thermal conductivity: 0.05 – 0.25 W/mK* *- No metals* *- No conductors*
Mechanical performance	The materials that connect the two glass panes should have a minimum tensile strength to contain the IGU, while allowing for small movement due to thermal differences	*Spacer: high compressive strength and high young's modulus* *Sealant: high tensile strength and low young's modulus*
Low water vapour permeability	Water vapour should not be able to enter the cavity to provide sufficient durability	*Hermetically sealed* *Grade 2*
Low gas permeability	Air should not be able to enter the cavity and gases should not be able to escape the cavity to provide sufficient durability and thermal performance	*Hermetically sealed* *Grade 1*

3.3.2 Component level

The IGU should comply with the following design criteria. These criteria are predominantly hard criteria, because they are based on measurable performance requirements of the IGU.

High thermal insulation	The IGU should at least comply with the thermal insulation value, U-value, of the standard double-glazed IGU or better.	***U-value*** *Vacuum 0.4 W/m2K* *Triple 0.5 W/m2K* *Double+coating 1.2 W/m2K* *Double 2.7 W/m2K*
No thermal bridges	The IGU and the edge seal materials should not allow thermal bridges to form	*Low thermal conductivity material*
Mechanical performance	The spacer together with the sealants need to provide mechanical stability and tightly sealed corner connections	*Spacer is rigid and provides mechanical stability. Sealant is flexible and tensile strong to allow for movement*
Allow movement	The edge seal component at the same time needs to allow movement of the glass panes, to accommodate for expansion and compression of the IGU, due to atmospheric pressure changes, temperature fluctuations or wind loads, and reduce stress in the primary sealant.	*Allow small movement for Compression and expansion*
High environmental resistance	The IGU is part of the building envelope and should protect from all environmental factors	*- UV-resistance* *- Wind loads*
Water and airtight	The IGU should provide a water and airtight barrier.	*Hermetically sealed: Grade 1* *Tightly sealed corner connection*

3.3.3 Additional criteria

In addition to the clear material and component criteria that are already defined in the requirements and regulations in the NEN norms. However, these norms do not consider the end-of-life or to improve the durability. New durable design should approach the service life of glass or enable the possibility for circular strategies, through demountable edge seal connection. All new techniques should be evaluated against the small-scale connection of the IGU. Demountability is a soft criterion, the rest are also hard criteria.

No contamination	The additional materials used to make the connection, should leave no contaminations on the glass or should be easily cleaned off, to enable recycling of the glass.	*- Minimal effort needed to clean off contamination to the glass* *- Enable glass recycling* *- Do not obstruct glass recycling*
Demountable	The design of the IGU must consider the end-of-life or circularity strategies. Providing a demountable design will enable the reuse, recycling or remanufacturing of the glass	*- Easier reuse* *- Easier remanufacturing* *- Easier recycling* *- Less time consuming*
Durable	The durability of the IGU should be more in line with the durability of the glass. Or the design of the IGU should allow easier reuse at the end-of-life of the IGU, so the glass is not forced into premature end-of-life	*- Economical reasonable working life of IGU = 20-30 years* *- Glass durability = 100 years* *- New durable design should approach the service life of glass*
Small-scale	Known alternative connection techniques should be able to provide sufficient strength and comply with all the other design criteria on the small-scale connection that is the IGU edge seal	*4-10-4* *6-12-6* *4-12-5* *4-10-5* *mm thickness on linear connections*

4. Material & technical research

This chapter presents a literature-based and exploratory material and technical research aimed at identifying opportunities to improve the durability and circularity of the insulated glass unit (IGU) edge seal. By reviewing existing scientific literature, material databases, and technical precedents from glass engineering and façade design, the chapter establishes a knowledge base for alternative material choices and connection strategies.

The goal of this chapter is to evaluate existing materials and connection techniques against the identified design criteria, with particular emphasis on thermal performance, mechanical stability, durability and circularity. The findings of this research serve to define the boundaries of what is currently feasible and to inform the subsequent design phase, where these insights are translated into concrete design principles and concepts for a redesigned IGU edge seal.

4.1 Alternative material research

In the previous chapter, the most important design criteria for material have been identified. Alternative materials intended to replace the existing edge seal should comply with these criteria to maintain performance, while improving sustainability. In this chapter, the database software from Ansys Granta EduPack is used as research tool to discuss each criterion in relation to potential alternative materials and evaluate their suitability (appendix A) (*Data reproduced courtesy of Ansys, Inc., (2025)*). Through a process of progressive elimination, materials that did not satisfy the predefined design criteria were excluded from further consideration. The software enabled comparative visualization of material performance using Ashby-type property charts.

Material	*Definition*	*Types*
Metals	*Class of chemical elements, compounds, or alloys characterized by high electrical and thermal conductivity, shine, and malleability. They are typically hard, solid, and opaque materials, formed by metal atoms that readily lose electrons to create positive ions.*	*- Aluminium - Copper - Iron - (Stainless) Steel*
Technical Ceramics	*Synthetic, inorganic, non-metallic materials engineered for superior performance in extreme environments. They feature extreme hardness, high-temperature resistance, corrosion resistance, and specific electrical properties.*	*- Aluminium oxide - Silicon carbide - Silicon nitride - Zirconia*
Glass	*An amorphous solid (non-crystalline) material, typically transparent, formed by rapidly cooling molten, inorganic, and often raw materials like silica sand, soda ash, and limestone.*	*- Aluminosilicate glass - Borosilicate glass - Soda-lime glass*
Stone and bricks	*Durable, fire-resistant construction materials used for building walls, facades, and landscaping. Stone is a natural material, while bricks are manufactured, uniform clay blocks.*	*- Granite - Limestone - Dutch Brick - Hand-formed Brick*
Natural woods	*The raw, unprocessed material derived directly from tree trunks, branches, and limbs, consisting of organic wood fibres without synthetic additives like glue or plastic. Known for its durability, unique grain patterns and warmth.*	*- Hardwoods - Softwoods*
Elastomers	*A category of polymers known for their high elasticity, allowing them to stretch under tension and return to their original shape when released. They feature weak intermolecular forces and a cross-linked structure, making them durable, flexible, and resistant to impact.*	*- Neoprene - Rubber - Silicone*
Polymers	*Any of a class of natural or synthetic substances composed of very large molecules, called macromolecules, which are multiples of simpler chemical units called monomers. Polymers make up many of the materials in living organisms and are the basis of many minerals and man-made materials.*	*- Natural polymers (Cellulose, lignin, resins) - Synthetic polymers (Plastics, Poly-materials)*
Composites	*A material which is produced from two or more constituent materials. When combined, is stronger than those individual materials by themselves.*	*- Concrete - Fibre reinforced plastics*
Foams	*Lightweight, shock-absorbent, thermally insulating, and durable substances formed by trapping gas bubbles within a solid or liquid matrix, creating a cellular structure.*	*- Polyurethane - Polystyrene - Neoprene*
Fabrics	*A flexible, flat material made by weaving, knitting, crocheting, or felting natural or synthetic fibres. Designed to bend without breaking. Fabric material properties are determined by fibre type and structure and can vary significantly.*	*- Knitted - Non-woven - Woven*
Fibres	*A natural or synthetic substance composed of long, thin, flexible strands, often significantly longer than they are wide. Natural fibres are prized for breathability and comfort. Synthetic fibres are often chosen for strength, durability, and low cost.*	*- Natural fibres (Cotton, Silk, Wool) - Synthetic fibres (Nylon, Polyester)*

Table 6: Overview of materials (Data reproduced courtesy of Ansys, Inc., (2025))

4.1.1 Compatibility and small scale

The primary requirement for material selection is compatibility with glass, particularly with regard to bonding behaviour, thermal expansion, moisture resistance, and long-term durability. In this context, compatibility refers to the ability of a material to form a stable and durable connection with glass without causing premature failure due to insufficient adhesion, differential thermal movement or material degradation (*Mognato et al., 2018*). Since IGU edge seals are subjected to continuous thermal cycling, mechanical loading and moisture exposure, the selected materials must demonstrate similar physical and mechanical behaviour to ensure reliable long-term performance. Besides that, the materials of the edge seal of the IGU have to be manufacturable at the small-scale of often between the 12 to 20 mm.

Material categories considered incompatible with the proposed design approach are natural woods, concrete, stone and brick (Appendix A). These are excluded due to their limited compatibility with glass, small scale application and unsuitable mechanical and thermal properties for edge seal applications.

4.1.2 Thermal performance

Thermal conductivity describes a materials ability to transfer heat flow (*Thermtest.com, 2026*). Materials with low thermal conductivity can resist the heat flow and are commonly known as insulators. From the existing edge seal designs (Table 3) it can already be concluded that any material with a low thermal conductivity will significantly improve the thermal performance of the IGU *(Van Den Bergh et al., 2013*).

Material selection using Granta EduPack further supports this conclusion. Although this program only presents the thermal resistivity, the conclusion should be the same. Thermal resistivity is the property of a material that describes its resistance to heat transfer by conduction, convection and radiation. It is the opposite of heat flow and therefore thermal conductivity. Higher thermal resistivity will therefore improve the thermal performance. From Figure 4, it is evident that ferrous (teal), non-ferrous metals (red) and technical ceramics (yellow) both exhibit low thermal resistivity and are therefore considered conductors. This supports the conclusion that these material categories can be excluded from future edge seal designs.

In contrast, materials with high thermal resistivity and low conductivity will result in better thermal performance and should be considered. Some general categories of materials that should be included are polymers, aerogels and composites. More specific examples include polyurethane foam with lambda of 0.026 W/mK or aerogels with lambda of 0.015 W/mK *(Joost de Vree, 2026*). Currently no spacer systems on the market utilize these materials *(Van Den Bergh et al., 2013*).

Although the low thermal conductivity is desirable, other requirements, such as structural strength, moisture vapour tightness and durability must also be considered.

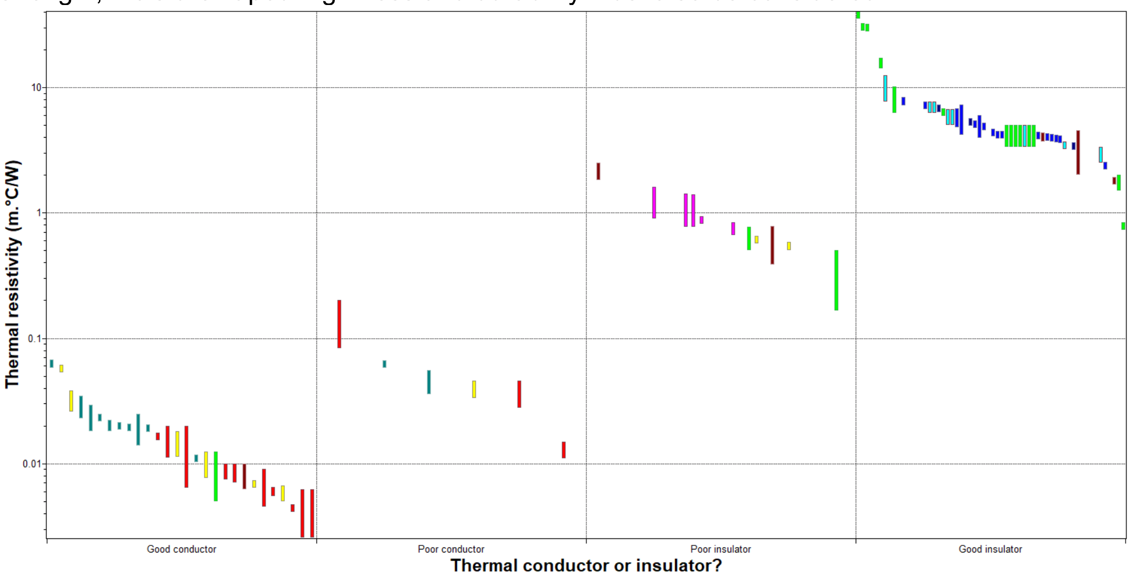


Figure 4: Thermal resistivity showing whether the material is a conductor or insulator (Images used courtesy of Ansys, Inc., (2025))

4.1.3 Mechanical performance

In addition to the thermal performance, the tensile strength and mechanical stability of the material must be sufficient to ensure the structural integrity of the IGU. Following the initial thermal performance assessment, only the material categories classified as thermal insulators were considered for further mechanical evaluation.

The secondary sealant is responsible for providing elasticity and tensile resistance while simultaneously accommodating differential movement between the glass panes. The secondary sealant therefore functions as a flexible structural connection, comparable to a spring mechanism, which must both absorb deformation and maintain sufficient bonding strength to hold the glazing unit together. Consequently, alternative materials for the redesigned edge seal system should demonstrate mechanical properties equal to or exceeding those of current secondary sealant materials . Figure 5 presents the Granta Edupack analyses of tensile strength set out against the Young's modulus to find an acceptable alternative material for the sealant. Materials in the upper-left quadrant of the table have the highest tensile strength and flexibility and therefore comply with the design criteria. However, any material than finds itself left or above the silicone elastomer (light blue) should be considered sufficient. The only material category that can be found in that area of the figure are elastomers. However, by compromising some flexibility to gain more tensile strength, also the polymer category (blue) should still be considered an acceptable alternative.

The spacer should provide the mechanical stability. Account for compression forces and form a rigid connection that makes sure to hold the glass panes at a specific distance from each other. The spacer material should be rigid material and should be able to resist sufficient compressive strength and peak loads. Figure 6 presents the Granta Edupack analyses of compressive strength set out against the Young's modulus to find an acceptable alternative material for the spacer. Materials on the top right corner of the table have the highest compressive strength and stiffness and therefore comply with the design criteria. The material categories that can be found in that area of the figure are glass (pink) and composites (dark red).

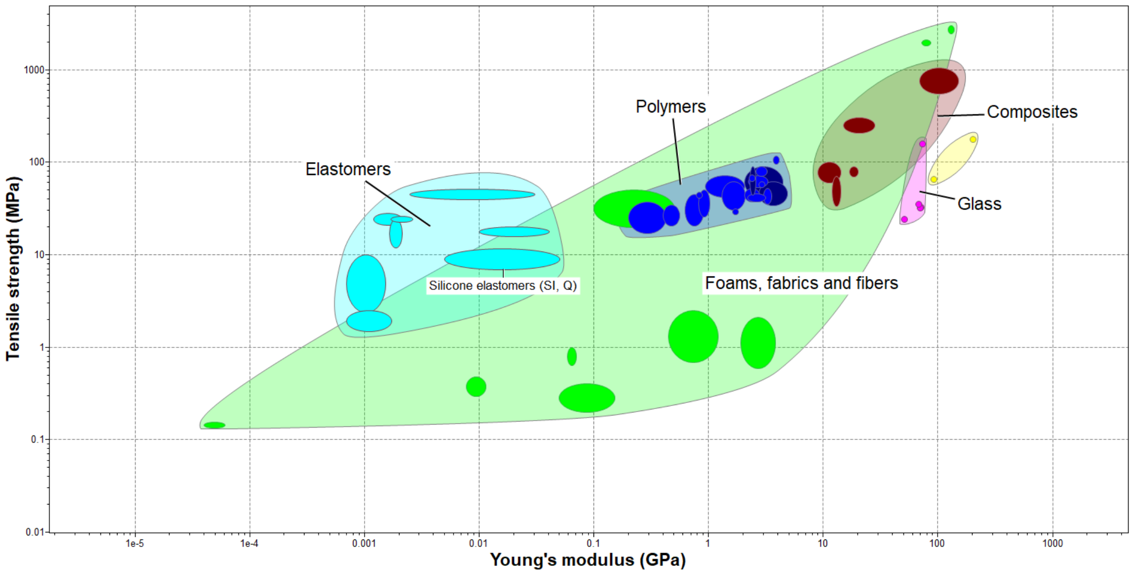


Figure 5: Tensile strength (MPa) against Young's modulus (GPa) to determine possible secondary sealant materials (Images used courtesy of Ansys, Inc., (2025))

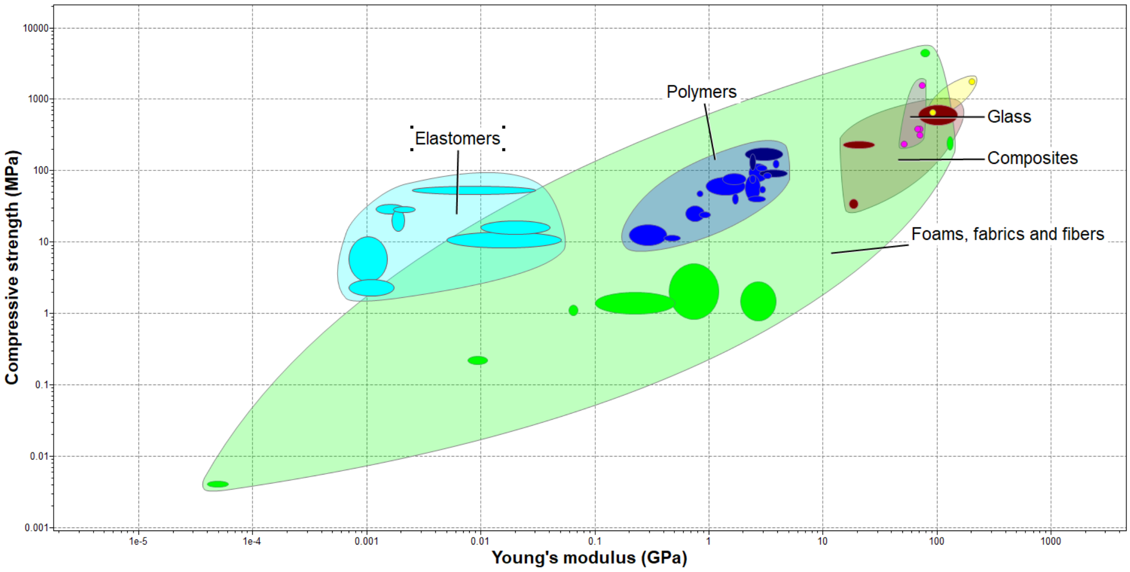


Figure 6: Compressive strength (MPa) against the Young's modulus (GPa) to determine possible spacer materials (Images used courtesy of Ansys, Inc., (2025))

4.1.4 Low gas and water vapour permeability

Gas retention and moisture resistance are critical for maintaining IGU performance over time. Therefore, materials with low gas and water vapour permeability need to be selected. High gas permeability would lead to the loss of insulation gases from within the unit, while high water vapour permeability would allow water vapour to ingress the cavity, causing condensation, reducing transparency and advancing the degradation of the edge seal *(Van Den Bergh et al., 2013*).

In Granta EduPack, only a few materials contain information about the water vapour and air permeability, so these materials are plotted against each other in Figure 7. Only polymer-based materials provide sufficient and reliable permeability data. Within this material category, the range of materials listed in Figure 7, provide both low water and air permeability. Future selection of these materials is possible considering the more important water or air permeability factor.

To understand the durability of other materials that do not have information about their gas and water vapour permeability, the durability can be assessed against important environmental factors (*Wolf, 1992*).

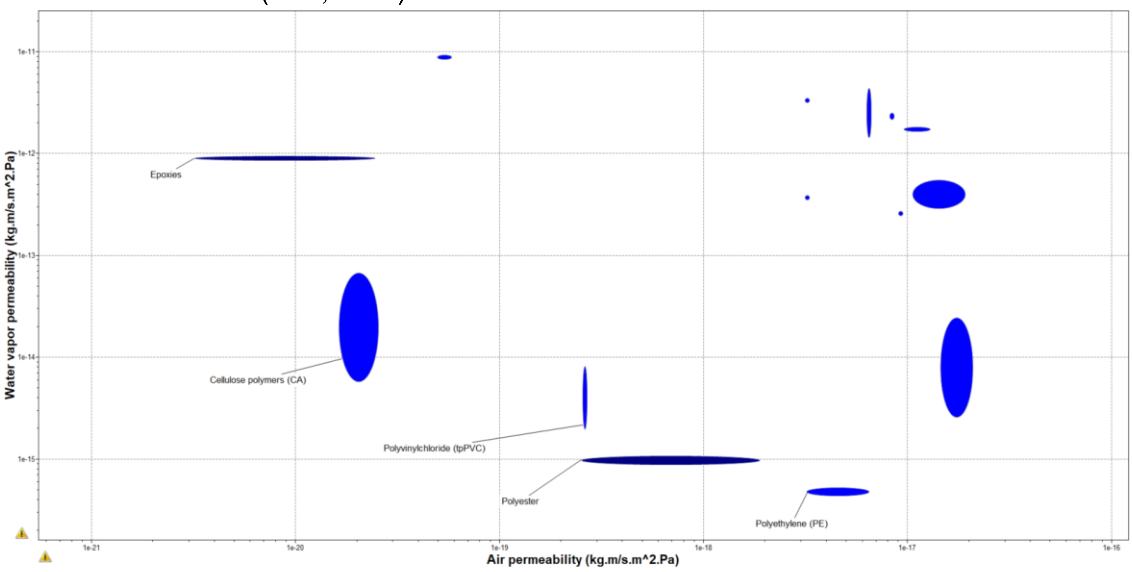


Figure 7: Water vapor permeability against Air permeability (Images used courtesy of Ansys, Inc., (2025))

4.1.5 Durability

Durability is an important factor for the long-term performance of the materials, to extend the service life of the IGU. The material should at least be resistant to direct contact with water and UV-radiation (*Wolf, 1992*).

Figure 8 shows the materials and their resistance to UV radiation. Almost all elastomers (light blue) and polymers (blue) can be found in the left two columns, meaning they do not have a good resistance to UV radiation. Silicone is the only elastomer left with good UV radiation.

Most glass (pink) and composites (dark red) can be found in the right two columns and are therefore considered durable materials in terms of UV resistance.

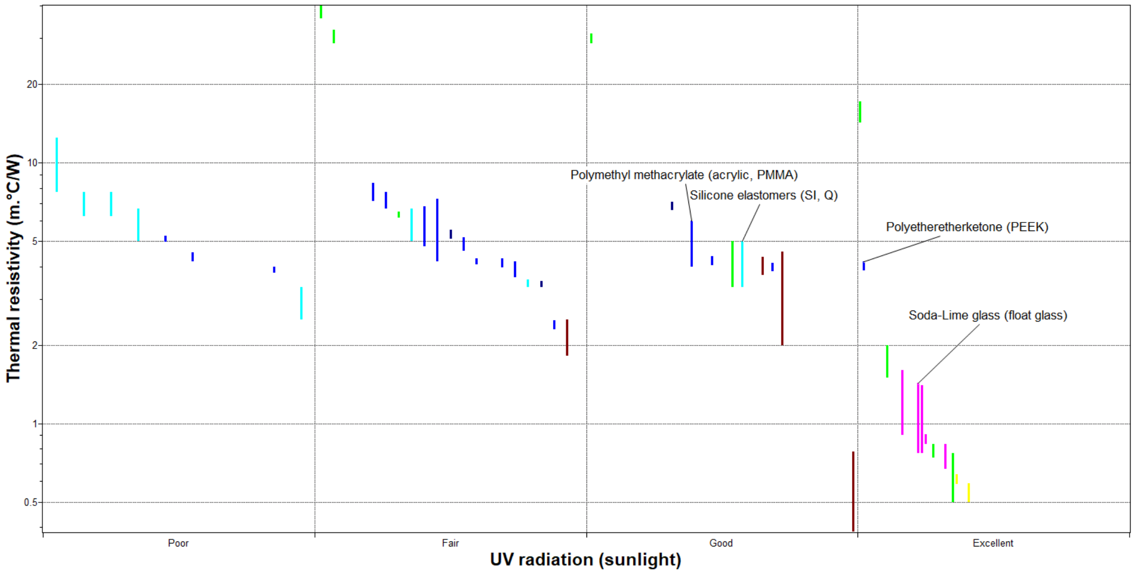


Figure 8: Thermal resistivity (m°C/w) against UV radiation (sunlight) to determine durable materials (Images used courtesy of Ansys, Inc., (2025))

4.1.6 Conclusions

In this chapter, the Granta EduPack database was utilized to try and find a material or what material combination that can be identified as potentially suitable alternative for the redesign of the IGU edge seal system, based on the compatibility, thermal, mechanical, permeability, and durability analyses, several material categories.

The compatibility assessment first established that the selected materials must maintain stable adhesion and mechanical interaction with glass under long-term environmental exposure and cyclic loading conditions. Material categories such as natural wood, concrete, stone, and brick were excluded.

The thermal performance analysis demonstrated that materials with low thermal conductivity significantly improve the thermal efficiency of the IGU and reduce the formation of thermal bridges. Consequently, metallic materials and conductive technical ceramics were excluded from further consideration.

The mechanical performance assessment further refined the material selection. Here, a distinction has been made between the requirements for the spacer and the sealants, because they require two opposite properties. For the secondary sealant application, elastomeric materials demonstrated the most suitable combination of tensile strength and flexibility. Certain polymer materials may also provide acceptable alternatives when slightly reduced flexibility can be compensated by increased tensile strength. For the spacer application, glass-based materials and fibre-reinforced composites demonstrated the most suitable combination of compressive strength and stiffness required to maintain geometric stability within the IGU.

Finally, the durability assessment demonstrated that ultraviolet resistance forms a critical limitation for many elastomers and polymers. Only, plexiglass (PMMA), polyether ether ketone (PEEK), polytetrafluoroethylene (PTFE), polyethylene Terephthalate Glycol (PETG) and silicone remain. In contrast, glass and composite materials generally exhibited superior environmental durability and UV resistance.

Table 7 shows an overview of all the different material categories against the different design criteria. From the table it can be concluded that Each material category exhibits specific limitations and no single material immediately complies with all the design criteria for materials.

Material	Compatibility	Low thermal conductivity	High compressive strength	High tensile strength	Young's modulus	Low water vapour permeability	Low gas permeability	Durability	Key limitations
Metals	+ +	- -	+ +	+ +	Rigid	N/A	N/A	+ +	High thermal conductivity
Technical Ceramics	+ -	- -	+ +	+ +	Rigid	N/A	N/A	+ +	High thermal conductivity
Glass	+ +	+ -	+ +	+ -	Rigid	N/A	N/A	+ +	Low tensile strength
Stone and bricks	- -	+ -	+ +	- -	Rigid	N/A	N/A	+ +	Not compatible Low tensile strength
Natural woods	- -	+ +	+ -	- -	Rigid/ Flexible	N/A	N/A	- -	Not compatible Low tensile strength Not Durable
Elastomers	+ +	+ +	- -	+ -	Flexible	N/A	N/A	- -	Low compressive strength Not Durable
Polymers	+ +	+ +	+ -	+ -	Rigid/ Flexible	+ -	+ -	+ -	Leaves contaminations Lot of variability in properties
Composites	+ -	+ -	+ +	+ +	Rigid	N/A	N/A	+ -	Lot of variability in properties
Foams	+ +	+ +	+ -	+ -	Rigid/ Flexible	N/A	N/A	+ -	Lot of variability in properties
Fabrics	+ +	+ -	+ -	+ -	Rigid/ Flexible	N/A	N/A	+ -	Lot of variability in properties
Fibres	+ +	+ -	+ -	+ -	Rigid/ Flexible	N/A	N/A	+ -	Lot of variability in properties

Table 7: Overview materials categories assessed against the design criteria (Data reproduced courtesy of Ansys, Inc., (2025))

Overall, the analyses indicate that the most promising redesign strategy for the IGU edge seal system consists of combining elastomeric or polymer-based sealant materials with rigid composite or glass-based spacer materials. Such a hybrid material approach has the potential to improve the thermal performance, durability, and circularity of IGUs while maintaining the required structural and environmental performance characteristics.

4.2 Alternative connection techniques research

The improvement of glass structures is closely linked to technological developments regarding the connection systems. Since the edge seal is not only a material system but also functions as the connection between the glass panes, insights from existing and innovative glass connection techniques may inform alternative design strategies. This chapter will therefore look into the different connection techniques used in architectural glass applications and evaluates their relevance for this research by plotting them against the design criteria.

Three main categories of glass connections are discussed: permanent, reversible and glass-to-glass connections. In all connection types, it is important to avoid direct glass-material contact. Glass is a very brittle material that is unable to deform plastically in order to increase the contact surface and reduce local stresses. Therefore, these interlayer materials need to be flexible enough to redistribute stress peaks, but at the same time need to have sufficient strength and stiffness to transfer loads without breaking.

Connection	*Sub-category*	*Types*
Permanent	Adhesives	*UV-curing, Epoxy, Structural silicones*
	Hybrid	*Embedded, Laminated*
Reversible	Mechanical	*Profiles, Clamped, Friction grip, Bolts, Spider fitting, Interlocking*
Glass-to-glass	Heat bonding	*Fusing, Welding*
	Additive manufacturing	*3D-printing,*

Table 8: Overview of connection techniques

4.2.1 Permanent connections

Permanent connections are commonly made with glued joints between elements to keep them connected and to avoid direct contact between the glass. The current design of the IGU edge seal can also be considered a permanent connection. Within the permanent connections, two subcategories can be identified: adhesives connections and hybrid connections.

Adhesive connections, are connections that use adhesives or mortars to bond glass either to glass or to other materials (*Bedon & Santarsiero, 2018*). Adhesives are chemical substances with a high adhesive and cohesive connection strength to materials *(Van Lancker et al., 2016*). The long-term durability behaviour of these adhesive connections is determined by the type of connection, type of adhesive and their exposure to environmental factors *(Van Lancker et al., 2016*). Different types of adhesives exist. Structural silicone is the most common adhesive used for low-stress glass connections, because of its high flexibility and deforming temperature it is well qualified to account for thermal deflections. Higher stress connections ask for rigid adhesives, like acrylics or epoxies. Adhesive connections are often used in linear connections with exposure to the external weathering factors, like moisture, temperature deflection and UV-radiation (*Bedon & Santarsiero, 2018*). All adhesives are subjectable to degradation and therefore are not durable. Lastly, adhesives to glass connections often leave contaminations to the glass when destroyed and make recycling of the glass very difficult (*Elstner et al., 2024*).

Current research exist into making easier **demountable adhesive connections**. Often these adhesives require an external stimulus to initiate the debonding of materials. This external input can be thermal, hydrolytic, chemical, electrical or even mechanical in nature. Thermally detachable adhesives are designed to lose adhesion strength when exposed to elevated temperatures. These systems often rely on reversible polymer networks, thermally expandable particles or phase-transition mechanisms that weaken the adhesive interface during heating (*Atif et al., 2025*). On a molecular level this research has been taken a step further. By incorporating ferrimagnetic iron oxide nanoparticles into EMAA, the nanoparticles generate localized heat which melt the EMAA, resulting in rapid bonding and debonding (*Cheng et al., 2021*).

However, whether an adhesive connection is technically demountable is only one aspect of circular applicability. The adhesive system should also be capable of being removed without leaving significant contamination, residue, or causing damage to the glass surface. Any remaining adhesive residues, chemical interaction, or surface degradation may compromise the optical quality, structural performance, or recyclability of the glass, thereby limiting the effectiveness of the demountable connection within a circular reuse strategy.

The second subcategory of permanent connections mentioned here are hybrid connections. **Hybrid** connections are considered hybrid, because they combine permanent adhesive connections with mechanical metal connections (*Kouvela, 2022*). These connections are considered permanent in this chapter, because the metal is bonded in the glass panes and held together using an adhesive. Even though the metal part may in turn be able to be connected to another unit using a reversible connection, within the glass the metal part is permanently connected. However, this embedded connection can only be considered if laminated glass is used. Therefore, it is considered out of the scope of this research.

Based on these considerations, permanent connections should not be considered for the redesign of the edge seal component of the IGU. Their irreversible nature, limited durability and limited glass circularity due to contaminations left by the adhesives on the glass panes, make these connections incompatible with the design criteria.

4.2.2 Reversible connections

Reversible connections offer the possibility of disassembly and component replacement, making them particularly relevant from a circular design perspective. These connections are typically mechanical and rely on metal connectors to transfer loads without permanently bonding materials. Common reversible connection types include mechanical profiles, clamped connections, friction-grip connections, bolted connections, spider fittings and interlocking systems (Figure 9).

Bolted connections are the mechanical connection standard for glass roof and façade structures (*Bedon & Santarsiero, 2018*). **Spider fittings** are an improved design of these bolted connections that use bolts and wires to mechanically fix the glass and transfer loads. These connections require drilling holes in the glass. Load transfer occurs through surface contact between the bolt and the glass borehole, leading to high local stresses (*Bedon & Santarsiero, 2018*). The connections are sensitive to surface flaws around the boreholes, which can increase the risk to brittle failure. As a result, thermally strengthened glass is often required. These connection types are mainly used for large scale structures and work well in transferring loads between glasses. These characteristics make such systems unsuitable for the small scale and thin glass panes typical of IGUs.

Profiled and **clamped** connections avoid drilling and cutting of the glass. Instead they accomplish a connection by forming a mechanical clamp, gripping the glass tightly (*Bedon & Santarsiero, 2018*). However, they rely on sufficient pre-compression to prevent slipping. They will also require a soft interlayer material to avoid immediate contact between glass and the metallic material of the profile or clamps and risk the brittle nature of glass to be exposed to high local stresses (*Bedon & Santarsiero, 2018*). Stress relaxation over time may reduce clamping force, increasing the risk of failure. Additionally, the presence of metal components introduces thermal bridging. An advantage of this connection technique however is the scale connection they form with the glass, increasing the transparency and reducing the optical disruption.

Interlocking principles defines that an element should be kinematically constrained to its position by self-locking, using only its shape and the geometry of the elements around it, without the need for additional connectors or binders (*Oikonomopoulou et al., 2018*). These connections use the compression strength and the self-weight of the blocks to assembly. The chape of the interlocking blocks should have sufficient force distribution to allow direct glass to glass contact, otherwise an interlayer must be introduced (*Oikonomopoulou et al., 2018*). Interlocking connections research mainly focus on their applicability to cast glass blocks or stacked glass elements (*Oikonomopoulou et al., 2018*). Cast glass blocks however are outside of the scope. Despite that, interlocking principles are still interesting reversible connections to be considered in small scale applications like the IGU edge seal design.

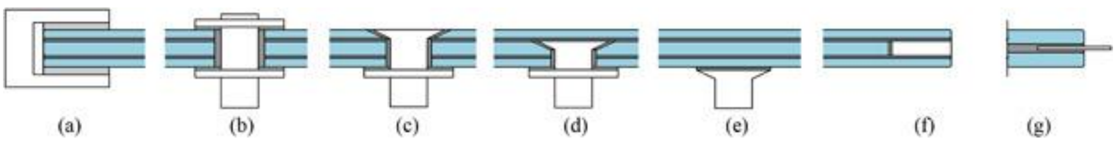


Figure 9: a) Clamped; b) bolted; c) bolted with countersunk bolt; d) hybrid with countersunk bolt; e) adhesive; f) embedded with thick insert; g) embedded with thin insert (Bedon & Santarsiero, 2018)

Overall, reversible connections score highly on demountability and circularity. However, bolted and clamped connections introduce thermal bridges due to the high conductivity of the metal fixings used. Bolted connections require boreholes in the glass that increases local stresses and therefore require thermally tempered glass. To avoid high peak stresses from direct metal to glass contact, all reversible connections also require an interlayer material. Their applicability to IGU edge seals is also restricted, because of the small-scale, bolts and clamps will not have sufficient strength or will not fit within the window frame. Interlocking provide the most promising principles, but available research is limited to cast glass blocks and is not directly applicable to float glass IGU small scale connections.

4.2.3 Glass-to-glass connections

Glass-to-glass connections represent a relatively new area of research and innovation, which have become an integral part of contemporary architectural design (*Invisible Windows*, n.d.). These techniques allow for a seamless transition between various glazed elements without introducing additional materials, resulting in mono-material systems (*Invisible Windows*, n.d.). Two main categories of glass-to-glass connections are identified in this research: heat bonding and additive manufacturing.

Heat bonded connections use the interesting properties of glass to their advantage. Due to its heterogeneous composition, glass does not have a specific melting point. Instead it has a range of temperature over which the glass will melt and change in viscosity (*Rammig, 2012*). This characterization has been used by glass blowing, to connect glass pieces can be shaped and manipulated when hot and viscous and will solidify together when cooled (*Eskes, 2018*). In building technology, this principle has re-emerged in current research with two specific techniques: fusing and welding. With **welding**, the glass is locally heated and connected to another locally heated glass piece (*Eskes, 2018*). With **fusing** glass, multiple pieces of glass are set together in a specific mould and heated in a kiln and connected together (*Eskes, 2018*). In Figure 10, these techniques are shown in comparison to an adhesive connection.

Figure 10: Left to right: Adhesive connection; welded connection; fused connection (Eskes, 2018)

Parallel to these developments, computational design is becoming more and more important in the building industry. Naturally, the possibility for **additive manufacturing** of glass is being researched. A few specific glass additive manufacturing techniques can be identified: fusing deposition modelling, 3d printing, selective laser sintering, stereolithography (*Xin et al., 2023*). They all make use of the same special intrinsic properties of glass as the heat bonded connections do. Recent research examples show that additive manufacturing of glass is indeed possible, but most research is still in the early experimental stages.

The particularly interesting technique of using selective laser sintering on glass, is the ability to do specific surface interventions on microscopic scale (*Khmyrov et al., 2016*). Most interesting research to consider is the newest development where **3d-printing of glass** is directly done onto float glass. Seel et al. (*2018*) is doing research on fused glass deposition modelling. Seel et al. (*2018*) have proven that it is feasible to print float glass directly on a sheet of float glass and use their fusing temperature to glue them together. However, for this to work the composition of the glass needs to match their thermal expansion for them to have sufficient strength between the bonded layers (*Seel et al., 2018*). They assessed the bending strength of this bond and proved that a load can be transferred between 3d printed glass and the float glass substrate. They also stated that borosilicate glass is better for 3D printing, due to its thermal expansion coefficient between 20 and 3000 degrees Celsius. Lower means higher thermal shock resistance and therefore less surface flaws and better bond strength (*Seel et al., 2018*). Stern et al. (*2024*) has taken the research one step further, where they tried to print recycled container and float glass. They have concluded that it is very much possible to melt post-consumer container and float glass to create 3D printed structures (*Stern et al., 2024*). They also combined the post-consumer float glass directly to a substrate of glass which can be seen in Figure 11.

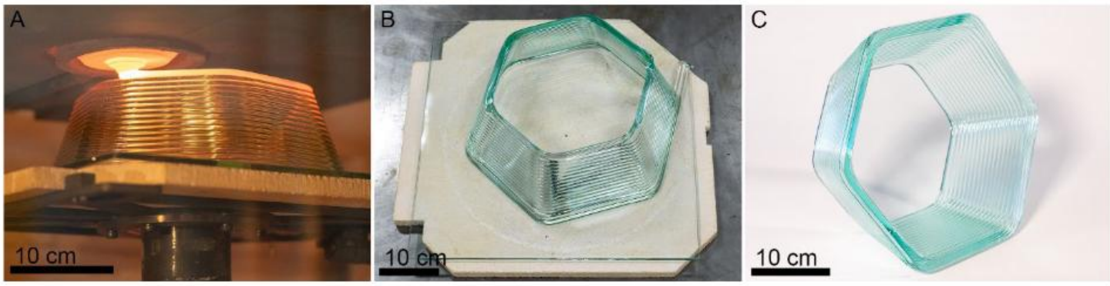


Figure 11: Additive manufacturing, 3D printing of glass to float glass substrate (Stern et al., 2024)

Other additive manufacturing techniques for glass-to-glass bonding use a laser to generate the necessary heat for bonding the glass (*Xin et al., 2023*). The mean advantage of using a laser as the heat source for welding of glass is that the laser uses less energy. With the technique described in the review of Xin et al. (2023) the CO2 laser provides a concentrated directed energy deposition heating the glass wire filament to above the glass transmission temperature. Providing almost the same result as 3D printing of float glass.

The newest development in additive manufacturing is **Ultra-short pulsed laser welding** technique (*van Abeelen et al., 2025*). This technique has been developed to improve the thermal performance of vacuum glass even further. By replacing the highly conductive metal support pillars to glass would improve the Ug-value by 10 - 20% (*van Abeelen et al., 2025*). Additionally, a directly bonded glass pillar, made from the same material as the glass panes, without the need for any adhesives, would improve recycling and visual appearance. It demonstrates a new technique for manufacturing glass support pillars using laser welding to bond, and laser cutting to shape the pillar to the substrate glass. This closely resembles the goal for this master's thesis, but is only proven on the even smaller scale of the support pillars of vacuum glass.

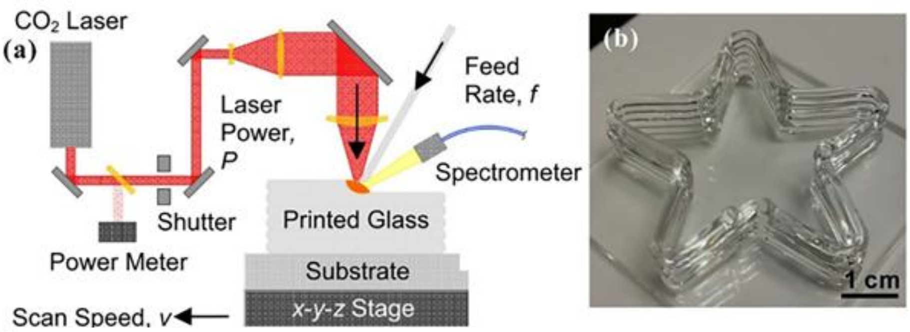


Figure 12: CO2 laser fusing using directed energy deposition heating the glass wire filament (Xin et al., 2023)

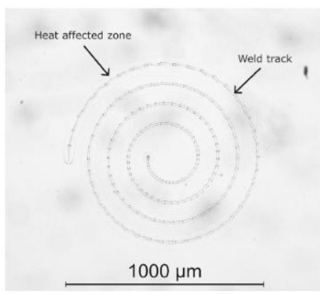


Figure 13: Ultra-short pulsed laser weld on vacuum glass pillar (van Abeelen et al., 2025)

The primary advantage of glass-to-glass connections is that they eliminate material contamination and allow for one-piece recycling. In addition, less thermal bridging occurs in comparison to connection with metal and all connected elements share the same service life and thermal expansion coefficient (*Rammig, 2012*). Another significant advantage is the elimination of boreholes, which avoids stress concentrations and reduces the need for complex structural calculations (*Seel, 2018*; *Rammig, 2012*).

However, these techniques are still under development and have not yet been tested or validated at the small scale required for IGU edge seals. Moreover, they remain irreversible and do not allow for movement between components, which may be problematic under thermal and pressure-induced deformations within the IGU.

4.2.4 Conclusions

This chapter investigated existing and emerging glass connection techniques and evaluated their relevance for the redesign of the IGU edge seal system based on the established design criteria. Three main categories of connection systems were identified: permanent, reversible and glass-to-glass connections. Each category demonstrates specific advantages and limitations in relation to thermal performance, structural behaviour, durability, demountability, and circularity.

Permanent adhesive-based connections currently remain the dominant connection strategy within IGU technology due to their ability to provide airtightness, flexibility, and structural bonding performance. However, permanent adhesive systems also introduce significant limitations from a circularity perspective. Adhesive degradation over time, irreversible bonding, contamination of glass surfaces and difficulties related to disassembly and recycling make conventional permanent connections incompatible with the circular design ambitions of this research. Although current developments in thermally detachable and stimulus-responsive adhesives demonstrate promising potential for future reversible bonding strategies, these technologies remain experimental and still present challenges related to residue formation, durability, and long-term performance.

Reversible mechanical connections offer significant advantages in terms of demountability and material reuse. Mechanical systems such as bolted, clamped, and interlocking connections enable disassembly without permanent bonding and therefore align more closely with circular construction principles. Nevertheless, conventional mechanical glass connections are generally designed for larger-scale structural glass applications and are less suitable for the small dimensions and thin glazing configurations characteristic of IGU edge seals. In addition, metal-based mechanical fixings introduce thermal bridges and localized stress concentrations, requiring additional interlayer materials to prevent brittle glass failure.

Glass-to-glass connections represent the most innovative and promising category investigated in this chapter. Heat bonding and additive manufacturing techniques demonstrate the possibility of creating mono-material glass assemblies without introducing secondary connection materials. However, despite their promising potential, glass-to-glass connection technologies remain largely experimental and currently lack validation for the small-scale, flexible, and hermetically sealed requirements of conventional IGU edge seal systems. Furthermore, these techniques generally create rigid and irreversible connections that may not sufficiently accommodate thermal movement and pressure-induced deformation within insulated glazing units.

Table 9 summarizes the evaluated connection techniques against criteria relevant to IGU edge seal performance. Overall, the analysis demonstrates that none of the investigated connection categories independently satisfies all functional and circular design requirements for the redesign of the IGU edge seal.

Heat bonded glass-to-glass connections show the biggest potential to replace the rigid spacer connection. In the table they are considered to be not demountable, because in theory the glass connection can not be separated without breaking the glass. However, within the context of circular glass design, demountability may be less critical for mono-material glass connections. Since the connection consists entirely of glass and does not introduce contaminating secondary materials, the complete assembly may still remain suitable for direct remelting, recycling, or potentially even remanufacturing processes without requiring prior material separation.

Connection	*Demountable*	*No contaminations*	*Durable*	*Small scale*	*No thermal bridge*	*High thermal insulation*	*Mechanical stability*	*Allow movement*	*High environmental resistance*	*Air and watertight*	*Key limitations*
Adhesives											
UV-curing	- -	- -	+ -	+ +	+ +	+ -	+ -	+ -	- -	+ -	Not demountable, Leaves contamination Not durable
Epoxy	- -	- -	+ -	+ +	+ +	+ -	+ -	+ -	- -	+ -	Not demountable, Leaves contamination Not durable
Structural silicones	- -	- -	+ -	+ +	+ +	+ -	+ -	+ -	- -	+ -	Not demountable, Leaves contamination Not durable
Hybrid											
Embedded	+ -	- -	+ +	- -	+ -	+ -	+ +	+ -	+ +	+ +	Laminated glass
Mechanical											
Profiles	+ +	+ -	+ +	-	- -	- -	+ +	+ -	+ +	+ -	Thermal bridging, High local stresses
Clamped	+ +	+ -	+ +	-	- -	-	+ +	+ -	+ +	+ -	Thermal bridging, High local stresses
Friction grip	+ +	+ -	+ +	-	- -	- -	+ +	+ -	+ +	+ -	Thermal bridging, High local stresses
Bolts	+ +	+ -	+ +	- -	- -	- -	+ +	+ -	+ +	+ -	Thermal bridging, High local stresses, drilling necessary Not on small scale of IGU
Spider fitting	+ +	+ -	+ +	- -	- -	- -	+ +	+ +	+ +	+ -	Thermal bridging, High local stresses drilling necessary Not on small scale of IGU
Interlocking	+ +	+ -	+ +	+ -	- -	+ -	+ +	+ -	+ +	- -	High local stresses, Not on small scale of IGU
Heat bonding											
Fusing	- -	+ +	+ +	+ +	+ +	+ +	+ +	- -	+ +	+ +	Not Demountable without breaking, No movement
Welding	- -	+ +	+ +	+ +	+ +	+ +	+ +	- -	+ +	+ +	Not Demountable without breaking, No movement
Additive manufacturing											
3D-printing	- -	+ +	+ -	+ -	+ +	+ +	+ +	- -	+ +	+ +	Not Demountable without breaking, No movement
Ultra-short laser welding	- -	+ +	+ -	+ +	+ +	+ +	+ +	- -	+ +	+ -	Not Demountable without breaking, No movement

Table 9: Overview of connections evaluated on the design criteria with their key limitations

4.3 Conclusions

This chapter investigated material combinations and connection strategies capable of reducing contamination, facilitating material separation, and extending the service life of the IGU. Through literature-based exploration and systematic evaluation of materials and connection techniques the following conclusions can be made.

Material screening using the Granta EduPack database software demonstrated that not one specific material option remains, that complies with all the material design criteria. At the material level, the analyses demonstrate that the spacer and sealant components require fundamentally different material properties and therefore cannot be effectively replaced by a single material category. For the spacer component, the most suitable materials are glass-based materials due to their compatibility with float glass, similar thermal expansion behaviour, high compressive strength, durability, and mono-material recyclability. Unlike conventional metallic spacers, glass does not introduce thermal bridges and does not contaminate the glazing panes during recycling or remanufacturing processes. For the sealant component, flexibility, tensile strength, gas tightness and movement accommodation remain essential performance requirements. Silicone continues to demonstrate the most suitable overall balance between flexibility, durability, and environmental resistance for conventional IGU applications. In addition, alternative polymer materials such as PMMA, PEEK, and PTFE show potential due to their favourable thermal resistance, chemical stability and durability properties.

The connection analysis further demonstrates that conventional permanent adhesive systems conflict with circular design ambitions due to their irreversible nature and the contamination they leave on the glass surface after disassembly. Although reversible mechanical systems improve demountability, they remain unsuitable for small-scale IGU edge seal applications because of thermal bridging, local stress concentrations, dimensional limitations, and the requirement for metallic fixings. Among the investigated connection techniques, heat-bonded glass-to-glass connections demonstrate the greatest potential for redesigning the spacer component of the IGU edge seal. Techniques such as glass fusing, laser welding, and additive manufacturing enable the creation of mono-material glass connections without introducing secondary materials or conductive metal components. Although these connections are technically irreversible, their mono-material composition allows direct recycling and reduces contamination, thereby limiting the necessity for complete demountability. For the sealant connection, however, rigid glass-to-glass bonding remains unsuitable because the edge seal must accommodate thermal expansion, atmospheric pressure changes, and differential movement between the glass panes. Consequently, flexible and debondable adhesive systems represent the most promising solution for the sealant component. In particular, thermally debondable adhesive systems demonstrate strong potential because they can provide sufficient sealing and bonding performance during service life while enabling controlled separation and reduced contamination during end-of-life processing.

Overall, the findings indicate that the most promising redesign strategy for the IGU edge seal system consists of combining a heat-bonded glass spacer connection with a flexible and preferably thermally debondable polymer-based sealant system. Such a hybrid approach has the potential to extend the service life of the IGU, reduce contamination during disassembly, facilitate cleaner material separation, and improve the recyclability and reuse potential of individual components while maintaining the required structural, thermal and environmental performance characteristics of the insulated glazing unit.

Component	*Original material*	*Alternative material*	*Original connection*	*Alternative connection*
Spacer	Aluminium	Glass	Adhesive	Heat bonding
Sealant	PIB, Silicone	PMMA, PEEK, PTFE	Adhesive	Thermally demountable adhesive

Table 10: Conclusion alternative material selection and most suitable alternative connection technique

5. Research-through-design

In this chapter, a research-informed design approach is applied in which different material combinations and connection techniques are explored to assess their suitability as alternatives to the conventional IGU edge seal and to investigate the potential for demountable and reusable solutions. Insights from the previous research chapters are translated into physical prototypes and systematically assessed against the defined design criteria.

Through these experiments, the research aims to identify feasible edge connection systems that can replace conventional IGU edge seals while supporting improved end-of-life scenarios, disassembly, and material reuse. Answering the question: How can experimentally developed alternative edge connection systems for insulated glass units be engineered to improve durability and circularity, while maintaining compliance with defined performance requirements?

5.1 Methodology

The experiments can be divided into four phases: sample preparation, prototyping, performance testing and final design development. First, post-consumer IGU samples are analysed and prepared for testing and prototyping. Subsequently, alternative materials and connection principles are explored through sketching, prototyping, and iterative experimentation. The experimental work consists of two parallel research tracks. The first experiment focuses on the development and testing of fused glass-to-glass connections. The second experiment investigates the development of secondary connection techniques for thermally reversible connections. Lastly, the developed prototypes are evaluated against the key performance criteria, including durability, mechanical strength, thermal behaviour, and air- and watertightness.

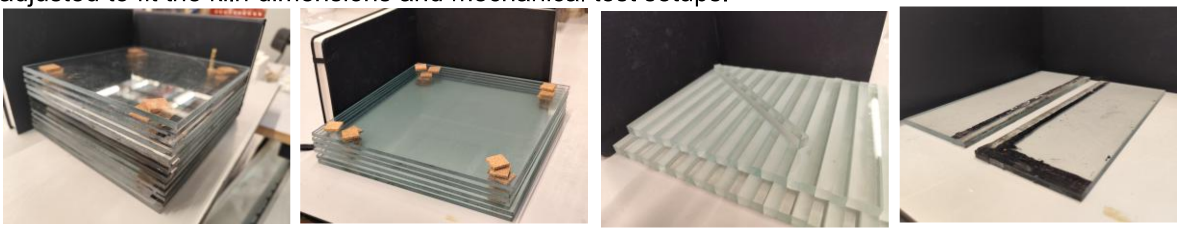
Phase	***Main Goal***	***Key Activities***	***Expected Outcome***
Phase 0 – Sample preparation	Prepare reusable post-consumer IGU glass samples for experimentation	- Open post-consumer IGUs by removing primary and secondary sealants - Scrape residual sealant from glass surfaces - Cut glass into smaller test samples using waterjet cutting - Clean samples using glass cleaning agents (e.g. Glassex or propanol) - Identify tin side and air side of float glass	Clean, standardized glass samples suitable for testing and prototyping
Phase 1 – Sketching & Prototyping	Develop and explore alternative IGU edge seal concepts	- Research material combinations and connection principles - Translate concepts into experimental setups - Create sketches and small-scale prototypes - Conduct preliminary compatibility testing - Test variables such as surface preparation, kiln temperature, and firing schedules	Identification of promising and feasible connection concepts for further testing
Phase 2 – Testing against design criteria	Evaluate prototypes against technical and circularity requirements	- Test mechanical performance (strength and stability) - Assess thermal behaviour and insulation performance - Evaluate acoustic properties where relevant - Examine sealing performance against air and moisture ingress - Investigate durability, disassembly potential, reuse, and failure mechanisms	Comparative understanding of strengths and weaknesses of each design alternative and selection of the best-performing concepts
Phase 3 – Final design	Develop and validate the most promising IGU redesign	- Select optimal material combinations and connection techniques - Produce a full-scale IGU prototype - Evaluate interaction between glass panes, cavity, and edge seal - Explore façade integration, detailing, installation, and maintenance considerations	Coherent final IGU redesign demonstrating improved durability and circularity potential

Table 11: Methodology of experimental phases

Phase 0: Sample preparation

All samples were prepared from two post-consumer insulating glass units (IGUs) provided by Vlakglas Recycling Nederland and shown in Appendix B. The IGUs glass panes are separated from each other and the spacer by cutting through the primary and secondary sealants using a (heated) utility knife or oscillating multi-tool. Remaining sealant residue is scraped from the glass surfaces using a box cutter and putty knife.

The glass panes are cut into smaller test samples using the Sanken CNC 5-assige (60°) waterjet cutter at the Glass Lab of the Faculty of Architecture, TU Delft. Sample dimensions are adjusted to fit the kiln dimensions and mechanical test setups.

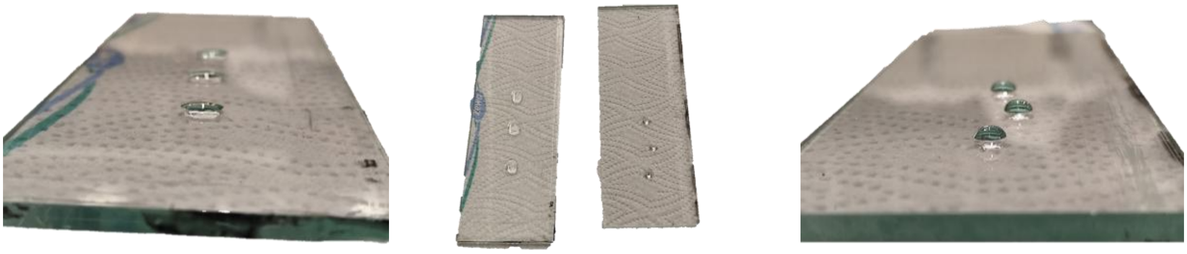


a. 200 x 200 mm **b. 250 x 250 mm** **c. Glass strips** **d. Others**

Figure 14: Overview of glass samples after waterjet cutting (own images)

After the separation, the glass samples are cleaned using propanol or a glass cleaning agent and paper to remove any remaining surface contamination prior to testing/processing.

Lastly, the different sides of float glass (tin side and air side) were subsequently identified and marked using the water droplet method. In this method, water spreads more readily on the air side, whereas droplets remain more cohesive (firm) on the tin side (Figure 15). During the float glass manufacturing process, molten glass solidifies while floating on a bath of molten tin, resulting in slight differences in the properties of the tin side and the air side of the glass. Inconsistent orientation of the glass samples may therefore lead to irregular fusion behaviour, including incomplete bonding or the formation of visual defects (*Shelby, 2005*). Consequently, for all fusing tests, the tin side of the glass was positioned facing downward, while fusion was performed between the two air-side surfaces (*GlassCampus, n.d.*).



a. Air side **b. Identify** **c. Tin side**

Figure 15: Identification of tin and air side of the glass samples (own images)

Phase 1: Sketching and prototyping

In this phase, multiple design alternatives for the edge seal of the IGU are explored through an iterative process of sketching and prototyping. Sketch concepts are subsequently translated into small-scale prototypes to evaluate their practical applicability. Early-stage testing is conducted to assess the compatibility between selected materials and to determine whether the proposed connection techniques can be successfully implemented. Alterations should be made to the designs considering the first results and outcome of the prototyping experiments.

Prototypes are produced using different surface preparation methods, firing schedules, kiln temperatures and holding times. The prototypes are visually inspected after production for bonding quality, deformation, cracking and material compatibility.

Experiment	***Goal***
Kiln and firing schedule experiments	Determine suitable processing temperatures and firing durations
Material compatibility and bonding tests	Evaluate adhesion and compatibility between glass and selected materials

Table 12: Overview of experiments performed phase 1

5.2 First design considerations

This stage of the research started from the ambition to completely eliminate all contaminating materials from the insulated glass unit (IGU). The initial concept was to develop an IGU consisting entirely of glass by applying a glass-to-glass fusion connection technique. A fully glass assembly would consist of a single material with a comparable service life throughout the system, eliminating issues related to differential ageing between components. Furthermore, the absence of additional materials would simplify recycling and potentially improve the durability of the overall unit.

However, the material and technical investigations presented in the previous chapters demonstrated that a fully glass IGU is not a feasible solution. Instead, it can be indicated that a multi-material solution appears to offer the most promising redesign strategy. Although glass exhibits excellent durability, it is also a brittle material that is sensitive to stress concentrations. Thermal expansion, atmospheric pressure changes and wind loads require the edge seal system to accommodate small movements within the IGU. A fully rigid glass-to-glass connection would be unable to absorb these movements, increasing the risk of fracture. In addition, manufacturing challenges such as glass slumping and distortion were identified during the development of fused glass connections. The preferred concept combines a heat-bonded glass spacer with a secondary connection that provides flexibility, environmental resistance and sealing performance.

This conclusion also creates opportunities for improving the circularity of IGUs. Rather than striving for a completely monolithic glass assembly, the redesign can focus on minimising material contamination and enabling future disassembly. By concentrating coatings, sealants, and other contaminants on only one glass pane, the remaining glass components can be more easily reused, remanufactured, or recycled at the end of the product's service life. Such a strategy is particularly relevant because advanced coatings are often applied to improve the thermal performance of modern glazing systems and cannot realistically be eliminated from the design.

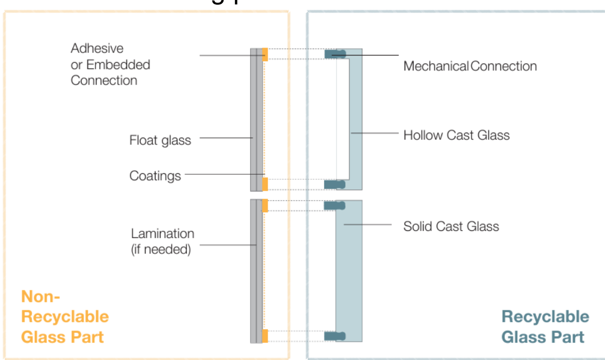


Figure 16: Recyclable fused glass on one side and the non-recyclable part on the demountable side (Kouvela, 2022)

Consequently, the experimental work proceeds along two parallel development tracks. The first track focuses on the further development of the **fused glass spacer connection**, as this remains the most promising approach for improving durability and reducing material diversity within the edge seal system. The second track investigates a connection strategy for attaching the second glass pane to the fused spacer assembly. Instead of a magical trigger, the connection would probably need an outside element to activate the debonding mechanism.

The objective of this second connection is to develop a connection that combines strong adhesion during use with complete reversibility at the end of its service life. Ideally, such a connection would firmly bond to the glass under operational conditions, while allowing for full separation without leaving residues or causing damage to the glass surface. Like a magical trigger that will engage the debonding mechanism.

Various debonding mechanisms were considered, including moisture-activated systems, chemically reversible bonds, biodegradable materials, and mechanically detachable connections. However, many of these approaches introduce practical limitations, contamination risks, or additional components that are undesirable within the constrained geometry of an IGU edge seal.

A **thermally activated debonding mechanism** was therefore identified as the most promising solution. The initial concept consists of integrating a heating wire within the connection zone. When activated, the wire generates localised heat that weakens or breaks the adhesive bond, enabling controlled separation of the glass components. The development of this thermally debondable connection is investigated as a proof of concept for improving the circularity and end-of-life recovery potential of future IGU systems.

Figure 17 presents the first design variations combining the fused glass spacer connection with alternative materials and connection techniques for attaching the second glass pane and creating a complete IGU assembly.

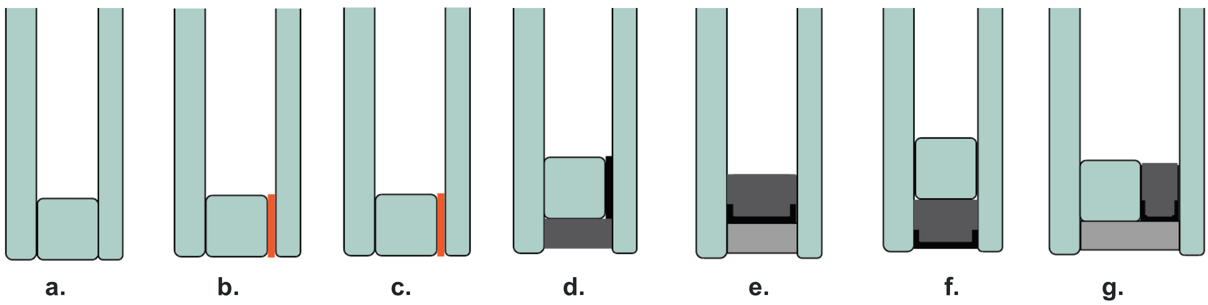


Figure 17: First design alternatives sketch designs (own image)

a. Double sides fused IGU
b. One-sided fused IGU + the second pane connecting using thermal polymer
c. One-sided fused IGU + the second pane connecting using 3D printed thermal polymer
d. One-sided fused IGU + primary sealant + secondary sealant
e. EdgeTech Super Spacer warm edge technology + structural silicone
f. One sided fused + super spacer warm edge technology
g. One sided fused + desiccated silicon foam + PIB + structural silicone

5.3 Development of fused connection

After the literature research into materials, it looks promising to investigate the possibility of making a fused glass-to-glass connection as an alternative spacer element within the IGU. First, to understand the theory behind fusing and figure out the best firing schedule for this first connection. Then start by making the first prototype of the connection and alternate parameters according to the findings.

5.3.1 Fusing

Glass fusing is a thermal process in which separate glass elements are heated in a kiln until they soften and bond together (*Brady, n.d.*). Fusing knows a lot of different techniques that all use the same principle. The technique depends on a lot of different variables and is dependent on **the goal**. In this research, the focus lies on achieving a controlled glass-to-glass connection that is strong enough to provide sufficient mechanical and thermal properties for the IGU, while maintaining the original geometry of the components to fit within the small-scale tolerances of the edge seal.

The behaviour of glass during the fusing process is governed by several material and process-related parameters (*Brady, n.d.*). One of the most critical factors is the **viscosity** of the glass, which decreases with increasing temperature. At tack fuse temperatures, the glass reaches a viscosity that allows surface bonding without significant flow. Closely related to this is the **coefficient of expansion (COE)**. Only glass with matching COE values can be fused together successfully, as differences in thermal expansion may lead to internal stresses and cracking during cooling (*Brady, n.d.*). For this experiment, all glass used is float glass, so this will not be a problem.

Another important consideration is the distinction between the **tin side and air side** of float glass. Due to the float glass production process, the tin side contains trace amounts of tin, resulting in slightly different surface chemistry compared to the air side. These differences can influence surface reactions during heating, as well as the formation of defects such as devitrification or irregular bonding. Therefore, **compatibility** of the **chemical formula** of the glass samples is important to ensure reliable results (*Brady, n.d.*). That is why the identification of the air and tin side of the glass has been added as a sample preparation step in phase 0 of the experiment.

The fusing process is further defined by the **firing schedule**, which consists of controlled heating (**ramp**), holding (**hold**), and cooling phases (*Brady, n.d.*). The ramp rate determines how quickly the temperature increases, while the hold time at a specific temperature allows the glass to reach equilibrium and achieve the desired level of bonding. It is important to note that small variations in temperature or hold time can significantly influence the outcome; for example, a slight increase in temperature may have a similar effect to extending the holding time (*Brady, n.d.*). Common fusing principles often are related to a specific temperature as shown in Table 13.

	Fahrenheit	*Celsius*
Annealing	1050	565
Drape	1200	650
Slump	**1250**	**675**
Fire Polish	1350	735
Tack Fuse	**1425**	**775**
Contour Fuse	1500	815
Full Fuse	1575	860
Full Flow	1800	980
Comb	1700	925

Table 13: Typical temperatures for different kiln forming principles for float glass

Heating and cooling the glass in a kiln introduces stresses to the glass (*Brady, n.d.*). Holding the glass at a specific temperature will release that stress. This temperature is called the **annealing temperature**. All different COE glass have their own different annealing temperature (*Brady, n.d.*). This is an important step to not forget when building the firing schedule for this experiment.

In addition to temperature, **heat distribution** and **glass thickness** play a crucial role in the fusing process. Uneven heating or variations in thickness can lead to internal stresses, deformation, or incomplete bonding. The so-called “**6 mm rule**” indicates that glass tends to stabilize around a certain thickness during fusing, which may influence the final geometry of the connection (*Brady, n.d.*).

A common defect in glass fusing is **devitrification**, which refers to the formation of a crystalline, opaque surface on the glass (*Brady, n.d.*). This can occur due to prolonged exposure to high temperatures, contamination, or unsuitable firing conditions. To minimize the risk of devitrification, several measures should be taken, including using clean glass surfaces, minimizing holding times, applying relatively fast heating ramps, avoiding unnecessary reheating cycles, and ensuring that no coatings or contaminants are present on the glass surface (*Brady, n.d.*).
Another defect is **slumping** of the non-supported pieces. Due the lower viscosity of the heated glass, it will bend with the gravity.

Specifically for the goal of this research, The specific fusing technique applied in this experiment is tack fusing. **Tack fusing** involves heating glass elements until the surfaces in contact soften sufficiently to form a bond, without fully melting the individual pieces. As a result, the original shapes of the glass components are largely preserved, and a visible interface between the elements remains. This makes tack fusing particularly suitable for creating glass-to-glass connections, where dimensional stability and precise geometry are required.

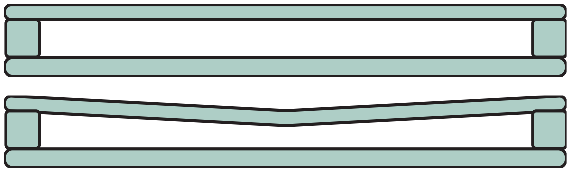


Figure 18: Slumping (own image)

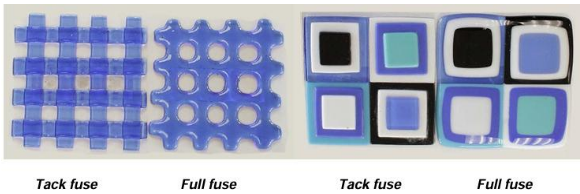


Figure 19: Tack fuse vs Full fuse (Brady, n.d.)

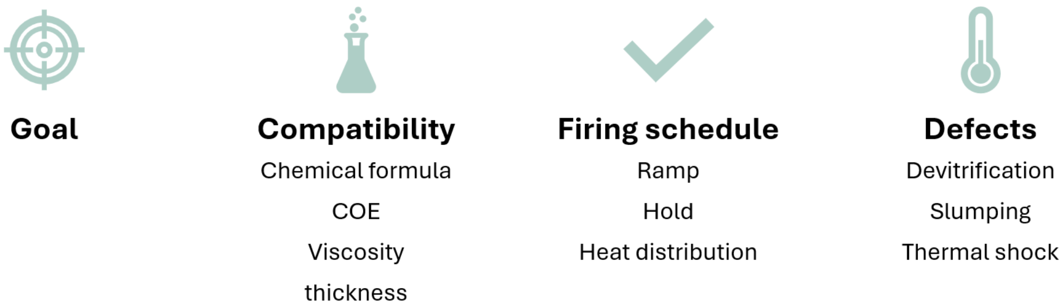


Figure 20: All parameters to consider when fusing (own image)

These parameters demonstrate that tack fusing is a highly sensitive process in which temperature, time, and material compatibility must be carefully controlled to achieve consistent and reliable glass-to-glass connections.

5.3.2 Experimental setup

Determining the correct **firing schedule** for the glass fusing is the most important step. To fit within the small-scale of the IGU edge seal and the even smaller tolerances, the samples need to be precisely glued together, without deformation or sagging from the glass.

The first firing schedule provides a baseline for the samples in this research and is set using the proven parameters from the research of Van der Velden (*2020*). This research showed several successful tack fused samples with fused temperature of 650 degrees Celsius with a hold time at one hour or three hours. More evenly fused samples with less significant no-bond-zones were produced with a three-hour hold. Therefore, this will be the baseline for the first fusing experiment of this research, after which the firing schedule can be adjusted to improve the fuse quality and strength. An overview of the final firing schedules can be found in the Appendix D.

The aim of test 2 is to have the opportunity to change some of the parameters from test 1 to improve the fuse and surface quality of the samples. This experiment only one parameter will change to try and improve the fuse quality. Therefore, the hold and ramp will stay the same. Increased the temperature to 680 degrees Celsius with the same 3-hour hold. Since thickness of shear force samples (test 4) was 30 mm thick. The samples needed a little bit more careful cooling to secure the sample without thermal shock. Therefore annealing thick slabs of Bullseye glass was used as a guideline and an extra annealing step was added (*Davis, 2023*).

To improve the surface quality, the **kiln surface** needs to be prepared, by making the fire brick as smooth as possible. First, by scraping off the main irregularities, like residual molds or glass from other experiments. Then, by vacuuming or wiping the dust from scraping off.

Now that the parameters have been set to produce acceptable fusing results. The next three firings will be used to produce samples specifically for the development of thermally debondable connections and design criteria testing.

	Sample	*Dimensions*	*Kiln*	*Set parameters*		*Aim*
1	6x A+A 2x A+T	200x70x4/5 mm + 10x10 mm glass strip	Medium	Fusing Hold Annealing Hold	650°C 3h 560°C 5h	- Set baseline for firing temperature - Determine if the air or tin side influences the results of the fusing
2	2x	200x200x4/5 mm + 10x10 mm glass strips	Medium	Fusing Hold Annealing Hold	680°C 3h 560°C 5h	- Adjust parameters according to findings first fusing to improve fuse quality or surface quality
3	5x	200x200x4/5 mm + 10x10 mm glass strips	Big	Fusing Hold Annealing Hold	680°C 3h 560°C 5h	- Produce samples for additional testing for developed thermally debondable connection
4	8xshear	100x100x15 mm + 100x100x15 mm	Big	Fusing Hold Annealing Hold Thick slab annealing	680°C 3h 560°C 6h 500°C 400°C	- Produce test samples for phase 2: testing against the design criteria - Produce samples for additional testing for developed thermally debondable connection - Prove slumping
	8xtensile	100x100x4 mm + 10x10 mm glass strip				
	4xslump	100x100x4 mm + 10x10 mm glass strips				
	2x IGU	250x250x4/5 mm + 12x15 mm glass strips				
5	4x	250x250x5 mm + 12x15 mm glass strips	Big	Fusing Hold Annealing Hold	680°C 3h 560°C 5h	- Produce samples for phase 3: final IGU design

Table 14: Overview of fusing tests performed

5.3.3 Results

All glass samples successfully fused together during the thermal bonding process. However, differences in **fuse quality** were observed between the firing tests. The fuse quality obtained during the first firing test can be classified as a poor tack fuse, as the applied temperature and dwell time were insufficient to achieve adequate interfacial bonding between the two glass panes. Although the samples adhered to one another, complete bonding was not achieved. Visual inspection of the sample shows different colour patches within the interlayer, representing no-bond patches that reflect light in a different way than the sufficiently fused samples. These insufficient fused samples may result in the formation of a dominant weak zone along the longitudinal centre of the specimens. Following adjustments to the firing programme, including an increase in the fusing temperature to 680°C during the second and subsequent firing cycles, the fuse quality improved significantly. Visual inspection indicated a more homogeneous bond with a reduced number of no-bond zones.

The **surface and optical quality** of the fused glass specimens were adversely affected by inadequate kiln surface preparation. Visible dots, surface irregularities, contamination from firebricks, and dust particles caused optical distortions and light refraction defects. Although the surface quality improved slightly throughout the successive firing rounds, minor imperfections remained visible in all samples.

Lastly, several forms of **glass deformation** were observed during the experiments, from slight movement of glass strips off the edges to slumping of unsupported glass. After the initial firing test, more careful placement of the specimens and the introduction of firebrick barrier blocks reduced the extent of these deformations. Nevertheless, significant deformations occurred during test 4. The intentionally unsupported samples demonstrated that sagging of glass can occur even at relatively low fusing temperatures like in this experiment. Unfortunately, the IGU specimens from test 4 exhibited unexpected behaviour: one sample showed yellow discolouration, likely caused by degradation or alteration of the coating layer or excessive leftover oils even after cleaning the glass, while another IGU glass strip experienced severe deformation, rendering the specimen unsuitable for further testing.

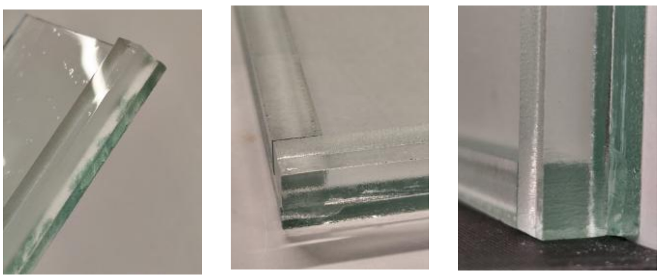


Figure 21: Results fuse quality (own images)

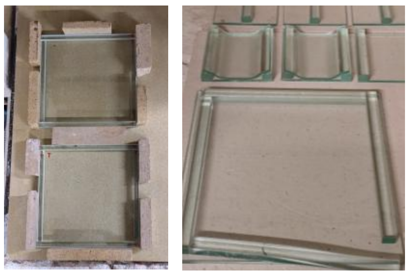


Figure 22: Results deformations (own images)

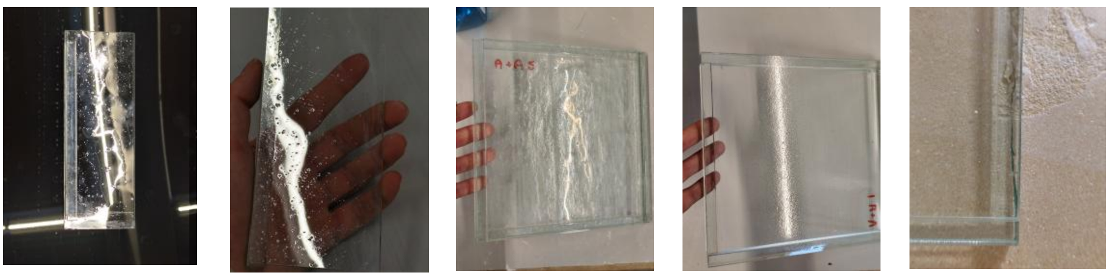


Figure 23: Results surface quality (own images)

5.3.4 Conclusion

Overall, although some differences in fuse, surface and optical qualities could be observed, all the samples have been fused together, so the development of a fused connection was successful.

Sample		*Fuse success?*	*Fuse Quality*	*Surface Quality*	*Optical quality*	*Deformation*	*Key Take Away*
1	A+A 1	YES	- -	- -	+ -	+ +	Poor fuse quality - Only patches of glass are fused together > Increase temperature Poor surface quality - visual light distortion, dents and contamination of fire brick > Prepare and clean kiln surface > Add ThinFire shelf paper > Make an even mold Slight deformation - Some displacement of glass strips > Contain edges with barriers
	A+A 2	YES	- -	- -	+ -	+ +	
	A+A 3	YES	- -	- -	+ -	+ +	
	A+A 4	YES	- -	- -	+ -	+ -	
	A+A 5	YES	- -	- -	+ -	+ +	
	A+A 6	YES	- -	- -	+ -	+ -	
	A+T 1	YES	- -	- -	+ -	+ +	
	A+T 2	YES	- -	- -	+ -	+ -	
2	1	YES	+ +	+	+ -	+ +	Good fuse quality Good surface quality, not yet perfect No visible deformations
	2	YES	+ +	+	+ -	+ +	
3	1	YES	+ +	+ -	+ -	+ +	Good fuse quality Poor surface quality - visual light distortion, dents and contamination of fire brick > Prepare and clean kiln surface > Add ThinFire shelf paper > Make an even mold No visible deformations
	2	YES	+ +	+ -	+ -	+ +	
	3	YES	+ +	+ -	+ -	+ +	
	4	YES	+ +	- -	+ -	+ +	
	5	YES	+ +	- -	+ -	+ +	
4	Shear 1-8	YES	+ +	+	+ -	+ +	Good fuse quality Good surface quality, not yet perfect Slight deformation - Slumping - Major displacement of glass strip > Contain edges with barriers
	Tensile 1-8	YES	+ +	+	+ -	+ +	
	Slump 1-2	YES	+ +	+	+ -	- -	
	Basic 1-2	YES	+ +	+	+ -	+ +	
	IGU 1-2	YES	+ +	+ -	- -	- -	
5	1	YES	+ +	+	+	+ +	Good fuse quality Good surface quality, not yet perfect No deformations
	2	YES	+ +	+	+	+ +	
	3	YES	+ +	+	+	+ +	
	4	YES	+ +	+	+	+ +	

Table 15: Results of glass-to-glass fusing tests

To understand if the fused glass-to-glass connection can indeed replace the aluminium spacer in the edge seal of the IGU, the fuse strength must prove sufficient and the spacer should perform thermally. Therefore, the connection is tested against these criteria in phase 2 of the research.

5.4 Development of thermally debondable connection

In addition to the development of the fused glass spacer connection, a second experimental track was initiated to investigate a connection method for attaching the second glass pane. The objective of this research is to improve the circularity of insulated glass units by enabling easier separation of components at the end of their service life. To achieve this, a thermally debondable connection is explored. For the proof-of-concept experiments, a heating wire was selected as the thermal activation mechanism. The heating wire provides a simple and controllable method to generate localised heat within the connection zone, making it suitable for experimentally evaluating the feasibility of thermally debonding the connection. The focus of the experiments is therefore not on optimising the activation method itself, but on demonstrating the principle of a thermally detachable connection.

5.4.1 Setup

For this experiment, a laboratory power supply with controllable current and voltage output was used. The power supply is connected to the heating wire using an electrical connector to a positive and a negative cable. The heating wire was positioned between the two materials intended to be bonded and lightly compressed using a glue clamp to ensure consistent contact pressure and improve thermal transfer between the wire and the surrounding materials.

The heating wire is a resistance wire. Resistance wire is a specialized type of wire with high electrical resistance. When electric current passes through it, the metal atoms resist the flow of electrons, converting electrical energy directly into intense heat.

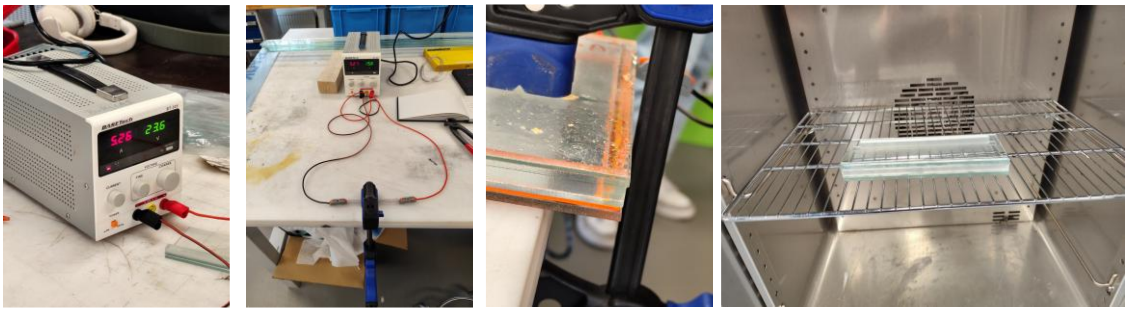


Figure 24: Images of test setup thermally debondable connection (own images)

Parameters that influence the amount of heat coming from the resistance wire are thickness of wire, density of wire iterations and electrical resistance. According to Ohm's law, electrical resistance is defined as the ratio between voltage and current. During the experiments, it was observed that the thermal output of the heating wire was primarily dependent on the applied current, while the voltage output remained limited due to the electrical resistance within the system. Using this setup, temperatures ranging between approximately 70°C and 100°C were achieved.

5.4.2 Material selection

Based on the preceding material study, plexiglass (PMMA), polyether ether ketone (PEEK), polytetrafluoroethylene (PTFE), polyethylene Terephthalate Glycol (PETG) and silicone were identified as potential candidate materials for the edge-seal component. PMMA, commonly known as Plexiglas, was initially selected for testing due to its transparency, relatively low melting temperature and compatibility with glass. Experimental observations demonstrated that PMMA could be heated and softened effectively using the resistance wire. However, PMMA exhibited no adhesion to the glass substrate. Although the material melted under thermal activation, it did not create a structural bond with the glass surface. Similarly, PEEK and PTFE were excluded from further testing due to their lack of adhesion to glass.

Insights from additive manufacturing research, where thermoplastic materials are directly printed onto glass substrates, indicate that PETG exhibits moderate adhesive properties when combined with glass substrates (Van der Werf, 2026). PETG was therefore selected for further proof-of-concept testing to investigate the feasibility of a thermally demountable glass connection activated by a heating wire.

	Kind of material	*Glass transition*	*Melting point*	*Compatible glass*	*Adhere to glass*
PMMA	Thermoplastic	105	160 – 200	Yes	No
PEEK	Thermoplastic	143	320 – 350	Yes	No
PTFE	Thermoplastic	115	327 – 348	Yes	No
PETG	Thermoplastic	75 – 80	220 – 260	Yes	Yes
Silicone	Synthetic rubber	-	-	Yes	Yes

Table 16: Overview of materials selected and properties (Jasonxue, 2025; Raja et al., 2016)

Silicone was considered due to its compatibility and excellent adhesion to glass. However, as a thermoset material, silicone does not soften and remelt, making it unsuitable for a thermally debondable connection. Despite this limitation, silicone remains a valuable material for fulfilling the structural and functional requirements of an edge seal. Therefore, while silicone was excluded from the thermally debondable proof-of-concept experiments, it remains relevant as a potential material for future IGU edge-seal designs.

5.4.3 Results

Three different materials were tested using the setup. PMMA and 3D printed PETG did not have a strong adhesive connection to the glass samples. PMMA softened under heating but did not form any attachment to the glass surface. The 3D-printed PETG samples also failed to create a durable connection. Due to the relatively large sample size and limited heat distribution from the resistance wire, only small regions of the PETG interlayer reached a sufficient temperature for bonding. Although local adhesion was observed during heating, the connection did not remain after the samples had fully cooled.

Only PETG plate material (Vivak) successfully bonded to the glass and maintained adhesion after cooling. Among the materials evaluated, this was the only material that produced a stable connection, making it the most promising candidate for further investigation of a thermally debondable glass connection.

PMMA **3D printed PETG** **PETG**

Figure 25: Overview of materials selected (own images)

	Current (A)	*Voltage (V)*	*Resistance (Ω)*	*Melted?*	*Adhesion?*
PMMA	5.25	1.5	0.29	Yes	No
3D printed PETG	5.25	23.6	4.5	Partly	Temporarily
PETG	5.25	6.4	1.2	Yes	Yes

Table 17: Overview of set parameters

During the experiments, several failure mechanisms and practical limitations were observed.

One of the principal risks associated with this experimental setup was the occurrence of **thermal shock**. Since the heating wire locally heated the edge regions of the glass assembly, significant temperature gradients could develop between the heated edges and the cooler centre regions of the glass panes. To reduce the risk of thermally induced fracture, all specimens were preheated and cooled gradually within an oven before and after activation of the heating wire, thereby promoting more uniform temperature distribution throughout the samples.

Unfortunately, the oven treatment introduced additional challenges. The elevated temperatures required to reduce thermal gradients approached or exceeded the softening temperature of the PETG. As a result, specimens exposed to the oven showed increased **deformation** compared to samples heated only by the resistance wire. While the oven step reduced the risk of glass fracture, it simultaneously influenced the geometry and behaviour of the thermoplastic interlayer.

In most cases, overheating resulted in **melting of the electrical connectors**, interrupting the experimental process and showing the limitations of the experimental setup.

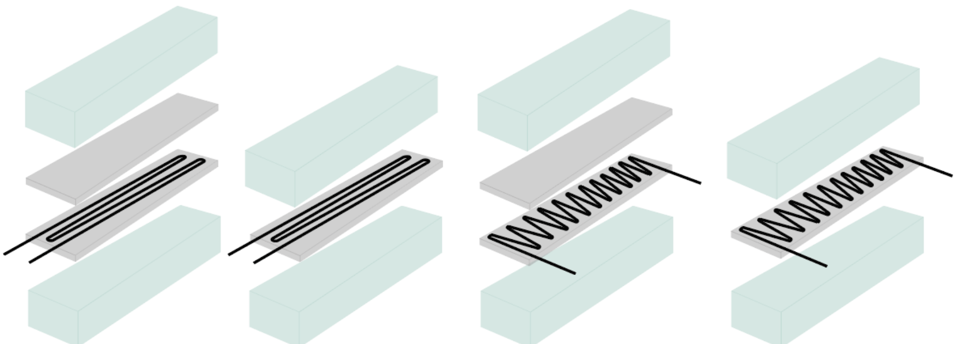
Despite these limitations, the experiments demonstrated that embedded resistance heating can successfully generate localised heating within the connection zone and can activate and soften thermoplastic materials. This confirms the feasibility of using resistance heating as a potential debonding mechanism for thermally detachable glass connections.

Thermal shock **Deformation** **Melting of electrical connector**

Figure 26: Results (own images)

The final PETG test iterations demonstrated varying levels of debonding performance. The final experimental iterations showed the greatest potential when a dense distribution of resistance wires was used. Due to the limited power output available in the experimental setup, increasing the wire density improved heat distribution and resulted in more effective thermal activation of the PETG interlayer. Nevertheless, the debonding performance varied considerably between samples. Some specimens could only be separated by applying substantial mechanical force and additional tools, while others required considerably less force following thermal activation.

Although separation could be achieved in several cases, glass chipping and localised contamination were frequently observed during the debonding process. In some experiments, severe damage to the glass surface occurred, indicating that the current connection configuration is not yet suitable for practical application. The results demonstrate that while the principle is feasible, significant optimisation is required to improve both bond quality and controlled debonding behaviour.



Separated?	No	Yes	Yes	Yes
Force applied	Full force and tools	Medium force	Full force and tools	Little force
Glass chipping	-	Medium	Medium	A lot
Contamination	-	None	None	A lot

Table 18: Results strength of PETG thermally bondable samples

5.4.4 Conclusion

The experimental results identified PETG as the most promising material for investigating a thermally activated debonding concept. In contrast to PMMA, PETG demonstrated both thermal activation and adhesion to the glass substrate. However, the quality and consistency of the bond remained highly dependent on heat distribution and temperature control during the activation process.

Thermal shock remains one of the primary technical challenges associated with this connection concept. Future research should therefore focus on improving thermal management strategies to minimise temperature gradients within the glass and reduce the risk of thermally induced fracture. In addition, several experiments were limited by overheating of the electrical connectors and time constraints, restricting the number of parameter variations that could be investigated. Future research could focus on optimising the resistance heating system through:

- Thicker resistance wires
- A larger number of wires
- Multiple shorter wire segments
- Alternative wire geometries, such as zigzag patterns, to improve heat distribution

Overall, the experiments demonstrated the feasibility of using embedded resistance heating to activate and weaken a polymer-based glass connection. While the developed proof-of-concept did not yet provide a reliable structural bonding or debonding solution, the results indicate that thermal activation has potential as an end-of-life disassembly strategy for insulating glass units (IGUs). By integrating a resistance heating wire within the IGU edge seal during manufacturing, the connection could potentially be activated at the end of its service life to facilitate controlled separation, material recovery and improved recycling or reuse of the glass components.

Phase 2: Test against design criteria

The prototypes are assessed for mechanical, thermal, and sealing performance. Mechanical testing evaluates the strength and stability of the connections. Thermal testing evaluates the behaviour of the connection under temperature variation. Sealing performance is assessed by observing air leakage, moisture ingress, and deformation of the edge connection.

The prototypes are additionally evaluated on circularity-related criteria, including disassembly potential, material separation, reuse possibilities, and visible failure mechanisms. The test results are compared to identify the most promising design alternatives.

Requirement	*Test*
Thermal performance	Determine material CTE and thermal conductivity though material properties Determine component U-value and thermal bridges through numerical simulation
Mechanical performance	Determine material mechanical strength though material properties Determine failure mechanism glass-to-glass fusion connection through shear test Determine failure mechanism thermally bonded connection through 3-point bending test
Durability	Determine durability through accelerated aging test Determine water leakage rate through static water test Determine air leakage rate through smoke test
Circularity	Determine LCA

Table 19: Overview of tests performed

5.5 Thermal performance

Since the IGU has been developed to reduce the heat gain and heat loss through the transparent parts of the façade, assessing the thermal performance of the redesign of the edge seal component and materials selected is an important first step to validating the research.

5.5.1 Material CTE and thermal conductivity

To assess the material, it was considered that all materials should have a low thermal conductivity. Float glass has a relatively low thermal expansion and moderate thermal conductivity, making it dimensionally stable under temperature changes. Silicone and PETG have significantly higher thermal expansion coefficients and much lower thermal conductivity, meaning they deform more with temperature fluctuations but function as thermal insulators. Metals exhibit very high thermal conductivity, which increases thermal bridging in IGUs. Thermal resistivity is the inverse of thermal conductivity. Therefore, silicone and polyethylene terephthalate glycol (PETG) provide better thermal insulation than metallic spacers.

Material selected	($x10^{-6}$ /K) *Thermal expansion coefficient*	(W/mK) *Thermal conductivity*	(mK/W) *Thermal resistivity*
Float glass	8 – 9	1.0	1.0
Silicone	200 – 300	0.2 – 0.35	2.9 – 5.0
PETG	60 – 80	0.20 – 0.24	4.2 – 5.0
Aluminium	23 – 24	205 – 237	0.004 – 0.005
Stainless steel	16 – 17	14 – 16	0.063 – 0.071

Table 20: Overview of thermal material properties

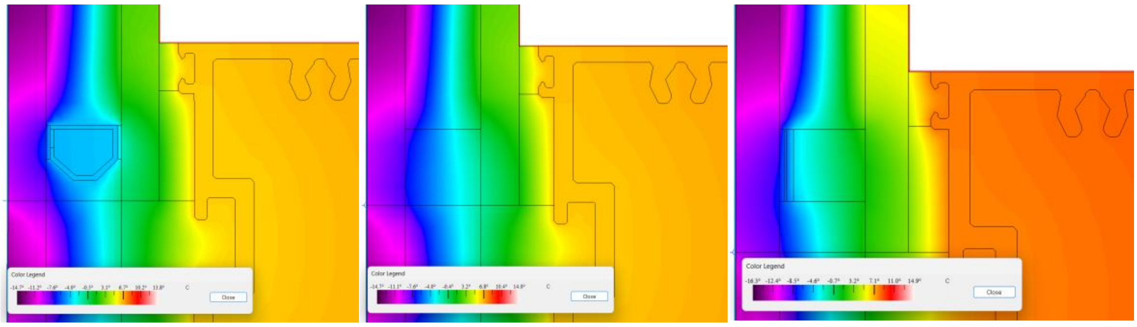
5.5.2 Component U-value and thermal bridges

To evaluate the thermal performance of the proposed edge seal designs, both the overall component U-value and the presence of thermal bridges were assessed through numerical simulation. The software programs, called THERM and Berkeley Lab WINDOW, are used for this analysis (*Lawrence Berkeley National Laboratory (LBNL), 2026a, 2026b*). Berkeley Lab WINDOW was first utilized to construct the glazing systems using data from the integrated Glass Library (Appendix J), after which the glazing configurations were imported into THERM for two-dimensional thermal simulation of the edge seal region.

The exact glass composition and coatings of the post-consumer IGU panels are unknown. Therefore, standard Optifloat glass from Pilkington was chosen to run the simulations, as this corresponded to the glass used for the experimental spacer specimens. No additional low-emissivity coatings or advanced glazing properties were included in the analysis.

Consequently, the simulations represent a simplified double-glazing systems without coatings, resulting in a **U_{glass}= 2.55 W/m2K**. This value remains within the typical performance range of conventional double-glazed systems and therefore satisfies the performance criteria established at the beginning of this research.

The generated glazing system in Berkeley Lab WINDOW was then imported to the THERM program (Appendix K). The different spacer designs and materials are implemented and allowed a comparison of the thermal behaviour of the alternative edge seal concepts and identification of potential **thermal bridges** occurring at the spacer connection between the glass panes.



U-value glass: 2.55 W/m2K U-value glass: 2.55 W/m2K U-value glass: 2.55 W/m2K
U-value frame: 4.44 W/m2K U-value frame: 4.35 W/m2K U-value frame: 3.95 W/m2K

Figure 27: Results THERM (Lawrence Berkeley National Laboratory (LBNL), 2026a)

Overall, the simulation results provide a first indication of the thermal effects of the alternative edge seal concepts within a curtain wall façade system. The glass configuration and framing conditions remained unchanged, only the spacer material and geometry were modified. A slight improvement in thermal performance was observed.

The U-value of the assembly showed a marginal improvement when the conventional aluminium spacer was replaced with a fully fused glass connection. A more pronounced improvement in the overall U-value was achieved when highly insulating materials such as PETG and silicone were introduced into the edge seal design.

In the analysis also the heating wire is schematically placed in the edge seal. Although the heating wire is made from metal with a relatively high conductivity. Because it does not come in contact with the glass directly, but is rather imbedded in the PETG, it does not risk creating a thermal bridge.

Based on these results, the thermal performance and the absence of significant thermal bridges appear sufficient to meet the design criteria established in this research. However, the results should be interpreted as comparative rather than absolute, given the simplified simulation assumptions.

5.6 Mechanical performance

Mechanical performance testing of the proposed alternative spacer material and fused glass connection is essential to evaluate whether the system can withstand the repeated external loads working on the spacer. Glass is known to perform well under compressive loading. Within the spacer of an IGU however, is also subjected to rotational forces, localized peak stresses and limited tensile stresses caused by thermal expansion, pressure fluctuations, and deformation of the glazing assembly. Therefore, the spacer system must not only maintain the separation between the glass panes, but also resist excessive movement and rotational deformation while transferring compressive, tensile, and shear forces safely throughout the assembly.

5.6.1 Material mechanical properties

Float glass has an inherent modulus of rigidity (shear modulus) of 30 GPa. However, the ultimate shear strength, the maximum shear stress the material can endure before failure, depends significantly on surface treatment, micro-flaws and whether it is bonded to other materials. Therefore, the pure shear strength of glass before catastrophic failure is the 25 to 35 MPa (*Boutar et al., 2026*). When adhered to adhesives, the shear strength depends on the specific chemical bond. For instance, tests using epoxy on standard soda-lime-silica float glass report bonded shear strengths between 6 MPa and 8 MPa, heavily depending on whether the adhesive is applied to the air-side or the tin-side of the glass (*Boutar et al., 2026*).

For safety structural reliability, the spacer should not fail or detach before fracture of the glass itself occurs. Therefore, the fused glass connection is required to achieve a mechanical performance equal to or greater than the strength of the glass substrate. While imperfections and local no-bond zones may occur within the fused interlayer, the connection should ideally behave as a continuous glass bond. The aim of the mechanical testing is therefore to determine whether the fused glass interface performs weaker than, equal to, or stronger than the glass itself. Through shear testing of the fused specimens, an estimation can be made of the bond strength and structural reliability of the proposed connection system.

Materials selected	(MPa) *Compression strength*	(MPa) *Tensile strength*	(MPa) Shear strength	*(MPa) Allowable Shear Stress*	(GPa) *Shear modulus*	(GPa) *Young's modulus*
Float glass	800 – 1000	30 – 90	25 – 35	10 – 15	~30	70 – 73
Silicone	5 – 15	2 – 10	0.5 – 2	0.2 – 0.8	0.001 – 0.01	0.001 – 0.05
PETG	50 – 80	45 – 55	35 – 50	15 – 25	0.7 – 0.9	2.0 – 2.2
Aluminium	150 – 300	90 – 310	70 – 210	40 – 120	25 – 28	68 – 71
Stainless steel	170 – 1000	500 – 1000	300 – 600	150 – 300	72 – 81	190 – 210

Table 21: Overview of mechanical material properties

5.6.2 Shear testing fused glass connection

To evaluate whether the fused glass-to-glass connection can potentially replace the aluminium spacer in the IGU edge seal, its shear strength must be sufficient. Mechanical testing was therefore conducted using a custom shear test setup.

Shear testing setup

The glass samples are fixed within a rigid steel frame, after which force is applied gradually to the connection area under controlled loading conditions. The applied force is continuously measured by the load cell and transmitted to a computer for real-time monitoring and recording of the force-displacement behaviour during testing.

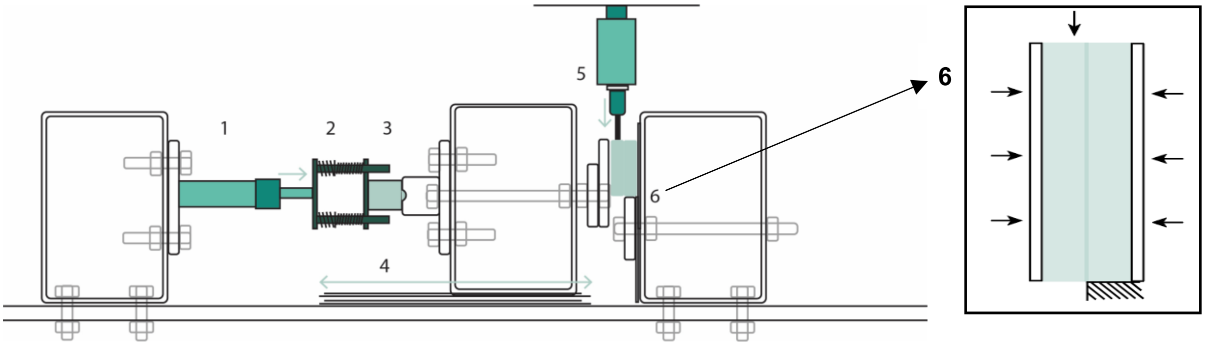


Figure 28: Schematic visualization of setup shear testing fused glass samples (own image)

	Name	***Function***
1	5-ton Luka hydraulic cylinder	Apply normal force to sample. The hydraulic cylinder can manually be pumped up to the needed force using a hydraulic oil hand pump.
2	Loaded springs	4 springs ensure equal distribution of the force.
3	Load cell	The applied force is measured using a load cell connected to a digital data acquisition system.
4	Rail	The rail allows the middle steal block to move easily to its position and helps deliver the normal force to the sample.
5	700 kN Hydraulic cylinder	Shear force is applied using a universal testing machine equipped with a load cell to record force-displacement behaviour.
6	Sample support	The sample must be supported by completely rigid and even surfaces to avoid peak stresses from occurring. An interlayer material, like neoprene and a non-friction film to allow sliding of the sample, can be added. The rigid support on the bottom of the glass must only cover 1 glass pane, so the other glass pane is free to move down.

Table 22: Name and function of components shear testing setup

During the initial trial, testing difficulties were encountered due to unexpected load redistribution within the setup. The **normal force** was initially set to approximately **5 kN** or **3.5 kN**, representing roughly one quarter of the expected failure load range.

During testing, the normal force seemed to increase simultaneously with the shear force. Even though this force is supposed to be a constant. Under normal circumstances a gradual reduction in measured force can be observed, followed by a slight increase once initial cracking occurs. At this stage, the specimens require additional deformation space, resulting in contact with the loading boundaries and a corresponding increase in measured normal force.

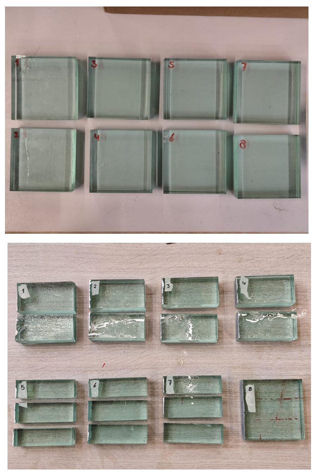


Figure 29: Images of samples shear testing (own images)

However, in the trial runs it became clear that the specimens exceeded the load capacity of the testing configuration and were able to push against the normal force. The resulting force interaction led to misalignment of the vertical shear loading direction and produced unreliable measurement data. To resolve this issue, the effective contact area was reduced by cutting the original glass samples into smaller sections, either in half or in thirds, in order to improve load control and achieve more stable and repeatable test conditions.

The modified specimens were subsequently labelled according to their subdivision. Samples 1.1 and 1.2 were derived from the original Sample 1 and were used in the final trial runs. Sample 2.1 corresponds to S1-W50, where "W50" indicates a reduced width of 50 mm from the original 100 mm specimen. Similarly, Sample 2.2 corresponds to S2-W50, while Sample 5.1 corresponds to S1-W33, representing a one-third width reduction. This naming convention was applied consistently across all subdivided specimens.

In total, ten samples were tested.

Shear testing results

Sample	(mm) Dimensions	(kN) Normal force	(kN/s) Loading rate	(kN) Shear force at failure	(mm) Displacement at failure	Kind of failure
Trial	100x50x30	4.9 – 5.8	0.01	/	/	Peak stress
S1-W50	100x50x30	4.9 – 5.8	0.01	73.1	1.17	Shattered
S2-W50	100x50x30	4.9 – 5.3	0.01	42.7	1.04	Shattered
S3-W50	100x50x30	4.9 – 5.9	0.01	61.6	1.01	Shattered
S4-W50	100x50x30	4.6 – 5.4	0.01	49.7	1.10	Shattered
S5-W50	100x50x30	4.6 – 5.3	0.01	53.3	1.11	Shattered
S6-W50	100x50x30	4.7 – 5.9	0.01	59.9	1.33	Shattered
S1-W33	100x33x30	4.7 – 5.2	0.01	40.3	1.56	Shattered
S2-W33	100x33x30	3.5 – 3.9	0.01	36.3	1.58	Shattered
S3-W33	100x33x30	3.2 – 3.8	0.01	34.5	0.92	Shattered
S4-W33	100x33x30	3.5 – 4.5	0.01	35.3	0.92	Shattered

Table 23: Results shear testing fused glass samples

All samples exhibited a broadly similar failure behaviour. In several cases, initial crack formation was already observed during the loading phase, as illustrated in Figures 30 and 31. These visual observations correlate with the recorded force–time data, showing a progressive increase in load prior to sudden failure. Ultimately, all specimens failed in a brittle manner, characterised by total shattering of the glass.

Overall, the results indicate a relatively broad range of failure loads, from 34.5 kN to 73.1 kN (Table 23). In contrast, the displacement at failure shows limited variation across all samples, which is consistent with the brittle nature of glass.

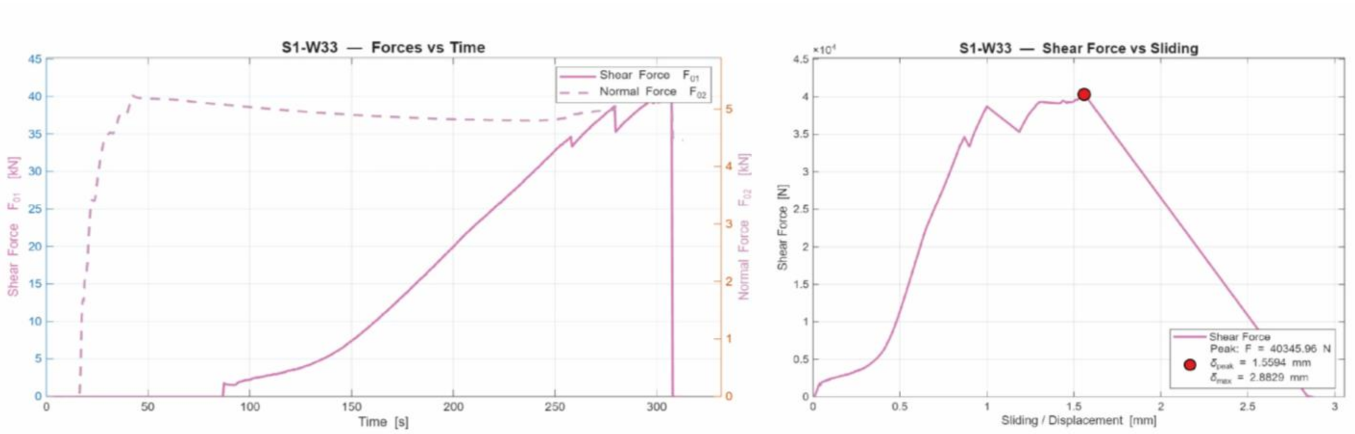
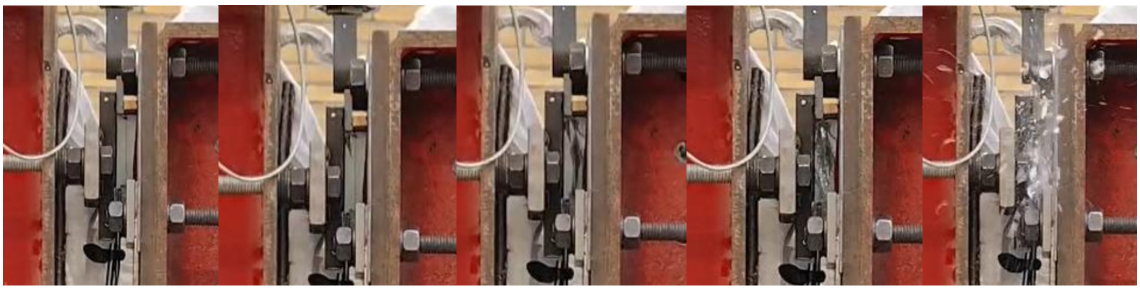


Figure 30: Shear test sample S1-W33: test results



t = 0 **t = 260** **t = 275** **t = 290** **t = 310**

Figure 31: Images of crack formation during shear testing S1-W33 in corelation with time intervals of Figure 30

Crack distribution
From the crack distribution a lot can be said about the interlayer behaviour. It was expected that any imperfections or local non-bonded zones within the fused interlayer would represent the weakest part of the assembly. In such a case, crack propagation would be expected to follow the path of least resistance through the interlayer, potentially accompanied by localized secondary cracking around the glass-to-interlayer interface.

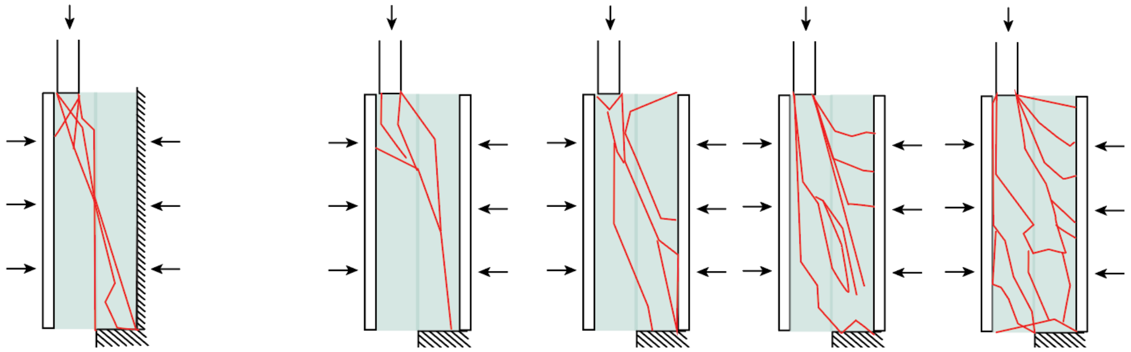


Figure 32: Expectation vs reality of crack distribution (own image)

However, visual inspection of the specimens after shear testing did not reveal a clear or consistent crack pattern along the interlayer. No distinct preferential crack propagation through the fused interface could be identified.

Instead, failure occurred in an uncontrolled brittle manner, dominated by complete shattering of the glass elements. After closer examination of the fractured specimens, the fused interlayer was in most cases no longer distinguishable as a continuous feature within the broken glass fragments. This suggests that failure was governed primarily by bulk glass fracture rather than interfacial debonding within the fused connection.

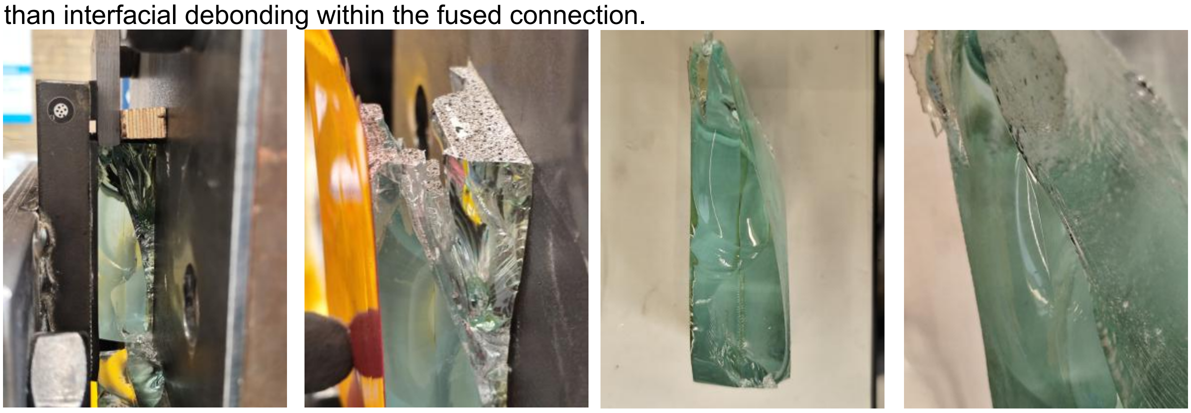


Figure 33: Shear test samples S1-W50: Images showing the crack distribution

Overall, the glass-to-glass fusion connections developed in test 4 (Chapter 5.3) indicate that the fused interface approaches the strength of the glass itself. However, due to the inherently brittle nature of glass, failure remains abrupt and somewhat unpredictable, limiting the controllability of the overall failure behaviour. From a structural perspective, this suggests that the fused connection can be considered viable for IGU applications in terms of strength performance, as it does not appear to constitute the weakest link within the system.

5.6.3 3-point-bending testing glass and PETG connection

3-point-bending setup

For the 3-point-bending test a standard setup from the faculty of Architecture at the TU Delft was used. Since the standard setup uses a width of twenty centimetres and the samples were exactly twenty centimetres an alternative support structure from aluminium was created to support the sample at a width of twelve centimetres. Exactly in the middle of the sample the bending force will be distributed. To avoid direct glass to metal contact and peak stresses, a plastic interlayer was used on all support areas.

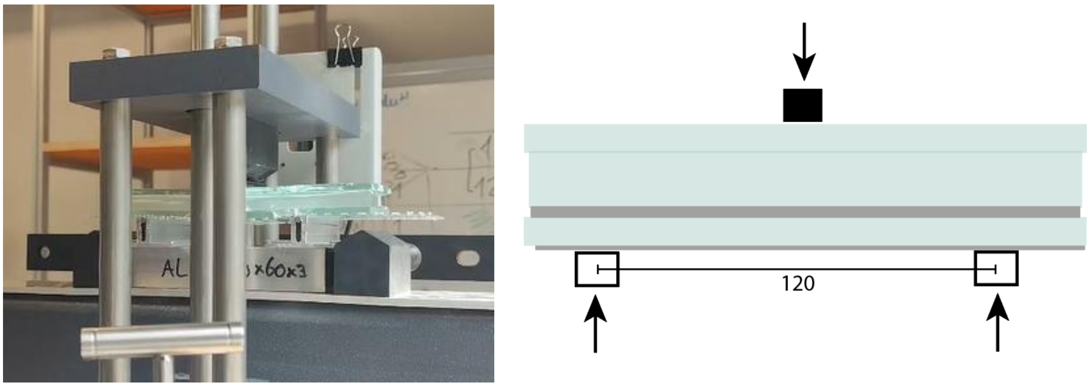


Figure 34: Setup 3-point-bending test (own images)

3-point-bending results

Initial cracking already happened with only 0.785 kN force and a very small displacement of only 0.7 mm.

After visual inspection of the broken sample, it could be concluded that the glass was the main failure. The PETG followed the crack of the glass and behaves like a brittle rigid material. However, more tests should be performed to confirm.

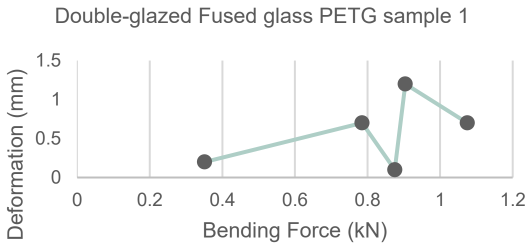


Figure 35: Results 3-point-bending test

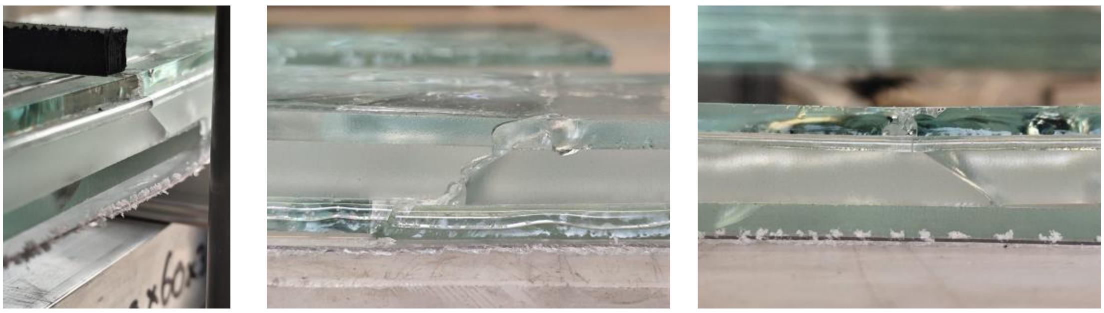


Figure 36: Images showing crack distribution 3-point-bending (own images)

While PETG demonstrated the ability to form a reversible connection, its relatively rigid behaviour limits its ability to accommodate the movements that occur within an IGU as a result of thermal expansion, pressure fluctuations and mechanical loading. Unlike conventional sealants such as silicone, PETG does not possess the flexibility required to continuously absorb these movements throughout the service life of the glazing unit. This observation highlights an important trade-off within the proposed concept As a result, PETG is unlikely to function as a standalone edge seal material and would still require the application of a flexible sealant layer, such as silicone, to maintain long-term performance.

5.7 Durability of the proposed edge seal concepts

To fully assess the durability and long-term performance of the proposed edge seal concepts, accelerated ageing testing would normally be required. Such testing is commonly used for insulating glass units (IGUs) to simulate long-term environmental exposure within a shortened testing period. Through exposure to elevated temperatures, humidity, and cyclic climatic conditions, the ability of the edge seal to maintain its functionality throughout its intended service life can be evaluated.

The primary durability requirements of an IGU edge seal are water vapour and gas tightness. The ability of the edge seal to prevent moisture ingress into the cavity. Moisture penetration can lead to condensation within the IGU and may negatively affect both optical quality and thermal performance. The edge seal to prevent the exchange of gases between the cavity and the surrounding environment. For gas-filled IGUs, this is particularly important to retain insulating gases such as argon and maintain the intended thermal performance over time.

Within the scope of this research, no accelerated ageing tests were conducted. Consequently, the long-term durability of the proposed glass-to-glass and glass-to-PETG edge seal concepts cannot yet be quantified. However, the developed concepts demonstrated sufficient mechanical integrity during manufacturing and handling, indicating their potential suitability as edge seal systems. Future research should focus on evaluating both concepts through standardized accelerated ageing tests to determine their resistance to moisture ingress and gas leakage over time.

Particular attention should be given to the glass-to-PETG connection, as differences in thermal expansion between the materials and the long-term behaviour of the polymer under environmental loading may influence seal performance. For the glass-to-glass concept, the absence of dissimilar materials may reduce some durability concerns, although the long-term airtightness and resistance to microcracking of the fused connection should also be verified experimentally.

Therefore, while the proposed concepts show promising potential, further durability testing is required before their applicability in long-service-life insulating glazing systems can be confirmed.

5.8 Circularity of the proposed edge seal concepts

In addition to thermal, structural, and durability performance, the circularity potential of the developed edge seal concepts was assessed. Within the construction industry, circular design aims to maintain the value of materials and products for as long as possible by enabling reuse, repair, remanufacturing, and high-quality recycling at the end of their service life. For insulating glass units (IGUs), one of the main challenges is that conventional edge seals permanently bond multiple materials together, making separation difficult and often resulting in downcycling or disposal of valuable glass components. The developed concepts address this challenge through either mono-material design principles or reversible connections.

The glass-to-glass connection offers significant circularity advantages because it consists entirely of glass components. As a mono-material assembly, the connection eliminates the need for material separation during recycling and can therefore be processed as a single material stream. Furthermore, the connected glass components exhibit comparable durability and service life, preventing premature failure of one component from limiting the lifespan of the other. At the end of its service life, the entire assembly can be recycled without contamination from dissimilar materials, contributing to a high-quality closed-loop recycling process.

The glass-to-PETG connection achieves circularity through a different mechanism. Although it combines two materials, the connection is intentionally designed to be thermally debondable. By applying controlled heat through a resistance wire, the PETG spacer can be separated from the glass panes.

A particularly important opportunity created by the debondable connection is the potential for remanufacturing existing IGUs. In conventional insulating glazing, the gradual diffusion of argon gas through the edge seal reduces thermal performance over time. Once argon concentrations become insufficient, the entire IGU is typically replaced despite the glass panes themselves remaining structurally intact. The proposed debondable system allows the unit to be opened, the depleted gas cavity to be restored, and the original glass panes to be reused in a newly assembled IGU. This extends the functional lifespan of the glass components and reduces the demand for new raw materials and energy-intensive glass production.

Although the proposed concept significantly reduces contamination compared to conventional IGUs, the goal of concentrating all contamination on a single removable side was not fully achieved. The experiments demonstrated that the thermally debondable connection still requires adhesion to the glass spacer. During disassembly of the glass-to-PETG connection, residual material contamination and local glass chipping were observed. Indicating that complete separation without affecting the glass surface remains challenging.

From the conclusion of the mechanical performance, it was also concluded that silicone would still be needed to provide the mechanical durability and allow movement. Adding silicone means adding another adhesive connection that can not be thermally debonded.

Therefore, while the concept improves circularity by reducing the quantity and location of contamination, it cannot yet be considered a fully contamination-free solution. Additional development is required to further improve the quality of glass recovery after disassembly.

A promising direction for future development could be the introduction of an intermediate release layer between the glass and the silicone sealant. Such a layer would ideally provide sufficient adhesion during service life while allowing clean separation at end-of-life without leaving adhesive residues or causing glass damage. Similar to peel-off adhesive systems, this approach could potentially combine the durability of silicone with improved disassembly and recovery performance, thereby further increasing the circular potential of the edge seal system.

5.9 Conclusion

The evaluation of the proposed IGU edge seal concept against the defined design criteria indicates an overall positive performance across thermal, mechanical, durability, and circularity aspects.

The thermal assessment indicated that replacing conventional metal spacers with glass and polymer-based alternatives can reduce thermal bridging and slightly improve the overall thermal performance of the glazing assembly.

Mechanical testing demonstrated that the fused glass connection approaches the strength of the glass itself. Failure consistently occurred through brittle fracture of the glass rather than through debonding of the fused interface, indicating that the connection does not represent the weakest component of the assembly. This suggests that glass fusion is a viable alternative to conventional spacer materials from a structural perspective. In contrast, the PETG connection exhibited relatively rigid behaviour and failed together with the glass substrate during bending tests. While this confirms its ability to transfer loads, it also indicates that PETG lacks the flexibility required to accommodate long-term movements within an IGU. Consequently, a flexible sealant such as silicone remains necessary to ensure durable performance.

Durability could not be experimentally verified within the scope of this research. Nevertheless, the fused glass connection benefits from material compatibility and the absence of dissimilar interfaces, suggesting favourable long-term behaviour. The durability of the thermally debondable connection remains more uncertain due to ageing behaviour under environmental influences.

From a circularity perspective, both concepts demonstrate clear advantages over conventional edge seal systems. The fused glass connection creates a mono-material assembly that can be recycled without material separation, while the thermally debondable connection introduces the possibility of disassembly, remanufacturing and reuse of existing glass panes. However, the objective of creating a completely contamination-free connection was not fully achieved. Residual material contamination, local glass chipping and the continued need for silicone reduce the circular performance of the final concept. As a result, the proposed design represents a compromise between durability and circularity, prioritising long-term performance while significantly improving end-of-life recovery potential compared to conventional IGUs.

Durability	*Circularity*	*No contaminations*	*Small scale*	*No thermal bridge*	*High thermal insulation*	*Mechanical stability*	*Allow movement*	*High environmental resistance*	*Air and watertight*
+	+ +	+ -	+ +	+ +	+ +	+	+	+	+

Table 24: Conclusion final design against design criteria

Overall, the results demonstrate that a hybrid edge seal system combining glass fusion with a reversible polymer connection is technically feasible and offers promising opportunities for more durable and circular insulating glass units. However, further validation through full-scale testing, accelerated ageing experiments and environmental assessment is required before practical implementation can be considered.

Phase 3: Final design

Based on the evaluation of the tested prototypes, the most promising material combinations and connection techniques were selected and integrated into a final design proposal. To validate the interaction between the individual components, a “full-scale” IGU prototype was developed, representing the glass panes, edge seal and cavity as a complete system.

In addition, the integration of the redesigned IGU within a façade system was explored. Considerations regarding installation, detailing and structural integration were evaluated, together with the potential implications of the proposed design for durability, circularity and maintenance.

5.10 Manufacturing

The proposed edge seal concept introduces a manufacturing process that differs from conventional IGU production.

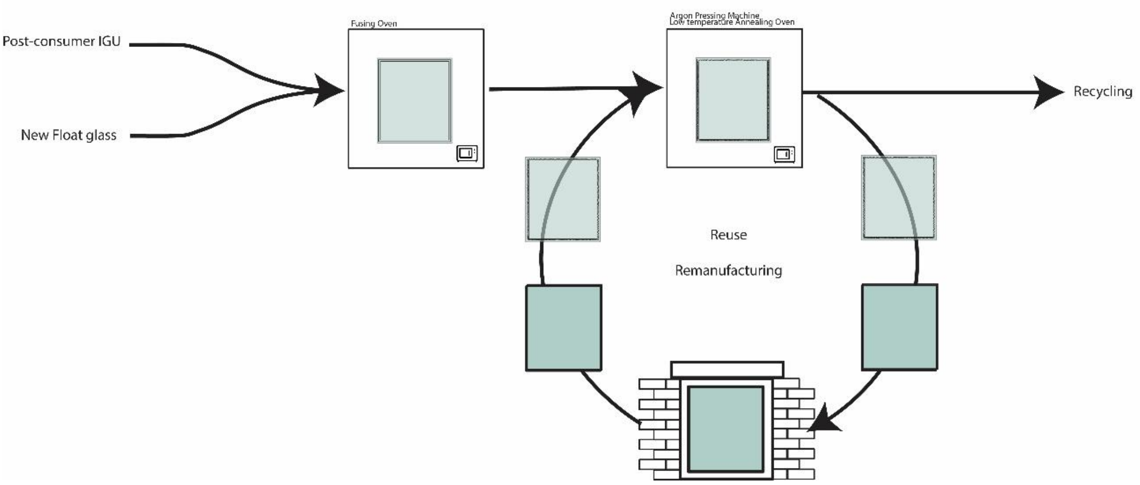


Figure 37: Manufacturing (own image)

The process either starts with new float glass or preferably post-consumer glass panels. The recovered post-consumer IGUs first need to be separated and inspected. A quality assessment is required to identify defects such as scratches, coatings damage, contamination, cracks or edge damage that could compromise future performance. Following inspections, the glass is cleaned and prepared for processing.

The fused glass spacer is then manufactured through a glass fusion process in a kiln. This step is the most energy-intensive and time-consuming stage of production, requiring elevated temperatures and extended heating and cooling cycles.

Once the fused glass spacer has been produced, the remaining manufacturing stages can be performed at significantly lower temperatures. The glass components are assembled, the cavity is filled with argon gas, and the thermally debondable PETG connection is created through a controlled heating and pressing process. These operations could potentially be combined within a single production step, reducing manufacturing complexity and energy consumption compared to the fusion stage.

After assembly, the IGU enters its operational phase within the building façade. Throughout its service life, the glazing unit functions similarly to a conventional IGU while benefiting from the improved thermal performance and circularity of the redesigned edge seal.

At the end of its service life, the circular lifecycle begins. Rather than disposing of the entire IGU, the thermally debondable connection can be activated to separate the glazing unit.

To minimise the risk of thermal shock and glass fracture, the unit may first be placed in a low-temperature annealing oven, allowing gradual and controlled heating prior to disassembly. Once separated, individual components can be inspected and assessed for reuse.

Glass panes that remain in good condition can be reused in a remanufactured IGU. Components that have degraded beyond acceptable performance levels can be replaced, while materials that have reached the end of their useful life can be recycled. Through this approach, the proposed design enables repeated cycles of reuse, remanufacturing and recycling, reducing material consumption and extending the service life of the glass beyond that of a single IGU lifecycle.

5.11 Implementation in façade

The final result of this manufacturing process and the final design of this master's thesis should fit within the small scale and tolerances of the standard IGU façades. Therefore, the redesign of the IGU edge seal can be placed within any façade system. Figure 38 shows an example of the new IGU edge seal design within a standard aluminium curtain wall façade system.

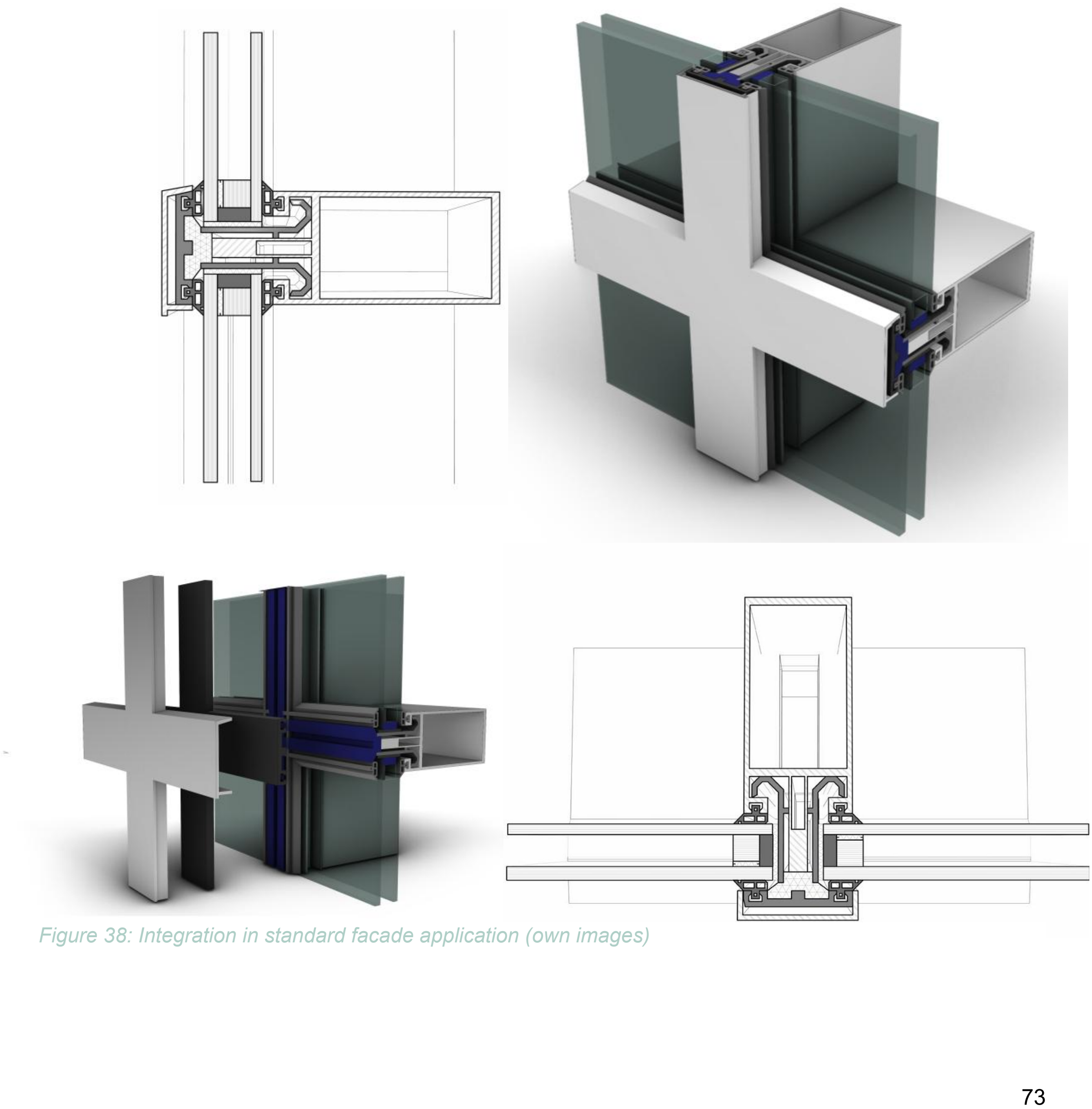


Figure 38: Integration in standard facade application (own images)

5.12 Final design considerations

The final edge seal concept was developed through different design iterations. Each alternative aimed to improve the durability and circularity of the IGU while maintaining the required thermal, mechanical and environmental performance.

The first design ambition was to create a fully glass-based IGU by replacing both the spacer and sealant functions with glass fusion connections. Such a solution would create a mono-material assembly with excellent recyclability and eliminate contamination from polymers and metals. However, this concept would not be able to accommodate for movement within the IGU and would be hard to manufacture.

The second concept retained the fused glass spacer while introducing conventional primary and secondary sealants, such as PIB and silicone. This approach separated the structural spacer function from the sealing function and more closely resembled existing IGU technology. However, this concept does not enable circularity.

The last two concepts replace the conventional sealant with a thermally demountable PETG connection. the intention was to enable controlled disassembly and future manufacturing.

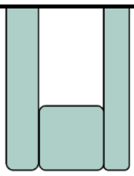
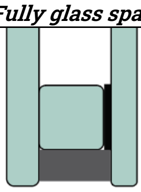
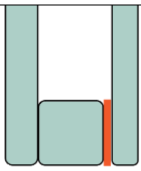
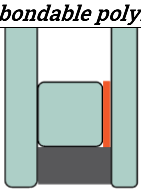
	Advantage	*Disadvantage*
 ***Fully glass spacer***	- Fully mono-material construction. - No contamination. - High compatibility between connected materials. - Reduced thermal bridging. - Potential durability similar to the glass itself.	- Brittle connection with limited ability to accommodate movement. - Sensitive to local stress concentrations. - No practical method for disassembly or remanufacturing. - High manufacturing complexity.
 ***Glass spacer with standard PIB and silicone***	- Reduced thermal bridging compared to metal spacers. - High mechanical stability. - Good movement accommodation. - Proven air and water tightness.	- Permanent adhesive bonds prevent disassembly. - Glass contamination remains present. - Limited reuse and remanufacturing potential.
 ***Glass spacer with a thermally debondable polymer***	- Potential for reversible assembly. - Improved disassembly and material separation. - Reduced contamination compared to conventional sealants. - Opportunity for remanufacturing and reuse of glass panes. - Reduced thermal bridging.	- PETG behaves relatively rigidly, limiting ability to accommodate IGU movements - Risk of thermal shock during debonding. - Long-term durability remains uncertain. - Residual contamination and glass chipping observed during separation
 ***Glass spacer with PETG and silicone***	- Improved thermal performance. - High mechanical stability. - Good movement accommodation. - Potential for future disassembly. - Improved circularity compared to conventional edge seal.	- Silicone remains permanently adhesive connection. - Complete contamination-free separation not achieved. - Durability and remanufacturing performance require further validation.

Table 25: Final design considerations

The final design combines the advantages of the previous concepts. A fused glass spacer provides structural integrity and reduces thermal bridging, PETG enables future debonding and disassembly, while silicone accommodates movement and provides durable sealing performance. The final design therefore represents a compromise between durability and circularity. The addition of silicone improves long-term performance but reduces the degree of reversibility achieved by the thermally debondable connection.

Future design considerations

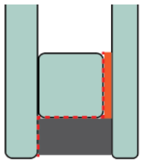
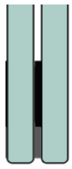
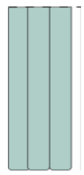
		
Glass spacer with PETG and silicone and seal foil	*Integration of glass fusing solution in vacuum glazing*	*Integration of glass fusing solution in structural glazing*

Table 26: Future design considerations

A remaining challenge is the contamination caused by the adhesion between the sealant and the glass surface. Ideally, the edge seal would incorporate an intermediate release layer or peel-off foil that provides sufficient adhesion during service life while allowing clean separation at end-of-life. Such a solution could potentially combine the durability of silicone with contamination-free disassembly, enabling true remanufacturing and high-quality glass recovery. However, no suitable material was identified during this research. Existing release layers generally reduce adhesion to a level that compromises the mechanical and environmental performance required for IGU applications. Or are currently only applicable in high end medical equipment and are not feasible within a building construction.

An alternative application in which glass fusion may prove more suitable is vacuum glazing. Unlike conventional IGUs, vacuum glazing systems experience limited cavity pressure fluctuations due to temperature and atmospheric changes. As a result, movement accommodation within the edge seal is less critical. Vacuum glazing already relies on micro-pillar spacers and previous research has demonstrated the feasibility of glass-based spacer technologies (van Abeelen et al., 2025). Consequently, glass fusion may be particularly suitable for future vacuum glazing applications, where the benefits of a rigid glass connection could be utilized without requiring significant movement accommodation.

Lastly, glass fusion may offer opportunities in other glazing technologies. One potential application is structural glazing, where glass components are connected to transfer loads and create transparent structural assemblies. The mechanical testing performed in this research demonstrated that the fused glass connection approaches the strength of the glass itself, suggesting potential for applications where material compatibility and durable glass-to-glass connections are required.

Furthermore, glass fusion may offer opportunities for the production of thicker glass assemblies. Manufacturing non-standard glass thicknesses through conventional float glass production requires adjustments to production settings and can disrupt highly standardized manufacturing processes. By contrast, fusing multiple thinner float glass panes could provide a more flexible method for creating alternative glass thicknesses while maintaining standard float glass production.

However, the feasibility of both applications remains uncertain. Glass fusion is an energy-intensive process and introduces additional manufacturing steps compared to conventional production methods. Therefore, further research is required to evaluate the structural performance, energy consumption, economic viability and industrial scalability of glass fusion technologies beyond the scope of IGU edge seal systems.

6. Discussion

Performance of the proposed edge seal concept comparison with state-of-the-art solutions
The proposed hybrid edge seal concept demonstrates that durability and circularity can be addressed simultaneously while maintaining the primary thermal, mechanical and environmental performance requirements of an IGU. Unlike most existing innovations, which primarily focus on thermal performance improvements, the proposed design specifically targets service-life extension and end-of-life recovery. The combination of a fused glass spacer and a thermally debondable sealant creates a clear separation between structural and reversible functions within the edge seal.

Discussion of glass fusion as a spacer alternative
Glass fusion offers several advantages, including compatibility with glass, absence of contaminating materials, and reduced thermal bridging. The connection approaches the durability of the glass itself, potentially extending the service life of the edge seal. The fused connection eliminates the need for conventional spacer materials and associated material interfaces.

However, fused glass remains a rigid and brittle connection that may be sensitive to local stress concentrations. Although the small-scale experiments demonstrated the feasibility of creating durable glass-to-glass connections, further research is required to assess their structural behaviour under realistic loading conditions.

An alternative application in which glass fusion may prove more suitable is vacuum glazing. Unlike conventional IGUs, vacuum glazing systems experience limited cavity pressure fluctuations due to temperature and atmospheric changes. As a result, movement accommodation within the edge seal is less critical. Vacuum glazing already relies on micro-pillar spacers and previous research has demonstrated the feasibility of glass-based spacer technologies. Consequently, glass fusion may be particularly suitable for future vacuum glazing applications, where the benefits of a rigid glass connection could be utilized without requiring significant movement accommodation.

Discussion of thermally debondable connections
Thermally debondable polymers provide a promising route towards reversible IGU assembly. The experiments demonstrated that PETG has the potential to function as a seal that can be intentionally separated at the end of its service life. Such a connection could enable remanufacturing strategies in which gas-filled cavities are restored and existing glass panes are reused rather than discarded before reaching the end of their material lifespan.

However, the long-term behaviour of thermally debondable materials under UV exposure, moisture, temperature fluctuations, and mechanical loading remains uncertain. Additional research is required to evaluate aging effects and long-term adhesion performance.

Furthermore, the experimental investigation of thermally debondable connections remained exploratory in nature. Only a limited number of materials could be assessed due to constraints in time, resources and material availability. Consequently, PETG cannot be considered the optimal solution, but rather a proof-of-concept material demonstrating the feasibility of reversible polymer-based connections. Other thermoplastics or thermally reversible polymers may offer improved mechanical performance, durability or debonding characteristics and should therefore be investigated in future research.

A further challenge relates to the temperatures required for remelting and debonding the polymer. The local application of heat introduces a significant risk of thermal shock when combined with glass substrates. As a result, the practical implementation of thermally debondable connections within conventional IGUs may raise safety concerns during disassembly and remanufacturing. While the concept demonstrates circular potential, the required thermal activation process may limit its applicability in glass-based systems.

Therefore, the applicability of thermally debondable connections within conventional IGUs remains uncertain, and future research should investigate both alternative substrate materials and polymer systems with lower activation temperatures

Trade-offs between durability and circularity
Traditional IGUs achieve durability through permanent adhesive bonds, but these bonds reduce circularity. Increasing demountability often introduces concerns regarding long-term durability, airtightness, and water tightness. The proposed concept attempts to balance these competing requirements by combining a permanent glass fusion connection with a reversible sealant system.

The research demonstrates that improving circularity does not necessarily require complete elimination of adhesives, but rather strategic use of reversible connections. A remaining challenge is determining the optimal balance between ease of disassembly and long-term performance under environmental exposure.

Nevertheless, determining the optimal balance between ease of disassembly and long-term environmental resistance remains a challenge that requires further investigation.

Circularity implications
The proposed design directly addresses one of the main barriers to glass reuse: contamination from permanent sealants. By limiting contamination to a single removable side, the concept significantly improves the potential for reuse, remanufacturing and high-quality recycling.

The concept aligns with circular economy principles by enabling material recovery at a higher value level than conventional recycling. In particular, remanufacturing may provide greater environmental benefits than recycling because it preserves the embodied energy of the glass panes.

More broadly, the research demonstrates how circularity can be incorporated at the product design stage rather than relying solely on end-of-life waste management.

Feasibility of manufacturing
While the technical feasibility of the concept has been demonstrated at laboratory scale, manufacturing feasibility may ultimately determine its practical applicability. The additional processing steps required for glass fusion and thermal debonding could affect production costs, throughput and energy consumption compared to conventional IGU manufacturing.

In particular, the glass fusion process introduces additional manufacturing steps that may increase production time and energy consumption compared to conventional IGU manufacturing. The feasibility of integrating glass fusion into existing production lines therefore requires further investigation. Similarly, the environmental and economic implications of introducing additional heating and processing steps should be assessed before large-scale implementation can be considered.

Consequently, both the industrial scalability of glass fusion and the economic feasibility of the complete edge seal concept remain uncertain and require further study.

Research limitations
Several limitations should be considered when interpreting the findings of this research.

- The study was conducted at proof-of-concept level and does not represent a market-ready product. the interaction between the fused glass spacer and the thermally debondable sealant was evaluated primarily through separate experiments. The long-term performance of the complete hybrid edge seal system as an integrated assembly remains to be validated.
- Long-term durability was not verified through accelerated ageing or weathering tests. Air tightness, water tightness and gas retention performance were assessed conceptually rather than through standardized certification testing. Similarly, mechanical performance was evaluated using simplified specimens and may not fully represent the behaviour of complete IGU systems.
- No complete Life Cycle Assessment (LCA) was performed. Consequently, the environmental benefits associated with reuse and remanufacturing were not quantified. Furthermore, the environmental impact of the glass fusion process and the heating requirements of thermally debondable materials remain unknown.
- Using post-consumer glass, although this choice increases the circular relevance of the research, introduces variability in material properties due to previous usage, degradation, coatings and residual contamination. These factors may have influenced the experimental results and reduce reproducibility.

7. Recommendation

Based on the findings of this research, the following recommendations are proposed for future research and development:

Technical validation:

- Perform accelerated ageing tests according to NEN-EN 1279 standards.
- Investigate long-term air tightness, water tightness and gas retention performance.
- Develop and test full-scale IGU prototypes under realistic operating conditions.
- Evaluate the long-term performance of the complete hybrid edge seal system.

Further development of connection technologies:

- Optimize the glass fusion process to reduce energy consumption and manufacturing complexity.
- Investigate alternative glass fusion geometries and edge seal configurations.
- Explore alternative thermally debondable materials with lower activation temperatures and improved durability.
- Assess the risk of thermal shock during debonding and develop safer disassembly methods.

Circularity and environmental assessment:

- Perform a complete Life Cycle Assessment (LCA) of the proposed concept.
- Compare the environmental impact with conventional dual-sealed IGUs.
- Investigate remanufacturing strategies and circular business models for reusable IGUs.

Alternative applications and implementation:

- Investigate the applicability of glass fusion technologies in vacuum glazing systems, where movement accommodation is less critical.
- Assess manufacturing feasibility, industrial scalability and economic viability.
- Explore alternative edge seal designs that further improve durability and circularity.

8. Conclusion

This research investigated how the edge seal component of insulated glass units (IGUs) can be redesigned to improve durability and circularity while maintaining the functional requirements of contemporary glazing systems. Based on the literature review, material screening, experimental testing and design evaluation, several conclusions can be drawn.

The literature confirms that The **edge seal system** is the weakest component of an **insulated glass unit (IGU)**, determining its service life rather than the glass itself. Conventional IGUs typically fail after 20–30 years due to degradation of sealants, while the glass panes remain functional. Current IGU designs are largely linear rather than circular, because permanent adhesive connections prevent clean disassembly and contaminate glass during recycling, leading to downcycling or disposal rather than reuse. Existing industry innovations mainly focus on improving thermal performance but generally do not address durability and circularity.

The material screening and design evaluation demonstrated that no single material can simultaneously fulfil all spacer, sealing, durability and circularity requirements. As a result, the most promising redesign strategy was found to be a hybrid edge seal concept consisting of a **fused glass spacer connection** combined with a **flexible polymer-based sealing system**.

The experimental investigations demonstrated that **glass fusion** can create a durable glass-to-glass connection that approaches the strength of the glass itself. By replacing the conventional metal spacer, thermal bridging is reduced while contamination from spacer materials is eliminated. The fused glass connection therefore contributes positively to **thermal performance, durability and recyclability**.

In addition, the experiments demonstrated the feasibility of **thermally debondable polymer connections**. These reversible connections introduce the possibility of **controlled disassembly** and **future remanufacturing** of IGUs. In particular, the concept offers the potential to reopen glazing units, restore depleted gas cavities and reuse existing glass panes rather than replacing the entire unit before the glass has reached the end of its functional lifespan. Although the proposed concept significantly **reduces contamination** compared to conventional IGUs, complete contamination-free separation was not achieved. Residual polymer contamination, glass chipping and the continued need for silicone prevent full material separation.

The research also demonstrated the limitations of pursuing maximum circularity. The thermally debondable PETG connection showed relatively rigid behaviour and was unable to independently fulfil the movement accommodation requirements of an IGU. Consequently, **a silicone sealant** remained necessary to ensure **durability, flexibility and long-term environmental resistance**. The final design therefore represents a compromise between durability and circularity rather than a fully reversible solution.

Overall, the proposed **hybrid edge seal concept** scores highly on almost all design criteria. However, the research is only supported by a **proof-of-concept**. Further validation through accelerated ageing, full-scale testing and life cycle assessment is required, the research demonstrates that redesigning the edge seal offers a promising strategy for extending the service life of IGUs and increasing their circular potential. The findings contribute to the development of more durable and circular façade systems by shifting the focus from end-of-life waste management towards design-level interventions that address the root causes of premature IGU replacement.

9. Reflection

To complete the 8-month period of this master's thesis we look back on the graduation process and reflect on the research approach.

Graduation process

This master thesis focussed on the very specific redesign of the IGU edge seal component. The process of selecting a master thesis topic was more complicated than expected. I started very early on with going through the list of possible research directions and thinking about what aligned best with my interests. I really wanted to focus on finding a problem that was relevant and a solution that could support the circular economy. I strongly agree with the circularity principles, that we should really try and keep all materials in use for as long as possible and see recycling as a later solution. I knew from the course future materials that glass was a very durable material, but that is does not come to its potential in the current linear economy. After, I found the research of previous student Sofia Kouvela, I kept coming back to her research. I agreed with her problem statement and the reason she started her research and I was intrigued by her design solution. I wanted to make some prototypes and be able to show some physical practical prototypes at the end of my master thesis. Since she did not get the change to build prototypes during her master thesis, I felt that I could bring her research one step further and also give my own spin to the design.

Most important thing I have come to recognise during my graduation process has been that there is a very good reason that the current IGU design has been around for fifty years. After figuring out all the design criteria, it really showed the complexity of the edge seal functions within an IGU. After going through all of the alternative materials and looking into a lot of different alternative connection techniques it was clear that none of the alternatives could really fit within the complicated design criteria. And it was clear that I underestimated the complexity of the edge seal component. Therefore, I really had to allow myself to accept that I would not be able to, within this master thesis, find the perfect alternative IGU design. This was the hardest part of the research. Because I started with great hope. But along the way I came across a lot of disappointing conclusions. My biggest setback was around A2. Where I really hoped to already have an idea of what a valid solution would be, but instead I had to take a step back and rethink the first design considerations.

One of the most important insights gained during this research was the inherent tension between durability and circularity within IGU edge seal design. Initially, the project aimed to maximise both objectives simultaneously by developing a highly durable and fully reversible edge seal system. However, as the research progressed it became clear that these objectives are often conflicting. This tension became a central theme throughout the project and ultimately shaped the final design decisions. Rather than attempting to maximise one objective at the expense of the other, the research focused on finding a balanced solution that could improve circularity while maintaining the functional requirements necessary for long-term use.

I know I have learned a lot, not only on the edge seal specifically, but also on the way that a research process will never go as expected. Some things I have noticed is, for experimental test, how dependant you are as a student on staff members of the faculties. You really have to be on top of your own work, to fix certain things on time and to always account for setbacks. I feel like with building an experimental setup the workings of Murphys law will always be challenging. You have to assume everything that can go wrong will go wrong, and even then, you are not always prepared.

In the end, although my final design might not be the solution to the perfect durable and circular edge seal. I am really happy with the progress I made. Looking back, this transition from idealism to compromise represents one of the most valuable outcomes of the graduation process. It reinforced the importance of validating theoretical concepts through experimentation and demonstrated that successful design innovation often lies not in achieving perfection, but in finding the most appropriate balance between competing requirements.

Research approach
For this research, a combination of research strategies were used; literature research, material and technical research and research-informed design, and could be distinguished in three clear research phases. The literature research provided the necessary background information and a deeper understanding of the technical requirements of the edge seal. In the second phase, material selection through systematic elimination is combined with exploration of innovative connection techniques.

For the last part, a research informed design approach was used. Design decisions were systematically supported by literature, standards, material screening and experimental testing. The iterative interaction between research and design helped identify practical limitations and opportunities throughout the project. At the same time, the approach required a broad scope of investigation, limiting the extent to which individual aspects could be explored. Nevertheless, the methodology provided a structured and transparent framework for developing and evaluating innovative edge seal concepts for circular IGUs.

However, due to the broad scope of the approach the research limited the depth that could be achieved within individual topics. Not all design assumptions could be experimentally validated within the available period. Small-scale experimental results may not fully represent real-world performance. The final design remains at proof-of-concept level and lacks full-scale validation. The research does present opportunities for future studies to build upon the developed framework and design criteria. Emerging materials and reversible connection technologies may enhance future iterations of the design.

Research and design
Throughout this graduation project, research and design were strongly interconnected and continuously influenced one another. In the beginning, a more linear approach was followed, in which research first produced knowledge and design subsequently applied it. Literature studies, material analyses and experimental testing informed design decisions, while the development of design concepts and prototypes generated new research questions and directions for investigation. The project evolved into an iterative research-informed design process, in which research continuously informed design decisions and design development generated new research questions.

This iterative process became particularly evident during the experimental phase. Initial research suggested that a fully glass-based edge seal would offer the highest circularity potential due to its mono-material composition and absence of contamination. However, prototyping and testing revealed practical limitations related to brittleness, movement accommodation and manufacturing complexity. These findings directly influenced the subsequent design iterations and shifted the focus towards hybrid solutions that combined different materials and connection techniques.

As a result, the final design did not emerge directly from the literature review, but from the continuous interaction between theoretical knowledge and experimental observations. The prototyping process therefore functioned not only as a means of validating ideas, but also as a method of generating new knowledge about the behaviour and feasibility of alternative edge seal concepts.

Studio Building Technology
The emphasis of the master Building Technology is on the design of innovative and sustainable building components and their integration into the built environment. This research directly aligns with the objectives of the master's thesis studio in Building Technology by addressing the performance, durability and material behaviour of a critical building component at system level by looking into innovation technologies and sustainable material options.

Specifically, this master's thesis aligns with the circularity in the built environment aims of the master Building Technology. In the current linear economy, raw materials are taken from the earth to make products and to use them till their end-of-life. Afterwards we throw them away as landfill waste. The research mainly focusses on the redesign and remanufacturing of the edge seal component of the IGU. By applying these circular design principles to the edge seal design, we help move the building sector more towards a circular economy.

Ethical reflection

No significant ethical dilemmas were encountered during the execution of this research. The project primarily focused on material performance, circularity and technical feasibility, and did not involve human participants, personal data or socially sensitive information.

Nevertheless, ethical responsibility remains important when conducting experimental research and presenting design proposals. The proposed edge seal concept has only been validated at proof-of-concept level and should therefore not be interpreted as a market-ready solution. Long-term durability, environmental resistance and regulatory compliance have not yet been fully verified through standardized testing. Presenting the concept as a proven alternative would therefore be scientifically unjustified and potentially misleading.

From a broader societal perspective, the research contributes to the transition towards a more circular built environment by exploring strategies to extend product lifespans and reduce material waste. Although the practical applicability of the proposed concept remains uncertain, the research demonstrates how design interventions can support more responsible resource use and encourage reconsideration of current linear construction practices.

Bibliography

Ansys, Inc. (2025). *Ansys Granta Edupack* (Version R2) [Computer software].

Atif, M., Ali, B., Ramzan, I., Younas, A., Imran, M., Ahmed, M. H., & Dilawaiz. (2025). Thermally stimulated bio-acrylate based detachable adhesives with sustainable bonding-debonding design. *International Journal of Adhesion and Adhesives*, *136*, 103853. https://doi.org/10.1016/j.ijadhadh.2024.103853

Bedon, C., & Amadio, C. (2020). Mechanical analysis and characterization of IGUs with different silicone sealed spacer connections - Part 1: Experiments. *Glass Structures and Engineering*. https://doi.org/10.1007/s40940-020-00122-w

Bedon, C., & Santarsiero, M. (2018). Transparency in Structural Glass Systems Via Mechanical, Adhesive, and Laminated Connections—Existing Research and Developments. *Advanced Engineering Materials*, *20*(5), 1700815. https://doi.org/10.1002/adem.201700815

Boutar, Y., Eliášová, M., Bábor, P., & Tichá, P. (2026). Correlation of surface chemistry and shear strength in epoxy-bonded float and low-iron glass joints. *International Journal of Adhesion and Adhesives*, *146*, 104261. https://doi.org/10.1016/j.ijadhadh.2026.104261

Brady, D. (n.d.). *Understanding Firing Schedule*. Glass Campus Publishing.

Bristogianni, T., & Oikonomopoulou, F. (2023). Glass up-casting: A review on the current challenges in glass recycling and a novel approach for recycling “as-is” glass waste into volumetric glass components. *Glass Structures & Engineering*, *8*(2), 255–302. https://doi.org/10.1007/s40940-022-00206-9

Cheng, X., Zhou, Y., Charles, A. D. M., Yu, Y., Islam, M. S., Peng, S., Wang, J., Rider, A. N., Lim, M., Timchenko, V., & Wang, C.-H. (2021). Enabling contactless rapid on-demand debonding and rebonding using hysteresis heating of ferrimagnetic nanoparticles. *Materials & Design*, *210*, 110076. https://doi.org/10.1016/j.matdes.2021.110076

Cupać, J., Datsiou, K. C., & Louter, C. (2024). Reuse potential of architectural glass: Experimental study on the strength of used window glazing. *Glass Structures & Engineering*, *9*(3), 321–337. https://doi.org/10.1007/s40940-024-00267-y

Davis, A. (2023, November 16). Annealing Thick Slabs. *Bullseye Glass*. https://www.bullseyeglass.com/annealing-thick-slabs/

DeBrincat, G., Babic, E., & ARUP. (2018, August). *Re-thinking the life-cycle of architectural glass*. https://www.arup.com/insights/re-thinking-the-life-cycle-of-architectural-glass/

Elstner, M., Contino, A., & Zaccaria, M. (2024). Recycle Glass: A contribution to the Circularity of Flat Glass. *Challenging Glass Conference Proceedings*, *9*. https://doi.org/10.47982/cgc.9.572

Eskes, N. (2018). *Connecting Glass to Glass with Glass*. https://repository.tudelft.nl/record/uuid:73f48f2b-5da9-438f-86d0-52e3bcc70385

Ferdous, W., Manalo, A., Siddique, R., Mendis, P., Zhuge, Y., Wong, H. S., Lokuge, W., Aravinthan, T., & Schubel, P. (2021). Recycling of landfill wastes (tyres, plastics and glass) in construction – A review on global waste generation, performance, application and future opportunities. *Resources, Conservation and Recycling*, *173*, 105745. https://doi.org/10.1016/j.resconrec.2021.105745

Glass Doctor. (2018, March 13). *What is IGU Glass? Learn About Insulated Glass Units*. Glassdoctor.Com. https://glassdoctor.com/blog/what-is-an-insulated-glass-unit-or-igu

GlassCampus. (n.d.). Retrieved https://www.glasscampus.com/tutorials/pdf/Identifying_Tin_Side

Greenberg, H. (2025, June 3). Understanding Desiccants: Function & Types. *Edco Supply Co*. https://www.edcosupply.com/blog/what-are-desiccants/

GSF Glasgroep B.V. (n.d.). *isoMAX*. GSF isoMAX. Retrieved 16 December 2025, from https://isomax.nl/

Guardian Industries Holdings Site. (2026). *Vaccum Insulated Glass*. Guardianglass.Com. https://www.guardianglass.com/eu/en/our-glass/glass-types/vacuum-insulated-glass

Invisible Windows. (n.d.). Retrieved 15 January 2026, from https://www.invisiblewindows.co.uk/news/glass-to-glass

Jasonxue. (2025, May 19). Understanding the Melting Point of Plastic Material. *Jieya*. https://jieyatwinscrew.com/blog/melting-point-of-plastic-material/

Joost de Vree. (2026). *Warmtegeleidings-coëfficiënt (lambda)*. https://www.joostdevree.nl/w/warmtegeleidingscoefficient

Khmyrov, R. S., Protasov, C. E., Grigoriev, S. N., & Gusarov, A. V. (2016). Crack-free selective laser melting of silica glass: Single beads and monolayers on the substrate of the same material. *The International Journal of Advanced Manufacturing Technology*, *85*(5), 1461–1469. https://doi.org/10.1007/s00170-015-8051-9

Kouvela, S. A. (2022). *Re-LOOP TRANSPARENCY*. https://repository.tudelft.nl/record/uuid:374dc027-fdbb-447d-9167-be6e71da16ee

Lawrence Berkeley National Laboratory (LBNL). (2026a). *THERM* (Version 7.8) [Computer software]. https://windows.lbl.gov/therm-software-downloads

Lawrence Berkeley National Laboratory (LBNL). (2026b). *WINDOW* (Version 7.8) [Computer software]. https://windows.lbl.gov/window-software-downloads

Likins-White, M., Tenent, R., & Zhai, Z. (2023). Degradation of Insulating Glass Units: Thermal Performance, Measurements and Energy Impacts. *Buildings*, *13*, 551. https://doi.org/10.3390/buildings13020551

Mognato, E., Piero Quaia, P., Miklus, R., & Hatezic, D. (2018, February 18). *Compatibility tests on laminated glass panes with the other material*. Stazione Sperimentale del Vetro. Glassonweb.Nl. http://www.glassonweb.com/article/compatibility-tests-laminated-glass-panes-with-other-material

Nizich, A. J., Sanders, H. E., & Burkhart, K. L. (2022). A Strain-Normalized Serviceability Limit State for the Secondary Seal of Insulating Glass Units with Rigid Box Spacers: Optimizing Serviceability of IGU Seals. In C. C. White & H. Miyauchi (Eds), *Durability of Building and Construction Sealants and Adhesives: 7th Volume* (Vols STP1633-EB, p. 0). ASTM International. https://doi.org/10.1520/STP163320200074

Oikonomopoulou, F., Bristogianni, T., Barou, L., Jacobs, E., Frigo, G., Veer, F., & Nijsse, R. (2018). Interlocking cast glass components, Exploring a demountable dry-assembly structural glass system. *Heron*, *63*.

Oikonomopoulou, F., DeBrincat, G., & Fuhrmann, S. (2023). Glass and circularity. *Glass Structures & Engineering*, *8*(2), 165–166. https://doi.org/10.1007/s40940-023-00230-3

Overend, M., & Zammit, K. (2012). A computer algorithm for determining the tensile strength of float glass. *Engineering Structures*, *45*, 68–77. https://doi.org/10.1016/j.engstruct.2012.05.039

Peters, G., Brincke, E. T., & Dijkhuijs, J. V. der L. (2024). Glass a Scarce Commodity: A Future Scenario. *Challenging Glass Conference Proceedings*, *9*. https://doi.org/10.47982/cgc.9.653

Raja, A., Ai, T. J., & Astanti, R. (2016). A Clustering Classification of Spare Parts for Improving Inventory Policies. *IOP Conference Series: Materials Science and Engineering*, *114*, 012075. https://doi.org/10.1088/1757-899X/114/1/012075

Rammig, L. (2012). Direct Glass Fabrication – New Applications of Glass with Additive Processes. In *Challenging Glass 3* (pp. 315–321). IOS Press. https://doi.org/10.3233/978-1-61499-061-1-315

Reshamvala, M., Rauh, K., Kießlich, P., Ayvaz, I., Länge, J., Elstner, M., Pfanner, D., & Schuster, M. (2024). Case Study on the Re-use Potential of Insulated Glass Units. *Challenging Glass Conference Proceedings*, *9*. https://doi.org/10.47982/cgc.9.638

Rota, A., Zaccaria, M., & Fiorito, F. (2023). Towards a quality protocol for enabling the reuse of post-consumer flat glass. *Glass Structures & Engineering*, *8*(2), 235–254. https://doi.org/10.1007/s40940-023-00233-0

Saint-Gobain. (2025, November 6). https://www.saint-gobain.com/en

Saint-Gobain Building Glass UK. (2018). *Solar & Thermal—1E - Thermal Insulation* [Saint-Gobain]. Document Hub. https://www.saint-gobain-glass.co.uk/document-hub/

Seel, M., Akerboom, R., Knaack, U., Oechsner, M., Hof, P., & Schneider, J. (2018). Fused glass deposition modelling for applications in the built environment. *Materialwissenschaft Und Werkstofftechnik*, *49*(7), 870–880. https://doi.org/10.1002/mawe.201800075

Shelby, J. E. (2005). Introduction to Glass Science and Technology. *The Royal Society of Chemistry*. https://doi.org/10.1039/9781847551160-FP005

Stern, M., Townsend, E., Massimino, D., & Becker, K. (2024). Advancing Sustainable 3D Printing: The Feasibility of Recycled Glass as a Building Material With Additive Manufacturing. *Challenging Glass Conference Proceedings*, *9*. https://proceedings.challengingglass.com/index.php/cgc/article/view/583

Swisspacer. (2026). *Insights_WarmEdge_Knowledge*. Www.Swisspacer.Com. https://www.swisspacer.com/en/insights/warm-edge-knowledge

Technoform. (n.d.). *Thermally optimized warm edge spacers*. Www.Technoform.Com. Retrieved 12 January 2026, from https://www.technoform.com/en/solutions/insulating-glass-edge-bond/hybrid-warm-edge-spacers

Teich, M., Scherer, C., Schuster, M., Brandenstein, M., & Elstner, M. (2024). Reuse and remanufacturing of insulated glass units. *Glass Structures & Engineering*, *9*(3), 339–356. https://doi.org/10.1007/s40940-024-00276-x

Thermtest.com. (2026). *Thermal Conductivity – What It Is and It's Formula*. https://thermtest.com/what-is-thermal-conductivity

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

Van Den Bergh, S., Hart, R., Jelle, B. P., & Gustavsen, A. (2013). Window spacers and edge seals in insulating glass units: A state-of-the-art review and future perspectives. *Energy and Buildings*, *58*, 263–280. https://doi.org/10.1016/j.enbuild.2012.10.006

Van der Velden, M. (2020). *The increased thermal performance of a structural cast glass brick wall*. https://repository.tudelft.nl/record/uuid:d230d385-5734-4b5e-97b8-e544004d652d

Van Lancker, B., Dispersyn, J., De Corte, W., & Belis, J. (2016). Durability of adhesive glass-metal connections for structural applications. *Engineering Structures*, *126*, 237–251. https://doi.org/10.1016/j.engstruct.2016.07.024

Wang, Z., Liu, J., Li, D., Li, J., Wang, C., & Liu, Y. (2024). Thermal-deformation behaviors of the primary sealants in double, triple, and multi glazed insulating glass units. *Construction and Building Materials*, *450*, 138631. https://doi.org/10.1016/j.conbuildmat.2024.138631

Weller, B., Köhler, M., & Engelmann, M. (2016). Experimental Study on Durability of IGU Sealant Constructions. *Challenging Glass Conference Proceedings*, *5*, 249–260. https://doi.org/10.7480/cgc.5.2250

Wolf, A. T. (1992). Studies into the life-expectancy of insulating glass units. *Building and Environment*, *27*(3), 305–319. https://doi.org/10.1016/0360-1323(92)90032-K

Xin, C., Li, Z., Hao, L., & Li, Y. (2023). A comprehensive review on additive manufacturing of glass: Recent progress and future outlook. *Materials & Design*, *227*, 111736. https://doi.org/10.1016/j.matdes.2023.111736

Yeung, J. (2024, December 2). *Architectural Glass 101: Transparent Trends in 2024 | ArchDaily*. Archdaily.Com. https://www.archdaily.com/1024185/architectural-glass-101-transparent-trends-in-2024

Appendix

Contents Appendix

A. Ansys Granta EduPack

- MaterialUniverse
  - Composites
    - Metal
    - Polymer
  - Concrete, stone, ceramic, brick, glass and bitumen
    - Concrete, stone and brick
    - Glass
    - Technical ceramic
  - Foams, fabrics and fibers
    - Fabrics
    - Foams
    - Man-made fibers
    - Natural fibers
  - Metal, ferrous and non-ferrous
    - Ferrous alloys
    - Non-ferrous alloys
  - Polymers and elastomers
    - Elastomers
    - Polymers
  - Wood, plywood, glulam, bamboo, straw and cork
    - Bamboo
    - Cork
    - Engineered woods
    - Hardboard
    - Hardwood (oak)
    - Softwood (pine)
    - Straw bale
    - Wood panel composites

Figure 39: All building materials (Data aquired from Ansys, inc.(2025))

B. Post consumer IGU samples overview

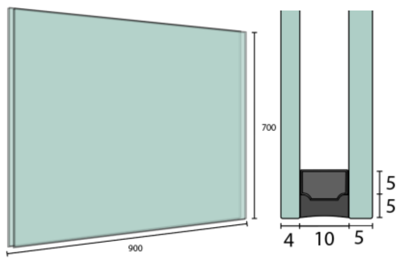
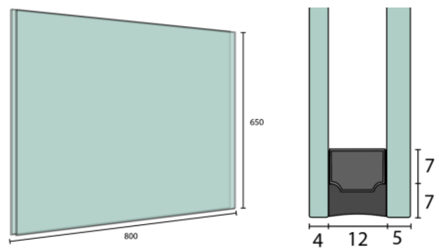
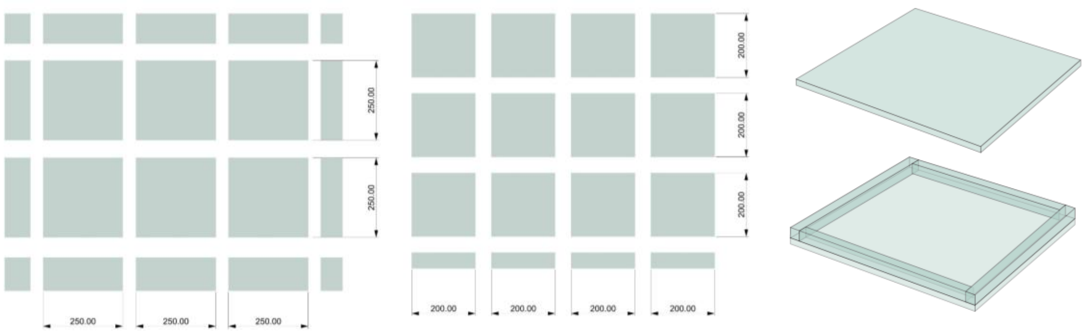
Vlakglas Recycling Nederland	***Sample IGU 1:***	***Sample IGU 2:***
Code	011 4342 77303 03-1996 FBJ 161:DS:1094.0 P K7465/93 5mm-4mm KLAR ENERGI ARGON 938 720 9	ARVAPLUS 01 89
Glass	Annealed float glass	Annealed float glass
Surface	900 x 700 mm	800 x 650 mm
Thickness 1	5 mm	5 mm
Thickness 2	4 mm	4 mm
Edge Seal	Standard dual edge seal	Standard dual edge seal
Cavity	Argon filled: 10 mm	Argon filled: 12 mm
Spacer	Aluminium spacer with desiccant	Aluminium spacer with desiccant
Primary sealant	PIB: 5 mm	PIB: 7 mm
Secondary sealant	Silicon: 5 mm	Silicon: 7 mm
Dimensions		

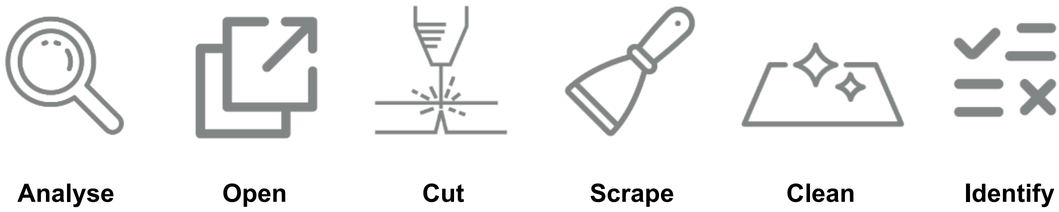
Table 27: Overview post-consumer IGU samples



a. Sample IGU 1: 4mm and 5 mm **b. Sample IGU 2: 4mm and 5mm** **c. Glass strips = spacer**

Figure 40: Cutting scheme for waterjet cutting (own images)

C. Sample preparation



Open post-consumer IGU

To be able to reuse the post-consumer glass from the IGU and remanufacture it into a new IGU, first the glass panes must be separated from the spacer. There is some new development in the industry, that does this automatically with the help of a new machine called IG2Pieces. However, for the experiment, the steps will be performed manually.

Industrially, the IG2Pieces system technology automatically separates end-of-life or defective insulated glass units (IGUs) without damaging the materials (HEGLA GMBH & CO, 2026). The insulated glass can be supplied to the system by a vacuum lifter, for example. A sensor-supported recognition system analyses the insulated glass and identifies relevant separation points, like glass and cavity thickness. Next, the IGU is automatically separated precisely between the glass and the spacer. The intact removal of the individual components enables both the reuse of high-quality panes, as well as type-specific recycling (HEGLA GMBH & CO, 2026).

Figure 41: IG2Pieces machine (HEGLA GMBH & CO, 2026)

Separating an IGU is the most time consuming part of making the IGU circular. IG2Pieces is designed to ensure a cost-effective process. Automated handling eliminates the need for manual separation and creates a standardised workflow with maximum process reliability. The resulting material purity provides increased recycling value, reduces CO_2 emissions and actively supports the goals of the circular economy (HEGLA GMBH & CO, 2026).

For the purpose of this research, the steps of the IG2Pieces machine are recreated and performed **manually**. The first step of the process is to analyse the glass and spacer thickness.

Using a box cutter and a lot of effort, a whole cut can be made between the glass and the spacer, through the primary and secondary sealant. The secondary sealant was easy to cut through with a simple box cutter. However, the PIB was harder to cut, because it was more sticking to the knife and elastically deforming with the knife. Also, after cutting through, the PIB would again stick to itself, resulting in having to go through the PIB with the knife multiple times. Therefore, recommendation for future research is to heat up the knife. This will make it easier to also cut through the PIB. After cutting through the sealants, the glass could slowly be lifted up and be separated from the spacer. The second separation was easier, since there was less compression from the gravity of the top glass, therefore sealants created less resistance. Then the spacer could easily be removed.

After the separation, the contamination of the sealants was still clearly visible on the glass. In later steps, the contamination will have to be scraped and cleaned off.

a. Analyse **b. Cut top pane** **c. Remove top glass** **d. Cut bottom pane** **e. Remove spacer**

Figure 42: Overview of manually performed steps to open/separate the post-consumer IGU (own images)

Cut samples

To be able to test different materials and connection techniques, the size of the experimental samples should be smaller and we would need multiple. However, it is valuable to use the glass from the post-consumer IGU. So the separated glass panes from the IGU must be cut into smaller sample sized pieces.

The cutting process is performed by the waterjet cutting machine available at the waterjetroom of the glasslab at the TU Delft Facutly of Architecture. Waterjet cutting is selected due to its ability to cut glass with high precision while minimizing the introduction of thermal stresses, which could otherwise affect the material behaviour during subsequent fusing experiments.

A cutting scheme is developed to efficiently divide the available glass panes into multiple, even sized glass samples. The idea was to create standardized samples of medium and large squares with the possibility to create allround glass spacers made with glass strips with the same thickness as the cavities of the original IGU samples. Figure 12.a shows the cutting scheme for the IGU sample 1 for both the 4 mm and the 5 mm thick glass. The original 900x700 mm glass plane is divided into the larger squares of 250x250 mm. The outer edge has been cut off, to exclude the contamination from the edge seal components. The idea was to use these clean, large samples as the final version of the redesigned IGU. Figure 12.b shows the cutting scheme for the IGU sample 2 for both the 4 mm and the 5 mm thick glass. The original 800x650 mm glass is divided into medium squares of 200x200 mm. These medium samples and the leftover pieces from both glass panes will be used for all the prototyping and intermediate testing. For these samples, the contaminated edge was included, to create a larger amount of samples.

Lastly, to complete the idea of the fully fused glass IGU and to create a glass-to-glass connection of the glass panes and the spacer, separate glass strips should be created that can fit around the outer edge of the samples. For the medium samples, a cavity thickness of 10 mm was referenced, creating glass strips of 10x10 mm with a length of 200 mm. For the larger samples a cavity of 12 mm maintained, creating glass strips of 12x15 mm with a length of 250 mm.

Scrape samples

The manual cutting technique used to open the IGU is much less refined than the industrial IG2Pieces machine. Therefore, the additional step of scraping of the residual contamination material was necessary. Using a simple box cutter, all the left over contamination from the edge seals could easily be scraped off. Three different residual contaminants can be identified: white caulk, primary and secondary sealant.

First, the white caulk was the easiest to scrape off. Since it is not necessary for structural purposes, but the with caulk was probably just used as surface finishing seal on the outside of the window. However, it looked like it was painted over with white paint. Therefor it did still leave the most contamination on the glass, even after scraping (Figure 14.e).

Secondly, the secondary sealant was relatively easy to scrape off. Since it is a soft silicone material, with the right angle of the blade, it came readily off.

Lastly, the primary sealant was again the hardest to scrape off. The PIB is elastic and adheres strongly to itself. Therefore, the PIB sometimes crumbled up, making it harder to continue. However, if the blade was in the correct angle, the PIB came off easily and stayed together as a long string (Figure 14.d).

a. Start b. White caulk c. Secondary seal d. Primary seal e. Result

Figure 43: Overview of scraping steps performed (own images)

Clean samples

Proper surface preparation is essential to ensure successful bonding during the fusing process. Any contamination present on the glass, such as dust, oils or residual sealants, can interfere with surface contact and lead to defect after fusing (Bullseye Glass, n.d.).

After all the main contamination is scraped off, there is still some leftover contamination from the edge seal. Also the glass has become greasy from handling and dirty from the waterjet cutter. Therefore it is important that the surface is properly cleaned, before the experiments can commence.

A commercial glass cleaner (e.g. Glassex) can be used as a preliminary cleaning step, followed by acetone to ensure a residue-free surface. Acetone is effective in removing oils, grease, and fine residues left from handling or previous materials. For this research, the acetone was most useful to clean off some small left over PIB. The cleaning agents should be applied using a clean cloth. In the case of this experiment however, a simple kitchen paper was used.

It is important that, after cleaning, the glass is handled carefully to avoid recontamination. Contact with bare hands should be avoided, as skin oils can negatively affect the fusing process. Therefore, the use of gloves is recommended during handling and placement of the samples. Also the Kiln surface should be prepared and cleaned. This will be further explained in Experiment 1: Glass-to-Glass connection.

Identify sample sides

Float glass is made in the float glass line. Molten glass is floating over a bed of molten tin to create the distortion-free surface of glass. During the glass making process, a small amount of tin is absorbed by the molten glass. This side is also called the "tin side" of the glass. The side that is facing the air during the production process is called the "air side" (*GlassCampus, n.d.*).

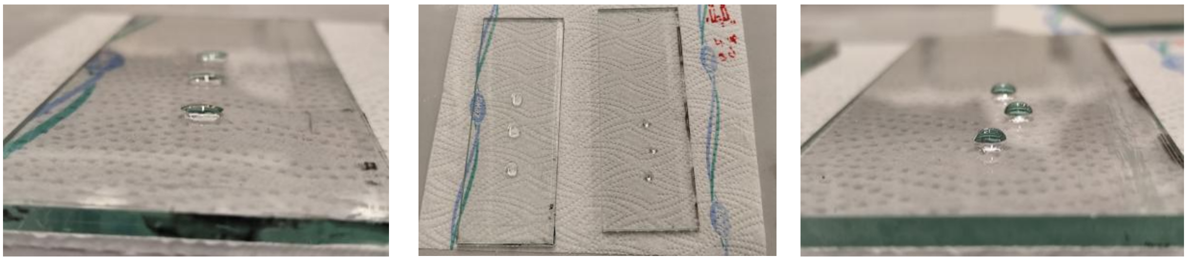
Although the different sides of the glass appear to be the exact same, slightly different surface chemistries can be exhibited. For example, the tin side is more susceptible to devitrification. As a result, the air side generally provides better conditions for coatings, adhesion, and optical quality *(Guardian Industries Holdings Site, 2026a*). And is therefore commonly used facing the cavity of an IGU. Variations in surface chemistry between the tin side and air side can also influence bonding behaviour during thermal processing. Inconsistent orientation of the glass samples may therefore contribute to irregular fusion, such as incomplete bonding or the formation of visual defects *(Shelby, 2005*). Therefore, to fuse onto float glass, the tin side should be put facing down and the two air sides should be fused together

Therefore, identifying the tin side and air side is an important step to prepare for the experiment. Different methods exist to identify the tin side of the float glass: water droplet, UV light and digital detector.

First the water droplet method, this method is fairly simple, but is the least reliable. After you clean the glass thoroughly, place a single drop of water gently onto the glass from about 1 to 1.5 inches away on both sides of the glass (*Racenstein, 2026*). Then compare the results. If the water drop spreads out, it's the air side (*Figure 15.a*). If it stays firm, it's the tin side (*Figure 15.c*).

The second possible method is the UV light method. Using a UV light source, like a flashlight, in a darker room, the different sides will show different diffusion of the light (*Racenstein, 2026*). Hold the light source beneath the glass at a 45º angle to the glass. If the tin side is facing down, a slight blue-white fluorescence will become visible (*GlassCampus, n.d.*).

Lastly, the easiest a most reliable way to identify the different sides is to use a digital detector especially made for this purpose. Simply place the meter on both sides of the glass and the detector will immediately let you know which side is the tin surface (*Racenstein, 2026*).



a. Air side **b. Identify** **c. Tin side**

Figure 44: Identification of tin and air side of the glass samples (own images)

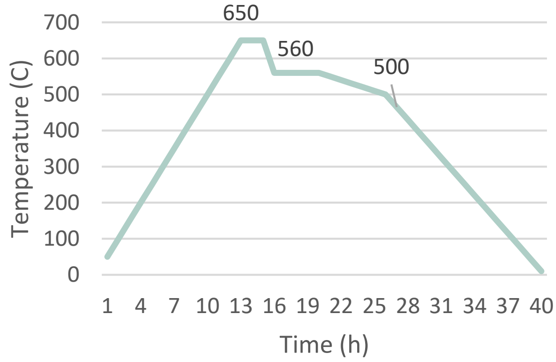
For this experiment, only the water droplet method was available. Although it is considered to be the least reliable method, the results of the test seem promising and show a clear visible difference (*Figure 15*). Therefore, the results of the test were considered to be valid.

A secondary conclusion of the experiment was that, for both IGU samples, the tin side always was the original outside surfaces of the IGU, while the air side was oriented inwards towards the cavity. This is in line with the literature and thereby also confirms that the water droplet method is valid.

D. Firing Schedules

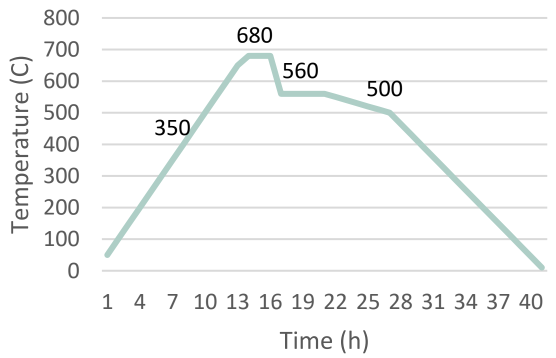
Experiment 1: test 1:

Phase	Ramp (°C/h)	Temp (°C)	Hold (h)
1	50	650	3
2	-160	560	5
3	-10	500	0
4	-35	25	END



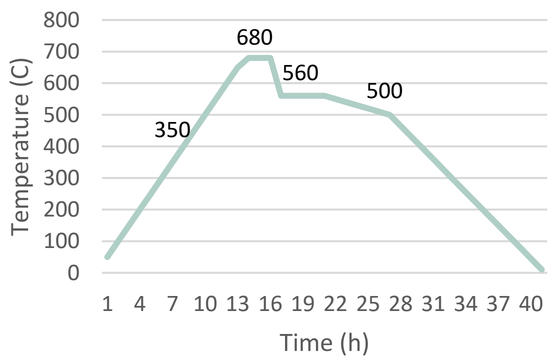
Experiment 1: test 2:

Phase	Ramp (°C/h)	Temp (°C)	Hold (h)
1	50	**680**	3
2	-160	560	5
3	-10	500	0
4	-35	25	END



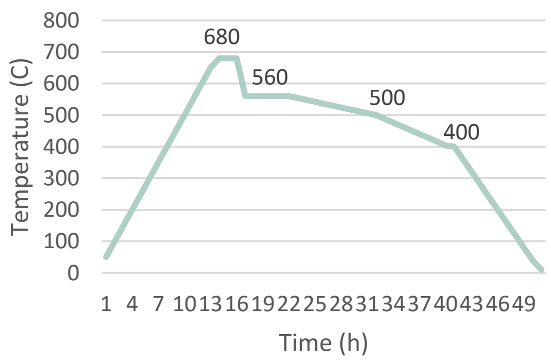
Experiment 1: test 3 & test 5:

Phase	Ramp (°C)	Temp (°C)	Duration (h min)
1	50	20	13h 15min
2	0	680	3h
3	-160	680	45min
4	0	560	5h
5	-10	560	6h
6	-35	500	13h 35min
7	END	25	END



Experiment 1: test 4:

Phase	Ramp (°C)	Temp (°C)	Duration (h min)
1	50	20	13h 15min
2	0	680	3h
3	-160	680	45min
4	0	560	6h
5	-6	560	10h
6	-12	500	8h
7	-40	400	9h 20min
8	END	25	END



E. Development of Fusing connection

Test setup

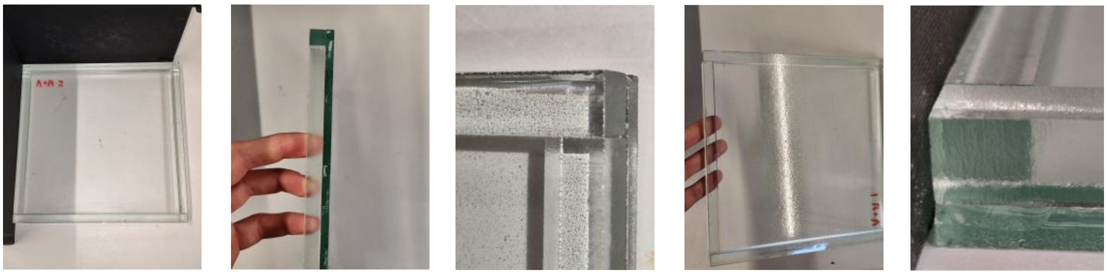
Kiln	*Dimensions*
Medium	1000x500x700
Big	1500x1000x1000

1 2 3 4 5

Medium Medium Big Big big

Figure 45: Overview of kiln setup

Results



2/2 Successful **Fuse strength** **Fuse quality** **Surface quality** **Deformation**

Figure 46: Results Experiment 1 Test 2 (own images)

5/5 Successful **Surface quality** **Fire brick quality**

Figure 47: Results Experiment 1 Test 3 (own images)

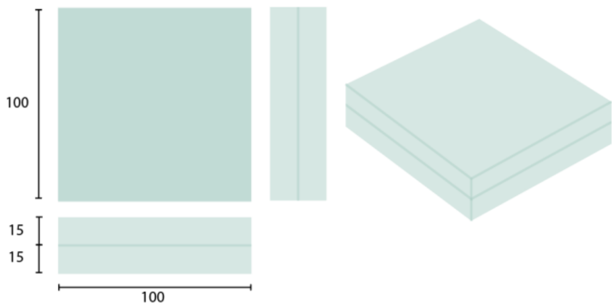


Figure 48: Schematic visualization of shear sample

F. Development of thermally detachable connection

3D printed PETG

Since PMMA is not compatible with glass, and will therefore not adhere to the glass surface, the principle could not yet be tested for polymer-glass connection. Another polymer has to be selected to that is compatible with glass. Therefore, looking into other research about 3D printing different polymers directly onto float glass will give is the insight into which polymer adheres the best. From ongoing research (Pieter), it was retrieved that PETG variants are the best polymers to stick to the float glass after 3D printing. Since 3D printing also uses heat to adhere the polymer to the glass, it makes sense that this would enable the principle to be tested.
Therefore the aim of the first part of test 2 is to try direct printing of PETG to float glass, to understand the temperatures required. The samples 3D printed PETG can then in the second part of test 2 be tested using the heating wire.

Setup/parameters:

Material	HF PETG
Nozzle temperature	250 °C
Bed temperature	80 °C
Duration	30 minutes

Table 28: Parameters: Experiment 2 Test 2.a

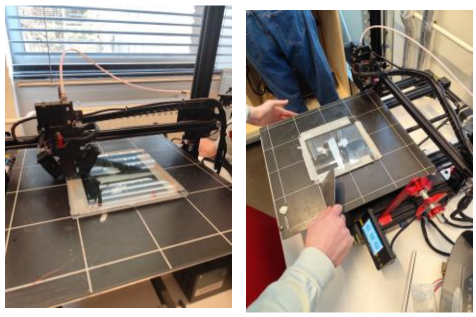


Figure 49: Experimental setup: Experiment 2 Test 2.a (own images)

The printer was set at a offset height of 8mm. therefore two glass elements of 4 mm thickness were needed and placed on top of each other. The bottom pane was fixed to the bed using double sided carpet tape. The two glass panes were connected to each other using simple masking tape on the edges. The experiment was repeated 3 times with slightly different STL files with different groove sizes and amount for the heating wire to be placed into.

Results:

- The high flow PETG variant printed nicely on the float glass and would remain stuck to the glass even after cooling down. However, the bond is not strong. With little effort the printed layer could be taken off.
- Only slight adjustments to the bed of the 3D printer needed to be done, to account for little tolerances in the displacement of the glass and the horizontal level.

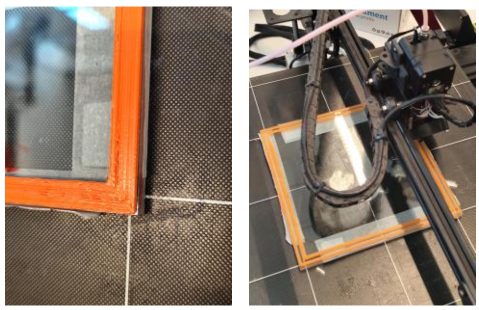
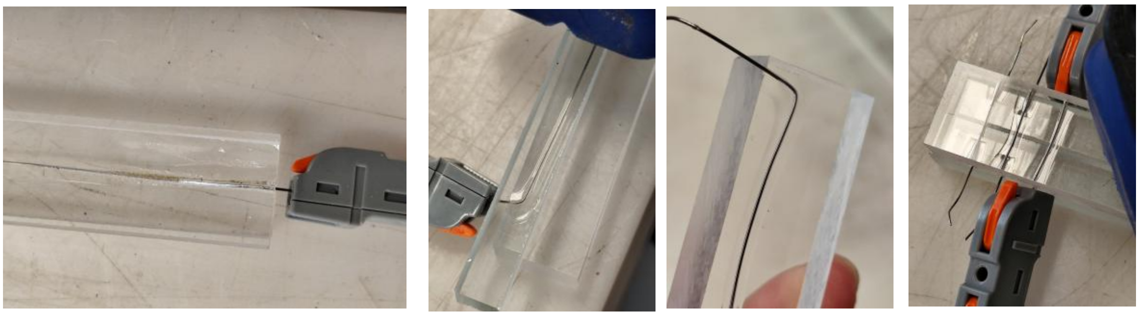


Figure 50: Results: Experiment 2 Test 2.a (own images)

Take away:

The heating wire will not stay in between the grooves. So, for future references, it might be more optimal to stop the printing process halfway through, place the wire, and then print over the wire, to make sure that it will stay in place. However, I believe that then you will have the same problem of the wire not staying in place, and you have to watch out for the nozzle. Or the grooves should be designed with even less tolerances, so the wire has to be locked in to place.
We now have confirmed that PET G will indeed stick to the glass after 3D printing.

Results:



PMMA-PMMA successful **PMMA-glass not successful**

Figure 51: Results Experiment 2 Test 1 (own images)

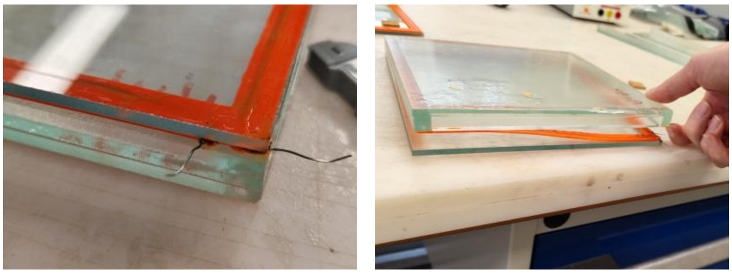


Figure 52: Results Experiment 2 Test 2.b (own images)

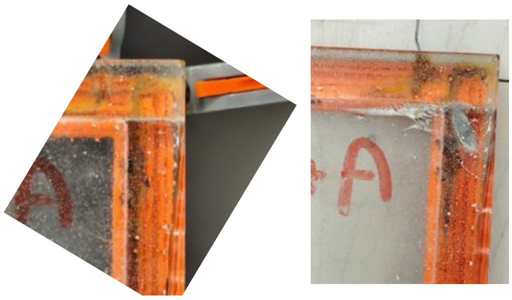


Figure 53: Before and after heating the wire. The thermal shock caused a crack between the glass spacer and the top glass pane (own image)

PETG-PETG successful **PETG-glass temporarily successful**

Figure 55: Results: Experiment 2 Test 3

Figure 54: Results samples from oven deformation

G. Shear test setup

	Name	*Function*
1	5-ton Luka hydraulic cylinder	Apply normal force to sample. The hydraulic cylinder can manually be pumped up to the needed force using a hydraulic oil hand pump.
2	Loaded springs	4 springs ensure equal distribution of the force.
3	Load cell	The applied force is measured using a load cell connected to a digital data acquisition system.
4	Rail	The rail allows the middle steal block to move easily to its position and helps deliver the normal force to the sample.
5	700 kN Hydraulic cylinder	Shear force is applied using a universal testing machine equipped with a load cell to record force-displacement behaviour.
6	Sample support	The sample must be supported by completely rigid and even surfaces to avoid peak stresses from occurring. An interlayer material, like neoprene and a non-friction film to allow sliding of the sample, can be added. The rigid support on the bottom of the glass must only cover 1 glass pane, so the other glass pane is free to move down.

Table 29: Name and function of shear setup components

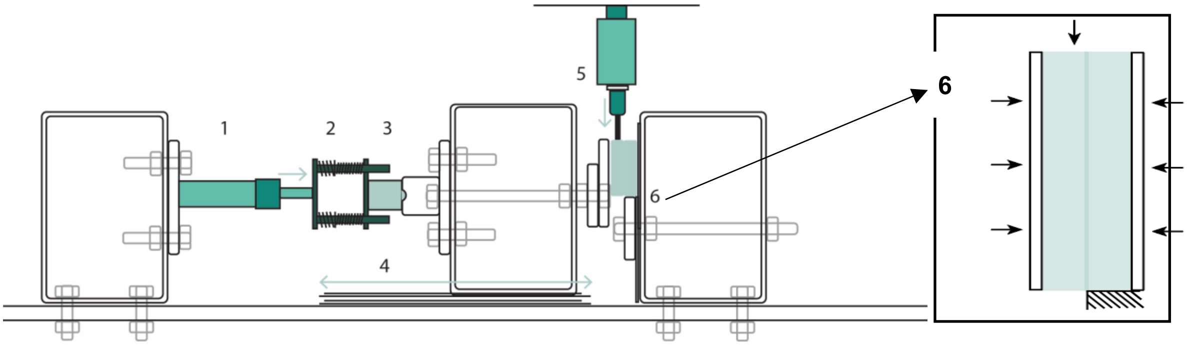


Figure 57: Schematic visualization of setup shear testing fused glass samples (own image)

Figure 56: Pictures of setup shear testing fused glass samples (own images)

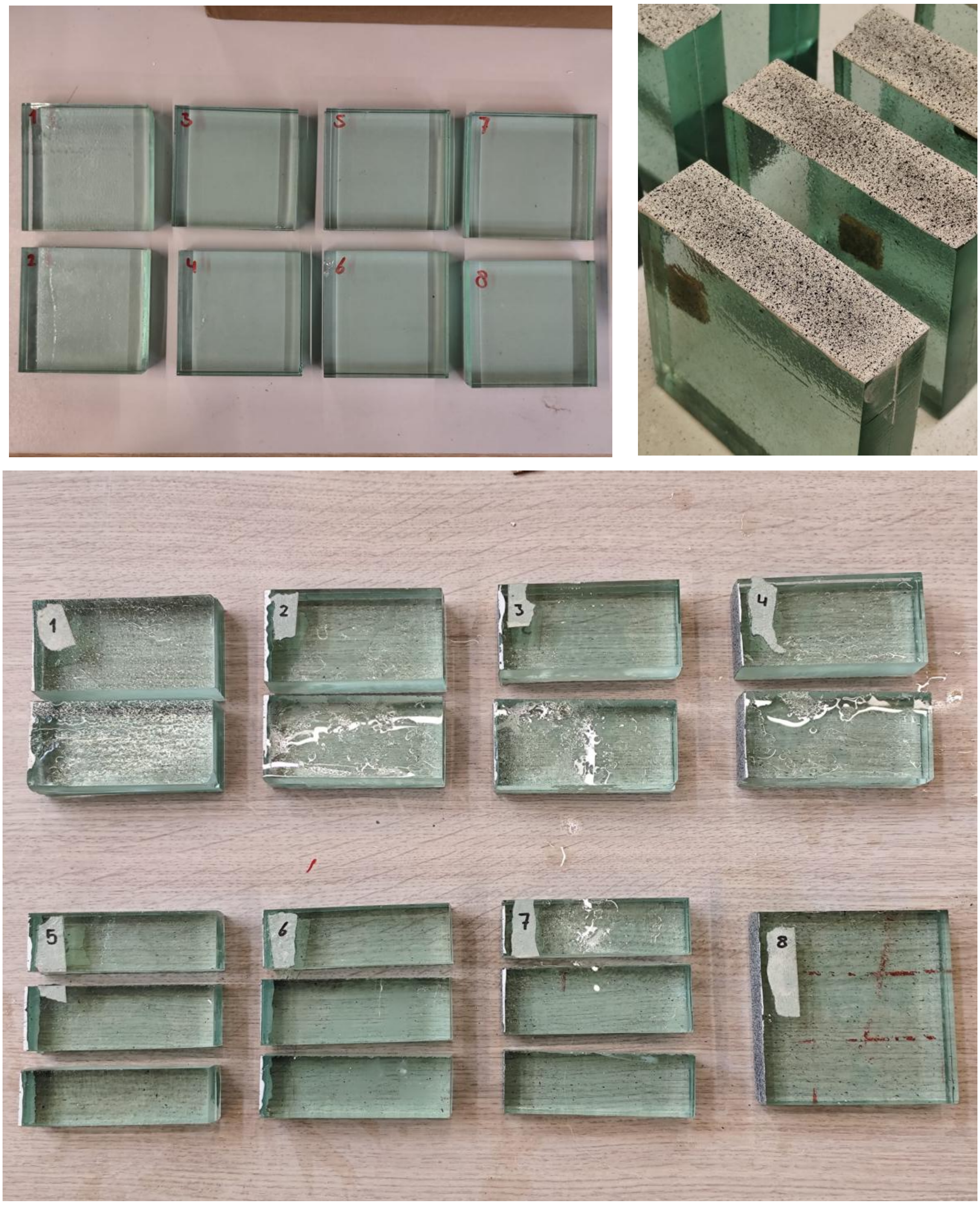


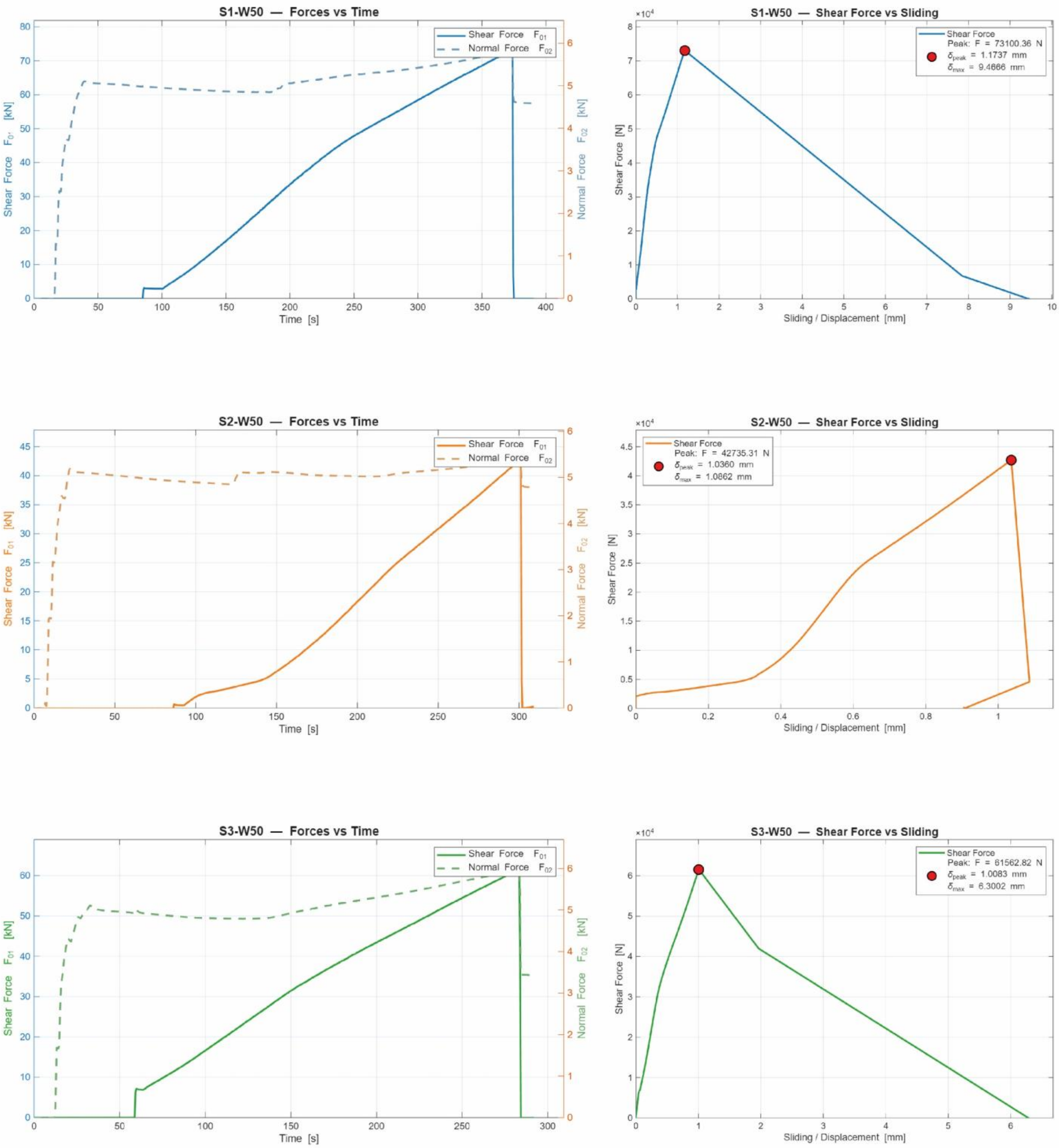
Figure 58: Overview of samples for shear testing (own images)

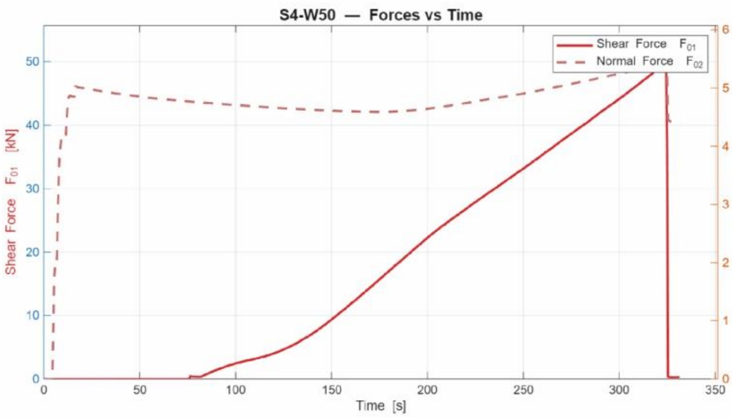
Top two images show first preparation of samples, however, after a few trial runs of the test, the samples seemed to be to strong for the machine and were able to push against the normal force, resulting in disallignment for the vertical shear force and unusable results. Therefore, we had to reduce the contact area over which the shear force could be distributed. Samples were then labled 1.1 and 1.2 from the original sample 1. Sample 1 was used for the trial runs. Sample 2.1 resembles sample S1-W50. W resembles the with 100 mm divided by twoo is 50 mm and divided by 3 is 33 mm.

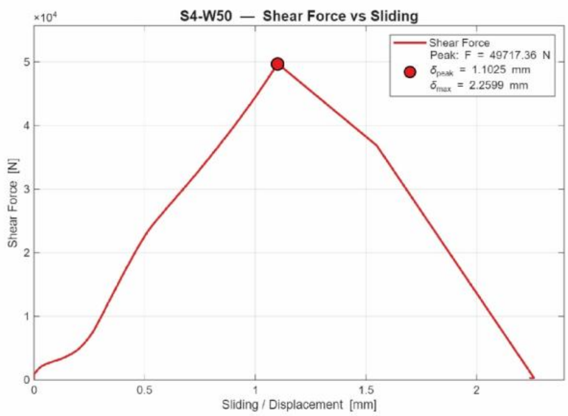
Sample 2.2 = S2-W50; Sample 5.1 is S1-W33; enz.

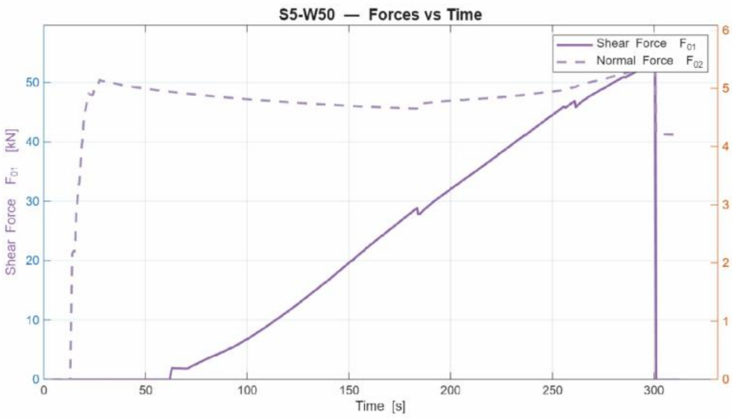
H. Shear test results

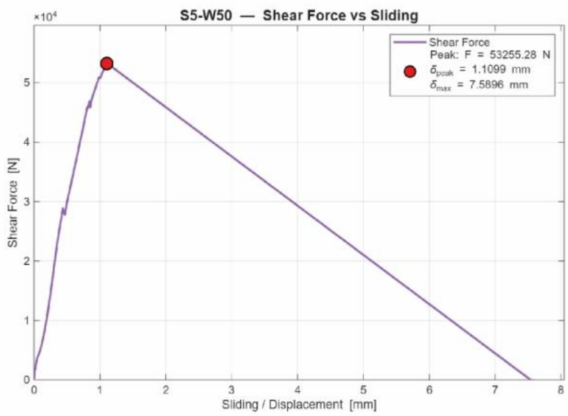
Figure 59: Sheat test results graphs

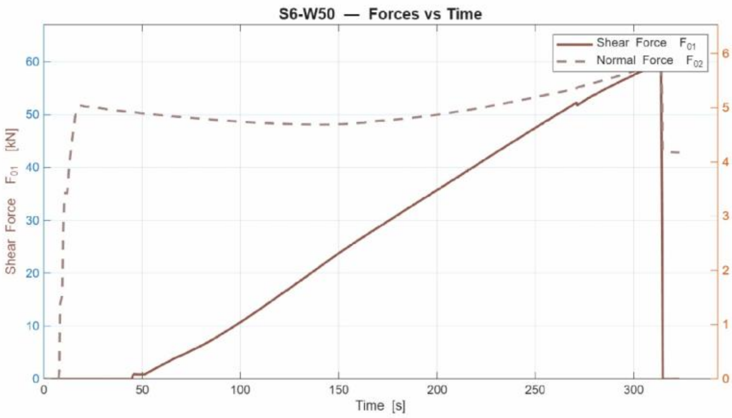


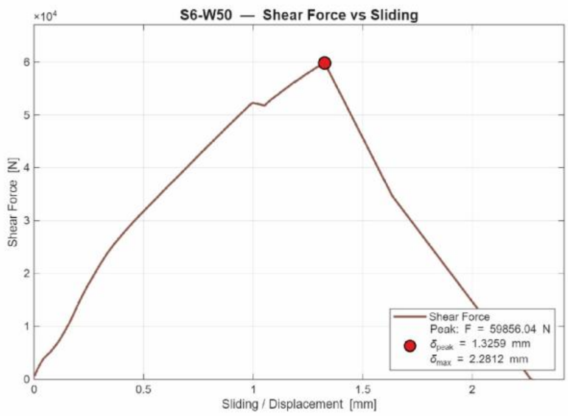

S4-W50 — Forces vs Time
Shear Force F01
Normal Force F02
Shear Force F01 [kN]
Normal Force F02 [kN]
Time [s]

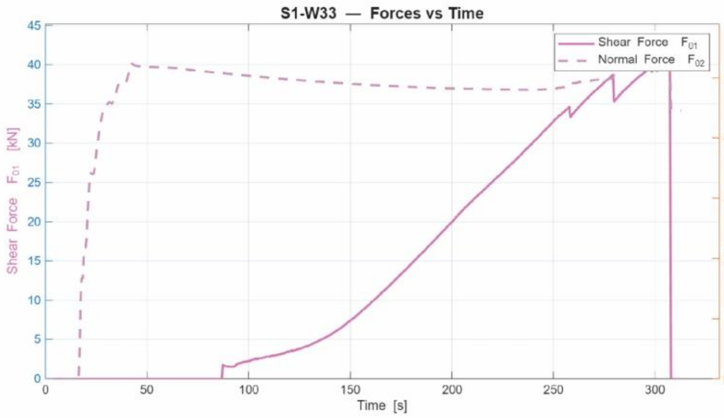

S4-W50 — Shear Force vs Sliding
Shear Force
Peak: F = 49717.36 N
δpeak = 1.1025 mm
δmax = 2.2599 mm
×10^4
Shear Force [N]
Sliding / Displacement [mm]

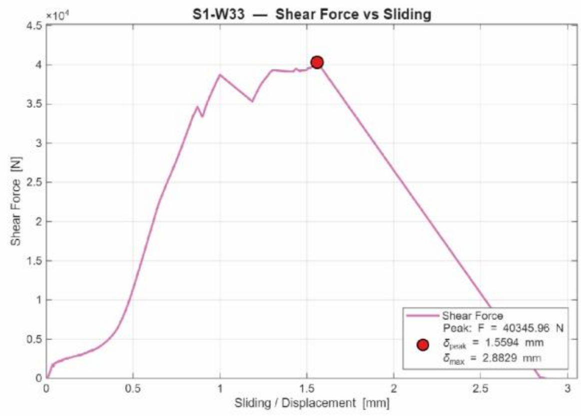

S5-W50 — Forces vs Time
Shear Force F01
Normal Force F02
Shear Force F01 [kN]
Normal Force F02 [kN]
Time [s]

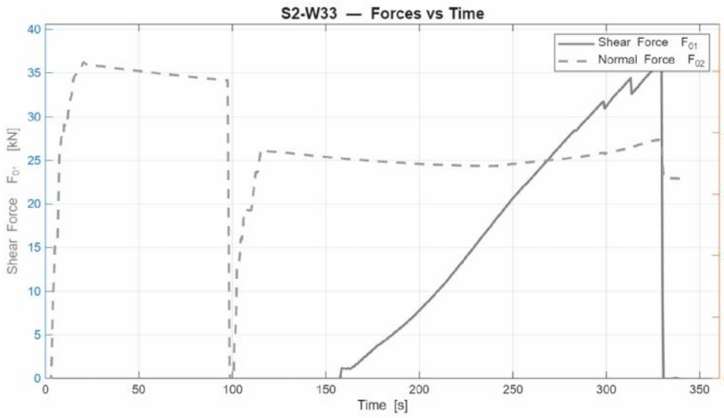

S5-W50 — Shear Force vs Sliding
Shear Force
Peak: F = 53255.28 N
δpeak = 1.1099 mm
δmax = 7.5896 mm
×10^4
Shear Force [N]
Sliding / Displacement [mm]

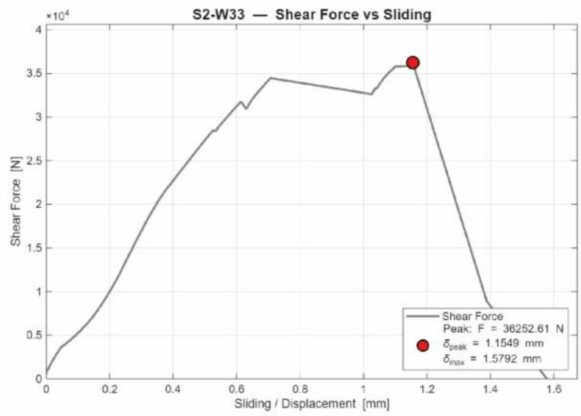

S6-W50 — Forces vs Time
Shear Force F01
Normal Force F02
Shear Force F01 [kN]
Normal Force F02 [kN]
Time [s]

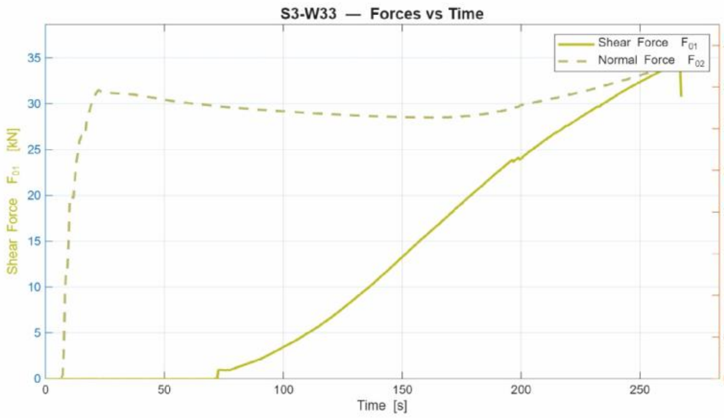

S6-W50 — Shear Force vs Sliding
Shear Force
Peak: F = 59856.04 N
δpeak = 1.3259 mm
δmax = 2.2812 mm
×10^4
Shear Force [N]
Sliding / Displacement [mm]

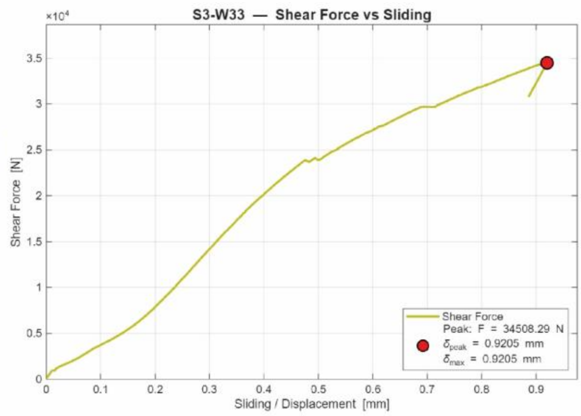

S1-W33 — Forces vs Time
Shear Force F01
Normal Force F02
Shear Force F01 [kN]
Normal Force F02 [kN]
Time [s]

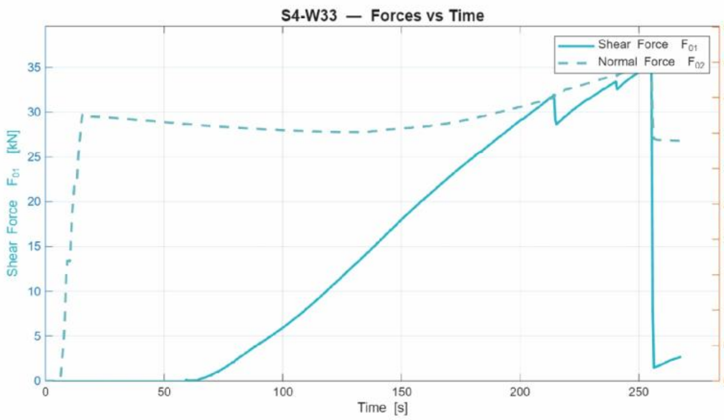

S1-W33 — Shear Force vs Sliding
×10^4
Shear Force
Peak: F = 40345.96 N
δpeak = 1.5594 mm
δmax = 2.8829 mm
Shear Force [N]
Sliding / Displacement [mm]

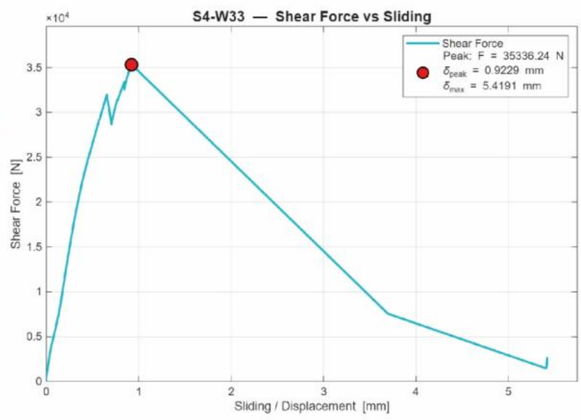

S2-W33 — Forces vs Time
Shear Force F01
Normal Force F02
Shear Force F01 [kN]
Normal Force F02 [kN]
Time [s]

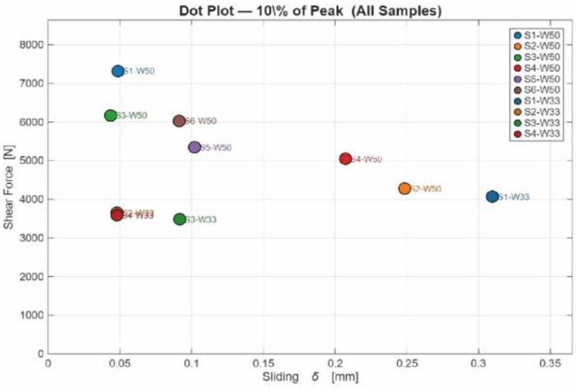

S2-W33 — Shear Force vs Sliding
×10^4
Shear Force
Peak: F = 36252.61 N
δpeak = 1.1549 mm
δmax = 1.5792 mm
Shear Force [N]
Sliding / Displacement [mm]

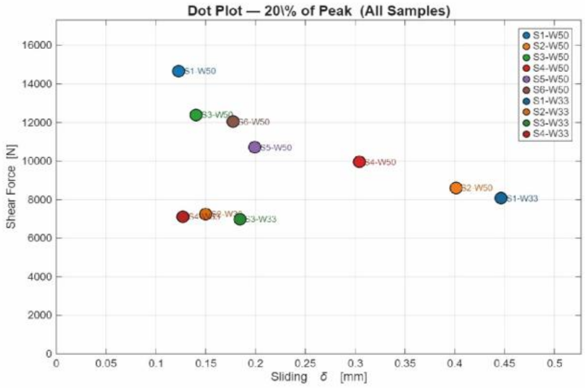

S3-W33 — Forces vs Time
Shear Force F01
Normal Force F02
Shear Force F01 [kN]
Normal Force F02 [kN]
Time [s]

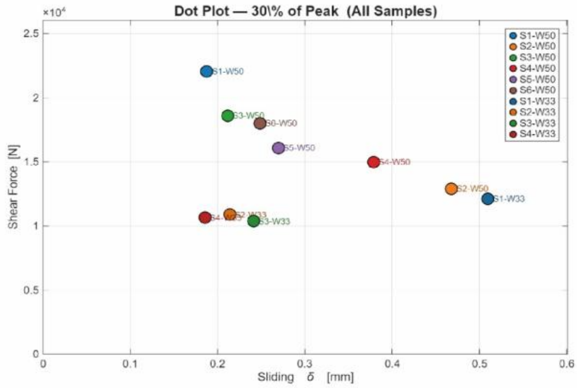

S3-W33 — Shear Force vs Sliding
×10^4
Shear Force
Peak: F = 34508.29 N
δpeak = 0.9205 mm
δmax = 0.9205 mm
Shear Force [N]
Sliding / Displacement [mm]

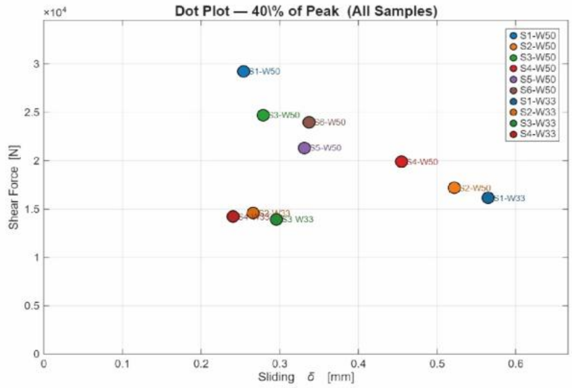

S4-W33 — Forces vs Time
Shear Force F01
Normal Force F02
Shear Force F01 [kN]
Normal Force F02 [kN]
Time [s]

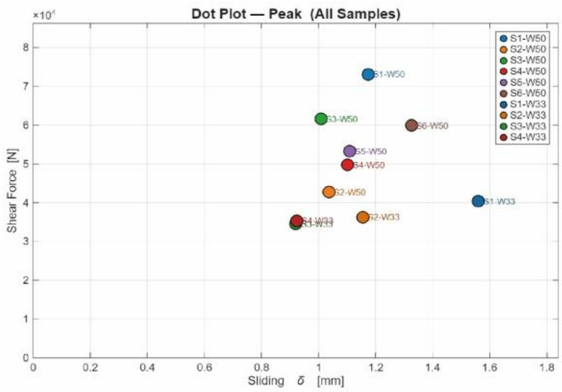

S4-W33 — Shear Force vs Sliding
×10^4
Shear Force
Peak: F = 35336.24 N
δpeak = 0.9229 mm
δmax = 5.4191 mm
Shear Force [N]
Sliding / Displacement [mm]

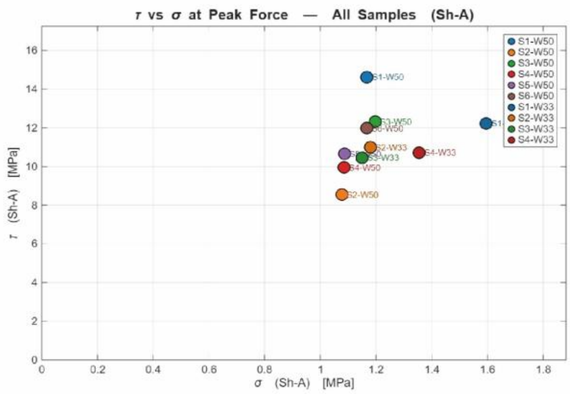

Dot Plot — 10\% of Peak (All Samples)
Shear Force [N]
Sliding δ [mm]

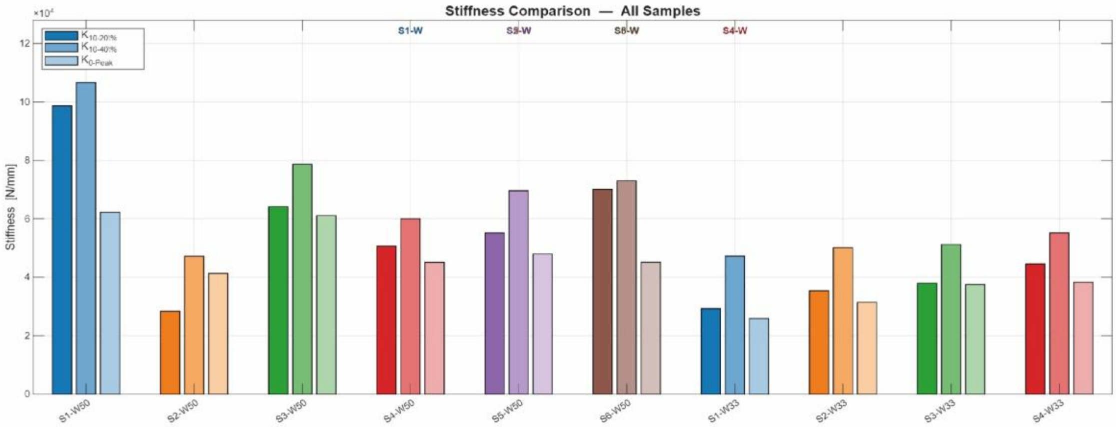

Dot Plot — 20\% of Peak (All Samples)
Shear Force [N]
Sliding δ [mm]

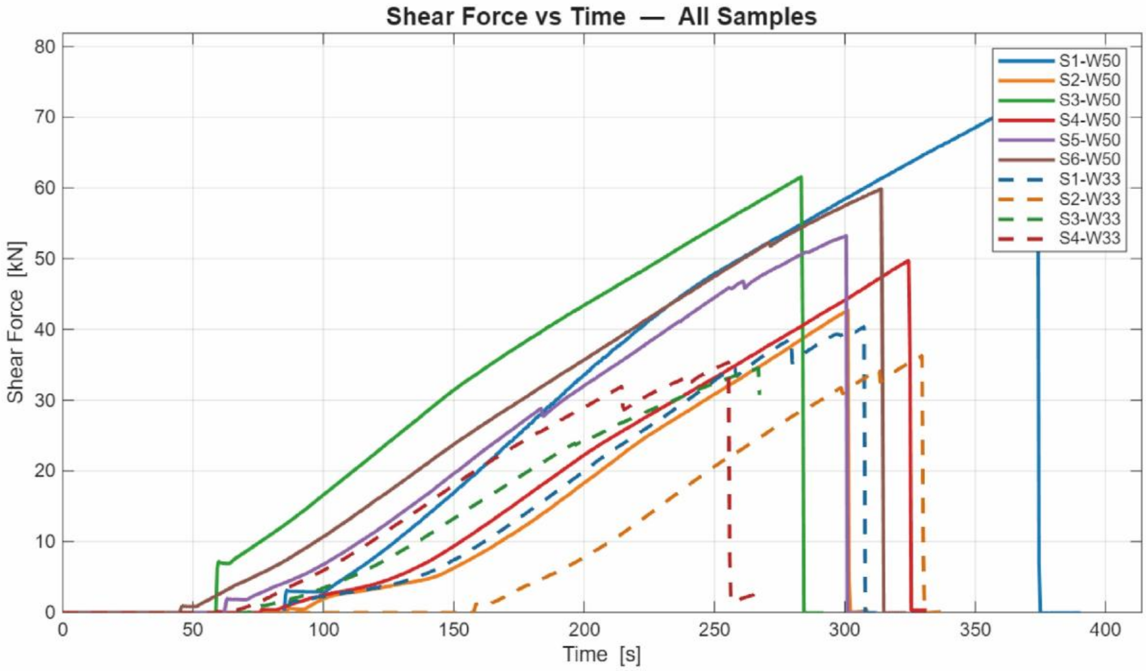

Dot Plot — 30\% of Peak (All Samples)
Shear Force [N]
Sliding δ [mm]

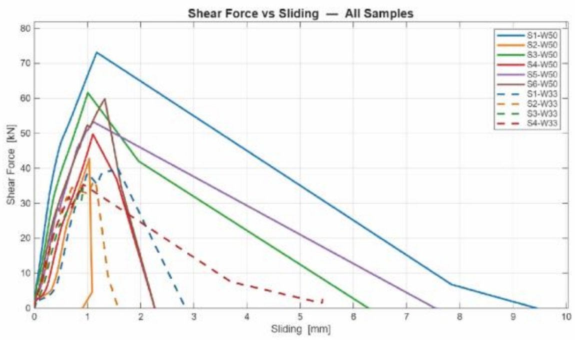

Dot Plot — 40\% of Peak (All Samples)
Shear Force [N]
Sliding δ [mm]

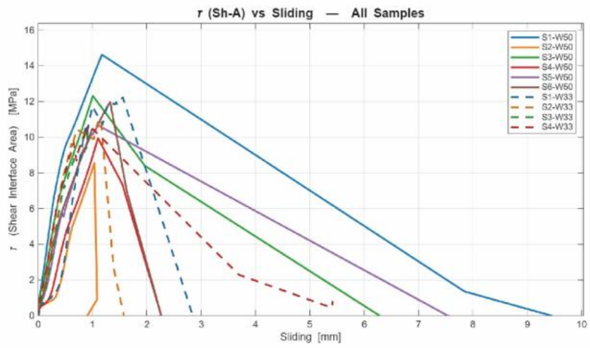

Dot Plot — Peak (All Samples)
Shear Force [N]
Sliding δ [mm]

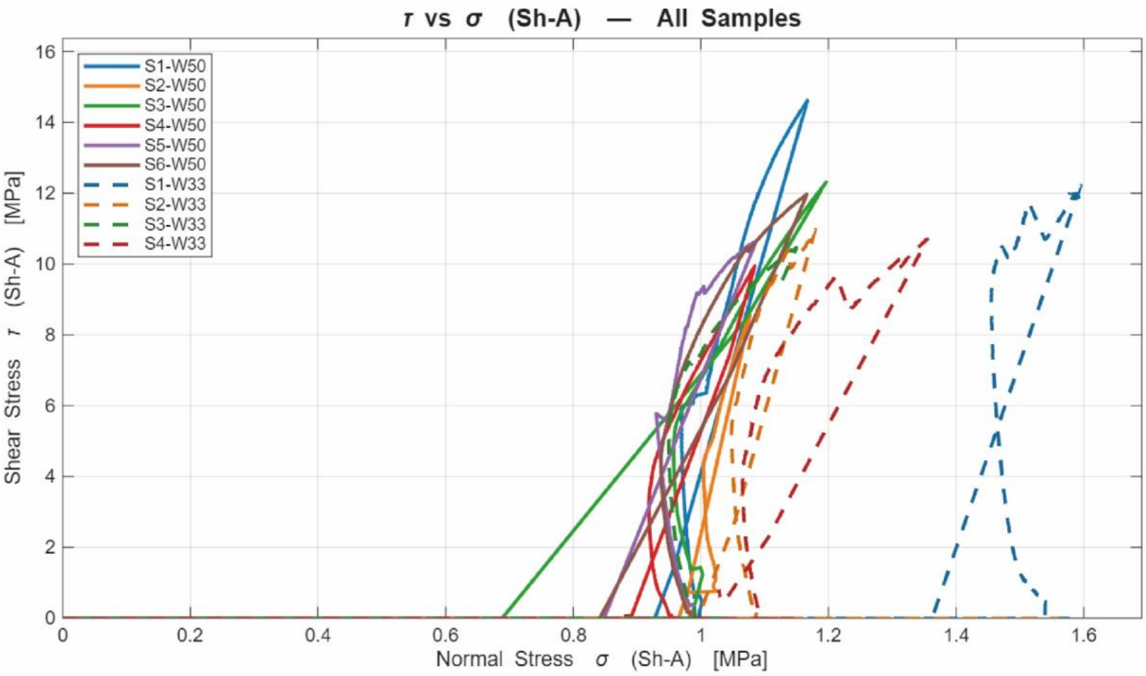

τ vs σ at Peak Force — All Samples (Sh-A)
τ (Sh-A) [MPa]
σ (Sh-A) [MPa]


Stiffness Comparison — All Samples
Stiffness [N/mm]
S1-W50
S2-W50
S3-W50
S4-W50
S5-W50
S6-W50
S1-W33
S2-W33
S3-W33
S4-W33


Shear Force vs Time — All Samples
Shear Force [kN]
Time [s]
S1-W50
S2-W50
S3-W50
S4-W50
S5-W50
S6-W50
S1-W33
S2-W33
S3-W33
S4-W33


Shear Force vs Sliding — All Samples
Shear Force [kN]
Sliding [mm]
S1-W50
S2-W50
S3-W50
S4-W50
S5-W50
S6-W50
S1-W33
S2-W33
S3-W33
S4-W33


τ (Sh-A) vs Sliding — All Samples
τ (Shear Interface Area) [MPa]
Sliding [mm]
S1-W50
S2-W50
S3-W50
S4-W50
S5-W50
S1-W33
S2-W33
S3-W33
S4-W33


τ vs σ (Sh-A) — All Samples
Shear Stress τ (Sh-A) [MPa]
Normal Stress σ (Sh-A) [MPa]
S1-W50
S2-W50
S3-W50
S4-W50
S5-W50
S6-W50
S1-W33
S2-W33
S3-W33
S4-W33

I. **Shear test pictures**

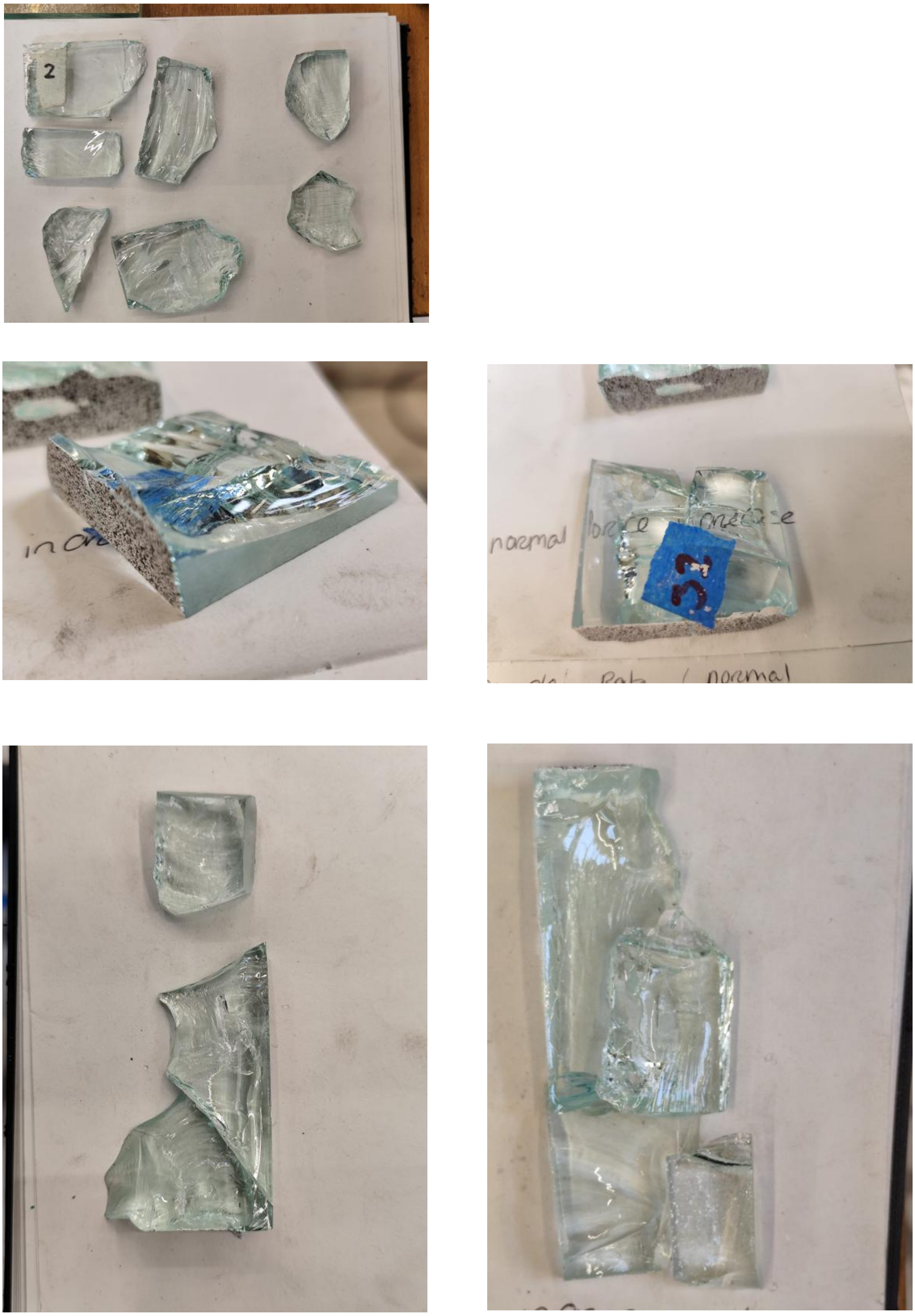


Figure 60: Shear testing picture of fragments (own images)

J. WINDOW

4118	OptifloatClear10r	Optifloat Clear 10mm	Pilkington	IGDB v104. #	9.970	0.774	0.075	0.074	0.882	0.083	0.082	0.000	0.840	0.840	1.000
4119	OptifloatClear12r	Optifloat Clear 12mm	Pilkington	IGDB v104. #	12.010	0.749	0.072	0.071	0.876	0.081	0.081	0.000	0.840	0.840	1.000
4115	OptifloatClear4m	Optifloat Clear 4mm	Pilkington	IGDB v104. #	3.850	0.857	0.078	0.077	0.903	0.083	0.083	0.000	0.840	0.840	1.000
4116	OptifloatClear6m	Optifloat Clear 6mm	Pilkington	IGDB v104. #	5.890	0.825	0.076	0.075	0.896	0.082	0.082	0.000	0.840	0.840	1.000
4117	OptifloatClear8m	Optifloat Clear 8mm	Pilkington	IGDB v104. #	7.890	0.801	0.076	0.075	0.890	0.083	0.082	0.000	0.840	0.840	1.000
9874	BLGRN6.LOF	Optifloat™ Blue-Green	Pilkington Noı	IGDB v14.6 #	5.918	0.481	0.055	0.055	0.753	0.070	0.070	0.000	0.840	0.840	1.000
9875	BLGRN8.LOF	Optifloat™ Blue-Green	Pilkington Noı	IGDB v11.4 #	7.950	0.402	0.052	0.052	0.700	0.066	0.066	0.000	0.840	0.840	1.000
9876	BLGRN10.LOF	Optifloat™ Blue-Green	Pilkington Noı	IGDB v11.4 #	9.398	0.358	0.050	0.050	0.667	0.065	0.065	0.000	0.840	0.840	1.000
9853	BRONZ5.LOF	Optifloat™ Bronze	Pilkington Noı	IGDB v11.4 #	4.699	0.553	0.056	0.056	0.594	0.058	0.058	0.000	0.840	0.840	1.000
9851	BRONZ3.LOF	Optifloat™ Bronze	Pilkington Noı	IGDB v11.4 #	3.200	0.648	0.062	0.062	0.682	0.064	0.064	0.000	0.840	0.840	1.000
9854	BRONZE6.LOF	Optifloat™ Bronze	Pilkington Noı	IGDB v14.6 #	5.918	0.480	0.053	0.053	0.510	0.055	0.055	0.000	0.840	0.840	1.000
9857	BRONZ12.LOF	Optifloat™ Bronze	Pilkington Noı	IGDB v11.4 #	12.497	0.249	0.045	0.045	0.291	0.045	0.045	0.000	0.840	0.840	1.000
9856	BRONZ10.LOF	Optifloat™ Bronze	Pilkington Noı	IGDB v11.4 #	9.398	0.340	0.047	0.047	0.386	0.048	0.048	0.000	0.840	0.840	1.000
9855	BRONZ8.LOF	Optifloat™ Bronze	Pilkington Noı	IGDB v11.4 #	7.950	0.394	0.049	0.049	0.441	0.051	0.051	0.000	0.840	0.840	1.000
9809	CLEAR19.LOF	Optifloat™ Clear	Pilkington Noı	IGDB v11.4 #	18.745	0.551	0.061	0.061	0.808	0.075	0.075	0.000	0.840	0.840	1.000
9807	CLEAR12.LOF	Optifloat™ Clear	Pilkington Noı	IGDB v11.4 #	12.497	0.642	0.064	0.064	0.843	0.079	0.079	0.000	0.840	0.840	1.000
9806	CLEAR10.LOF	Optifloat™ Clear	Pilkington Noı	IGDB v11.4 #	9.398	0.698	0.066	0.066	0.861	0.080	0.080	0.000	0.840	0.840	1.000
9805	CLEAR8.LOF	Optifloat™ Clear	Pilkington Noı	IGDB v11.4 #	7.950	0.726	0.067	0.067	0.869	0.081	0.081	0.000	0.840	0.840	1.000
9804	CLEAR6.LOF	Optifloat™ Clear	Pilkington Noı	IGDB v11.4 #	5.664	0.774	0.072	0.072	0.883	0.081	0.081	0.000	0.840	0.840	1.000
9803	CLEAR5.LOF	Optifloat™ Clear	Pilkington Noı	IGDB v11.4 #	4.699	0.796	0.074	0.074	0.888	0.082	0.082	0.000	0.840	0.840	1.000
9802	CLEAR4.LOF	Optifloat™ Clear	Pilkington Noı	IGDB v17.4 #	3.900	0.864	0.077	0.077	0.904	0.082	0.082	0.000	0.840	0.840	1.000
9801	CLEAR3.LOF	Optifloat™ Clear	Pilkington Noı	IGDB v17.4 #	3.000	0.876	0.078	0.078	0.907	0.082	0.082	0.000	0.840	0.840	1.000
9800	CLEAR2.LOF	Optifloat™ Clear	Pilkington Noı	IGDB v17.4 #	2.240	0.887	0.079	0.079	0.910	0.082	0.082	0.000	0.840	0.840	1.000
9808	CLEAR16.LOF	Optifloat™ Clear	Pilkington Noı	IGDB v11.4 #	15.621	0.594	0.063	0.063	0.825	0.077	0.077	0.000	0.840	0.840	1.000
9920	EnAdvLE2.LOF	Energy Advantage™ Low-I	Pilkington Noı	IGDB v17.4 #	2.240	0.748	0.120	0.114	0.844	0.111	0.107	0.000	0.164	0.840	1.000
9932	SolarE3.LOF	Solar E™	Pilkington Noı	IGDB v17.4 #	3.200	0.459	0.117	0.077	0.601	0.092	0.075	0.000	0.166	0.840	1.000
9933	SolarE4.LOF	Solar E™	Pilkington Noı	IGDB v17.4 #	3.912	0.450	0.117	0.076	0.599	0.092	0.075	0.000	0.166	0.840	1.000
9934	SolarE5.LOF	Solar E™	Pilkington Noı	IGDB v17.4 #	4.700	0.442	0.116	0.075	0.597	0.092	0.075	0.000	0.166	0.840	1.000
9935	SolarE6.LOF	Solar E™	Pilkington Noı	IGDB v17.4 #	5.918	0.438	0.117	0.072	0.599	0.093	0.076	0.000	0.166	0.840	1.000
9936	SolarE8.LOF	Solar E™	Pilkington Noı	IGDB v17.4 #	7.900	0.419	0.116	0.069	0.593	0.092	0.076	0.000	0.166	0.840	1.000
9937	SolarE10.LOF	Solar E™	Pilkington Noı	IGDB v30.0 #	9.940	0.403	0.119	0.073	0.605	0.095	0.081	0.000	0.166	0.840	1.000
9961	SolarEGrey8.lof	Solar-E™ Grey	Pilkington Noı	IGDB v18.1 #	7.900	0.171	0.107	0.050	0.229	0.076	0.050	0.000	0.167	0.840	1.000
9954	SolarEEvGn6.lof	Solar-E™ EverGreen	Pilkington Noı	IGDB v18.0 #	5.918	0.202	0.111	0.052	0.448	0.086	0.063	0.000	0.167	0.840	1.000
9956	SolarEArBl8.lof	Solar-E™ Arctic Blue	Pilkington Noı	IGDB v18.1 #	7.900	0.155	0.106	0.051	0.300	0.080	0.056	0.000	0.167	0.840	1.000
9957	SolarEBlGn8.lof	Solar-E™ Blue-Green	Pilkington Noı	IGDB v18.1 #	7.900	0.238	0.108	0.057	0.450	0.087	0.067	0.000	0.167	0.840	1.000
9960	SolarEEvGn8.lof	Solar-E™ EverGreen	Pilkington Noı	IGDB v18.1 #	7.900	0.162	0.109	0.052	0.401	0.093	0.066	0.000	0.167	0.840	1.000
9955	SolarEGrey6.lof	Solar-E™ Grey	Pilkington Noı	IGDB v17.2 #	5.918	0.231	0.110	0.060	0.298	0.076	0.053	0.000	0.167	0.840	1.000
9951	SolarEBlGn6.lof	Solar-E™ Blue-Green	Pilkington Noı	IGDB v17.2 #	5.918	0.289	0.110	0.058	0.512	0.084	0.066	0.000	0.167	0.840	1.000
9950	SolarEArBl6.lof	Solar-E™ Arctic Blue	Pilkington Noı	IGDB v17.2 #	5.918	0.197	0.110	0.052	0.359	0.078	0.057	0.000	0.167	0.840	1.000
4566	planibelg_4.gvb	Planibel G 4 mm	AGC Glass E	IGDB v53.0 #	3.850	0.734	0.115	0.108	0.826	0.107	0.100	0.000	0.168	0.840	1.000
4567	planibelg_6.gvb	Planibel G 6 mm	AGC Glass E	IGDB v53.0 #	5.850	0.714	0.114	0.104	0.819	0.106	0.099	0.000	0.168	0.840	1.000
4140	KGlass_4mm.nsg	K Glass 4mm	Pilkington	IGDB v104. #	3.820	0.725	0.120	0.108	0.837	0.117	0.111	0.000	0.168	0.845	1.000
4138	KGlassOW6mm.r	K Glass OW 6mm	Pilkington	IGDB v64.0 #	5.960	0.736	0.128	0.121	0.837	0.117	0.112	0.000	0.168	0.842	1.000
9759	6_SlTechGry.OC	6mm SolTech™ Grey	Oceania Glas	IGDB v76.0	5.820	0.239	0.106	0.058	0.304	0.076	0.055	0.000	0.168	0.840	1.000
9927	EnAdvLE12.LOF	Energy Advantage™ Low-I	Pilkington Noı	IGDB v17.4 #	12.500	0.563	0.101	0.081	0.791	0.109	0.101	0.000	0.169	0.840	1.000
9962	SolarEPlusArBl6.	Solar-E™ Plus Arctic Blue	Pilkington Noı	IGDB v30.0 #	5.920	0.170	0.110	0.048	0.305	0.079	0.053	0.000	0.170	0.840	1.000
9963	SolarEPlusBlGn6	Solar-E™ Plus Blue-Green	Pilkington Noı	IGDB v30.0 #	5.920	0.242	0.112	0.053	0.414	0.087	0.061	0.000	0.170	0.840	1.000
9966	SolarEPlusEvGn	Solar-E™ Plus EverGreen	Pilkington Noı	IGDB v30.0 #	5.920	0.172	0.111	0.051	0.378	0.090	0.063	0.000	0.170	0.840	1.000
9967	SolarEPlusGrey6	Solar-E™ Plus Grey	Pilkington Noı	IGDB v30.0 #	5.920	0.195	0.110	0.052	0.240	0.085	0.054	0.000	0.170	0.840	1.000
9968	SolarEPlusGrBl6	Solar-E Plus on Graphite I	Pilkington Noı	IGDB v30.0 #	5.930	0.277	0.113	0.055	0.354	0.085	0.057	0.000	0.170	0.840	1.000
9966	SolarEPlusEvGn	Solar-E™ Plus EverGreen	Pilkington Noı	IGDB v30.0 #	5.920	0.172	0.111	0.051	0.378	0.090	0.063	0.000	0.170	0.840	1.000
9967	SolarEPlusGrey6	Solar-E™ Plus Grey	Pilkington Noı	IGDB v30.0 #	5.920	0.195	0.110	0.052	0.240	0.085	0.054	0.000	0.170	0.840	1.000
9968	SolarEPlusGrBl6	Solar-E Plus on Graphite I	Pilkington Noı	IGDB v30.0 #	5.930	0.277	0.113	0.055	0.354	0.085	0.057	0.000	0.170	0.840	1.000

Figure 61: Overview of small section of glass library (WINDOW)

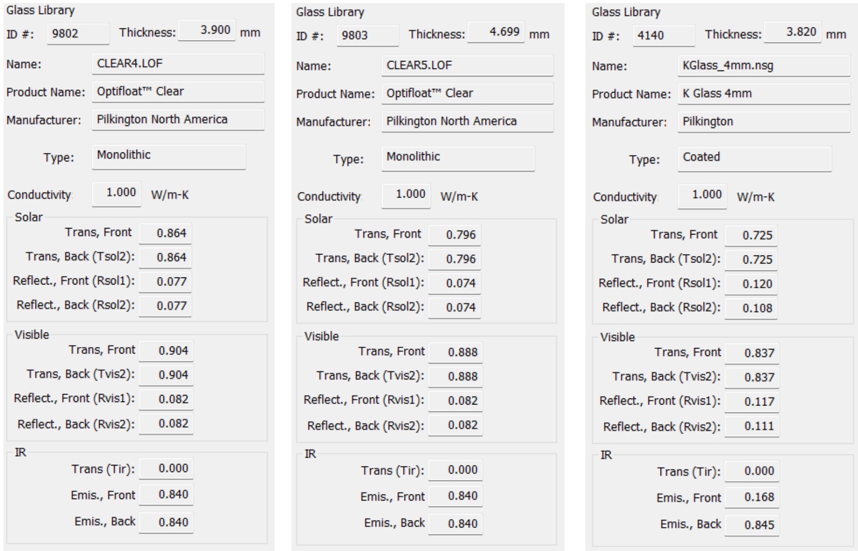


Figure 62: Overview of selected glass material properties (WINDOW)

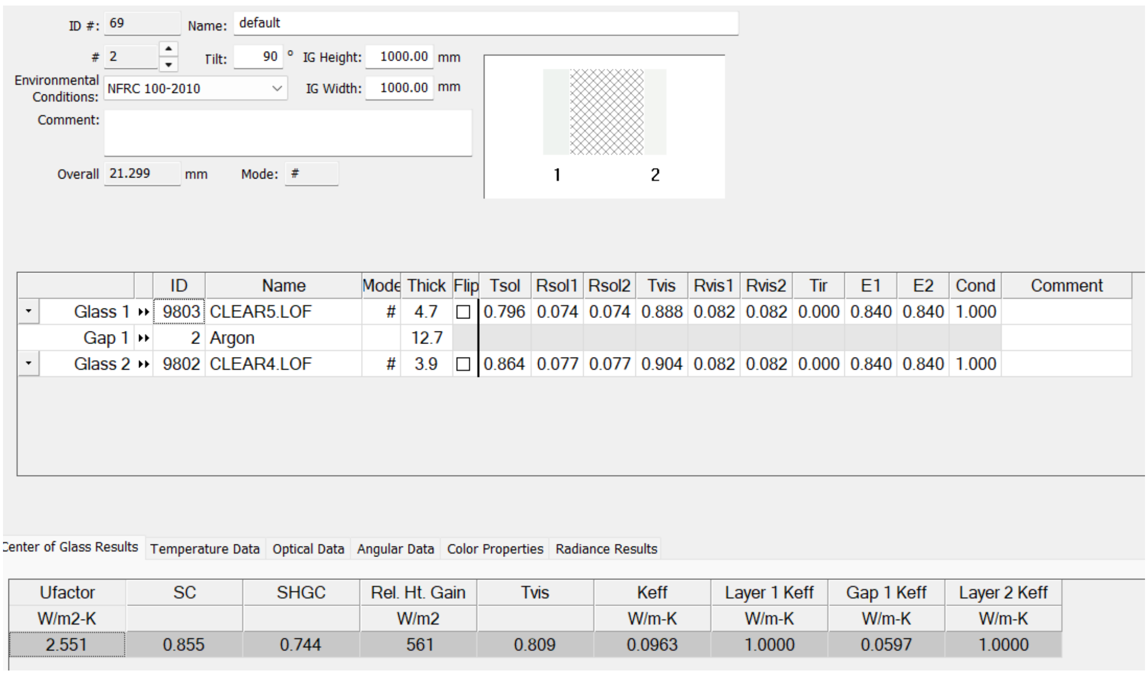


Figure 63: Selected glazing system setup and properties (WINDOW)

K. THERM

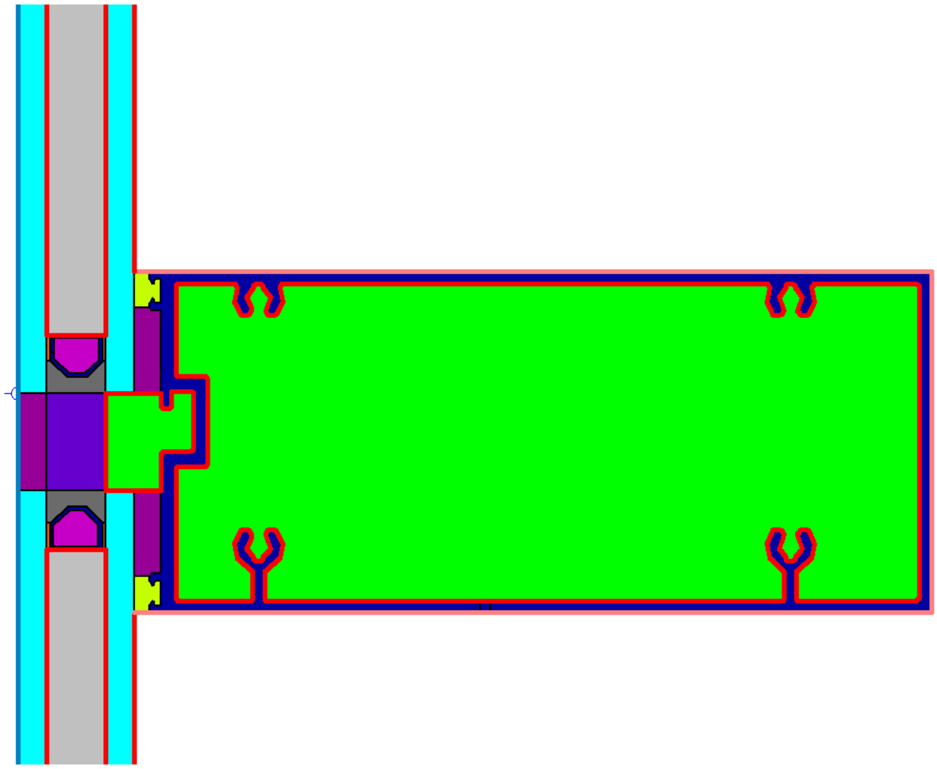


Figure 64: THERM original spacer setup

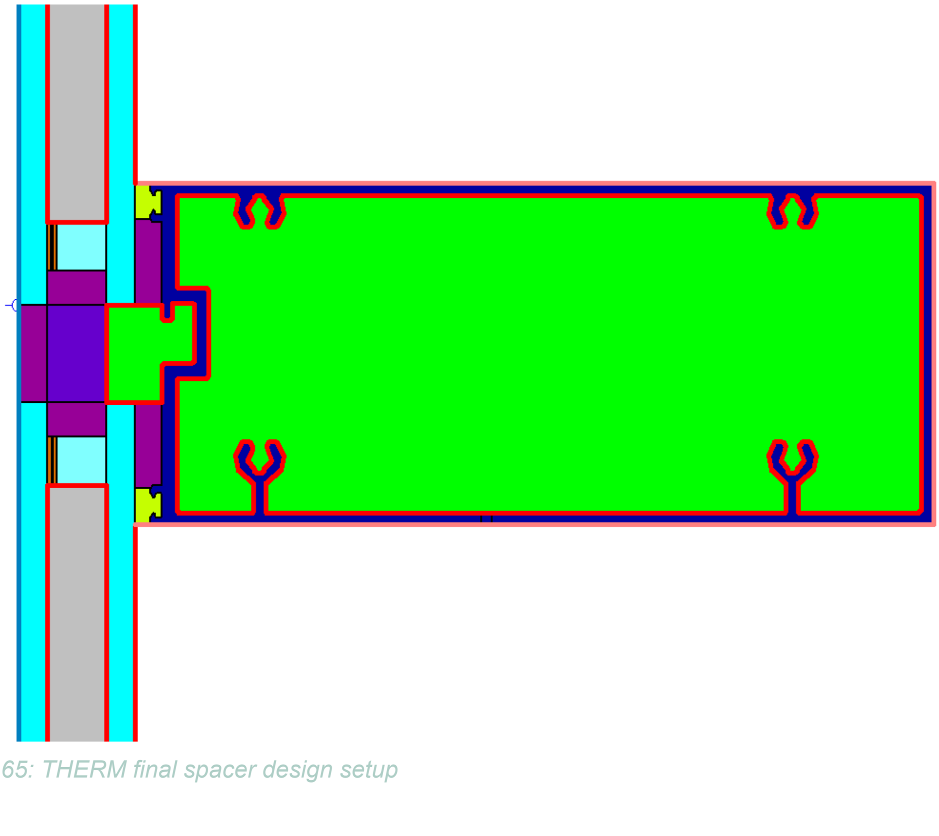


Figure 65: THERM final spacer design setup

Materials selected in THERM:

LIGHT BLUE:	GLASS (plate or float)
PURPLE:	SILICONE
DARK BLUE:	ALUMINIUM ALLOW (painted)
GREEN	FRAME CAVITIY
YELLOW;	EPDM (Ethylene Propylene Diene Monomer)
DARK PURPLE:	FOAM RUBBER
LIGHT GREY	ARGON
BROWN	PIB (Polyisobutylene)
PINK	SILICA GEL (Desiccant)

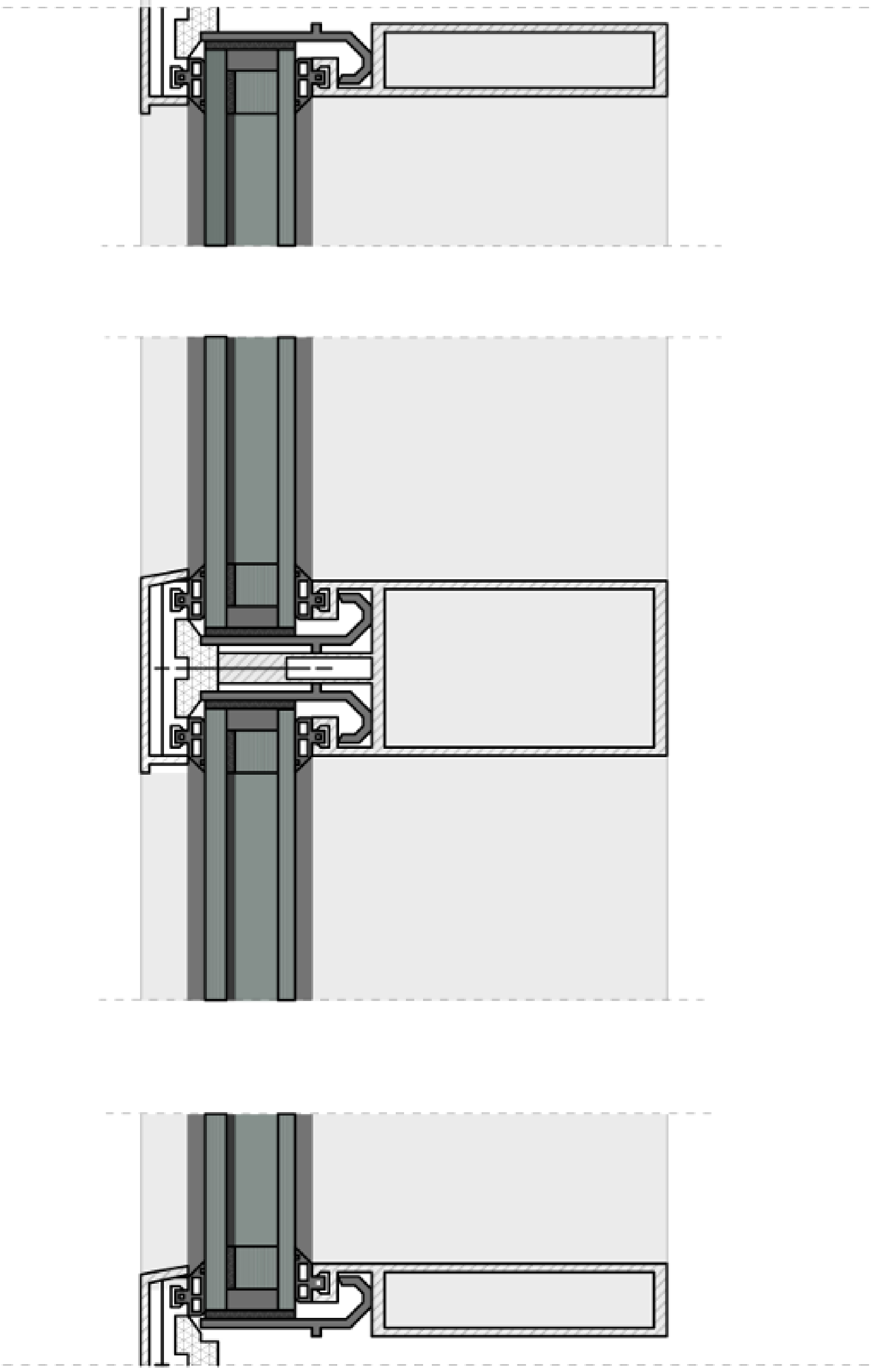
Table 30: Materials selected in THERM

Boundary conditions:

RED	FRAME CAVITY SURFACE
BLUE	NFRC 100-2010 EXTERIOR
PINK	INTERIOR THERMALLY BROKEN FRAME

Table 31: Boundary conditions selected in THERM

L. Façade detail



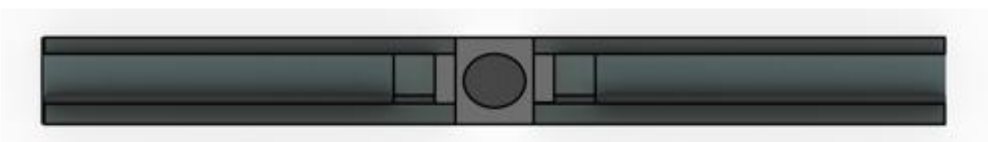


Figure 66: Vertical and horizontal facade detail (own images)

M. Assembly

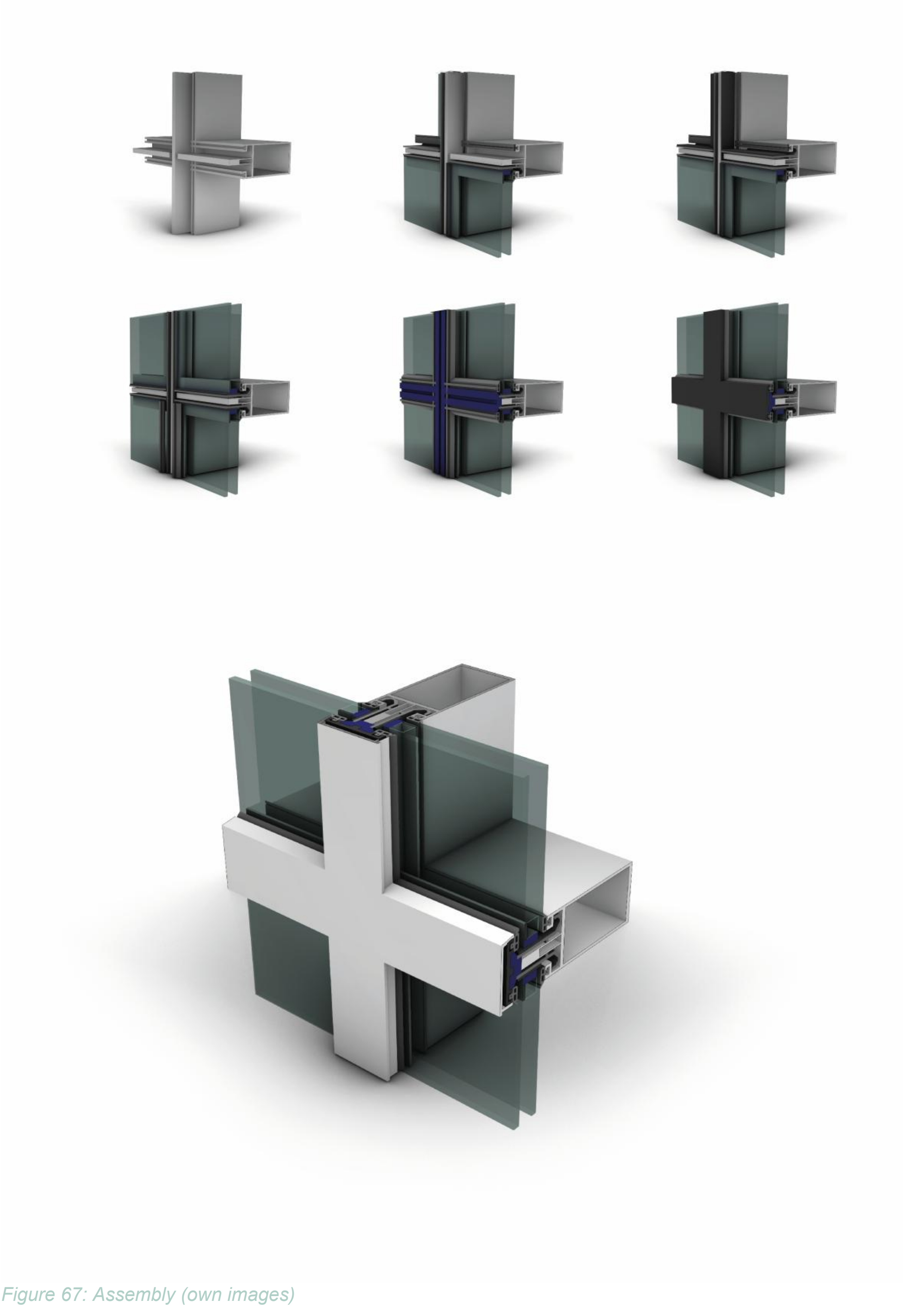


Figure 67: Assembly (own images)

N. Final Prototype pictures

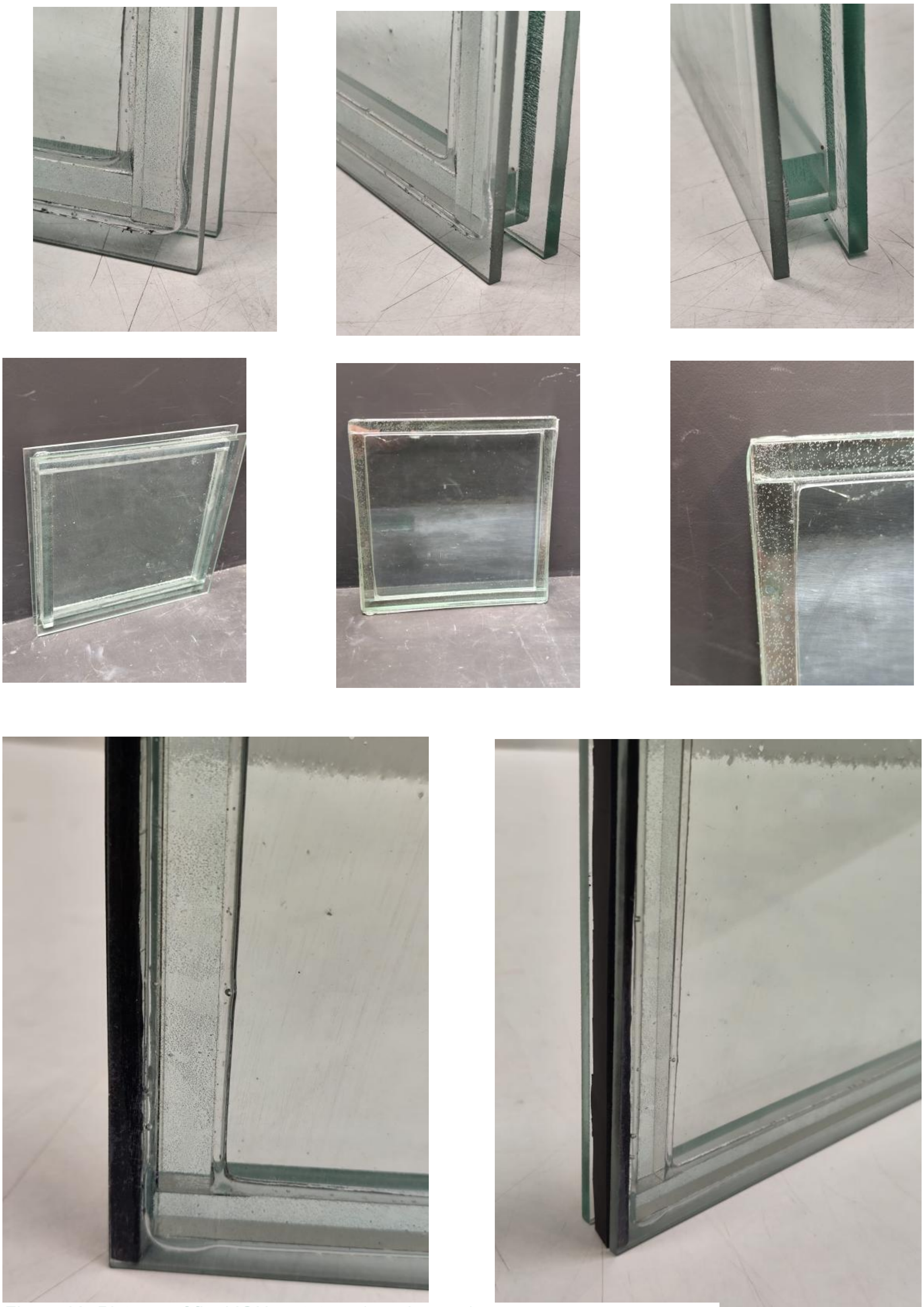


Figure 68: Pictures of final IGU prototype (own images)