A method for human-centered appraisal of façade design for serviceability

Graduation Thesis Report

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Abstract

In the wake of the climate crisis, the building industry faces a unique challenge - to strike a balance between global sustainability challenges and the high standards of human comfort. A building's façade plays an important role in reducing operational carbon emissions in a building, while maintaining acceptable levels of indoor comfort. In doing so, contemporary façade solutions often lead to an increase in embodied carbon in a building. Further, strategies to reduce embodied carbon, such as use of recycled or reused glass fail to meet conventional standards. This thesis explores the potential of a material efficient approach in design of façade glazing by means of reduction in glass thickness.

Reduction of 1mm thickness of glass can save up to 3 $kgCO_2eq/m^2$ of façade area. However, reduction in glass thickness may lead to deformations in glazing well beyond serviceability limits. This may have a negative impact on glazing properties such as its mechanical performance, thermal performance, durability, optical performance, acoustic performance and overall occupant satisfaction. While effects of deformation on objective performance parameters can be calculated and mitigated, there has been no research on how acceptance of deformation in terms of occupant satisfaction can be measured. As a consequence, serviceability limits are mainly governed by objective criteria alone. Occupant acceptance towards deformation has always been assumed to be low and glass panes are designed to be more rigid than may be necessary. Without measurement of occupant acceptance thresholds of deformation it is not possible to perform a comprehensive assessment of limits on deformation, and the potential to reduce glass thickness in glazing.

A novel method has been designed in this thesis to determine occupant satisfaction towards level of deformation in glass; with the intention of arriving at acceptance thresholds comparable to those set by objective criteria. As the first step in research a state-of-the-art review on the subject of serviceability criteria and potential for material efficiency in glazing was conducted by means of a systematic literature review and a façade industry survey. Based on the findings from the review an experiment was designed and developed. The proposed method is designed to be conducted in an office environment or a laboratory with volunteers who are asked to indicate their level of satisfaction towards deformations in glass. The deformations in glass are created by varying air pressure inside the cavity of an insulated glazing unit (IGU) using an electro-pneumatic system designed for this experiment to replicate two common loading conditions related to serviceability – climate loading and wind loading. Preliminary tests were able to provide a sufficient proof of concept for the experimental setup.

Feasibility tests for the experimental setup were conducted wherein the mechanical behavior and optical behavior of glass under deformation was objectively measured. The deformation patterns in glass panes displayed geometrically nonlinear behavior in line with predictions of finite element analysis. It was also found that the static deformation (pillowing) does not have any perceivable impact on the view through the façade panel. However, deformation of glass is perceived through distortion of the reflected images, such as ceiling lights and reflecting objects. Further objective optical experiments must be conducted under dynamic loading conditions so as to compare these with results of subjective testing. Subjective testing of the experimental method with a few volunteers is required before conducting the final experiment.

A novel method was thus formulated for a human-centered appraisal of façade glazing deformation. A comprehensive understanding of impact of glazing deformation is necessary to explore the potential of material efficiency in façade glazing. The experimental setup was found to be versatile and scalable enough to conduct multi-objective experiments to assess the impact of deformations on mechanical behavior, thermal performance, acoustic performance and durability.

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1 Introduction

1.1 Context

Given that the building industry contributes to nearly 40% of the annual global Greenhouse Gas (GHG) emissions, it is important to carefully analyze the contributing factors, and find solutions in order to reduce emissions, while still maintaining acceptable levels of quality and comfort. According to the global decarbonization trajectories, the building industry needs to reduce these emissions by 50% by 2030 to reach net zero by 2050 and achieve the climate goals of the Paris Agreement (Arup & SGG, 2022).

Embodied carbon refers to a quantity of CO2e associated with the materials used to construct and maintain the building throughout its life span. Operational carbon refers to emissions associated with the heating, cooling and energy use of the building (Arup & WBCSD, 2021). Out of the total emissions of the current building stock, nearly two-thirds come from building operation, and one-thirds from embodied carbon (Zani et al., 2021).

To reduce the upfront embodied carbon in the new building stock, decarbonization strategies such as designing for material efficiency, reuse of salvaged materials and using materials with higher recycled content are used. Facades play an important role in controlling the operational energy of a building during its life cycle. Hence, the focus of façade engineering has been more on design to reduce operational carbon, than on reducing embodied carbon in facades themselves. The strategies to reduce operational carbon typically imply addition of more material, leading to an increase in embodied carbon of facades. Hence, a balanced approach for reducing both operational and embodied carbon of the building stock is necessary.

1.1.1 The role of facades in embodied carbon of a building

While operational energy is based on many user-related factors and can be optimized during the building's life cycle, the embodied energy in a building is trapped in the building for its life time (Arup & SGG, 2022). The building envelope contributes to 10-30% of total embodied carbon of the building (Arup & SGG, 2022; Hartwell et al., 2021). According to a study conducted by Arup and Saint Gobain Glass (SGG) in 2022 on 16 façades representative of European façade typologies, the embodied carbon of facades was found to range from 160 to 520 kgCO2e/m2 of façade. As the complexity of a façade system increases, e.g. with the use of IGUs with three or more plies, or the use of sun-shading systems, it further increases the embodied carbon. While embodied carbon of aluminum can be offset by using recycled raw material, with glass, the embodied energy remains a challenge.

1.1.2 The role of glass in embodied carbon of a building

Nowadays, the use of double glazed and triple glazed units is fairly common, while in some cases, systems with even more layers are being used (Starman et al., 2020). Glass is an important contributing factor to the embodied carbon in facades. In a recent case study conducted by (Arup & SGG, 2022), it was calculated that the contribution of glass to the embodied carbon of facades was in the range of 26 to 60% depending on the facade typology. In terms of contribution to the building's embodied carbon, another case study conducted by (Arup & WBCSD, 2021) highlights that contribution of glass is typically around 4% and that of Aluminum is around 6% of the total.

Figure 1 summarizes the contribution of glass towards embodied carbon of a building as found from the literature review. The overall contribution of façade glass in global greenhouse gas (GHG) emissions is approximately 1.6%. Although the percentage seems low, it should be observed that reduction in embodied energy of glass, by using a material efficient approach could reduce the imposed load on the building. This would help reduce the embodied carbon of the building structure, and thus, the entire building.

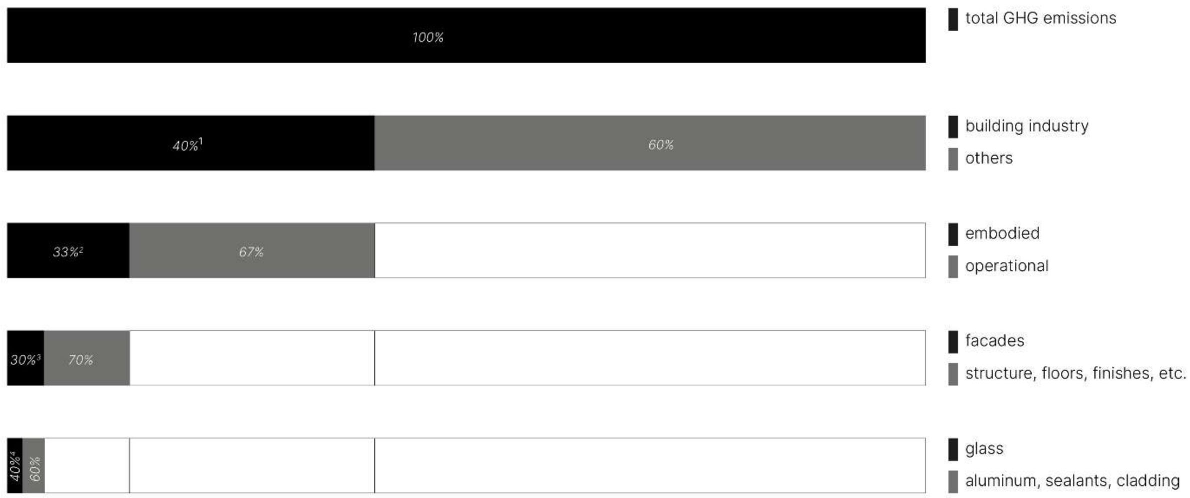

Figure 1: Diagram indicating contribution of glass and facades to embodied carbon of the building, in relationship with global emissions. (1. UNEP, (2020); 2. Zani et al., (2021). Facade Design Process to Establish and Achieve Net Zero Carbon Building Targets; 3. Hartwell, et al. (2021). Circular economy of façades: Real-world challenges and opportunities.; 4. Arup & SGG. (2022). Carbon footprint of facades: significance of glass.; 5. Mao et al. (2015). Energy Consumption, Environmental Impacts and Effective Measures of Green Office Buildings: A Life Cycle Approach.)

1.2 Reducing embodied carbon in façade glazing

1.2.1 Reuse of glass

Reuse of building elements ranks high in the list of strategies for reducing carbon footprint in buildings. Extensive research is going on, on the subject of reuse of structural elements, services and facades (*PerpetuAl: Circular Aluminum Facades*, 2022; *ReCreate: Deconstruction and Reuse*, 2021). The precondition for re-use is that disassembly of the construction does not damage the building element in a way that makes it unfit for use. Further, the salvaged elements must match the current construction specifications and standards.

In case of building facades, though the disassembly of the framing system and glass may be possible, their reuse is hampered by the fact that their sizes and specifications may not be versatile enough to match a new application. Additionally, for an IGU, it is imperative to test the remaining life of the edge seal, if it were to be used in a new building. Reused glass panes might have some scratches or other defects that may be unacceptable for new clients (Zaccaria, 2022). Thus, there are many practical challenges in the reuse of façade glass. Often, glass panels salvaged from disassembled buildings are either downcycled, or these are crushed together with other building materials and put into landfills or recovered to low-grade applications (Arup, 2018).

1.2.2 Use of recycled glass

The possibility of recycling glass in a closed loop system is one of its most important material properties. (Arup, 2018). The remelting of glass consumes less energy compared to manufacturing new glass, and less CO2 is released in the process. Thus the use of recycled glass is a potential way of reducing carbon footprint of buildings. Currently, recycled glass is used in the production of glass wool, solar panels, and certain varieties of flat glass. In terms of flat glass production, every ton of cullet utilized saves 1.2 tons of raw materials, 300 kWh of energy and 300 kg of CO2 emissions (Arup, 2018). However, for very high quality glass, with no visual defects, lesser the percentage of cullet, the better. Glass companies often use some percentage of cullet in glass production depending on the expected quality of the final glass sheet.

Companies like AGC are manufacturing and marketing 'low carbon glass' which claims a 40% less carbon footprint compared to their standard product (AGC, 2022). In a lecture at the AGC Technovation Center in Belgium, titled 'Introduction to Low Carbon Glass', (Zaccaria, 2022) stated that one of the main reasons for this reduced carbon footprint is the use of around 30% of cullet in the composition. However, this cullet is sourced primarily from the factory itself i.e. from post-production scrap material from cutting and processing of float glass. Sourcing of cullet from demolition/ disassembly waste is still not a common practice. Contamination is the biggest technical challenge to overcome in order to increase the availability of quality cullet for the remelt process (Arup, 2018).

Hence, although increasing the cullet percentage in float glass is a way to reduce carbon footprint of glass, it is a challenging process to put in practice due to lack of a reverse supply chain for glass from building owners to glass manufacturers, need for sourcing good quality cullet to match factory standards, and selective disassembly of building facades (Zaccaria, 2022). Another important barrier in the process is the 'acceptance' of recycled glass among clients who at times do not wish to compromise on the expected quality of product. However, with a growing awareness towards the need for decarbonization, the acceptance of recycled materials may increase in the near future.

1.2.3 Material efficiency in glass

Optimizing material use in structural components such as floor slabs, columns and beams is a common practice in terms of reducing embodied carbon in new construction. As long as the elements satisfy the structural requirements of ultimate and serviceability limit states, it is possible to eliminate excess material. In terms of facades, material optimization in glass can potentially lead to savings in embodied carbon since glass is a main contributing material to the total weight of the façade. In a typical building, glass is over 4 times heavier than aluminum in façade. The mass of glass is around 2.2% and that of Aluminum is around 0.5% (Mao et al., 2015). Efficient use of glass will not only reduce its own contribution to total embodied carbon, but by reducing implied weight on the building's structure, can also help reduce the material use of structural steel and concrete.

Material efficiency in glass can be achieved either by reducing the area of glass in façade or by reducing the thickness of glass itself. In this research, the focus is on glass thickness, since its impact is more universal, i.e. it does not depend on the surface area of glass. Float glass is available in typical sizes (4mm, 6mm, etc.) from the suppliers. Specification of glass thickness by engineers is typically based on multiple performance criteria such as desired strength of glass and desired thermal, optical, acoustical performance of façade. Thus, in order to specify thinner glass, firstly, it must be readily available and secondly, it must be ensured that the performance criteria are satisfied to subjective and objective levels of acceptance.

Market availability of thinner glass

Typical float glass used in windows is soda-lime glass, which is the most commonly used types of glass. Through processes such as heat-strengthening, chemical strengthening increase the stress capacity of float glass making it more resistant to loading. Typically, the float-lines can manufacture glass ranging between 3.0mm to 20.0mm thickness. Nowadays, another composition of glass namely Aluminosilicate glass (thin glass) is also widely used in applications such as mobile phone or tablet screens and automobile applications. Glass manufacturers such as AGC are now able to supply thin glass (Falcon) in sizes as big as typical float glass and thickness ranging from 0.5mm to 2.0mm (AGC, 2020). This glass typically finds applications in the building industry as one of the internal panes of an insulated glazing unit (IGU) with 3 or more panes, or as one of the layers in vacuum-insulated glazing unit (VGU). The advancement in research of thinner glass, provides a strong basis for exploring material efficiency in façade glazing.

1.3 Limits on thickness of façade glazing

1.3.1 Limit state design for facade glazing

Limit state design is a methodology for designing structural elements which considers both, the effects of actions (forces and moments) and resistance offered by the material; and it forms the basis for most of the building codes, for structural design (SGG, 2018). While most building codes provide a detailed guidance for design of structures using steel, concrete and masonry, a standardized guidance for design of structural glass had been missing until recently. Currently, the European Glass Code is under development. The draft guidelines in the form of FprCEN/TS 19100 have been released in April 2022 for public comment, and there is still almost two years for a European Standard (EN) for glass to be issued (Coult & Overend, 2022).

Glass displays a behavior different from steel or concrete, in the sense that the breakage of glass is immediate, as soon as the stresses in glass exceed permissible ultimate limits, since a sheet of glass is brittle, lacks ductility and has surface inconsistencies (Wuest & Luible, 2020). Hence, it is imperative to keep stresses within glass under specified limits. Further, during the instance of breaking, and for a specified amount of time after, the fractured glass must not cause human injury and/or economic loss.

Therefore, in the building codes for glass, alongside the standard Ultimate Limit State (ULS) and Serviceability Limit State (SLS), two additional limit states, namely Fracture Limit State (FLS) and Post Fracture Limit State (PFLS) have been included. While the ULS, FLS and PFLS deal with load combinations during accidental or one-off scenarios, the SLS deals with more frequent load combinations, and thus, is important during the use phase of facades. Appendix 1 discusses the limit states for glass in further detail.

In terms of glass, as long as the stresses are within the 'ultimate' or failure limits, the deformations can be termed as objectively 'acceptable'. However, façade glazing plays many roles other than resisting loading, such as thermal and acoustic insulation, fire resistance, providing views of the surroundings, contributing to overall aesthetics and providing a feeling of safety and security to occupants. Therefore, it is the SLS that finally limits the deformation, to a value much lower than the ultimate limit. This is mainly to ensure that the 'serviceability' of façade glazing, which is a combination of its functions is maintained.

1.3.2 Implications of use of thinner glass on serviceability

Typically, the main impact that material efficiency has on structural elements such as floor slabs or beams is the possibility of minor deflections under loading. Deflection of an element is not a sign of failure, rather a result of elasticity of material, which returns to its original form once the load is removed. Deformations in glass are typically caused as a result of wind loading or climatic loading i.e. differences in temperature or pressure between the sealed cavity and the surrounding atmosphere. Higher deformations may even result from barrier or impact loading. The magnitude of deformation of glass under loading depends on factors such as its thickness, rigidity, load sharing effect (in case of 2 or more panes of glass), aspect ratio of glass panes and properties of spacers and sealants. These factors are discussed in further detail in Chapter 2.2.

In terms of glass, material efficiency will impact amount of deformation and stresses compared to when typical glass thicknesses are used. According to (Respondek, 2018), reduction of glass pane thickness from 4mm to 2mm in a quadruple-glazing unit under climatic loading increased a deflection slightly, i.e. from 1.17 to 1.23mm, but reduced the stresses significantly, i.e. from 2.72 kPa to 1.42 kPa. The effective benefit in carbon savings given that the glass thickness was halved, would be considerable.

However, higher deformations have a considerable impact on the thermal, optical or acoustic performance of glazing. Further, deformations in glass are typically seen as a sign of lower quality, and the dynamic deformation or vibration of glass may cause alarm in occupants. The effects of deformations in glass are discussed in further detail in Chapter 2.3. It is critical for a material efficient design approach to limit or overcome the impact of deformation on glazing performance in order to achieve an overall benefit in terms of embodied carbon savings.

1.3.3 Variations in serviceability limits in practice

As indicated earlier, draft guidelines for structural glass design in the form of FprCEN/TS 19100 have been released in April 2022 for public comment. These guidelines provide expressions for combinations of loads to be followed while designing for ULS and SLS. Before the release of this draft, engineers in Europe referred to local standards based on EN 16612:2019. Outside Europe, different national standards specify their own limits for glass deflection (ASTM International, 2016; Buildings Department Hong Kong, 2018).

A façade industry survey conducted as part of this research shows that the 'limits' on deflection followed differ based on not only different countries, but also the type of project, place of application of glass, etc. This has been discussed in detail in Chapter 3.3.4. Variations in acceptance limits based on location are common in structural design. For instance, the lateral deflection limits on high rise buildings in China are around H/800, in London around H/500, in Korea H/300 and in Taiwan H/200 (IStructE & IABSE, 2018).

Thus, unlike the ultimate limits that are standardized based on effect on mechanical properties of glass, the serviceability limits may vary. This highlights the potential scope for a shift in serviceability limits. Thus, if permissible deflection of glass can be higher, it supports the potential reduction of glass thickness.

1.4 Problem Statement

Compared to use of recycled or reused glass, material efficiency as a strategy for reducing embodied carbon in façade can be more easily put into effect. However, material efficiency by means of reducing glass thickness will result in higher deformations in glass will have an effect on the performance of glazing such as durability, thermal, optical, acoustical performance. These effects can be quantified as a function of amount of deformation. Based on this information, acceptable thresholds as per these criteria can be arrived at, and serviceability limits on deformation can be set objectively.

However, occupant acceptance of deformation is subjective. The level of occupant acceptance has always been assumed to be low, but not measured. It can be assumed that like the objective criteria, occupant acceptance of deformation is also proportional to the magnitude and frequency of deformation in glass. The relationship between occupant acceptance and deformation of glass must be measured and acceptance thresholds should be determined so as to compared these with the acceptance thresholds as per objective criteria. Without the knowledge of limits based on occupant acceptance, the resultant deformation limit is biased towards objective criteria. Thus, the possibility of a shift in 'acceptable' serviceability limit remains unexplored. This gap in knowledge is the basis for the current research project.

1.5 Research proposal

1.5.1 Hypothesis

This thesis proposes an experimental method to measure occupant satisfaction towards glazing deformation based on the following hypothesis:

'The relationship between occupant satisfaction and level of deformation can be empirically measured based on which acceptance thresholds towards glazing deformation can be arrived at.'

In addition to this, the final experiment involving volunteers aims to validate the following hypothesis:

'Occupant acceptance threshold can be raised if the occupants have confidence in the strength of glass and prior knowledge about embodied carbon benefits of using thinner glass.'

1.5.2 Research Question

Based on the hypothesis, the following research question has been drawn out:

'How can we empirically determine the relationship between and occupant satisfaction and level of deformation in façade glazing?'

1.5.3 Design Question

The design objective of this research can be summarized using the following design question:

'What is a feasible method to empirically determine the relationship between and occupant satisfaction and level of deformation in façade glazing?'

1.5.4 Sub questions

The research question is broken down into the following sub-questions:

1. What are the factors influencing amount of deformation in façade glazing?
2. What are the effects of deformation of façade glazing on its performance?
3. What are all the serviceability criteria that govern the limits on façade deformation?
4. Which criteria and industry standards are followed in practice to determine the glass thickness and deflection limits?
5. What is a feasible method to empirically determine the relationship between and occupant satisfaction and level of deformation in façade glazing? (design question)
6. What is the level of occupant acceptance towards façade deformation under wind or climatic loads?

1.5.5 Research Approach

Each sub question is based on a different theme, and requires a different research method. Therefore, a mixed-method approach has been followed for this project. The methods followed for each sub-question are listed in Table 1. Questions 1 and 2 help us gather the background information on the subject. Questions 3 and 4 are about state-of-the-art knowledge on serviceability criteria and limits followed in practice. Question 5 prompts the development of a novel methodology for assessment of occupant acceptance and hence, is the design question. To answer question 6, an experiment based on the methodology developed by Question 5 needs to be used to arrive at acceptance thresholds.

Table 1: Research methods for sub-questions.

No.	Question	Method
1	What are the factors influencing amount of deformation in façade glazing?	Literature Review
2	What are the effects of deformation of façade glazing on its performance?	Literature Review
3	What are all the serviceability criteria that govern the limits on façade deformation?	Façade Industry Survey and Literature Review
4	Which criteria and industry standards are followed in practice to determine the glass thickness and deflection limits?	Façade Industry Survey and Literature Review
5	What is a feasible method to empirically determine the relationship between and occupant satisfaction and level of deformation in façade glazing?	Research Through Design
6	What is the level of occupant acceptance towards façade deformation under wind or climatic loads?	Experiment

1.5.6 Research Objective

As indicated previously, without any data on occupant acceptance thresholds, a comprehensive calculation of serviceability limits is not possible. The main objective of this research is the design of a method to measure this data in order to fill this knowledge gap. Analysis of the gathered data will lead to acceptable limits based on occupant satisfaction, which can be weighed against limits based on the objective criteria such as durability, thermal, optical and acoustic performance.

1.5.7 Scope and Limitations

The primary focus of this research is on the criteria of occupant acceptance of deformation. Information about deflection limits based on the objective criteria i.e. glazing performance and the methods for arriving at these limits has been discussed as part of literature review and façade industry survey. In terms of occupant acceptance, deformation due to wind loading and climate loading has been considered whereas the effect of impact and barrier loading is outside the current scope of research.

The experimental method is flexible and involves many independent and confounding variables. The main implication of the project is the role of prior knowledge among occupants about the material capacity of thinner glass and benefits it offers in terms of saving embodied carbon, on acceptance thresholds. Therefore, for the scope of this project, most variables other than prior knowledge have been fixed. The method thus can be used to test the implications of other variables in the future, such as variations in indoor environment quality, variations in activity or relative position of the volunteer with respect to the façade.

The occupant acceptance criteria includes 4 dependent variables – perception of safety, satisfaction with the quality of view, disturbance in activity and general acceptance of deformed glass. However, the same experimental setup can be used to measure more qualitative variables. The project excludes acceptance of deformation from exterior of the façade, which can also be tested in the future using the same experimental setup.

1.6 Outline of the report

This report presents the research and design outcomes of an 8 month long graduation thesis. The current chapter discusses the background research conducted to arrive at research objectives for the thesis. It also presents the research question, design question and the sub-questions with an outline of the research approach. As the next step in the research, a state-of-the-art review was conducted in two parts – literature review and façade industry survey. The systematic literature review was carried out, to understand existing limit state design criteria for glass, existing standards on determination of glass thickness and permissible deflections and the effects of excess deformation on the performance of glazing. The key findings from this review have been discussed in Chapter 2. It was anticipated that desktop research alone might not be sufficient for answering questions related to industry practices and standards. Hence, further information was gathered through a façade industry survey. The design of this survey, followed by quantitative and qualitative analysis of the results has been discussed in detail in Chapter 3.

The design of the proposed experiment has been presented in Chapter 4. The concept for the experiment has been discussed, followed by the process of identification of experiment variables. This is followed by detailed information on the design of the experiment with volunteers, the experimental setup (prototypes, electro-pneumatic systems, etc.), calculations for validations and feasibility tests conducted to validated the method. Towards the end of each of the Chapters 2, 3 and 4 a short discussion is provided, highlighting key observations and interpretations.

In Chapter 5, a discussion of the results from the entire research process, is provided. Here, the focus is on comprehensive understanding of serviceability criteria and the adaptation of the setup for a multi-criteria assessment. In Chapter 6, critical conclusions of the research project have been highlighted, and future research steps and improvements have been proposed. A reflection on the graduation process, impact of this research and personal reflection is presented in Chapter 7. In addition, 2 reflection questions have been developed and answered in this chapter. Finally, a list of references, schedule of figures and tables, and appendices have been provided, to support the data provided in this report.

2 Literature review

2.1 Literature review process

2.1.1 Introduction

The determination of optimum glass thickness for a glazing unit is a complex process, primarily governed by limit state design. For SLS, the deformation and vibrations in glass are of main concern, since these have an effect on the performance of glazing (e.g. durability of edge seal, thermal performance, etc.), as well as occupant satisfaction. The project aims to review the current glazing design practices and standards, and explore the impact of façade deformations on occupant acceptance. After a preliminary literature review on the context of the research question was conducted, the next step in this research was to conduct a systematic literature review to answer the following sub questions :

1. What are the factors influencing amount of deformation in façade glazing?
2. What are the effects of deformation of façade glazing on its performance?
3. What are all the serviceability criteria that govern the limits on façade deformation?
4. Which criteria and industry standards are followed in practice to determine the glass thickness and deflection limits?

This chapter highlights the key findings from the systematic literature review. Since literature review alone was not sufficient to provide information on sub questions 3 and 4, the answers to these are also discussed further in Chapter 3, Façade Industry Survey.

2.1.2 Methodology

For the systematic review, the databases Scopus and Web of Science were used. Relevant keywords were extracted from the research question and the sub-questions. Since glass deflection has an effect on performance of glazing, such as thermal, optical, structural, etc. a few more sets of relevant keywords were listed and grouped based on glazing properties. Thus, a series of separate search terms was generated and a preliminary search was conducted. However, it was anticipated that this methodology might exclude results that lie at the intersection of sub questions. Hence, a comprehensive search term was created using keywords from the preliminary search. Appendix 2 provides the table of keywords and the search terms used for finding relevant papers.

This two-step search process helped gather an extensive list of relevant papers, which was organized using EndNote, which is a reference managing software. Important notes from the literature were summarized using MS Excel in a data extraction sheet. Further, for a more detailed analysis, the references were linked to Atlas.ti, which is a software for coding (marking-up) and analyzing data. Thus, an interlinked framework was created using Excel, EndNote and Atlas.ti, which is flexible, so that new literature can be easily added in the due course of research. Table 2 summarizes the steps in management of found literature and the software used to do so.

Table 2: Steps in management of found literature and software used.

	Step 1	**Step 2**	**Step 3**
Steps in literature review	Structured listing and saving of papers, reports, websites, etc. for future citation	Preliminary analysis and categorization of literature	Reading papers and parallelly coding concepts for future co-occurrence analysis, code-document tables, etc.
Software used	**EndNote**	**MS Excel**	**Atlas.ti**
Reason	Helps in automating referencing and citation for reports in MS Word	Helps in quick note-taking and filtering of papers based on different categories	Helps in searching for similar concepts and identify patterns, missing links, etc.

The comprehensive search term led to listing of results, some of which were not closely related to the aim of the search. Such literature was eliminated by modifying the search term to exclude certain keywords (e.g. glass fiber reinforced polymers, rubbers, etc.). Further, literature older than the year 2000 was eliminated. In this case, only one paper by (Griffis, 1993) made an exception since human comfort criteria were well summarized in this. The literature thus found was ranked based on relevance and year of publishing – higher ranking for more relevant and more recent papers – which helped select the more usable literature. While scientific literature from various geographical locations was referred to, the reports, case studies and standards were restricted to those conducted in the EU and the UK. Standards from the EU, UK, USA and Hong Kong were also referred to understand serviceability criteria and methods of calculation.

2.1.3 Summary of Results

A total of 61 sources have been referred to in the course of the thesis. These can be broadly categorized into 2 main types – Background review and Main review. While the background review papers help in formulating a strong argument for the thesis topic and have been mainly discussed in the Introduction of this report, the main papers are referred to mainly to answer the sub-questions, as part of the systematic review.

These 61 sources have been assigned categories and sub-categories based on their relevance to a topic or sub-topic respectively. Figure 2 indicates the frequency distribution of literature referred based on these categories and sub-categories. A detailed list of these references can be found in Appendix 3.

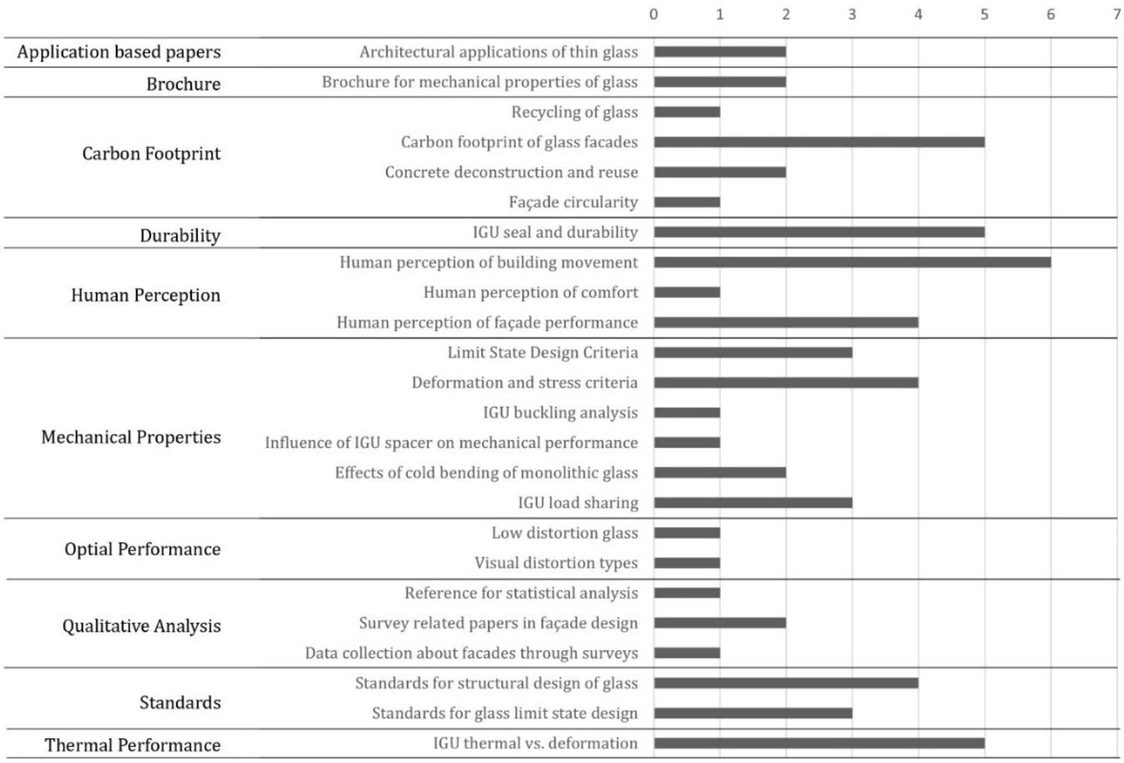

Figure 2: Bar Graph showing frequency distribution of categories and sub-categories of references.

As seen in Figure 2, for the main review, literature related to effects of deformation on Mechanical properties, Durability, Optical performance and Thermal Performance were found. In terms of effects of mechanical performance, literature was found pertaining to both, monolithic glass and insulated glazing units (IGU)s. The papers concerning IGUs were especially related to effects of glass deformation on sealant durability and thermal performance, while those concerning monolithic glass were primarily related to effect of deformation (bending) on mechanical performance of glass such as cold bending distortion and buckling. Further, there were sufficient papers related to load-sharing behavior of the glass panes and air cavities of IGUs.

Literature related to effects of deformation on Acoustical performance and Occupant Satisfaction were not found. Papers related to human perception of movement in buildings, comfort and façade performance were found, but there were no papers directly related to human perception of deformation in façade glazing. These have been referred to, to determine potential variables in the experimental setup.

For the background review, papers categorized as Application-based, Brochures, Carbon Footprint and Standards were used. The brochures were particularly helpful in terms of material properties and characteristics of thin glass and low carbon glass. Student theses from previous years gave an overview of the potential applications of thin glass in facades, the results, foreseen challenges and scope for further research. Standards were mainly referred to for basic definitions of limit states and to understand limits on glass deformation if specified.

For the design and analysis of Façade Industry Survey, papers categorized as Qualitative Analysis are used as a reference. In addition to these, lectures, reports from industry etc. were also referred to for specific sub-topics to broaden the understanding for background research. A visit to AGC Technovation Center in Belgium in October 2022 also helped gain further insight on state-of-the-art of the design and manufacturing of thin glass and vacuum insulated glazing units (VGUs). To understand the previous research on the subject, TU Delft Repository was also useful.

2.2 Factors influencing deformation of glazing

In this chapter, factors that have an influence on either magnitude or frequency of vibration in terms of façade glazing are discussed. Apart from external conditions like wind and climate loading, intrinsic properties of the glass panel, such as the rigidity and thickness of glass and the added stiffness due to spacers and sealants also influence glazing deformation. In addition, properties of the panel under consideration, such as aspect ratio and number of layers also influence the amount of deformation.

2.2.1 Wind and climate loading

For serviceability conditions, two main loading scenarios are considered, namely wind loading and climatic loading. Wind loading can cause either a positive or a negative pressure on the outer glass pane, depending on the wind direction with respect to the building. Wind loading is dynamic, which can be represented as variations in pressure induced on glass over time. Figure 3 shows a graph of wind pressure history converted from data from field measurements over a period of 1 hour (Zammit et al., 2008). Thus, deformations induced by wind loading are dynamic and govern the vibration frequency of glass.

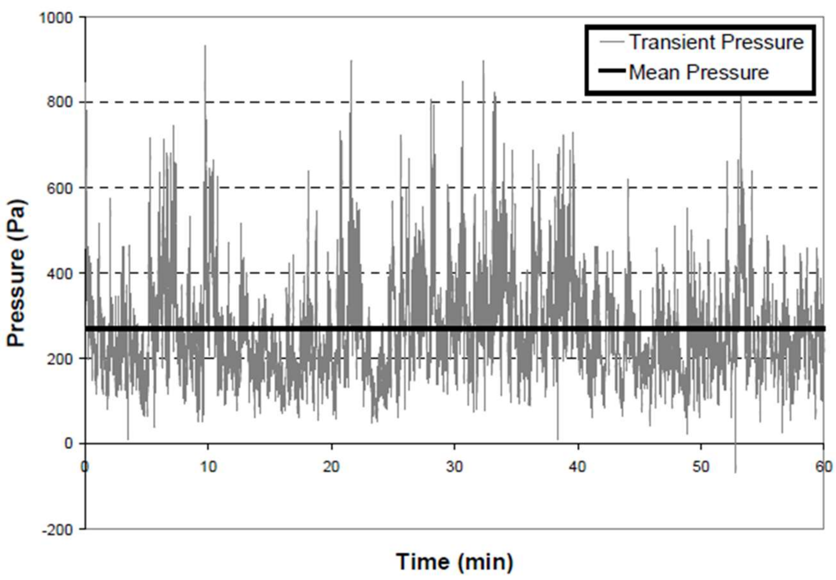

Figure 3: Wind pressure history based on field measurements conducted over a 1-hour period. (Source: Zammit et al., 2008)

Climatic loading is mainly a result of difference between air pressure and cavity pressure, and/or difference between air temperature and cavity temperature. As a response to change of air pressure (p) and/or temperature (T), the volume of the air cavity (v) changes as the panes tend to achieve a state of equilibrium, in accordance with the general gas equation :

$$\frac{p_0 v_0}{T_0} = \frac{p_1 v_1}{T_1} = \text{constant}$$

Since the edges of the panes are attached to the frame, change of volume implies change in width of air cavity. In case of a change in atmospheric pressure and homogenous change in gas temperature, the static values in glass increase roughly proportional to total increase in thickness of the gas cavity (Respondek, 2018). Thus, more the number of panes in glazing, the effect of climatic loads on deflection and stresses is higher.

From a serviceability perspective, deformations caused by both, wind and climatic loading need to be within limits. For the calculation of amount of deformation for given pressure and temperature variations, numerical and analytical methodologies are provided in research papers by (Galuppi & Royer-Carfagni, 2020; Heiskari et al., 2022; Stratiy, 2018) and experimental assessments have been discussed in a paper by (Bedon & Amadio, 2020).

2.2.2 Load sharing effect

Under the impact of external loading, the glass panes of an IGU mechanically interact with the hermetically sealed air cavity between them. External load acting on the surface of glass is distributed to all glass panes in the unit. The total of resultant loads on glass panes equals the external load. This phenomenon, known as load sharing effect implies that IGU behaves as a linear elastic system (Galuppi & Royer-Carfagni, 2020). Figure 4 shows a free body diagram of an IGU under wind load, deforming as an effect of load sharing (Heiskari et al., 2022).

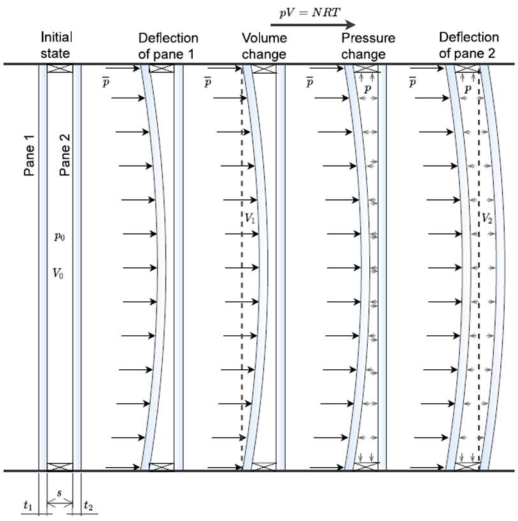

Figure 4: Free body diagram of an IGU under external load including the load sharing. (Source: Heiskari et.al., 2022, p. 4)

The load resistance of an IGU is a function of the load resistance of each lite of the IGU and the proportion of total load carried by each lite (McMahon et al., 2018). This proportion is a result of pressure variation in the interpane cavities as a result of the applied actions, and it depends on the flexural stiffness of the panes and the gas compressibility (Galuppi & Royer-Carfagni, 2020). There has been extensive research on load sharing effect in DGUs. (Galuppi & Royer-Carfagni, 2020) provide a universal method of calculating the pressure variations in interpane cavities and corresponding displacement field of glass panes, using Green's function. This method can be applied to IGUs of arbitrary geometry, various boundary conditions, various number of panes entrapping a perfect gas.

Further, (McMahon et al., 2018) present data from experimental analysis of different configurations of IGUs that address the effect of glass pane thicknesses, load orientation and aspect ratios. This helps validate the numerical and analytical research conducted in other literature. The impact of load sharing on deflection can also lead to interesting conclusions related to glass thicknesses. Typically, decisions related to glass thicknesses are rule-based. However, if the load sharing effect is considered, it may lead to a reduction in glass thicknesses of around 26-54%, according to numerical analysis conducted by (Heiskari et al., 2022).

2.2.3 Thickness and rigidity of glass

The amount of deflection in glass is inversely proportional to its rigidity, and the glass thickness (Respondek, 2018). This may limit the possibility of use of thinner glass in facades. However, the rigidity can be increased by lamination, and also change in aspect ratio. Further, the load sharing effect also helps reduce deflections. (Respondek, 2018) observes the effect of thicknesses on deformation under wind and climatic loading. Under wind loading, the load sharing effect impacts the deflections on glass, and thus, even if thinner glass is used in an IGU, their deflection is reduced, compared to effect on a single pane under the same loading.

Under climatic loads, as a result of change of temperature and/or air pressure, the glass panes would deflect as the cavity tends to achieve a state of equilibrium through expansion or contraction of its volume. In such cases, if the external glass is thicker, and more rigid than internal panes, the internal panes show higher deflections. However, it was found that with modification of a glass pane thickness d from 4 mm to 2 mm in a quadruple-glazed unit, the increase of deflection w is very slight (from 1.17 to 1.23mm), yet the decrease of stress σ is significant (from 2.72 to 1.42kPa). This has been presented in Table 3. This is because change of volume of the cavity equalizes the change in pressure to a greater extent, and the resultant load decreases.

Table 3: Effect of reduction of glass thickness on deflection and stresses as tested by Respondek, 2018.

Glass thickness in quadruple glazing	Deflection	Stress
4mm	1.17 mm	2.72 kPa
2mm	1.23 mm	1.42 kPa

2.2.4 Spacers and sealants

Most numerical assessments to measure the impact of load sharing in an IGU assume the spacer stiffness to be infinite. However, it has been proved by (Bedon & Amadio, 2020) that different spacer bars and primary and secondary sealants also have an influence on the gross response of the IGU. Shear tests on small IGUs and four-point bending tests were carried out. One of the important outcomes of the tests was that silicone layers improve the load bearing performance of IGUs, showing around 23% improvement increase in ultimate load and around 15% increase in bending stiffness. However, it also showed a progressive stiffness degradation as a result of increase in imposed loads. Although the tests had limitations of a finite amount of IGUs of reduced sizes, it can be assumed that spacers and silicone sealants can help improve the overall bending stiffness of and IGU, thus reducing deformation.

2.2.5 Aspect ratio

According to (Quaglini et al., 2020), vertically installed rectangular plates can accommodate larger deflections as compared to square plates, and thus, larger curvatures, while staying within the limits of distortion amplitude and maximum tensile stress in glass. According to (Datsiou & Overend, 2016), for rectangular plates, with higher aspect ratios, if the thickness of the glass increases, it displays larger distortions. It can be inferred that in case of cold bending of monolithic glass plates, which may be representative of glass behavior under imposed loading, thinner glass would deform more, yet the stresses and optical distortion will be within limits.

In the case of IGUs, although specific literature that relates the aspect ratio with displacements was not found, the paper by (Galuppi & Royer-Carfagni, 2020) provides expressions that, for any shape, type of loading and edge-constraint of the IGU, show a relation between the implied loads, pressure variations and displacement of glass panes.

2.3 Effects of glass deformation on glazing performance

2.3.1 Mechanical behavior

Stress

Deflections in glass as a result of actions, correlate to the stresses induced in glass. A common method of calculating the stresses and deflections in plates subjected to forces and moments is by using the Kirchhoff-Love plate theory (Galuppi & Royer-Carfagni, 2020; Heiskari et al., 2022). Increasing deflection shows a corresponding increase in the maximum stresses (Respondek et al., 2022). However, for IGUs, a detailed numerical analysis is required to include the load sharing effects. Further, the shape and aspect ratio of the glazing may also have an effect on the stress state in glass. (Respondek et al., 2022) compare the effect of the shape of glass in their paper using FE modelling and numerical analysis.

Deformation and stresses are also related through the thickness of the glass pane. For higher thicknesses in the external pane of an IGU, higher stresses were found as compared to thinner glass panes (Respondek, 2018). There is a critical value of thickness with the highest values of stress in component glass panes, under the influence of change of atmospheric pressure. This means at a critical thickness, the pane may be subject to higher stresses, and both, lowering and increasing the thickness after this point will result in lower stresses in glass.

Buckling performance

For single glass members, or monolithic panes, buckling analysis can be rationally carried out under several boundary conditions, and based on analytical formulations and standardized approaches from literature (Bedon & Amadio, 2018). Effects of cold bending on mechanical performance of monolithic glass have been presented in (Datsiou & Overend, 2016; Quaglini et al., 2020).

The two important effects of cold bending have been observed in these papers, namely, a. the change in deformation mode, i.e. change from hyper-paraboloid form to a synclastic form and b. cold-bending distortion, or a local instability that appears on curved plates once certain deflection limits are exceeded. The former effect might mean thinner glass when curved beyond a limit would tend to snap into a changed form, and might break, and the use of more rigid clamps may shift the snap-though limit above safe levels (Quaglini et al., 2020). The authors further suggest that bending the glass plates beyond their buckling limit (δb*) into an asymmetric, approximately hyper paraboloid geometry may increase the stability against wind-induced buckling.

For IGUs, characterized by load sharing effects, specific studies and methods are required to assess their buckling performance. (Bedon & Amadio, 2018) studied buckling performance of 2-side supported IGU using a refined FE model. It was found that the buckling of IGUs was in close correlation with composite columns, and thus the gas seems to have negligible effect in this. Lower glass thicknesses and high sensitivity to geometrical imperfections would lead to a reduced buckling resistance in IGUs.

2.3.2 Durability of IGUs

As long as the stress values as a result of excessive deformation are within ultimate limits, the glass is safe from breakage. However, this does not mean that deformation within ULS limits has no effect on the life of glazing. Durability is an important serviceability requirement. Excessive deformation in glass may lead to straining of the sealants, which may lead to deterioration of the sealed air cavity.

(Besserud et al., 2012) demonstrate a methodology to test the durability of IGUs bent out of plane, using full scale samples of a curtainwall (bent at 50mm intervals, up to 200m), several smaller samples of IGU and finite element modelling. The full scale samples was used to validate the findings from a corresponding finite element model. In the small units, the strains recorded from the full scale and finite element bending tests were implied by using clamps, and then these were subjected to weathering in the laboratory and tested using frost point test and argon retention test. The test were conducted as per ASTM standards. It was found that the samples passed both tests and that cold bending feasibility can be achieved given sufficient sealant quality is maintained.

Further, (Starman et al., 2020) provide an analytical expression for a strain field estimation for different deformation modes which helps to identify the critical location of primary sealants in their paper. Using this methodology, feasibility of a six-pane IGU has been evaluated. To validate the results, a standard DGU was used as a reference, since there are no standards available to compare to. The primary sealant strains in both cases were compared, and feasibility of the six-pane IGU was validated.

2.3.3 Thermal performance of IGUs

To evaluate the impact of glass pane deformation on the thermal performance of IGUs, (Hart et al., 2012) conducted a field study at 4 different locations in the US, in summer and winter conditions. In the study, the size of glazing, thickness of glazing, gap widths at ends and center of panes, temperature at ends and centers of panes and gas fill percentage were measured and analyzed. It was found that units which had smaller than optimal gap widths exhibited significant U-value change due to temperature induced reduction in gap width. The effect was higher in high-performance triple glazing units.

According to calculations, a 12mm gap seems optimum (Hart et al., 2012; Respondek, 2018). If the gap reduced below this, the U-value increase seems to be compounding, and if the gap increases, the U-value increase seems to increase linearly. A 20ºC temperature difference indicates a U-value change of 4.6% (Hart et al., 2012). The authors suggest that IGUs should be designed with a gap wide enough to mitigate variations in U-value. (Respondek, 2020) observes that effect of wind loading on gap thickness change in negligible in the context of heat lost estimation.

2.3.4 Optical performance of glazing

Although literature specific to the effects of deformation of glazing on the optical performance was not found, several papers that assessed the mechanical behavior of glass un

der bending have shown impacts on optical performance. (Datsiou & Overend, 2016; Quaglini et al., 2020) indicate optical distortions as one of the main effects of cold bending of monolithic glass plates beyond their buckling limits. In 4 point bending tests, deformation of glass beyond the buckling limits causes one of the diagonals to become stiffer causing optical distortions, assessed by (Datsiou & Overend, 2016) using a zebra-board. The amplitude of the cold bending distortion can be used to evaluate the optical quality of the curved glass plate as recommended in EN 12150-1:2000, which limits the amplitude of roller wave distortions in fully toughened glass to 0.5 mm over a length of 300 mm. This limit has been considered as an acceptance limit as per the aforementioned authors.

2.4 Assessment methods for effects of deformation on glazing

Based on the factors influenced by glazing deflection, criteria for serviceability can be identified, namely mechanical performance, durability, thermal performance, optical performance, acoustic performance and occupant satisfaction. These have been listed in the second column of Table 4. The first 5 criteria can be assessed on the basis of measurable properties, termed as performance indicators. These have been listed in the third column. For occupant satisfaction, a measurable property has not yet been defined, specifically pertaining to glazing deflection.

Table 4: List of serviceability criteria for glass deflection.

No.	Criteria	Performance indicators	Assessment methods as per literature review	Alternative Assessment Methods
1	Mechanical performance	Stress and strain states	Numerical and analytical methods and lab testing	Not required
2	Durability	Edge strain in glass, strain capacity of sealant	Numerical and analytical methods and lab testing	Not required

3	Thermal performance	U-value of glazing	Numerical and analytical methods and field measurement	Not required
4	Optical performance	Level of distortion of view or reflected image	Zebra-board testing (not sufficient)	Field testing, high precision optical simulations
5	Acoustic performance	R-value	Not found	Field testing, Lab testing
6	Occupant satisfaction	Not defined	Not found	Empirical assessment through experiment

It is important to note that the mechanical performance limits of serviceability are different from the ultimate limits. These correspond to effects such as cold bending distortions and buckling, which are caused by stresses well within ultimate limit states. Further, based on the findings from literature review, the methods of assessment for each of the factors have been listed in the fourth column. It was found from the literature review that for assessment of mechanical performance, durability and thermal performance, there are sufficient numerical and analytical methods as well as lab tests to determine limits on deflection. The critical performance indicators for each of these are well defined. These are stress and strain states, edge strain and U-value, respectively. Thus, it can be assumed that for scenarios in which glass thickness is reduced, there is an existing scientific framework of assessment of deflection limits.

For optical performance, level of distortion could be a performance indicator (Datsiou & Overend, 2016). However, limited information was found for assessment of level of distortions. As the optical performance is concerned with distortion of view through the glass, or distortion of the image reflected by the glass, limits can be set through field testing, specifically on the site of application. If that is inconvenient, a high precision optical simulation may be required. Numerical and analytical assessment can be performed for optical testing, but these fall beyond the scope of current research.

For acoustic performance, a critical indicator would be sound insulation, measured using the R-value. Similar to optical performance, for acoustic performance, field testing can be performed, along with lab testing using deflected samples. Even though there is no literature specific to this subject, there is enough theoretical knowledge on which these assessments can be based. However, given the nature of deflection, these might have to be specifically adapted.

Occupant satisfaction as a criteria for glazing serviceability has not been addressed specifically in the found literature. Often, acceptance is stated as a criteria for defining serviceability limits on deflections and vibrations in structural members. The building codes often mention limits on deflections, but are not clear on the research on which these are based. Thus, there seems to be a gap in research on the measure of occupant satisfaction as well as assessment methods for the same. This requires a specific definition of occupant satisfaction as a criteria for serviceability.

2.5 Standards for determination of glass thickness and deflection limits

This chapter discusses the findings from the literature review on the determination of glass thickness, determination of deflection and the limits on deflection. More information about the standards and practices followed in the industry was collected from the Façade Industry Survey, discussed in Chapter 3.

2.5.1 Determination of glass thickness

The process of determination of glass thickness is not explicitly mentioned in the FprCEN/TS 19100. It was found that the Code of Practice for Structural Use of Glass by the (Buildings Department Hong Kong, 2018) specifies expressions (Equation 1 and Equation 2) to be used for designing thickness of glass. Here, it is stated that for a glass pane simple supported on four sides with aspect ratio (b/a) less than 5, the minimum required glass thickness should not be less than the minimum of the following 2 expressions :

$$t_1 = 4.87a^{0.965}b^{0.22}\left(\frac{R}{c}\right)^{0.545}$$

$$t_2 = 2.33(ab)^{0.665}\left(\frac{R}{c}\right)^{0.87} - 1.62\left(\frac{a}{b}\right) + 1.2$$

Equation 1: Expression for determination of glass thickness for aspect ratio (b/a) < 5, as per the Hong Kong Building Code.

If the aspect ratio (b/a) is greater than 5, the minimum thickness is given by :

$$t_3 = 6.2a^{1.15}\left(\frac{R}{c}\right)^{0.5}$$

Equation 2: Expression for determination of glass thickness for aspect ratio (b/a) > 5, as per the Hong Kong Building Code.

Where,

a Length of shorter side of glass pane (m)

b Length of longer side of glass pane (m)

R Factored design pressure on individual glass pane (kPa) = γ_f X design pressure

c Strength coefficient ($c = c_1 \times \gamma_d \times \gamma_s$)

in which

c_1 Glass type (Heat treatment)

= 1.0 for annealed glass

= 2.0 for heat strengthened glass

= 4.0 for tempered glass

γ_d Load duration factor

γ_s Glass surface treatment reduction factor

The design of glass pane thickness depends not only on the dimensions of the glass pane, the aspect ratio, factored design pressure and load duration, but also on properties of glass to be used i.e. type of glass (annealed, heat strengthened or tempered) and the surface treatment on glass.

2.5.2 Determination of deflection of glass pane

Deflections of glass panes can be calculated for a specific application using finite element method (FEM) calculations. However, building codes also provide simplified expressions that determine deflections under design pressure for glass, directly related to the dimensions of glass, type of glass and applied pressure. Two such expressions are given in the Code of Practice for Structural Use of Glass 2018 by the of Buildings Department Hong Kong, as shown in Equation 3. These are in line with those provided by (ASTM International, 2016).

Four-side simply supported: $\delta = t\, e^{r_0 + r_1 x + r_2 x^2}$

In which $x = \ln\left[\ln \frac{p(ab)^2}{Et^4}\right]$

Two-side simply supported: $\delta = \frac{5pa^4}{32Et^3}$

Where

δ = Center deflection (mm)

a = Length of shorter side of glass pane (mm) or loaded span in two-side simply supported case (mm)

b = Length of longer side of glass pane (mm)

t = Minimum glass pane thickness (mm)

p = Design pressure on individual glass pane (kPa)

E = modulus of elasticity of glass = 70 x 10^6 (kPa)

$$r_0 = 0.553 - 3.83\left(\frac{b}{a}\right) + 1.11\left(\frac{b}{a}\right)^2 - 0.0969\left(\frac{b}{a}\right)^3$$

$$r_1 = -2.29 - 5.83\left(\frac{b}{a}\right) - 2.17\left(\frac{b}{a}\right)^2 + 0.2067\left(\frac{b}{a}\right)^3$$

$$r_2 = 1.485 - 1.908\left(\frac{b}{a}\right) + 0.815\left(\frac{b}{a}\right)^2 - 0.0822\left(\frac{b}{a}\right)^3$$

Equation 3: Expressions for determination of glass deflection. (Source: Buildings Department, Hong Kong, 2018)

This establishes the fact that determination of glass deflections are fairly standardized, and these depend on the dimensions of the glass pane, thickness of the glass pane, modulus of elasticity of glass and the design pressure on individual glass pane.

2.5.3 Deformation limits as per standards

Table 5 lists down the deformation classes for different levels of criticality, given in FprCEN/TS 19100-2. For Deformation Class 1 - SLS, it does not specify any measures, as the deflections do not seem to have any detrimental effects. For deformation class 2 - SLS, the deflection limits have been provided (Table 6), for different applications, such as floors, railings and facades, along with the boundary conditions. Specifically for IGUs, continuously supported on all edges, the limit at the center is L/50, where L is the length of the short edge. For IGUs supported along 2 or 3 edges, or those that are point fixed, the limit is even more stringent, i.e. L/150, where L is the length of the unsupported edge. (European Committee for Standardization, 2021b) Further, for deflection class 3 – ULS, the code specifies minimum nominal mechanical edge cover depths for different applications, accounting for the glass chord shortening. Chord shortening is difference of the length of chord (linear distance between the two ends of an arc) of bent glass component compared to original length of the glass component.

Table 5: Deformation classes for different levels of criticality. (Source: FprCEN/TS 19100-1:2021)

Deformation class [a]	Load combination acc. to EN 1990	Description	Example
1-SLS	Frequent	Deflections or displacements of pure aesthetical relevance	Sagging of canopies but drainage is ensured, pillowing of IGUs without detrimental effects on the edge sealing, etc.
2-SLS	Characteristic	Deflections or displacements affecting integrity, functionality or durability of the glass component in the unfractured state	Ponding and stagnation of water, deflection effects of IGUs with loss of airtightness with edge seal damage, deflection combined with interlayer overstressing, deflections of glass floors obstructing walkability, etc.
3-ULS	Fundamental	Deflections or displacements or effects thereof affecting safety	Glass floor or parapet slipping off supports, deflection leading to contact with hard material, etc.
[a] See Part 2 of this TS for specific rules on deformation classes.			

Table 6: Deflection limits for glass components of deformation class 2 for SLS. (Source: FprCEN/TS 19100-2)

	Support condition	Deflection limit of the support of the edges	Deflection limit at a free edge	Deflection limit at centre
Glass component	Continuously supported along all edges	according to EN 13830:2015+A1:2020, 5.7		L/50[a]
	Continuously supported along 2 or 3 edges	according to EN 13830:2015+A1:2020, 5.7	L/100[c]	
	Locally clamped along 2 or 3 edges	L/150[b]	L/100[c]	L/50[a]
	Point-fixed		L/100[c, d]	L/50[a, d]
Floor	Continuously supported along all edges			L/200, any protective upper ply should not be taken into account for deflection calculation[a]
Floor or Stair tread	Continuously supported along 2 edges			L/200, any protective upper ply should not be taken into account for deflection calculation[a]
Balustrade	Clamped at lower edge		Deflection should not open a gap wider than 50 mm between two adjacent elements at 1 m above finished floor level	
IGU	Continuously supported along all edges	according to EN 13830:2015+A1:2020, 5.7		L/50[a]
	Continuously supported along 2 or 3 edges	according to EN 13830:2015+A1:2020, 5.7	L/150[c]	
	Point-fixed		L/150[c]	

[a] L is the length of the short edge.
[b] L is the distance between two point-fixings.
[c] L is the length of the unsupported edge.
[d] Either the deflection limit of l/100 at the edge or l/50 in the centre should be applied, not together. The decision whether to apply one or the other limit depends on the individual case.

(Buildings Department Hong Kong, 2018) also provides simplified standards for deflection limits for glass panes. These depend on the spans, loading condition and support condition and are based on the expressions in Table 7. For glass panes simply supported on 3 or 4 sides, compared to the limits given in FprCEN/TS 19100-2, this code allow slightly lower levels of deflections, but of the same order. This code, however, does not specify limits for IGUs separately.

Table 7: Deflection limits of glass panes as specified. (Source: Code of Practice for Structural Use of Glass, Buildings Department, Hong Kong, 2018, p. 19, 20)

Case	Deflection limit
Four side simply supported	1/60 of short span
Three-side simply supported	Min [b/60, a/30]
Two-side simply supported	1/60 of the loaded span
Cantilever	1/30 of the span
Point Supported	1/60 of the longer span between supports

2.6 Discussion

From the review, it was observed that glass thickness alone is not the governing factor to determine the amount of deflection in glass. Apart from thickness, deflection also depends on loading conditions, aspect ratios, size of glass panels, number of panes of glass, lamination and the stiffness of spacers and sealants. This implies that if we were to reduce glass thickness, there are other factors which may be manipulated to maintain the level of performance of glazing. This finding is fundamental to the argument in favor of a transition towards use of thinner glass for facades.

The current standards do not consider limits based on combinations of criteria and promote design for a few worst case scenarios. There is substantial variation in standards from different countries for glass structural design. These standards also allow certain case-specific exceptions, making some standards more stringent than others. Most standards provide simplified expressions for determination of deflections and limits. The standards also consider factored values for loading, which are generalized into a small number of categories and leave no room for efficiency in design. Standardized limits on deflection are restrictive in nature and may not consider possible scenarios where the use of thinner glass is possible.

The literature review was important to highlight gaps in research related to serviceability criteria. The review helped understand the available assessment methods for determination of limits on glazing deformation with respect to mechanical performance, durability, thermal performance and, to some extent, optical performance. However, as anticipated, sufficient data related to effects of deformation on factors such as human-comfort, aesthetics, occupant satisfaction etc. was not found during the search. Additionally, the numerical and analytical methods to measure effects of deformation on durability of IGUs, thermal performance and optical performance are independent of each other and exclusive. Therefore, a comprehensive assessment of effect of deformation on more than one performance criteria cannot be performed using these methods.

Deformation in glass is mainly characterized by nature of loading, and is thus, time-dependent. Since deformations resulting from climatic loading rely on pressure and temperature changes, these deformations are slower in time and remain for a longer period in glass as compared to effects of wind. This time dependency also indicates that the effect of climatic loading on thermal performance could be higher than that of wind loads. In terms of occupant acceptance, time-dependency is an important factor to be assessed. Since wind loading is temporary as compared to climatic loading, optical performance and consequently occupant satisfaction may be more affected by climatic loading as compared to wind loading. Further, wind loading may cause fatigue to the sealants, which may deteriorate the sealants more than the effects of climate loading, thus, having a higher impact on durability than climate loading.

The subject of serviceability limits in glass is vast and complex, especially because of the multiple roles a façade glazing system plays in today's built environment. To arrive at favorable limits which balance both, reduction in embodied carbon and high serviceability demands is a challenge which demands dedicated multi-dimensional research. Therefore, it is worthwhile to explore a potential singular method for assessment of effects of deformation on combination of performance criteria under different loading conditions. A comprehensive understanding of effects of deformation under different loading conditions is required to arrive at realistic serviceability limits on deflection which will thus inform efficiency in glass thickness.

3 Façade Industry Survey

3.1 Introduction

3.1.1 Learnings from the literature review

The literature review was found to be insufficient in gathering data on the state-of-the-art on serviceability limits followed and criteria considered for setting these limits. The literature review had already pointed out the factors affecting glass deformation and effects of deformation on glass performance. It also provided the information available in standards which serves as the basis for recommendation of glass thicknesses and serviceability limits on deflections.

However, it was noticed that the standards varied from country to country, and a clear explanation for the limits based on which serviceability criteria these were linked to was not found. It was not clear from the literature review what the decision making process is, for specifying glass thicknesses for facades. Since there is little effective guidance for design of glazing systems using a standardized approach, it is anticipated that different engineers follow different standards (Coult & Overend, 2022). A clear knowledge gap in terms of occupant acceptance of deformations was evident from the literature review. These missing links in information reinforced the need for a survey of the designers and engineers involved in the process of design of façade glazing.

3.1.2 Survey Objectives

The purpose of the survey is to understand what standards and practices are followed in the industry when specifying glass thickness. It is anticipated that the priorities towards several serviceability criteria may vary based on the specific requirements of the project. For instance, durability of the IGUs might be of a higher priority compared to the optical performance of the IGU under deformation. Moreover, the survey is an important step in research to reinforce the existence of the knowledge gap with respect to serviceability. The survey exercise was thus conducted in parallel with the literature review.

The main expectations from the survey responses are: information about current practices, relative weightage given to different serviceability criteria, level of consideration of human-centered criteria and perceived impacts of reduction of glass thickness in facades. The survey was successful in meeting the objectives and even gathering more information to support the findings of the literature review.

3.1.3 Hypothesis

The survey intends to validate the hypothesis that was based on the findings of the literature review:

“Variation and inconsistency in serviceability limits on glazing deformation and methods to determine these limits act as barriers for material efficient design of façade glazing.”

3.1.4 Survey design

Stakeholder Identification

It was decided to circulate the survey amongst the main actors in decision making process of façade design, namely, Facade Consultants, Facade Contractors, Glass Manufacturers, Sealant Manufacturers, Architects and Researchers. The respondents were identified through professional channels by researchers and a consolidated list with over 200 respondents was be prepared.

Survey format

The survey was in an online format and was created using Qualtrics. It consists of a combination of multiple choice and free-text questions. The list of questions their format and choices is given in Appendix 6. The survey was divided into 6 main sections, namely, personal information, embodied carbon in glass facades, serviceability limits of glass, technical criteria for serviceability, human-centered criteria for serviceability, and awareness about thin glass. This division helped the structure and sequence of the questions. This will also help in the process of analysis of the responses.

The questions were worded as concisely as possible, trying not to be open-ended. Most questions had multiple choices, while some were descriptive, with text boxes for filling out responses. For questions where relationships between the options was expected, suitable slider scales have been provided. All the scaled in the survey range from 1 to 5. This was done to keep the answering process easy, and also to compare responses to various questions on the same level.

The survey was tested internally with colleagues and improved before sending. It was ensured that the survey must not take more than 10 minutes to answer, since the length of the survey has an effect on the quality of responses.

The survey format was designed in line with TU Delft's Human Research Ethics Committee (HREC) norms and an approval from the HREC was received before circulating the survey. At the start of the survey, a Participant Information Sheet was provided, which explained the project in brief and the purpose of the survey. It was explained how the personal information collected during the survey would be handled to safeguard the respondent's privacy.

3.1.5 Scope of the survey and limitations

The survey was aimed at getting a complete picture of the decision making process, the barriers, needs and opportunities for a material efficient design approach for façade glazing. Guidance and recommendations were also received as a part of the responses, but were not the main purpose of the survey. The survey questions were restricted to asking about reducing the thickness of glass, and not about specification of 'thin glass' or 'ultra-thin glass'. The questions were linked to the serviceability limit state design criteria, and did not concern the ultimate, fracture or post-fracture behavior of thinner glass.

In the future, interviews with specific respondents are proposed to be conducted. The purpose of the interviews would be to dive deeper into specific questions related to serviceability concerning their field of expertise. However, given the time constraints of the thesis, the interview stage was not carried out.

3.1.6 Data retrieval and analysis

Survey was circulated on March 6th, 2023 to more than 200 professionals from the 6 identified types of organizations. The list of professionals was compiled from professional network of the authors. The survey link was shared via email, and it was active for 1 month. In this time period, 75 responses were received, out of which 8 responses were considered unusable, since these had only answered the introductory questions. The remaining 67 responses were considered fit for analysis. Out of these, 54 respondents have completed the survey fully while the remaining 13 (19.4%) respondents have answered between 48% and 78% of the questions.

Initial survey analysis of the first 48 responses was conducted to set up the workflow of analysis and get preliminary results. The data retrieved from Qualtrics in .csv format was cleaned up in MS Excel. This file was then linked to a Python script developed for the analysis. The responses received were of both, numerical and textual types. A Python script was developed using Jupyter notebook for the numerical results to be plotted as bar charts, box plots, data frames and lists.

Textual responses were categorized into 2 sub-categories: 'list' and 'descriptive' types. The list type of responses refer to questions regarding which criteria is considered in practice, which optical defects are taken into account and which optical defects are a result of excess deflection of glass. The responses to these questions were manually filtered into lists of mutually exclusive terms. The frequencies of these terms (criteria, optical defects etc.) were then plotted as graphs. The descriptive responses refer to questions such as which information would be required to help specify thinner glass, and why would the respondent recommend or not recommend use of thinner glass in facades. For these responses, the method followed has been detailed in Chapter 3.4.5.

3.2 Respondents' Background

Figure 5 indicates the distribution of organizations that the respondents work at, their roles in these companies and the maximum level of education they have completed. 31 (46.2%) respondents work at Facade Consultancy company, and 14 (20.8%) work at a Glass Manufacturing company and 10 (14.9%) work at a Façade Contractor company. There were also 7 respondents that indicated their organizations as Material Supplier (interlayers), Main Contractor (3), Engineering Consultancy, Specialist consultancy for abnormal loads on structures and General Contractor. More than 50% of the respondents are either Consultants or Engineers in their professional role, and more than 90% of the respondents have at least completed a Bachelors' degree.

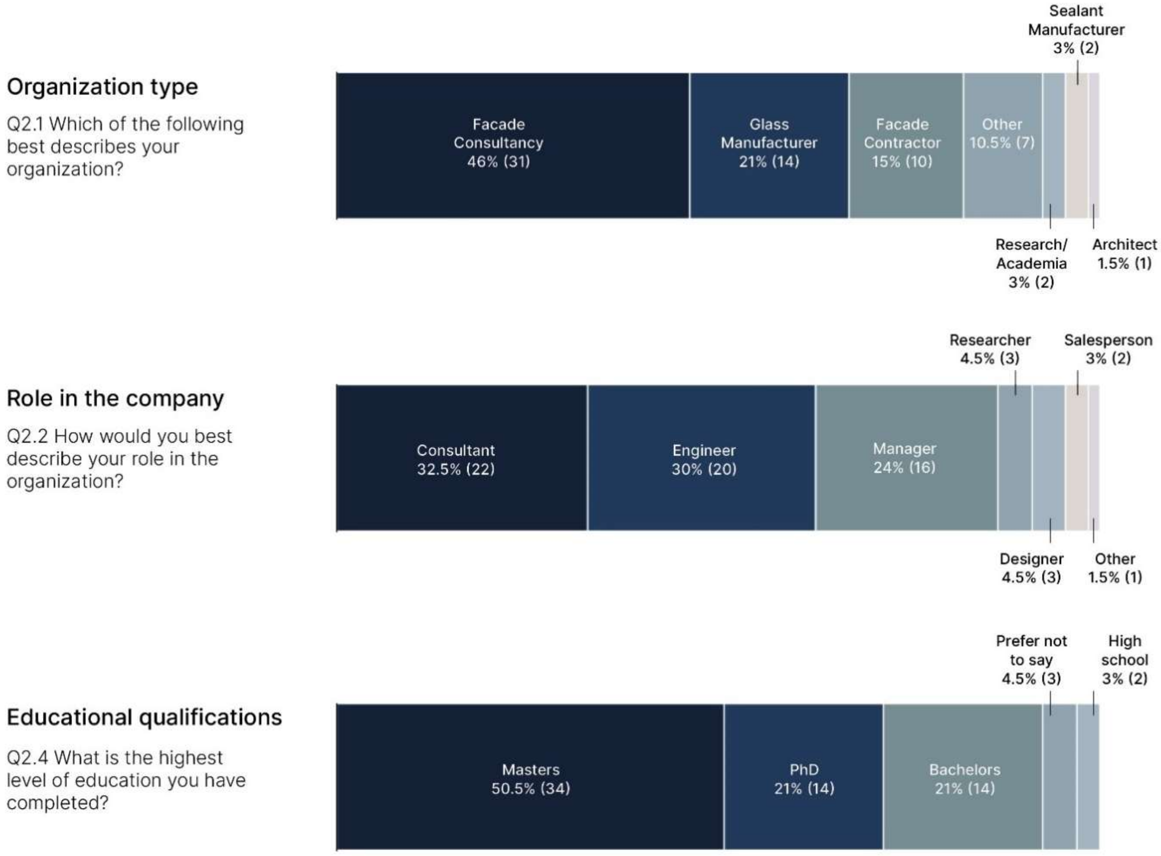

Figure 5: Respondents' Background (a) the type of organization they work at (b) their role in their organization and (c) highest level of education they have completed.

Figure 6 indicates countries where the respondents are based out of. 39 (59%) respondents are based out of the UK, 7 (10.5%) out of Netherlands, 5 (7.5%) out of Germany, 3 (4.5%) from Belgium and France each, 2 (3%) from Spain and USA each and the rest are located in Switzerland, UAE, India, Italy and Lithuania each. Since there are many Façade Consultancy companies in the UK, this distribution seems fair as per expectations.

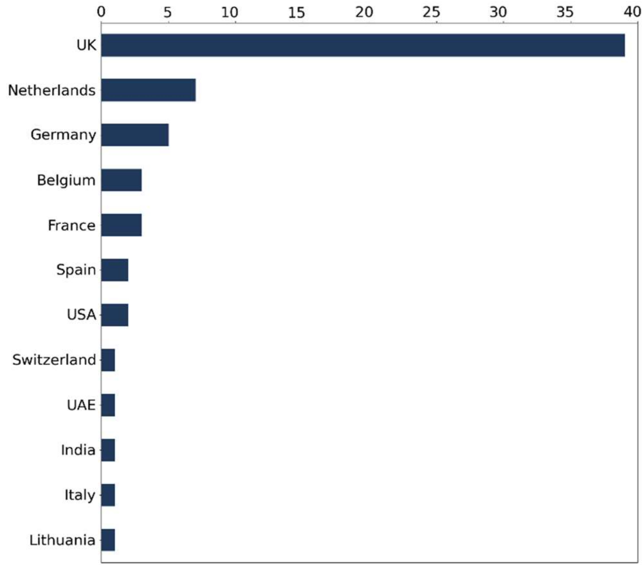

Figure 6: Bar graph showing countries where the respondents are located.

Figure 7 indicates the countries where main projects that the respondents work on, are located. This data helps us understanding which regions do the responses relate most to, and which local regulations are being referred to in the survey. Since most of the survey respondents are from Façade Consultancy offices based in the UK, UK was the most indicated country 52 (38.5%) times, followed by USA 13 (10%) and France 10 (7.4%) times. Netherlands, Germany and Italy were indicated 7 (5%) times each. Other countries listed are located in Europe, Asia, Middle East and South America.

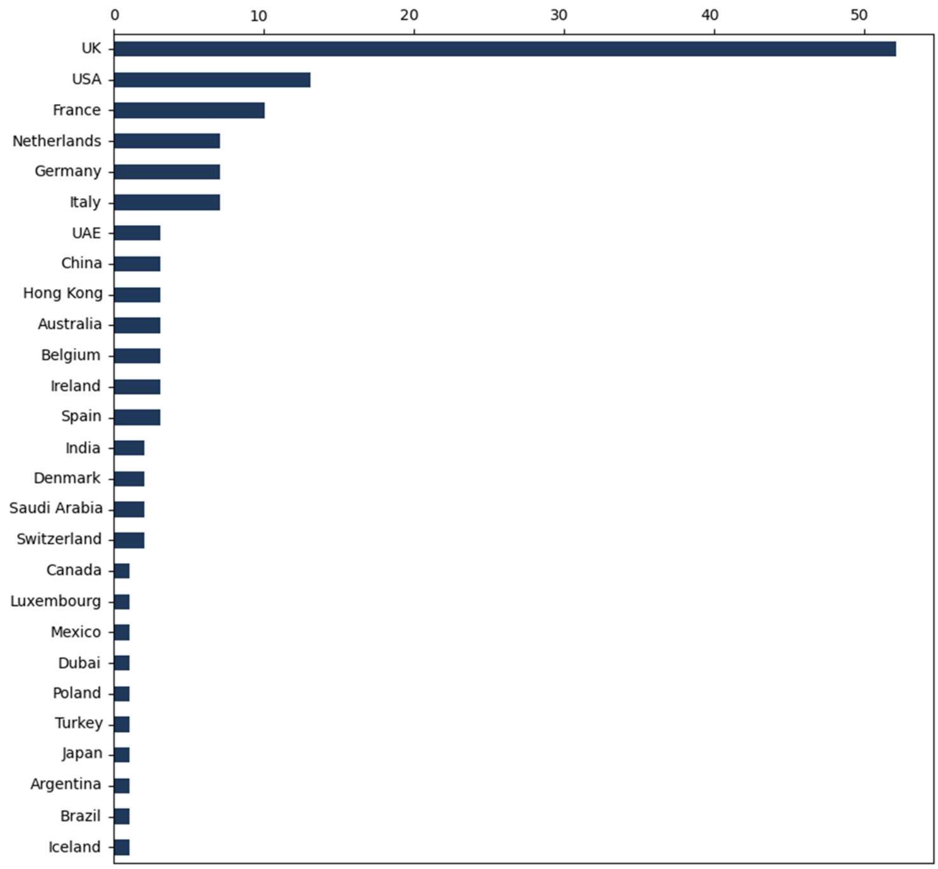

Figure 7: Bar graph showing the location of main projects that respondents work on.

The respondents were also asked to indicate to what extent environmental impact is a governing factor in the projects they work on. As shown in 13 (19%) of the respondents indicated it to be 'very high', 24 (36%) indicated it to be 'high' and 22 (33%) indicated it to be 'medium'. The respondents were also asked to indicate the level of knowledge they have about serviceability limits of glass in facades. 33 (49%) respondents indicated 'high' and 27 (40%) respondents indicated their knowledge to be 'moderate' while the remaining 7 (10%) rated their knowledge as 'low'. They were also asked whether they have to satisfy serviceability limits in their professional role, to which 53 (79%) respondents answered 'yes' and the remaining 14 (21%) indicated 'no'. The respondents who answered 'yes' were asked what are all the serviceability criteria that they would design for. The responses are discussed in Chapter 3.4.1.

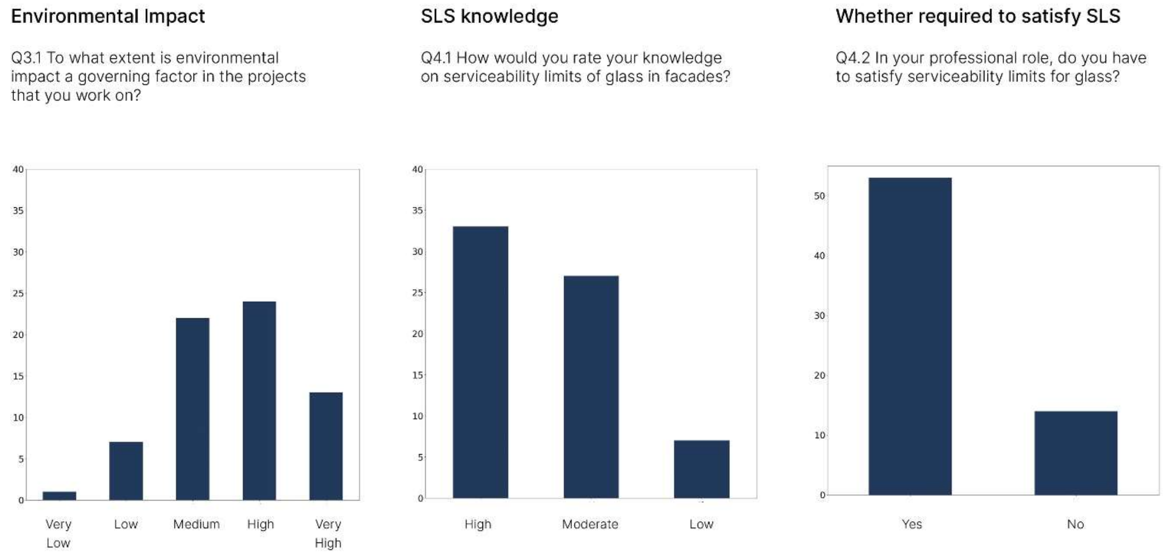

Figure 8: Bar Graphs indicating (a) Environmental Impact (b) SLS knowledge (c) whether they are required to satisfy SLS criteria in their professional role.

The data on respondents' professional qualifications, location, project locations and knowledge about SLS tells us that the selected sample provides a fair representation of the 'population' i.e. professionals in the façade industry in Europe. The data also tells us that most respondents were reasonably qualified to answer questions related to serviceability criteria of façade glazing.

3.3 Assessment of numerical responses

3.3.1 Perceived effectiveness of material efficiency, recycle and reuse

The respondents were asked to rate on a scale of 1-5, to what extent they find the 3 strategies of material efficiency, use of recycled glass and use of reuse glass effective in reducing the embodied carbon (Q3.3) in façade glazing. The findings are represented in a box plot as shown in Figure 9 (a). The statistical interpretation of box plots is shown in Appendix 7.

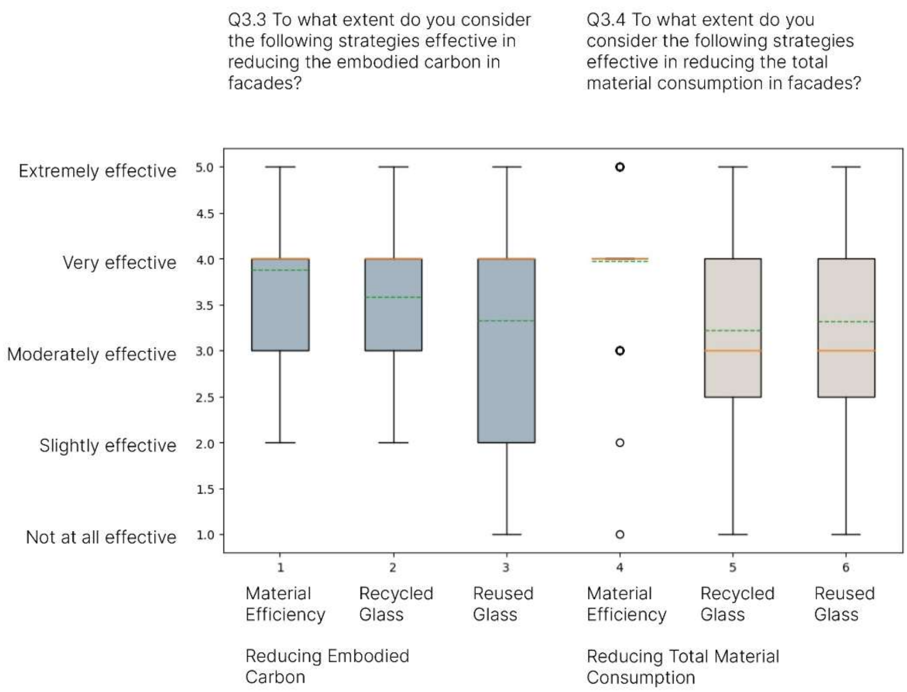

Figure 9: Perceived effects of material efficiency, recycled glass and reused glass as strategies for (a) reducing embodied carbon and (b) reducing total material consumption in facade glazing.

The findings show a large divergence in the answers for these questions, especially for reused glass. 75% of the respondents have rated material efficiency and recycled glass to be more than 'moderately effective', showing similar distributions. Based on the mean values (marked with a dashed line), material efficiency was found to be rated as more effective than the other two strategies.

The respondents was also asked to rate the effectiveness of the same strategies in reducing total material consumption (Q3.4). The findings are shown in Figure 9 (b). Material efficiency was rated to be 'very effective' by most respondents, with a few exceptions indicated as circles in the box plot. The answers showed a wide divergence in both, recycled and reused glass. The distribution is slightly skewed and it shows that the mean responses were above 'moderately effective', with reused glass showing slightly higher mean than recycled glass.

The responses to both these questions show that material efficiency is perceived to be more effective compared to using recycled or reused glass in facades, when it comes to reducing the embodied carbon and total material consumption. These findings support the hypothesis that material efficient approach is worth exploring in façade glazing.

3.3.2 Perceived effectiveness of reducing glass thickness

The respondents were asked to rate on a scale of 1-5 to what extent they consider reducing glass thickness in reducing embodied carbon (Q3.5) and reducing total material consumption (Q3.6) in façade glazing. As seen in Figure 10, the responses to both questions show a similar distribution between 'slighly effective' to 'extremely effective', with the median at 'very effective' and the mean in between 'moderately effective' to 'very effective'. The findings show that the respondents were optimistic towards material efficiency as a suitable sustainable strategy for facades.

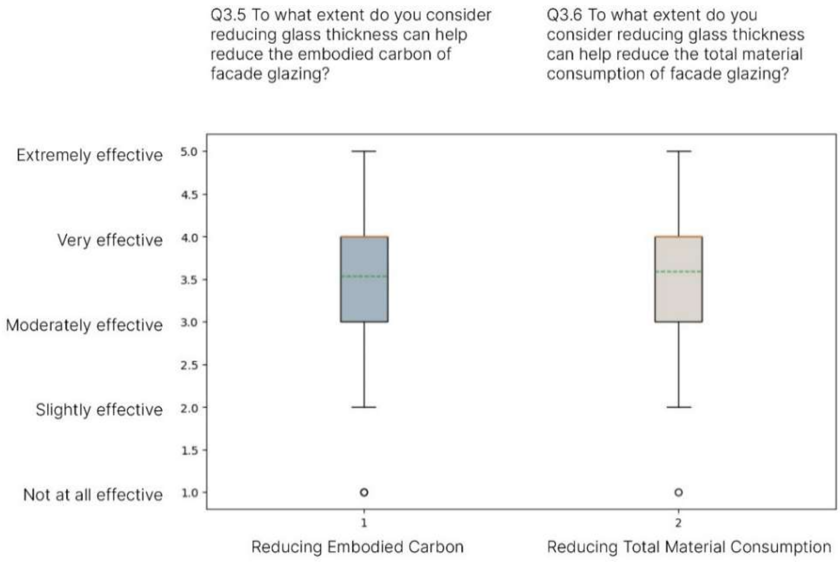

Figure 10: Perceived effectiveness of reducing glass thickness on embodied carbon and total material consumption in facade glazing.

3.3.3 Perceived effects of deformation on performance of façade glazing

Literature review indicated that deformation, as a result of wind and climatic loads, has an impact on façade glazing's durability, thermal, optical and acoustic performance, and occupant satisfaction. The following hypothesis was proposed during the research – 'the effect of deformation on certain performance factors of façade glazing is more significant for serviceability than others'. To test this hypothesis, the respondents were asked to rate on a scale of 1-5, to what extent excess deformation, well beyond serviceability limits, will have an effect on the listed factors (Q4.4).

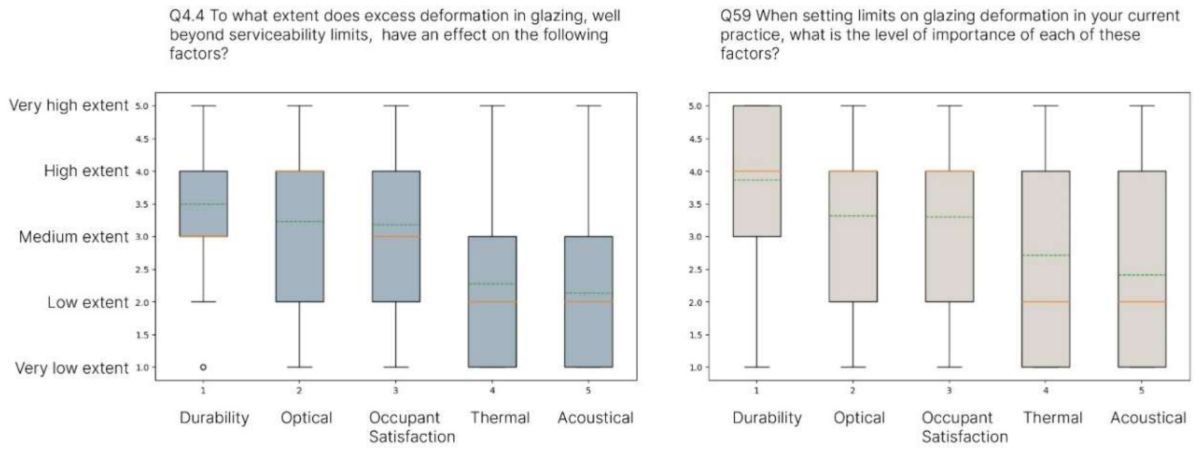

Figure 11: (a) Perceived effects of deformation on glazing performance and (b) current considerations of factors when setting serviceability limits.

The findings as plotted in Figure 11 (a) show that durability was rated higher than the rest, since the distribution of responses shows divergence between low extent to very high extent, with 50% of responses between 'medium extent' to 'high extent'. This was followed by optical performance and occupant satisfaction, both of which show a normal distribution with the mean values slightly above 'medium extent'. The effect on thermal and acoustic performance was rated lower, with 50% responses ranging between 'very low extent' to 'moderate extent'. As per the mean values, durability was rated the highest and acoustical performance the lowest.

The respondents were also asked to rate these factors based on their level of importance in setting serviceability limits on glazing deformation. Although all the responses show a wide divergence, it can be seen from Figure 11 (b) that 50% respondents (above the median line) rated the importance of durability between 'high extent' to 'very high extent'. For the other 4 factors, only 25% of the values fall in this range. Optical performance and occupant satisfaction show a similar distribution with the medians at 'high extent' and the mean values slightly higher than 'medium extent'. Thermal and acoustic performance also show a similar distribution with medians at 'low extent' and means in between 'low extent' and 'medium extent'. The skew in their distributions indicate thermal and acoustic performance are considered relatively less important compared to the optical performance and occupant satisfaction.

The findings supports our hypothesis and indicate that effect on durability is of highest importance when setting serviceability limits on deformation. The dependence of occupant satisfaction on optical performance of glazing can be one of the reasons why the responses for both these factors show similar distribution. Similar assumption can be made about the thermal and acoustical performance as they both depend on the magnitude of deformation which affects the gap width in case of insulated glazing.

3.3.4 Guidelines followed in practice

Based on the findings of the literature review, the following hypothesis was proposed: 'Apart from the local, national or international standards, consultants and engineers also rely on their own standards, data from previous projects, rules of thumb, glass manufacturer's recommendations, etc. while specifying the thickness of glass.' The respondents were asked to rate how often they follow these options. The findings are indicated in Figure 12 in the form of a box plot.

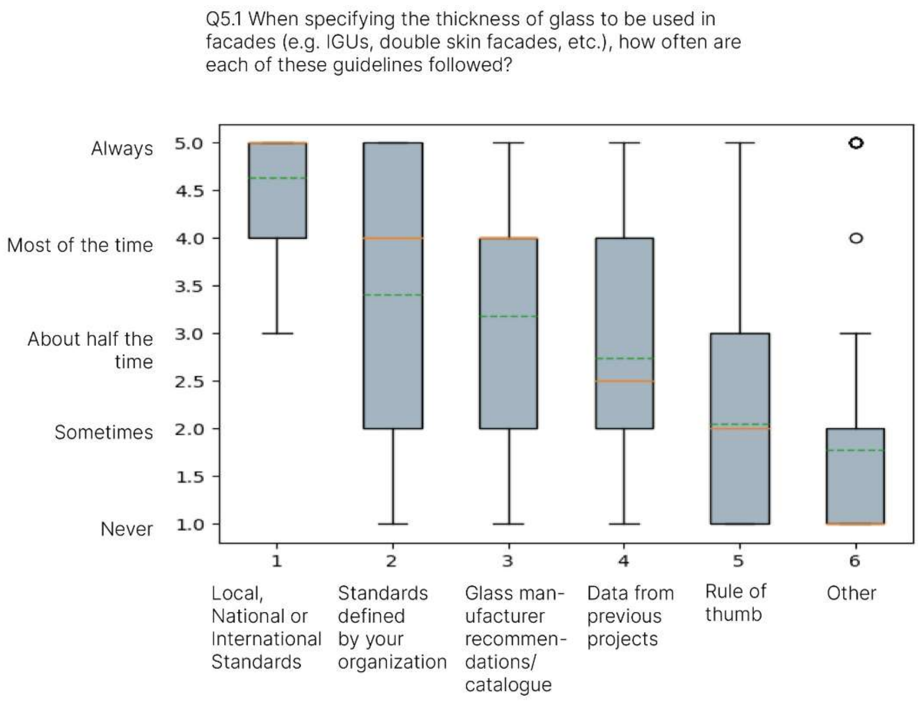

Figure 12: Guidelines followed while specifying glass thickness.

It is seen that 75% of the respondents indicate that they refer to local, national or international standards between 'most of the time' and 'always'. The median also lies at the maximum value i.e. 'always', which indicates that 50% respondents have indicated 'always' as their answer.

Standards defined by their organization shows a wide, but skewed divergence, which indicates 50% of the respondents refer to these between 'most of the time' and 'always', while 25% indicated a response between 'never' and 'sometimes'. Glass manufacturer's recommendations and data from previous projects are referred less often than standards, and rule of thumb is used the least often. Amongst the other guidelines followed were – insurance requirements, certified test results, inputs from consultants, peers and third party experts (e.g. in case of thin glass), climatic conditions and safety standards.

3.3.5 Significant Mechanical performance factors

For serviceability, it is considered that the mechanical performance of glass is well within its ultimate limits. If thinner glass was to be used, it is expected that the mechanical performance remains within these ultimate limits, even though the glass undergoes higher deformations. The respondents were asked which of the factors pertaining to mechanical performance would they not ignore if thinner glass was to be specified. The format for this question was multiple choice, multiple answer and the findings are plotted as bar graph as shown in Figure 13.

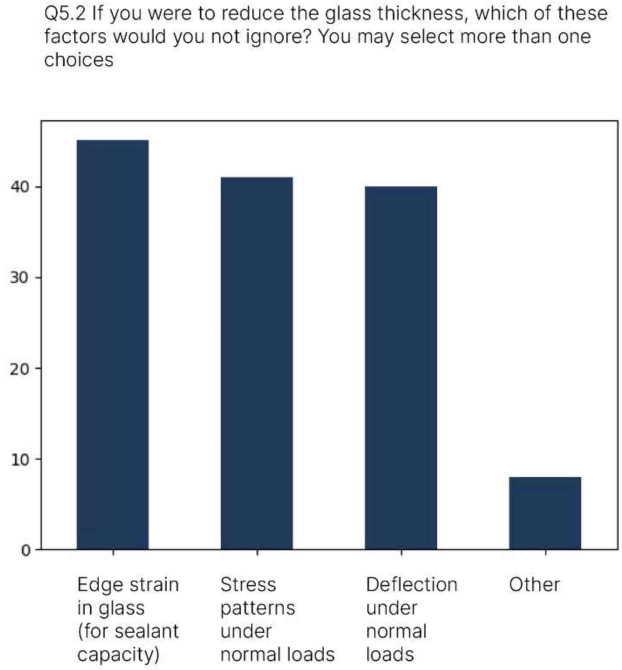

Figure 13: Which factors cannot be ignored if glass thickness was to be reduced.

It was found that the number of responses received for all 3 options provided, namely, edge strain in glass (for sealant capacity), stress patterns under normal loads and deflection under normal loads, were almost equal. The other responses received were stress at maximum load, safety requirements, thermal performance of glass, edge deflection, satisfaction of ULS conditions, ageing and surface degradation (specially on chemically toughened glass) and eigen frequency.

3.3.6 Impact of reducing glass thickness on factors other than façade performance

Other than façade performance, glazing also contributes to other factors in a building such as costs, perceived value, aesthetic quality, etc. If the glass thickness was to be reduced, it would have an impact on these factors as well. The respondents were asked to indicate the level of impact the reduction of glass thickness could have on some of these factors. A 7-pointer scale was provided for this question, ranging from 'extremely negative' (1) to 'extremely positive' (7) with 'no impact' (4) in the middle. Figure 14 shows the findings from this question.

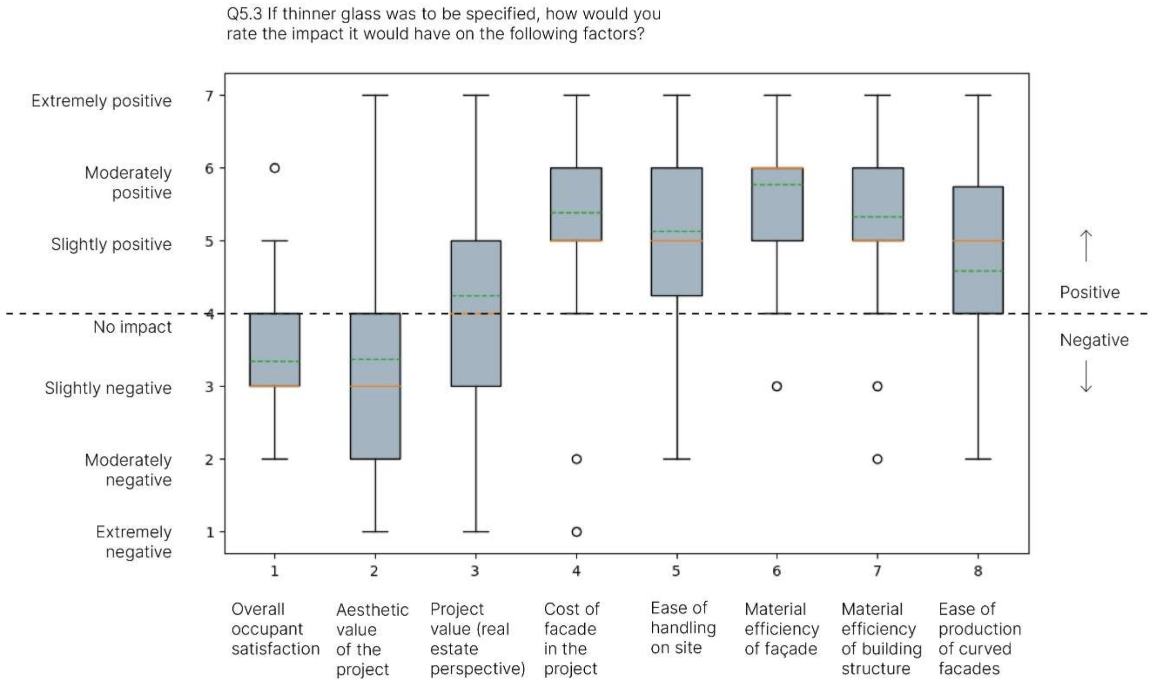

Figure 14: Level of impact of reducing glass thickness on factors other than facade performance.

Almost all respondents (except a few outliers) indicated a positive impact on cost of façade, material efficiency of façade and material efficiency of the building structure. This is an important consideration for overall project costs, which might be seen as one of the main drivers for material efficient approach. In terms of ease of handling on site and ease of production of curved facades, 75% of the respondents indicated that reduction in glass thickness will have a positive impact, while the rest indicated up to 'moderately negative' impact on both.

In terms of project value from a real estate perspective, the responses show a wide divergence from extremely positive to extremely negative, with the mean close to (slightly higher than) and the median exactly at 'no impact'. Hence, it is difficult to arrive at an inference about the effect on project value. In terms of overall occupant satisfaction and aesthetic value of the project, 75% respondents indicated a negative impact. The divergence was smaller for occupant satisfaction, with 50% respondents indicating between 'no impact' and 'slightly negative' impact. For aesthetic value, the divergence range was from extremely positive to extremely negative. However 50% of the respondents indicated the level would be between 'no impact' and 'moderately negative' impact.

It can be inferred that while cost benefits and material efficiency could acts as drivers for the reduction of glass thickness, the impact on aesthetics and overall occupant concerns might be reasons to not do so.

3.3.7 Impact of reducing glass thickness on occupant satisfaction

A key finding from the literature review was the knowledge gap in terms of impact of glass deformation on occupant satisfaction. Excess deformation of glass is known to cause alarm among the occupants. Other than alarm, it may even affect the acoustical environment, quality of view and aesthetics for an occupant. The respondents were asked to rate on a scale of 1-5 what the level of impact reduction of glass thickness would have on factors related to occupant satisfaction, in order to compare these with each other. Figure 15 shows the findings from the same.

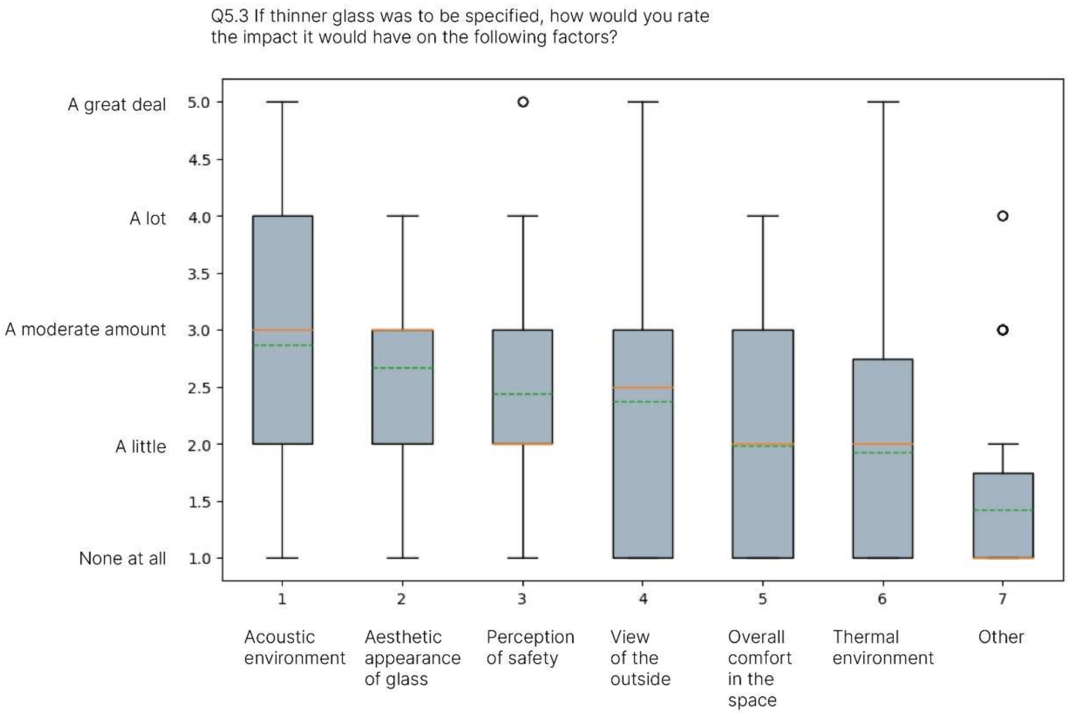

Figure 15: Level of impact of reduction of glass thickness on occupant satisfaction.

In terms of acoustic environment, a wide divergence is observed, with the median lying at 'a moderate amount' and the mean slightly below the median. However this factor has been rated the higher than the other factors, based on the range of distribution and the mean value. The median in case of aesthetic appearance of glass is also at 'a moderate amount'. Hence, 50% of the respondents believe the impact on aesthetics is between 'a moderate amount' and 'a lot'.

In case of perception of safety, the median lies at 'a little', which indicates 50% of the respondents consider deformation to have between 'none' to 'a little' impact on perception of safety, and 25% of the respondents consider it to have higher than 'moderate amount' of impact.

In case of the view of the outside, overall comfort and thermal performance, the divergence is wide, although 75% of respondents consider the level of impact on these to be between 'no impact' and 'a moderate amount'. On average, higher impact on view is observed, as compared to overall comfort and thermal performance. The other factors listed by the respondents were – 'a little' impact on lighting inside space, 'a little' impact on spatial quality, 'a lot' of impact on office space quality and 'a lot' of impact on roller wave distortions.

Additionally, a few comments on the occupant satisfaction were received in this context. One of the respondents indicated that prior knowledge of the use of thinner glass might have 'a little' impact on the overall occupant satisfaction, and not knowing would not have a noticeable visual impact. One respondent indicated 'a little' impact on the occupant's contribution to carbon reduction. Another respondent pointed out the need for reflection of the impacts in project specifications.

Since all the means lie in the same range, if we were to calculate a population mean for this distribution, it would lie between 'a little' to 'a moderate' level of impact. Thus it can be inferred that deformation in glass would have on average, a similar impact on all the listed factors.

3.4 Assessment of textual responses

3.4.1 Criteria for serviceability in practice

The respondents were asked (Question 4.3) whether they have to satisfy the serviceability limits for glass in their professional role. As discussed in Chapter 3.2, 53 (79%) respondents answered 'yes' and the remaining 14 (21%) indicated 'no'. The respondents who answered 'yes' were asked what are all the serviceability criteria that they design for. The purpose of this question was to understand which criteria and standards are used in practice and to test the following hypothesis: 'There is a large variation in standards followed, criteria considered and limits assigned across the façade industry.' Such variations could act as barriers for use of thinner glass for facades.

An inductive method of analysis is being implemented in this case. Initial analysis of the responses was conducted manually to filter responses that talk about standards, criteria and limits, and to observe patterns in responses. The table has been included as Appendix 8. With each response, information about the organization and professional role of the respondent, their location, location of their projects and level of SLS knowledge were considered, as these variables may have an influence on their response.

Table 8: Categorization of criteria listed by the respondents

No.	Criteria Type	Criteria considered	No.	Criteria Type	Criteria considered
1	Acoustic	Acoustic Performance			Intrusion resistance
2	Durability	Adhesive/cohesive failure of edge seals and weatherseals			Mechanical Performance
		Condensation resistance			Mode of breakage
		Durability			Post breakage behaviour
		Weathering conditions			Resonance
3	Feasibility	Client needs			Safety
		Availability as per standard stock			Soft body impact class 2
		Production feasibility			Stability
		Technical feasibility			Vibration frequency
4	Fire	Fire resistance			VIV and other wind instabilities
5	Maintenance	Cleaning and maintenance			Altitude difference
6	Mechanical	Breakage by climatic loads, thermal stress or impact	7	Optical	Optical defects - reflection disortion
		Deflection			Optical defects - roller wave distortion
		Deflection for occupant comfort			Optical performance
		Deflection under barrier loads			Solar factor
		Deflection under climatic loads			visual replacement
		Deflection under mechanical loads	8	Sustainability	Carbon Footprint
		Edge deflection			Conflict materials
		Edge stability			Life cycle
		Eigen frequency			Recycled content
		Glass Strength	9	Thermal	Thermal Performance
		Glass Stress limits			

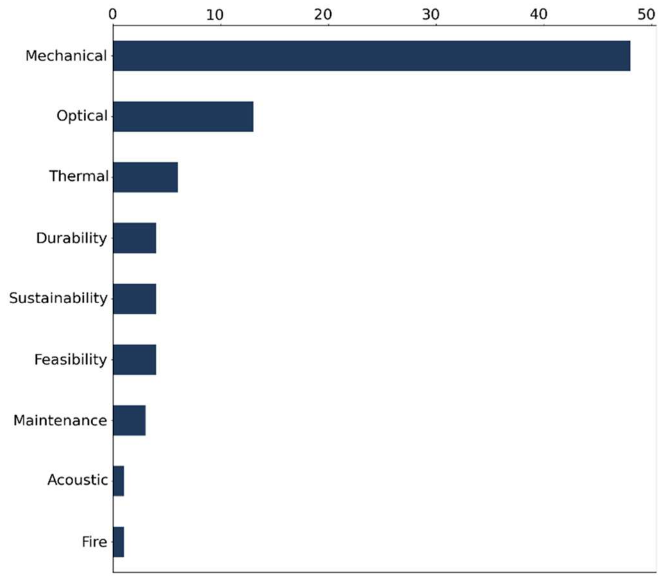

Figure 16: Frequency distribution of serviceability criteria by their categories.

Table 8 shows the categorized list of all the criteria indicated by the respondents. These have been grouped in categories namely Acoustic performance, Durability, Feasibility, Fire, Mechanical performance, Optical performance, Sustainability and Thermal performance. Figure 16 indicates the frequency distribution of the listed serviceability criteria by their categories. To get an idea of which respondent group (based on their organization) indicated which categories of criteria, a cross-tabulation in the form of a heat map has been prepared, as shown in Figure 17.

Mechanical performance is most indicated by façade consultants, followed by glass manufacturers, others and façade contractors. Glass manufacturers also indicate categories of durability, feasibility, maintenance, optical, sustainability and thermal performance. Facade consultants have mentioned mechanical performance and optical performance more often than other performance criteria. However, some of the mechanical criteria such as edge stability and edge deflection also affect durability. Thus, it can be said that durability, mechanical and optical performance are the main concerns of consultants. This validates our findings shown in Chapter 3.3.3.

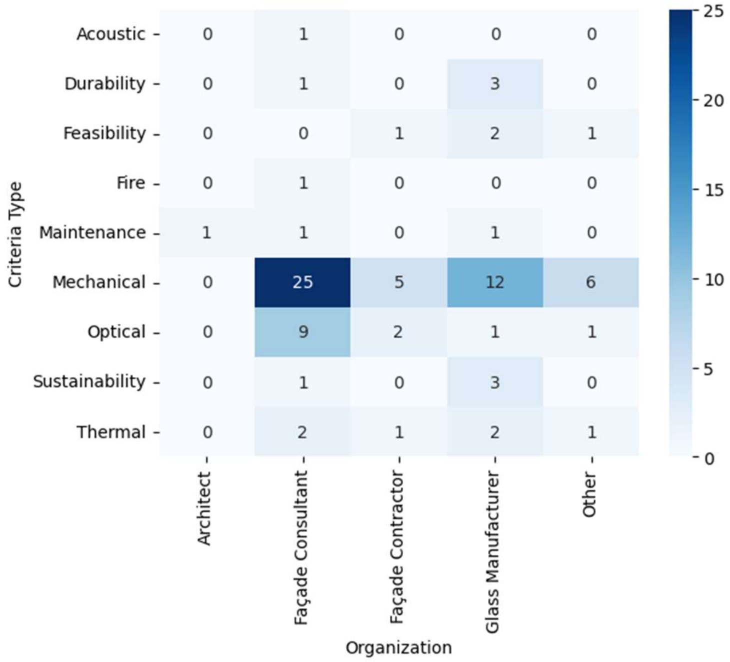

Figure 17: Cross-tabulation of Criteria type vs. Organization.

3.4.2 Limits and standards followed in practice

Out of the 53 respondents answering Question 4.3, 13 respondents have listed the deflection limits they follow and 15 respondents provided the standards they follow in their practice. A table with all the limits and standards along with the respondents' organization, location and project location has been provided as Appendix 9.

The limits vary based on project locations, and standards being followed. The most commonly specified limit is L/65 or its equivalent in mm, ranging from 25mm to 50mm, used typically in the UK, but also in other countries in Europe and the USA. The highest deflection limit mentioned is L/60. This was indicated as a 'typical limit' by a consultant working in the Middle East, Europe and Asia. The French standard NF DTU 39 specifies a limit of L/60 or 30mm whichever is lesser. Other limits mentioned in the responses are as low as L/180, with an exception of L/1000 which was specifically mentioned for glazing with high optical performance requirement. CWCT standards, BS EN 16612 and local standards are mainly referred to by most of the respondents, whereas specific standards such as BS 5234 (partitions), BS 6180 (barriers in and about buildings) and BS 6262-3 (glazing for buildings) are only referred to by the glass manufacturers.

In addition to the information regarding limits and standards, the consultants also highlighted a few specifics from their practice. One of the consultants mentioned that in some cases even though thinner glass meets the warranty requirements, they aren't able to specify it due to stringent standards in specific regions. While in other cases they are able to make concessions in glass thickness. This suggests that at time standards also act as barriers in specification. Other than standards, it was mentioned that the aesthetic ideal of perfectly flat glass, prior knowledge about use of thinner glass and conventional perception towards glass were also mentioned as a barrier in transition to thinner glass. It was mentioned that although acceptable natural frequency of glass is between 3.5Hz and 4.0Hz, a natural frequency below 2Hz can be easily excited by hand, which might make the glass 'appear' weak even though it is structurally suitable for use. Often in practice, the outer panes are made thicker to avoid distortion of reflections and to bias the climatic loads on inner panes, since distortions are perceived as a sign of 'poor quality'.

Edge seal deflection of L/175 was mentioned as a commonly used standard. However, it is based on an old criterion related to resistance of IGU seals to deflection. It was suggested that this limit needs re-checking. Such criteria that affect the longevity of the IGU were classified as 'irreversible SLS' by one of the respondents and the criteria such as deflections and vibrations as 'reversible SLS'.

Warranty provision for glazing was termed as one of the main drivers for serviceability. Different warranty periods of materials were pointed out by one of the respondents; namely glass: 60 years; DGU: 12 years; Laminates: 7 years; Argon retention: 2 years. The overall warranty of the IGU is then mainly decided based on the laminates, i.e. 7 years, even though the glass might last much longer than the limit.

One of the consultants mentioned the process of decision making as follows: '1. find out the required loads / forces that we need to design. 2. choose the optimal glass composite out from the standard stock. 3. if necessary due to structural calculation, then choose the thermally strengthened glazing.' This highlights the role of available standard stock sizes in the decision making process. Non availability of thinner options must also act as a barrier in the decision making process.

3.4.3 Optical defects

The respondents were asked to indicate which optical defects they are most concerned with in terms of façade glazing, and which of these defects depend on excessive deformation of glass under climatic/ wind loading. The responses were received in the form of free text, which was filtered and common optical defects from the answers was extracted. Figure 18 and Figure 19 show bar graphs representing frequency of answers for these two questions respectively. Further, Table 9 lists some more defects mentioned in the survey, which have been grouped into 4 broader categories namely bulk glass defects, coating defects, manufacturing defects and lamination defects.

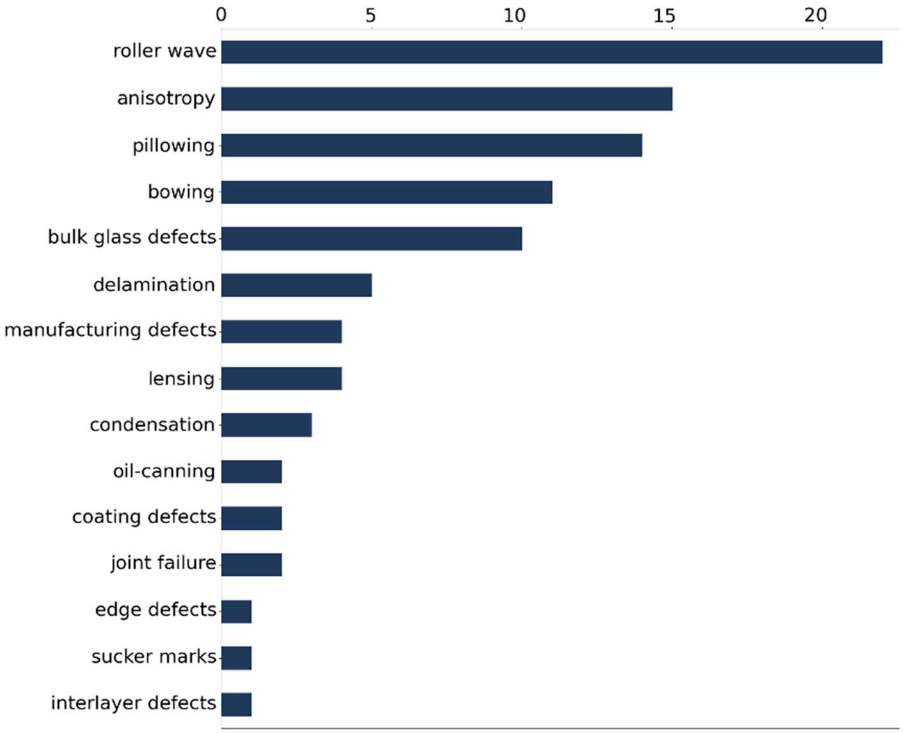

Figure 18: Optical defects that the respondents are most concerned with in facade glazing.

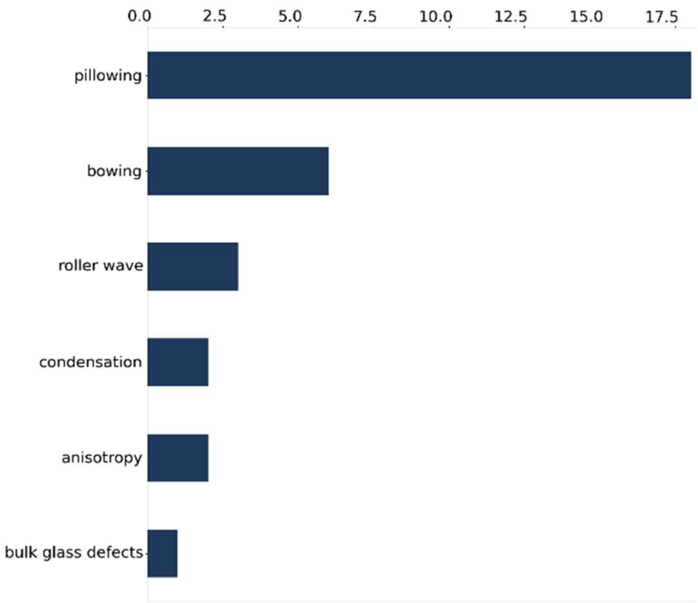

Figure 19: Optical defects that are a result of excessive deformation, as indicated by the respondents.

Table 9: Classification of types of defects in materials or as a result of manufacturing

Bulk glass defects	Inclusions/ Impurities
	Seeds
	Bubbles in glass
	Scratches

	Cracks Chipping Blemishes Staining
Coating defects	Heat speckles Orange peel effect
Manufacturing defects	Edge seal inconsistency Poor edge deletion
Lamination defects	Bubbles in interlayer

From the graphs, it can be seen that roller wave, anisotropy, pillowing, bowing and bulk glass defects are some of the main defects the respondents are concerned with. Out of the first graph, the defects of concern that mainly depend on deflection i.e. those shown in the second graph, are pillowing, bowing and condensation. Although some respondents have mentioned roller wave, anisotropy and bulk glass defects in this list, these are a result of heat-strengthening, lamination or the process of glass manufacturing, and hence, can be excluded from consideration.

Each optical defect has a visual effect that qualifies as 'unacceptable'. For instance, anisotropy causes iridescence which can affect the color seen through glass, or bulk glass defects affect the aesthetic of glass. In terms of optical defects caused by deflections, pillowing and bowing mainly cause distortions of reflections and condensation causes an unclear view through the glass. The effect of pillowing and bowing on the view through the glass needs to be tested. While the use of non-reflective coatings might be a way of mitigation of the effect of pillowing and bowing, condensation can be avoided through maintenance of temperature of the assembly. In other words, if the optical defects cause by deflection are clearly understood, these can be controlled while using thinner glass for facades.

Further, it was noted by a few respondents that deformation under wind loads is temporary and faster compared to that under climatic loads. Thus, defects such as pillowing or bowing are considered more critical, since they are more 'permanent'. It was also noted that since deformations are dependent on panel sizes, smaller panels may cause lesser distortions in reflection. One of the respondents indicated that compared to distortions of transmitted image, which may have psychological effects on the occupant such as stress, distortions of reflections do not directly impact the occupant. The common perception of distorted reflections as poor quality glass was also highlighted in a few responses as a 'barrier' for the use of thinner glass.

3.4.4 Perceived barriers to use of thinner glass and feasibility of overcoming them

In a couple of consequent questions, the respondents were asked to rate on a scale of 1-5 to what extent they think the listed factors are barriers for the use of thinner glass, and to what extent they agree that 'it seems feasible to overcome these barriers'. Figure 20 shows two box plots derived from the responses to these questions respectively. The options provided were determined based on literature review and reasonable assumptions. Further barriers were received in the free text option 'other' provided in these questions.

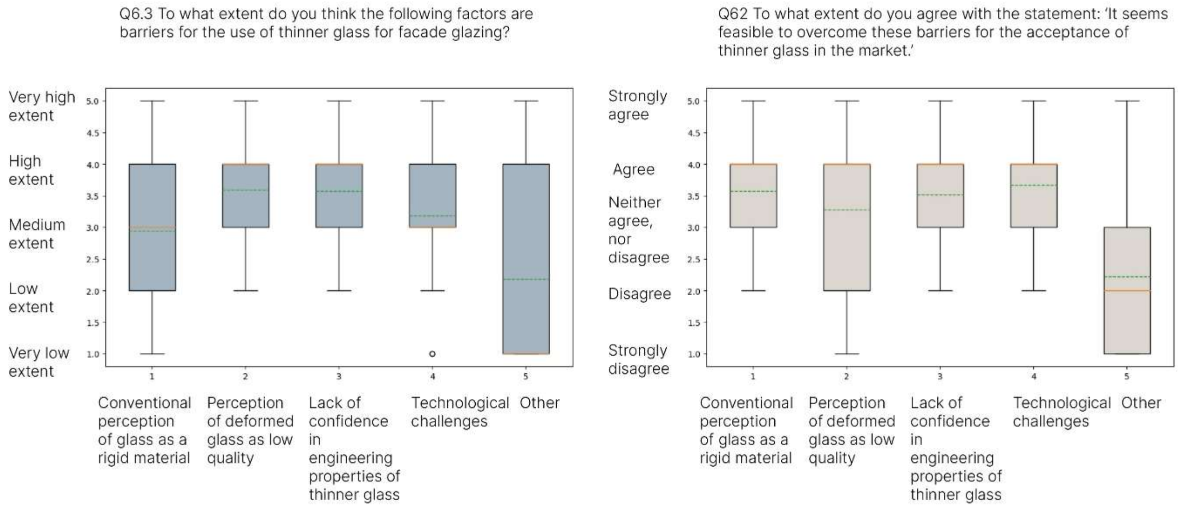

Figure 20: Box plots showing responses to the questions about (a) the perceived barriers in the use of thinner glass for facades and (b) the feasibility of overcoming these barriers.

It can be observed from Figure 20 (a) that 'perception of deformed glass as low quality' and 'lack of confidence in engineering properties of thinner glass' are ranked the highest, based on their distribution and mean values, closely followed by 'technological challenges'. For all three of these statements, 50% of the respondents have indicated values between 'medium extent' and 'high extent'. There is a wide divergence observed for 'conventional perception of thin glass as a rigid material', with the median and mean values both being around 'medium extent'. 50% of the respondents have indicated values between 'low extent' to 'high extent' and 25% have indicated between 'very low extent' and 'low extent'.

Figure 20 (b) measures the perceived feasibility of overcoming each barrier. In this case, it is apparent that 'conventional perception', 'lack of confidence' and 'technical challenges' are perceived as feasible to be overcome, by 75% respondents, as they indicate values above 'neither agree nor disagree' but 25% of the respondents tend to 'disagree'. However, in terms of perception of deformed glass as low quality, a wide divergence is observed, with the mean value just above the neutral comment.

It can be said that the perceived low quality of deformed glass is one of the main barriers, which may or may not be feasible to overcome. However, lack of confidence in thinner glass, technological challenges and conventional perception of glass as a rigid material is feasible to overcome. We can say that although we are able to use thinner glass in facades, it may be still perceived as low quality.

Apart from the options listed in these questions, the other barriers mentioned by the respondents are listed in Appendix 10. Based on plot (b), 50% of these have been ranked as not seemingly feasible to overcome. Conservative serviceability limits provided in the standards and the standards not being up to date were highlighted by a few respondents. Perceived difficulty in satisfying architectural requirements, acoustical requirements and performance of IGUs was also highlighted.

It was also noted that consultants tend to stick to conventional way of working and there is a bias towards conventional materials. The changes in detailing and glazing systems as a result of reduction of glass thickness might also act as barriers. It was also highlighted that there may be some barriers to manufacturing thinner glass, such as changes in factory requirements, increase in optical defects due to processing, etc. Additionally, it was mentioned that the structural strength of glass will be questioned. The perceived risk of breakage during handling, and post-breakage behavior might increase costs and required changes in warranties and liabilities.

In addition to this question, some barriers were also listed as a response to questions Q5.4 and Q7.4 discussed in Chapters 3.4.5 and 3.4.6. A combined list of barriers is provided in Appendix 10.

Thus, in addition to occupant's perception of glass and confidence in its strength, stringent regulations, high performance requirements, changes to conventional practice and technical challenges are perceived as the main barriers by the respondents.

3.4.5 Information required to help specify thinner glass

The respondents were asked (Q5.4) what information could help them specify thinner glass for facades. The responses were collected as free text. The following hypothesis was the basis for this question: 'Lack of information about factors related to thinner glass is a barrier in reducing glass thickness'. The respondents not only highlighted what information they would required, but also specific needs that would have to be satisfied to transition to thinner glass. They also highlighted barriers they face, and the governing factors for setting glass thicknesses and deflection limits. Further they added some suggestions for transitioning towards thinner glass.

For a qualitative analysis of the responses, a coding exercise was conducted. A basic code structure was created concerning themes namely barriers, governing factors, driving factors for change, information required, needs, reasons and conditions for/ against recommendation of thinner glass, responsible stakeholders and suggestions received. The coding was done for responses to Q5.4 (about information required) and Q7.4 (reasons for/ against recommendation) simultaneously using Atlas.ti. The code headings, their descriptions and the questions that they intend to answer are listed below. A detailed list of codes is provided in Appendix 11 . Based on the methodology provided in the Coding Structure chapter in the book Qualitative Data Analysis (Miles & Huberman, 1994), the following process was followed for coding and qualitative analysis:

1. Exporting free text response data to Atlas.ti (deriving a set of auto-generated codes based on numerical and choice-based responses)
2. Identifying common themes for Q5.4 and Q7.4 using an inductive approach
3. Creating a preliminary coding structure based on identified themes
4. Detailed coding on Atlas.ti based on coding structure for all 67 responses
5. Cleaning up coding structure to merge repetitive or similar coding
6. Performing code-document analysis and code-cooccurrence analysis to arrive at results

No.	Code	Description	Sub question
1	BARR	Perceived barriers to reducing glass thickness	What are the barriers/ challenges for use of thinner glass?
2	GOVFAC: Thk	Governing Factor: Glass thickness	What are the factors governing glass thickness?
	GOVFAC: Def	Governing Factor: Deflection	What are the factors governing glass deflection limits?
3	DRFAC	Driving factor for change	What factors are responsible for driving transition towards use of thinner glass?
4	INFO	Information required to specify thinner glass	What information would help you specify thinner glass?
5	NEED	Needed or required information	What information would help you specify thinner glass?
6	REC: Condn	Conditions to be met for recommendation	What are the conditions to be satisfied for recommendation of thinner glass?
	REC: Neg	Reasons for not recommending	What are the reasons for not recommending the use of thinner glass
	REC: Pos	Reasons for recommending	What are the reasons for recommendation of thinner glass?
7	ROLE	X (role) is reponsible for Y	What is the role of stakeholders in deciding the use of thinner glass?
8	SUGG	Suggestions on the subject	What are some recommendations from the industry for transitioning towards thinner glass?

Table 10 shows a list of information required as indicated by the respondents cross-tabulated with the organization type they belong to. It can be seen that the façade consultants, contractors and the glass manufacturers require actual deflection limits for thinner glass. Other significant requirements are effect of deflection on durability, structural and thermal performance; impact on risks; limitations on the size of glass panes, actual design loads, and potential carbon savings. It can be seen that the consultants and glass manufacturers indicate the highest number of requirements.

The respondents also highlighted specific needs that if fulfilled, could help transition to use of thinner glass. This list can be seen in Table 11. The main need indicated was the need to update the standards, along with a list of suggestions from the respondents as to what to include in the standards. These included additional glass thickness calculations from the manufacturers, improved glass stress limits, more realistic load combinations with lower safety factors and inclusion of framing while calculating façade stiffness. The need to educate stakeholders at all levels in the supply chain was also highlighted in the responses.

The listed barriers have been added to Appendix 10 along with the barriers listed in the previous chapter. Table 13 lists the suggestions provided by the respondents, some of which are – reducing the size of glass panels, accommodating deflections within façade geometries, using vacuum glazing with thin glass, and using deflections in glass as proof of low carbon glazing.

The respondents indicated the main driving factors (coded: DRFAC) that could potentially lead to reducing glass thickness. The two main driving factors listed were carbon reduction and change in standards. A list of governing factors for deflection and thickness was also derived from the responses. The role of connections and lamination interlayer was indicated as the factor that could help limit deflections in case of thinner glass. Some respondents noted that besides the technical governing factors, the project type (whether high-end or not) was one of the main governing factors affecting decision related to glass thickness.

An interesting output from the survey was in terms of which stakeholders are responsible for change. Most respondents indicated that the architects must be more accepting of deformations in glass by prioritizing material efficiency. Some respondents indicated that the decision rests with the clients. Interestingly, it can be seen from Table 12 that a few glass manufacturers indicate that the consultants being conservative, whereas the consultants indicated that the standards are conservative. It is however also indicated by some respondents that educating the stakeholders about the benefits of material efficiency is possible.

Table 10: Crosstabulation of organization types and the required information they indicated.

	ORG::1_GlassMan	ORG::2_SealMan	ORG::3_FacCons	ORG::4_FacCont	ORG::6_Architect	ORG::7_Other	Totals
INFO: Actual deflection limits for all conditions	3		4	2			9
INFO: Actual qualification of visual comfort			1				1
INFO: Cost impact		1	2				3
INFO: Criteria for serviceability limits	1						1
INFO: Data on user acceptance of distortions	1		2				3
INFO: Detailed load info, non-factored and frequency						1	1
INFO: Detailing of connections		1					1
INFO: Effect of deflection on durability	3	1	1	2	1		8
INFO: Effect of deflection on frame integrity		1					1
INFO: Effect of deflection on optical performance	1		1		1		3
INFO: Effect of deflection on structural performance	1	1	1	1	2		6
INFO: Effect of deflection on thermal, acoustical, serviceability			3		1		4
INFO: Feasibility of replacement				1	1		2
INFO: Impact of glass connection on deflection		2					2
INFO: Impact on risk			2	1		1	4
INFO: Impact on warranty			2				2
INFO: Limitations on size of pane	1	1	1	1			4
INFO: Loading: Design load for barrier	3						3
INFO: Loading: Design loads for wind	3			1			4
INFO: Loading: Permissible point load area and limits	2						2
INFO: Loading: Repartition standardization	1						1
INFO: Manufacturer's data: aspect ratio to thickness confirmation			1				1
INFO: Manufacturer's data: sizes, toughening, coating, risks of bre...	1		1				2
INFO: Potential Carbon savings	1	2	3				6
INFO: Potential material weight reduction			1				1
INFO: Scientific evidence		1				1	2
Totals	22	11	26	9	6	3	77

Table 11: Crosstabulation of organization types and the needs that they indicated.

	ORG::1_GlassMan	ORG::2_SealMan	ORG::3_FacCons	ORG::4_FacCont	ORG::6_Architect	ORG::7_Other	Totals
NEED: Change in aesthetic goals			2				2
NEED: Changes to conventional design approach		1					1
NEED: Distinction between performance and deflections						1	1
NEED: Partial factors clearly defined			1				1
NEED: Scale of production	1	1					2
NEED: To educate stakeholders	1		3	1		1	6
NEED: To lower acoustical requirements	1		1				2
NEED: To lower safety factors			1				1
NEED: To update standards			2	4			6
NEED: Updated calculation tools			1	2		1	4
NEED: What to include in standards	3		3	2		1	9
NEED: Wind tunnel calculations				2			2
Totals	6	2	14	11	0	4	37

Table 12: Crosstabulation of organization types and the barriers indicated by them.

	ORG::1_GlassMan	ORG::2_SealMan	ORG::3_FacCons	ORG::4_FacCont	ORG::6_Architect	ORG::7_Other	Totals
BARR: Consultants being conservative	2			1			3
BARR: Cost of implementing change	1						1
BARR: Difficulty of structural calculations	1						1
BARR: Expectation: High levels of robustness				1			1
BARR: Expectation: High optical performance			1	1		1	3
BARR: Manufacturing lines not being well equipped	1						1
BARR: Not learning from other countries/ peers	1						1
BARR: Occupant/ user concerns regarding deformation						1	1
BARR: Perception of deformation as inferior quality			1		1		2
BARR: Perception of deformation as unsafe	1		1			1	3
BARR: Required scale of change is large	1						1
BARR: Standards being conservative	2		1	3			6
BARR: Standards being non uniform across countries	1			1			2
BARR: Standards not being up to date				1			1
Totals	11	0	4	8	1	3	27

Table 13: Crosstabulation between organization types and the suggestions indicated by them.

	ORG::1_GlassMan	ORG::2_SealMan	ORG::3_FacCons	ORG::4_FacCont	ORG::6_Architect	ORG::7_Other	Totals
SUGG: Allowing deformation on predetermined axes					1		1
SUGG: Increase allowable stiffness of PVB			1				1
SUGG: Integrate thinner glass with appropriate geometries					1		1
SUGG: Introduction of Carbon Tax			1				1
SUGG: Lowering specification by facade consultant				1			1
SUGG: Opportunity: Deformation as proof of low carbon facade			1				1
SUGG: Opportunity: Reducing emb carbon in an inexpensive way				1			1
SUGG: Optical defects to be tightly controlled			1				1
SUGG: Reducing glass size	1		2				3
SUGG: use of thin glass and vacuum glass	1						1
Totals	2	0	6	2	2	0	12

3.4.6 Likeliness to recommend thinner glass

The last question in the survey was in 2 parts. First, the respondents were asked to indicate on a scale of 1-5 to what extent they are likely to recommend the the use of thinner glass for facades knowing that: a. the glass may display relatively higher deformations under climatic or wind loads b. it significantly helps reduce embodied carbon in facades. Secondly, they were asked to explain their response in a free text format. The hypothesis behind this question was that the likeliness or unlikeliness to recommend thinner glass would depend on certain conditions that need to be satisfied. This was proved right, since certain respondents listed down specific conditions for recommendation. These have been listed in Table 14 as REC: Condn. Further, the respondents also gave some reasons 'for' and 'against' use of thinner glass, which have been listed as REC: Pos (positive) and REC: Neg (negative) respectively.

From the graph shown in Figure 21, it can be seen that most respondents indicated they are 'somewhat likely', followed by a number of respondents that indicated 'extremely likely' to recommend use of thinner glass. However, there is also a considerable number of respondents who were not likely, or neutral about the recommendation. The answers to both parts of the question were corelated during the qualitative analysis. It can be seen from Table 14 that the the main reason 'for' recommendation was carbon reduction, as indicated by 8 façade consultants, 3 glass manufacturers and 3 façade contractors. The main reason 'against' recommendation can be seen as 'occupant perspective', followed by 'doesn't offer much value'. The occupant perspective is also related to the conditions listed, of which the most frequent one were that the glass should still meet the specified performance and that the strength of glass should not be an issue. It was also noted that the specification depends on the project type and will have to satisfy the specific requirements of the project in consideration.

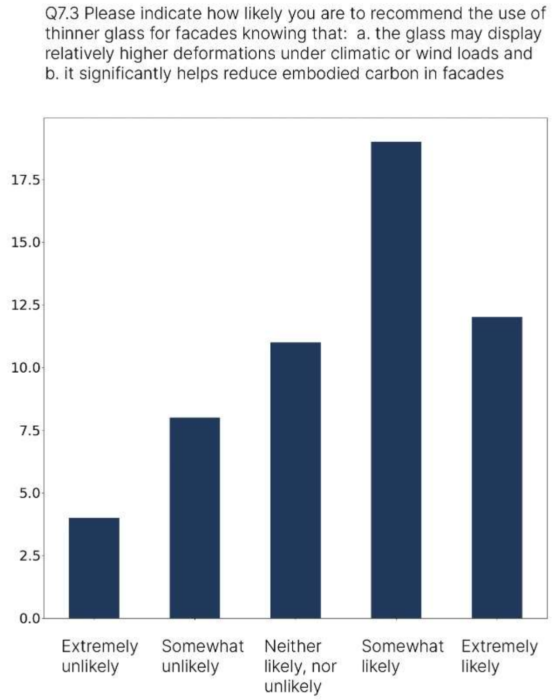

Figure 21: Graph showing frequency distribution of how likely the respondents are to recommend use of thinner glass.

Table 14: Crosstabulation between type or organization and reasons for (REC: Pos), against (REC: Neg) and conditions (REC: Condn) to recommend use of thinner glass.

	ORG::1_GlassMan	ORG::2_SealMan	ORG::3_FacCons	ORG::4_FacCont	ORG::6_Architect	ORG::7_Other	Totals
REC: Condn: Actual cabon savings		1	1				2
REC: Condn: Actual deflection			1				1
REC: Condn: Alignment with standards	1						1
REC: Condn: Based on project requirements			1			1	2
REC: Condn: Based on type of project	1		2				3
REC: Condn: Change in standard design approach		1					1
REC: Condn: Level of safety is not compromised				1			1
REC: Condn: Proof of concept		1					1
REC: Condn: Service life should not reduce	1		1				2
REC: Condn: Should achieve specified performance			1			3	4
REC: Condn: Strength should not be an issue			2	1			3
REC: Neg: Architecture perspective	1		1				2
REC: Neg: Conservative consultants	1						1
REC: Neg: Conservative standards	1						1
REC: Neg: Doesn't offer much value			1	1			2
REC: Neg: Increased risk and costs			1				1
REC: Neg: Occupant perspective	2					1	3
REC: Neg: Perceive technical challenges: coating			1				1
REC: Neg: Standards would need to change				1			1
REC: Pos: Accepting compromises			1				1
REC: Pos: Acknowledgement of benefits			2			1	3
REC: Pos: Carbon Reduction as Key Driver	3	1	8	3			15
REC: Pos: Contractors are willing				1		1	2
REC: Pos: Cost				2			2
REC: Pos: Perception can be changed			2	1			3
Totals	11	4	26	11	0	7	59

3.5 Discussion

The façade industry survey highlighted the willingness of the industry to transition towards thinner glass in facades, especially driven by embodied carbon concerns. It also highlighted the barriers and needs faced by the industry in doing so. Three key needs pointed out in the survey were - the need to update the glass standards to allow for higher deflections, the need for educating the stakeholders in terms of benefits of a material efficient approach and the need for hard data and research to able to push for these changes.

The survey was filled out by stakeholders in the façade industry who are a part of the decision making of glass thickness and other specifications. The number of responses analyzed (67) gives a fair representation of the population of façade consultants, contractors and glass manufacturers in the industry. The number of sealant manufacturers, researchers and architects contacted was less and the same is evident in the number of responses received. However, in terms of decision makers having enough knowledge about serviceability, the sample size and diversity can be considered as fair for the purpose of analysis.

In the first part of the survey, the effectiveness of a material efficient approach and specifically the reduction of glass thickness was validated. This supports our hypothesis that there is potential in a material efficient approach as a strategy for embodied carbon reduction. The following part of the survey was related to the perceived effects of glass thickness reduction and resultant deformations on the performance of glazing. It was found that the main concerns were about durability, optical performance and occupant satisfaction. In terms of occupant satisfaction, it was highlighted that the effects on aesthetics might pose as a barrier for acceptance, as deformation of glass is considered a sign of lower quality.

In the later part of the survey, a general optimism of the respondents towards material efficient approach was measured. Although a consensus on glass thickness reduction was not found as expected, some important barriers and conditions for recommendation were highlighted. The general perception was that the standards are not up to date and changes in standards could act as a key driver in the process was clearly indicated. There is also a lack of sufficient scientific evidence and proof of concept with respect to glass thickness reduction, without which the transition would not be possible.

The responses also shed some light upon the fact that there is no data available in terms of user acceptance of deformations, although it has been listed as an important decision making criteria. The willingness to educate stakeholders including occupants was mentioned multiple times in the survey. This points towards the idea that raising the acceptance threshold is both desirable and possible. This reinforces the next step of the research thesis, which is the setting up of an experiment to gather hard-data with respect to acceptance thresholds of deformation, which must be compared with limits based on technical criteria.

One of the key observations from the responses received was that although the respondents indicated a willingness towards change and listed suggestions, there is a lack of clarity in terms of which agencies in particular can actually bring about this change; and what role each agency could potentially take up to actively bring about this transition.

There is scope for improvement in the survey process, especially in terms of framing the questions. In some of the responses, a high variation was observed. Although this is statistically valid, a part of the reason for this could be a broader interpretation of the question. The survey was successful in generating a useful database. A more in-depth data analysis can be conducted based on specific research questions which come up in future research.

4 Design of Experiment

4.1 Introduction

This research is based on the following hypothesis:

'The relationship between occupant satisfaction and level of deformation can be empirically measured based on which acceptance thresholds towards glazing deformation can be arrived at.'

The hypothesis assumes a causal link between the predictor (i.e. independent) variables which are deformations and vibrations, and the outcome (i.e. dependent) variables which are occupant satisfaction parameters (Field, 2009). To scientifically measure the relationship between deformations and vibrations, and occupant satisfaction, an experimental method is proposed. Experiments to study human interaction or human response to changes in facades should be conducted in controlled realistic conditions and must involve people (Luna-Navarro & Overend, 2021). Methods specific to such experiments which involve assessment of objective as well as subjective parameters have been developed in the recent years. Further, testing facilities such as the MATELAB (Luna-Navarro & Overend, 2021) have been designed specifically to capture occupants' perception of indoor environment and their interaction with the indoor environment control systems. Such facilities provide flexibility for testing different façade systems (on account of façade systems being demountable) and also testing a variety of indoor environment quality (IEQ) parameters. A similar approach has been taken for the design and development of a method and the experimental setup to measure the causal link between occupant satisfaction and façade deformation.

Hypotheses can be expressed in terms of variables (Field, 2009). The proposed experimental method is designed around the dependent, independent and confounding variables, which are derived from our hypotheses and identified before the design of the experiment. This process has been discussed in Chapter 4.2. The design of the experimental method is divided into two parts (i) design of experiment with volunteers and (ii) design of the experimental setup. The first part is concerned with subjective measurements of occupant satisfaction based on real-time experiences of volunteers as the deformations and vibrations in glass are manipulated by the researchers. This has been discussed in Chapter 4.3. In the second part, the objective is to replicate the effect of climate and wind loads on the test façade in a controlled way, such that it is repeatable for several experiments. This part is concerned with measurements using sensors to formulate an objective relationship between the variables, and then to conduct further tests with the volunteers. This has been discussed in depth in Chapter 4.4. Chapter 4.5 discusses the feasibility tests conducted to validate the experiment. The main conclusions from the design of the experiment with volunteers, the design of the experimental setup and feasibility tests are discussed in Chapter 4.6.

4.2 Identification of variables

4.2.1 Factors affecting tolerance towards building's motion

Human response to motion in a building or in building components depends on how the motion is perceived, and the tolerance threshold of that motion. Human response to motion is subjective, yet, there are several measurable factors that have an influence on human response. A paper authored by (Griffis, 1993) provides a list of 10 factors affecting human response to building's motion. These are (a) Frequency and Period of Building (b) Sex (c) Age (d) Body Posture (e) Body Orientation (f) Expectancy of Motion (g) Body Movement (h) Visual Cues (i) Acoustic Cues (j) Type of Motion. For this information, Griffis refers to a paper from 1971 by Khan F. and Parmelee R. titled 'Service Criteria for Tall Buildings for Wind Loadings', which seems to base this information on tests with volunteers. Another paper from the same decade by (Chang, 1973) has been cited by most recent researchers to define human response parameters.

The factors mentioned in these papers concern the perception of motion of the structural system of a building. In case of the structural system, the human body is in contact with, and at times, is supported by the components in motion. Thus, the perception of motion is through physical contact with the structure. These factors are quantifiable, and thus can be used as indicators to determine the magnitude of occupant satisfaction. However, these factors do not apply directly to facades since the perception of motion in facades is primarily visual. Therefore, there is a need to define a specific set of variables for this purpose. The factors provided in (Griffis, 1993) can be grouped into 5 categories, namely (i) Nature of Motion, (ii) Individual Traits, (iii) Relationship between body and the component, (iv) Prior Knowledge and (v) Environmental Factors. This categorization can be used for defining variables for our experiment, as it covers all the broad parameters at play.

4.2.2 Variable types - Dependent, Independent and Confounding

Based on the hypothesis mentioned earlier, a causal relationship between deformation and vibrations in glazing and occupant satisfaction is to be formulated. The magnitude and frequency of deformation may both impact occupants' perception of comfort. These variables, when manipulated with give us variations in levels of occupant satisfaction. Thus, the variables related to nature of deformation are 'independent' variables in our case. Specific variables to quantify occupant satisfaction do not readily exist, and are identified based on parallel hypotheses drawn from the findings from Literature Review and Façade Industry Survey. In our case, these variables are the 'dependent variables'.

In experimental research, in addition to the independent and dependent variables, a third set of variables known as confounding variables also play a significant role. Confounding variables by definition may affect both, the dependent and independent variables. In this case, confounding variables relate to conditions surrounding the occupant and the test façade, which also may have an effect on the measurement of occupant satisfaction, such as presence or absence of sounds associated with glass vibrations, or good or bad indoor environment quality. Identification of these variables is also done based on findings from literature review and parallel hypotheses.

4.2.3 Defining variables for the experiment with volunteers

A number of variables for the experiment have been identified and grouped based on their categories and types. Table 15 provides an overview of the variables defined for this experiment. The following chapters discuss these parameters in detail. Figure 22 shows the list of variables in context of the occupant and façade glazing, which forms the basis for setup of the experiment.

Table 15: Variables defined for experiment with volunteers

Category	Type of Variable	Variable
Nature of motion	Independent	1. Center of glass deflection 2. Frequency of deformation 3. Duration of deformation

Individual Traits	Confounding	1. Age 2. Sex 3. Country of origin 4. Country having lived in for most part of life 5. Level of Education
Relationship between the occupant and facade	Confounding	1. Distance in between body and façade 2. Body's orientation 3. Body's motion 4. Activity performed/ Engagement with façade.
Prior knowledge	Confounding	1. Expectancy of motion 2. Knowledge about material's capacity 3. Knowledge about benefits of using thinner glass
External Factors	Confounding	1. Acoustic Cues 2. Visual Cues 3. View 4. Time of the day 5. Weather 6. Type of façade 7. Indoor Environment Quality (temperature, humidity, air quality etc.)
Occupant Satisfaction	Dependent	1. Perception of Safety 2. Acceptance of Deformation 3. Satisfaction with respect to view 4. Disturbance in activity

Variables for nature of motion (Independent)

Nature of motion variables are the independent variables for this experiment which are manipulated in order to observe consequent changes in the dependent variables. In our case, the deformation and vibration are the two main parameters that define the 'motion' of glass. Vibrations are determined in terms of frequency. Although both, the values of deformation and vibration in wind and climatic loading scenarios are not fixed, for the experiment, we can assume a constant values for these during a singular instance of the experiment.

COG deflection

Deformation limits are typically on center of glass (COG) deflections. While ULS limits on COG deflection relate to maximum permissible stresses, within these limits a glass deformation is considered safe. However, for SLS, a limit generally given as ratio between longer span and deflection (e.g. L/65) is provided in standards. COG deflection is an independent variable in line with the hypothesis that higher deflections might have a negative impact on occupant satisfaction.

Frequency of deformation

The frequency of deformation of glass panel under wind or climate loading give us the rate at which the glass elastically vibrates. Under climatic loading, the frequency may be very slow, since it is caused by change in air pressure or temperature. In case of wind loading, the frequency will be higher, since wind loading is not static. Using frequency as an independent variable we can test the hypothesis that higher frequency may cause a negative impact on occupant satisfaction. We may also observe whether higher frequency deformations are more perceivable compared to low frequency deformations.

Duration

Human tolerance towards sudden change in state of façade glazing may be different from tolerance towards continuous motion. Occupant satisfaction may vary with time. Thus, the duration of motion is also a critical performance indicator for comparison between effects of instantaneous and prolonged deformation or movement in glass on occupant satisfaction.

Variables for Individual Traits (Confounding)

Individual acceptance thresholds vary based on individual traits such as age, sex and background. These variables are confounding, as these may indirectly have an effect on human response towards independent variables. Although personal thresholds may still be very subjective, the age, sex and background might give a realistic estimate of acceptance thresholds.

Age

According to (Griffis, 1993), the sensitivity of humans to motion is an inverse function of age. Although this was in relation with motion of structural components in buildings, the variable of age (or age groups) can be used to test the hypothesis that older people are more sensitive towards deformation in façade glazing.

Sex

The paper by (Griffis, 1993) also states that although the general trend in response across genders remains the same, women have been found to be slightly more sensitive to motion. Again, the same needs to be verified with respect to façade glazing, which is why sex is a critical confounding variable.

Background: Country of origin and country of residence

At a conference (IStructE & IABSE, 2018) on serviceability of building structures, it was noted by a few engineers that the acceptable deflections in different countries by law were different. For instance, the deflection limits on high rise buildings in China are around H/800, in London around H/500, in Korea H/300 and in Taiwan H/200. This may suggest that an individual's background may have an impact on their personal acceptable thresholds. In terms of background, the country of one's origin may differ from the country where the respondent has lived for most of their life. This is why both the variables are considered to get a fair understanding of responses.

Education

The format of the experiment is by means of an online survey. Although the level of one's education is not necessarily related to their response to glass deformation, this may give a generic idea to what extent the respondent may have understood both the content, and the purpose of the survey, and whether this could have an effect on their response.

Variables for relationship between the occupant and facade (Confounding)

Distance in between body and façade

Since the engagement of an occupant with façade is mainly visual, the distance between the individual and the façade governs the amount of disturbance in a person's view cause by glass deformation. If a person is closer to the glass, there is a higher chance of them sensing the motion in glass, as compared to if they are farther.

Body's orientation

In addition to distance, the effect of glass deformation also depends on the orientation of the individual with respect to the façade. This parameter can be used to test the hypothesis that angle of orientation of the occupant with respect to façade has an impact on their acceptance of deformation.

Body's motion

Similarly, if the occupant is in motion, and not spending a long time in front of the glazing, the tolerance may even be higher, given that their engagement with glazing is relatively temporary. Body's motion may also mitigate the effect of movement of glass. To test these hypotheses, this parameter of body's motion with respect to facade can be used.

Activity performed/ Engagement with façade

Based on the application of façade glazing, it can be assumed what the engagement of an individual with the glazing will be. If we consider the example of a store room vs a viewing gallery, a user would be expected to engage more with the glass in the viewing gallery, and thus the tolerance for deformation in that case would be low For instance, if an occupant is sitting in a room with a glazed ceiling, for the most part it can be that the glazing is out of sight, and thus, the tolerance towards deformation may be high.

Variables for Prior knowledge (Confounding)

To test our main hypothesis i.e. 'the acceptance threshold can increase if occupants have confidence in the strength of glass and prior knowledge about embodied carbon benefits of using thinner glass', another set of variables is introduced, those concerning 'Prior Knowledge'. These are (a) prior knowledge about expectancy of motion, (b) prior knowledge about strength of material and (c) prior knowledge about embodied carbon benefits of using thinner glass.

Expectancy of motion

Prior knowledge about movement in structure, or predictable behavior of materials may impact human response to that situation (Griffis, 1993). The occupant's expectation from a façade is mostly that as a layer that provides light, view and maybe ventilation, and that insulates them from external environmental conditions. But, in the event of heavy wind, the expectation of a façade is more as a protective layer, as compared to other properties of glazing. If prior knowledge about possibility of strong winds is not present, there is a possibility that the occupant may be alarmed by the sudden deformation. Further, if at the event of deformation, other cues such as sounds are present, that also might have an effect on tolerance, as the combination of our senses helps us judge the situation better.

Knowledge about material's capacity

Secondly, tolerance also depends on knowledge about the material. In the case of a tent or a fabric canopy/ parasol, the occupants are not alarmed by deformation of the material under wind load. The prior knowledge that the material can accommodate certain level of deformation and that in the event of failure would not cause significant harm, helps with the acceptance of deformation. However, glass has been always perceived as a rigid material, and deformations, even well within ultimate limits might cause an alarm among occupants. Further, in case of failure of a component of a glass bridge that has been designed for the PFLS (Coult & Overend, 2022), prior knowledge about its capacity is required for someone to remove or replace the component. In the case of façade glazing, if thinner glass were to be used, it is important that the occupants are aware of possible deformations and the extent of deformation which may render the glass unsafe.

Knowledge about benefits of using thinner glass

Thirdly, acceptance thresholds can be breached in cases where occupants are aware of a certain trade-off which may have beneficial effects. For example, a lower quality glazing may be acceptable for a building if the client is aware that the glass has been manufactured using higher recycled content (Zaccaria, 2022). Similarly, in case of use of thinner glass in the facades, if the occupants are aware about the capacity of the glass as well as the embodied carbon savings it helps achieve, the acceptance of deformations may be higher.

Variables for External Factors (Confounding)

The experiment primarily relies on the visual perception of glass deformation while deliberately eliminating other variations in the environment. The presence or absence of sound and vibrations along with deformations in buildings has an effect on the perception of building movement (Griffis, 1993).

Acoustic Cues

The presence or absence of acoustic cues in case of a windy condition has an effect on perception of motion of glass facades. This may or may not affect the acceptance towards deformation of glass. Acoustic cues not related to the motion may also matter, as these may influence the state of mind of an individual. Additionally, absence of acoustic cues, in case a person is wearing noise cancelling headphones in an office environment may cause a different reaction towards glass deformation, compared to that in presence of acoustic cues.

Visual Cues

Again, considering a windy scenario, the movement of glass in combination of movement of objects in view might have an effect on overall perception of motion. This is typically the case when a person is able to see movement of trees in wind. However, if the view is comprised of objects that remain visually stationary in wind, the movement of only glass may have a different effect. Thus visual cues are an important parameter to consider.

Type of View

Since the impact of glass deformation on view of the outside would also govern the acceptance of deformation, it is important to do the test in different types of view. The views can be simply graded from being more rectilinear (buildings, streets) to being more organic (many trees). This can be used to test the hypothesis that acceptance thresholds are higher when the view is more organic. It would also matter whether the view of the outside is from a height or at ground level.

Time of the day

Human response to environmental conditions varies with time. Especially in an experiment with occupants, the time of the day when these experiments are conducted matter in terms of readings taken. Even if the parameter of time may not directly impact human response, it is better to conduct the experiments in a similar time frame to avoid variations in readings.

Weather

External weather conditions such as overcast sky or bright sunshine or windy weather may impact how the occupant perceives the motion in façade glazing. Since this is a variable beyond the control of researchers, it is important to record the external weather conditions during the experiments.

Type of façade

The experiment may be conducted with one or more types of façades. The presence or absence of coatings, reflectivity of glass, and such parameters that impact the optical performance of glass may also affect the acceptance threshold of glazing deformation. Thus, it is important to record the exact type of façade and specification of glass during the experiment.

Indoor Environment Quality (temperature, humidity, air quality etc.)

Since the experiment deals with human response, the indoor environment quality is a critical parameter as human response may vastly be affected by this. The temperature, humidity and air quality are some of the parameters that must be recorded during an experiment since these may affect the acceptance thresholds.

Variables for Occupant Satisfaction (Dependent)

The relationship between occupants and façade glazing is mainly visual. Occupant satisfaction with the view is therefore a main serviceability requirement. Four variables that can help quantify occupant satisfaction with glass deformation have been identified, namely (a) Perception of safety, (b) Level of acceptance of deformation, (c) Satisfaction with quality of view and (d) Disturbance in activity.

Perception of Safety

Glass is traditionally perceived as a robust and rigid material, which is expected to protect us from external conditions such as heavy winds. In this case, deformation and vibration of glass might imply a threat to safety of the occupants. This implies that the extent to which perception of safety is disturbed could be a measure of acceptance of glass deformation.

Acceptance of Deformation

Deformed glass is conventionally perceived as a sign of low quality, as the expectation from glass surfaces is to be extremely flat. Acceptance may change based on perceived quality of a product. This implies that different degrees of deformation could have different levels of acceptance of deformation.

Satisfaction with respect to view

Glass deformation may impact the visual performance of façade glazing, causing distortions in view. The view is a combination of reflected images in glass, and view through the glass. Distortions in any one of these may be a cause for subjective degradation of view. The level of dissatisfaction with the view can be corelated to the magnitude of deformation or vibrations, which is why this is a dependent variable.

Disturbance in activity

Façade glazing is always seen as a passive membrane between the exterior and the interior and is not expected to move. Unexpected motion in facades is likely to cause disturbance in the day to day activities of occupants. The level of disturbance can be a valid measure of dissatisfaction with deformation.

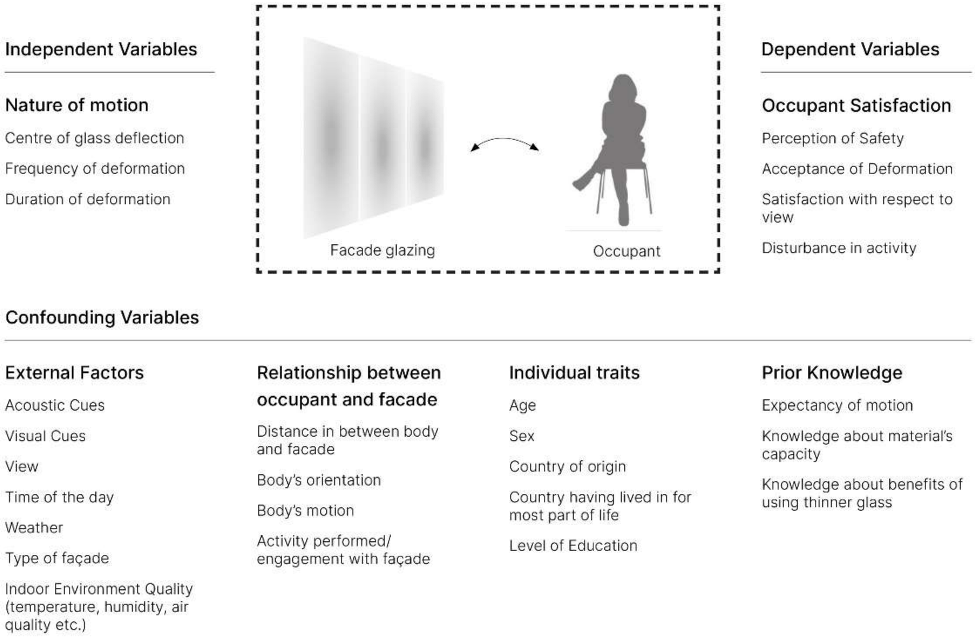

Figure 22: Variables for the experiment adapted from : Griffis, L. G. (1993). Serviceability Limit States Under Wind Load. Engineering Journal. This forms the basis for the experimental setup.

4.3 Design of the experiment with volunteers

4.3.1 Overview

The list of variables as shown in Figure 22 forms the basis for the design of the experiment with volunteers. Manipulation of the independent variables i.e. nature of motion in glass will have an effect on our dependent variables, i.e. occupant satisfaction. The experiment is thus designed around these two sets of variables. Ideally, maintaining constant values for the confounding variables will lead us to arrive at a direct relationship between the nature of motion and occupant satisfaction. However, our hypothesis prompts us to explore the effect of prior knowledge on occupant satisfaction in an attempt to raise the acceptance threshold. Therefore, it is proposed to conduct the experiment with different sets of people, with and without prior knowledge about the expectancy of motion, material capacity and benefits of using thinner glass. For each of these sets, the proposal is to manipulate the deformation and vibrations and to retrieve occupant satisfaction data.

4.3.2 Respondents

Sample Size

To determine the sample size for the experiment, a power analysis using G*Power was conducted. Power analysis gives the probability to detect true association or difference between variables in an underlying population. It was found that a minimum sample size of 12 people is optimal if the experiment were to be conducted with one group, and 35 people if the experiment were to be conducted with more than one group.

Grouping

The three variables of prior knowledge are : expectancy of motion, knowledge about the material capacity and knowledge about benefits of using thinner glass. Based on whether or not people in the sample have this prior knowledge, 16 different combinations are possible. However, people volunteering for this experiment will be informed about possibility of movement in glass in advance, because otherwise, given a lab setting their reaction may be extreme, and unusable for analysis. Therefore, if only knowledge about material capacity and about benefits are considered, that leaves us with 4 possible combinations i.e. people have no knowledge about both factors, or have knowledge about one of the factors or have knowledge about both factors.

Further, if people have no knowledge about material's capacity, but only knowledge about its benefits, it can be assumed that their reaction could be the same as if they had no knowledge about both factors. This can be assumed since not knowing about material capacity may cause alarm in any case. Therefore, from the 4 combinations, only 3 possible combinations are tested as shown in Table 16. These can be tested in 3 separate groups of people with around 12 people each. To minimize variance due to separation in groups, the groups will have to be mixed in a way that the confounding variables related to personality traits are balanced.

Table 16: Grouping of respondents based on level of prior knowledge about material's capacity and benefits of using thinner glass.

A	GROUPS BASED ON PRIOR KNOWLEDGE				
	Variables	**GROUP A (12 people)**	**GROUP B (12 people)**		**GROUP C (12 people)**
1	Expectancy of motion	**YES**	**YES**	~~**YES**~~	**YES**
2	Knowledge about material's capacity	NO	YES	~~NO~~	YES
3	Knowledge about benefits of using thinner glass	NO	NO	~~YES~~	YES

Background

It is proposed that if the experiment is conducted on a large scale, diverse samples with people from mixed backgrounds should be selected for each group. However, at a small scale this is difficult. In this case, people from a similar age group and background can also be studied to minimize variance in smaller sample sizes.

4.3.3 Context and activity

For the experiment results to be representative of a considerable number of use cases, the selection of context and activity performed by the individual during the experiment is crucial. It is proposed to replicate an office environment for the experiment wherein the volunteer is expected to read at a desktop computer. An office environment is found to be a fair representation since the person's engagement with the façade is neutral, yet the person is aware of its presence. A working environment and activity was chosen as it is mostly conducted during the day time, wherein our experiment is set. Since we are also testing the level of disturbance of activity, the activity selected was reading a paper on the screen, so it may be easier for the person to gauge when they feel disturbed by the motion in glass.

4.3.4 Stages of the experiment

Values of independent variables

The number of stages of the experiment with each volunteer is determined by the combinations of independent variables i.e., in this case by the combination of the amount of deformation, the frequency of deformation and the duration of deformation. If the experiment is to be conducted in a limited time frame, the duration of deformation can be kept constant. To test the effect of duration of the deformation on occupant satisfaction, a separate experiment can be conducted with deformation and vibrations being constant.

With COG deformations and frequency, countless number of variations between 0 and respective maximum permissible values are possible. The first step is to identify a suitable range for both the factors and secondly, sub-divide it into sub-levels, e.g. 3 levels corresponding to high, medium and low magnitudes. For COG deflections, the limit as per standards is considered as L/65. To test our hypothesis, this limit must be exceeded in the experiment. So highest deformation should exceed L/65, but stay within the ULS deflection. The medium deflection should be around L/65 and the lower deflection should be the minimum detectable deflection. The minimum detectable deflection limit can be determined in the beginning by objective means.

Frequency variation can be used to mainly represent wind loading effect. In terms of frequency, certain high frequencies may not be detectable by the human eye and lower frequency deflections may not be representative of a wind loading effect. Therefore, a suitable range of frequency which is detectable and gives a fair representation of effect of wind must be determined prior to the experiment.

Stages

Once the high, medium and low values of magnitude and frequency of deformation have been determined, there are 9 possible combinations. Each of these combinations can be tested in one stage of the experiment. However, testing of all 9 combinations may be redundant if fewer critical combinations can help determine valid results. 3 critical combinations are recommended for an experiment, namely – (i) high deformation at low frequency, (ii) low deformation at high frequency and (iii) high deformation at high frequency. The first combination could provide us more insights about the effects of the amount of deformation, while the second combination could provide more insights about the effects of frequency. The third combination can give us insight into the combined effects of both factors. Therefore, the experiment can be conducted in 3 stages with each of these combinations for changes in nature of motion.

Table 17 shows the three stages decided for the proposed experiment considering a panel of the size 1m x 1.5m, where permissible deformation based on L/65 is approximately 23mm. As an example, the higher deflection limit is considered as 50mm (which should be verified to be lower than the ULS limit) and the lower deflection limit is estimated to be 15mm. The duration of the motion is fixed in this case to 10 seconds.

Table 17: Three stages of the experiment based on combinations of independent variables.

B	NATURE OF MOTION (INDEPENDENT)			
	Variables	**STAGE 1: High deformation at Low frequency**	**STAGE 2: Low deformation at High frequency**	**STAGE 3: High deformation at high frequency**
1	Amount of deformation (permissible 23mm for L=1.5m)	50mm	15mm	50mm
2	Frequency of deformation	Low	High	High
3	Duration of deformation	**Fixed: under 10s**		

4.3.5 Balancing the confounding variables

As shown in Figure 22, there is a long list of confounding variables which may have an effect on the dependent variables. To nullify their impact, the confounding variables must be either fixed at constant values or balanced among the samples. As mentioned earlier, the presence or absence of prior knowledge will be fixed per group. Since individual traits may vary, these need to be balanced between the groups. Table 18 shows the five variables for individual traits and the questions that would be asked for these in the survey. It should be ensured that all the groups would have similar proportions of male and female candidates, and that they are of a similar age group or range, and with a similar level of diversity in their background. If the experiment is conducted at a university, the 'education' variable can be fixed, e.g. by inviting students from the Masters program.

Table 18: Variables and questions related to individual traits.

C	INDIVIDUAL TRAITS (CONFOUNDING)						
	Variables	**Questions**	**Options**				
1	Age	Could you please indicate your age?	Scroll through				
2	Sex	How do you describe yourself?	M	F	non binary	Self describe	Prefer not to say
3	Country of origin	Which country were you born in?	Scroll through				
4	Country having lived in	Which country have you lived in for most part of your life?	Scroll through				
5	Education	What is the highest level of education you have completed?	**Fixed: Masters students**				

For the proposed experiment, in terms of relationship between the façade and the occupant, the most critical values of each factor are selected and fixed. Recommendations for these are given in Table 19. The occupant is positioned close to the façade since it is assumed that this is where effects of deformation will be most apparent. Their orientation with respect to façade is side-ways, since this is generally considered as a standard in case of office layouts, especially in open office spaces. The occupant is seated and relatively stationary with respect to the façade and performing the activity of reading a paper on a desktop monitor.

Table 19: Values of variables related to relationship between the facade and the body.

D	RELATIONSHIP WITH FAÇADE (CONFOUNDING)	
	Variables	**Values**
1	Distance in between body and facade	**Fixed: close**
2	Body's orientation	**Fixed: sideways**
3	Body's motion	**Fixed: stationary**
4	Activity/ Engagement with façade	**Fixed: office/ reading on screen**

While external factors such as indoor environment, acoustic cues and visual cues can be controlled, the weather outside can only be monitored. Table 20 shows the recommended states of external factor variables. A certain uniformity can be achieved if the experiments are conducted at the same time period in a relatively uniform weather conditions.

Since the experiment deals with distortions in view, the view outside the laboratory matters. The proposed experiment will be housed in a mobile laboratory, which allows for an informed selection of view. It is recommended that a view with is predominantly rectilinear be selected, since it is easier to detect distortions in this case.

The acoustic and visual cues related to motion in glass, such as sounds associated with mechanisms or movement of supports must be kept to a minimum. The presence of such cues could have an additional influence on human response, which will dilute our reading of impact of motion in glass.

Table 20: Values of variables related to external factors.

E	EXTERNAL FACTORS (CONFOUNDING)	
	Variables	**Values**
1	Acoustic cues	**Fixed: absent**
2	Visual cues	**Fixed: absent**
3	View	**Fixed: With prominent straight lines**
4	Time of the day	**Fixed: daytime**
5	Environmental factors - temperature, humidity and air quality	**Fixed: average**
6	Type of façade	**Fixed: average**
7	Altitude	**Fixed: Floor level**
8	Weather	Recorded

4.3.6 Questionnaire

In the beginning of the experiment, a short questionnaire to record information about individual traits such as age, sex and background will also be filled by the volunteers. During the experiment, the occupants will be asked to record the their level of acceptance or satisfaction via another questionnaire. Both these surveys will be designed and hosted using a trusted service (such as Qualtrics) and the data collected in .csv format. The survey is accessed via a QR code placed near the experiment setup, and can be filled out by the volunteers using their mobile phones. The data management recommendations of the HREC will be followed to ensure that the privacy of the volunteers is not compromised.

The questionnaire about occupant satisfaction is common for all stages of the experiment. Each question has 2 part. The first is a binary response (Yes/ No) question asking whether the particular effect was experienced or not; and if the response is affirmative (Yes), the second part asks the respondent to rate on a scale of 1-5 the extent to which the effect was experienced, with 1 being the lowest level of acceptance and 5 being the highest. Table 21 shows the list of questions and the options for the survey. The responses correspond to each of the effects or dependent variables, i.e. perception of safety, acceptance of deformation, satisfaction with the view and disturbance in activity.

Table 21: Dependent variables and questions related to these.

F	ACCEPTANCE/ SATISFACTION						
	Variables	**Questions**	**Values**				
1	Perception of safety	Did you feel **scared** due to the movement of glass?	Yes	No			
		Which of the following best describes how you felt when the glass moved?	extremely unsafe	very usafe	fairly unsafe	slightly unsafe	safe
2	Acceptance of Deformation (Includes magnitude and frequency combination?)	Do you consider the current deformation of glass acceptable?	Yes	No			
		To what extent do you consider the deformation acceptable?	very low extent	low extent	medium extent	high extent	very high extent
3	Satisfaction with respect to view	Are you satisfied with your view through the window?	Yes	No			
		How would you rate your level of satisfaction of the view through the window?	very low	low	medium	high	very high
4	Disturbance in activity	Were you disturbed by the glass deformation in your activity?	Yes	No			
		How would you rate your level of disturbance?	unbearable	very annoying	annoying	perceptible	non perceptible

4.4 Design of the experimental setup

4.4.1 Overview

The design of the experimental setup is based on the design of the experiment with volunteers discussed in the previous chapter. In this chapter, the decision making process for the experimental setup is discussed, along with the mechanisms used for inducing deformation and vibration in glazing. To test the working of proposed mechanism, two prototypes , one in PMMA and one in aluminosilicate thin glass (1.1mm thk) were connected to a controlled air pressure system and tested. The chapter discusses the results and findings from these exercises and provides recommendations for conducting this exercise in a laboratory setting. The experiment is proposed to be set up in the Light Van, which is a mobile laboratory located at the TU Delft. Light Van is suitable for this experiment as it allows mounting and demounting of different glazing panels for testing and to create an office setup.

4.4.2 Physical setup vs. Virtual setup

Physical Setup

In a physical setup, a controlled environment representative of an office space is created in which the participant is expected to perform a task for a certain time period. The positioning of the volunteer with respect to the façade, their orientation and environmental conditions in the laboratory are derived from the decisions made during the design of the experiment. A standard size of glazing is to be tested is selected for the set-up.

Deformations and vibrations are induced in glazing either mechanically, e.g. using an actuator with a push-pull mechanism or pneumatically, e.g. using air pressure variations. In a physical setup, along with the responses from the volunteer, objective measurements of the effects of deformation such as changes in optical performance, lighting conditions, facial expression mapping etc. can be also recorded. The facial expressions of the participant are numerically recorded by means of a facial action unit, set up facing the volunteer. Subjective data of human response is collected by means of a questionnaire after a certain stage of the experiment.

Virtual set-up

In a virtual setup, a simulated environment is created to replicate an office space using modeling and rendering software. The virtual set-up could allow for testing multiple variations of glass sizes, and relative positioning of volunteers with respect to the facade. Other confounding parameters can be determined based on the design of the experiment. Varying degrees and frequencies of controlled deformations in glazing can be simulated in a virtual setup. The recording of responses of the participant will only have to be done through a questionnaire. The collection of facial responses will be restricted by the virtual reality glasses. In a virtual setup, only the elements necessary for the experiment can be simulated and external factors such as acoustic and visual cues can be eliminated.

Comparison

Conventional perception towards glass and the knowledge of the instantaneous nature of its breaking (without a warning) raises safety concerns among people in the presence of moving (or vibrating) glass. Physical proximity in this case certainly raises more safety concerns compared to being farther away from moving or vibrating glass. Therefore, to gain a realistic judgement of human response to vibrations at different scales, a physical setup is better compared to a virtual setup for this experiment.

Although the engagement of a person with glass in a virtual setup may not raise safety concerns comparable to that of a physical setup, virtual setup too has many advantages. Experimentations in virtual setup using simulations are relatively faster and allow for testing a higher number of variations in terms of different glazing sizes, rates of deformation, relative positioning of participants, views seen through glass, etc. Compared to a physical setup, these are also relatively cheaper.

A third possible approach is a combination of physical and virtual setups. While physical setups can be used for benchmarking people's responses, a virtual setup can be used as an extension of the experiment to test more scenarios. Conducting a virtual experiment alone would not give realistic results. Therefore, it is recommended that experimentation be conducted using a physical setup, with an optional extension using virtual reality if required. For the purpose of this research, given the time constraints, only a physical setup has been tested.

4.4.3 Experiment setup concept

To achieve variations in deflection in glass, two possibilities were evaluated. One was the use of actuators for out of plane displacement of corners of glass pane and the other was use of air pressure on the entire glass surface. Actuators are slower compared to pressure systems and they would typically lead to a single curvature. Using actuators to displace corners will also cause displacement of the edges whether the edges are unsupported or attached to linear supporting frames (Datsiou & Overend, 2016). Figure 23 shows the different modes of deformation in glass as observed by (Staaks & Eekhout, 2004) wherein the edges of the glass start becoming curved after a certain out of plane displacement is reached at the two unsupported corners. (The advantage of actuators is higher level of control over the displacements.

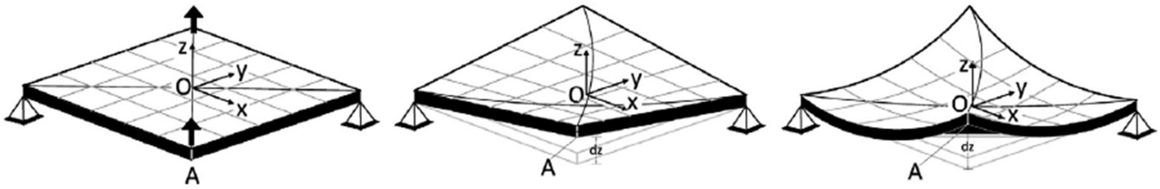

Figure 23: Deformation modes in glass (a) undeformed; (b) mode 1 deformation; (c) mode 2 deformation (source: Datsiou & Overend, 2016)

On the other hand, pressure systems can generate a double curvature as seen in Figure 24. Variation in displacement can be achieved almost instantly by controlling the input and output pressure within a cavity. By using pneumatic valves that can be electronically controlled (electro-pneumatic systems), it is also possible to achieve a dynamic variation in air pressure inside the hermetically sealed cavity. To replicate effect of climatic loading in an IGU with 'n' number of panes and 'n-1' number of cavities, each cavity can be pressurized and required deflection achieved. To replicate the effect of wind loading in IGU with 'n' number of panes, an additional pane 'n+1' will have to be added to the assembly, and only the additional cavity thus created can be pressurized. The first n panes will then deflect in line with the Load Sharing Effect (Galuppi & Royer-Carfagni, 2020; Heiskari et al., 2022; Starman et al., 2020). (Respondek et al., 2022)

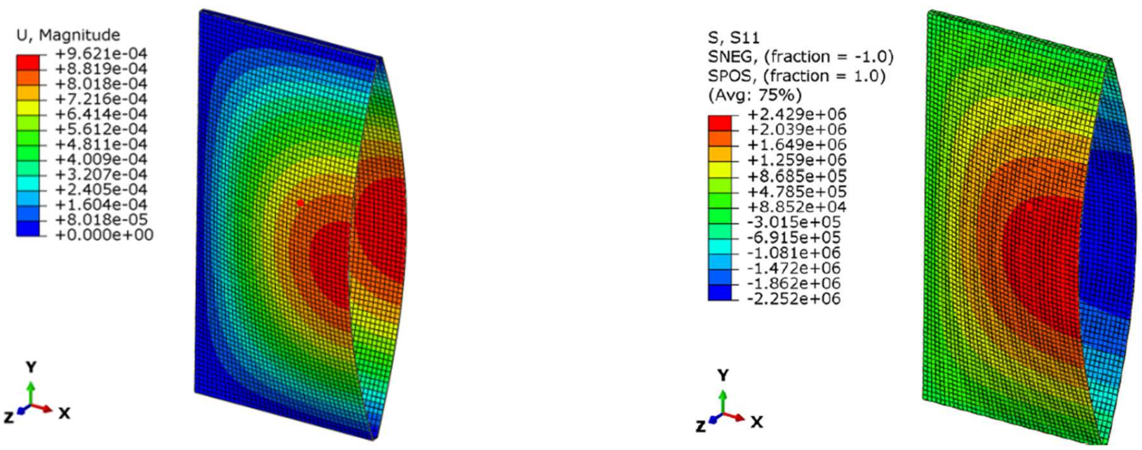

Figure 24: FEM analysis results from Respondek et al., 2022 (a) deflection map and (b) stress map of a square IGU of 800mm side under the influence of air pressure difference between the exterior and interior of cavity.

Based on these ideas, a conceptual design of the experiment was setup with pressure controlled deformation in façade panels. To conduct the experiment with volunteers, the panels are mounted on the external wall of a laboratory setup designed to replicate an office environment. Volunteers are called in one at a time, and based on different combinations of movements in glass, are asked to fill a questionnaire to indicate their level of acceptance of deflection and vibration. Based on the retrieved data, acceptance thresholds of deformation can be achieved using statistical means. Figure 25 represents the conceptual setup for the experiment.

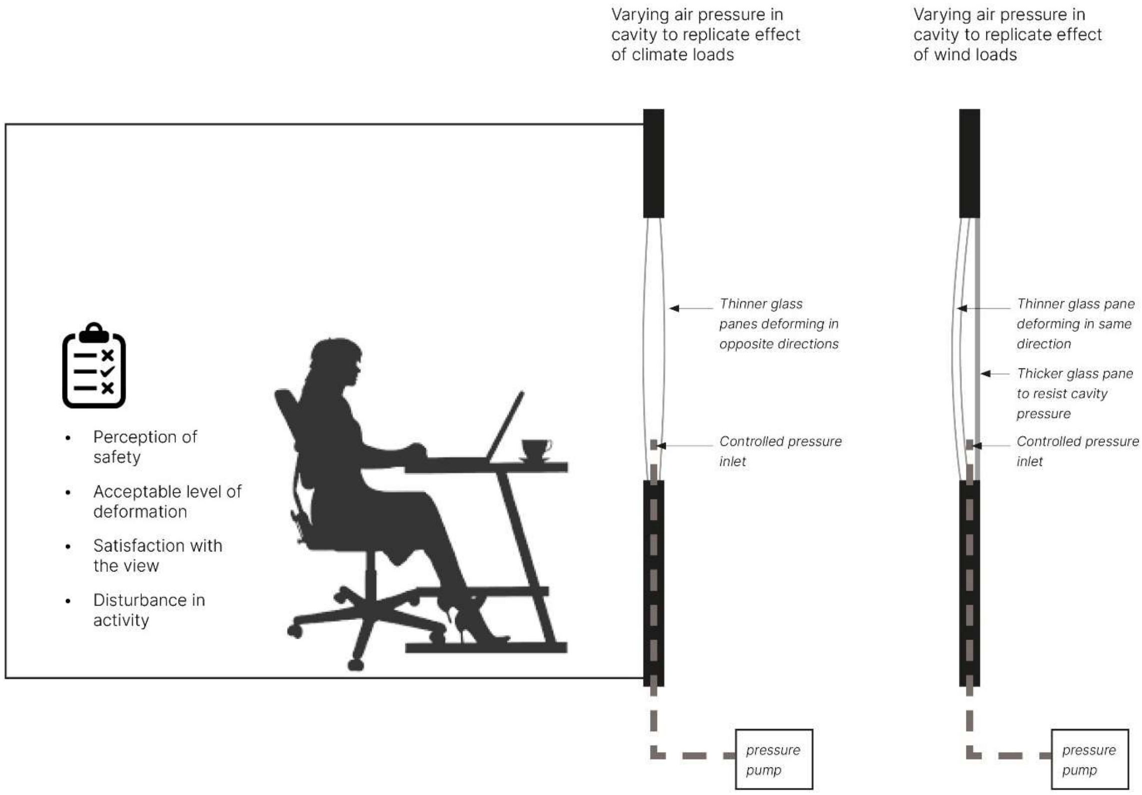

Figure 25: Conceptual setup of experiment based on pressure system to test the effect of (a) climate loading and (b) wind loading.

The Lightvan

The Lightvan is a multifunctional mobile laboratory built in a delivery vehicle. The setup was built in 2014 as a collaboration between Faculty of Architecture TU Delft and Department of Built Environment, TU Eindhoven mainly to conduct experiments related to daylighting in specific environments (Hordijk et al., 2014). The mobility of the van allows for change in orientation depending on desired light direction and views. The back of the van is a demountable frame with a window to install façade panels to be tested. The Lightvan was found suitable to conduct this experiment since it is large enough to accommodate an office setup for one person, and is well equipped with electrical supply, lighting and furniture. The sizes of the façade panels for the experiment (1467mm x 972mm) are based on the available size of opening in the Lightvan.

4.4.4 Preliminary validation of concept

The relationship between the applied pressure on a rectangular plate of glass, its thickness and maximum deflection (deflection at the center) is given by Equation 4. This equation can be used as long as the length (b) is smaller than or equal to 2 times the width (a), which is true in our case. Here, w is the pressure in MPa, E is the Young’s modulus in MPa and t is the thickness of plate in mm. Similarly, Equation 5 can be used to determine the relationship between applied pressure on glass, its thickness and maximum stress (stress at the center) in glass.

$$\Delta_{\max(at\ center)} = \frac{0.142wa^4}{Et^3\left(2.21\left(\frac{a}{b}\right)^3+1\right)}$$

Equation 4: Equation for maximum deflection (deflection at center) in rectangular plate simply supported on all edges under uniform loading.

$$\sigma_{\max(at\ center)} = \frac{0.75wa^2}{t^2\left(1.61\left(\frac{a}{b}\right)^3+1\right)}$$

Equation 5: Equation for maximum stress (stress at center) in rectangular plate simply supported on all edges under uniform loading.

The relationship between pressure and wind speed can be determined by the equation w = 0.5 x ρ x v^2, where ρ is the density of air (considered 1.2 kg/m^3) and v is the wind speed in m/s. We have seen in Figure 3 that incident wind pressure is not constant over time, and it reaches a peak value of up to 1000Pa. This is equivalent to a wind speed of 132 km/h (36.7 m/s) if we consider an air density of 1.5 kg/m3. For the experiment, a maximum value of applied pressure of 2000 Pa was considered for the experiment, which represents a wind speed on over 200 km/h (55.6 m/s). This was decided mainly in order to achieve deformations higher than the recommended limit of L/65, or 23mm while still staying within ultimate state limits for glass thickness up to 4mm.

For the purpose of validation of the concept for the experiment, these formulae were incorporated in an excel sheet, included in Appendix 5. Since the dimensions and maximum pressure are determined, the excel sheet was used to achieve maximum deflections and stresses based on variation in glass pane thicknesses. Maximum allowable stresses in glass based on type of glass can be given by the characteristic tensile bending strength, as seen in Table 22.

Table 22: Characteristic Tensile Bending Strength of glass based on glass types.

Glass Type	Characteristic Tensile Bending Strength (MPa)
Annealed	25 MPa
Heat Strengthened	45 MPa
Fully Tempered	80 MPa

Comparison of these limits and stresses as per the excel sheet can be done to make decisions regarding the glass type and thickness to be used for the experiment. One of the aims of the experiment is to check whether deflection limits above the standard serviceability limits are acceptable. The standard serviceability limit on deflection of glass according to most building regulations was found to be L/65; i.e. a deflection of 22.56mm for a panel with dimensions 1467mm x 972mm. From the table, it can be observed that a glass pane of 1467mm x 972mm x 4mm under 2000Pa pressure undergoes a deflection of 34.44mm and stress of 60.32MPa. This information leads us to the possibility of conducting the experiment using Fully Tempered glass panes, with minimum 4mm thickness.

4.4.5 Validation of experimental method from parallel research

A recent study published in the MDPI journal (Kozłowski et al., 2023) presents a similar experimental setup to assess the effect of climatic loads on deflections and stresses in IGUs. The results from the experiment were compared with numerical and analytical models. One of the conclusions of the study was that the numerical and analytical models overestimated the deflections by 16% and stresses by 32%. This highlights the role of the edge supports and connections which induce a rotational stiffness at the edges of glass, which may not be accounted for in numerical and analytical models. This validates the use of a physical setup for subjective and objective measurements in our experiment.

The researchers have used an IGU of dimensions 500mm x 500mm of toughened glass panes of 6mm thickness separated by a 16mm spacer. The use of larger sizes of panes will need a significant increase in amount of air/ gas injected to achieve a significant deflection. This was evident from the preliminary tests conducted for this experiment using full size panels from AGC, which demonstrated the need for larger inlet and outlet tubes and air supply at a higher flow rate.

The research conducted by (Kozłowski et al., 2023) helps validated the experimental method used in this experiment, although the intent of both these experiments are different. In our research, the effect of wind loading can also be simulated by varying the frequency of air inlet and potential simultaneous variations in air flow.

4.4.6 Glass build-up for experiment

The IGUs for this research project are provided by AGC-Interpane. Findings from the calculations mentioned in the previous chapter helped in specifying glass for these IGUs. Based on the concept, two variations of build-up were proposed – double glazed unit with 4mm fully tempered glass panes and triple glazed unit with 2 panes of 4mm fully tempered glass and a laminated outer pane of 6mm glass +1.52mm (interlayer) + 6mm glass. The pressure in the outermost cavity has to be retained by the outermost laminated glass, and hence it is thicker. Figure 26 shows the proposed build up variations.

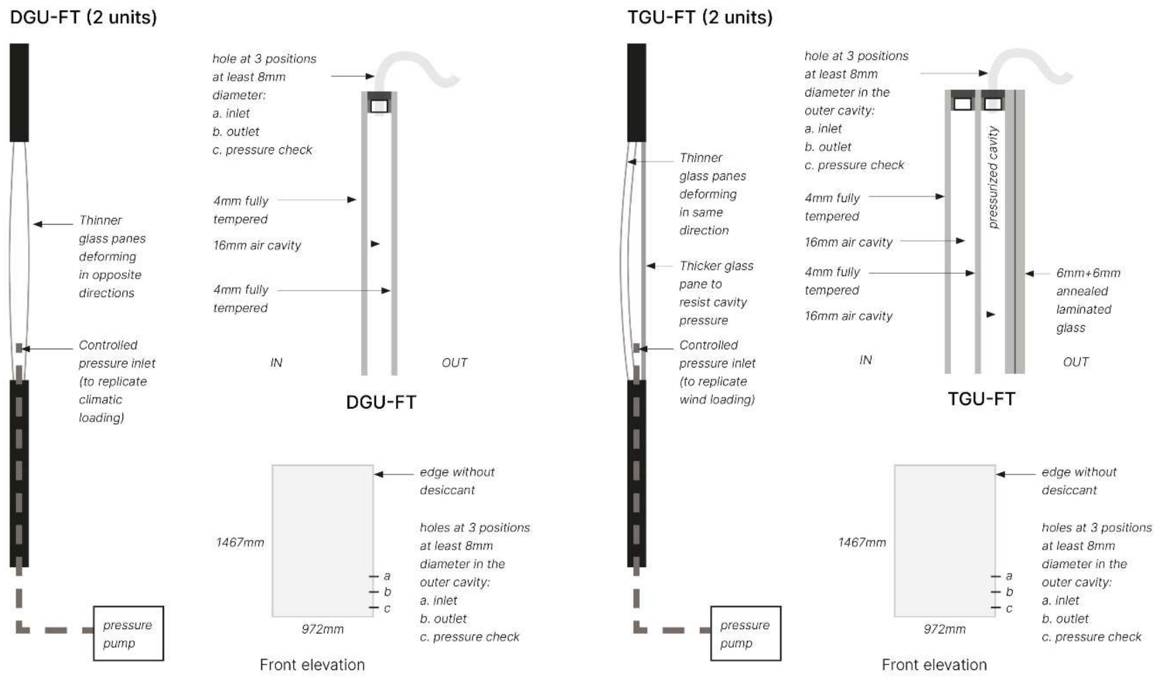

Figure 26: Proposed build-up for the experiment (a) Double glazed unit and (b) Triple glazed unit.

For the inlet and outlet of air in the cavity, 3 holes with 8mm, 6mm and 6mm diameters were proposed in the spacer bars of the build-up. AGC-Interpane typically provides desiccants in one smaller side and one longer side of the IGU. Therefore, the holes were proposed to be located on the longer edge without desiccant. The holes were proposed to be positioned closer to the center of the edge, so that they are away from clamps that support the IGU.

For safety concerns, it is always a better option to have all panes of glass in the build-up as laminated. However, the factory was not able to provide laminated glass in the desired thicknesses in the specified time frame. Hence, it was decided to apply a self-adhesive protective transparent film on the inner panes of the glass build-up to keep the volunteers safe from accidental injury in case of glass breakage. However, the film increases the possibility of disturbance in visual performance due to presence of air bubbles or impurities due to improper installation.

For future experiments it is recommended that the inner pane is laminated. Further, in triple glazed unit, similar behavior is expected from the inner pane and the middle pane, as an effect of load sharing. Hence, it is recommended to also use laminated glass for the middle pane in future experiments. For the calculations for validation the effective thickness of laminated glass will have to be considered. The expressions for effective thickness is different for determination of deflections (Equation 6) and determination of stresses (Equation 7).

$$h_{eq,\delta} = \sqrt[3]{(1-\varpi)\sum_i {h_i}^3 + \varpi\left(\sum_i h_i\right)^3}$$

Equation 6: Expression for determination of effective thickness for deflection in laminated glass.

$$h_{eq,\sigma} = \sqrt{\frac{(h_{eq,\delta})^3}{(h_i + 2\varpi h_{m,i})}}$$

Equation 7: Expression for determination of effective thickness for stresses in laminated glass.

Here, h_{eq} is the effective thickness, h_i is the thickness of the i^{th} pane, and $h_{m,i}$ is the distance between the mid-plane of ply i and mid-plane of the whole laminated glass pane. ϖ is the shear transfer coefficient of the interlayer where $0 < \varpi < 1$. $\varpi = 0$ implies no shear transfer, or freely sliding panes and $\varpi = 1$ represents full shear transfer, or rigidly fixed panes. The value of ϖ for specified interlayer can be obtained from the supplier.

4.4.7 Prototypes for preliminary testing

Two prototypes were built during the course of design of the experiment for preliminary testing of air pressure system and testing the performance of self-adhesive transparent film. The first prototype was made using 2mm thick sheets of PMMA of size 500mm x 400mm and the second was made using chemically strengthened aluminosilicate thin glass (AGC Falcon glass) of 1.1mm thickness and 500mm x 500mm size. Spacers for both prototypes were solid hardwood of 15mm x 15mm square section. For the PMMA prototype, the hardwood spacer was shaped to create a rebate of 2mm x 8mm on the inner and outer faces of the spacers, to prevent the glue from creeping into the cavity. For the thin glass prototype, the solid square section was used as it is. Figure 27 and Figure 28 show the PMMA prototype filled with air pressure using a bicycle pump. A hand-made zebra board was used to check for optical distortions, if any. But it was difficult to judge as the lines of the zebra board were very narrow. Figure 29 is an image of the thin glass prototype after a breaking test was conducted to test the effect of using a self adhesive film.

Figure 27: PMMA prototype with added air pressure in the cavity.

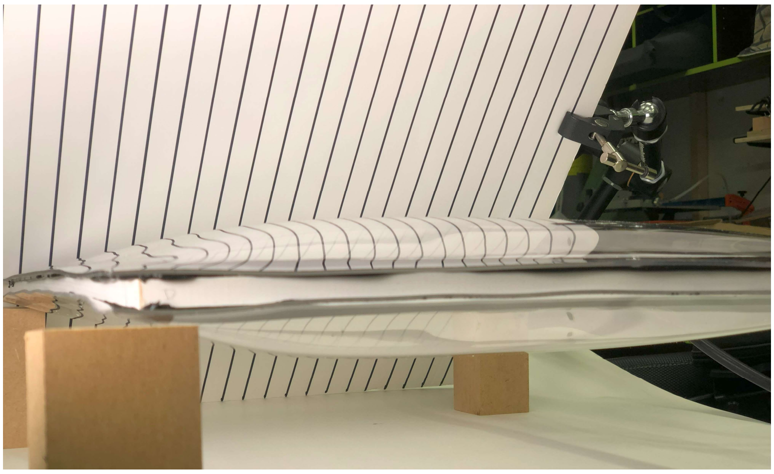

Figure 28: PMMA prototype with added air pressure in the cavity, side view.

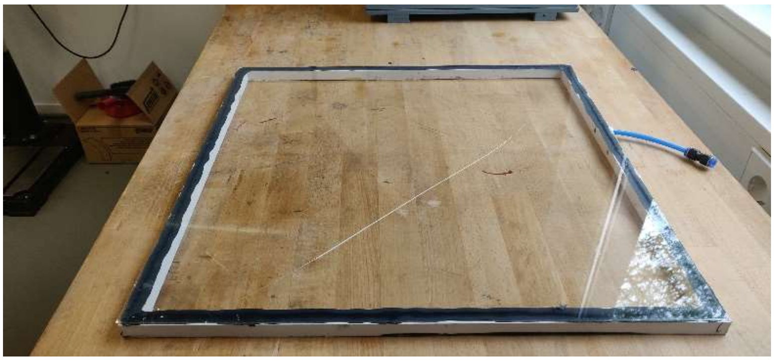

Figure 29: Prototype in aluminosilicate thin glass (AGC Falcon, 1.1mm thick) showing a linear crack after undergoing a breaking test with safety film.

Comparison between sealants

4 types of sealants were compared for the prototypes in terms of their drying times and elasticity (for glass pane deformation) after drying. There were Montage (mounting) kit from Bison, PIB sealant tape from Premseal, UK, Dowsil 791 (silicone sealant) from Dow and Kommerling Kodiglaze s (2 component silicone sealant). Table 23 shows the advantages and disadvantages of the sealant with respect to the experiment.

Table 23: Comparison between sealants for prototype building.

Sealant	Advantages	Disadvantages
Dowsil 791	• Can sustain required air pressure (tested PMMA + Hardwood and with Thin glass + PMMA adhesion up to 0.3 bar) • Provides flexibility for edge straining	• Drying time is 24 hrs. min. • Application better to be done using an air compressor powered sealant gun • Difficult to achieve a clean detail • Difficult to wipe out from surfaces
Bison Montage (Mounting) Glue	• Transparent after drying • Provides sufficient adhesive strength for experiment • Can be applied using hand held sealant gun	• Relatively less flexible for edge straining compared to Dowsil • Drying time is 24 hrs. min. • Difficult to wipe out from surfaces • Not tested for air tightness for the experiment

PIB Sealant Tape	• Easy to apply to surfaces, clean finish • Low chance of spill-over, and dimension (15mm x 2mm maintained) • Provides flexibility for edge straining • Provides sufficient adhesive strength for experiment • Drying time around 2 hrs.	• Corner sealing is difficult • Needs even pressure for best adhesion • Not tested for air tightness for the experiment
Kommerling Kodiglaze S (2 component silicone sealant)	• Faster curing time (less than 2 hours) compared to other sealants • Provides flexibility for edge straining	• Application must be done using pneumatic sealant gun • Difficult to achieve a clean detail • Difficult to wipe out of all surfaces

Since the silicone sealants were found better in terms of elasticity, for the PMMA prototype Dowsil 791 was used and for the thin glass prototype, Kommerling Kodiglaze was used. For both prototypes a layer of PIB sealant was used to prevent spillover of the silicone sealant towards the cavity. While both the prototypes were used to test the air pressure system, only the thin glass prototype was used for testing of the self adhesive transparent film. Figure 30 shows the process of building the glass prototype.

Applying PIB tape — 2 component glue — Applying glue using a pneumatic gun — Placing glass — Final product

Figure 30: Process of building a prototype using aluminosilicate glass

Theoretical validation of glass prototype

As discussed earlier, safety concerns and lack of availability of laminated glass for inner pane led to the need to use self-adhesive transparent film. Before use on the panels for the final experiment, the ability of the safety film to keep the shattered glass pieces from projecting in air was tested on the thin glass prototype. The suitability of the prototype was first theoretically validated by considering the strain energy in glass induced by air pressure as the equating factor between the prototype and full size panel. For simplification, an infinitesimally thin linear strip at the center of both glass panels is compared.

Figure 31 shows a linear relationship between the axial force applied (F) and corresponding extension (x) of a bar with cross sectional area (A) and length (L). The strain energy (U) (or the work done) is the area below the line and is given by the expression $U = Fx/2$. Since axial stress $\sigma = F/A$, we have $F = \sigma A$. We know that the strain is given as $\varepsilon = x/L$ and that the young's modulus, $E = \sigma/\varepsilon$. By replacing these values, we get

$$U = \sigma\varepsilon AL/2 = \sigma^2 V/2E$$

Where V is the total volume of the bar.

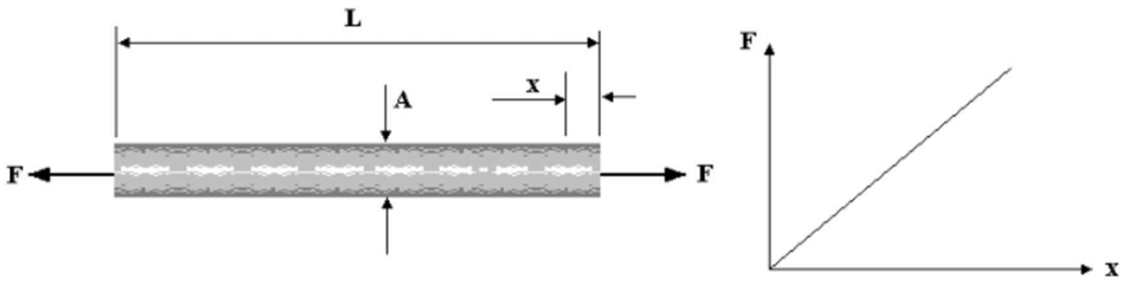

Figure 31: Relationship between force F and elongation x within the elastic limit.

Figure 32 shows the bending stress distribution at the center of the linear strips for both glass thicknesses, along with the corresponding compressive and tensile stresses and strains. Now, considering the expression for strain energy mentioned above, we can say that

$$U_1 = \sigma_{c1}^2 V_1/2E = \sigma_{c1}^2 L_1 h_1 b/2E$$

$$U_2 = \sigma_{c2}^2 V_2/2E = \sigma_{c2}^2 L_2 h_2 b/2E$$

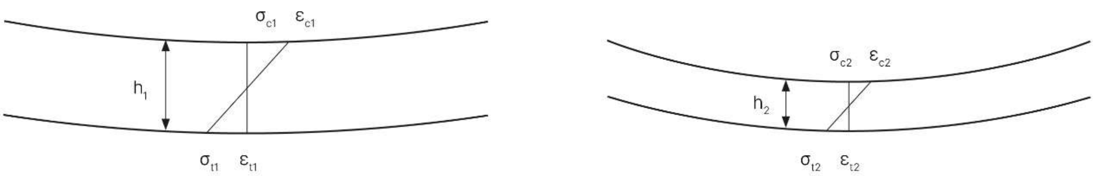

Figure 32: Comparison of bending stress distribution in thicker and thinner glass under bending.

The thickness h_1 of the full size panel in fully tempered (FT) glass is 4mm, and the protype to be tested in chemically toughened aluminosilicate glass (CT-ASG) has a thickness h_2 of 1.1mm. The failure stress for FT glass is generally considered as 80 MPa. At this stress, the glass will reach its maximum strain energy. This strain energy or higher should be achieved in the prototype before breaking, so that it can be deemed as a fair representation of the full sized panel. This is done by calculating the stress in CT-ASG by equating the two strain energy expressions and substituting all the known values.

$$U_1 = U_2$$

$$\sigma_{c1}^2 L_1 h_1 = \sigma_{c2}^2 L_2 h_2$$

$$(80)^2 \times 1500 \times 4 = \sigma_{c2}^2 \times 500 \times 1.1$$

$$\sigma_{c2} = 264.23 \text{ MPa}$$

For Falcon glass (CT-ASG) the failure stress is 325 MPa. Therefore, the prototype will break at a strain energy higher than the maximum strain energy of the full size prototype in FT. Thus we prove that the smaller prototype is a fair representation of the full size panel to conduct a breaking test for self-adhesive film.

Testing the self-adhesive transparent film

The film was first sprayed with soap water before application on the prototype. This method is used to make the process of removal of air bubbles and impurities easier. The visual performance was then compared with clear glass. It was found that minor impurities and bubbles have the potential to hamper the visual performance to a large extent, especially if the outside view is that of rectilinear objects, such as edges of buildings, streets, etc. However, if the surroundings have trees or more organic forms, it is difficult to perceive a difference.

The breaking test was conducted in 2 parts as shown in Figure 33. In the first part, one pane was coated with the self adhesive film and the other side wasn't (Figure 33, 1a and 1b) . By pressurizing the cavity, the glass was deformed till a point when the uncoated glass broke. By doing so, the principle was confirmed that the safety film raises the stiffness of the glass. The second experiment was conducted with safety film installed on both sides of the panel (Figure 33, 2a and 2b). This test was to check whether the safety film is able to retain the broken glass pieces in place. Again, the cavity was pressurized till one of the glass panes broke. During the experiment, the hardwood frame began to deform, causing air leaks in the cavity. This was possibly due to the increased stiffness of both the glass panes due to the coating. The deformed edge of the frame was clamped and the experiment was repeated till one of the glass panes gave way. It was observed that almost all pieces of broken glass were retained by the safety film. A few small pieces were able to fly out. From the slow motion video it seems like these pieces were from the edges of the frame which were not sealed well enough with the silicone sealant.

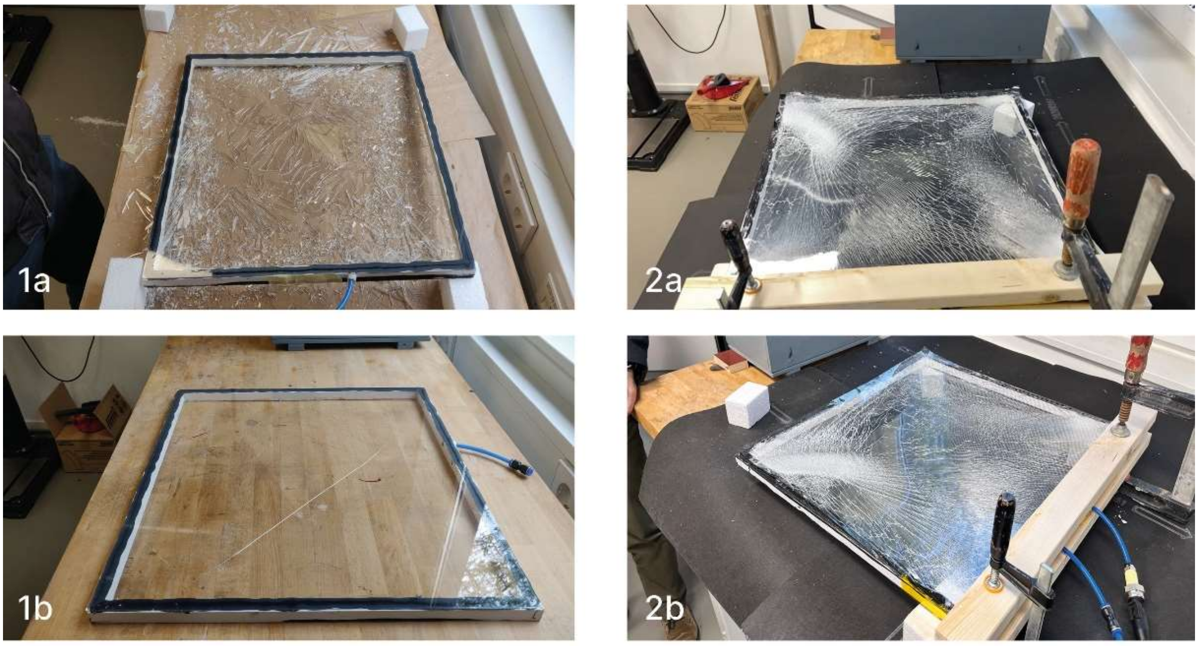

Figure 33: Two step breaking test of self-adhesive film. (1) Glass panel with film on one pane. (1a) Shards of uncoated glass spread around after breaking (1b) Single crack in coated glass did not propagate (2) Glass panel with film on both sides. (2a) Shards of broken glass were held together by film. (2b) Frame edge was clamped to prevent bending.

4.4.8 Design of the air pressure system

Overview

As indicated earlier, air pressure variation in the cavity can be generated by means of an electro-pneumatic system. As the name suggests, the system has an electronic system connected a pneumatic system. The electronic system is used to signal the opening and closing of valves to start or stop the air flow through the pneumatic circuit. For this purpose, it was decided to use solenoid valve connected to an Arduino. An Arduino is a microprocessor that can be coded to give out signals as specific time interval. The solenoid valve receives these signals and instantaneously opens and closes the air flow circuit. For this experiment, an air flow circuit with 6mm tubing was considered as standard, and the connectors and valves procured accordingly.

Solenoid Valve

Solenoid valves are commonly used to translate electronic signals into mechanical movement. An electromagnet at the core of a solenoid valve, when energized, moves the plunger i.e. a rod passing through the electromagnetic coil. This movement allows opening or shutting off the flow of air through the valve. There are numerous types of valves, which can regulate different combinations of air flow. For the purpose of this experiment, a 3 way 2 solenoid valve is used. It has an input, P, an output A and an exhaust port T. Figure 34 shows the working principle of a Normally Closed (NC) type of valve. The valve has two phases, depending on whether or not current is flowing through the coil. When the current is OFF, the valve remains closed, letting no air through. When the current is ON, the valve lets air flow through. The maximum flow through the valve is governed by the flow output of the air compressor. Using a flow control valve (manual) the flow can be reduced to a desired amount. To increase the flow, a reduction in tube cross sectional area will be required.

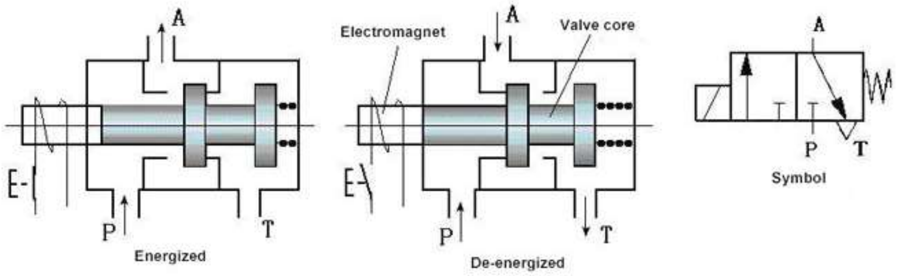

Figure 34: Working principle of a Solenoid 3 way 2 valve. (source: https://www.atosolenoidvalves.com/how-does-3-2-pneumatic-solenoid-valve-work.html)

Valve control

An Arduino Uno is used in the experiment to communicate signals to the pneumatic valve. The code is able to control the time at which the valve is turned on and turned off and time interval for which it remains on and remains off.

Pressure reading

In addition to valve control, the Arduino is also used to record the air pressure in the cavity. This is done by means of a pressure transducer which can be attached directly to the cavity of the IGU. The pressure transducer gives out an analog signal, which can be input and converted into the corresponding pressure readings. For this experiment a stainless steel pressure transducer of 0 - 30 PSI (0 - 2.06 bar) range was used which outputs an analog signal in the range of 0.5V to 4.5V.

Deflection reading

In addition, the Arduino is also connected to a distance measurement device to corelate the pressure readings with the deflection readings. The distance measurement device used for testing the prototypes was an ultrasonic sensor, which sends digital signals to Arduino at certain time intervals. The sensor used for the prototype was HC-SR04 with 4 pins (Voltage Common Collector or VCC, Trigger, Echo, Ground) For the final experiment, however, it is proposed that a laser device be used. Since glass is transparent, an opaque adhesive film will have to be used to take objective measurements using the laser device. This measurement can only be conducted once, to obtain a relationship between the cavity air pressure and the deflection. For the experiment with the volunteers, only the pressure measurements should suffice.

Safety

Use of laminated glass or a self adhesive safety film is a measure to avoid injury to people in the event of breakage. But each time testing till breaking limits is not necessary for this experiment. The minimum permissible and maximum permissible pressure inside the cavity can be determined based on calculations as mentioned in Chapter 4.4.4. Since air pressure within the cavity is being constantly monitored by means of the pressure transducer and input into Arduino, these limits are entered in the code as 'shut-off' limits, so that once the pressure reading reaches this limit, the Arduino can instruct the circuit to shut off air flow into the cavity. By this way, we can ensure that the glass deformation does not reach breaking point. In addition, to ensure the electronic circuit is safe from unexpected surges in power supply, a voltage regulator is used, which doubles up as a fuse.

Circuit

Figure 35 shows the schematic of the electro-pneumatic circuit for the experiment. The Arduino is able to send out a 5V signal, which is why it cannot be directly used to power the valve. The solenoid valve procured for the experiment works on a power supply of 12V. An adjustable power supply unit is used in this experiment to supply a constant voltage to the valve. In between, there is a voltage regulator module used which is calibrated to supply a 12V voltage to the circuit. This additonal step is taken so that the voltage regulator could also work as a fuse in case of an unexpected surge in the supply voltage. To open or close this circuit, a Mosfet module of 5V-36V range (also known as Switching Driver Module) is used. The Mosfet is connected to the Arduino to receive 5V inputs and it acts as a switch in the 12V circuit that controls the valve. The Pressure transducer is also connected to the Arduino. Figure 36 shows the circuit built based on the schematic. In this circuit, a breadboard is used as an extension of the circuit to connect pressure sensor, distance sensor and the valve control to the Arduino.

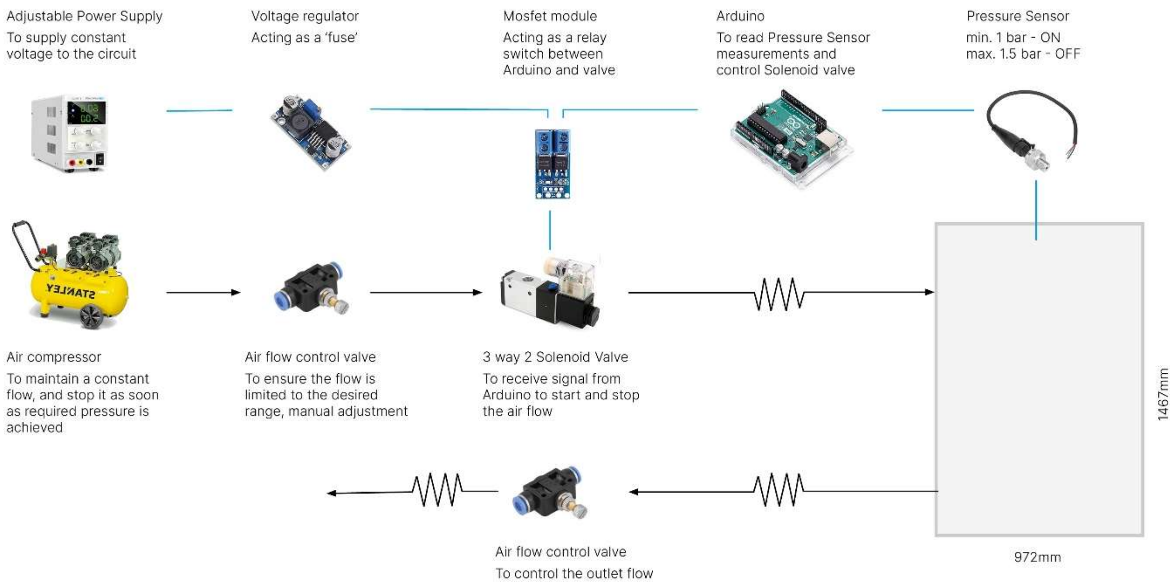

Figure 35: Diagram for the electro-pneumatic setup

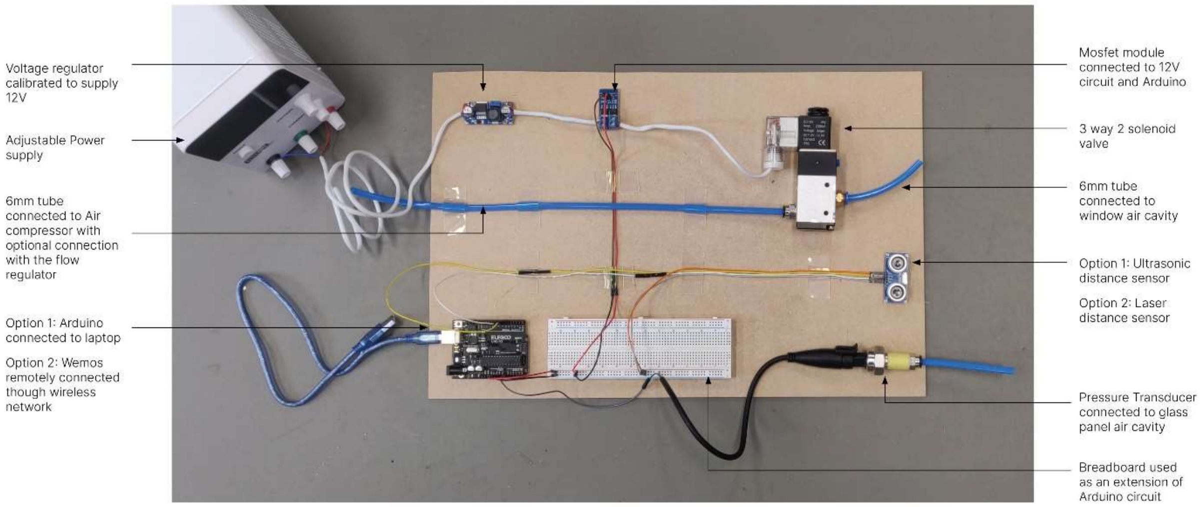

Figure 36: Picture of the circuit built based on the schematic

An air compressor with a storage tank is used to supply air to the pneumatic circuit. Most compressor come with a flow control valve built-in. However, if required an additional flow control valve can be added to the circuit for a finer control over the air flow. The solenoid valve needs a certain minimum air pressure to operate, so the flow control valve can be used to calibrate the air flow circuit accordingly. As mentioned ealier, 6mm polyurethane tubing and compatible connectors are used for this circuit. Wherever necessary the connectors are sealed with a PTFE tape. Most of the connectors used here are the push and fix type. However, for a more air-tight circuit, it is advisable to use metallic connectors and seal these with PTFE tape.

The valve is able to supply air inside the cavity at a frequency communicated by the Arduino. For controlling the rate of exhaust of air from the cavity, an air flow control valves can be attached to the exhaust pipe. However, this will only allow for reducing the exhaust, compared to the natural exhaust rate through the particular hole. To increase the exhaust rate, a bigger hole or an additional hole is required. This will have to be calibrated before the experiment, depending on the desired frequency of motion in glass. In order to have more control over the speed of exhaust, a parallel electropneumatic system is also possible, which is connected to a Vaccuum genarator module which can be controlled with Arduino. This is proposed to be explored in future research.

4.4.9 Testing the air pressure system on PMMA prototype

Preliminary tests were conducted in the laboratory using the electropneumatic circuit shown in Figure 36 and the PMMA prototype. The PMMA prototype was used as it could achieve higher degree of deformations without breaking, compared to the thin glass prototype. These tests were an integral part of the design of the experimental setup, following the core method of research through design.

Initially, separate codes were created to test the 3 individual components i.e. the pressure transducer, ultrasonic distance sensor and the pneumatic valve. Then, these codes were combined into a single script and the working tested. Figure 37 shows a screenshot of the test setup and the readings recorded in the Arduino IDE interface. The mechanism was found to work as planned, as simultaneous readings were gathered from both, the pressure sensor and distance sensor. An additional line of code was entered for safety, to ensure that once the pressure in the cavity reaches a pre-determined maximum or a minimum, the system will shut off and come back to normal.

Figure 38 shows the code structure for the calibration and the experiment with the volunteers. For the calibration of the experiment, both the pressure and deflection sensors need to be active. Once the calibration is done, a relationship between the pressure measurements and deflection measurements can be drawn For the experiment with the volunteers, the presence of a deflection sensor will obscure a clear view through the glass. Hence, it can be removed and only the pressure sensor readings can be recorded, which can be corelated with deflections based on the relationship drawn.

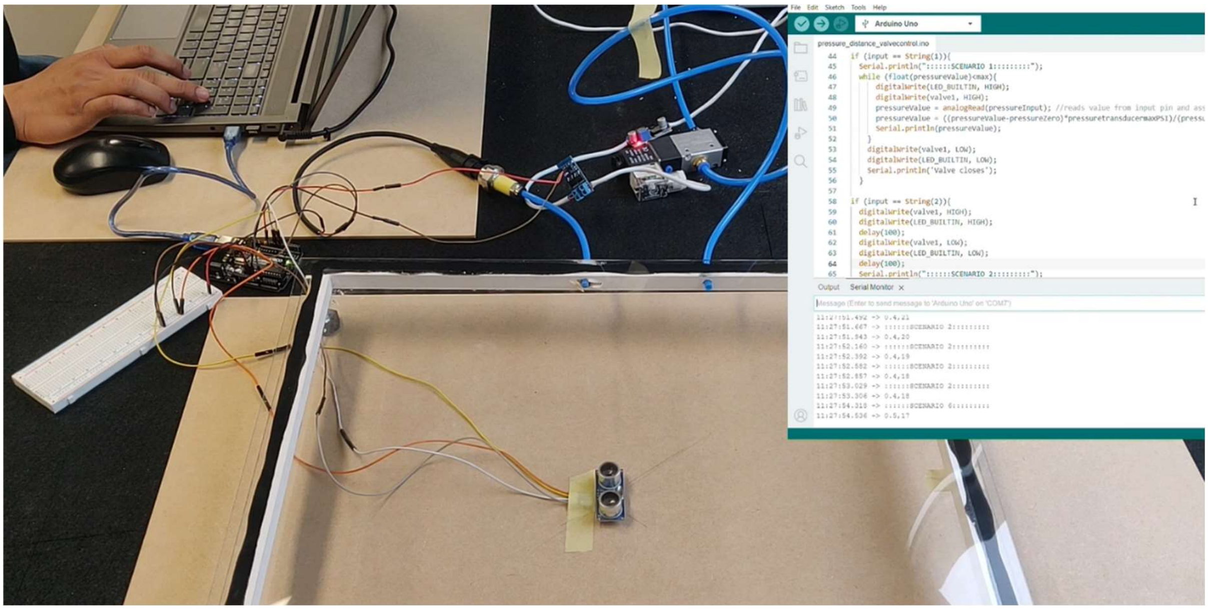

Figure 37: Testing of the air pressure system integrated with pressure sensor, ultrasonic distance measurement device and solenoid valve supplying pulsating air pressure into the prototype.

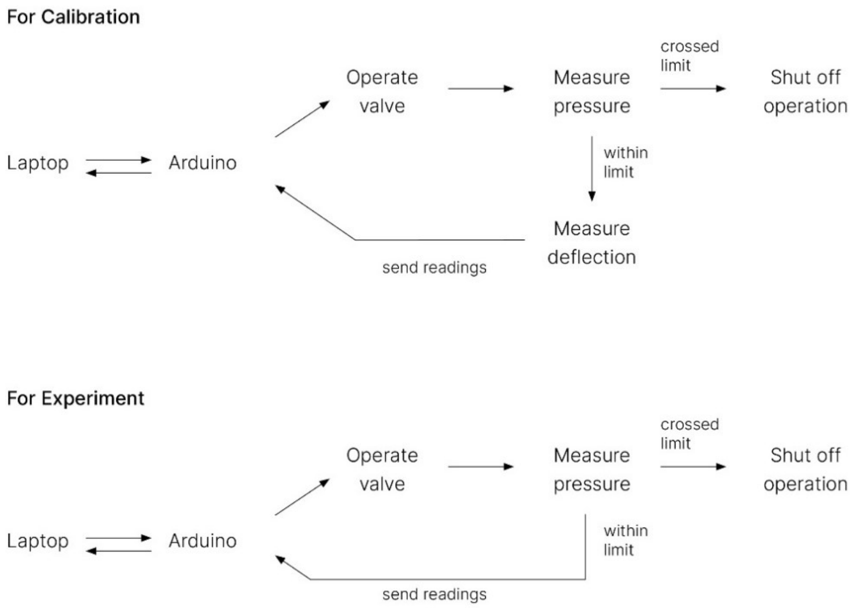

Figure 38: Code structure for calibration and for experiment with volunteers.

4.5 Feasibility tests on full size panels

4.5.1 Introduction

The experiment and the setup has been designed around the size of panels that can be installed in the Light Van. The air pressure system has been tested on both, the glass prototype and PMMA prototype. However, the feasibility of the experiment must be also tested with the full size panels. This chapter discusses the setup, process and the results from two types of feasibility tests - mechanical behavior of the glass panels under pressure loading and optical performance of glass panels. Testing the mechanical behavior was necessary to observe whether the deflections caused by the air pressure system were in line with predictions of FE analysis and hand calculations. These were also important to check the level of air tightness of the system for it to function as per expectations. The optical tests were necessary for an objective analysis of the effects deformation on the reflections in glass and the view through the glass.

4.5.2 Setup

For conducting the experiments, 6 panels in glass were received from AGC Interpane, Germany (Figure 39) of sizes suitable to be installed in the Light Van (1467mm x 972mm) and specifications as seen in Figure 26. 3 of these panels are double glazed units (DGUs) for testing of climatic loading and the other 3 are triple glazed units (TGUs) for testing of wind loading conditions (Figure 40). Out of each set of 3 DGUs and 3 TGUs, 2 are made using fully tempered glass and 1 is in annealed glass. The annealed glass units were ordered with the intention of using them for objective measurements of optical performance, as the fully tempered glass may inherently lead to visual distortions. The fully tempered glass panels are intended to be used for the experiment with volunteers, as fully tempered glass has a higher failure stress (80 MPa) compared to annealed glass (25 MPa) and the breaking pattern is in the form of smaller bead-like pieces instead of sharp shards of annealed glass.

For the current thesis, the fully tempered glass DGU and TGU were tested for both, mechanical and optical performance, as relatively higher air pressure could be achieved in the cavity without risking failure, compared to annealed glass. These panels are available at the Architectural Engineering + Technology group at the Faculty of Architecture for further research.

Figure 39: Delivery of panels from AGC to Faculty of Architecture, TU Delft

The panels for testing were installed on a demountable wooden frame which is a part of the Light Van. This frame was demounted from the Light Van and installed on a portable metal base for ease of maneuvering. The frame was stabilized in vertical position using fastening straps that ran over the top of the frame and around the portable base. These straps were screwed at the top of the frame to prevent slippage leading to instability. At the bottom, four wooden members were used as a measure to prevent lateral movement of the bottom edge of the frame with respect to the base. The frame has a base on which the glass panels can rest and 4 clamps; 2 on either side, to hold the glass panels in place. At the top, the frame has a separate demountable panel, which was not used due to the low ceiling height of the laboratory. The tests were conducted in the 'Think' lab at the Faculty of Architecture.

Figure 40: Panels received from AGC: 3 DGUs and 3 TGUs for testing

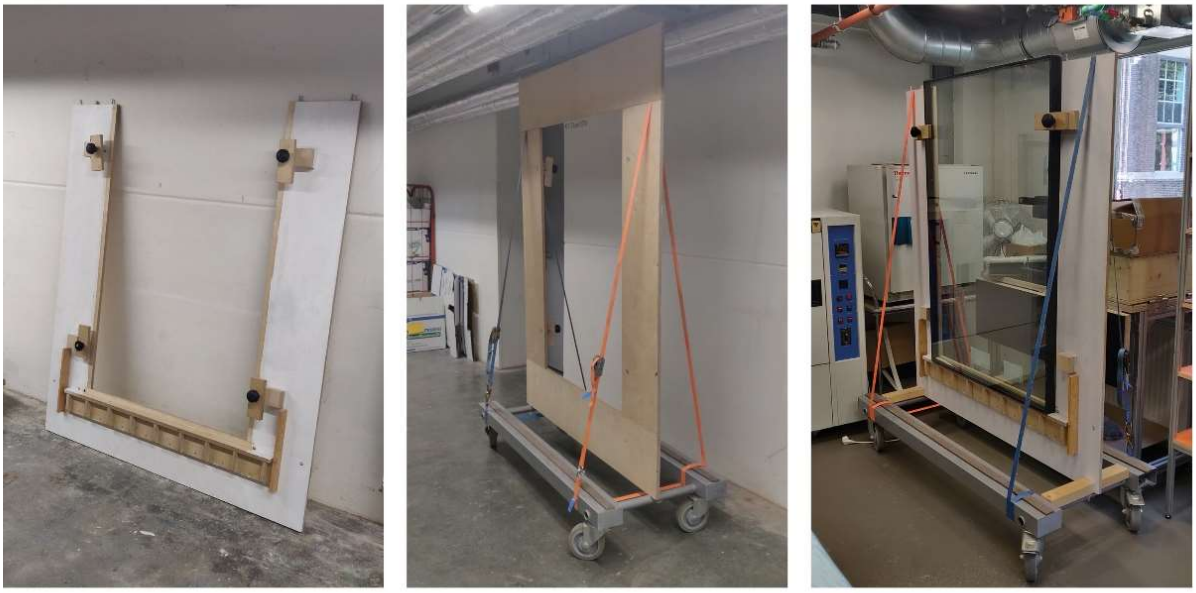

Figure 41: Setting up the rig for installation of glass panels on a movable platform.

Application of self-adhesive safety film

As discussed in Chapter 4.4.7, a self adhesive transparent safety film was tested on the thin-glass prototype. Since none of the internal panes on the full size panels are laminated, self-adhesive film must be installed on each, before conducting any experiment. Before installing the panels on the frame for testing, it was decided to apply the film on the internal panes of TGUs, which are 4mm thick. The safety film must not hamper the optical performance of glass to an extent that it becomes an additional cause for unacceptance of view. However, the film application in this case was not successful, as the application led to bubbles on the surface of the film and circular marks, as seen in Figure 42, rendering it unusable for any optical tests. Finally, the panels without film were used for the experiment. Safety measures such as the use of transparent safety barriers made in PMMA were used while performing the experiments. Even if the safety film were successful, there are still chances of disturbance of view through glass due to presence of dust particles or higher chance of scratches. For future tests, especially with volunteers, it is recommended to either use laminated glass or perform the tests using recommended safety measures.

Figure 42: Safety films applied on the full size panels showed bubbles and marks even after 2 attempts.

Sealing the cavities air-tight

The panels have pre-drilled holes in the spacer bars to allow air pressure sensors and air supply tubes for the experiment. During installation, some of these holes had to be sealed and others had to be made slightly larger through drilling. For drilling new holes, it was recommended to drill the holes in an upside-down manner so that the debris of the sealant and the aluminum spacer does not fall back in the cavity. Once the 6mm air supply tubes and pressure transducer were inserted in the cavity holes, the holes were sealed using silicone sealant. The sealant typically takes between 24 to 48 hours to dry. The drying time is crucial in planning of the experiments. It is also recommended to use separate inlet pipes and pressure transducers for each panel to avoid removing and re-installing these. The silicone sealant is also susceptible to fatigue damage, so the inlet pipes and pressure transducers should be fixed firmly in place.

Preparing the checker board and zebra board

Since glass is transparent, it is difficult to perceive small distortions on its surface. Typically, zebra boards with back-lighting are used in glass factories to detect optical distortions in glass, such as rollerwave distortions. For performing optical tests with our setup, the zebra board with black and white stripes of 12.5mm width laid out at 45^{o} angle and checker board with squares of side 50mm were printed on A0 sheets and installed on a board of size 1.0m x 1.2m. As shown in Figure 43 and Figure 44, these were used in our experiments to perceive distortions in view and reflections resulting from deformations in glass. These have been further discussed in Chapter 4.5.4.

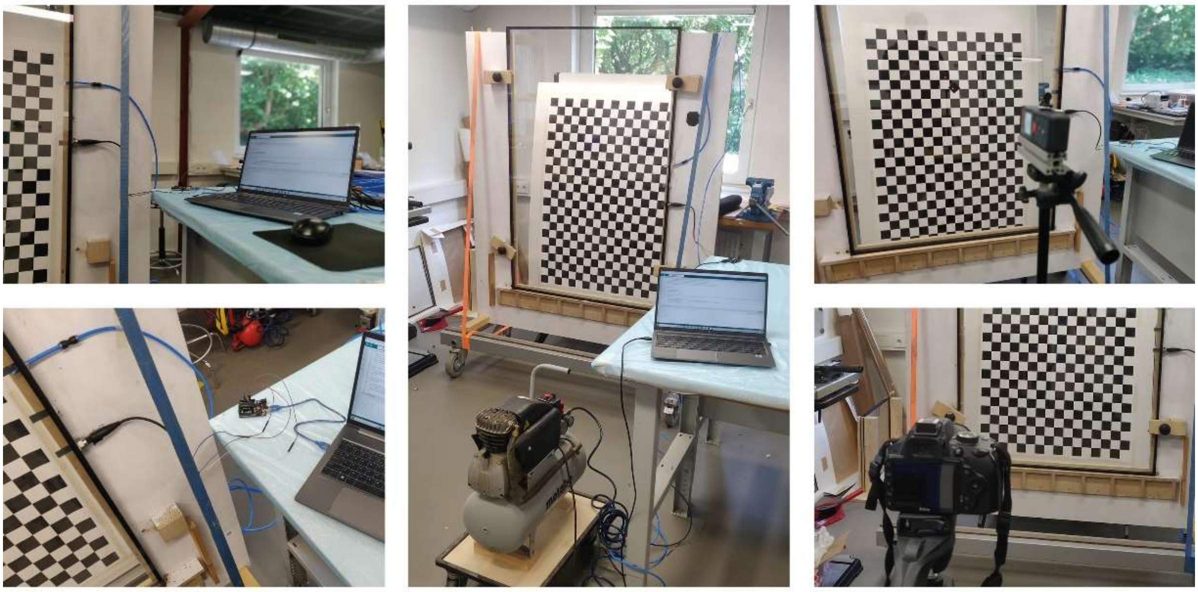

Figure 43: Use of checker board behind glass panel to test optical distortions of the view through glass using a camera. The same setup was also used to measure deflections with respect to pressure variations in cavity using a laser measuring device.

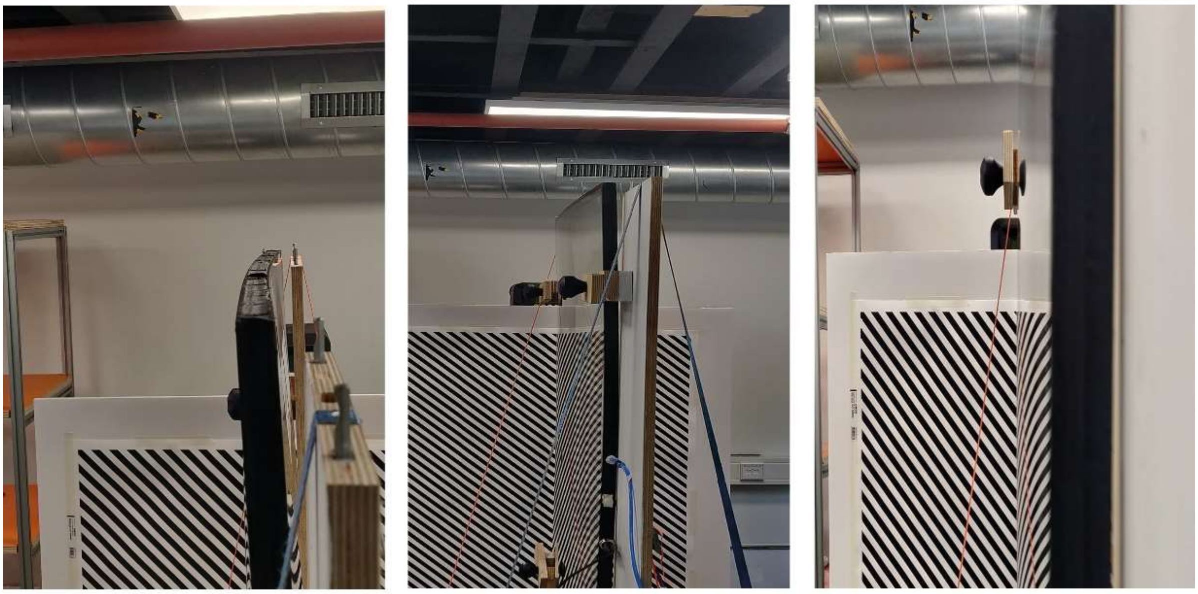

Figure 44: Use of zebra board to detect relative deformation in glass from a side-view. The side-view also shows that the top edge of the glass pane started bending when the cavity was subject to added air pressure.

4.5.3 Testing Mechanical Behavior

A preliminary validation of the concept of the experiment was carried out as discussed in Chapter 4.4.4. However, this was based on formulas typically used in case of small deflections (δ ≤ h/2) where δ is the center of glass deflection and h is the thickness of glass. These calculations are however not sufficient to predict the behavior of glass under larger deformations. The feasibility of the experiment is governed by the behavior of glass with respect to change of pressure in the cavity and testing whether the deflections predicted as per calculations are actually achieved in the glass panes.

One of the most important reasons for corelating measured pressure and measured deflections is that during the experiment with the volunteers, deflection measurements at center of glass cannot be recorded without disturbing the view. The measurement device must be installed on or near the center of glass. Comparatively, taking pressure measurements has negligible impact on view as the pressure transducer can be inserted in the cavity sideways as seen in Figure 43.

Table 24 compiles the readings from pressure transducer (Row 1) with deflections at the center of glass, derived from numerical calculations, FEM Analyses and lab measurements. The pressure transducer used for this experiment reads pressure in Pounds per Square Inch (PSI) units, up to one decimal place. Therefore, the pressure readings available to us range from 0.0, 0.1 to 0.6. These are then converted into SI unit of Pascals (Pa) for ease of calculation. For the experiment, the Serviceability Limit (Row 2) is determined from the most commonly used standard of L/65 according to the findings from Literature Review and Façade Industry Survey. The deflection measurements are compared with this limit for reference. The goal of the feasibility study is also to check the behavior of glass beyond this deflection limit.

Row 3 in the table lists the deflections and stress predictions in 4mm thick glass plate as per numerical calculations, based on Equation 4 and Equation 5. However, these formulas as we know are only valid for smaller deflections and only give information on behavior of the center of glass. Therefore, a model was generated on Ansys to observe the mechanical behavior of the entire plate, corresponding to each step in pressure increase. The model was created as a simply supported plate, with linear edge supports, restricting deflection of edges normal to the plane of the plate. Two point supports at adjacent corners were introduced, with restriction along Y axis and one point support was introduced at one of these points with restriction along X axis. A linear analysis was performed first, to gather deflection, stress, strain and strain energy data. Row 4 lists the readings from the Linear analysis for deflection and maximum principal stress. It can be seen that these values are in close correlation with the predictions of numerical calculations listed in Row 3.

However, it was observed from a few preliminary tests of full sized panels that the deflection behavior of the panes is not in line with Linear analysis predictions. The reason for this is that for large deflections, as the plate deforms elastically, the change in geometry leads to stiffening of the plate further. The action of this stiffening is the reason behind lesser deflection as compared to that predicted by linear analysis. Therefore, using the same FEM setup, a geometrically non-linear analysis was carried out in Ansys. In Ansys, when the calculation for 'large deflections' is performed, the effect of the following 4 actions is considered – large rotation, large strain, stress stiffening and spin softening. The results from the geometrically nonlinear analysis are listed in Row 5. The deflection and stress patterns according to linear and nonlinear analyses are shown in Figure 45, Figure 46, Figure 47 and Figure 48. Further, in Appendix 12 the strain and strain energy patterns are also shown.

Table 24: Data on deflections and stresses in glass - corresponding to (1) air pressure in cavity and (2) serviceability limit of L/65 - derived from (3) numerical calculations, (4) Linear FE Analysis, (5) Nonlinear FE Analysis, and experimental measurements of (6) TGUs and (7) DGUs

1	**Pressure Measured (PSI)**	**0.0**	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**
	Pressure Measured (Pa)	**0.0**	**689.5**	**1379.0**	**2068.5**	**2758.0**	**3447.5**	**4137.0**
2	Serviceability Limit	23	23	23	23	23	23	23
3	Pane 4mm Calc Deflection (mm)	0	11.87	23.75	35.62	47.5	59.37	71.25
	Pane 4mm Calc Stress (MPa)	0	20.8	41.59	62.39	83.19	103.98	124.78
4	FEM Linear Deflection (mm)	0	12.28	24.55	36.83	49.1	61.38	73.65
	FEM Linear Stress (MPa)	0	19.41	38.81	58.22	77.62	97.03	116.43

5	FEM Nonlinear Deflection (mm)	0	8.23	12.31	15.24	17.61	19.65	21.45
	FEM Nonlinear Stress (MPa)	0	27.39	71.66	119.21	167.9	216.99	266.14
6	TGU-1	0	5	10	13	13	13	13
	TGU-2	0	5	9	11	11	13	13
	TGU-3	0	3	8	10	11	12	12
7	DGU-1	0	8	15	18	21	23	#N/A
	DGU-2	0	6	11	14	21	28	#N/A
	DGU-3	0	10	15	20	24	26	#N/A

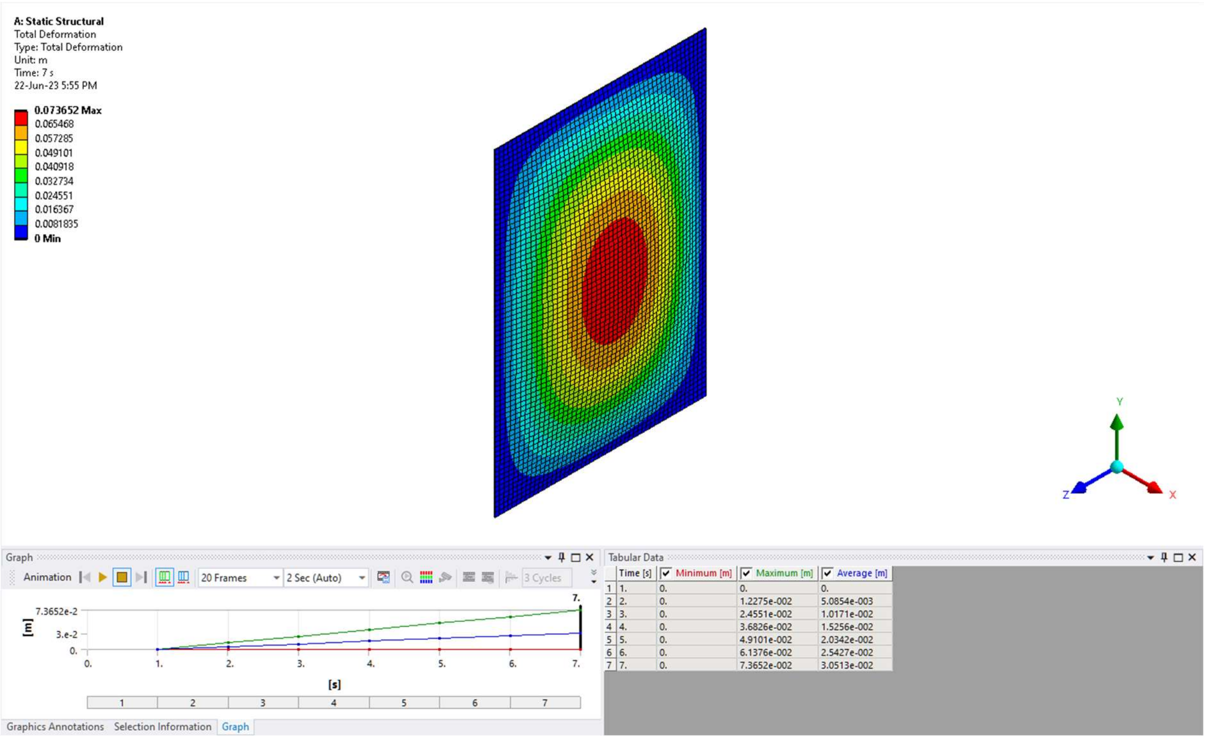

Figure 45: Linear FE Analysis results for deflection.

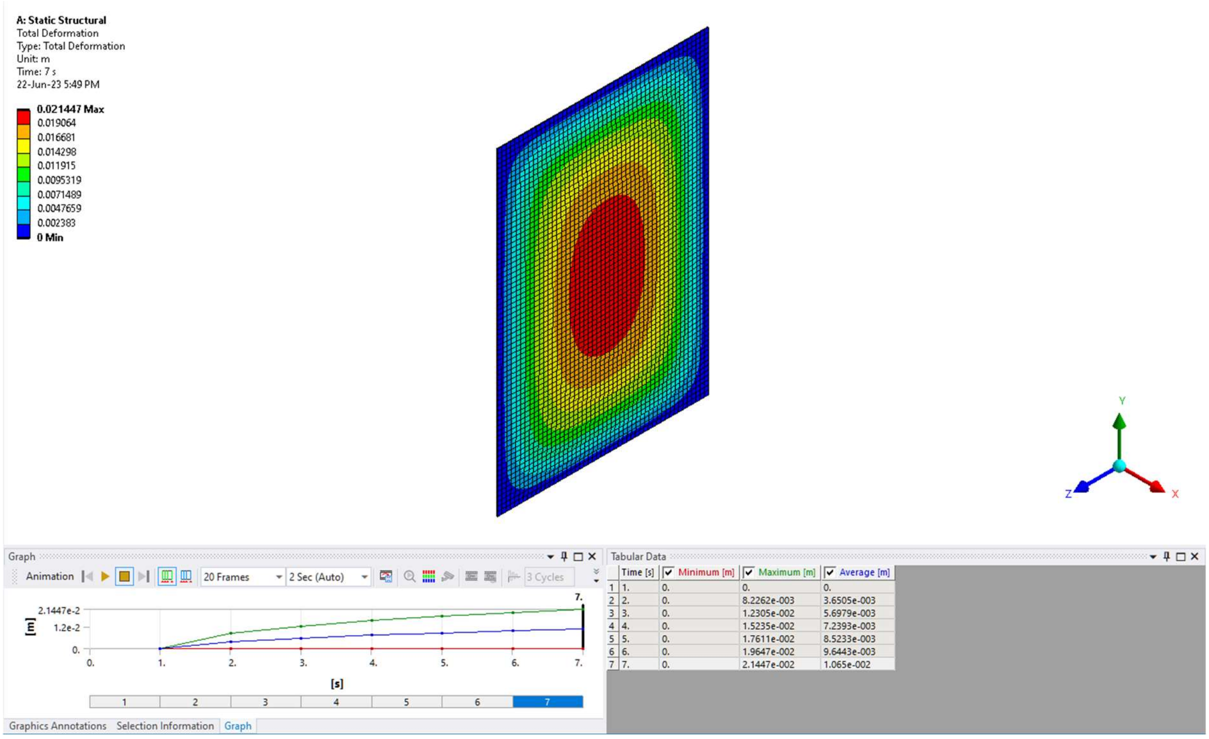

Figure 46: Nonlinear FE Analysis for deflection.

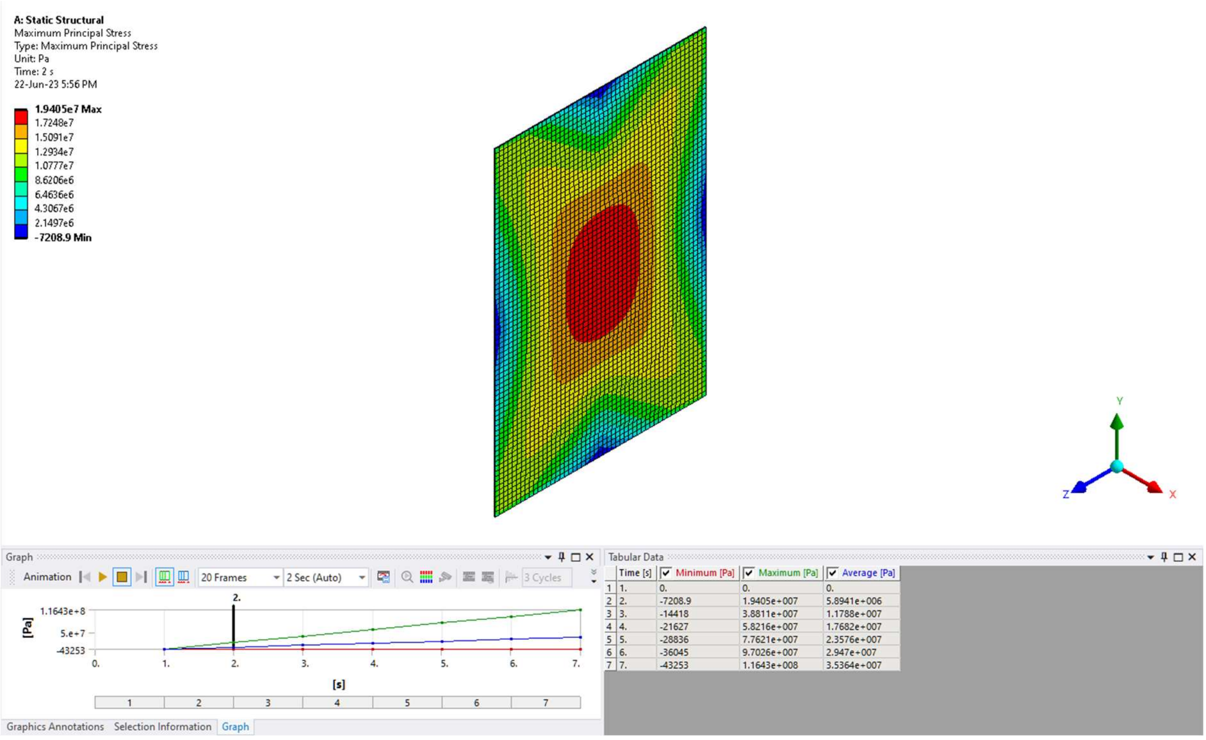

Figure 47: Linear FE Analysis results for Principal Stress.

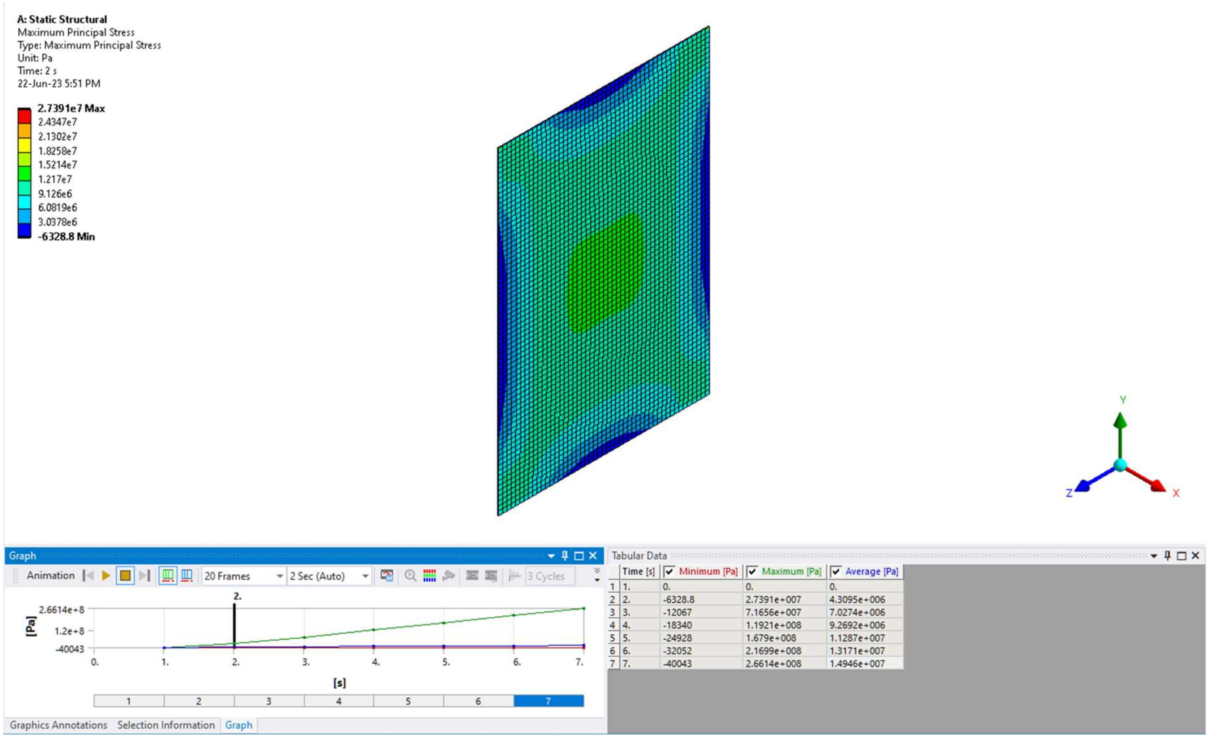

Figure 48: Nonlinear FE Analysis results for Principal Stress.

Figure 49 shows a comparison of predicted deflections in 4mm thick glass of size 1467mm x 972mm using a linear analysis and nonlinear analysis. The nonlinear analysis results indicate a stiffening of glass as expected due to the change of geometry in the plate. It is worth noting that the predicted deflection even at 4137 Pa pressure still remains within the serviceability limit of 23mm. Figure 50 shows a comparison of predicted principal stresses for the same configuration of glass. The nonlinear predictions show a significant increase in stress as the pressure increases as compared to the linear predictions, crossing the permissible design stress limit of 80MPa at around 1500Pa air pressure.

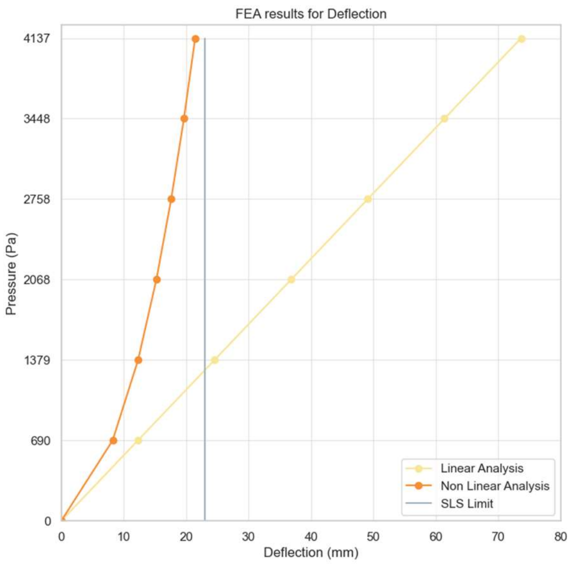

Figure 49: Deflection predictions using linear and nonlinear analysis using Ansys.

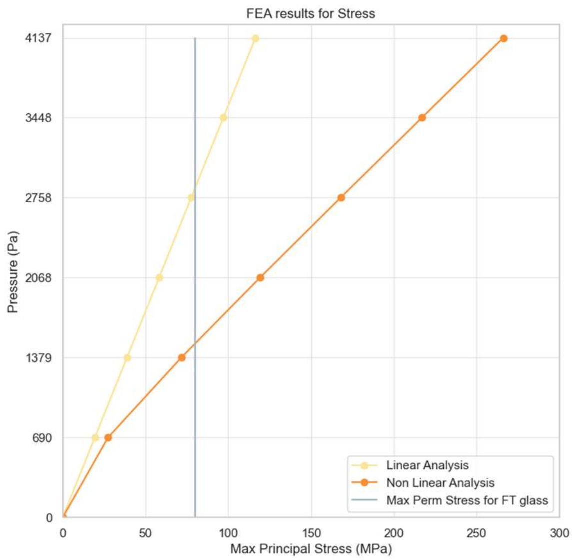

Figure 50: Maximum Stress predictions using linear and nonlinear analysis using Ansys FEM

The experimental measurements were carried out for the fully toughened TGU and DGU using the setup as shown in Figure 43. A laser measuring device with an accuracy of 1mm was used to take measurements at each pressure step. The readings were taken as the air pressure in the cavity was increase from 0.0 PSI up to a maximum of 0.6 PSI in case of the TGU. The pressure was recorded with the pressure transducer connected to the Arduino. The deflection was calculated by subtracting the readings at each pressure step from the maximum reading taken at when the pressure in the cavity was 0.0 PSI.

The readings were taken at 3 instances for each of the units. The results from the deflection readings from each of these 6 repetitions are given in Row 6 and Row 7 in Table 24. These results have also been plotted in Figure 51 and Figure 52 for comparison with the nonlinear FEM Analysis predictions. In Figure 51 it can be clearly seen that the DGU deflection (blue lines) closely follows the predicted nonlinear behavior (orange line). The serviceability limit of 23mm has also been plotted for reference. It was observed that the serviceability limit was reached at or before 3488Pa air pressure. Further, it can be confirmed that linear analysis is not a good representation of mechanical behavior in the case of this experiment.

Further, Figure 52 shows the deflection readings of the TGU (blue lines) in comparison with the predicted nonlinear deflection as per FEM Analysis (orange line). A peculiar result was observed in this case. As the outer cavity (between the 6+6mm laminated glass and 4mm mid-pane) was pressurized beyond 2068Pa, the deflection of the innermost pane started to show constant values. When compared to behavior of the DGU in the same setup, the behavior of the TGU seems abnormal. Theoretically, the load sharing effect should deflect the middle pane (4mm) and the inner pane (4mm) equally. The same behavior was observed for all 3 repetitions of the experiment with the TGU. One possible reason for this behavior could be that the inner cavity (between the two 4mm panes of glass) is unable to retain pressure after a 2068Pa pressure is reached in the outer cavity. This may be the result of the silicone sealant used to seal out the extra holes in the cavities give way after a certain pressure is reached. Another explanation could also be that the outer cavity has a leak, however since we can see the pressure readings increase, this is less probable to have happened. A third explanation could be the action of the safety film on the TGU inner pane. The safety film will increase the stiffness of the glass pane by a certain amount. However, this does not explain well the constant readings, as one would still expect a gradual increase in deflection, although at a slower rate as compared to the predictions.

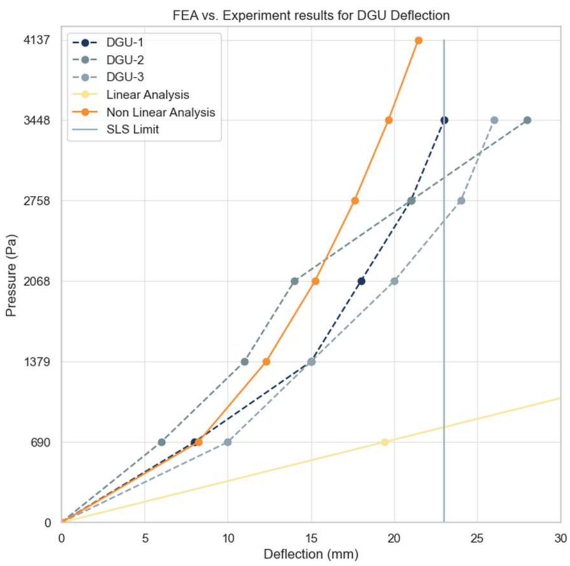

Figure 51: Comparison between deflection readings from experiment with DGU and nonlinear prediction of deflection.

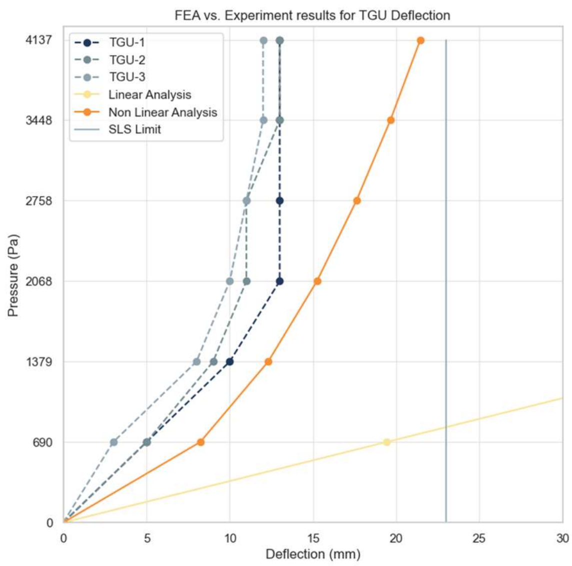

Figure 52: Comparison between deflection readings from experiment with TGU and nonlinear prediction of deflection.

Testing the mechanical behavior of DGU and TGU was an important step to test before testing the optical behavior of the pressurized panels. Since the TGU deflections were not able to reach the 23mm serviceability limit in the experiment, it was decided to conduct the optical experiments using only the DGU. In the future, it is recommended to repeat the experiment by re-sealing both the cavities. Experiment with the TGU is important to test the wind effect, as the air pressure system is designed to supply pressure at a certain frequency in the outer cavity, deforming the mid-pane and inner pane in a similar manner.

One other key observation can be made by comparing the deflections as seen in Figure 51 and the stresses associated with the higher pressure levels in Figure 50. The stresses predicted are certainly much higher than the design stress and even the failure stress of glass. However, no failure of glass was observed during the experiment even at air pressure as high as 3448 Pa in case of the DGU at which principal stress of 220MPa is predicted. These stress predictions seem unrealistic, given the glass did not break. The reason behind this may be that the thickness of the glass is small (4mm). As per (Respondek, 2018) thinner the glass pane, lesser the stresses. In future experiments it is suggested that a more detailed FEM analysis be conducted to arrive at more accurate stress values.

4.5.4 Testing Optical Behavior

The magnitude of deformations in glass can be perceived by using black and white patterns reflected off of its surface. As mentioned earlier, we can use zebra boards for testing effects of deflection in glass on reflections and checkerboards to test distortion of the view through glass. Figure 53 shows how the back-lit zebra board reflecting off a glass surface can help detect the slight distortions which are otherwise difficult to detect with the naked eye. Here, the background being black helps to confine the reflections to only those of the zebra board.

For tests of distortion of view through the glass, a checkerboard can be used. Typically, checkerboards are used to detect distortions in an image caused by a camera lens. Further, digital tools such as the OpenCV library in Python are available to correct these distortions in the image. Checkerboard pattern is used so that the software can easily detect the positions of the corners based on the color mapping (black vs. white) and compare it with the real-world dimensions of the checkerboard for calculation of the optical distortion.

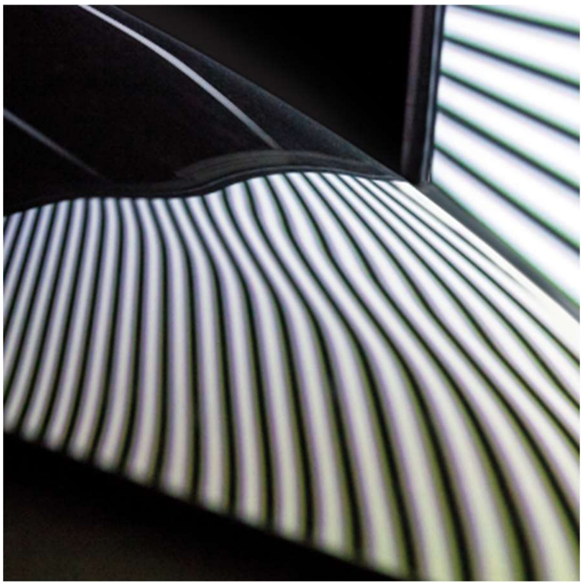

Figure 53: Use of back-lit zebra board for detecting optical distortions on glass surface. Source : https://www.isravision.com/

Figure 54: Use of checkerboard for detecting points for calibration of image using OpenCV library in Python. Source : https://docs.opencv.org/4.x/dc/dbb/tutorial_py_calibration.html

In the case of this experiment, it was found that the DGU panels are well suited for the optical tests as they could be deformed beyond serviceabtiliy limits. Further, since fully tempered glass panels were tested, the same were used for optical performance tests to achieve known mechanical behaviour; even though annealed glass DGU would have a better optical performance. The setup for the optical tests was similar to the one for mechanical behavior tests, except the orientation of the panel. For optical testing, the panel was oriented such that it was against a window, through which there was a view of some trees, as well as parking, as it offered a combination of organic and rectilinear forms; which are important for both, subjective and objective analysis. The orientation was also such that the reflections of the lights in the ceiling could be clearly seen in the photographs.

The tests were conducted in 3 parts. For the first round, zebra board was used as a backdrop behind the façade glazing panel. The distance between the backdrop and the glass panel was 1m. A DSLR camera was mounted in front of the façade panel at a distance of 2.5m from the glass panel as shown in Figure 55. The experiment was conducted during day time and it was made sure that the reflections of the ceiling lights were visible in the photographs. To minimize the movement of the camera during the experiment, the camera was controlled with a laptop, through a wired connection. Figure 57 and Figure 56 shows the optical tests being conducted using this setup. It is important to note that the researchers being at a safe distance from the setup is not only preferred from a safety perspective, but also that their reflections and movements do not interfere with the image quality.

The cavity pressure was being monitored using a pressure transducer connected to the cavity of the glass panel, in the Arduino IDE interface. The pressure was controlled manually in this case. The experiment was conducted in steps, wherein for each step the cavity pressure was maintained at a fixed value. For the zebra board experiment, the 5 pressure steps were 0.0, 0.1, 0.2, 0.3 and 0.4 PSI. For the checker board and the experiment with background view, 2 steps were used, with 0.0 and 0.3 PSI. Inflating glass beyond 0.3 PSI was considered risky since the glass pane may suffer from fatigue loading during such experiments.

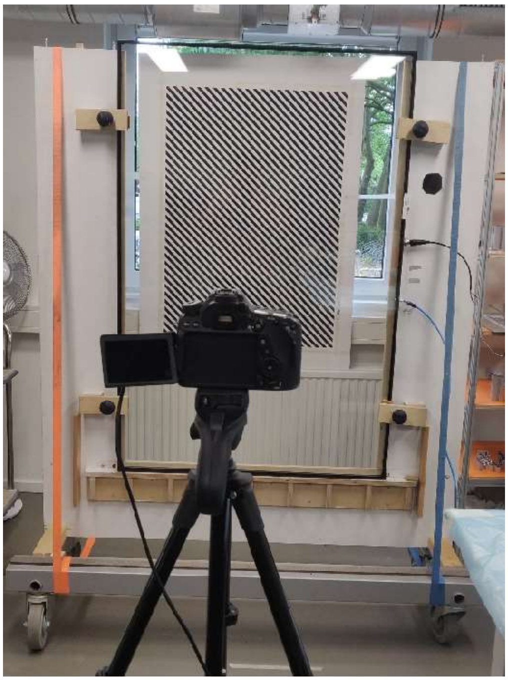

Figure 55: DSLR camera setup in front of the glass panel, and zebra board behind.

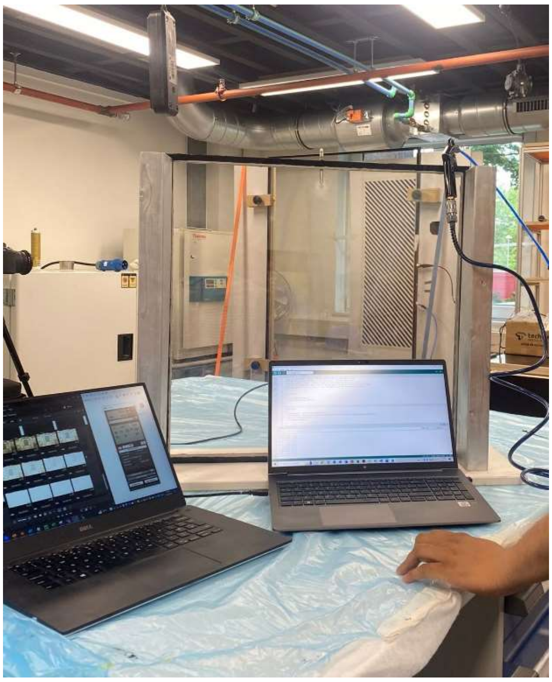

Figure 56: Safety barrier from behind which the camera was being controlled and the pressure readings being monitored.

Figure 57: Optical tests being conducted in the laboratory setup with DSLR camera controlled remotely and the pressure readings being monitored from behind safety panel.

For each pressure step in the experiment, multiple images were taken using the DSLR camera. The camera settings were manually adjusted and fixed at ISO 100 and aperture value of 8". Automatic focus was used for all the pictures. Multiple photographs were with varying shutter speeds in the range starting from 1/4000 sec to 30 sec. All the images for each pressure step were then merged into a single HDR image with standardized exposure. This is important from the perspective of objective and subjective comparison between 2 or more images. Consequently, 5 HDR images for zebra board and 2 images each for checkerboard and outside view were produced for comparison as seen in Figure 58, Figure 59 and Figure 60. For this experiment, the comparison was made manually using Photoshop by laying out the images over one another and observing the GIF images for any disturbances in both, the reflections upon glass and distortion of the pattern/ view through the glass. This comparison can even be done using computer vision software.

The main observation made from these images relates to the perception of deformation in glass through distortions. It was observed that the deformation was perceived mainly through distortions of reflection of celing lights. The pattern or view behind the glass shows not visible distortions to the naked eye in all three cases. Even when the corresponding images were overlapped, no perceptible distortions of the pattern or view behind the glass were visible. This suggests that the glass did not behave as a 'lens' upon pillowing, when viewed from a point along the axis normal to its original plane. This may change based on the change of the angle of the camera with respect to the plane of glass.

Further, for all cases of different relative angles, the distance between the camera and the façade panel should be changed to observe whether distortions are more perceptible when we are closer to the façade panel or far away. In addition, the distance between the façade panel and the pattern behind must be also changed and tested to compare how does the proximity of the objects in the view to the façade relate to their perceived distortion. Further, the same setup can be used to conduct subjective tests with a few selected scenarios based on observations from the objective tests.

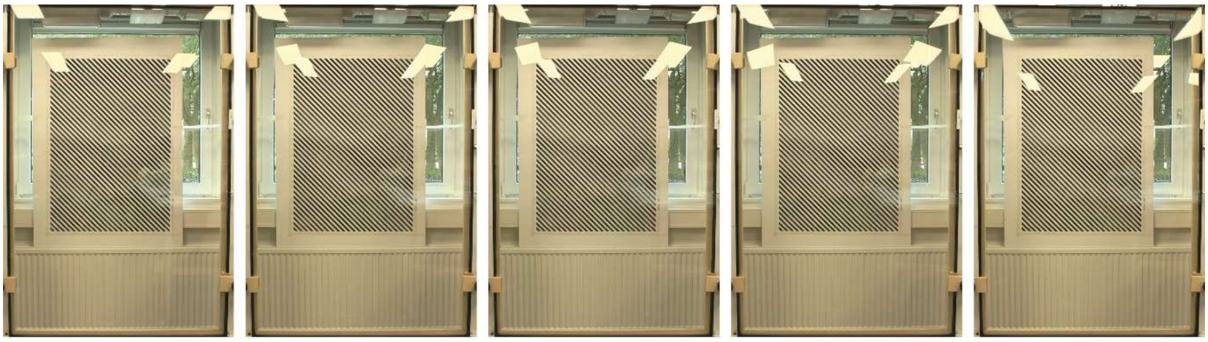

Figure 58: Five HDR images from experiment using a Zebra board.
Pressure readings for images from left to right are 0.0, 0.1, 0.2, 0.3 and 0.4.

Figure 59: HDR images of checkerboard at pressure levels of 0.0 PSI (left) and 0.3 PSI (right).

Figure 60: HDR images of the outside view at pressure levels of 0.0 PSI (left) and 0.3 PSI (right).

4.6 Discussion

Scientific research implies a causal relationship between variables. For this experiment, as there was no precursor for identification of variables, older scientific research related to serviceability limits on structural components, such as floor slabs or deflection limits on high rise buildings were used. However, the relationship between the body and movement in the structural components is direct, as the body is supported by and in contact with the structure. The relationship between façade and the occupant is primarily visual. Hence, most variables are related to visual perception of motion. There is a scope to dive deeper into identification of the dependent variables that contribute towards the overall 'occupant satisfaction'.

The experiment design process was done in two parts – design of the experimental method which would involve participation of people and the design of the mechanism and the physical setup. The design of the experimental method influences the design of the setup. Since the effect of both static and dynamic deformations is to be measured, the setup is designed in a way to generate deformation and vibrations. The use of an electro-pneumatic system over a mechanical system also was influenced by the fact that the variations in deformation were to be fast and without restricting occupant's view of the outside during the experiment. However, it was later realized that the setup is versatile and adaptable, offering a possibility of measuring the objective parameters as well.

In the process of design and testing, several gaps in knowledge were identified, which open us scope for future research. One such gap was the conversion of actual wind data into signal output from the Arduino. This has been further discussed in Chapter 5.2.1. The distance measurement used to record continuous serial measurements during the prototype testing was an ultrasonic sensor. It was not found to be accurate, and it has limitations in terms of frequency of distance measurement. Therefore a static laser measurement device was used during feasibility tests. But this device was not able to provide serial readings at different pressure steps. A suggested improvement is the use of Serial distance measurement laser devices or Linear Variable Differential Transformers (LVDTs). Laser devices need an opaque surface for measurement, and thus the glass surface may have to be coated with a film at the point of measurement. LVDTs are more commonly used to measure deflections in structural components (floor slabs, beams etc.) and give a live reading of deflection. However, the frequency of their reading might be slow for rapid vibrations in glass. LVDTs may be useful and inexpensive in case of climatic loading, while laser measurement in case of vibrations. Another method for measurement of deflections is 3D scanning. However, the process is currently expensive and also restricted to static deformations.

Safety is one of the major concerns as the experiment is designed to be conducted with volunteers. Ideally, the deforming panes should be laminated. But when that is not possible, it is recommended that a safety film be installed and a breaking test be conducted before conducting the experiment with any volunteers. However, imperfections in the film application and risk of scratched hampered the process of experimentation. Another level of safety is ensured by Including the maximum permissible limits on cavity pressure in the code that controls the mechanism.

The experiment was designed around the provisions of the Light Van. However, finally, the feasibility experiments were conducted in a laboratory, using the demountable frame of the Light Van. However, since the clamping was only done on two sides, the top and bottom edges showed significant deformation at high pressure levels. For future experimentation, the design of the frame should also be improved to restrict deformation of the edges, while acting as simple supports.

Testing with volunteers using this setup can be integrated in the architectural decision making process. It is envisioned that this setup can be integrated during the façade prototype approval phase which is a critical step in decision making when it comes to design and production of façades. For retrofitting or renovation projects, this setup may also be used on site, and data on acceptance of deformation be gathered from the current and future users of the building.

5 Discussion

5.1 Serviceability Criteria

5.1.1 Scope for a shift in serviceability limits

Deflection in glass below the ultimate limit lies in the 'acceptable' range from a mechanical performance perspective, but it may lie outside an acceptable range from the perspective of durability or optical performance. Similarly, deflection in glass below the durability limit may be outside the acceptable optical performance limit, and deflection well within the optical limits may be outside the occupant satisfaction limits and so on. Serviceability limits on deflection are one of the main parameters governing the thickness of glazing in facades.

Current serviceability limits are standardized as hard limits without a concrete basis for their definition. Deflections and thickness of glass are interrelated, and often depend on the glass dimensions, aspect ratios, type of glass and the loading conditions. Building codes from different regions show slight variations in permissible deflections. Additionally, building codes such as SIA guidelines, FprCEN/TS 19100 make exceptions for certain types of glazing, such as those covering a smaller area or those not exposed to excessive loading. Such exceptional scenarios only have to meet ULS criteria, which permits higher deflections, related to SLS criteria, allowing for material efficiency. It is important to question the standardization of deflection limits as a hard limit, and check the possibility of providing a range of acceptable deflections based on application, region, predicted loading conditions etc. A shift in serviceability limits on deflection will imply a potential to use thinner glass in facades. Given that new policies such as the Part Z (UK) are being proposed to regulate the total amount of upfront embodied carbon in buildings, reassessment of serviceability limits has become crucial.

Determination of serviceability limits based on all serviceability criteria is a complex process. Firstly, an exhaustive set of performance criteria must be defined. Secondly, specific limits based on each performance criteria need to be determined. Finally, a decision about the most critical serviceability criteria for a given application will have to be chosen, to determine the overall serviceability limit. In this thesis, the main criteria were identified and availability of relevant assessment methods was checked by means of the literature review and façade industry survey.

5.1.2 Serviceability Criteria from literature review and industry survey

As with most building components, maintenance of the expected performance while resisting potential actions must be considered as the base serviceability requirement for glazing. Thus, the criteria for serviceability must concern the pre-defined expected performance requirements of glazing. The limits on deflection would be those beyond which the expected performance requirements of glazing are not maintained.

A list of serviceability criteria retrieved from the survey is given in Table 8. From the literature review we had listed the following as our main serviceability criteria – mechanical performance, durability, optical, thermal, acoustic performance and occupant acceptance. From the façade industry survey, this list was validated, and additional criteria were listed, namely, sustainability, feasibility, fire and maintenance. We have seen that the mechanical performance primarily is concerned with ultimate limits. However, even within ultimate limits, bending of glass may have effects such as buckling or cold bending distortions. Therefore, these can be considered for the deflection limit calculations.

The sustainability criteria listed in the survey relate to the carbon footprint of the façade, and life cycle impact. These do not have a direct relationship with serviceability of a façade and cannot be considered as criteria to define limits on deflection. Feasibility in terms of production and handling is a concern which will have an impact on the glass thickness from a supply chain perspective. Moreover, it can be assumed that if the limits based on feasibility of production and handling are met, the limits for maintenance will also be covered, since it deals with service life after installation of glass facades.

Hence, a final list of criteria derived from the review can be listed. As long as the feasibility of manufacturing and handling is achieved, the service criteria that can be used for determination of deflection limits are –

mechanical performance, durability, optical performance, thermal performance, acoustic performance and occupant satisfaction.

5.1.3 Determination of limits based on performance criteria

1. **Mechanical performance:** As mentioned above, deflections even within ultimate limits may lead to unwanted mechanical behavior in glass, such as cold bending distortions and buckling. It was found that research on mechanical behavior has been carried out (Datsiou & Overend, 2016; Quaglini et al., 2020) which can be referred to for setting limits to avoid unwanted mechanical behavior under excessive deformation in glass. Further validation can be achieved using available FEM software.
2. **Durability:** For measuring the impact of reduced glass thickness, literature (Bedon & Amadio, 2020; Besserud et al., 2012; Gubbels et al., 2014; Respondek, 2018) provides enough information on reliable numerical, analytical and experimental assessment methods. Testing with different sealants would be required in case of considerable increase in edge-strains in glass.
3. **Thermal Performance:** Reduction of thickness of the gas-filled gaps leads in most cases to worsening of the thermal properties of a partition, but also to decreased deflection and stress in the IGUs exposed to a climatic load (Respondek, 2018). However, U-value is influenced by more parameters, such as presence of low-e coatings, gas in cavity, etc. Change of U-value may affect operational carbon of the building, and change of glass thickness relates to the embodied carbon. As a balanced approach, overall impacts of these changes will have to be assessed.
4. **Optical Performance:** The limit stated by EN 12150-1:2000 has been considered as an acceptable limit in the papers that study cold bending distortion (Datsiou & Overend, 2016; Quaglini et al., 2020). However, impact of deflections caused by wind loading on optical performance may be different from those cause by climatic loading. There is scope for specific research to be carried out related to this subject. Further, the acceptance of these limits based on human perception of distortions must be assessed to set effective limits.
5. **Acoustic performance:** There was no literature found on the acoustic impacts of deflections. Change of geometry of glass and variation in gap thickness would be the main causes of change in acoustical performance. There is scope for research in this specific subject, and a need for assessment methods to be defined in order to set serviceability limits.
6. **Occupant satisfaction:** Since specific literature regarding this topic has not been found, there is a need to first define the satisfaction criteria in specificity. Then, there would be a need to gather empirical data to arrive at 'acceptance' limits of deflections based on these criteria. It is important to locate the human-centered criteria in the spectrum of other effects of deflection, in order to make a balanced judgement for setting serviceability limits to glass.

5.1.4 Occupant Satisfaction sub-criteria

Theoretically, the fulfilment of the first 5 criteria in the list of criteria should be enough to define serviceability limits on deflection. Thus, in this case that the performance of glazing under such a limit can be termed as satisfactory. However, there is an influence that glazing deflection directly has on the occupant, such as a sense of disturbance, or annoyance due to unexpected movement of glass. It may even evoke a feeling of alarm, since excessive deflection in glass is often a result of an excessive load acting on it, and the breaking of glass is an unacceptable condition. Thus, human tolerance towards glass deflection can be indicative of the level of satisfaction, i.e. if the glass deflection is tolerable, occupant satisfaction level is maintained. Thus, occupant satisfaction is a combination comfort criteria, (thermal, optical, acoustic, etc.) and the tolerance of occupants towards glass deflections.

Occupant satisfaction is also related to the perceived aesthetic value of glass. Deformation in glass is perceived as a sign of low quality in a building. Architects and clients may demand a very high quality finish from glazing, which makes the use of thinner glass that shows deformations challenging. However, there have been examples where certain architectural measures have been taken to not perceive glass deformations, such as breaking continuity in glass facades to avoid seeing distorted reflections, or using glass with more transparency and less reflectivity.

Thus it can be said that occupant satisfaction can be assessed as a combination of the sub-criteria, namely, perception of safety, satisfaction with the view, acceptance of deformation and disturbance in activity. These 4 have therefore been chosen as the parameters to measure the occupant acceptance for our experiment.

5.1.5 Interdependency of criteria

It is important to note that the criteria listed above are not independent of each other's influences. For example, durability of an IGU depends on the life of the primary and secondary sealants. Deflection causes a change in the strain state of the glass pane, thus inducing a strain in the sealants. If such deflections are frequent, as a result of repetitive actions, they may impact the life of the sealant. Further, repetitive deflections coupled with weathering, have a higher impact on the life of the sealant, increasing the probability of sealant failure. It is known that sealant failure could lead to unacceptable consequences such as moisture infiltration in the cavity or gas leakage, eventually leading to unacceptable change in the thermal performance of glazing. Thus, it can be seen that mechanical performance could affect durability, which could affect the thermal performance of glazing. Figure 61 is a schematic diagram indicating interdependencies between the 6 criteria listed. As discussed earlier, it can be seen that occupant satisfaction also is impacted either directly or indirectly by other performance criteria.

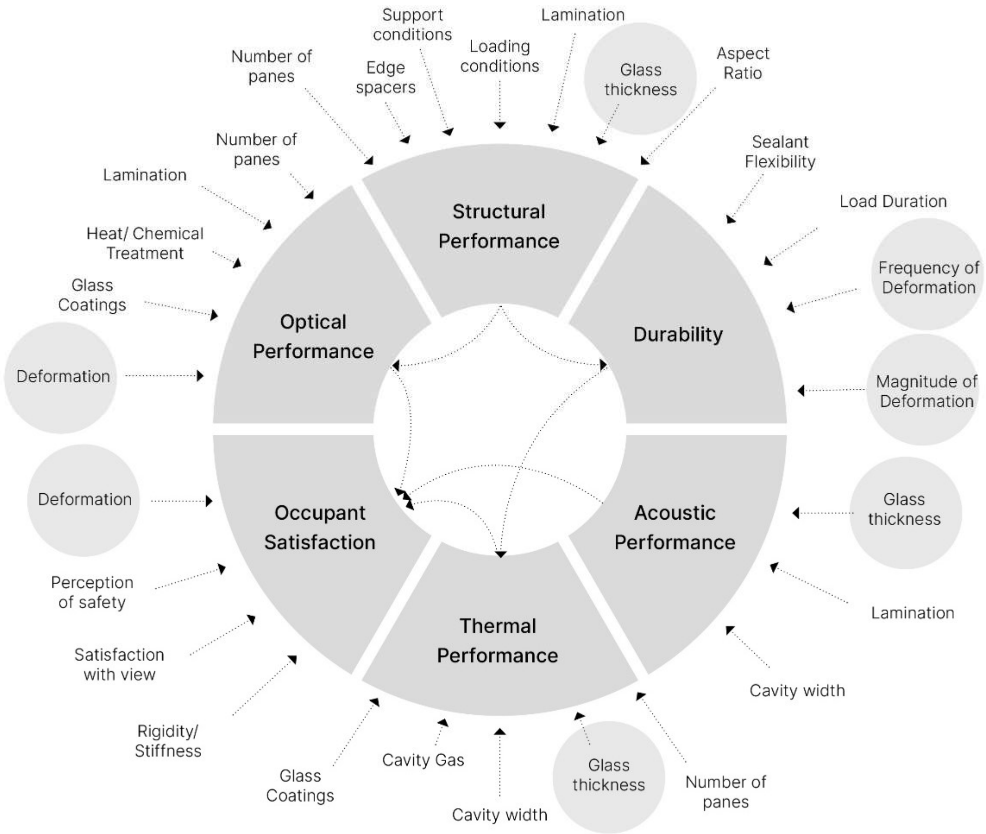

Figure 61: Interdependencies of factors affected by deflection in glass

In addition to the interdependencies, Figure 61 also shows that glass thickness and deformation do not alone influence any of the given criteria. There are more than one factors at play. For instance, durability relies considerably on the flexibility of the sealant and duration of loading. Similarly, mechanical performance depends on number of panes, lamination, support conditions etc. This also means that effects of reduction in glass thickness can be mitigated by adjusting some other parameters.

5.1.6 Weighting of criteria

Given a certain sample of glazing for a certain application under the impact of a specific loading case, and with specific dimensions, individual deflection limit values can be determined for each criteria, using the assessment methods and calculations, as indicated in Table 4. The larger goal is to determine a serviceability limit as a single value of deflection which satisfies the serviceability requirements. However, serviceability requirements for a residential apartment might be different, as compared to a store room. It is important to note that the serviceability values might differ even though the ultimate values remain the same, since the ultimate values deal mainly with glass failure.

Therefore, the determination of deflection limit for serviceability can be seen as a multi-criteria decision making (MCDM) process. Depending on the application of glazing, different criteria might have different weightage in design. For instance, if we take an example of glazing for a store room where a controlled temperature condition is desired, the thermal performance and durability criteria would be weighted higher than occupant satisfaction. Similarly, for a viewing gallery at a scenic place, the optical criteria for serviceability would be weighted higher than the others. Figure 62 shows a schematic process of determination of SLS deflection (δ_{SLS}) from weighted deflection limits of all 6 criteria. A mathematical expression is to be determined for the process. This will depend on which MCDM method is best suited to this process, which at the moment, lies beyond the scope of research.

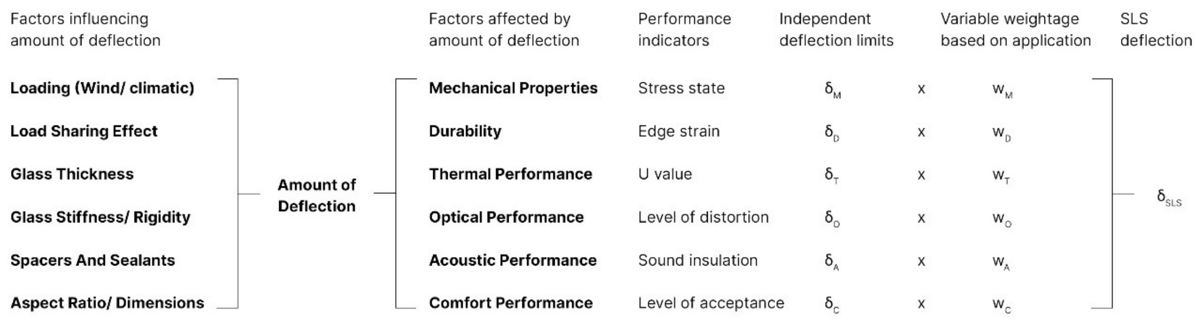

Figure 62: Process of weighted determination of serviceability limit state

The most significant outcome of this discussion is that without a clear definition of limits on occupant satisfaction, the weighted determination of SLS limit will not be complete. Thus, potential opportunities to allow higher deflections, or, in other words, a reduced glass thickness might be missed out. A comprehensive understanding of limits as per each criteria is required, so that an informed decision can be made about the optimal glass thickness for a given façade glazing scenario.

5.2 Multi-criteria serviceability assessment

The experiment in this thesis was primarily designed keeping in mind subjective testing with volunteers. Therefore, it was chosen that the load will be applied using air pressure, and not mechanically. The resultant system not only allows us to control the amount of loading but also offers a possibility to generate dynamic load by means of controlling inflow and outflow of air in the cavity. Another advantage of the system is that the framework, the façade panel and the air pressure system can be easily disconnected. This allows us to test more than one panels, in a variety of laboratory conditions. In the previous discussion, the need for a comprehensive understanding of deflection limits based on various performance criteria was highlighted. The adaptable nature of this experimental setup can thus be exploited to assess more performance criteria than only occupant satisfaction. However, the next step in research is the appropriate translation of wind data for dynamic loading. The next chapter discusses the proposed concept for wind data translation and the following chapters discuss possible test scenarios using this setup.

5.2.1 Wind data interpretation for dynamic loading

Currently the experiment setup utilizes a solenoid valve to generate a frequency for inflow and outflow of air. The air is supplied at a constant pressure by the air compressor. The air flow can be maintained at a certain value using a flow control valve. Thus, this setup is able to generate a uniform inflow and outflow of air at different frequencies as required. However, wind loading on a glass pane is not of a fixed magnitude and frequency. The wind loading patterns determined by measurement of incident pressure over time duration are shown in Figure 63. The pressure over time graph indicates that the at each time-step (at which measurement is recorded), there is a high variation in the incident pressure. It is the peak values at which the impact of incident wind may cause high deflections. The main challenge is interpretation of this variation in wind pressure over time in order to simulate it for the experiment.

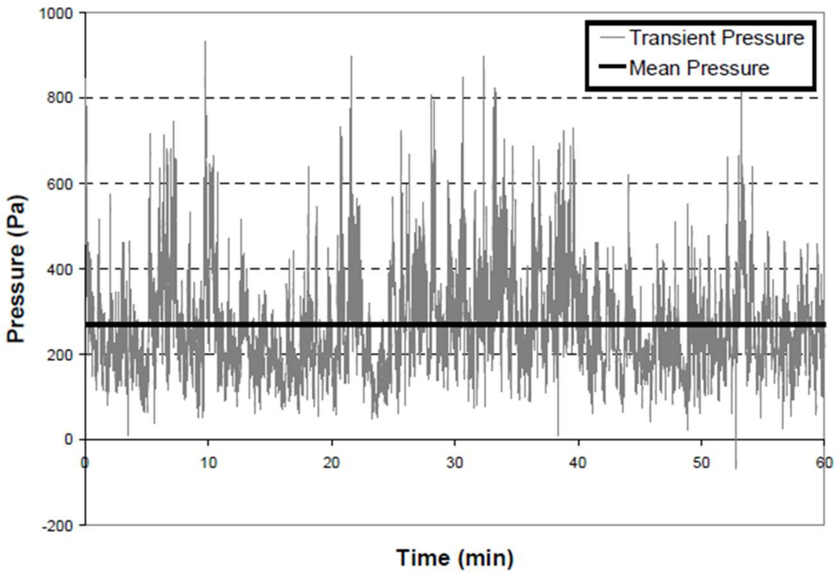

Figure 63: Graph showing wind pressure measured over time on a façade under direct wind exposure

In principle, simulation of this effect can be achieved by varying the flow rate at a constant frequency. The variation in flow rate can be between the peak values as gathered from the graph. The frequency of air supply can match with the data set. For example, if the readings are taken every one-fourth of a second, the output frequency could be 4 Hz. The finer the measurements of incident frequency, the higher the output frequency will have to be. At the same time, frequency of output will also have to be controlled in a similar manner, by using another valve. But change in flow rate has not been explored for the current thesis. This remains open to future research.

In terms of exhaust from the air cavity, currently the setup relies on the size of the opening for exhaust air. If the size of the opening is larger, the exhaust of air is faster and vice versa. A controlled exhaust system has not been implemented. One of the ways to do this is by the use of a vacuum generator valve. Figure 64 shows the working principle of this valve. Point A is the compressed air supply point and point C is the exhaust. Point D indicates the opening (connected to the cavity) for generation of vacuum. As compressed air is passed through A, the Due to the narrowing of the channel B, air is sucked in from the opening D. This way, air supply through the valve generates a vacuum in the cavity. The air supply into this valve can also be connected to Arduino and the frequency of vacuum generation be coordinated with the frequency of air supply. This way, a faster exhaust of air from the cavity is possible. This method has not yet been practically tested in our application, and is open for future research.

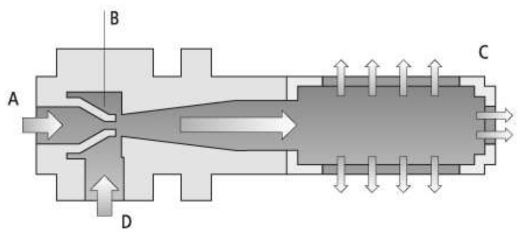

Figure 64: Working of a vacuum generator valve. (source: https://www.schmalz.com/en/vacuum-knowledge/basic-knowledge/operating-principles-of-vacuum-generation/)

5.2.2 Mechanical performance assessment

For the feasibility study, we already were able to test certain mechanical behavior. A relationship between the cavity air pressure and resultant deflection was achieved. The results were able to confirm the geometrically nonlinear behavior of the glass pane under uniform loading, when compared to the results from finite element analysis. However, the deflections were only measured at pressure steps as large as 0.1 PSI i.e. 689.5 Pa. Also these measurements were taken at static intervals, when the pressure was kept steady. There is scope to obtain a more accurate relationship between cavity air pressure and deflection by means of a more sensitive pressure transducer and a laser deflection measurement device which can provide serial information via a data logger.

Further, by use of strain gauges and accelerometers; and comparisons with finite element data, it is possible to test different loading scenarios and observe specific effects in the laboratory. Specifically, through strain measurements at the edges, the impact of different loading conditions on potential deterioration of the edge seal can be measured. Different loading conditions can be simulated using the electropneumatic system. Figure 65 shows a schematic representation of this setup.

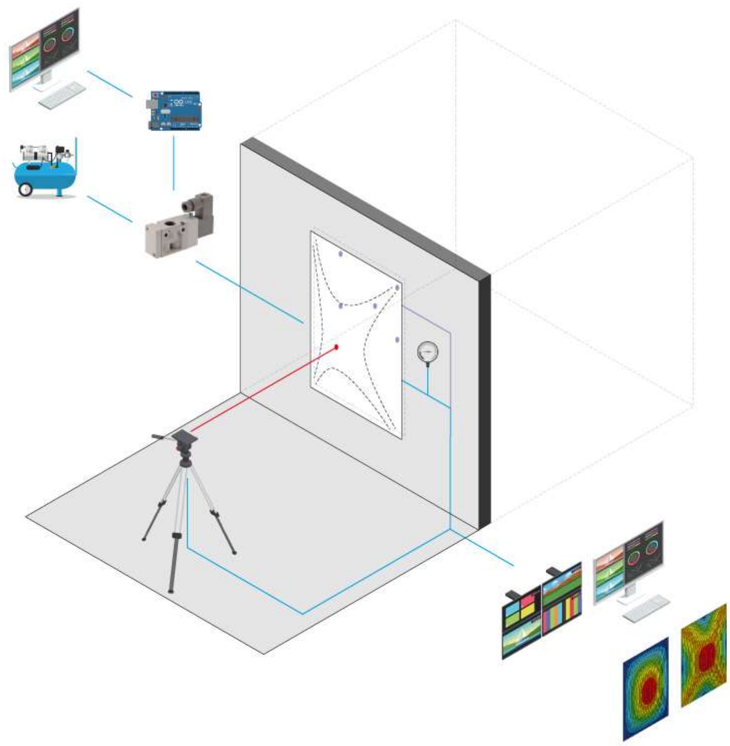

Figure 65: Mechanical testing setup using laser deflection measurement device; strain gauges and accelerometers to obtain accurate data on mechanical behavior under different loading conditions.

5.2.3 Optical Performance assessment

Objective optical testing can be conducted mainly to assess the impact of deformation in glass on the distortion of view through glass, distortion of reflections in the glass and also change in illuminance resulting from the deformation. The test with checkerboard was carried out during the feasibility testing phased of this thesis for a DGU. However, in this experiment the camera was aligned towards the centre of the glass along its normal axis; and only static pressure steps were tested. The setup used for this experiment has been shown in Figure 66. Furhter testing can be carried out using this setup by changing the distance between the camera and the façade, and angle of view for different levels of static and dynamic deformation.

An HDR image generation is critical for such experiments in order to capture images with similar brightness and colour levels to objectively compare them with each other. This can be done by capturing multiple images with different shutter speeds and combining these in an HDR generator software. For objective comparisons, several evaluation metrics can be used, namely: Root mean square error (RMSE), Peak signal-to-noise ratio (PSNR), Structural Similarity Index (SSIM), Feature-based similarity index (FSIM) etc. SSIM is a recommended for the purpose of this experiment as it extracts 3 key features from an image: luminance, contrast and structure.

It has also been generally observed that humans perceive deformation in glass mainly by means of changes in reflected images and lights in the glass surface. The amount of change in reflection can also be objectively measured by using a zebraboard setup as shown in Figure 67. It is recommended to use a back-lit zebraboard for this setup and that the surroundings should be as dark as possible so a fair amount of image clarity is achieved. The analysis of the HDR images can be conducted in a similar way as mentioned above.

Further, the same setup can be used to test the effect of deformation on image distortion. The setup can be oriented towards views of different types. It is easier if the setup is installed in a mobile laboratory like the Light Van. These tests are again, image-based and would require an evaluation metric for objective measurement of similarity between two images.

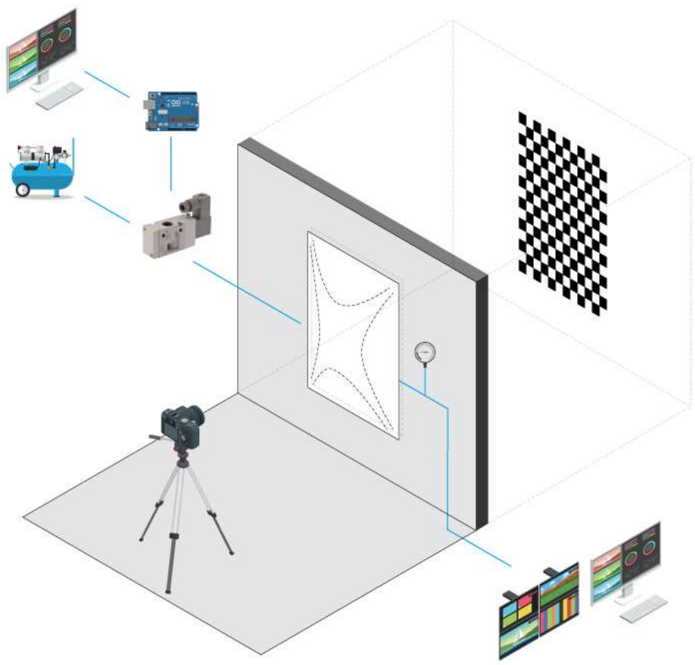

Figure 66: Optical test setup using a checkerboard and camera to capture HDR images for objective comparisons.

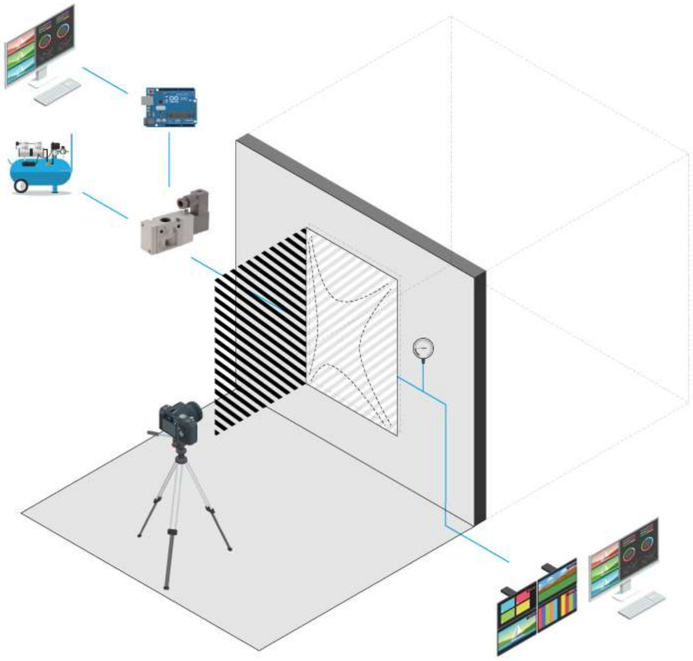

Figure 67: Optical test setup using a zebra board and camera to capture HDR images for objective comparisons of reflections.

Figure 68: Optical test setup for analysis of distortion of exterior view with camera to capture HDR images for objective comparisons.

5.2.4 Subjective assessment of occupant satisfaction

The experimental setup has been primarily designed around subjective experiments conducted with volunteers to measure their level of satisfaction with the view, perception of safety, acceptance of deformation in glass and disturbance in their activity. For testing effects of dynamic loading over a period of time, this experiment can be conducted with one volunteer at a time in a controlled environment, simulating a day to day activity, as shown in Figure 69. The volunteers get a chance to engage with the façade for a longer duration and rate their experience as the amount and frequency of deformation in glass are manipulated.

Another variation of this experiment is for the measurement of climatic loading. This experiment can be conducted at a much faster rate; and even more than one participants can be invited at a time to evaluate deformed glass at different pressure steps, as seen in Figure 70. For comparison, benchmarking can be done using a perfectly flat façade panel. In both loading cases, the volunteers can be grouped based on confounding variables to be tested. In the case of this thesis, the main confounding variable was prior knowledge about the benefits of using thinner glass and confidence in the structural capacity of glass that deforms. Furthermore, for subjective testing, relevant scales of measurement of acceptance and statistical framework for analysis needs to be developed; so as to arrive at scientific results. This subject is open for further research.

Figure 69: Subjective test setup for analysis of effect of distortions on occupant satisfaction with a single volunteers or groups of volunteers recording their perception towards deforming glass.

Figure 70: Subjective test setup for analysis of effect of distortions on occupant satisfaction with a single volunteers or groups of volunteers recording their perception towards deforming glass.

5.2.5 Thermal Performance Assessment

One of the main concerns with deformations in IGUs is the impact it has on the thermal performance. There have been studies in the past in which the impact on thermal perfomance due to climatic loading was measured on site (Watson et al., 2015). However, these tests can also be easily conducted in a laboratory using a 'hot box' setup. The façade panel installed in a thermally insulating can be subject to different levels of deformation while the temperature in one of the rooms is controlled at a certain level. A schematic diagram of the setup for this experiment is shown in Figure 71Figure 72. The heat flux through the glass panel can be measured using a heat flux meter. Further, the temperature in the second room can be measured and a time-based analysis of thermal insulation of the IGU can be achieved. Since the thermal insulation of an IGU is more dependent on the gap width than the glass thickness, it is also important to arrive at the minimum and maximum 'acceptable' gap width levels, according to thermal serviceability.

5.2.6 Acoustic Performance Assessment

Similar to a setup for thermal performance assessment, the acoustic performance assessment can be conducted in a sound insulating laboratory environment. To test the impact of deformation on sound insulation, a recording room with sound absorbent material can be setup with a decibel meter and sound at different frequencies can be produced in the other room using a sound generator. Similar to thermal limits, a minimum and maximum 'acceptable' range of deformation can be arrived at, within which the sound insulation of the glass panel meets serviceability requirements. A schematic diagram of the setup for this experiment is shown in Figure 72.

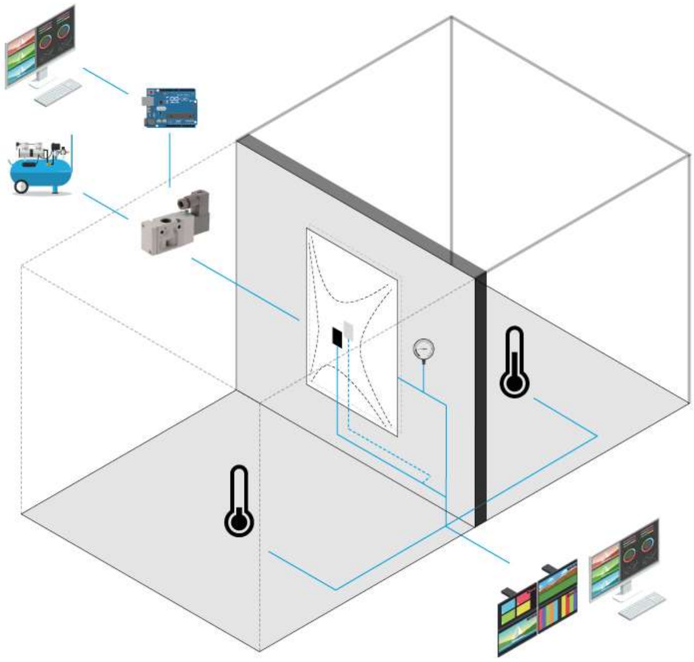

Figure 71: Thermal testing in a hot-box setup where temperature in one of the rooms is controlled and that in the other is recorded using temperature sensors and heat flux meters.

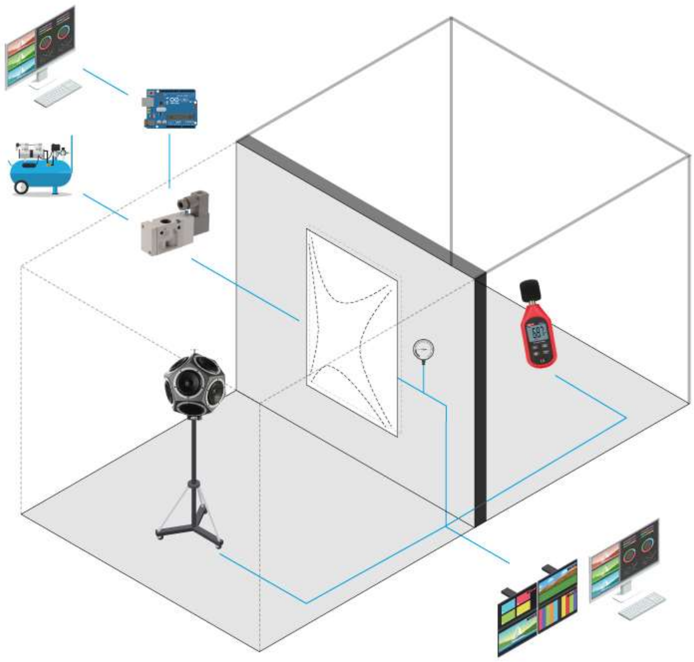

Figure 72: Acoustic performance measurement in an insulated room setup where a sound generator is placed in one room and a decibel meter in the other, to measure the impact of deformation on acoustic insulation.

6 Conclusions

The aim of this research was to develop a method to determine relationship between level of deformation in glass and occupant acceptance towards deformation; with the intention of arriving at acceptance thresholds. The literature review and façade industry survey prompted the need for such a method in order to explore the potential of a material efficient approach towards design of façade glazing. An experimental method was designed to measure occupant acceptance towards deformations in glass using this setup. Variables for this experiment were adapted from those that are used to determine serviceability limits for structural components. Besides measurement of relationship between deformation and acceptance, this method also accommodates testing of the impact of prior knowledge about material capacity and benefits of material efficiency on the acceptance of deformation. This method needs to be tested in the future to determine occupant acceptance thresholds comparable to those defined for objective criteria.

The experimental setup was designed and developed based on the concept of using air pressure for loading the glass panes to replicate two common loading conditions related to serviceability – climate loading and wind loading. A double glazed unit (DGU) was chosen as the case for testing. For this, one setup uses a DGU construction of 4-16-4 and the second setup uses a triple glazing unit (TGU) of 4-16-4-16-6.6 configuration. The DGU was used to test the effect of climatic loads, created by positively pressurizing the cavity creating a pillowing effect. The TGU was used to recreate a dynamic wind loading effect by pressurizing and de-pressurizing the outer cavity in time-steps so as to deflect the mid-pane and the inner pane. The mechanism was tested on smaller prototypes and on full-size panels of dimension 1467mm x 972mm and was found to be working as expected, creating the desired effects; thus providing a proof of concept for the experimental setup.

The feasibility of this experimental setup was tested for its mechanical behavior and optical distortions. It was found that the static deformation (pillowing) does not have any perceivable impact on the view through the façade panel. However, the distortions in glass are perceived through distortion of the reflected images, such as ceiling lights and reflecting objects. In addition to this, future objective optical experiments must be conducted under dynamic loading conditions; and subjective experiments with volunteers must be conducted under both static and dynamic loading conditions.

The objective testing with TGU could not be conducted as deflections beyond the serviceability limits were not achieved despite pressurizing the cavity. This may be due to possible leaks to the sealant of the inner cavity. This can be overcome in the future for conducting the objective and subjective experiments using the TGU. The mechanical tests also revealed that the behavior of the glass panes under uniform loading closely follow the predictions of geometrically nonlinear behavior predicted by finite element analysis. However, the stress predictions as per nonlinear loading were found higher than fracture stress of glass. This might be the effect of relatively small thickness of the glass panel compared to its length and breadth; however, this phenomenon needs to be addressed in detail though further research.

Of course, experimentation with volunteers is best suited for human-centered appraisal of façade design. However, acceptance thresholds may still vary considerably over changes in time, location, people's background, building typology, etc. A series of experiments in a variety of contexts and different user groups should be carried out to cover the wide spectrum of subjectivity and arrive at more concrete results. To speed up this process, the physical setup can be combined with a virtual setup. The physical setup can be used for benchmarking of actual human response in a limited number of scenarios, and further assessment of different scenarios facilitated by a virtual setup. For quantitative and qualitative analysis of the experiment results, a statistical framework needs to be prepared in order to scientifically arrive at accurate results.

Since the survey and the experiment both involve interaction with people, safety concerns formed a large part of the process. The design of the industry survey and design of the experiment were both approved by the Human Research Ethics Committee (HREC) of TU Delft. The data gathered from the surveys and experiments is stored in a secure storage on TU Delft's server. Safety concerns regarding experimentation with volunteers can be overcome by application of safety films on glazing. The safety film is tested to be sufficiently strong to retain the broken glass pieces in case of an accidental breakage in glass. However, imperfections in film arising from poor application procedure and risk of scratches were a major hindrance for optical testing. It is recommended that laminated samples be used for such experiments as far as possible. Additionally, the maximum and minimum permissible cavity pressure values have been included in the Arduino code so that the system can shut off when any of these limits are crossed.

The merit of this method lies in the fact that it can be used for a comprehensive multi-objective testing for serviceability. The experimental setup was found to be versatile and scalable enough to conduct experiments to assess the impact of deformations on mechanical behavior, thermal performance, acoustic performance and optical performance. A recent research published in the Applied Sciences Journal employs a similar mechanism using air pressure for measurement of mechanical properties of glass under deflection (Kozłowski et al., 2023). Since the current research mainly concerns occupant acceptance, one of the immediate next steps in research would be the application of this setup to conduct subjective tests from the outside of the façade, which is more concerning from an aesthetic perspective. Overall, the successful implementation of the setup, the mechanism and the results from mechanical and optical testing have helped open rather optimistic avenues for further research in multiple directions to tackle the complex subject of serviceability of façade glazing.

7 Reflection

7.1 Graduation Process

7.1.1 How is the graduation topic positioned in the studio?

Building facades face a unique challenge in the future – striking a balance between global sustainability challenges such as climate change, material scarcity, energy poverty etc. and trying to meet the high standards of human comfort. The Facades and Products graduation studio focuses its research on developing novel solutions to face this challenge. As much as there is need to focus research on new materials and new technologies, there is also an urgent need to critically analyze the conventional. This graduation topic is appropriately positioned in the studio as it questions the current serviceability norms that govern, and at times, justify the specification of glass thickness in facades. A critical analysis is crucial to understand whether a balance between material efficiency in glass and human acceptance of glass deformation can be achieved; and if yes, what are the ways to achieve it.

7.1.2 What is the relationship between the methodical line of approach of the graduation studio (related research program of the department) and your chosen method?

Typically, the methodical line of approach of the studio is either research through design or research through experiment. Topics related to novel ideas in facades typically follow the former approach and those related to research on new materials follow the latter. This topic lies at the intersection of both these approaches. Rather than a novel design or novel material, the thesis develops a novel methodology of an experiment to explore potential of material efficiency in a conventional material i.e. glass. The design of the experimental setup follows a research through design approach. The experimental setup itself facilitates research through experiment.

7.1.3 What is the relation between your graduation project topic, your master track and your master program?

Building Technology (BT) curriculum deals with the non-subjective or technical aspects of building design, and is rightly positioned within MSc Architecture, Urbanism and Building Sciences (AUBS). Even though BT curriculum focuses on technical aspects while maintaining a strong relationship with the needs from a user's perspective, it is typically associated with quantitative research. Human acceptance of glass deformations is at the core of this thesis topic. Thus, in addition to quantitative research, there is also a need to conduct qualitative research from the perspective of building occupants. The proposed experimental methodology can be used to measure both objectively and subjectively, the effects of glazing deformation on human comfort. It can also be used to measure acceptance at a larger scale of a street or a neighborhood, which governs the perceived 'value' of the project. This topic is of value to not only facade engineers but also architects and urbanists involved in the decision making process of building façades.

7.1.4 How are the research and the design related? How did your research influence your design/ recommendations and how did the design/ recommendations influence your research?

The words 'research' and 'design' individually have different connotations. While research pertains to academic exploration over a longer period of time in the realm of a broader subject, design pertains to a solution, often for a very specific problem in a given time and context. However, both these terms influence one another. In context of buildings, the design of its components significantly relies on knowledge generated through previous research. Similarly, as the design of components advances to meet the challenges of the future, it opens up new avenues for research.

In the context of this thesis, the decision to design a novel methodology was mainly a product of research. The study of current serviceability norms followed in practice, which was conducted through a literature review and a façade industry survey, highlighted a knowledge gap in terms of occupant acceptance of glazing deformation. Thereafter, specific research into experimental methods was conducted to better define the scope of the proposed experiment. However, as the design progressed, it also prompted more specific research topics related to the mechanisms, their inter-operability, theoretical validation and potential outcomes. Thus, research at a smaller scale was conducted to answer each of these questions and drive the design process forward. Interestingly, the outcome of this thesis i.e. the experimental setup is to facilitate further research.

While research at a broader scale was the main driving factor behind design of the methodology, the process of design prompted the need for more specific research on smaller sub-topics. For example, since laminated glass panels were not available for the final experiment, it was decided to apply a self adhesive transparent film to ensure safety in case of glass breakage during the experiment. For this, a small experiment to test integrity of a safety film was conducted, to prove that it is fit for use in the final experimental setup. Thus it can be said that while research is an integral part of the design process, the design process prompts the need for further research.

7.1.5 How did the research approach work out & did it lead to the results you aimed for?

Once the research question and sub-questions were defined, it was observed that different sub-questions required different methods of research. Hence, a mixed-method research approach was followed, which involved literature review, façade industry survey and research through design of an experimental setup.

While the literature review about serviceability norms in practice was found insufficient, the combined results of literature review and façade industry survey led to a comprehensive state-of-the-art knowledge about serviceability criteria followed in practice, perceived effects of glazing deformation on its performance and perceived barriers in transitioning towards use of thinner glass for facades. In addition to these expected results, subjective information in the form of opinions and apprehensions was also retrieved. These results were then analyzed qualitatively to infer patterns in the rationale of the responses. One of the main reasons for successful retrieval of results was that the number of responses analyzed (67) was a suitable sample size. In addition, the survey had a combination of numerical and 'free text' questions and some of the questions helped validate information received from the others.

In terms of design of the experiment, the research was a back and forth process. The process involved building of the prototypes, the electro-pneumatic circuit and the design of the stages of the experiment. Since the prototypes were built manually using a hardwood frame and were manually assembled in the workshop with limited expertise, at some instances they gave way to the cavity pressure. The electro-pneumatic circuit required a series of specific connections, some of which were not available, and had to be manually prepared. For instance, the pressure transducer is too large to fit directly in the spacer, so a customized connection was created for this purpose. Further the prototypes do not provide a fair representation of the final panels, so the calibration of the experimental setup could only be done after the final panels were received, which delayed the process. Hence, although the design of the experiment was not a linear process, suitable proof of concept was achieved for creation of the final experimental setup.

7.2 Impact of the graduation project

7.2.1 How do you assess the academic and societal value, scope and implication of your graduation project, including ethical aspects?

The project has a substantial academic value since it is not restricted to a single domain of expertise. The project demands a multi-disciplinary understanding of topics including mechanical behavior of glass, factors affecting human perception, fundamentals of electro-pneumatic systems and statistical analysis of retrieved information from the experiments. In addition, the researchers also have to take into account practical concerns such as logistics and time to be spent on prototype building. At an academic level, the project itself benefits from a multidisciplinary design thinking approach.

Serviceability is mainly concerned with the use-case scenario of building elements, governed by human acceptance levels. However, conventional standards ignore an intrinsic characteristic of human acceptance levels – that these are not fixed. This also means that with the right methods, these levels can also be raised or lowered by design. This project not only proposes a methodology to measure these levels, but also compares conditions which have a potential to raise acceptance thresholds. Thus, the project has a significant societal impact, as it fundamentally challenges the norms that consider human acceptance levels as fixed.

The scope of this project is limited to the effect of deformations in façade glazing under wind and climatic loading on occupant acceptance criteria. The occupant acceptance criteria includes 4 themes – perception of safety, satisfaction with the quality of view, disturbance in activity and general acceptance of deformed glass. The project excludes acceptance of deformation from exterior of the façade.

The main implication of the project is the role of prior knowledge among occupants about the material capacity of thinner glass and benefits it offers in terms of saving embodied carbon, on acceptance thresholds. The experiment methodology is flexible and involved many variables. But for the scope of this project, most variables other than prior knowledge have been fixed. The methodology thus can be used to test the implications of other variables in the future, such as variations in indoor environment quality, variations in activity or relative position of the volunteer with respect to the façade. Overall, the project promotes and ethical approach towards design by providing a methodology for participatory design.

7.2.2 To what extent are the results applicable in practice?

Traditionally, influence of dynamic wind loads on building facades is analyzed either using FEM models, or wind tunnel tests on façade prototypes. FEM analysis provides a detailed understanding of mechanical behavior of glass. Wind tunnel tests are quite extensive and require a specialized setup, and are suitable to observe influence of wind loads on glass and other façade components. However, to analyze the impact of deformation on occupant acceptance, these methods are not suitable. The proposed experimental setup is flexible and can be set up not only in a lab, but also at construction sites, or in offices where acceptance analysis can be easily conducted.

To measure the impact of deformations of durability of the sealant, this setup can be utilized for an accelerated durability tests through repetitive movement of the seal. To measure the impact on optical performance, this setup can be installed in a lab or even on the construction site at various heights to observe impacts of deformation from both, inside and outside. Thus the outcome of the thesis is fairly applicable in practice, requiring minor adjustments based on the purpose of the experiment.

7.2.3 To what extent has the projected innovation been achieved?

The lack of a methodology to measure acceptance thresholds towards glazing deformations prompted the proposal of a novel solution. The project was successful in providing a proof of concept for a novel methodology. While the components of the experiment, namely, the method of conducting an experiment with the volunteers, electro-pneumatic systems, data retrieval and analysis techniques themselves are not novel, the combination of these to solve the problem at hand is innovative. Thus, the projected innovation has been achieved to a satisfactory extent in the thesis.

7.2.4 Does the project contribute to sustainable development? What is the impact of your project on sustainability (people, planet, profit/prosperity)?

Material efficiency through optimization (e.g. in steel, concrete, timber) is a common method implemented with the intention of reducing embodied carbon in buildings. The project attempts to pave way for transitioning towards use of thinner glass in facades. Thus, the project contributes towards sustainable development beneficial for our planet by providing a methodology of assessment of thresholds that are conventionally considered high and fixed. As mentioned earlier, the project promotes a participatory design approach towards facades, thus prioritizing people’s perception over conventional standards. Reduction of material consumption increases the profitability of the project for the developers, but also reduces the pressure on our resources. Compared to use of recycled glass and reused glass, which are not acceptable in certain projects due to their perceived lower quality, use of thinner glass can be considered to have a relatively higher value.

7.2.5 What is the socio-cultural and ethical impact? What is the relation between the project and the wider social context?

A participatory design approach seems to imbue an ethical dilemma among architects and engineers, wherein stakeholder perspectives have to be considered in combination with their expert propositions. With the methodology proposed in this project, it is envisioned that for a particular project, acceptance of façade deformations can be tested with the future occupants of the building. From this perspective, the project takes an ethical stand in favor of a participatory design approach.

It has been observed that serviceability limits are non-standard around the world. For instance, the acceptable horizontal displacement of tall buildings under wind/ earthquake loading is different in different countries, and so are the standards limiting these. Acceptance is closely tied with the socio-cultural context. The presence of a methodology to measure acceptance thresholds makes the need for fixed limits redundant. It also attempts to raise acceptance towards efficient facades, by means of educating occupants about the benefits of using thinner glass. Thus, the project has a significant socio-cultural impact and ethical impact with a deep connection with the wider social context.

7.2.6 How does the project affect architecture / the built environment?

By providing a way of transitioning towards 'lean' facades, the project attempts to have a positive impact on the sustainability of the built environment. Additionally, the project questions the traditional way of using glass, conventional perception of glass as a rigid material and unacceptance of deformations in glazing. It proposes that instead of rejecting deformations, the architect should design for inclusion of deformations in glazing. There is a need for a paradigm shift from what has been considered aesthetically appealing towards what pragmatically contributes towards sustainable development. By providing methods for material efficiency in glazing, the project challenges the conventional norms and pushes the architect towards reimagining the use of glass in facades.

7.3 Reflection Questions (self developed)

7.3.1 In what way could you have improved the results of your thesis?

Prototyping and testing the experiment were a major part of development of the methodology. These processes take time and are dependent on factors outside of the direct influence of the researcher. One of the ways to improve the results would be to spend more time on prototyping, with the right materials, having enough buffer time for delivery and testing of components of the experiment and leave enough time towards the end for contingency.

The experiment setup also needs to be validated theoretically, so as to predict behavior of the components and the circuits. For example, the effect of lamination on deformation of a glass pane had to be theoretically verified before ordering the panes for testing. This was performed to a basic level in the thesis, but it can be improved with the use of FE modelling. Further, an in-depth understanding of pneumatics is required to accurately replicate the desired behavior of glass pane under dynamic loading. This would involve the use of data such as pressure variation over time on a façade over a storm condition, translated to equivalent frequency and flow rate controlled by valves in the experiment.

7.3.2 What could be an alternative approach to solve this problem?

A physical setup for the experiment was chosen over a virtual (VR enabled) setup, since a physical setup would provide more accurate reactions from volunteers. Alternatively, the experiment can also be conducted in a fully VR enabled environment or a hybrid setup. The benefit of a VR enabled environment is that a large number of variations in the environment are possible to be tested. Another benefit is that a larger sample size can be tested, since the setup is more flexible and portable compared to a physical setup. In terms of environment, VR can allow us to get results for various orientations and distances from the facade, different levels and modes of deformation, and various building typologies and activities. A hybrid setup is even more suitable, since the VR environment can be used to measure a broad number of scenarios, while the physical setup can be used for benchmarking of real-time thresholds.

7.4 Personal Reflection

7.4.1 How do you assess the value of your way of working (your approach, your used methods, used methodology)?

The well structured format of the graduation studio helped one in following a systematic research and design approach for this thesis. However, the research and design process was intertwined with one another and was not linear. This approach was suitable for this research project, as a novel methodology was being developed. Therefore, it was imperative to conduct an extensive state-of-the-art review (in this case a combination of literature review and industry survey) including relevant research methodology for serviceability of building components like floor slabs and beams. The industry survey and involvement of industry partners helped in anchoring the thesis process in the realm of practice rather than being abstract, which was a personal goal envisioned at the start of the thesis process. Thus, the way of working was found suitable for the thesis project, and was also influenced by pre-determined research objectives.

7.4.2 How do you assess the value of the transferability of your project results?

Since the outcome of the thesis is an experimental methodology, and not a specific product, the result is bound to be transferable. The objective was to maintain a high level of transferability in order to facilitate future research on relevant subjects. As a result, detailed information about the process of development of the experiment including assumptions and exclusions, specification of the components used for prototypes and the electro-pneumatic circuit and codes to control the circuit as well as to analyze the data have been made available in this report. In terms of the results of the façade industry survey, publication of these results for dissemination of information is envisioned for the near future.

7.4.3 Did you encounter moral/ ethical issues or dilemmas during the process? How did you deal with these?

Reduction in the thickness of glass does impact the performance of glazing. At the same time, it raises concerns about safety and durability of the glass and is perceived to be of a lower quality as compared to conventional façade glazing. Given this context, pushing for reduction in glass thickness certainly leads one into a dilemma.

As compared to the technical effects of deformation, this project focuses more on the effect on occupant satisfaction. This approach was challenged and questioned by people from the facade industry during the survey. In addition, there is a uncertainty associated with whether the measured acceptance thresholds of deformation are actually higher than conventional deformation limits or not; and whether this information is sufficient to bring about desired change in the conventional limits.

However, without a scientific approach towards measurement of occupant acceptance, these questions would always remain unanswered. Each dilemma opens up a new avenue for scientific research. Therefore, acceptance of these dilemmas as opportunities rather than barriers was the way one chose to deal with them.

In terms of the façade industry survey and the experiment, one of the challenges was to maintain privacy of the respondents and assure them of the same. The surveys in this research have been designed in lines of the recommendations by HREC of TU Delft, and the data managed accordingly. The respondents are also informed before them filling out the survey that any personal information collected will be stored in a csv format in a safe storage at the TU Delft.

7.4.4 Learning from your own work, reflection on feedback by mentors and translation of feedback into work

The graduation process was crucial in terms of self-learning. The mixed-method research approach demanded a fair amount of knowledge about different sub-topics. While knowledge about new subjects such as building electro-pneumatic systems, designing of a survey and conducting quantitative and qualitative analysis of results was gained, the topic also provided an opportunity to deepen the knowledge about mechanical behavior of façade glazing and limit state design method. Writing contributed to a large extent to assimilate gathered information in a structured way, reflect on the process and to build a strong narrative for the graduation thesis.

Since the topic lies at the intersection of human-centered façade design and structural design, the mentor-team of Asst. Prof. Alessandra Luna Navarro and Prof. Mauro Overend is a suitable fit for the project. Timely feedback by mentors was a significant part of the progress of this thesis. Their feedback was always well-structured and specific to the problem at hand. This made it easy to translate their feedback into actionable steps. In addition, both the mentors were equally invested in the project, which really helped maintain a positive spirit throughout the research and design process. The project also benefitted from not only their expertise in the subject, but also their extensive industry network, which was responsible for the quality of results achieved from the industry survey and the experiment setup.

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Appendix 1

Limit state design of glass

Ultimate Limit State

EN 1990:2002 defines ultimate limit states as those concerning safety of people, and/or the safety of the structure. It is the state that concerns the maximum load carrying capacity of the construction (Wuest & Luible, 2020). ULS consist of load combinations which are persistent, transient, accidental or seismic (Coult & Overend, 2022). Based on relevance, verification for certain criteria such as loss of equilibrium of the structure, failure by excessive deformation or failure by time-dependent effects such as fatigue shall be undertaken (European Committee for Standardization, 2002). In terms of glass, the main verifying criterion is excessive deformation, that may lead to excessive stress in glass, which may lead to breaking.

The state at which stress of glass is exceeded would be defined considering the characteristic strength of glass, approximately factored as required by the load and installation conditions (SGG, 2018). For glass, the design resistance would be expressed as a maximum ULS allowable stress.

$$E_{ULS,d} \leq R_d$$

Where $E_{ULS,d}$ is the design value of effect of actions and R_d is the design value of corresponding resistance. Thus, for glass, R_d corresponds to maximum allowable stress. Combinations of actions, that are critical load cases for ULS, incorporate a leading variable action (Q) and any accompanying actions, in addition to permanent actions (G) and pre-stressing actions (P). Generally pre-stressing actions are not relevant in terms of planar façade glass. EN 1990:2002 provides 3 expressions for the combinations of actions, allowing either

$$E_{ULS,d} = E\{\gamma_{G,j} \cdot G_{k,j} + \gamma_P \cdot P + \gamma_{Q,1} \cdot Q_{k,1} + \sum_{i>1}(\gamma_{Q,i} \cdot \psi_{0,i} \cdot Q_{k,i})\} \quad j \geq 1; i \geq 1$$

Equation 8: Expression for combination of actions (a)

Or for ultimate limit states, the worst case out of the following 2 combinations

$$E_{ULS,d} = E\{\gamma_{G,j} \cdot G_{k,j} + \gamma_P \cdot P + \gamma_{Q,1} \cdot \psi_{0,1} \cdot Q_{k,1} + \sum_{i>1}(\gamma_{Q,i} \cdot \psi_{0,i} \cdot Q_{k,i})\} \quad j \geq 1; i \geq 1$$

$$E_{ULS,d} = E\{\xi_j \cdot \gamma_{G,j} \cdot G_{k,j} + \gamma_P \cdot P + \gamma_{Q,1} \cdot Q_{k,1} + \sum_{i>1}(\gamma_{Q,i} \cdot \psi_{0,i} \cdot Q_{k,i})\} \quad j \geq 1; i \geq 1$$

Equation 9: Expressions for combination of actions (b) and (c).

Where, γ is the partial factor and ψ is the factor of combination, frequent or quasi-permanent loading. Information regarding Partial Factor Method, Effects of actions for ULS and Process of determination of combinations of actions for ULS and SLS is provided in Appendix 1.

Fracture Limit State

Fracture limit states are those that are concerned with safety and protection of people and/or the structure during accidental fracture (Wuest & Luible, 2020). They ensure that at the event of fracture, the glass falls in a manner that does not cause unacceptable levels of human injury or economic losses (Coult & Overend, 2022). The safety of people in close proximity to the glass components are regarded, so as to avoid the risk of injury by falling into the element or broken fragments falling on people (European Committee for Standardization, 2021c). FLS in not only relevant in cases of glass floors and glass ceilings, but also in façade glazing, especially high rise facades, subject to accidental or impact loading.

The verification of FLS could be conducted either by experimental testing, or by theoretical assessment and is strongly dependent on application (European Committee for Standardization, 2021a; Wuest & Luible, 2020). Guidelines such as the FprCEN/TS 19100-2 specify procedures for both, experimental testing and theoretical assessment. Guidelines also determine the material selection and design of construction so as to minimize risk of injury or loss at the time of failure. For example, the Swiss standards (SIA guideline 2057) do not allow the use of single ply glass for ceilings, unless it is an exceptional thermally toughened safety glass continuously supported on all edges (Wuest & Luible, 2020).

Post-fracture Limit State

Post-fracture Limit States are those that concern the residual load bearing capacity when one or more glass plies have fractured (Wuest & Luible, 2020). According to (European Committee for Standardization, 2021c), PFLS is defined as the state wherein the required residual load bearing capacity of a glass component for a defined period of time is provided by redundancy of the glass component, undamaged plies of the component and/or structural alternative load path(s). They ensure that the fractured glass does not cause unacceptable risks of human injury or economics loss for a limited period of time after the fracture (Coult & Overend, 2022). The resistance of the component after failure of one, two or all plies is strongly dependent on the type of glass, size, support and alternative load paths, if any.

Similar to FLS verification, the PFLS verification can also be carried out either by experimental testing or theoretical assessment, for the residual glass component or alternative load path (European Committee for Standardization, 2021b). Since behavior of glass after fracture depends on a large variety of factors, such as glass type, glass construction, supports, number of fractured panes, whether the panes are loaded or not, for how long will they be loaded, etc. it is challenging to have a standardized approach. FprCEN/TS 19100-2 specifies certain procedures for experimental testing as well as theoretical assessment. An example for calculation as per the SIA is provided. Wuest and Luible, 2020 further state that for post-fracture load bearing requirements, the following expression, based on EN 1990:2002/ SIA 260:2013, can be used for verification, where, A_d is the PFLS situation, and not a load..

$$E_{d,NB} = \sum_{j>1} G_{k,j} + A_d + \psi_{1,1} \cdot Q_{k,1} + \sum_{i>1} \psi_{2,i} \cdot Q_{k,i}$$

Equation 10: Expression for combinations of actions for PFLS.

Serviceability Limit State

EN 1990:2002 defines serviceability limit states as those that concern the functioning of the structure or structural members under normal use, the comfort of people and the appearance of the construction works. These states correspond to conditions beyond which specified service requirements for a structure or structural member are no longer met. According to EN 1990:2002, the verification of serviceability should be based on criteria concerning deformations, vibrations and damage that affect the appearance, comfort or the functioning of the structure or that cause damage to finishes or non-structural members. These also include vibrations that cause discomfort or that limit functional effectiveness of the structure. It is important to note that the term ‘appearance’ in EN 1990:2002 is concerned with high distortions and excessive cracking, and not aesthetics.

The actions to be considered for serviceability may not always be external, such as wind or impact. Even climatic loads, such as changes in air temperature and pressure might cause deflections. With regards to climatic loads, this requires limitations to deflection, and limits as per prEN 16612 can be used (SGG, 2018).

$$E_{SLS,d} \leq C_d$$

Where $E_{SLS,d}$ is the design value of effect of actions and C_d is the design value of climate load. Thus, for glass, C_d corresponds to maximum allowable deflection. For climatic loading, considering lack of standardized regulations, the prEN 16612, BS 5516-2 and other standards indicated the following expression as per (SGG, 2018)

$$C_d = \min\left(\frac{span}{65}, 50\right)$$

For determination of SLS, the effects of actions are compared with the permissible deflections. Under prescribed load conditions, the effect of the actions is generated from combined load cases in terms of serviceability. Similar to that of ULS, the combinations of actions for serviceability can be calculated using the following expression, which is prescribed by EN 1990:2002 and DIN 18008.

$$E_{SLS,d} = E\{G_{k,j} + P + Q_{k,1} + \sum_{i>1}(\psi_{0,i} \cdot Q_{k,i})\} \quad j \geq 1; i \geq 1$$

Equation 11: Expression for combinations of actions for SLS.

Partial load factor for all load types is taken as 1.0 for the serviceability design.

Partial factor method

The partial factor method incorporates design values for actions, material properties, geometrical data and resistance in order to allow the determination of ULS and SLS (SGG, 2018). In the expressions for combination of actions, loads are multiplied by partial load factors (γ) to account for unfavorable deviations from characteristic values and errors in calculation and variations in structural behavior. In terms of characteristic values, the partial factor considers the reduced probability that various loads acting together will reach their characteristic values at the same time.

Effect of actions

For determination of ULS, the effects of actions are compared with the permissible stresses. Critical load cases are combinations of loads that may be acting together, for instance snow and wind, or wind and maintenance loads. For load cases, design values for loads are obtained using characteristic or representative values, in combination with partial and other factors. The design value of an action as per EN 1990:2002 is

$$F_d = \gamma_f F_{rep}$$

$$F_{rep} = \psi F_k$$

Where,

γ_f is the partial factor

ψ is the factor of combination, frequent or quasi-permanent loading

F_k is the Characteristic load

F_{rep} is the Representative load

Thus, the effect of actions is determined by the following expression

$$E_d = \gamma_{Sd} E\{\gamma_{f,i} F_{rep,i}; a_d\} \quad i \geq 1$$

Where,

a_d are the design values of geometrical data

γ_{Sd} is partial factor for modelling of the actions; may include deviations with regards to load application positions

Process of determining effects of actions for ULS (SGG, 2018)

The report titled Climatic Loads 3D Limit State Design for Glass & Glazing published by Saint Gobain Glass (SGG, 2018) summarizes the process of determining effects of actions and associated factors for ULS Stress in a clear diagram as seen in Figure 73. It is indicated that once the critical load case of combined actions is determined, another partial verification factor for ULS is applied to determine the overall effect of the actions (E_d). Further, it is also noted that the determination of ULS stress and SLS deflections will also depend on the glass types and thicknesses, as they influence the resistance to actions.

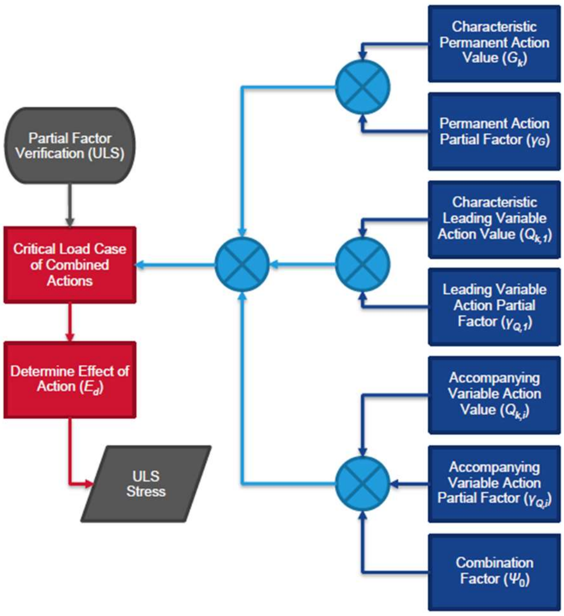


Figure 73: Determining effects of actions for ULS stress. (Source: SGG, 2018, p. 5).

Process of determining effects of actions for SLS

The report titled Climatic Loads 3D Limit State Design for Glass & Glazing published by Saint Gobain Glass (2018) summarizes the process of determining effects of actions and associated factors for SLS deflections in a clear diagram as seen in Figure 74. It is indicated that once the critical load case of combined actions is determined, another partial verification factor for SLS is applied to determine the overall effect of the actions (E_d). Further, it is also noted that the determination of ULS stress and SLS deflections will also depend on the glass types and thicknesses, as they influence the resistance to actions.

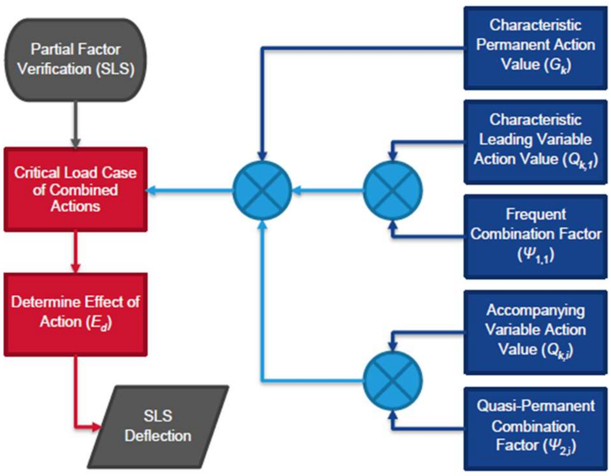


Figure 74: Determining effects of actions for SLS deflection. (Source: SGG, 2018, p. 5).

Example calculation of PFLS

The Swiss body for standardization SIA, specifies the NB concept for categorization of failure scenarios. The NB-concept has been proposed by the SIA 268 committee which is based on five different failure modes illustrated in Figure 75, namely:

a. NB0 No additional verification needed.
b. NB1 If one (or more) plies fail, the component shall stay in place after failure. No additional load must be applied.
c. NB2 If all plies fail, the component shall stay in place after failure. No additional load must be applied.
d. NB3 If one (NB3A) or two (NB3B) plies fail, the component must resist the accidental load combination.
e. NB4 If all plies fail, the component must resist the accidental load combination.

Such models help define scenarios in a structured manner, and can be taken forwards for calculations depending on the specific post-fracture performance requirements.

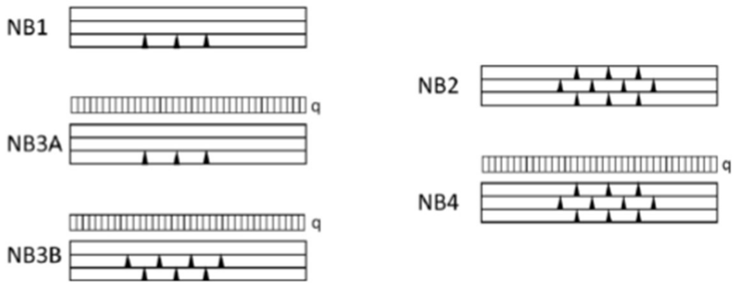


Figure 75: Schematic representation of NB classes 1 to 4. (Source: Wuest & Luible, 2020, p. 4)

Appendix 2

Search Terms for Literature review

Extraction of keywords based on the research question

Glass / IGU related	Deformation related	Façade/ building related	Exclusions
IGU*	deformation	façade	reinforce*
insulat* gla* unit*	displacement	building façade	fiber
glass	deflection	façade construction	fibre
glazing	distortion		composite
sealant	sagging		
edge spacer			
edge seal			

Several search terms were created based on the table above. However, since these terms related to a broad variety of subjects, it was difficult to narrow down the search to a limited number of results, specific to the subject. Finally, selected papers that were considered critical for topics related to 'effects of deformation on glazing performance' were selected, and the search term was built such that each of these papers is covered in the results. The following search term gave 1210 results on Scopus and includes the papers which were listed critical for this research. Manual filtering and exclusion was still required even after refining the search term. Finally around 36 papers were referred to from this list.

(("insulat* gla* unit*" OR "glass" OR "glazing" OR "sealant" OR "edge spacer" OR "edge seal" OR "rim seal") AND ("deformation*" OR "displace*" OR "deflection*" OR "distortion*") AND (plate* OR panel* OR pane OR "curtainwall*" OR "lite") AND NOT (reinforce* OR fiber OR fibre OR composite OR electro* OR print* OR chemi* OR medic* OR "fire" OR "metallic glass" OR animal* OR tyre*)) AND PUBYEAR > 1999 AND PUBYEAR < 2024 AND (LIMIT-TO (PUBSTAGE , "final")) AND (EXCLUDE (SUBJAREA , "PSYC") OR EXCLUDE (SUBJAREA , "HEAL") OR EXCLUDE (SUBJAREA , "PHAR") OR EXCLUDE (SUBJAREA , "IMMU") OR EXCLUDE (SUBJAREA , "ECON") OR EXCLUDE (SUBJAREA , "DENT") OR EXCLUDE (SUBJAREA , "DECI") OR EXCLUDE (SUBJAREA , "NEUR") OR EXCLUDE (SUBJAREA , "BUSI") OR EXCLUDE (SUBJAREA , "AGRI") OR EXCLUDE (SUBJAREA , "BIOC") OR EXCLUDE (SUBJAREA , "MEDI"))

Appendix 3
Categorized list of references

	Purpose	Category	Sub-category	Title	Author in text	Reference	Year
1	Background	Application based papers	Architectural applications	**Adaptive and composite thin glass**	Louter et al., 2018	Journal Article	2018
2	Background	Application based papers	Architectural applications	**Thin glass as cold bent laminated**	Schlosser, 2018	Thesis	2018
3	Background	Brochure	Brochure for mechanical	**AGC Falcon glass for thin and**	AGC, 2020	Catalog	2020
4	Background	Brochure	Brochure for mechanical	**AGC Low Carbon Glass**	AGC, 2022	Catalog	2022
5	Background	Carbon Footprint	Recycling of glass	**Re-thinking the life-cycle of**	Arup, 2018	Report	2018
6	Background	Carbon Footprint	Carbon footprint of glass	**Carbon footprint of facades:**	Arup & SGG, 2022	Report	2022
7	Background	Carbon Footprint	Carbon footprint of glass	**Net-zero buildings - Where do we**	Arup & WBCSD, 2021	Report	2021
8	Background	Carbon Footprint	Carbon footprint of glass	**Energy Consumption, Environmental**	Mao et al., 2015	Journal Article	2015
9	Background	Carbon Footprint	Carbon footprint of glass	**Introduction Low Carbon Glass**	Zaccaria, 2022	Generic	2022
10	Background	Carbon Footprint	Carbon footprint of glass	**Facade Design Process to Establish**	Zani et al., 2021	Conference	2021
11	Background	Carbon Footprint	Concrete deconstruction	**Reuse of concrete components in new**	Küpfer et al., 2023	Journal Article	2023
12	Background	Carbon Footprint	Concrete deconstruction	**ReCreate: Deconstruction and Reuse**	ReCreate:	Web Page	2021
13	Background	Carbon Footprint	Façade circularity	**PerpetuAl: Circular Aluminum**	PerpetuAl: Circular	Web Page	2022
14	Main	Durability	IGU seal and durability	**Durability of Cold-Bent Insulating**	Besserud et al., 2012	Conference	2012
15	Main	Durability	IGU seal and durability	**Primary Seal Deformation in**	Starman et al., 2020	Journal Article	2020
16	Main	Durability	IGU seal and durability	**IGU Seal and Flexible Spacer**	Watson et al., 2015	Book Section	2015
17	Main	Durability	IGU seal and durability	**Fatigue resistance of rim seals in**	Yamamoto M. & T.,	Journal Article	2018
18	Main	Durability	IGU seal and durability	**Durability of vacuum insulation**	Gubbels et al., 2014	Journal Article	2014
19	Background	Human Perception	Human perception of	**Spectator comfort in grandstands – an**	Browning, 2016	Journal Article	2016
20	Background	Human Perception	Human perception of	**Structural Design of Double Skin**	Sun Moon, 2011	Journal Article	2011
21	Main	Human Perception	Human perception of	**Pilot Experiments for Multi-Criteria**	Bedon, 2022	Journal Article	2022
22	Main	Human Perception	Human perception of	**Serviceability Limit States Under Wind**	Griffis, 1993	Journal Article	1993
23	Main	Human Perception	Human perception of	**Human Response to Motion in Tall**	Chang, 1973	Journal Article	1973
24	Main	Human Perception	Human perception of	**Quality criteria for multi-domain**	Chinazzo et al., 2022	Journal Article	2022
25	Main	Human Perception	Human perception of	**Motion in Tall Buildings**	Irwin, 1988	Book Section	1988
26	Main	Human Perception	Human perception of	**Wind-induced motion on tall**	Johann et al., 2015	Journal Article	2015
27	Main	Human Perception	Human perception of	**Dynamic façades – An exploratory**	Luna-Navarro et al.,	Journal Article	2022
28	Main	Human Perception	Human perception of	**Occupant-Facade interaction: a review**	Luna-Navarro et al.,	Journal Article	2020
29	Main	Human Perception	Human perception of	**Design, construction and validation of**	Luna-Navarro &	Journal Article	2021
30	Background	Mechanical Properties	Limit State Design Criteria	**Adaptable structures - what really is**	IStructE & IABSE,	Conference	2018
31	Background	Mechanical Properties	Deformation and stress	**Background Report Glass – Part 3:**	Pertermann, 2020	Report	2020
32	Background	Mechanical Properties	Limit State Design Criteria	**Developments in Structural Glass**	Coult & Overend, 2022	Magazine	2022
33	Background	Mechanical Properties	Limit State Design Criteria	**Eurocode - Basis of Structural Design**	European Committee	Standard	2002
34	Main	Mechanical Properties	IGU buckling analysis	**Buckling analysis and design proposal**	Bedon & Amadio, 2018	Journal Article	2018
35	Main	Mechanical Properties	Influence of IGU spacer on	**Mechanical analysis and**	Bedon & Amadio, 2020	Journal Article	2020
36	Main	Mechanical Properties	Effects of cold bending of	**The mechanical response of cold bent**	Datsiou & Overend,	Journal Article	2016
37	Main	Mechanical Properties	IGU load sharing	**Green's functions for the load sharing**	Galuppi & Royer-	Journal Article	2020
38	Main	Mechanical Properties	IGU load sharing	**On the thickness determination of**	Heiskari et al., 2022	Journal Article	2022
39	Main	Mechanical Properties	IGU load sharing	**Experimental Investigation of Load**	McMahon et al., 2018	Journal Article	2018
40	Main	Mechanical Properties	Effects of cold bending of	**Cold bending of vertical glass plates:**	Quaglini et al., 2020	Journal Article	2020
41	Main	Mechanical Properties	Deformation and stress	**Deflections and Stresses in**	Respondek et al., 2022	Journal Article	2022
42	Main	Mechanical Properties	Deformation and stress	**Numerical-and-Analytical Method of**	Stratiy, 2018	Book Section	2018
43	Main	Mechanical Properties	Deformation and stress	**Field measurement of wind-induced**	Li et al., 2011	Journal Article	2011
44	Background	Optical Performance	Low distortion glass	**Design, Development, and**	Basher et al., 2021	Journal Article	2021
45	Main	Optical Performance	Visual distortion types	**Digital prototyping of architectural**	Buro Happold 2021	Report	2021
46	Background	Qualitative Analysis	Reference for statistical	**Discovering Statistics Using SPSS**	Field, 2009	Book	2009
47	Background	Qualitative Analysis	Survey related papers in	**Unlocking the Re-use Potential of**	Hartwell & Overend,	Conference	2019
48	Background	Qualitative Analysis	Survey related papers in	**Main perceived barriers for the**	Prieto et al., 2017	Journal Article	2017
49	Background	Qualitative Analysis	Data collection about	**Circular economy of façades: Real-**	Hartwell et al., 2021	Journal Article	2021
50	Background	Standards	Standards for structural	**E1300 - 16 Standard Practice for**	ASTM International,	Standard	2016
51	Background	Standards	Standards for glass limit	**Code of Practice for Structural Use of**	Buildings Department	Standard	2018
52	Background	Standards	Standards for structural	**FprCEN/TS 19100-1 Design of glass**	European Committee	Standard	2021
53	Background	Standards	Standards for structural	**FprCEN/TS 19100-3 Design of glass**	European Committee	Standard	2021
54	Background	Standards	Standards for structural	**FprCEN/TS 19100-2 Design of glass**	European Committee	Standard	2021
55	Background	Standards	Standards for glass limit	**Climatic Loads 3D Limit State Design**	SGG, 2018	Report	2018
56	Background	Standards	Standards for glass limit	**Glass design in Switzerand**	Wuest & Luible, 2020	Conference	2020
57	Background	Thermal Performance	IGU thermal vs.	**A method of reducing the distorting**	Plotnikov, 2021	Journal Article	2021
58	Main	Thermal Performance	IGU thermal vs.	**Thermal performance impacts of**	Hart et al., 2012	Journal Article	2012
59	Main	Thermal Performance	IGU thermal vs.	**Influence of insulated glass units**	Respondek, 2018	Journal Article	2018
60	Main	Thermal Performance	IGU thermal vs.	**Heat Transfer Through Insulating**	Respondek, 2020	Journal Article	2020
61	Main	Thermal Performance	IGU thermal vs.	**Heat transfer and climatic loads at**	Penkova et al., 2017	Journal Article	2017

Appendix 4
Standards

No.	Standard/ Guidelines	Year	Relevance
1	prEN 13474		Draft guideline Glass in building - Determination of the strength of glass panes - Part 3: General method of calculation and determination of strength of glass by testing
2	prEN 16612 – draft guideline		is now a fully-fledged standard – BS EN 16612 Restricted to infill panels, etc. The SLS concerns the comfort of people. With regards to climatic loads, this requires limitations to deflection, and limits as per prEN 16612 can be used.
3	BS EN 16612		This document gives a method of determining the design value of the bending strength of glass. It gives the general method of calculation, and guidance for lateral load resistance of linearly supported glazed elements used as infill panels.
4	FprEN 16612:2019:		Glass in building - Determination of the lateral load resistance of glass panes by calculation
5			
6	EN 13031-1:2019		Deformation limitations on cladding panels are given Calculations of displacements SLS for cladding bars are given, but not for glass panels themselves.
7	NEN-EN 13031-1		NEN-EN 13031-1 specifies principles and requirements for the mechanical resistance and stability, serviceability and durability for design and construction of commercial production greenhouse structures, including their foundations, irrespective of the material used, for the professional production of plants (crops). Fire resistance-related aspects are not covered in this document.
8	NEN 2608:2014		Dutch standard for glass (adaptation of Eurocode) NEN 2608 gives the requirements and the method of determining the supporting power and deformations of mainly static loaded glass.
9	ÖNORM B 3716-1:2013		Austrian adaptation of Eurocode for glass
10	DIN 18008-1:2010-12		German Adaptation of Eurocodes for Glass

11	DIN 18008-2:2020		German standard for glass Glass in Building - Design and construction rules - Part 2: Linearly supported glazing
12	prCEN/TS 19100-2:2020, Table 9.1:		Deformation classes are proposed viz. 1-SLS, 2-SLS, 3-ULS etc. FprCEN/TS 19100 2 gives basic structural design rules for mechanically supported glass components primarily subjected to out of plane loading. Out of plane loaded glass components are made of flat or curved glass components. NOTE Out of plane loads are loads acting normal (e.g. wind) to or having a component (e.g. dead load, snow, ...) acting normal to the glass plane.
13	BS 5516-2		UK based reliance on these standards for glass, but these provide no guidance for limit state design.
14	BS 6262		
15	EN 1990:2002,		the design value of the effect of actions must be less than the design value of the corresponding resistance;
16	EN 1991-1-4:2005		Wind load determination
17	EN 1991-1-3:2003		Snow load determination
18	Structural use of glass in buildings – 2nd edition	2014	Guidance in glass design published by IStructE
19	Design of glass Structures	Mid-2022	European glass code, Technical Standard, released for public comments. Has 2 additional limit states (FLS and PFLS)
20	Design of glass Structures	Around Mid-2024	To be issued as a draft European Standard (prEN)
21	Design of glass Structures	Approx. 2026	To be published as a European Standard (EN)

Appendix 5

Calculations

Glass – simply supported on all edges with uniform loading: calculation of maximum deflections and maximum stresses based on variation in thickness.

b (mm)	a short (mm)	a/b	p (Pa)	p (bar)	Wind speed (km/h)	E (Pa)	t (mm)	max deflection (mm)	max. stress (Pa)	max. stress (MPa)
1467	972	0.66	2000	0.02	207.85	7.00E+10	1	**2204.40**	9.65E+08	**965.17**
1467	972	0.66	2000	0.02	207.85	7.00E+10	2	**275.55**	2.41E+08	**241.29**
1467	972	0.66	2000	0.02	207.85	7.00E+10	3	**81.64**	1.07E+08	**107.24**
1467	972	0.66	2000	0.02	207.85	7.00E+10	4	**34.44**	6.03E+07	**60.32**
1467	972	0.66	2000	0.02	207.85	7.00E+10	6	**10.21**	2.68E+07	**26.81**
1467	972	0.66	2000	0.02	207.85	7.00E+10	8	**4.31**	1.51E+07	**15.08**
1467	972	0.66	2000	0.02	207.85	7.00E+10	10	**2.20**	9.65E+06	**9.65**
1467	972	0.66	2000	0.02	207.85	7.00E+10	12	**1.28**	6.70E+06	**6.70**

Appendix 6

Industry survey questionnaire

Q. No.	Question	Format	Responses/ Options
Q2.1	Which of the following best describes your organization? - Selected Choice	Multiple Choice Single Answer	Glass manufacturer Sealant Manufacturer Façade Consultant Façade Contractor Academia and Research Architect Other (please specify)
Q2.1_7_TEXT	Which of the following best describes your organization? - Other (please specify) - Text	Free text	
Q2.2	How would you best describe your role in the organization? - Selected Choice	Multiple Choice Single Answer	Consultant Designer Engineer Salesperson Manager Researcher Other (please specify)
Q2.2_7_TEXT	How would you best describe your role in the organization? - Other (please specify) - Text	Free text	
Q2.4	What is the highest level of education you have completed?	Multiple Choice Single Answer	Completed Primary School Completed Secondary School Completed High School University Bachelors Degree University Masters Degree PhD Prefer not to say
Q2.5	Which country are you currently based out of?	Free text	
Q3.1	To what extent is environmental impact a governing factor in the projects that you work on?	Multiple Choice Single Answer	Very Low Low Medium High Very High
Q3.2	In which countries are some of the major projects you are working on located?	Free text	

Q3.3_1	To what extent do you consider the following strategies effective in reducing the embodied carbon in facades? - Material efficiency in facade design	Slider from 1 to 5	Not at all effective Slightly effective Moderately effective Very effective Extremely effective
Q3.3_2	To what extent do you consider the following strategies effective in reducing the embodied carbon in facades? - Recycling of facade material	Slider from 1 to 5	Not at all effective Slightly effective Moderately effective Very effective Extremely effective
Q3.3_3	To what extent do you consider the following strategies effective in reducing the embodied carbon in facades? - Reuse of façade components	Slider from 1 to 5	Not at all effective Slightly effective Moderately effective Very effective Extremely effective
Q3.4_1	To what extent do you consider the following strategies effective in reducing the total material consumption in facades? - Material efficiency in facade design	Slider from 1 to 5	Not at all effective Slightly effective Moderately effective Very effective Extremely effective
Q3.4_2	To what extent do you consider the following strategies effective in reducing the total material consumption in facades? - Recycling of facade material	Slider from 1 to 5	Not at all effective Slightly effective Moderately effective Very effective Extremely effective
Q3.4_3	To what extent do you consider the following strategies effective in reducing the total material consumption in facades? - Reuse of facade components	Slider from 1 to 5	Not at all effective Slightly effective Moderately effective Very effective Extremely effective
Q3.5_1	To what extent do you consider reducing glass thickness can help reduce the embodied carbon of facade glazing? - 1	Slider from 1 to 5	Very low extent Low extent Medium extent High extent Very high extent
Q3.6_1	To what extent do you consider reducing glass thickness can help reduce the total material consumption of facade glazing? - 1	Slider from 1 to 5	Very low extentLow extentMedium extentHigh extentVery high extent
Q4.1	How would you rate your knowledge on serviceability limits of glass in facades?	Multiple Choice Single Answer	High Moderate Low
Q4.2	In your professional role, do you have to satisfy serviceability limits for glass?	Multiple Choice Single Answer	Yes No
Q4.3	If yes, what are all the serviceability criteria that you would design for?	Free text	
Q4.4_1	To what extent does excess deformation in glazing, well beyond serviceability limits, have an effect on the following factors? - Durability of glazing unit	Slider from 1 to 5	Very low extent Low extent Medium extent High extent Very high extent
Q4.4_2	To what extent does excess deformation in glazing, well beyond serviceability limits, have an effect on the following factors? - Optical performance of glazing unit	Slider from 1 to 5	Very low extent Low extent Medium extent High extent Very high extent

Q4.4_3	To what extent does excess deformation in glazing, well beyond serviceability limits, have an effect on the following factors? - Thermal performance of glazing unit	Slider from 1 to 5	Very low extent Low extent Medium extent High extent Very high extent
Q4.4_4	To what extent does excess deformation in glazing, well beyond serviceability limits, have an effect on the following factors? - Acoustic performance of glazing unit	Slider from 1 to 5	Very low extent Low extent Medium extent High extent Very high extent
Q4.4_5	To what extent does excess deformation in glazing, well beyond serviceability limits, have an effect on the following factors? - Occupant satisfaction	Slider from 1 to 5	Very low extent Low extent Medium extent High extent Very high extent
Q59_1	When setting limits on glazing deformation in your current practice, what is the level of importance of each of these factors? - Durability of glazing unit	Slider from 1 to 5	Very low extent Low extent Medium extent High extent Very high extent
Q59_2	When setting limits on glazing deformation in your current practice, what is the level of importance of each of these factors? - Optical performance of glazing unit	Slider from 1 to 5	Very low extent Low extent Medium extent High extent Very high extent
Q59_3	When setting limits on glazing deformation in your current practice, what is the level of importance of each of these factors? - Thermal performance of glazing unit	Slider from 1 to 5	Very low extent Low extent Medium extent High extent Very high extent
Q59_4	When setting limits on glazing deformation in your current practice, what is the level of importance of each of these factors? - Acoustic performance of glazing unit	Slider from 1 to 5	Very low extent Low extent Medium extent High extent Very high extent
Q59_5	When setting limits on glazing deformation in your current practice, what is the level of importance of each of these factors? - Occupant satisfaction	Slider from 1 to 5	Very low extent Low extent Medium extent High extent Very high extent
Q5.1_1	When specifying the thickness of glass to be used in facades (e.g. IGUs, double skin facades, etc.), how often are each of these guidelines followed? - Local, National or International Standards	Matrix	Never Sometimes About half the time Most of the time Always
Q5.1_2	When specifying the thickness of glass to be used in facades (e.g. IGUs, double skin facades, etc.), how often are each of these guidelines followed? - Standards defined by your organization	Matrix	NeverSometimesAbout half the timeMost of the timeAlways
Q5.1_3	When specifying the thickness of glass to be used in facades (e.g. IGUs, double skin facades, etc.), how often are each of these guidelines followed? - Data from previous projects	Matrix	Never Sometimes About half the time Most of the time Always
Q5.1_4	When specifying the thickness of glass to be used in facades (e.g. IGUs, double skin facades, etc.), how often are each of these guidelines followed? - Glass manufacturer recommendations/ catalogue	Matrix	Never Sometimes About half the time Most of the time Always

Q5.1_5	When specifying the thickness of glass to be used in facades (e.g. IGUs, double skin facades, etc.), how often are each of these guidelines followed? - Rule of thumb	Matrix	Never Sometimes About half the time Most of the time Always
Q5.1_6	When specifying the thickness of glass to be used in facades (e.g. IGUs, double skin facades, etc.), how often are each of these guidelines followed? - Other	Matrix	Never Sometimes About half the time Most of the time Always
Q5.1_6_TEXT	When specifying the thickness of glass to be used in facades (e.g. IGUs, double skin facades, etc.), how often are each of these guidelines followed? - Other - Text	Free text	
Q5.2	If you were to reduce the glass thickness, which of these factors would you not ignore? You may select more than one choices. - Selected Choice	Multiple Choice Multiple Answer	Deflection under normal loads Stress patterns under normal loads Edge strain in glass (for sealant capacity) Other
Q5.2_4_TEXT	If you were to reduce the glass thickness, which of these factors would you not ignore? You may select more than one choices. - Other - Text	Free text	
Q5.4	What information could help you to specify thinner glass for facades?	Free text	
Q63	Which optical defects are you most concerned with, in terms of facade glazing?	Free text	
Q64	Which of these optical defects depend on excessive deformation of glass under climatic / wind loading?	Free text	
Q5.3_1	If thinner glass was to be specified, how would you rate the impact it would have on the following factors? - Overall occupant satisfaction	Matrix	Extremely negative Moderately negative Slightly negative No impact Slightly positive Moderately positive Extremely positive
Q5.3_2	If thinner glass was to be specified, how would you rate the impact it would have on the following factors? - Aesthetic value of the project	Matrix	Extremely negative Moderately negative Slightly negative No impact Slightly positive Moderately positive Extremely positive
Q5.3_3	If thinner glass was to be specified, how would you rate the impact it would have on the following factors? - Project value (real estate perspective)	Matrix	Extremely negative Moderately negative Slightly negative No impact Slightly positive Moderately positive Extremely positive
Q5.3_4	If thinner glass was to be specified, how would you rate the impact it would have on the following factors? - Cost of facade in the project	Matrix	Extremely negative Moderately negative Slightly negative No impact Slightly positive Moderately positive Extremely positive

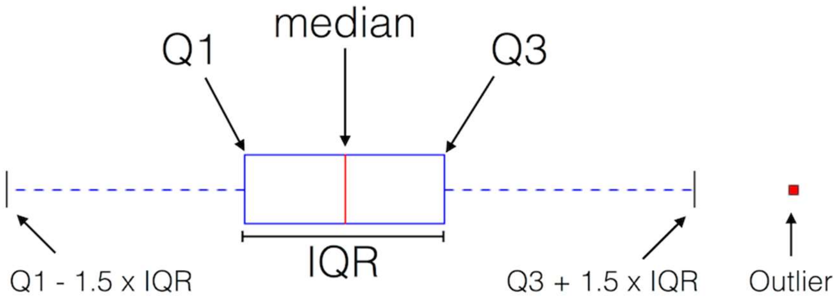
Q5.3_5	If thinner glass was to be specified, how would you rate the impact it would have on the following factors? - Ease of handling on site	Matrix	Extremely negativeModerately negativeSlightly negativeNo impactSlightly positiveModerately positiveExtremely positive
Q5.3_6	If thinner glass was to be specified, how would you rate the impact it would have on the following factors? - Material efficiency of faÃ§ade	Matrix	Extremely negative Moderately negative Slightly negative No impact Slightly positive Moderately positive Extremely positive
Q5.3_7	If thinner glass was to be specified, how would you rate the impact it would have on the following factors? - Material efficiency of building structure	Matrix	Extremely negative Moderately negative Slightly negative No impact Slightly positive Moderately positive Extremely positive
Q5.3_8	If thinner glass was to be specified, how would you rate the impact it would have on the following factors? - Ease of production of curved facades	Matrix	Extremely negative Moderately negative Slightly negative No impact Slightly positive Moderately positive Extremely positive
Q6.2_1	If thinner glass was to be specified, how much would it impact occupant satisfaction with respect to the following factors? - Percepton of safety	Matrix	None at all A little A moderate amount A lot A great deal
Q6.2_2	If thinner glass was to be specified, how much would it impact occupant satisfaction with respect to the following factors? - Overall comfort in the space	Matrix	None at all A little A moderate amount A lot A great deal
Q6.2_3	If thinner glass was to be specified, how much would it impact occupant satisfaction with respect to the following factors? - Acoustic environment	Matrix	None at all A little A moderate amount A lot A great deal
Q6.2_4	If thinner glass was to be specified, how much would it impact occupant satisfaction with respect to the following factors? - Thermal environment	Matrix	None at all A little A moderate amount A lot A great deal
Q6.2_5	If thinner glass was to be specified, how much would it impact occupant satisfaction with respect to the following factors? - View of the outside	Matrix	None at all A little A moderate amount A lot A great deal
Q6.2_6	If thinner glass was to be specified, how much would it impact occupant satisfaction with respect to the following factors? - Aesthetic appearance of glass	Matrix	None at all A little A moderate amount A lot A great deal

Q6.2_7	If thinner glass was to be specified, how much would it impact occupant satisfaction with respect to the following factors? - Other	Matrix	None at all A little A moderate amount A lot A great deal
Q6.2_7_TEXT	If thinner glass was to be specified, how much would it impact occupant satisfaction with respect to the following factors? - Other - Text	Free text	
Q6.3_1	To what extent do you think the following factors are barriers for the use of thinner glass for facade glazing? - Conventional perception of glass as a rigid material	Matrix	Very low extent Low extent Medium extent High extent Very high extent
Q6.3_2	To what extent do you think the following factors are barriers for the use of thinner glass for facade glazing? - Perception of deformed glass as low quality	Matrix	Very low extentLow extentMedium extentHigh extentVery high extent
Q6.3_3	To what extent do you think the following factors are barriers for the use of thinner glass for facade glazing? - Lack of confidence in engineering properties of thinner glass	Matrix	Very low extent Low extent Medium extent High extent Very high extent
Q6.3_4	To what extent do you think the following factors are barriers for the use of thinner glass for facade glazing? - Technological challenges	Matrix	Very low extent Low extent Medium extent High extent Very high extent
Q6.3_5	To what extent do you think the following factors are barriers for the use of thinner glass for facade glazing? - Other	Matrix	Very low extent Low extent Medium extent High extent Very high extent
Q6.3_5_TEXT	To what extent do you think the following factors are barriers for the use of thinner glass for facade glazing? - Other - Text	Free text	
Q62_1	To what extent do you agree with the statement: 'It seems feasible to overcome these barriers for the acceptance of thinner glass in the market.' - Conventional perception of glass as a rigid material	Matrix	Strongly disagree Disagree Neither agree, nor disagree Agree Strongly agree
Q62_2	To what extent do you agree with the statement: 'It seems feasible to overcome these barriers for the acceptance of thinner glass in the market.' - Perception of deformed glass as low quality	Matrix	Strongly disagree Disagree Neither agree, nor disagree Agree Strongly agree
Q62_3	To what extent do you agree with the statement: 'It seems feasible to overcome these barriers for the acceptance of thinner glass in the market.' - Lack of confidence in engineering properties of thinner glass	Matrix	Strongly disagree Disagree Neither agree, nor disagree Agree Strongly agree
Q62_4	To what extent do you agree with the statement: 'It seems feasible to overcome these barriers for the acceptance of thinner glass in the market.' - Technological challenges	Matrix	Strongly disagree Disagree Neither agree, nor disagree Agree Strongly agree

Q62_5	To what extent do you agree with the statement: 'It seems feasible to overcome these barriers for the acceptance of thinner glass in the market.' - Other	Matrix	Strongly disagree Disagree Neither agree, nor disagree Agree Strongly agree
Q62_5_TEXT	To what extent do you agree with the statement: 'It seems feasible to overcome these barriers for the acceptance of thinner glass in the market.' - Other - Text	Free text	
Q7.3	Please indicate how likely you are to recommend the use of thinner glass for facades knowing that: a. the glass may display relatively higher deformations under climatic or wind loads b. it significantly helps reduce embodied carbon in facades	Multiple Choice Single Answer	Extremely unlikely Somewhat unlikely Neither likely nor unlikely Somewhat likely Extremely likely
Q7.4	Please explain your answer in brief. (optional)	Free text	

Appendix 7

Box plots



Q1: *Quartile 1*, or median of the *left* data subset
after dividing the original data set into 2 subsets via the median
(25% of the data points fall below this threshold)

Q3: *Quartile 3*, median of the *right* data subset
(75% of the data points fall below this threshold)

IQR: *Interquartile-range*, Q3 - Q1

Outliers: Data points are considered to be outliers if
value < *Q1 - 1.5 x IQR* or
value > Q3 + 1.5 x IQR

Appendix 8
Criteria Manual Filtering

criteriatext	Criteria considered	Standards followed	Limits	Notes
3_FacCons 1_Consultant 1 1 UK UK Depends on client For residential 12 years due to warranty providers Although glass itself should exceed 60 years DGU warranties are rarely more than 12 years After 2 years the Argon will have escaped reducing performance Laminates no warranties available over 7 years So a laminate DGU reality is on 7 years		Warranties		
3_FacCons 1_Consultant 2 1 UAE Worldwide Eurocode/American standards - glass strength CWCT glass edge deflection	Glass Strength	CWCT standards		
	Edge deflection	US standards		
		Eurocode		
1_GlassMan 5_Manager 2 2 France Asia, USA				
7_Other Main contractor 5_Manager 1 1 UK UK The serviceability criteria from CWCT Standard for Systemised building envelopes	From CWCT	CWCT standards		
3_FacCons 1_Consultant 1 1 UK UK Strength, optical	Glass Strength			
	Optical performance			
7_Other Material supplier (LSG Interlayers) 1_Consultant 2 1 Germany Germany, UK, France, Italy, Spain, Turkey, Dubai, Saudi Arabia, Switzerland, Poland According to the local standards and potential client needs (for special projects).	Client needs	Local standards		
4_FacCont 5_Manager 2 1 UK UK As specified and recommended by CWCT.		CWCT standards		
1_GlassMan 5_Manager 1 1 Germany UK, Netherlands, France, Africa Technical /feasibility in production Mechanical (loads) Heat / weathering conditions Altitude difference to the production site of the IGU	Production feasibility			
	Technical feasibility			
	Deflection under mechanical loads			
	Weathering conditions			
	Altitude difference			

4_FacCont 5_Manager 1 2 Lithuania North & Central Europe, UK, Iceland				
3_FacCons 1_Consultant 1 1 UK UK flatness, risk of showing roller wave & other optical distortion, deflection under specified structural & thermal loads, behaviour after failure	Optical defects - roller wave distortion			
	Optical defects - reflection disortion			
	Deflection under mechanical loads			
	Deflection under climatic loads			
4_FacCont 3_Engineer 3 2 Netherlands UK				
3_FacCons 3_Engineer 1 1 UK Hong Kong, Australia, UK span/150 to span/175			L/150	
			L/175	
5_Researcher 6_Researcher 1 1 NA				
3_FacCons 3_Engineer 2 1 UK UK, USA, Australia, China, Hong Kong, France Deflection and strength	Deflection			
	Glass Strength			
3_FacCons 1_Consultant 1 1 UK UK dependent on the glass types: single glass standard deflections < L/65 barrier deflections <25mm or < L/65 double glazing standard deflections < L/65 but can be as low as L/125 or 15mm barrier deflections <25mm or < L/65 chord shortening usually 2-3mm			L/65 single glass std deflections	
			L/65 or 25mm for single glass barrier loading	
			L/65 to L/125 or 15mm for double glazing std deflections	
			L/65 or 25mm for double glass barrier loading	
			Chord shortening 2-3mm	
3_FacCons 5_Manager 1 1 UK UK, USA, Italy, France, China, Australia, UAE				
1_GlassMan 5_Manager 2 1 UK UK BS 6262-3, BS 6180, BS 5234, BS EN 16612 and own 'in house' standards.		BS 6262-3		
		BS 6180		
		BS 5234		
		BS EN 16612		
		In-house standards		
3_FacCons 3_Engineer 1 1 UK Middle East, China, Hong Kong, UK, Italy Depends on			L/180 for IGUs	Standards acting as barries
			L/100 for special cases	

the region and local perceptions. We typically design IGUs for L/180, however for certain suppliers we allow upto L/100. For non-IGU glass, we may design for L/60. Some regions are very strict and do not allow us to deviate from standards, even if the warranties are still satisfied.			L/60 for single glass	
3_FacCons 3_Engineer 1 1 UK UK Typically Span/65 or 50mm for glass deflection under wind loading and Span/65 or 25mm for glass deflection under barrier loading.			L/65 or 50mm for std deflections	
			L/65 or 25mm for barrier loading	
7_Other Specialist Consultant for abnormal loads on structures 1_Consultant 3 1 UK Worldwide, Europe Soft body impact Class 2 under CWCT requirements Glass stress limits in accordance with EN16612, with relevant partial load factors	Soft body impact class 2	CWCT standards		
	Glass Stress limits	BS EN 16612		
4_FacCont 2_Designer 1 1 Netherlands UK CWCT Technical Notes		CWCT standards		
3_FacCons 1_Consultant 2 1 UK UK				
3_FacCons 1_Consultant 2 1 UK UK BS EN 16612 â€“ 2019		BS EN 16612		
3_FacCons 3_Engineer 1 1 UK UK Deflection for occupant comfort (Reversible SLS) Deflection under cavity loads for external distortion (Reversible SLS). Adhesive/cohesive failure of edge seals and weatherseals (Irreversible SLS).	Deflection for occupant comfort			Mentions the concept of Reversible and Irriversible SLS
	Deflection under climatic loads			
	Adhesive/cohesive failure of edge seals and weatherseals			
3_FacCons 1_Consultant 3 2 UK UK				
4_FacCont 3_Engineer 1 1 Netherlands UK, Ireland, Netherlands, Germany Allowing for building movements (effects design of details more than the glass thickness) Out of plane deflection of glass units	Deflection			Allowing for building movements in the connection details
3_FacCons 1_Consultant 2 1 UK UK				
3_FacCons 5_Manager 1 1 USA USA, Canada, Mexico Varies. L/175 for IGUs, L/65 perhaps for single glazed. Or resonance.	Resonance		L/175 for IGU	
			L/65 for single glass	

3_FacCons 3_Engineer 1 1 UK UK, Europe, Americas, Asia, Australasia Deflection under applied loads such as wind, cavity pressure, barrier load. Visual distortion viewed in reflection, caused by cavity pressure or manufacturing distortion (such as roller wave). Deflection of the outer pane is often minimised by making the outer pane thicker and the inner pane thinner, to bias the climatic load deflection to the inner, which tends to present less of the external reflection when a high performance coating is used. Reassuring 'feel' to the glass, so that it does not wobble or flex alarmingly when people touch it. A natural frequency of at least 3.5Hz or 4.0Hz seems to be acceptable. A natural frequency below 2 Hz can easily be excited by hand and makes the glazing appear 'too weak' although it may actually be perfectly strong enough to resist applied loads. Large an perfectly flat glass is the current aesthetic ideal, which results in waste and greater thickness than required for safety or reliability. Breakage by climatic load, thermal stress or impact are common servicability considerations. Insulating glass is commonly designed to an edge deflection limit of span/175, or similar, which appears to come from an old criterion related to the resistance of IGU seals to deflection. This criterion affects the supporting frame and the glass when unsupported.	Deflection under mechanical loads		3.5 Hz to 4.0 Hz natural frequency	
	Deflection under climatic loads		L/175 edge deflection for IGUs	
	Deflection under barrier loads			
	Optical defects - reflection disortion			
	Optical defects - roller wave distortion			
	Breakage by climatic loads, thermal stress or impact			
	Deflection for occupant comfort			
3_FacCons 1_Consultant 1 1 UK UK Deformations, visual distortions, vibration	Optical defects - reflection disortion			
	Deflection			
	Vibration frequency			
3_FacCons 1_Consultant 2 1 UK UK 25mm deflection for balustrades L/65 for glazing units			25mm for balustrades	
			L/65 for IGUs	
5_Researcher 1_Consultant 1 2 USA USA				

6_Architect 2_Designer 1 1 India India Limited human involvement (in tall buildings) Autoclean/ drone cleaned panels Ease of access to panels (in medium rise buildings) Dirt retardant panels	Cleaning and maintenance			
1_GlassMan 5_Manager 3 2 Netherlands Switzerland, Germany, UK				
3_FacCons 3_Engineer 2 1 UK UK				
2_SealMan 1_Consultant 2 2 UK Europe, USA, Asia				
1_GlassMan 5_Manager 2 1 Germany Europe, USA center of glass deflection acc. US codes L/2 5 mm sometimes also l/1000 to reduce the optical distortions; l/100 center of glass deflection acc. DIN 18008; l/65 in the UK for the center of glass deflection; in the Austrian Standard for example it is allowed to have L/70 for the non supported edge of vertical glazing; etc.		US standards	L/1000 to reduce optical distortions	
		DIN 18008	L/100 as per DIN	
			L/65 for UK	
			L/70 for Austria for non supported edge of glazing	
2_SealMan 3_Engineer 2 2 Belgium UK, USA, Germany, Italy, Asia				
3_FacCons 1_Consultant 2 1 Netherlands Netherlands Safety, maintenance, carbon footprint	Safety			
	Cleaning and maintenance			
	Carbon Footprint			
3_FacCons 2_Designer 3 2 UK UK				
1_GlassMan 3_Engineer 1 1 Germany USA L1/60 if ULS is OK			L/60	
4_FacCont 3_Engineer 1 1 Netherlands UK, Netherlands Deflection Frequency (mostly for freestanding balustrades, not generally applicable to windows)	Vibration frequency			
4_FacCont 6_Researcher 2 1 Spain UK, USA, France, Spain Limit on glass		EN 16612:2019	L/65 or 50mm as per EN 16612:2019	

deflection to be checked on edges and center of pane (and limits depend on boundary conditions): - european standard EN 16612:2019 (L/65; 50mm) - french standard NF DTU 39 (L/60, 30mm); (L/100,50mm); (L/150;50mm). Limits to be considered on the framing support: -european standard EN 13830:2015		NF DTU 39	L/60 or 30mm, L/100 or 50mm; L/150 or 50mm as per French std NFDTU 39	
		EN 13830:2015	Limits on framing support	
3_FacCons 7_Other Part engineer, part designer 2 1 UK UK, Denmark, Spain Safety - Impact, barrier and wind load Design/Service life - Performance and visual Replacement	Safety			
	Performance and visual replacement			
1_GlassMan 3_Engineer 1 1 France France deflection, durability	Deflection			
	Durability			
7_Other Main Contractor and Developer 5_Manager 2 1 UK UK Load accommodation Safety Structural criteria Thermal criteria Glass standards	Glass Strength	Glass standards ?		
	Safety			
	Mechanical Performance			
	Thermal Performance			
3_FacCons 1_Consultant 2 2 UK UK				
1_GlassMan 3_Engineer 2 1 Germany USA, UK, Italy, Germany Recycling Content, conflict materials, Life Cycle	Recycled content			
	Conflict materials			
	Life cycle			
3_FacCons 3_Engineer 1 1 UK UAE, UK deflection, stability, fire resistance, thermal and acoustic insulation, edge stability...	Deflection			
	Stability			
	Fire resistance			
	Thermal Performance			
	Acoustic Performance			
	Edge stability			
3_FacCons 5_Manager 2 1 Switzerland Denmark, Luxembourg, Germany 1/75 or 1/100 (SIA 2057)		SIA 2057	L/75 or L/100	
1_GlassMan 6_Researcher 2 2 Belgium Belgium				
7_Other Main Contractor 3_Engineer 1 2 UK UK				
7_Other Engineering consultancy 1_Consultant 2 1 UK UK CWCT Standards, Technical Notes and referrred BS		CWCT standards		
		CWCT Technical notes		
		BS		
1_GlassMan 4_Salesperson 2 1 UK UK, Netherlands,	Deflection			
	Mode of breakage			

Belgium, Ireland, USA Impact resistance, deformation, mode of breakage, U value, g value	Thermal Performance			
	Optical performance			
3_FacCons 3_Engineer 1 1 UK UK L/65 or 30 mm whichever is the smaller			L/65 or 30mm	
1_GlassMan 5_Manager 1 1 Belgium Belgium, France, UK, Netherlands, Italy Deflection is the main criteria. Eigen frequency. VIV and other wind instabilities for other faÃ§ade components.	Deflection			
	Eigen frequency			
	VIV and other wind instabilities			
1_GlassMan 5_Manager 3 2 UK USA, UK, Italy, Germany, France, Brazil, Argentina, Japan				
4_FacCont 3_Engineer 1 1 Spain France, UK Under SLS: Deflection Vibration (first mode) Under ULS: Ultimate resistance Under ULS (Accidental): Impact performance Post-breakage resistance Other: Thermal Transmittance Optical trasmittance Solar factor Intrusion resistance	Deflection			
	Vibration frequency			
	Thermal Performance			
	Optical performance			
	Solar factor			
	Intrusion resistance			
4_FacCont 5_Manager 3 1 Italy UK				
1_GlassMan 4_Salesperson 1 1 UK UK, Ireland, India, UAE, Saudi Arabia Multiple				
3_FacCons 3_Engineer 1 1 France France, UK point load, wind and climatic load, barrier load	Deflection under mechanical loads			
	Deflection under climatic loads			
3_FacCons 1_Consultant 2 1 UK UK deflection, flatness, optical distortion	Optical defects - reflection disortion			
	Deflection			
	Optical defects - roller wave distortion			
3_FacCons 1_Consultant 2 2 UK UK				
3_FacCons 1_Consultant 1 1 UK UK Serviceability of the glass is often limited by the manufacturer of the DGU. The warranty provision for the glazing is a driver and therefore manufacturer guidelines are to be respected. typical limit are the 25mm deflection in line with the CWCT in combination with the appropriate line and barrier loading.		Manufacturer guidelines		
		CWCT	25mm	

1_GlassMan 1_Consultant 1 1 UK UK Structural stability, deflection limits, thermal performance, condensation resistance, safety and security, post breakage, maintenance, cleaning regime	Stability			
	Deflection			
	Thermal Performance			
	Condensation resistance			
	Safety			
	Post breakage behaviour			
	Cleaning and maintenance			
4_FacCont 3_Engineer 2 1 Netherlands Netherlands 1. find out the required loads / forces that we need to design. 2. choose the optimal glass composite out from the standard stock. 3. if necessary due to structural calculation, then choose the thermmally strengthened glazing	Composition from standard stock			
7_Other General Contractor 5_Manager 1 1 UK UK deflection limits due to imposed loads, wind, barrier, impact. visual comfort considered as is visual appearance due to deflections and climatic loads.	Deflection under mechanical loads			
	Optical performance			

Appendix 9

Limits and standards indicated in survey

Organization	Location	Project Location	Limits	Notes	Standards followed
Façade Consultant	UK	UK	25mm	typical limit	CWCT standards
Façade Consultant	UK	UK	25mm	for balustrades	0
Façade Consultant	UK	UK	2mm to 3mm	chord shortening	0
Façade Consultant	UK	UK, Europe, Americas, Asia, Australasia	3.5 Hz to 4.0 Hz natural frequency	acceptable limits (no standard mentioned)	0
Façade Consultant	UK	Hong Kong, Australia, UK	from L/150 to L/175	0	0
Façade Consultant	UK	UK	from L/65 to L/125 or 15mm	for double glazing std	0
Glass Manufacturer	Germany	Europe, USA	L/100	0	DIN 18008
Façade Consultant	UK	Middle East, China, Hong Kong, UK, Italy	L/100	for certain suppliers.	Limits depend on regional and local perceptions and standards.
Glass Manufacturer	Germany	Europe, USA	L/1000	for special cases, to reduce optical distortions	US standards
Façade Consultant	UK	UK, Europe, Americas, Asia, Australasia	L/175	typical edge deflection limit for IGUs	0
Façade Consultant	USA	USA, Canada, Mexico	L/175 for IGU	for IGU	0
Façade Consultant	UK	Middle East, China, Hong Kong, UK, Italy	L/180	typical limit for IGUs	Limits depend on regional and local perceptions and standards.
Façade Consultant	UK	Middle East, China, Hong Kong, UK, Italy	L/60	typical limit for non-IGU glass	Limits depend on regional and local perceptions and standards.
Glass Manufacturer	Germany	USA	L/60	0	0
Façade Contractor	Spain	UK, USA, France, Spain	L/60 or 30mm, L/100 or 50mm; L/150 or 50mm	0	NF DTU 39

Glass Manufacturer	Germany	Europe, USA	L/65	center of glass deflection limit for UK	0
Façade Consultant	UK	UK	L/65	for glazing units	0
Façade Consultant	UK	UK	L/65	for single glass standard deflections	0
Façade Consultant	USA	USA, Canada, Mexico	L/65 for single glass	for single glass	0
Façade Consultant	UK	UK	L/65 or 25mm	for single glass barrier loading	0
Façade Consultant	UK	UK	L/65 or 25mm	for barrier loading	0
Façade Consultant	UK	UK	L/65 or 25mm	for double glass barrier loading	0
Façade Consultant	UK	UK	L/65 or 30mm	0	0
Façade Contractor	Spain	UK, USA, France, Spain	L/65 or 50mm	0	EN 16612:2019
Façade Consultant	UK	UK	L/65 or 50mm	for standard deflections	0
Glass Manufacturer	Germany	Europe, USA	L/70	unsupported edge deflection limit for Austria	0
Façade Consultant	Switzerland	Denmark, Luxembourg, Germany	L/75 or L/100	0	SIA 2057
Other	UK	UK	0	0	BS
Glass Manufacturer	UK	UK	0	0	BS 5234
Glass Manufacturer	UK	UK	0	0	BS 6180
Glass Manufacturer	UK	UK	0	0	BS 6262-3
Façade Consultant	UK	UK	0	0	BS EN 16612
Glass Manufacturer	UK	UK	0	0	BS EN 16612
Other	UK	Worldwide	0	0	BS EN 16612
Façade Consultant	UAE	Worldwide	0	0	CWCT standards
Façade Contractor	Netherlands	UK	0	0	CWCT standards
Façade Contractor	UK	UK	0	0	CWCT standards
Other	UK	UK	0	0	CWCT standards
Other	UK	UK	0	0	CWCT standards
Other	UK	Worldwide	0	0	CWCT standards

Other	UK	UK	0	0	CWCT Technical notes
Façade Contractor	Spain	UK, USA, France, Spain	0	for limits on framing support	EN 13830:2015
Façade Consultant	UAE	Worldwide	0	0	Eurocode
Other	UK	UK	0	0	Glass standards ?
Glass Manufacturer	UK	UK	0	0	In-house standards
Other	Germany	Germany, UK, France, Italy, Spain, Turkey, Dubai, Saudi Arabia, Switzerland, Poland	0	0	Local standards
Façade Consultant	UK	UK	0	0	Manufacturer guidelines
Façade Consultant	UAE	Worldwide	0	0	US standards
Façade Consultant	UK	UK	0	0	Warranties

Appendix 10

Barriers and feasibility to overcome them

Text responses received in the 'Other' free text option in the questions.

BAR_OTH_TXT	OVBAR_OTH_TXT
acoustic requirements	acoustics
Architectural expectations	Effect on IGU performance
Assumed/perceived technological challenges	
Changes to glazing systems	Glazing systems
Concern about the mysterious 'strength of glass'.	
Cost	Cost if h<2mm
factory requirements	
Glass codes -conservative serviceability limits	revised serviceability requirements - codes
Handling, detailing connections	
post breakage behavior	glass processors quality is mostly not suitable and thinner glass may lead to more optical distortions, which they could blame on the thinner glass, not the fabrication technology
Standards and regulations	Manufacturing issues
Standards not being up to date	Standards not being up to date
supplier	
Tendency of facade consultants to stick to known practice and specify for the most stringent codes	Tendency of facade consultants to stick to known practice and specify for the most stringent codes
Thinner glass may involve a perceptive risk that it is difficult to handle it and can increase installation costs.	Bias towards conventional products
Warranties / liability	Warranties/liability

Following is a list of barriers listed in the survey:

1. Conservative design approach: Consultants being conservative
2. Conservative design approach Not learning from other countries/ peers
3. Lack of data: on engineering properties of thinner glass
4. Lack of data: on occupant/ user acceptance levels of deformation
5. Changes required: to glazing systems
6. Changes required: in warranties and liabilities
7. Perceived challenges: manufacturing
8. Perceived challenges: effect on glazing performance
9. Perceived challenges: handling and transportation
10. Perceived challenges: structural calculations
11. High level of requirements: architectural/ aesthetic quality
12. High level of requirements: robustness
13. High level of requirements: optical performance
14. High level of requirements: acoustic
15. Manufacturing challenges: lines not being well equipped
16. Manufacturing challenges: Cost and scale required to implement change
17. Perception: of deformation as inferior quality
18. Perception: of deformation as unsafe
19. Perception: of glass as a rigid material
20. Standards: being conservative
21. Standards: being non uniform across countries
22. Standards: not being up to date

Appendix 11
Code structure

For qualitative analysis of Q5.4 and Q7.4

- BARR
    - Consultants being conservative
    - Cost of implementing change
    - Difficulty of structural calculations
    - Expectation: High levels of robustness
    - Expectation: High optical performance
    - Manufacturing lines not being well equipped
    - Not learning from other countries/ peers
    - Occupant/ user concerns regarding deformation
    - Perception of deformation as inferior quality
    - Perception of deformation as unsafe
    - Required scale of change is large
    - Standards being conservative
    - Standards being non uniform across countries
    - Standards not being up to date
    - CRITERIATXT
- DRFAC
    - Carbon Reduction
    - Change in codes
    - Glass stress
    - Strength of glass
    - GDL_OTHER_TXT
    - GLTHK_IMP_SPL_TXT
- GOVFAC
    - Def: Connection detailing
    - Def: Conventional acceptable limits
    - Def: Lamination interlayer
    - Thk: Expected visual quality
    - Thk: Project location
    - Thk: Project Type
    - Thk: Project/ Client requirements
    - Thk: Risk and cost
    - Thk: Size of pane
    - Thk: Standards or consultant specs
    - Thk: Strength and deflection
    - Thk: Transportation
    - Thk: Where thinner glass is applied
- INFO
    - INFO_THIN
    - Actual deflection limits for all conditions
    - Actual qualification of visual comfort
    - Cost impact
    - Criteria for serviceability limits
    - Data on user acceptanct of distortions
    - Detailed load info, non-factored and frequency
    - Detailing of connections

- ○ Effect of deflection on durability
- ○ Effect of deflection on frame integrity
- ○ Effect of deflection on optical performance
- ○ Effect of deflection on structural performance
- ○ Effect of deflection on thermal, acoustical, serviceability
- ○ Feasibility of replacement
- ○ Impact of glass connection on deflection
- ○ Impact on risk
- ○ Impact on warranty
- ○ Limitations on size of pane
- ○ Loading: Design load for barrier
- ○ Loading: Design loads for wind
- ○ Loading: Permissible point load area and limits
- ○ Loading: Repartition standardization
- ○ Manufacturer's data: aspect ratio to thickness confirmation
- ○ Manufacturer's data: sizes, toughening, coating, risks of breakage in transit
- ○ Potential Carbon savings
- ○ Potential material weight reduction
- ○ Scientific evidence

○ NEED

- ○ Change in aesthetic goals
- ○ Changes to conventional design approach
- ○ Distinction between performance and deflections
- ○ Partial factors clearly defined
- ○ Scale of production
- ○ To educate stakeholders
- ○ To lower acoustical requirements
- ○ To lower safety factors
- ○ To update standards
- ○ Updated calculation tools
- ○ What to include in standards
- ○ Wind tunnel calculations
- ○ OPT_DEF_IMP
- ○ OPT_DEF_LOADING
- ○ OVBAR_OTH_TXT

○ REC

- ○ Condn: Actual cabon savings
- ○ Condn: Actual deflection
- ○ Condn: Alignment with standards
- ○ Condn: Based on project requirements
- ○ Condn: Based on type of project
- ○ Condn: Change in standard design approach
- ○ Condn: Level of safety is not compromised
- ○ Condn: Proof of concept
- ○ Condn: Service life should not reduce
- ○ Condn: Should achieve specified performance
- ○ Condn: Strength should not be an issue
- ○ Neg: Architecture perspective
- ○ Neg: Conservative consultants
- ○ Neg: Conservative standards
- ○ Neg: Doesn't offer much value
- ○ Neg: Increased risk and costs

- Neg: Occupant perspective
- Neg: Perceive technical challenges: coating
- Neg: Standards would need to change
- Pos: Accepting compromises
- Pos: Acknowledgement of benefits
- Pos: Carbon Reduction as Key Driver
- Pos: Contractors are willing
- Pos: Cost
- Pos: Perception can be changed

- ROLE
  - Architects: Decision makers
  - Clients: Decision makers
  - Consultants: Decision Makers
- SUGG
  - Allowing deformation on predetermined axes
  - Increase allowable stiffness of PVB
  - Integrate thinner glass with appropriate geometries
  - Introduction of Carbon Tax
  - Lowering specification by facade consultant
  - Opportunity: Deformation as proof of low carbon facade
  - Opportunity: Reducing emb carbon in an inexpensive way
  - Optical defects to be tightly controlled
  - Reducing glass size
  - use of thin glass and vacuum glass

Appendix 12

Linear and nonlinear analysis results

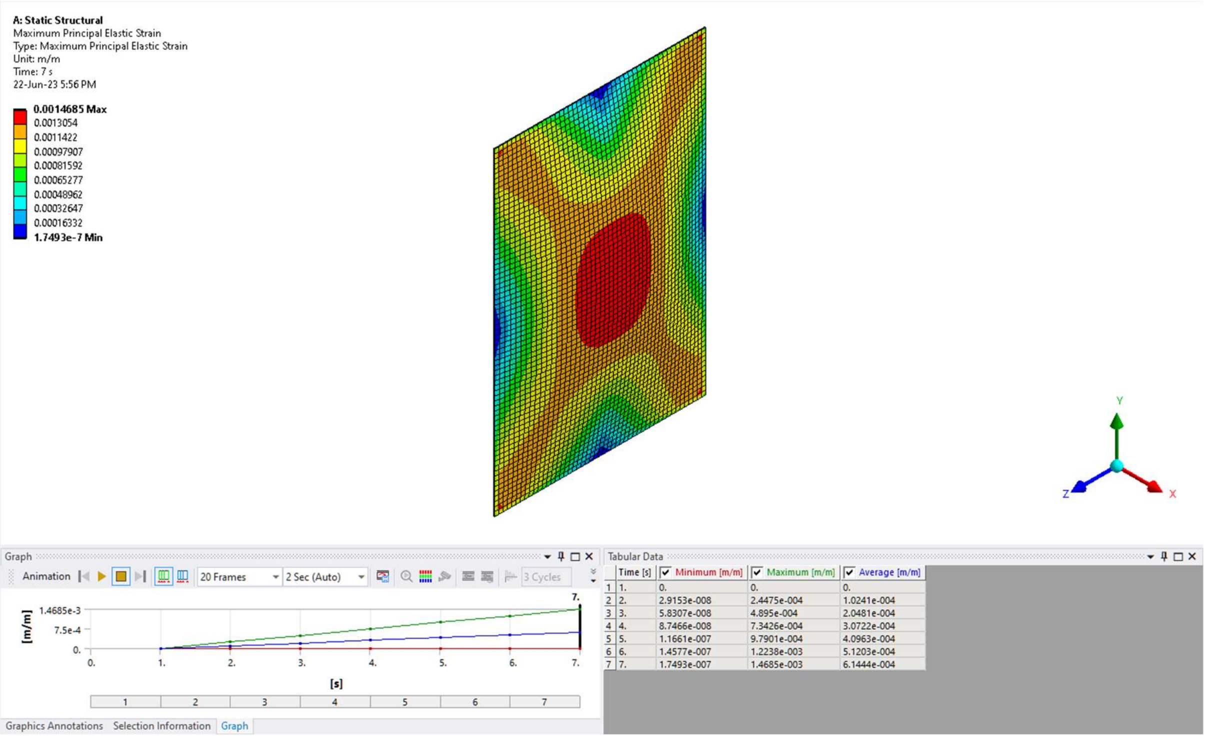


Figure 76: Principal Strain data as per linear analysis.

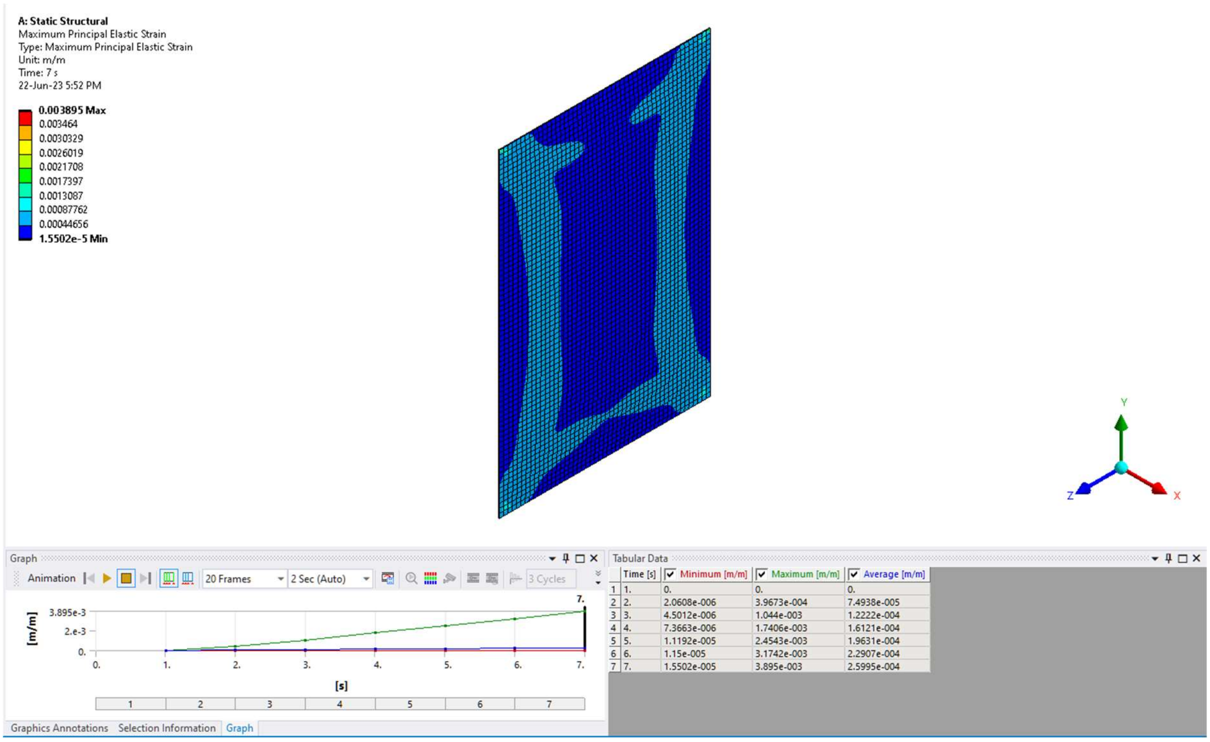


Figure 77: Principal Strain data as per nonlinear analysis

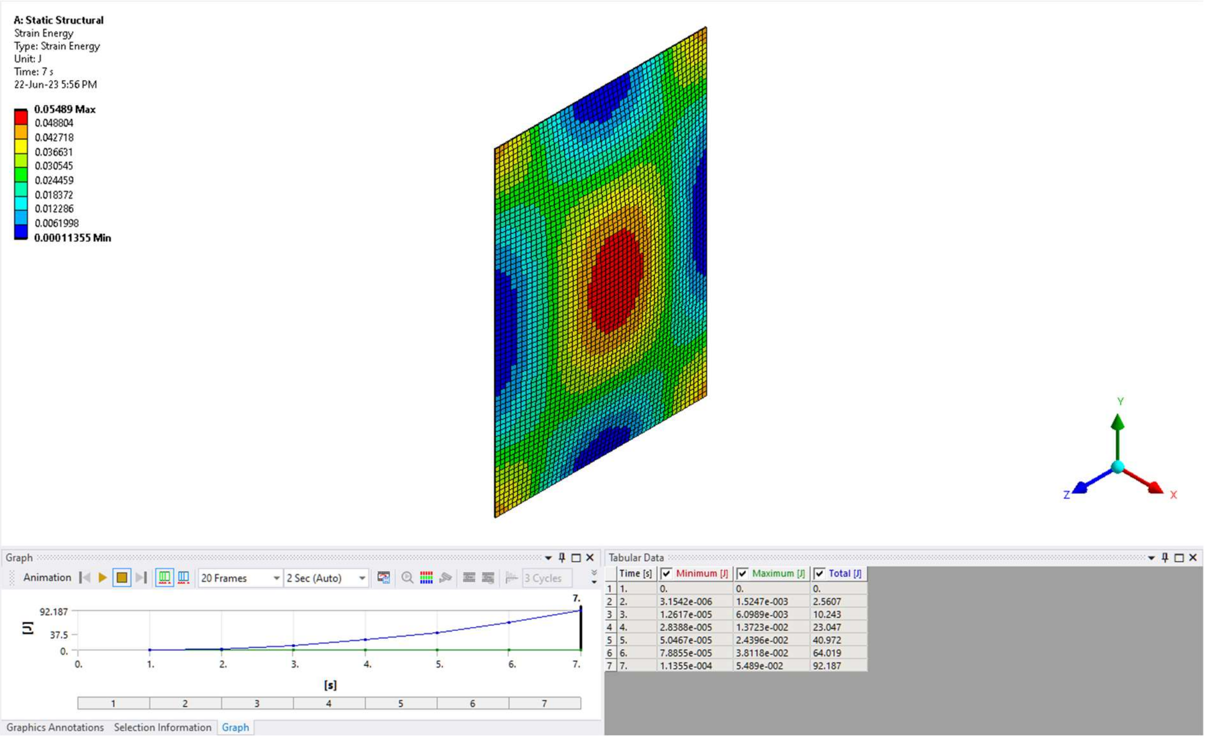


Figure 78: Strain energy data as per linear analysis

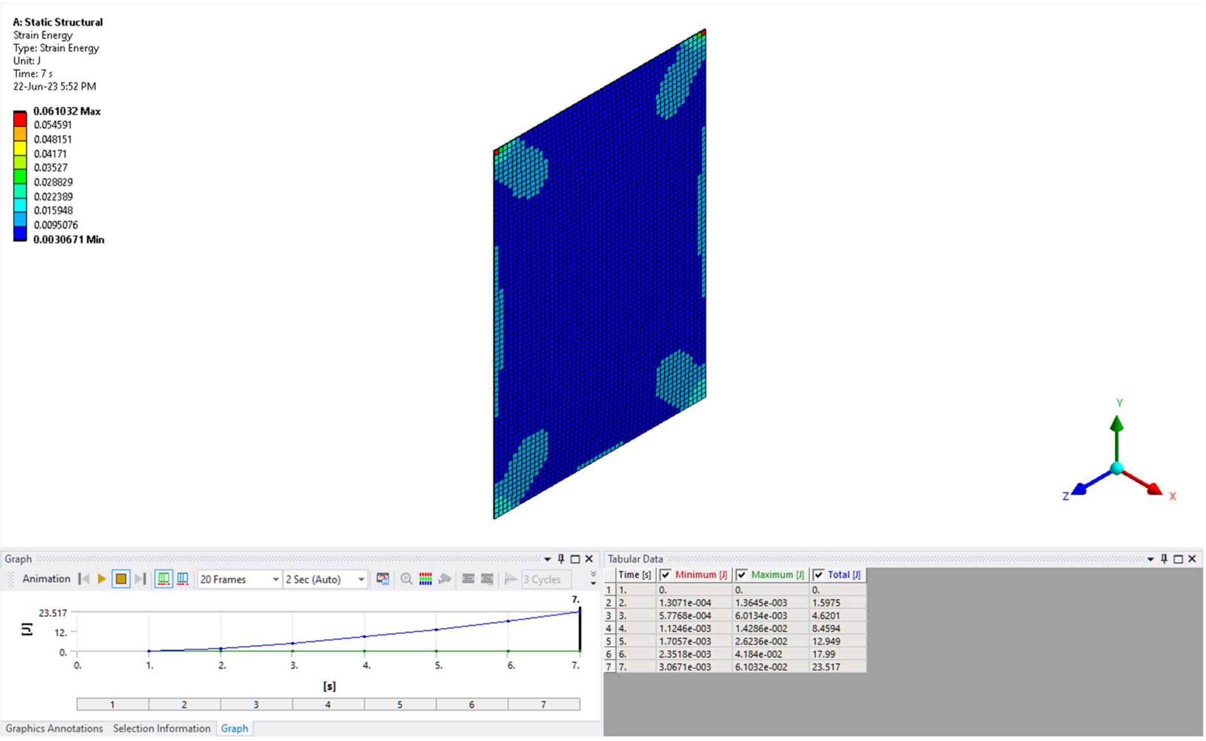


Figure 79: Strain energy data as per nonlinear analysis