Empirical Assessment of Glazing Serviceability Limit: **Exploring Occupant Acceptance.**

by

Mohammed I. Hassen

Student number:5741165

Faculty of Architecture, TU Delft

Building Technology Track

Mentors:

Dr. Alessandra Luna Navarro

Prof. Dr. Mauro Overend

Advisor:

Pedro de la Barra Leugmayer

Industry partner:

AGC

TU Delft Delft University of Technology

Abstract

The performance of a building envelope is crucial for minimizing operational carbon emissions and maintaining indoor comfort. Contemporary building envelopes, such as highly engineered glazed façades, achieve high performance levels but also add a significant amount of embodied carbon. For example, a 1mm reduction in glass thickness could save 7.7 kgCO2eq/m2. There is therefore an incentive to reduce the thickness of the glass panels, but the minimum thickness possible is often not governed by strength or manufacturing limits but rather by the deflection (serviceability) limits. Despite objective criteria guiding serviceability limits, occupant acceptance of deformation remains unexplored, leading to conservative designs. This research introduces a novel method for measuring occupant's perception of glass deformations, aiming to establish acceptance thresholds comparable to objective criteria. An experimental campaign was conducted to assess volunteers' levels of perception and acceptance of various glass deformations. The glass was deformed using an electro-pneumatic system at levels corresponding to below, above, and at the current serviceability limit. The results demonstrate the feasibility of measuring human responses to deformations in the glazing and provide essential data for setting serviceability limits. The experiments indicate that, based on occupant feedback, the current serviceability limit of *L*/50 may be relaxed, thereby presenting opportunities for material efficiency, such as the adoption of thinner glass in facades. The methodology effectively captures human responses, revealing heightened perception of glazing movement at night and a higher acceptance during the day. Changes in reflection were the primary reason for the perception of movement, with lower acceptability at night. Overall, participants felt safe regardless of their prior knowledge on glass properties, and providing this information to participants did not improve acceptance, which was already sufficiently high. The findings from this research fill an important knowledge gap in understanding occupant acceptance of glass deformations, crucial for comprehensive user satisfaction assessments and evidence-based reductions in glazing thickness.

Empirical Assessment of Glazing Serviceability
Limit: Exploring Occupant Acceptance

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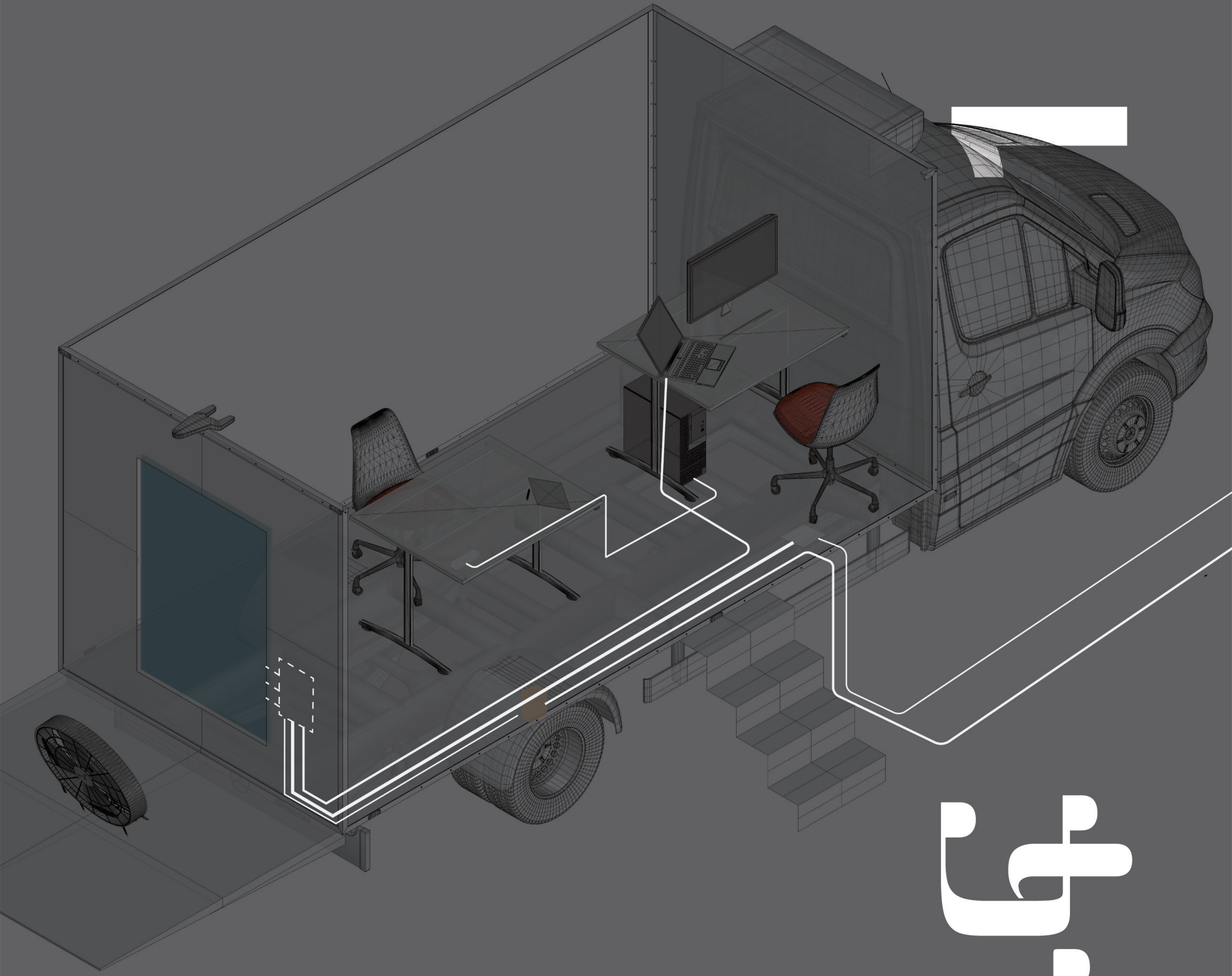
Table of Contents



Introduction

1 Introduction

1.1 Context: The Building Industry and Carbon Emission Reduction

The construction industry is experiencing remarkable growth and is anticipated to persist in this trend. In the next four decades, it is projected that the world will construct 230 billion square meters of new buildings, equivalent to adding a city the size of Paris every week. Despite recent improvements in energy efficiency within the building sector, these advancements have not sufficiently countered the increasing demand for energy. To meet the global climate goals set in the Paris Agreement, the global building sector should aim for a 30% improvement in energy intensity per square meter by 2030, compared to the levels in 2015 (UN Environment & International Energy Agency, 2017).

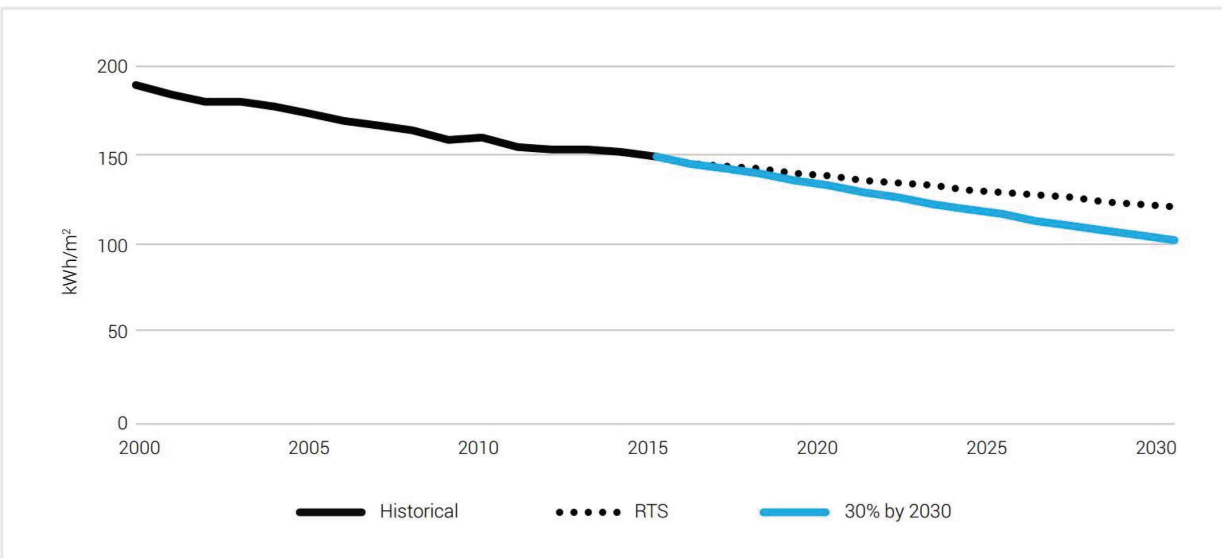


Figure 1: Energy Technology Perspectives 2017, IEA/OECD, Paris www.iea.org/etp/. EJ = exajoules; kWh/m2 = kilowatt-hours per square meter: RTS = Reference Technology Scenario. (Source: IEA 2017)

1.2 Glazing Material Efficiency and Building Performance

The building envelope significantly affects heating and cooling loads in buildings, consequently impacting the energy intensity per square meter. Highly insulating, multi-glazed units, as highlighted by Joshua S. Apte (2008) have the potential to enhance a building's energy efficiency. Currently, Multi-glazed Insulated Glass Units (IGUs) are widely used in the construction industry to improve operational performance. However, increasing the number of panes within these units, while beneficial for performance, poses challenges related to increased weight and thickness. This additional weight and thickness contribute to the carbon footprint of the envelope, which already has a significant contribution of 10-30% of the total building embodied carbon (Arup & SGS, 2022).

Furthermore, the increased weight and thickness cause complications in the production, transportation, and installation of such elements. To address these drawbacks, a potential solution lies in using glass panes with reduced thickness. However, thinner glass panes are more susceptible to deflection (Respondek, 2018).

1.3 Influence of Glazing Deflection on Façade Performance

Thin glass facades have the potential to improve material efficiency, nonetheless further considerations must be taken as deflections of the glazing increases. These considerations include stress distribution, durability of Insulated Glass Units (IGUs), thermal performance, and optical performance.

Stress:

The connection between deformation and stress extends throughout the entire thickness of the glass pane. In the external pane of an Insulated Glass Unit (IGU), it was observed that higher thicknesses lead to increased stresses compared to thinner glass panes (Respondek, 2018). There exists a critical thickness value where the component glass panes experience the highest stress levels due to atmospheric pressure changes. This suggests that at critical thickness, the pane may experience elevated stress, and either decreasing or increasing the thickness beyond this point will lead to lower stresses in the glass.

Durability of IGUs:

As long as the stress values arising from excessive deformation remain within the ultimate limits, the glass remains safe from breakage. Nevertheless, it is crucial to note that deformation within ultimate limit state (ULS) boundaries does not imply an absence of impact on the longevity of glazing. Durability is an important serviceability criterion. Excessive deformation in glass can strain the sealants, potentially causing the sealed air cavity to deteriorate.

Thermal performance of IGUs:

The influence of deflection on thermal performance is based on the intended gap size of the Insulated Glass Unit (IGU). IGUs designed with gaps smaller than the optimal size may exhibit noteworthy change in U-factor due to variability in gap dimensions caused by atmospheric pressure change. This issue is especially challenging for high-performance triple glazing, where even slight changes in gap dimensions can significantly affect overall performance. It is feasible to address this concern by designing an IGU with a sufficiently wide gap, thereby mitigating any potential deflection effects on performance (Hart et al., 2012).

Optical performance of glazing:

One of the optical distortions that can result from IGU panes deflecting is pillowing. It results from the hermetically sealed airspace changing volume due to temperature and atmospheric change. As 'pillowing' will affect equal thickness panes equally then a reduction in the visual affect would be to make the outer pane always the thicker one. A small added benefit is that asymmetric IGUs also have increased sound insulation as sympathetic resonance is reduced (EGL technical bulletin, 2017).

Glazing Thickness Reduction and Key Considerations Taken by the Industry:

Aside from its impact on façade performance, glazing also influences various aspects of a building, including costs, perceived value, and aesthetic quality. Reducing glass thickness can affect these factors, and a survey was conducted to assess the potential impact on different aspects (Sagar Oke, 2023). The result of the survey are as follows:

Almost all survey participants, with only a few exceptions, highlighted a favorable influence on the cost of the façade and the material efficiency of both the façade and the building structure. This holds significant importance for overall project costs and aligns with the emphasis on a material efficient approach.

In terms of on-site handling and the fabrication of curved facades using thin glass, 75% of respondents indicated a positive impact, while the rest of responses ranged from 'moderately negative' to 'no impact.' Responses on overall occupant satisfaction and aesthetic value displayed variability, with 75% noting a negative impact. Regarding occupant satisfaction, 50% indicated responses from 'no impact' to 'slightly negative'. Opinions on aesthetic value ranged from highly positive to extremely negative. However, half of the respondents expected the impact on aesthetics to be between 'no impact' and 'moderately negative’. While the advantages of cost savings and material efficiency may drive the inclination toward reducing glass thickness, concerns about aesthetics and overall occupant satisfaction may act as deterrents.

What are the Causes of IGU Deflection?

Discussing structural deflections becomes more comprehensible when addressing specific aspects. In examining occupant comfort related to Insulated Glass Unit (IGU) deflection, the primary focus is on serviceability. A serviceable structure is one that fulfills its intended purposes in everyday use. Deflections considered acceptable at the serviceability level differ from those occurring at a collapse or ultimate limit state. (Galambos et al., 1973)

In an Insulated Glass Unit (IGU) assembly, the gap is filled by gas during the unit's production, resulting in initial parameters such as pressure, temperature, and volume for the gas within. When subjected to operational conditions, the IGU experiences climatic loads that induce loads and deflections in the individual glass panes due to pressure variations between the gap and the surrounding environment. For example, an increase in atmospheric pressure or a decrease in gas temperature within the gap causes a concave deflection of the panes (Figure 2a), while the opposite changes lead to a convex deflection (Figure 2b). The extent of under or overpressure in the gap is influenced not only by climatic load values but also by the IGU's structural characteristics. Generally, it tends to increase with:

1. smaller IGU dimensions,
2. greater thickness of the gas gap, and
3. increased thickness of the component glass plates.

In situations involving wind exposure (Figure 1c), the tightness of the gap positively affects the load distribution within the IGU. Variations in gas pressure within the gaps cause part of the external load to be transferred to other panes in the unit (Respondek, Z., 2020).

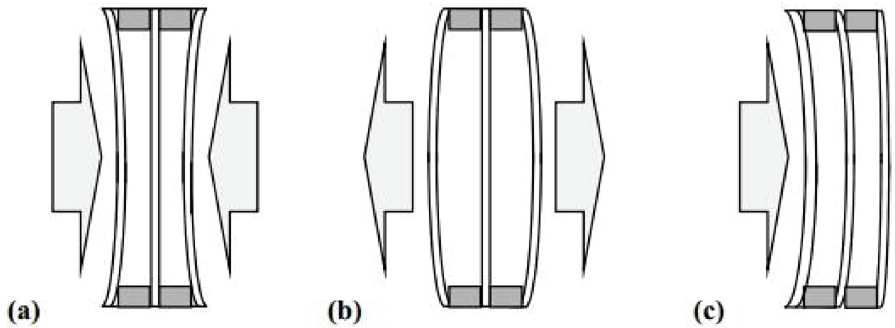


Figure 2: Typical deflection of insulated glass units (a) concave form of deflection, (b) convex form of deflection, (c)deflection characteristics of wind load (Source: Respondek, Z., 2020)

The deflection of glass within a sealed unit can be especially apparent during periods of elevated pressure and cooler temperatures, causing the air space inside the unit to contract and distort the glass panes. The extent of deflection and its degree are contingent, to varying degrees, on the following factors:

1. Barometric Pressure and Ambient Temperature: When units are sealed during low barometric pressure, a subsequent increase in external pressure causes a relative decrease in internal pressure. As this difference intensifies, it results in a more pronounced inward deflection. Similarly, a relatively higher temperature during manufacturing affects the deflection on an IGU, as the air in the cavity contracts upon cooling when the ambient temperature decreases. This contraction continues as external temperatures decrease during cold weather, reaching its maximum deflection during such periods.

2. Humidity**:** A higher relative humidity during the manufacturing process results in a greater amount of moisture retained by the air within the cavity. After the sealing process is completed and the desiccant has absorbed this moisture, the internal pressure is further reduced, causing an under pressure within the cavity.

3. Cavity Width and speed of application: During the application of hot melt, the air space adjacent to the spacer warms up, causing the air to expand and exit the unit until the sealing process is complete. As the unit gradually cools, the air contracts, leading to a decrease in pressure within the unit. This phenomenon is more pronounced in wider unit cavities, where a larger volume of air is warmed compared to narrower cavities (e.g., 20mm compared to 6mm). Two factors contribute to this: firstly, the faster the sealing operation, the less time available for the air space to heat up; secondly, components in a 6mm cavity unit would act as a greater heat-soak, resulting in relatively less air expansion.

4. Aspect Ratio: Large units with a low aspect ratio, where the width to height ratio is approximately 1:1, typically demonstrate the highest level of glass deflection. Conversely, high aspect ratio units, such as long height and narrow width, exhibit minimal deflection due to their small span and the inherent rigidity of the glass, which inhibits deflection. However, in such cases, there is an elevated

risk of glass fracture, particularly when incorporating decorative components like lead and color film.

5. Desiccant selection: Desiccant grades, particularly those that do not consider low deflection, containing a high proportion of molecular sieve with a pore size of 4 Angstrom units and above, may undergo nitrogen desorption when exposed to high temperatures during the sealing process with hot melt sealants. Similar to the previous point, this process effectively expels air from the unit cavity, and once the sealing is complete, the desiccant re-adsorbs nitrogen upon cooling. Such desiccants continue to adsorb nitrogen as ambient temperatures decrease, potentially leading to increased deflection, particularly in very low-temperature weather conditions. This deflection is observed with hot melt and two-part sealants. If, for technical reasons, a non-low deflection desiccant is used, the level of fill can also impact the degree of deflection, and it is advisable to seek guidance from suppliers before adjusting the level of fill.

6. Unit construction: Effects of cavity sizes and aspect ratios on deflection have been mentioned above. However, it's essential to consider the choice of glass and its flexibility. When using glass of varying thicknesses, the thinner glass will exhibit greater flexibility and, consequently, may experience more pronounced deflection compared to using glass of similar thickness. It is beneficial to place the thicker pane of glass on the exterior, as it tends to display less deflection, and visual issues related to deflection are typically more noticeable when viewed from the outside.

7. Method of application: When units are manufactured horizontally, there is a tendency for the top pane of glass to bend due to gravity. In contrast, if units are produced on rotary tables and the bottom pane is not adequately supported, it can be deflected even more than the top pane. This increased deflection is a result of the bottom pane having to bear the entire weight of the unit in the central area.

8. Incomplete Seal: In the event of an incomplete seal, a gap is present, facilitating the easy escape of air from the unit cavity. When the unit is subjected to high temperatures, the air within the cavity expands, and the heightened pressure compels air to pass through the gap. Conversely, during the cooling phase, as the air contracts, the resulting negative pressure may cause the seal gap to close by suction, creating an overall negative pressure within the unit. Over an extended period, this condition can lead to the gradual displacement of the spacer into the cavity or the potential fracture of one pane of glass.

This paper focuses on glazing deflection affected by barometric pressure and temperature, as these are the primary factors that directly correlate with the reduction in thickness of glazing. Factors affecting deflection considering the unit manufacturing condition are set aside for a manageable scope of research exploration.

1.4 The Need to Define Serviceability with Human Acceptance in Mind

A shift from perception to acceptability: A recent study conducted at the Universities of Bath and Exeter on the impact of wind-induced vibration on occupants' comfort has highlighted the distinction between human perception and acceptance of deflection and motion in structures (Heshmati et al. ,2020). The International Organization for Standardization (ISO) offers the latest serviceability criteria (ISO 10137, 2007) for wind-induced motion of buildings, presents frequency-dependent curves for vibration threshold. However, this proposed approach is considered insufficient (Lamb et al., 2016; Lamb and Kwok, 2017) for assessing the human acceptability of vibrations. Literature suggests that vibrations can be perceptible yet still acceptable, without adversely affecting performance and well-being (Burton, 2006; Denoon et al., 2000; Jeary et al., 1988). Conversely, a scenario may exist where sub-perceptible motion can be potentially unacceptable due to adverse effects on humans (Hammam et al., 2014). Furthermore, acceptability is context-dependent, contingent on occupants' activities in an environment and their expectations.

Although previous research has primarily focused on the deflection/movement of a building perceived through physical contact, it can be hypothesized that human acceptance of glazing deflection will differ from the human perception of deflection. Human perception of glass is influenced by the perception that glass is fragile and potentially dangerous (Honfi and Overend, 2013). Therefore, this research aims to investigate the disparity between human perception and acceptance by incorporating knowledge about the inherent capabilities of glass to occupants.

1.5 Problem Statement

The performance of a building envelope is crucial for minimizing operational carbon emissions and maintaining indoor comfort. Contemporary building envelopes, such as highly engineered glazed façades, achieve high performance levels but also add a significant amount of embodied carbon. CO_2 emissions from producing flat glass is 3.08kg CO2 /kg (Liu, Zhu, & Li, 2014). For example, a 1mm reduction in glass thickness could save 7.7 kg CO2 eq/m_2. There is therefore an incentive to reduce the thickness of the glass panels, but the minimum thickness possible is often not governed by strength or manufacturing limits but rather by the deflection (serviceability) limits.

Glass possesses flexibility and can bend considerably. The deflection of glass isn't inherently problematic. However, human perception of glass may differ from that of traditional structural materials, as it is usually viewed as fragile and potentially dangerous (Honfi, D., & Overend, M. 2013). There's a common perception that structures should be rigid, and any visible or perceptible deformation is seen as a sign of potential failure or, at the very least, an unsafe condition. Awareness of static deflection relies on visual cues, and a negative response often follows if the deformation is noticeable to the eye (Galambos et al., 1973).

Despite objective criteria guiding serviceability limits, occupant acceptance of deformation remains unexplored, leading to conservative designs. This leads to glass being thicker than strictly necessary. The field has lacked standardized guidance for glass design, and the final publication of a Eurocode for glass is still pending (Coult & Overend, 2022). As the building industry pushes for energy efficiency, the challenge lies in finding a balance of high-performance glazing with a reduced thickness without compromising the occupant’s satisfaction. The research aims to address the gap in data related to assessing occupant’s satisfaction in relation to glazing deflection, with the overarching goal of achieving material efficiency.

1.6 Research Proposal

Hypothesis

The absence of a clear threshold for human acceptance of glass deflections has led to the determination of glazing thickness under the assumption that humans possess a low tolerance for such deflections. This tendency contributes to the use of thicker glass than strictly necessary. The challenge is achieving a balance between high-performance glazing and reduced thickness without compromising occupant's satisfaction. Therefore, it is hypothesized that addressing the gap in data related to assessing occupant's perception and acceptance concerning glazing deflection will provide valuable insights into optimizing material efficiency without sacrificing occupants' satisfaction.

Research Question and Sub – Question

Main research question:

To what extent can we relax the serviceability limit on IGU deflection without being detrimental to the facade performance?

Sub Questions:

1. What is the serviceability limit in practice?
2. What are the factors affecting occupant's perception and acceptance of glazing deflection?
3. What is the threshold of occupant's acceptance to IGU deflection?
4. What are the implications of the experimental results on the embodied carbon of glazing and the design practice?

Research Objective

The objective of the research is to empirically determine the Occupant's acceptance threshold for glazing deflection. Once the threshold is experimentally determined, the research aims to explore the embodied carbon and design implications of relaxing glazing serviceability limit, comparing the current serviceability limit with the newly identified limit.

Methodology and Research Approach

The thesis aims to assess current serviceability limit, correlate occupant perception and acceptance to glazing deflection and determine the potential thickness and embodied carbon reduction that can result from identifying occupants' acceptance threshold. The methodology of the thesis includes the following step.

1. Literature review
2. Experimental setup design
3. Structural analysis

1. **Literature review:** the research relies on literature review to identify the serviceability limit in practice. For this, codes pertaining to glazing have been reviewed. Furthermore, a reflection on previous data gathered from an industry survey on the topic of serviceability in glass will give the research a benchmark on what to improve on. In order to identify the factors affecting the perception of deflection, previous studies on structural movement and human perception have been studied. Although there is no specific literature related to glazing deflection and occupant's satisfaction, the study has given indications on factors to consider while performing the experiment.
2. **Experimental setup: Correlating IGU deflection with occupants' perception and acceptance:** the experimental setup used an electro-pneumatic system to introduce pressure inside the IGU. The system uses a compressor to provide the necessary pressure resulting on a glazing deflection beyond the current serviceability limit. Prior to including participants, the center of glass deflection is calibrated with pressure inside the cavity. By performing this, the research aimed to decrease interference of deflection measurement during the experiment with participants. For safety measures, a transparent blast protection film has been applied on both surfaces of the IGU to prevent the glazing from shattering into pieces in case of failure of the glass. The pressure build-up inside the IGU is measured using a pressure transducer. For an additional safety measure, the experiment was set up in such a way that the pneumatic system will shut off if the pressure build-up inside goes beyond the predicted capability of the IGU.

   The IGU was mounted on the light van which was parked at North entry of the Faculty of Architecture. The light van had an office set up inside and during the experiment the participants were asked to fill in a survey to assess their perception and acceptance of deflection. Alongside the survey, an objective measurement of the participants facial expression was assessed with the help of a camera setup to analysis facial action units and gaze. The privacy of the volunteer has been maintained as per standards recommended by TU Delft.

   The results from the experiment were analyzed and used to answer the question of "What is the perception and acceptance of participants to different level of IGU deflection?"

3. **Structural analysis: Identifying the design load, setting up the finite element model and solving for the thickness of the glass:** the workflow starts by defining design load, the load is determined by considering the historical fluctuations of wind load readings in the Netherlands. Then a numerical simulation is set up. For the finite element model of the insulating glass unit, ANSYS and later in SJ Mepla was used. Accurately modeling and simulating IGU in ANSYS is quite complex but comes in handy for a quick and simplified check using a single solid pane with a uniform pressure applied on it. The method used in SJ Mepla can perform a nonlinear analysis with load sharing of panes of glass considered. SJ Mepla is convenient as it can be applied to various Insulated Glass Unit (IGU) constructions, encompassing different glass pane shapes, loading conditions, boundary conditions, and other assumptions. Additionally, the model incorporates the interaction of the panes, and the nonlinear analysis automatically accounts for the impact of geometric nonlinearity (von Kármán strains) on internal pressure generation. After the model is setup, the minimum thickness required to meet the set defection limit is checked. Finally, weight reduction from relaxing the current serviceability limit is checked for.

2

Literature review

2 Literature Review

2.1 Serviceability Limit in Practice

Every building or structure must comply with both ultimate limit states and serviceability limit states. Ultimate limit states ensure that each member is designed to handle the specified loads, preventing issues like buckling, yielding, instability, and fracture. On the other hand, serviceability limit states define the functional performance and behavior of the structure under load. These states encompass considerations such as deflection, vibration, and corrosion, addressing the service requirements of a structure or its elements under applied loads.

The significance of serviceability limit states has become progressively more important. With a heightened focus on serviceability, structural designers are now dealing with a more intricate task of designing for both deflection and strength. This necessitates the resolution of an interdisciplinary problem. The serviceability of a building structure directly impacts the satisfaction of its occupants. Addressing occupant's satisfaction concerning structural deflection requires collaboration among professionals from various fields, including psychologists, bioengineers, and medical professionals. Thus, professionals with diverse backgrounds, such as structural engineers and psychologists, must establish a common ground for communication to approach the problem rationally. This entails mastering and understanding new vocabulary in each field (Galambos et al., 1973).

Serviceability limit states, typically non-catastrophic, define the quality level expected from a structure or element. Their application involves subjective judgment and depends on the perceptions and expectations of the owner or user. Serviceability limit states are part of the contractual agreement between the owner or user, the designer and builder. Due to the subjective nature of the benefits and the challenges in defining or quantifying them, serviceability limit states often remain ambiguous. They can be classified into three categories, as outlined by (Griffis, 2003):

Deformation (deflection, curvature, drift)- Examples often involve harm to nonstructural elements (such as ceilings, cladding, partitions) due to deflections under dead, live, wind, or seismic loads, as well as damage from temperature changes, moisture, shrinkage, or creep.

Motion perception (vibration, acceleration)- Common examples include human discomfort caused by wind or machinery, especially if resonance occurs. Floor vibrations from people or machinery and acceleration in tall buildings under wind load are usual areas of concern in this category.

Deterioration-This category encompasses issues such as corrosion, weathering, efflorescence, discoloration, rotting, and fatigue.

Serviceability Limit of Glazing

Similar to other building components, ensuring the ongoing performance and resistance to potential actions is fundamental when considering the serviceability of glazing. Therefore, the serviceability criteria pertain to the predetermined performance expectations of glazing. The deflection limits would be those that, if exceeded, result in the failure to uphold the anticipated performance requirements of the glazing.

A recent study by (Oke, 2023) identifies serviceability criteria as including mechanical performance, durability, optical performance, thermal performance, acoustic performance, and occupant satisfaction.

Prior studies have extensively covered most of the criteria, particularly delving into the mechanical behavior as evidenced by research conducted by (Datsiou and Overend, 2016) and (Quaglini et al., 2020). To evaluate the impact of reduced glass thickness on durability, existing literature, including works by (Bedon and Amadio, 2020), (Besserud et al. 2012), (Gubbels et al. 2014), and (Respondek, 2018), offers comprehensive insights through reliable numerical, analytical, and experimental assessment methods. (Respondek, 2018) has specifically examined the influence of reduced glass thickness on thermal performance. In the context of optical performance, papers addressing cold bending distortion, such as those by (Datsiou and Overend, 2016) and (Quaglini et al., 2020), consider the limit outlined in EN 12150-1:2000 as an acceptable threshold. However, the acceptability of these limits based on occupant's perception of distortions needs evaluation to establish effective standards. It is noteworthy that there is a lack of specific literature addressing acoustics and occupant satisfaction concerning serviceability limits.

The existing literature lacks a specific focus on occupant satisfaction as a criterion for evaluating glazing serviceability. Frequently, acceptance is often recognized as a criterion for determining serviceability limit related to deflections and vibrations in structural components. Although building codes frequently set limits on deflections, the research basis for these limits is often not well defined. Consequently, there exists a research gap regarding the quantification of occupant satisfaction and the development of corresponding assessment methods. It is imperative to precisely define occupant satisfaction as a criterion for serviceability in order to address this gap.

The draft guidelines for structural glass design FprCEN/TS 19100-2 provides different serviceability limit for different deformation classes. The one relevant to this research is the deformation class 2 pertaining to IGU and deflection limit at the center is set at L/50. L being the length of the short side.

Outside Europe, various national standards establish their own limits for glass deflection (ASTM International, 2016; Buildings Department Hong Kong, 2018). A façade industry survey conducted as part of this research indicates that the deflection limits followed vary not only by country but also by project type and the specific application of the glass.

The research conducted by Buildings Department Hong Kong (2018) offers straightforward standards for deflection limits applicable to glass panes. These standards are contingent upon factors such as spans, loading conditions, and support conditions, relying on expressions outlined in Table 1. In the case of glass panes simply supported on 3 or 4 sides, this code permits slightly lower levels of deflections compared to the limits stipulated in FprCEN/TS 19100-2, although the magnitudes are of a similar order. Notably, this code does not specify distinct limits for Insulated Glass Units (IGUs). Similarly, AS 1288(Australian standard) does not contain a deflection limit for IGU's but it does contain a guidance limit of 20mm deflection. The assumption larger deflections of more than 20mm may become visually disturbing to any observer has led the companies like AGG (Australian glass group) to suggest deflection limit of IGU at span/90.

Table 1: 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 loaded span
Cantilever	1/30 of the span
Point supported	1/60 of the longer span between supports

Limits and Standards Followed in Practice

The research conducted by (Oke, 2023) has put out a survey to check the current serviceability limit practiced in the industry. The following is a summary of the response received. The specified limits for deflection vary depending on project locations and the standards adopted. The commonly used limit, particularly in UK but also in other European countries and USA, is L/65 or its equivalent in millimeters, ranging from 25mm to 50mm. The French standard NF DTU 39 sets a limit of L/60 or 30mm, whichever is less. Some responses indicate even lower limits, such as L/180, with an exception of L/1000 specifically mentioned for glazing with high optical performance requirements. L represents the longer span of the IGU.

2.2 Human Comfort and Structural Movement

A seldom explored facet of human reactions to the deflection and vibration of structures is the fear associated with the possibility of collapse when motion is perceived. There is a common belief that structures are inherently rigid, and any visible or perceptible deformation is interpreted as a sign of potential failure or, at the very least, an unsafe condition. This psychological aspect contributes to varying levels of fear or discomfort, amplifying the physiological effects of motion. Recognition of static deflection relies on visual cues, such as a sagging ceiling, cracked plaster, or walls. A negative response incurs if the deflection is visually perceptible (Galambos et al., 1973).

Although research studying the factors affecting perception of deflection in IGU is missing, there are studies exploring the factors affecting perception and tolerance of building motion. The perception and tolerance thresholds of acceleration, used as a measure of building motion, are dependent on several factors outlined below. These factors have been identified through motion simulators designed to replicate the behavior of buildings exposed to wind loads (Heshmati et al., 2020).

1. Frequency or Period of Building: Field tests indicate that perception and tolerance to acceleration generally increase as the building period increases (frequency decreases) within the range of frequencies commonly observed in tall buildings.
2. Sex: While the overall trend of response is similar for men and women, women tend to be slightly more sensitive than men to motion-related stimuli.
3. Age: Sensitivity to motion inversely correlates with age, with children exhibiting higher sensitivity compared to adults.

4. Body Posture: Human sensitivity to motion is proportionate to the distance of a person's head from the floor. The higher the position of the head, the greater the sensitivity. However, the freedom of head movement is also a factor, with a person sitting in a chair potentially being more sensitive than a standing person due to contact with the chair.
5. Body Orientation: Humans generally exhibit higher sensitivity to fore-and-aft motion compared to side-to-side motion, attributed to the free movement of the head in the fore and-aft direction.
6. Expectancy of Motion: Perception thresholds decrease when individuals have prior knowledge of impending motion. The threshold acceleration is approximately twice as high when there is no prior knowledge.
7. Body Movement: Perception thresholds are higher for walking individuals than for those standing, especially when the walking subject is aware of the impending motion. The difference in perception thresholds between walking and standing is more than twice as much when there is prior knowledge, but only slightly greater when there is no prior knowledge.
8. Visual Cues: Visual cues significantly contribute to confirming a person's perception of motion. The eyes can detect the motion of objects within a building, such as hanging lights, blinds, and furniture. Additionally, individuals are highly sensitive to the rotation of the building relative to fixed landmarks outside.
9. Acoustic Cues: Sounds generated by buildings due to swaying, contact surfaces in frame joints, cladding, partitions, and other elements, as well as external sounds like wind, play a crucial role in directing attention to building motion. These cues can lower the perception threshold even before individuals consciously perceive the motion.
10. Type of Motion: Occupants in tall buildings, under the influence of dynamic wind loads, may experience translational acceleration in the x and y directions and torsional acceleration due to building oscillation along-wind, across-wind, and torsional directions, respectively.

The findings above can be used as a basis to draft factors that can influence the perception of IGU deflection and later be proven experimentally. From the lists above, visual cues, acoustic cues, expectation of motion, body movement (i.e., activity), and age can be extrapolated. The remaining factors, such as the type of motion, are specific to the study of building motion.

2.3 Experimental Approach to Determining the Deflection Limit

Experimental approach to relate glass deflection with occupants' perception.

In the past different experimental setups on IGU were used to study deflections. The studies were focused on validating analytical and numerical models. The study conducted by (Hart et al., 2012) investigated the deflection in IGUs under operating conditions in various locations in the USA using laser devices. Peskova et al., (2017) measured a window model's heat flow and deflection in a climatic chamber. McMahon et al. (2018) investigated the load sharing in IGUs triple glazing by controlled pressure change on both sides of the sample. Buddenberg et al. (2016) measured pressure changes in gaps by subjecting IGU samples to cyclic temperature changes in a climatic chamber. In the article Striatiy (2017) used artificially induced over-pressure in the gap to simulate the climatic load and measured the deflection in the IGU mounted in a window frame. In his research article, Respondek (2019) describes a similar concept in more detail. It has been suggested that natural variations in atmospheric pressure or temperature can be replicated using an equivalent load generated by a specified alteration in gas pressure within the gap. In this manner, the desired pressure differential in the gap can be attained by introducing or extracting a specific mass of gas into or from the gap. Similar article demonstrates that the simulation of substantial loads can be achieved with the addition or removal of a small mass of gas in the gap. The objective of the study was to develop a test platform that enables the measurement of IGU model deflection under controlled and systematically generated climatic load variations allowing for precise adjustments over time. The stand is built from a massive main frame, which is the basis for the placement of deflection sensors, and is accompanied by a supporting frame, that allows placing glass panes with different thicknesses. The tested model of IGU is equipped with threaded elements, which makes it possible to regulate the gas pressure inside the gap and monitor its temperature. The test setup is illustrated on figure 3 below.

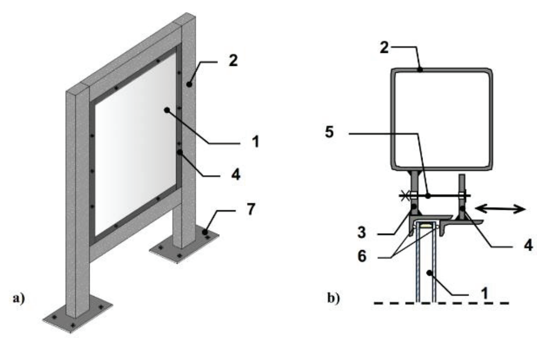


Fig 3

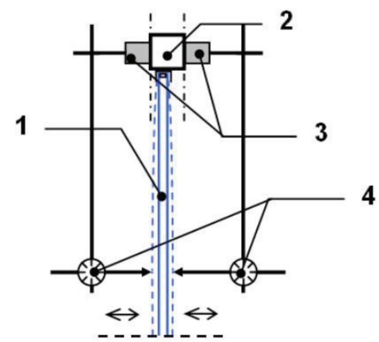


Fig 4

Figure 3: Stand for testing deflections in an IGU: a) view, b) detail of the model's support 1 – IGU model, 2 – main frame, 3 – fixed part of supporting frame, 4 – movable part of supporting frame, 5 – bolt, 6 – supporting rods, 7 – gusset plate.

Figure 4: Scheme of deflection measurement 1 – IGU model, 2 – main frame, 3 – magnetic base, 4 – dial gauge.

To measure the deflection of component glass panes, dial gauges in Figure 4 or laser devices are used. The simulation of changes in weather conditions will occur by changing the mass of gas in the gap, which forces changes in its pressure. By forcing pressure change in one of the gaps of the multi-glazed IGU, it is possible to simulate the pressure and suction of the wind. (Respondek, 2019)

Recently, a methodology has been developed to assess occupant's satisfaction to deflection (oke, 2023). The proposed methodology involves conducting an experiment within the Light van, a mobile laboratory situated at TU Delft. The Light van offers the flexibility to mount and demount different glazing panes for testing and facilitates the creation of an office-like setup. This controlled environment simulates an office space where participants engage in specific tasks for a defined duration. To comprehensively assess the impact of deformation, the research advocates for objective measurements, including alterations in optical performance, lighting conditions, and facial expression mapping.

Facial expressions of participants can be systematically recorded using a facial action unit positioned in front of the volunteer. Concurrently, subjective data on human responses can be gathered through a questionnaire administered at specific stages of the experiment. Deformations and vibrations in the glazing are induced through a pneumatic system. This system utilizes pneumatic pressure to generate a double curvature, as outlined in (Oke, 2023). Instant variation in displacement is achieved by controlling the input and output pressure within the sealed cavity. Additionally, dynamic variations in air pressure within the hermetically sealed cavity can be realized through electronically controlled pneumatic valves to enable a nuanced exploration of glazing behavior.

To carry out the experiment involving volunteers, the study recommends utilizing the Light van, a versatile mobile laboratory housed within a delivery vehicle. Constructed in 2014 through a collaborative effort between the Faculty of Architecture at TU Delft and the Department of Built Environment at TU Eindhoven, the Light van was primarily designed for experiments related to daylighting in specific environments (Hordijk et al., 2014). The van's mobility allows for adjustments in orientation to align with the desired light direction and views.

The rear section of the van features a demountable frame with a window, providing a space to install façade panes for testing as shown in Figure 6. The Light van is deemed suitable for this experiment due to its spacious interior, capable of accommodating a one-person office setup (Figure 5). Additionally, it is well-equipped with electrical supply, lighting, and furniture. The dimensions of the façade panes provided by AGC for the experiment (1467mm x 972mm) align with the available size of the opening in the Light van.

Figure 5: interior of the LightVan (Source: Hordijk et al., 2014)

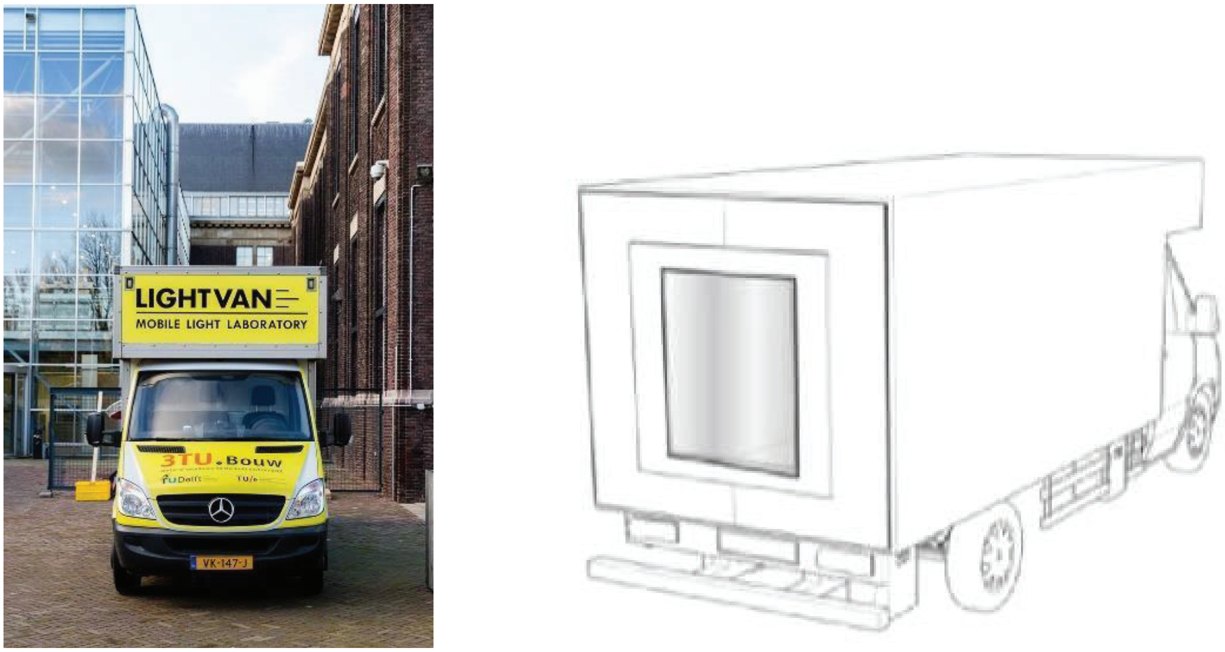


Figure 6: Exterior of the LightVan . Right side image shows the rear view of the van where the testing IGU is set on (Source: Hordijk et al., 2014)

2.3.2 Pneumatic system proposed

The research suggests the use of an air compressor to produce the necessary pressure inside the IGU. The pressure is controlled by a solenoid valve. Solenoid valves are commonly used to translate electronic signals into mechanical movement. An Arduino Uno is used in the experiment to communicate signals to the solenoid valve. The pressure reading inside the IGU is taken using a pressure transducer. The Arduino is also connected to a distance measurement device to correlate 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 research however suggests the use of laser device to obtain measurement. Figure 7 illustrates the full circuit proposed by (Oke, 2023). Regarding safety, the research suggests two approaches, using a safety film and introducing a system shutoff based on a calculated maximum or minimum permissible pressure.

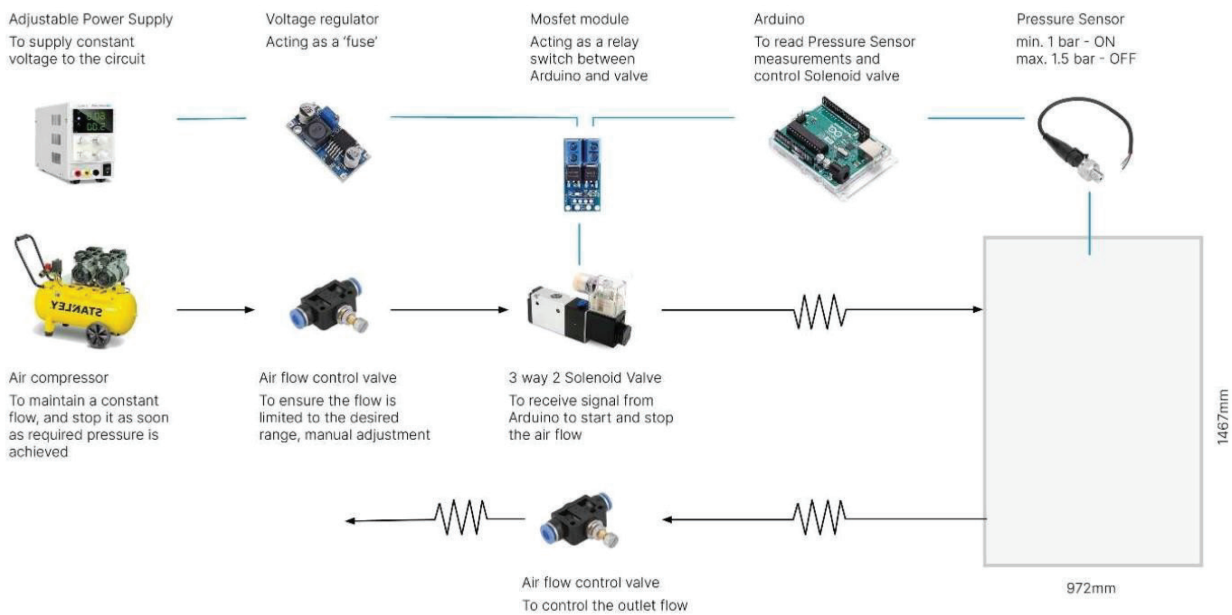


Figure 7: A schematic for the proposed pneumatic system (Source: Sagar Oke, 2023)

2.4 Determining thickness reduction based on deflection limit

Deflection of glass pane

Code of practice for Structural Use of Glass (2018) notes that deflection of a glass pane can be determined by following a simplified equations for rectangular glass panes or be computed by the finite element method allowing for large deflection effects where appropriate. Since this research is concerned with deflections greater than the current serviceability limit, finite element method is suitable to relate glass thickness with the deflection limit. To optimize for glazing thickness based on deflection limits using a finite element requires: a load input, the finite element model and the output can then be optimized for a certain goal. Figure 8 shows a schematic diagram of how to optimize thickness of a glass based on a set criterion like the deflection limit. The optimization scheme is a simplified adaptation of the proposed approach to study the influence of the design constraints on the thickness optimization of glass panes (Janne et al., 2023).

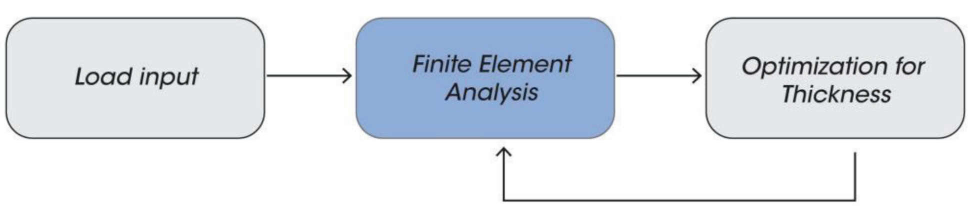


Figure 8: A simplified scheme of determining optimum thickness of glass

Final element model

The approach followed by Janne (2023) for the finite element model and analysis of insulating glass aligns with the procedure outlined in (Heiskari et al., 2022). The utilization of ANSYS Mechanical APDL is recommended according to (Janne et al., 2023). The finite element method is convenient due to its versatility, allowing application across various insulating glass unit (IGU) constructions. This includes different glass pane shapes, loading conditions, boundary conditions, and other assumptions.

Moreover, the model incorporates the interaction of the panes, and the nonlinear analysis which considers the impact of geometric nonlinearity (von Kármán strains) on the generation of internal pressure. This approach differs from methods where internal pressure is initially solved using a linear analytical method, and the response of the pane is addressed with a nonlinear finite element method separately. The latter method tends to underestimate the internal pressure of IGUs experiencing substantial deflections. Consequently, the former method is favored for its comprehensive consideration of these factors.

In Janne's (2023) research, the finite element model for the insulating glass unit comprises glass panes and a hermetically sealed cavity with spacers. Although the spacers play a role in creating the insulating cavity volume, they are not structurally accounted for in the analysis. Ideally, considering them would provide stiffness to the structure (Romanoff J, 2014). However, the research adopts a conservative and practical approach by neglecting this additional stiffness.

The air or gas within the cavity follows the ideal gas law (pv=nRT). The research (Janne, 2003) conducts a nonlinear static structural analysis using the Newton–Raphson procedure. The outer glass pane, also known as the exposed glass pane, undergoes uniformly distributed pressure (p). The edges of the four insulating glass unit (IGU) edges (8 glass panes edges) are constrained to allow only translation normal to the glass panes, permitting in-plane movement and free rotation. However, the central nodes of both panes are fixed in-plane to prevent rigid body motion, providing a realistic and conservative approach that aligns well with experimental results from (McMahon et al., 2018). It is important to note that this approach is conservative in terms of deflections. If the rotations of the edges were fixed, significant normal stresses would be generated on the top surface of the glass panes near the edges. However, assuming fixed rotations is unrealistic for bonded IGUs that are not clamped. Such a condition would also hinder the generation of deflection, leading to substantial disagreement with experimental results.

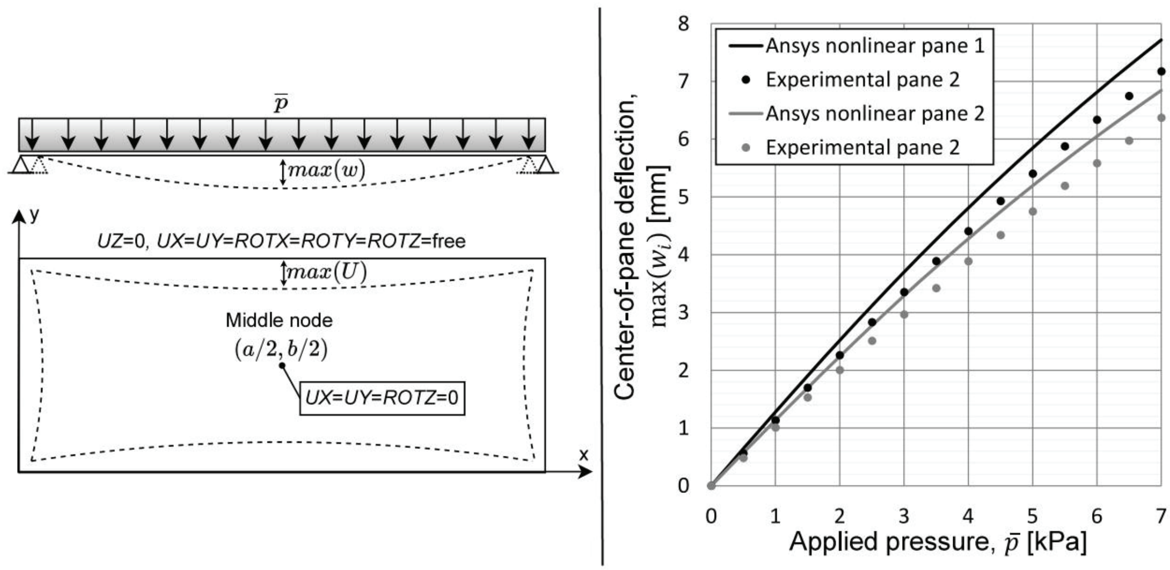


Figure 9: Boundary condition and the corresponding deformed shape (exaggerated) for a rectangular shape on the left-hand side. Maximum deflection, max(w), and maximum in-plane translation of the edge, max(u), are as presented. The edge conditions are equal for both panes. Central nodes of both panes are constrained for preventing rigid-body motion. On the right-hand side is center-of-pane deflection versus applied pressure for both panes of a rectangular IGU (a= 1260 mm, b = 750 mm, t1=t2=5.7 mm, s= 13 mm), a comparison between finite element results [12] and experimental results by McMahon et al. [9]. (Source: Janne et al., 2023)

The boundary conditions and comparison of the numerical results with the experimental results from the suggested finite element model in (Janne et al., 2023) is shown fig 9. The model suggested has deflection results in close proximity to the experimentally measured results by McMahon. Hence, the method can be adapted for further studies.

Optimization for IGU glass thickness

A recent paper utilizes the particle swarm optimization (PSO) method to determine the optimal thickness of Insulating Glass Units (IGU) for ships under various design constraints. In computational science, PSO (Mohammad et al., 2017) is a method that iteratively enhances a candidate solution concerning a given measure of quality. It operates with a population of candidate solutions, referred to as particles, and moves them in the search-space using simple mathematical formulas governing each particle's position and velocity.

The research investigates the impact of design constraints on the thickness optimization of glass panes. The glass variables considered were thickness (t1 and t2), the size of the glass unit (keeping the Aspect Ratio constant) and shape (triangular, circular, square, and rectangle) (Janne et al., 2023). Criteria that needed to be satisfied included maximum principal stress, deflection, in-plane movement of edges (with a strict limiting value of 2 mm to prevent water-tightness loss due to slipping from the mounting frame) and thickness ratio.

A PSO routine is implemented in a MATLAB script, executing Finite Element (FE) analyses (Figure. 10). The thicknesses of both panes vary while keeping the IGU shape and size constant. Once the optimum is found for a particular case, the size is increased, and the shape is changed iteratively until all cases are optimized.

The weight of each optimized IGU is calculated, and a weight against area comparison is presented to identify the shape with the largest area and least weight. To understand why a specific shape performs better, a comparison of the activation of design criteria is conducted to reveal which criteria limits the thickness. Finally, the optimized thicknesses are compared to the classification rules of suggested IGU design methods in ships.

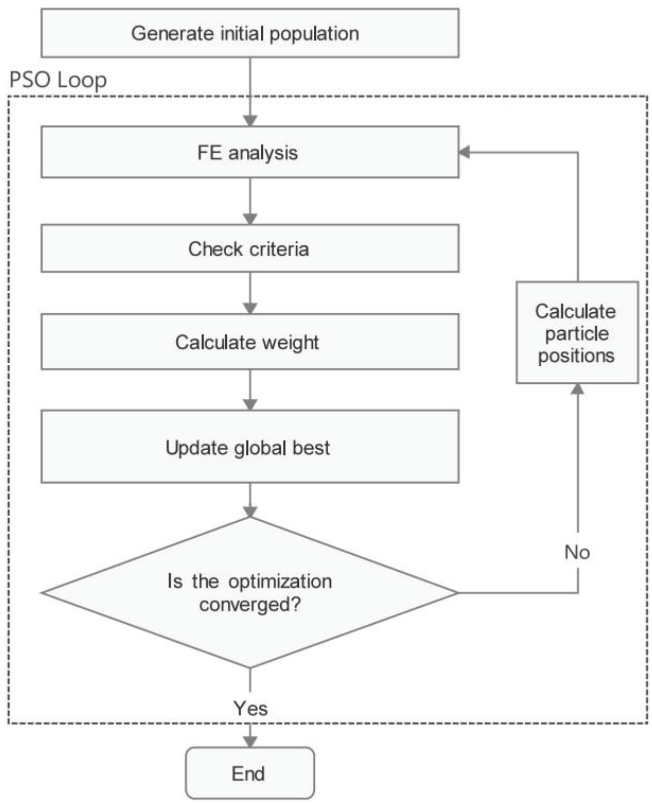


Figure 10: flowchart of optimization routine used in (Source: Janne et al., 2023)

In the building industry circular and triangular glass shapes aren't particularly common. Aspect ratio on the other hand can be a variable that can be considered as different aspect ratios with the same area coverage have different deflection response to the same design load. Figure 11 illustrates the effect of aspect ratio 1 and 4 on the maximum principal stress developed in the glass pane given a design load (Buddenberg et al., 2016). From this it can be deducted that the maximum principal stress is dependent on the aspect ratio and affects the minimum thickness in an IGU setup. Hence, the methodology used in the research to optimize IGU thickness in ships can be adapted to include aspect ratio as a variable to find an optimum thickness of the IGU pane thickness 1 and 2 given the deflection limit that is to be found from the experimental analysis setup in chapter 2.3. Aspect ratios that have a wider representation of the IGUs and that were able to provide good weight savings are 1.25 and 1.67 (DNV, rules for classification: Ships, 2022). The goal of this optimization is to determine the minimum weight for maximum area coverage and to compare the weight implications of the current industry serviceability limit with the proposed new serviceability limit.

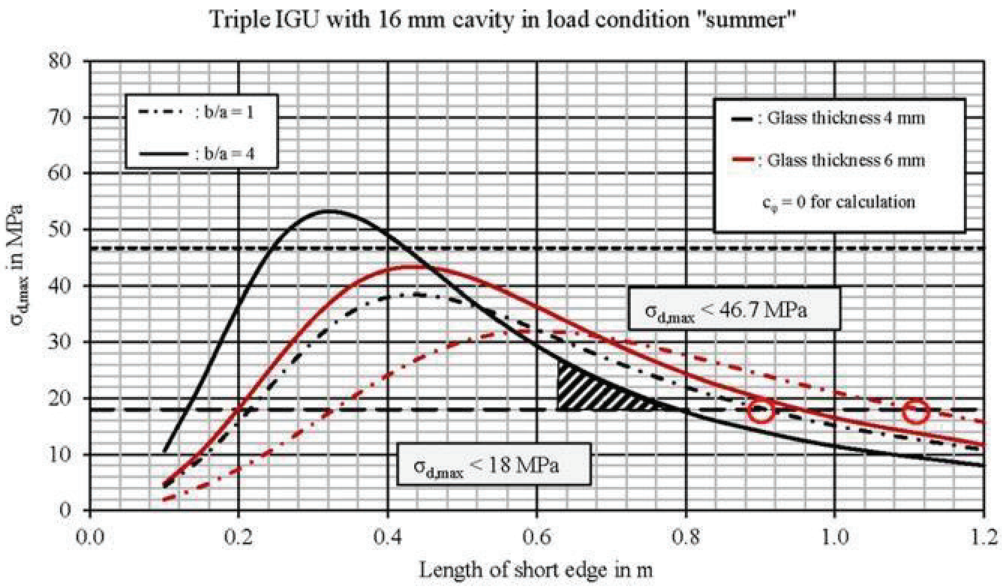


Figure 11: Design stresses of the glass panes for symmetric IGU in vertical application in load condition "summer" with 4 mm glass thickness (with a length short edge and b length long edge) (Source: Buddenberg, Stephan & Hof, Peter & Oechsner, M., 2016. Climate loads in insulating glass units: comparison of theory and experimental results.)

Design constraints used in optimization process

For a reasonable thickness optimization of the glass panes of an IGU, certain design constraints in addition to the center of glass deflection limit have to be set. These design constraints pertain to principal stress limit based on the ULS, production limits and water tightness. The lower limit for the pane thickness is chosen based on the available glass production unit. Companies like AGC, a glass manufacturer, can now provide thin glass (Falcon) in sizes equivalent to float glass, with a thickness ranging from 0.5 mm to 2.0 mm. The upper thickness limit is varied depending on the size of the glass pane and the applied load so that the optimization search domain is reasonable. It should be noted that continuous thickness values can be used in the optimization, while in reality there are only certain standard thicknesses available. The thickness ratio is chosen so that the outer plane must be always larger than the inner plane but can be only 3 times larger. The reason for is to have reasonable constructions.

Furthermore, it is intuitive decision for an IGU consisting of monolithic glass panes that the exposed pane is thicker than the unexposed pane. Finally, choosing the deflection limits is not a trivial task, as the optimized thicknesses are sensitive to it (Heiskari J et al., 2022). The deflection limit to be set is determined from the current serviceability limit study in chapter 2.1 and the experimentally assessed limit from 2.3. Since slipping of the pane from the mounting frame means loss of water tightness, a strict limiting value of the in-plane translation of the edges of as 2 mm is suggested (Janne et al., 2023).

Determining climatic loads: Analytical vs numerical vs experimental climatic loads

Traditional analytical calculation methods often overlook the deformation of the edge seal. For analytical determinations in such cases, the solution of the linear plate theory following Kirchhoff, specifically for rectangular, planar plates with immovable support, is frequently employed. Building upon this, Feldmeier (1999) devised an approach to address the design of the volume created beneath a plate due to area load.

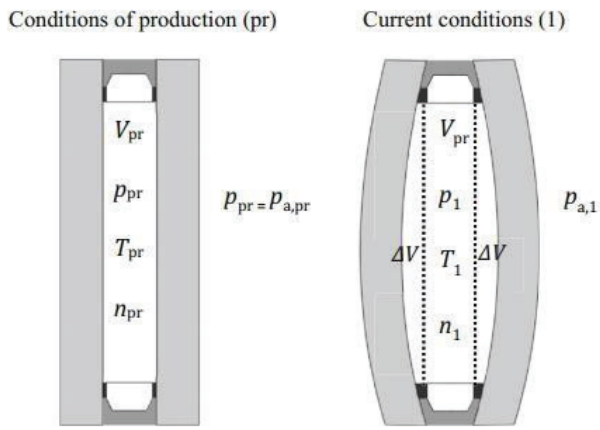


Figure 12: Deformations due to changes of temperature, atmospheric pressure and amount of substance compared to the conditions of production (Source: Buddenberg et al., 2016)

The linear plate theory according to Kirchhoff simplifies the assumption that plates deform in a geometrically linear manner. In reality, membrane action influences the bending, leading to plates exhibiting a more rigid behavior than predicted by Kirchhoff's linear plate theory. Consequently, climate loads are underestimated using this approach.

Moreover, Kirchhoff's plate theory does not account for the deformation of plates caused by shear forces. Both effects can be more accurately estimated by employing the finite element method and selecting appropriate elements for analysis.

Table 2 displays the disparities between analytically determined climate loads and stresses based on plate theory according to Kirchhoff, using the calculation method outlined in (DIN 18008-2, 2010), and finite element (FE) calculations. The climate loads were computed with "winter" load conditions from (DIN 18008-1, 2010), considering temperature and atmospheric pressure. The FE model was created in ANSYS 16.0, utilizing a Shell181 element for modeling the glass plate and an HSFLD241 element for modeling the gas volume, incorporating symmetries with fixed support on the edges of the glass plate. The analysis employed a geometrically nonlinear calculation method (Buddenberg et al., 2016).

Table 2: Comparison of climate loads and stresses based on Kirchhoff's plate theory with results of an FE model in consideration of the influence of geometrical nonlinearity and shear flexible plate for symmetric IGU for the load condition "winter" in accordance with (Source: DIN 18008-1, 2010)

Dimension (mm2)	Glass thickness (mm)	Cavity (mm)	ΔPK/ΔPFE (%)	Max stress, K/max stress, FE (%)
350x500	3	1x12	97	99.0
350x500	4	2x12	98.6	99.9
350x500	12	2x12	100	98.2

The stresses calculated analytically and numerically for glass panes of 3 and 4-mm thicknesses show minimal variation. Only in the case of very thick 12 mm glass panes a slightly higher difference of 1.8% is noticeable. In practical design considerations, these small differences are deemed negligible, justifying their disregard in practice. However, the climate load is already underestimated by 3% when considering a glass thickness of 3 mm.

For commonly used glass products in insulating glass units—namely, float glass, heat strengthened glass, and toughened glass—the following results are applicable under the condition of line support at all four edges of the construction during climate load: a bearing capacity of Rd = 18 MPa for float glass, Rd = 46.7 MPa for heat-strengthened glass, and Rd = 80 MPa for toughened glass (DIN 18008-1, 2010; DIN 18008-2, 2010; EN 572-, 2012; EN 1863-1, 2012; EN 12150-1, 2015).

The assumed loads for calculating climate loads, according to DIN 18008-1 (2010), are detailed in Table 3, while input values for production are presented in Table 4. Extreme pressure differences between the surrounding atmosphere and the space between the panes occur during "winter" (low temperatures and high-pressure conditions) and "summer" (high temperatures and low-pressure conditions). Table 2 provides control values for temperature differences and changes in atmospheric pressure, as well as information on the actual value of local height differences. For conditions differing from the standard case, the local altitude differences ΔH are considered. If the actual local altitude difference is greater than or demonstrably smaller than assumed in Table 3, adjustments should be made accordingly (DIN 18008-1, 2010).

Table 3: Combination of actions in accordance with (Source: DIN 18008-1, 2010)

Combination of actions	Temperature difference(K)	Change in atmospheric pressure (KN/m2)	Location height difference(m)
" Summer"	+20	-2.0	+600
"Winter"	-25	+4.0	-300

Table 4: Production conditions for the load conditions summer and winter in accordance with (Source: DIN 18008-1, 2010)

Combination of actions	Atmospheric pressure (hPa)	Temperature (degree Celsius)
" Summer"	1030	+19
"Winter"	990	+27

Buddenberg subjected specimens of insulating glass units to a climate test procedure based on EN 1279-2 (2003) with 56 cycles at −18 to +53 ◦C, in which each cycle took 12 h to be able to evaluate the mechanical behaviors of the edge seal under climate load and compare "actual" arising climate load with computational climate load.

By means of measurement of the atmospheric pressure and the pressure in the cavity during the test, the resulting pressure difference and thereby the climate load on the specimens during the testing were determined. To carry out a comparison between a conventional analytical determination of climate loads and actual arising climate loads, in Figure 13 and 14 the percentage differences are shown between analytically determined climate load considering the plate theory according to Kirchhoff and the experimentally determined climate loads. The following Illustration is the results of three specimens whose qualitative courses reflect the behaviors of all tested specimens in a representative fashion.

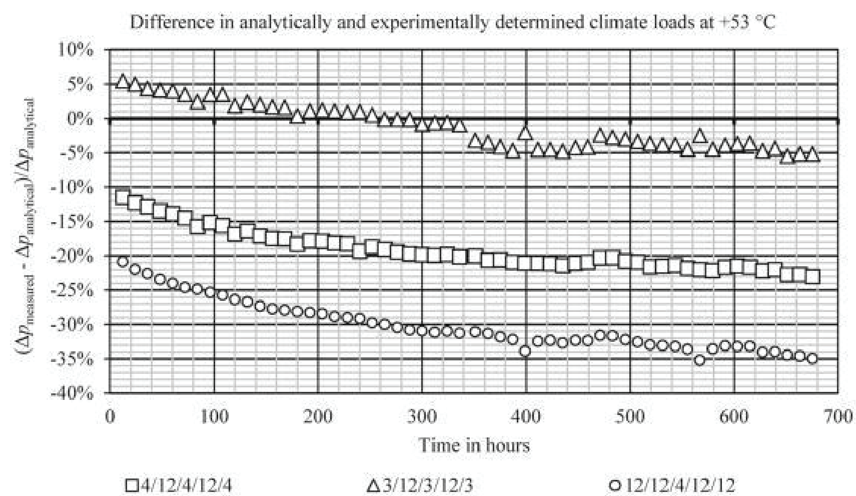


Figure 13: Symmetric IGU with 12 mm cavity and dimensions of 350 mm × 500 mm during cycling with difference in calculated and experimentally determined climate loads at +53 ◦C in percentage (Source: Buddenberg et al., 2016)

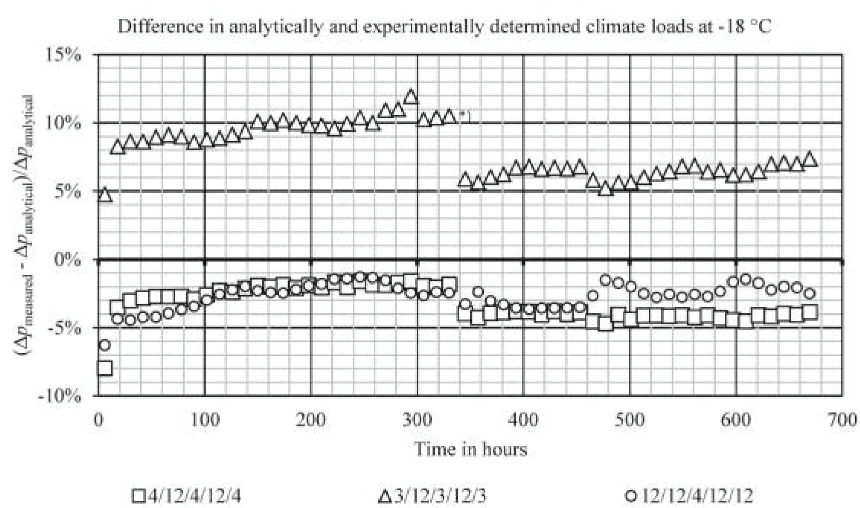


Figure: 14 Symmetric IGU with 12 mm cavity and dimensions of 350 mm × 500 mm during cycling with difference in calculated and experimental determined climate loads at −18 ◦C in percentage. (Asterisk) After 28 cycles, the test *was interrupted. Note that for specimens with 3 mm glass panes the climate load is relatively low with about 20 hPa so small absolute changes cause greater changes in percentage (Source: Buddenberg et al., 2016)*

The presented data in fig 13 and 14 illustrates the percentage differences between analytically and experimentally determined climate loads during the respective one-hour hold times at +53 and −18 °C for climate cycling.

Analytical climate load calculations utilized initial production data (temperature and air pressure) and geometric measurements of the specimens. Positive values indicate higher actual climate loads than analytically calculated ones, while negative values signify lower actual climate loads. It is crucial to consider the omission of membrane action in the analytical calculation, explaining why specimens with relatively as thin as 3 mm glass panes yielded higher experimentally determined climate loads (approximately 3% higher due to membrane action). Additionally, inaccuracies arose from the scatter of input parameters, including air pressure, temperature, gas volume, and specimen geometry, resulting in a deviation of approximately ±2.5%.

For triple insulating glass units (IGUs) with thicker glass panes (4 and 12 mm), significantly lower climate loads were observed in the first load cycle at +53 and −18 °C, respectively. Lower experimental climate loads, compared to analytically calculated loads, are attributed to edge seal deformation. With load cycles, climate loads at −18 °C approached analytically calculated loads, while loads at +53 °C decreased due to edge seal softening in tension during cycling. The deformation of the edge seal played a significant role in the differences between analytically calculated and experimentally determined climate loads.

Buddenberg's comparison of experimentally determined and analytically calculated climate loads during cyclic temperature loading at -18 and +53 °C revealed that the actual climate loads at +53 °C were lower and decreased with load cycles. At -18 °C, the calculated and actual climate loads were nearly identical. The lower loads at +53 °C were attributed to the deformation of the edge seal during cyclic temperature loading, which became more flexible with increasing load cycles until stabilizing at a constant level.

When assuming a flexible edge seal in calculations results in lower glass stresses compared to assuming a rigid edge seal. However, in the "winter" load condition, where significant edge seal deformation is not expected based on experimental data, this flexibility is not crucial. Conversely, the "summer" load condition can be influenced if a temperature increase is assumed, particularly when the glass panes' heat absorption level exceeds 30%. (Buddenberg et al., 2016).

2.5 Conclusion

The purpose of the research is to provide an empirical assessment of the threshold of occupant's acceptance to deflection. To achieve this, the research started with assessing current serviceability limit in practice. This was done by code reviews and reflecting on previous data gathered from an industry survey on the topic of serviceability in glass. From this study the research has found that although serviceability limit vary from place to place and the intended purpose of the IGU, the survey done on the industry (Oke 2023) shows that has a predominant answer of L/65. L representing the wider span of the IGU. Nonetheless, as a point of reference, the research takes the limit of L/50 (L representing the short span) stated on the draft guidelines for structural glass design FprCEN/TS 19100-2 as it is the limit to be adopted in the near future.

To corelate glazing deflection with occupant comfort, the literature studied experimental setups used in studying deflection of IGUs and one in particular involved participants. The setup proposed by Oke (2023) uses a pneumatic system to mimic glazing deflection caused by climatic load. It suggested a subjective assessment using a survey design to answer the question of what the perception threshold is and whether information about the capability of glass deflection, without causing safety hazards, can alter this acceptance limit. Furthermore, the use of objective measurement such as checking vitals and eye movement of participants has been suggested in order to correlate with the subjective results. The expected output of the experiment is determining threshold of acceptance to glazing deflection and test factors affecting this perception i.e. knowledge of glass capability etc.

To determine the embodied carbon and design implications of experimental results. Literature review on optimizing glazing thickness based on design constraints was done. The intention is to determine the optimum thickness of IGU based on the newfound deflection limit and compare it with the serviceability limit in practice now. The review found that it is suggested to use a finite element model if deflections of higher amounts are to be considered. The finite element model can have load input and an optimization scheme can be performed to find the thickness of the glass. Climatic load and the pressure developed can be determined, analytically, numerically (a non-linear FEA) or experimentally. Research suggests that if a simplified model of inelastic sealant is considered (which is done for practical reasons of simplifying the FE model) in the finite element model, it shall be considered that eccentricities between the numerical model and experimentally measured values will occur. Especially when considering climatic loading during the summer as the edge seal is more elastic due to the heat gained.

The structural analysis detailed in this chapter has examined the differences between experimental and analytical loads due to climatic conditions. However, to limit the scope of this exploration, only wind loads are considered when comparing the current serviceability limit with the relaxed limit revealed in Section 5. Nonetheless, developing further analytical models to explore the effects of climatic loads could provide a more holistic insight into the impact of relaxing the current serviceability limit.

3

Experimental design

3 Experimental Design - Creating Cyclic Motion

3.1 Introduction

To understand how glazing systems behave under various loading conditions and to assess the impact of different levels of center of glass deflection (CGD), an experiment has been set up to mimic the behavior of glass under wind loading.

Glazing systems in buildings are subjected to atmospheric load and wind loads. Atmospheric load is primarily caused by gradual changes in temperature, leading to slow and static deflection in glazing. This type of load changes the relative pressure between the cavity inside an Insulated Glass Unit (IGU) and the atmospheric pressure. Factors such as changes in altitude from the glass manufacturing site to the installation location, or atmospheric pressure fluctuations due to temperature changes, contribute to this static deflection. Previous research has shown that this type of deflection could impact occupant comfort by distorting the reflections that appear in the glazing. High Dynamic Range Imaging (HDRI) studies revealed that while the pattern or view behind the glass shows negligible visible distortions to the naked eye, distortions are mostly perceived through reflections of ceiling lights (Sager Oke, 2023). This suggests that the glass does not behave as a lens upon pillowing when viewed from a normal angle to its plane. The second type of load in glazing is wind loading, which refers to the pressure exerted by wind forces on the surfaces of the glazing. This can cause dynamic and cyclic deflections. The cyclic nature of such loading can potentially heighten the perception of glass movement, as reflected images in the glass changes relatively faster when compared to atmospheric loading.

This chapter details the experimental setup and methodology used in the study focusing on simulating wind loading and evaluating its effects on CGD and individual perception. The setup aims to provide insights into how different deflection levels influence the perception and acceptance of building occupants and assess the potential for material savings by relaxing the current serviceability limit.

3.2 Wind Loading: behavior and duration

In contrast to loads caused by change in atmospheric pressure, wind loading induces cyclic deflections in glazing, creating either overpressure or under pressure conditions. Wind loading can cause dynamic and rapid changes in deflection, making it essential to understand its behavior and impact on glazing systems. Wind-induced deflections can have a potential effect on the visual quality performance of glazing as it can cause a fluctuating distortion of reflected images on glazing.

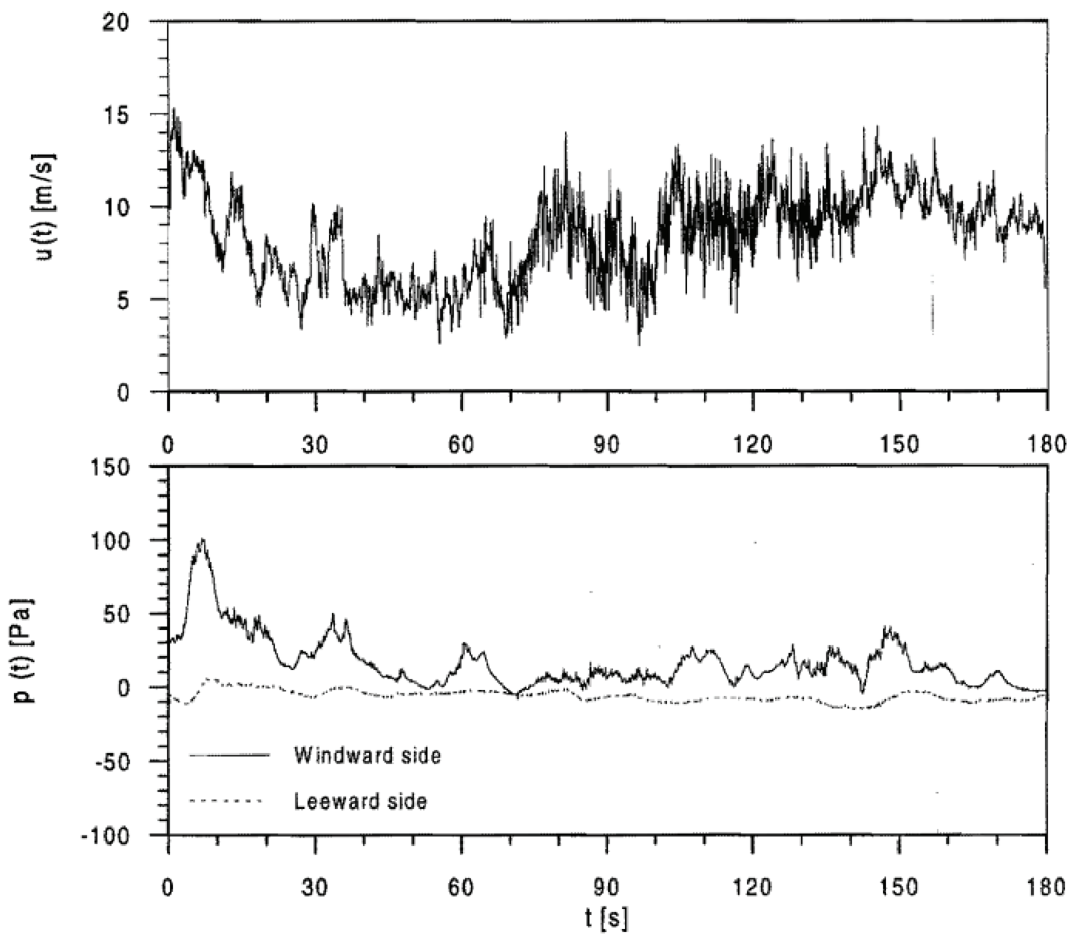


Figure 15: Simultaneous registration of wind velocity and wind-induced pressures in full scale on the main building of Eindhoven University of Technology. Source: Eindhoven Wind-induced pressure fluctuations on building facades. [Phd Thesis 1 (Source: Research TU/e/ Graduation TU/e), Built Environment]. Technische Universiteit Eindhoven. https://doi.org/10.6100/IR495154

Behavior of wind loads: Wind interacts with buildings in complex ways, influenced by factors such as building shape, surrounding terrain, and height. This interaction results in pressure differentials across glazing surfaces, causing varying deflection patterns. An example from previous research illustrates this complexity (Figure 15). A simultaneous record of wind velocity on both the windward and leeward pressures was measured on the main building of Eindhoven University of Technology. The study revealed that the fluctuations of wind velocity are more closely followed by the pressures on the windward side of the building than by the pressure fluctuations on the leeward side (Geurts, 1997). This demonstrates the varying impact of wind loads on different parts of a building's glazing. From the pressure time graph in Figure 15, it can be seen that the pressure gradually starts rising and fluctuates with in a certain threshold.

Duration of Wind Loads: The duration of wind loads can range from short, intense gusts to prolonged periods of steady wind. Very strong winds are generally associated with cyclonic storms, thunderstorms, dust storms or vigorous monsoons. Prolonged wind loading can lead to fatigue in the material, while short gusts can cause immediate and noticeable deflections. The higher the intensity of a gust, the lower is its duration (Holmes et al. 2014). For the purpose of this research, high intensity wind loads that have a small duration and have the probability of occurrence with the 100-year span of a building have been considered. The following subchapters explain the process of developing an experimental set up to mimic the cyclic loadings from this short duration high intensity gust of wind.

3.3 Experimental setup for the cyclic loading of glazing

To mimic cyclic loading a pneumatic system has been developed. Previous research has explored the use of such a system to mimic atmospheric loading (Sager Oke, 2023). It had introduced air inside the cavity of an IGU and inflated it to create the pillowing effect caused by the change in atmospheric pressure. For the study of wind loading on glazing, a similar approach has been taken. The approach includes the development of a pneumatic system that can pump air in and pump air out of the cavity creating cyclic motion. The subsequent section explains the various components of the system in detail. These components include an electronic system, an algorithm to control motion, and a pneumatic component to facilitate the movement of air in and out of the glazing cavity.

Preliminary sizing

To estimate the different components needed for the experiment, preliminary sizing has been made by considering how much air is needed to pump in and out of the cavity. Assuming air in the cavity is governed by the Ideal gas Law, we can calculate the necessary parameters to ensure accurate simulation of wind loads. The Ideal Gas Law is expressed as:

$PV=nRT$

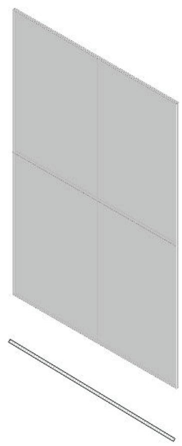
where:

P is the pressure,
V is the volume of the cavity,
n is the number of moles of air,
R is the universal gas constant, and
T is the temperature.

By manipulating the pressure inside the cavity, we can simulate the effects of wind loading on the glazing. This involves controlling the pressure difference (ΔP) between the interior and exterior of the glazing system. From the previous experiment conducted by sager (2003) it is indicated that with a pressure of 3447.5 pa inside the cavity on the IGU we get a deflection reading of 23 mm. The glass sample for AGU was modeled in rhino and the surface deformed to get a center of glass deflection of 23 mm. The volume from this model is used as a parameter for estimating the chage in volume of air needed to create such and deflection at such a pressure.

Air flow needed to deflect the IGU to 23 mm at a pressure of 3447.5 Pa is calculated as follows (Table 5):

Table 5: Tabulation of the calculation performed to estimate the pipe sizing for the experimental setup. In the calculation, the number of pipes, diameter of the pipe and pump size are determined.

Object	Calculation
 **Uninflated state**	Volume=0.228148 m3 T=19 c or 292.15 P=99000 Pa (winter condition cavity pressure)DIN 18008 Standard Pressure Conditions R=8.314 J / mol·K(universal gas constant) PV=nRT n_1=PV/RT n_1=9.298476223072 mol
 **Inflated state**	Volume=0.583629 m3 T=19 c or 292.15 P=99000 Pa(winter condition cavity pressure)DIN 18008 Standard Pressure Conditions + 3447 Pa=102,447 Pa R=8.314 J / mol·K(universal gas constant) PV=nRT n_2=PV/RT n_2=9.298476223072 mol
Required number of mol of gas	n2-1= 0.324mol 1 mol=24 L 0.324 mol=7.8 L of Air (air blown inside to create a pressure difference of 3447 pa and inflate the IGU to 23 mm) If the IGU is to inflate to 23 mm in 1 sec, 7.8 L/sec air flow is needed.

Maximum recommended air flow through a pipe	Outer diameter= 4 mm and inner diameter= 3mm Maximum recommended airflow =5.8 SCFM or 2.7 L/sec To pump 7.8 L volume of air in one sec 3 inlets with a tube of 3 mm inner diameter is required
Pump size	To pump 7.8 L/sec a pump with at least the capacity of 468 L/min is required

After calculating the volume of air, the maximum air flow in the pipe of the available 4 mm diameter pipe was calculated (Table 5) and the pump capacity found at the lab was compared.

The Initial volume was calculated using the room temperature of 19 degree celcius and a pressure of 99000 pa, which is stated as the winter condition cavity pressure by the Germen standard of DIN 18008. Next, the number of mole of gas that would be in the cavity under such a pressure was calculated. The extra pressure of 3447 Pa needed to deflect the glass to 23 mm is then added to the initial pressure and the number of mol in the cavity when it is deflecting is calculated. With a simple arthemetics, we get that 7.8 L of air/sec is needed to deflect the glass to a CGD deflection of 23 mm. To calculate the number of pipes needed to move air inside the cavity at such a speed , the maximum recommended air flow throught the pipes need to be considered with a pipe nominal size of 3 mm at a pump working pressure of 116 Psi/ 8 bars. From ANSI(American National Standards Institute) pipe schedues we find that a 5.8 SCFM or 2.7 L/s is possible, which leaves the number of inlets and outlets to 3 of each. The pump size found at the think lab is then compared to the required air flow of 164.2 L/min. The pump's maximum capacity was 45 L/min and thus the set up will need 4 of this pump.

3.3.1 The Pneumatic component

The pnumatic component is composed of parts necessary to simulate wind loading on glazing systems. The primary components include an air pump, tubings, a solenoid valves, a ball valve and connectors. These components work together to control the pressure within the glazing cavity, enabling the simulation of wind loads.

1. Air Pump: the pump's capacity and precision are important to ensure that the desired pressure levels and fluctuations are achieved.
2. Tubing: a polyurethane tubing connects the air pump to the glazing cavity and the solenoid valves. They must be durable and flexible enough to handle the varying pressure levels without leaking or degrading over time. The tubing should also have minimal resistance to ensure efficient airflow. Throughout the experiment a 4 mm and 8 mm thick tubing has been used and their respective importance will be discussed later.
3. Ball Valve**:** the manual ball valve is operated by hand, providing a straightforward and reliable method to control fluid flow. Its design allows for quick and easy operation with a simple quarter-turn of the handle as the electronic system might fail, the ball valve is used as a safety switch.

4. Solenoids: are essential for electronically controlling the airflow into and out of the glazing cavity. There are two main types of solenoid valves used in this setup: one-way solenoids and two-way solenoids.

   A one-way solenoid valve, also known as a unidirectional valve, allows airflow in only one direction. This type of valve is typically used to prevent backflow, ensuring that air moves in a controlled manner into the cavity but does not flow back into the pump or other components. The operation of a one-way solenoid valve is as follows: When the solenoid is energized, the valve opens up allowing air to flow through in the specified direction. When the solenoid is de-energized, the valve closes to preventing any backflow.

   A two-way solenoid valve, also known as a bidirectional valve, can control the flow of air in both directions, making it more versatile for switching between different channels. This type of valve has two ports: an inlet and an outlet. It switches between allowing air to flow in either direction based on the needs of the experiment. When the solenoid is energized, the valves can either open or close depending on the desired flow direction. This allows for more complex control of air pressure, enabling rapid switching between overpressure and under pressure conditions.

5. Connectors: for connecting the piping to the solenoid and the air compress a euro quick connect male and female fittings were used. Below is a schematic of how the pump connected (Figure 1 and 17).

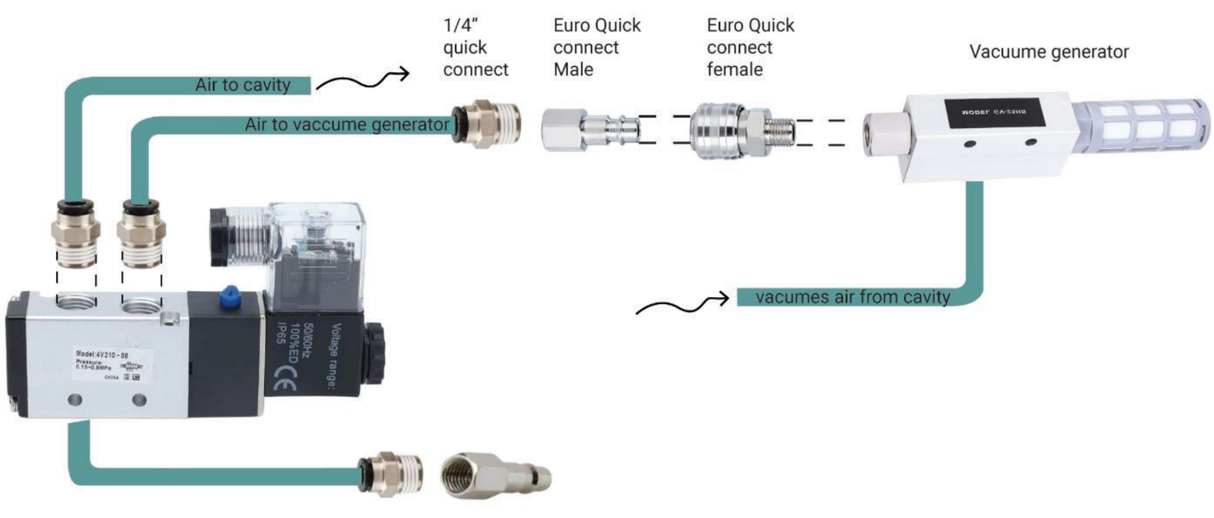


Figure 16: Pneumatic connectors. ¼ "Quick connect, male nipples, female quick connects.

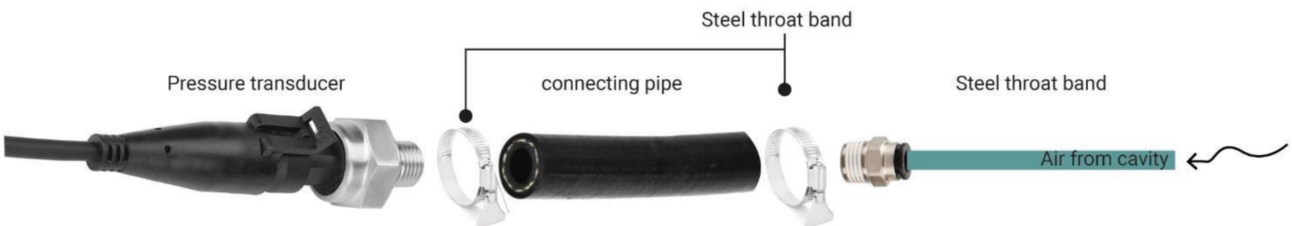


Figure 17: Pneumatic connectors for the pressure transducer

Figure18: Vacuum generator (left) and vacuum pump (right)

6. Vacuum generator and vacuum pump: To create a controlled cyclic movement of air, various approaches were tested using vacuum generators and vacuum pumps. The research included testing a vacuum generator with a capacity of 3.6 liters per second. Additionally, a specific vacuum generator model, CV-25HS, was evaluated. This model features a nozzle diameter of 2.5 mm, an inlet thread diameter of Rp1/4, and a spout thread diameter of Rp 1/2. It operates with air as the flow medium and supports a working pressure range of 1 to 6 bar, with a nominal pressure of 5 bar. The vacuum generator has a suction flow rate of 160 liters per minute and an air consumption rate of 265 liters per minute.

3.3.2 Electronic components

The pressure reading from inside the cavity was taken using a pressure transducer. It is a sensor that converts pressure into an electrical signal. When connected to an Arduino, it allows for the measurement and monitoring of pressure inside the cavity of the IGU. The pressure transducer is powered by the Arduino's voltage supply of 5V. The ground (GND) connection of the transducer is also connected to the Arduino's ground. The transducer's output pin, which provides the electrical signal proportional to the sensed pressure and is connected to one of Arduino’s analog input pins. The Arduino reads the analog signal from the transducer using the analog Read function. This function converts the analog voltage (ranging from 0 V to the reference voltage, usually 5V) into a digital value between 0 and 1023. The Arduino then processes the digital value to convert it into a meaningful pressure reading. This involves scaling the digital value based on the transducer's specifications. The Arduino is connected to a laptop to receive instructions and send back data. Now that we have pressure readings the Arduino is programmed to send signals into one of the 10 digital ports. Using these signals the solenoid valves are switched on and off with an electrical current. To control the current sent to the solenoid, a MOSFET is used as a switch. It operates on the signal received from the Arduino and acts as a switch opening and closing the circuit with an external power source. The 2-way solenoid has a voltage rating of 24 volt and the one-way solenoid was powered by a 12 volt. The power source leading to the one-way solenoid was connected to a voltage regulator calibrated to supply 12 volts. Both solenoids were connected to a power supply unit calibrated at a constant voltage of 24. This completes the circuit. The circuit can take pressure measurements from the cavity and switch the solenoids depending on the code instructions it receives from the laptop. The code is written and uploaded using the Arduino IDE environment. Below is a schematic of the electronic circuit (Figure 19).

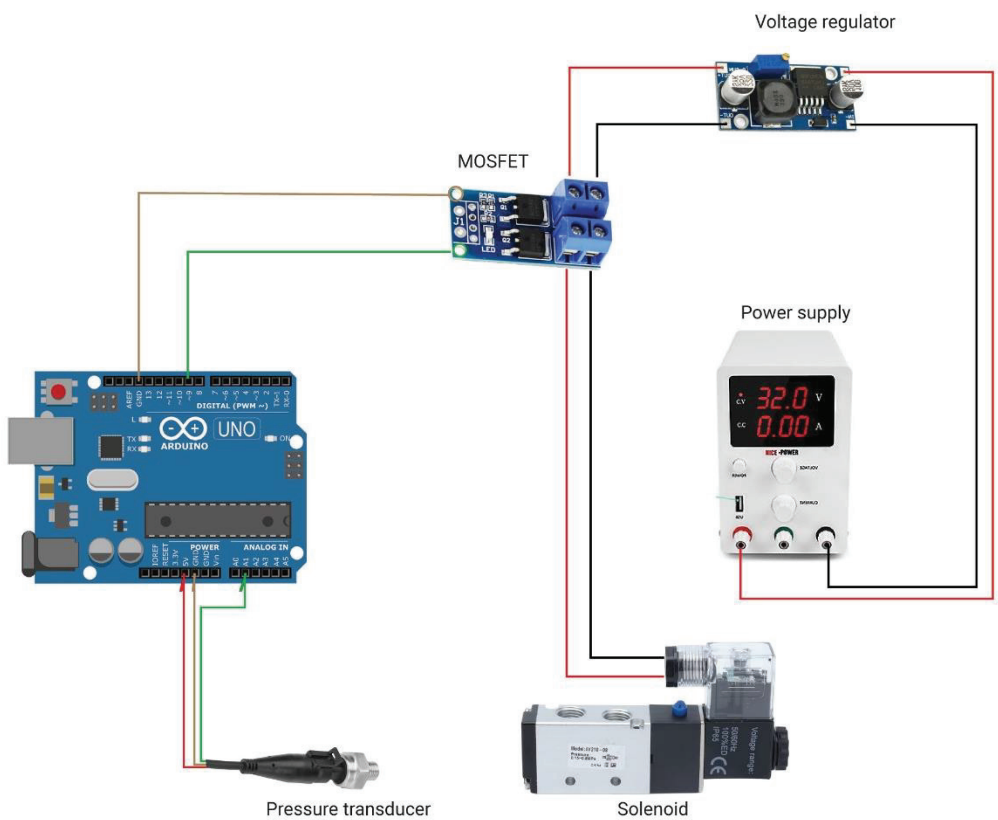


Figure 19: Electronic circuit, Arduino uno, solenoid, power supply, MOSFET, Voltage regulator and power supply

Schematics

To test for different schemes a 50x50 cm. test specimen made of Plexi glass with a cavity was used. Throughout the experiment different approaches to inflate and deflate a cavity inside a vacuum have been attempted. The first attempt was to control the air inlet only and have an open exhaust. The air intake was connected to a one-way solenoid which opens and closes the air flowing from the compressor into the cavity of the test specimen. It has been observed that when the air inlet and outlet have the same dimeter of 4 mm, the compressor would pump the cavity faster than the air can be released/leaked by the outlet which was left open. It can be extrapolated from this that although a cavity might have some air leakages it is still possible to pump air in a cavity and inflect the panes of Plexi/ glass.

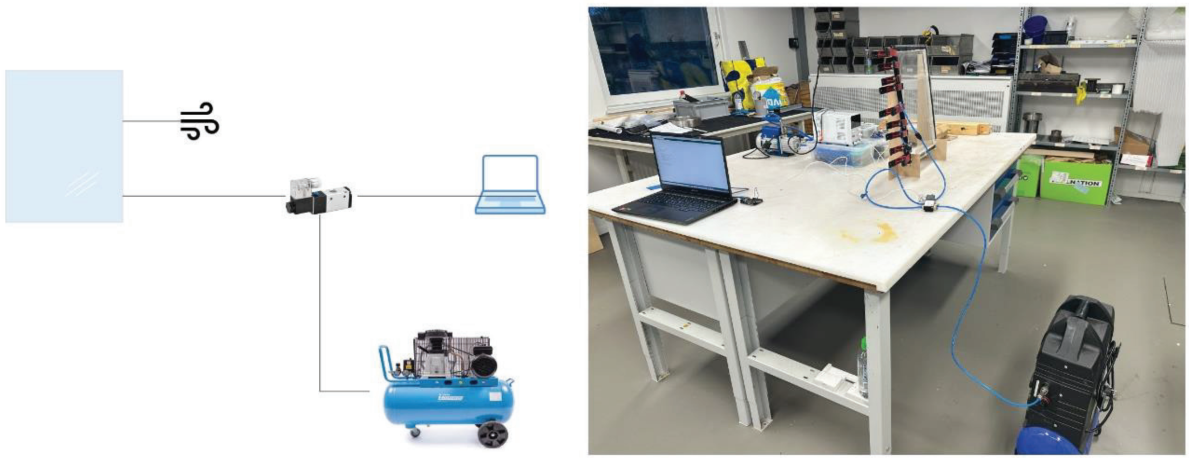


Figure 20: Scheme 1 of the Pneumatic system

In the second schematic, a solenoid was introduced to control the air outlet. As the air is pumped inside the cavity the solenoid connected to the compressor is activated to open while the second solenoid is closed, and the reverse happens when we let the air exhaust from the cavity. The observations from this experiment reveal that it is possible to let the air gradually escape from the cavity after pumping has stopped but the rate of air release decreases as the pressure in the cavity decreases. This might have also been caused due to the fact that the pressure exerted from the concave Plexi on the air inside the cavity decreases as the Plexi flattens and goes into its deflated state. The time taken to deflate the cavity with a natural exhaust from a certain pressure is on average 3x the amount of time it takes to inflate the cavity to the same pressure.

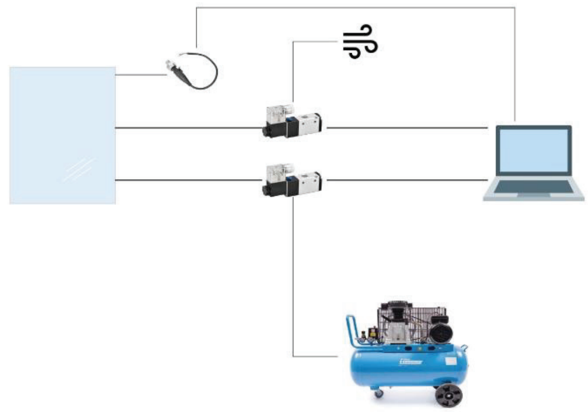


Figure 21: Scheme 2 of the Pneumatic system

To increase the rate of air release from the cavity a vacuum pump is introduced in the pneumatic circuit. The Pump indeed increased the speed of air release. It also created a more stable air flow out of the cavity. The vacuum capacity of the pump used was 3.6 L/min. The Pump was constantly working and as the solenoid connected to the pump is switched off the pump over works. This increased the leaking of oil from the oil cap. Although the rate of air flowing out has increased, more pumps are needed to match the rate of air inlet from the compressor. When thinking about scalability of the experiment, having multiple vacuum pumps is not cost effective and creates more connection points.

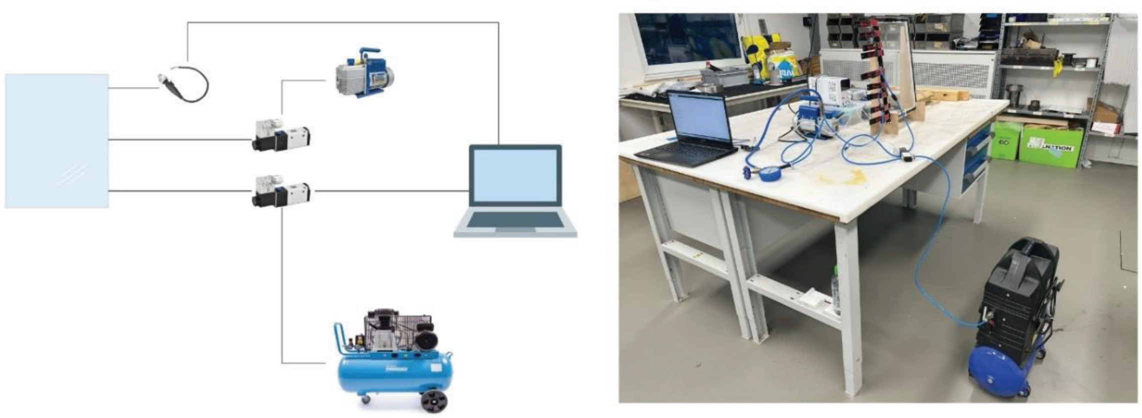


Figure 22: Scheme 3 of the Pneumatic system

As a solution to scalability the vacuum pump was replaced with a vacuum generator. The vacuum generator works with the same air flow coming from the air compressor. The air compressor is connected to a two-way solenoid. As the pressure in the cavity is low the solenoid opens to channel 1 and pumps air into the vacuum. The vacuum generator is connected to a one-way solenoid and is closed when air is blown in the cavity. When a desired pressure is reached in the cavity the two-way solenoid switches the air supply to channel 2 and pumps air towards the vacuum generator and the one-way solenoid connected to it opens. The vacuum generator has two ports. One port is connected to a pipe coming from the air compressor and the other is connected to a pipe from the cavity. It works with the principle of the venturi effect and as a fast-moving air is blown into port connected to the pump it creates a vacuum on the second port, puling the air out of the cavity.

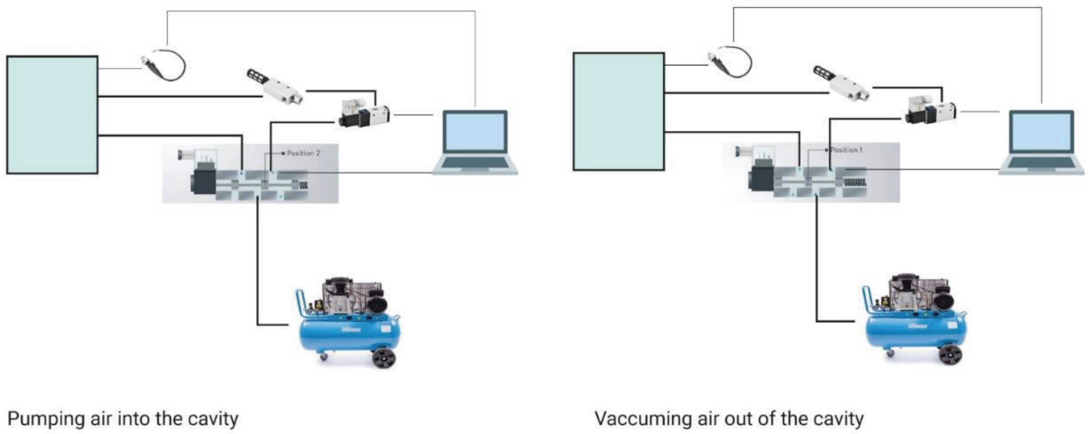


Figure 23: Scheme 4 of the Pneumatic system

The circuit is now complete and scalable with a relatively cheaper vacuum generator used. Following this the final set up was done to include manual safety switch and optimize the pneumatic circuit. The system is dependent on the proper functioning of the electronic circuits and a manual switch of ball valve was added to control the air coming from the air compressor. The air compressor used prior made noise and could account as a confounding factor during the experiment. To improve this the air supply was connected to a compressor which has the capacity of pumping air 55.2 m3/hr. or 15.3 L/sec at a working pressure of 10 bars. It is located in a room at basement of the faculty of architecture and the noise from the air compressor is contained with the room. Now that we have a bigger pump, we can split the air coming from the pump to use it to power a second vacuum generator. It is connected to the air releases of the two-way solenoid. As it switches to pump air out of the vacuum, the line connected to pump air in as shown in Figure 24 now connects to the second vacuum generator and the vacuum created sucks air out of the cavity. In the scheme the pipelines leading to the vacuum generators were replaced by a thicker polyurethane line of 10 mm OD and 6.5 mm ID. This increases the air flow which intern increasing the vacuum capacity of the vacuum generators.

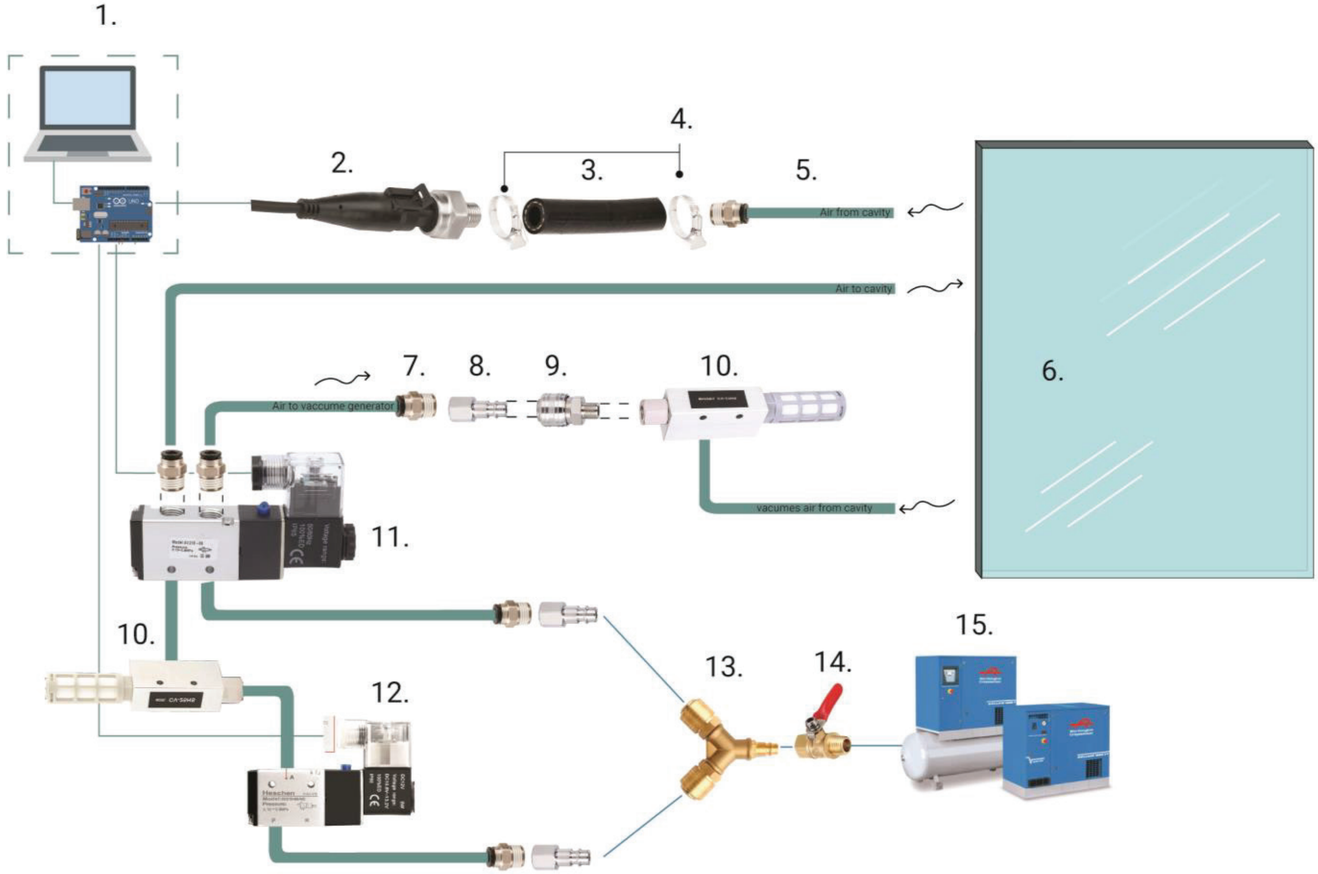


Figure 24: 1 Diagram of the electro pneumatic system used to control the air flow inside the cavity. See Table 6 for further detail.

Table: 6 Detail description of the pneumatic components used in Figure 3. The number tag of the components corresponds to the number tags on Figure 24.

Component number	Component	Description
1.	Laptop and micro-controller	-Micro-controller-Arduino
2.	Pressure transducer	-Range-0 - 30 PSI (0 - 2.06 bar) -outputs- Analog signal -Input- 0.5V to 4.5V. - Accurate to 0.1 when pressure is measured in Psi
3.	Hose	-compressed Air hose 5/8"
4.	Steel throat band	-Stainless Steel -Diameter 12mm x584mm ID [OD 155-178mm]
5.	Polyurethane pneumatic tube	-Working pressure- 0-1MPa -10mm OD 6.5mm ID
6.	Double glazing unit	-Size-1467mm x972mm -Glass build-up: 4 mm monolithic tempered glass + 16 mm air cavity + 4 mm monolithic tempered glass.

		-Characteristic tensile strength corresponds to 25 MPa.
7.	¼" quick connect	-10mm Tube OD x 1/4 BSP Push to Connect Fittings -Working range: 0-1 MPA and 0-60 °C.
8.	Euro quick connect male	-¼ inch BSP -Female Thread 15mm hexagon for tightening
9.	Euro quick connect female	- ¼ inch BSP -Euro Air Line quick coupling, male thread, 6.35 mm
10.	Vacuum generator	-Nozzle diameter: 2.5 mm. -Working pressure: 1 ~ 6 bar. -Suction flow: 160 l/min.
11.	Two-way solenoid	-Material- Aluminium -2 Position 5 Way Solenoid Valve -Air Inlet (P)= 1/4" -Outlet (A B) = 1/4" -Air Outlet (R S) = 1/8" -Pressure range: 25-116PSI (0-0.8MPa) -Voltage-24 volt
12.	One- way solenoid	-Material- Aluminium -3/2 way internally guided acting type. -Inlet connection- ¼ “. -Outlet connection- 1/8”. -Voltage-12 volts.
13	Splitter	-Brass 1/4 Inch. -Combination: 1 1/4-inch Y-shaped air hose adapter. -Maximum working pressure-20 (MPa).
14	Ball valve	-Brass ball valves with full pass nickel plated -Size: 1/2 inch
15.	Air compressor	-RollAir compressor 500TF -55.2 CFM

3.3.3 Algorithm

To create a cyclic loading an algorithm was developed in the Arduino IDE. It is based on receiving data from the pressure transducer and changing the signal that goes to the MOSFET switches to open and close the solenoids. The Arduino code is designed to control two valves for inflating and releasing pressure based on the readings from a pressure sensor. The sensor is connected to analog pin A1, and the pressure values are calculated using the specified calibration constants. The setup function initializes the serial communication and configures the pins for the two valves (inflateValvePin and releaseValvePin) as outputs.

In the loop function, the code first reads the pressure value from the sensor and converts it to a pressure value in PSI. For example, let's consider a desired maximum pressure of 0.2 and a minimum pressure of 0.1. If the pressure is below 0.2 PSI, the inflate valve is opened to pump air, and the pressure value is continuously updated until it reaches 0.2 PSI, at which point the inflate valve is closed. Then, if the pressure is at or above 0.2 PSI, the code enters another loop to release pressure by opening the release valve until the pressure drops to 0.1 PSI. After reaching 0.1 PSI, the release valve is closed. The control Valve function is used to simplify the process of opening and closing the valves by setting the corresponding pin states.

This process ensures the system maintains the desired pressure range by alternately inflating and releasing air. The schematic of the code is below, and the code is attached on appendix 3.

Wind loading on a building gradually increases and fluctuates around a certain pressure level. To replicate this behavior, the script begins by reading the current pressure inside the cavity and air is pumped inside the cavity until the predefined maximum pressure. This process is managed by the first while loop. Once the top pressure is reached, the script transitions to the second while loop, where it allows the pressure to fluctuate within the specified range, simulating the dynamic nature of wind loading as defined in the code and shown in Figure 25.

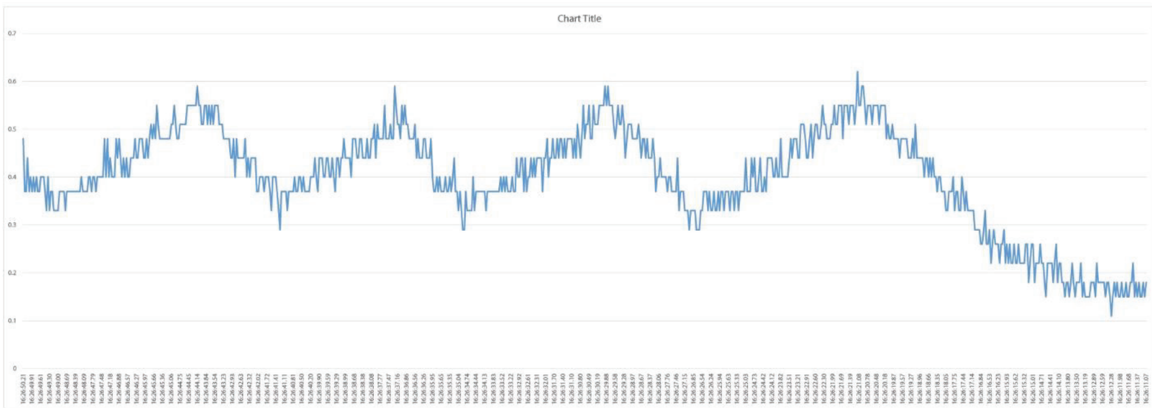


Fig 25. Pressure time series captured by the pressure transducer

3.4 Design for safety

AGC has provided the six glass panels to be tested, 3 DGUs and 3 TGUs. Of the samples 2 of each is made of a tempered glass and 1 is annealed glass (Figure .26). With a pane size 972 mm*1467 mm, they have 3 holes punctured on the side for connecting pipes and pressure sensors to the cavity. The IGUs were stored in the basement of the faculty of architecture.

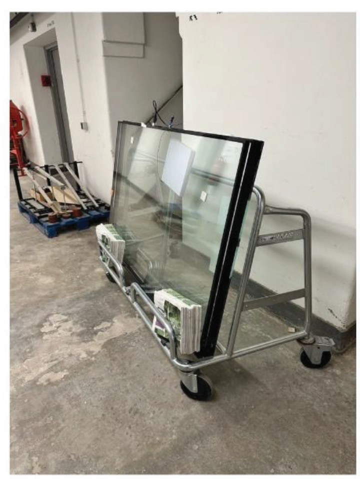


Figure 26: IGUs: 3 DGUs and 3 TGUs stored in the basement of faculty of architecture

Applying safety film

For the experiment with participants, the DGUs are to be used. Ensuring the safety of participants is important hence a safety film was applied to external faces of both panes of glass. The safety film was selected from the brochure of 3M in appendix 1. The criteria of selection were to have the thinnest safety film possible with the capability of retaining the glass while the IGU explodes from the pressure buildup inside the cavity. The S800, which had a thickness of 200 micrometer was selected as it was rated to the EN 12600:1B1 and EN356:P1A standards and its purpose was to reduce damage in explosions and retain glass. From the 3M website an authorized local dealership was selected to apply the safety film.

The procedure of application started by putting a soft plastic over the table at the think lab and cleaning the glass surfaces where the film will be applied. A glass cleaner was applied to remove any dirt, dust, or grease. A clean surface is crucial for proper adhesion of the film. The safety film was cut prior to the size of glass. Afterwards the surfaces were sprayed with soap and water solution. This solution will act as a lubricant, making it easier to position the film on the glass. The solution was generously sprayed onto the glass surface. This will help prevent the film from sticking immediately, allowing you to adjust its position. With the help of an assistant, the technician from the company Happy Sunlight carefully peeled off the rear side of the 3M safety film. At this stage it is important to avoid creasing or contaminating the adhesive side of the film. The adhesive side of the film was then placed to cover the whole glass surface. Next, starting from the center the excess water was removed by pressing it out towards the edge. The edge was then trimmed. The DGU was then rotated, and the procedure was repeated to apply the film on the second surface. Two IGUs from the sample had a safety film applied on, one is to be used for a break test and the other was set aside for the experiment with participants.

Figure 27: Safety film (left) and safety film application finished and when the glass is left to dry (right)

The double-glazed unit (DGU) intended for the break test was subjected to different curing periods: one specimen was left for 6 days and another for 15 days before testing. The safety film applicators recommended a 15-day waiting period to allow the film to attain its full strength. However, due to the tight schedule of the research, a break test was performed on the 6-day specimen. The left image in Fig. 28 shows that water bubbles had not fully dried and were noticeable against a black background. In contrast, the DGU left for 15 days also exhibited a defect, as shown in right image on Fig. 28. This defect was likely caused by positioning when drying the IGU; linear patterns of bubbles were observed on the underside. To address this, the affected side of the film was reapplied, and the IGU was stored with the surface facing up on a table in the think lab. This repositioning allowed the surface to dry properly, and the defects to completely disappear, ensuring clearer DGU for subsequent testing.

Fig 28. Air bubbles from the application of a safety film

For the DGU glass panels used in the experiment with participants, it was essential to break the glass and examine the fracture pattern and the hazard level. Although the safety film applied had a rating for glass retention, the frame holding the DGU to be set up on the light van doesn't mimic how a glass would be held in place in actual facades and the break test had to be performed. For the break test, the ASTM Blast Arena Test was referred.

The ASTM Blast Arena Test is a standardized testing procedure designed to evaluate the performance of materials and structures under explosive blast conditions. This test is crucial for assessing the resilience and safety of various building components, including Insulated Glass Units (IGUs), against blast loads. In this study, the ASTM Blast Arena Test was utilized to determine how an IGU specimen would break when subjected to induced air pressure inside the cavity. By simulating blast conditions, air pressure was incrementally increased within the IGU's cavity to mimic the impact of an explosive force. The test provided valuable data on the breaking point, fracture patterns, and overall durability of the IGU, thereby informing level safety while conducting the experiment with participants and improving the experimental design.

The Blast Arena Test, as illustrated in the diagram on Figure 29, includes a window subjected to a blast with a witness panel placed behind it. The test area is divided into hazard zones with specific thresholds: very low hazard threshold, low-hazard threshold, and high-hazard threshold. The hazard ratings, ranging from A to F, indicate the severity of damage: A (no break), B (no hazard), C (minimum hazard), D (very low hazard), E (low hazard), and F (high hazard). The IGU is assessed based on how far debris and fragments travel from the blast center towards these hazard thresholds.

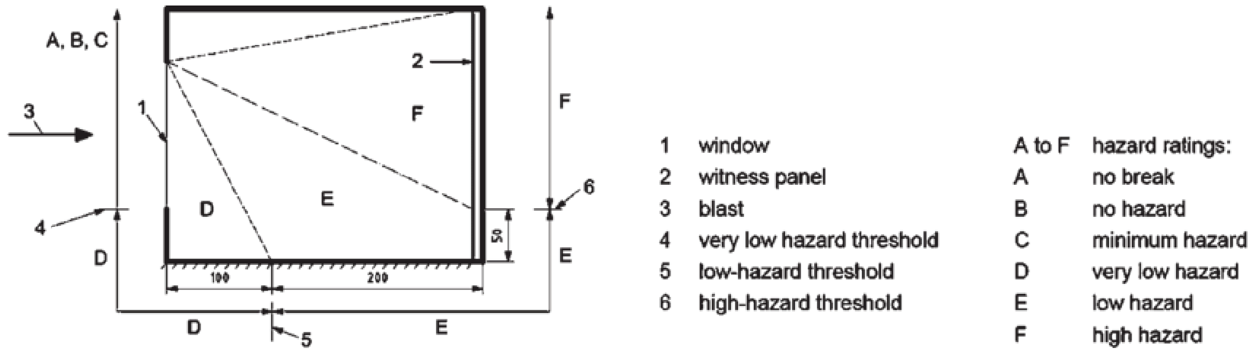


Figure 29: ASTM Blast Arena Test setup

The test was simplified considering that the source of blast is not an actual explosion but rather a pressure increases within the cavity. The test was conducted in a warehouse to contain any damage that might be caused during the test. The pneumatic system was also simplified to include only a pressure sensor, inflation pipe, MOSFET and one solenoid to control the pressure buildup as shown in fig 30.

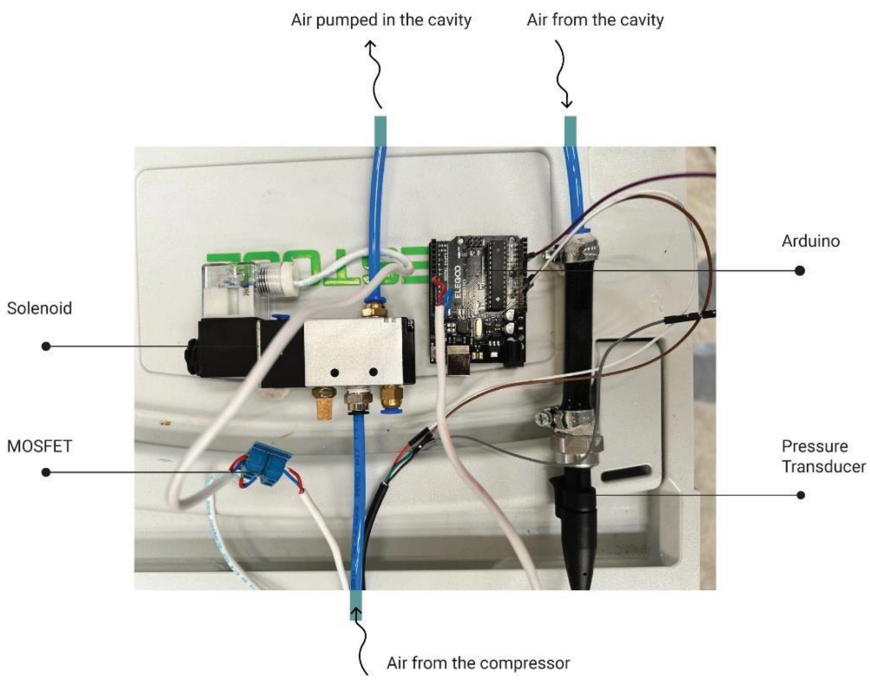


Figure 30: Electronic control system for the break test

During the break test, pressure readings and center of glass deflection were measured with the different build-ups. To measure the deflection an Infrared (IR) sensor was proposed. An IR sensor connected to an Arduino takes measurements by detecting infrared light and converting it into an electrical signal that the Arduino can read and process. The IR sensor is powered by connecting it to the Arduino's 5V power supply and ground (GND) pins. The sensor emits infrared light through an LED, which reflects off objects and returns to the sensor’s photodiode or phototransistor. This reflected light generates an electrical signal whose intensity depends on the strength of the reflection. The sensor sends this signal to one of the Arduino's input pins. The Sharp analog IR sensors (10-80 cm) tested sends a signal in variable voltage that the Arduino reads, providing a range of values corresponding to the intensity of the reflected light. The Arduino then processes this input according to programmed instructions. The specific code used to convert the voltage readings into a measurement was retrieved from git hub. To test the accuracy of the IR sensor a mockup was set up with the distances reading traced on the surface. The specific model of the IR sensor (GP2Y0A21YK0F) is only accurate from the ranges of 20 cm to 80 cm with a signal renewal of 38+/- 10 µs and its accuracy was rated for +/- 1 mm.

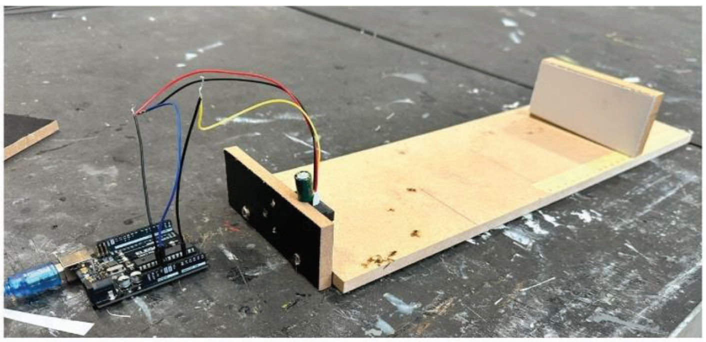


Figure 31: Testing of IR sensor

Although the manufacturer's ratings for the sensor were acceptable for measuring deflection during the break test, the mockup revealed that the sensor was unreliable. This unreliability was likely due to current fluctuations from the power source. To address this issue, a 100-microfarad capacitor was added to stabilize the current. While this modification improved the readings, there was still a deviation of +/- 5 mm in some measurements, as shown in Fig. 31.

Given the persistent inaccuracies, a simpler technique for measuring deflection was adopted for the break test (Fig. 32). This technique involved using a gauge meter constructed with a wooden frame. The meter was fixed on a stand, and the tip of the wooden rod was aligned with the center of the glass specimen. As the glass deflected, the movement of the rod was measured. A pointer attached to the rod moved against a background measuring meter, and this movement was recorded with a camera. The recorded video was then imported into Adobe Premiere Pro, allowing for frame-by-frame analysis. This enabled precise correlation of the physical deflection measurements with the digital readings from the pressure transducer.

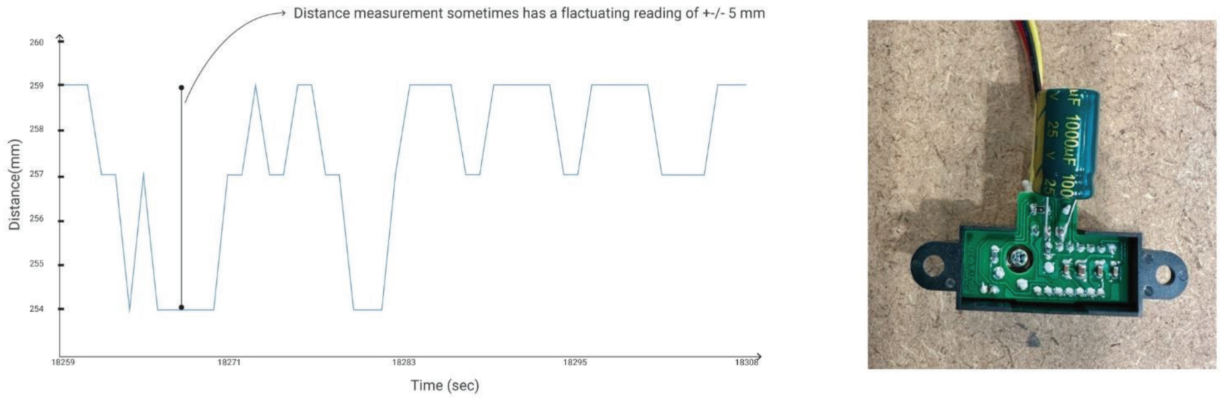


Figure 32: Readings from the IR sensor

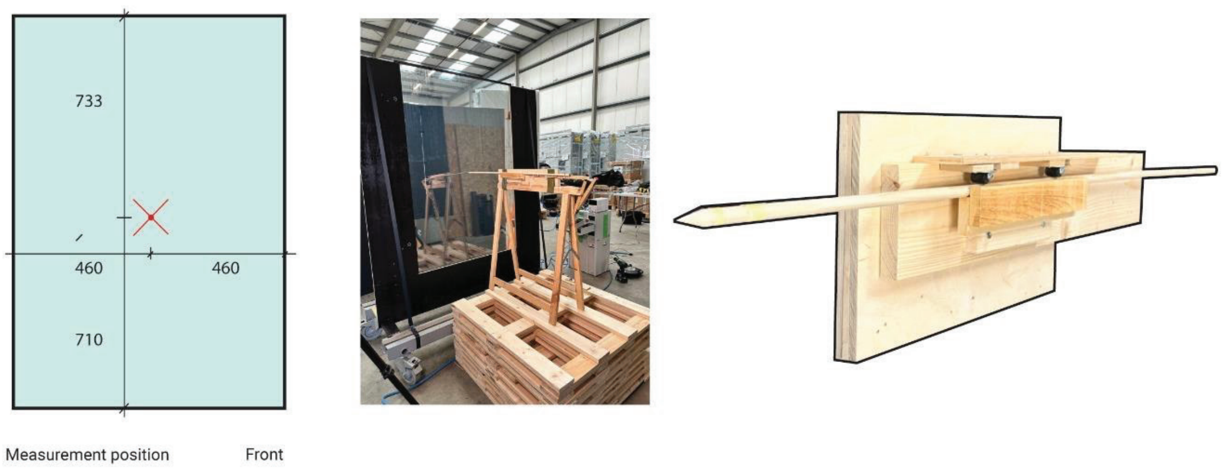


Figure 33: Measurement setup and wooden gauge meter

To document the break tests (Figure 34) 3 cameras were used, camera 1 was pointed at the gauge meter and set at 50 fps. Camera 2 was positioned in front of the glass to capture the breaking pattern. It was set at 200 fps to capture in slow motion. A black background was used on both sides of the glass. Backdrop 1 was used to cover the excessive light coming from the warehouse window backdrop 2 was used to capture the deflection of the glass without the obstruction of objects. To control the air flowing in the cavity of the glass a simplified electro pneumatic system was used. The experiment was done in stages, pumping the cavity to a certain pressure, releasing it and pumping it back again to a higher pressure. This was done to increase the data points of reading for correlating with the deflection measurements captured with gauge meter.

Figure 34: Break test setup

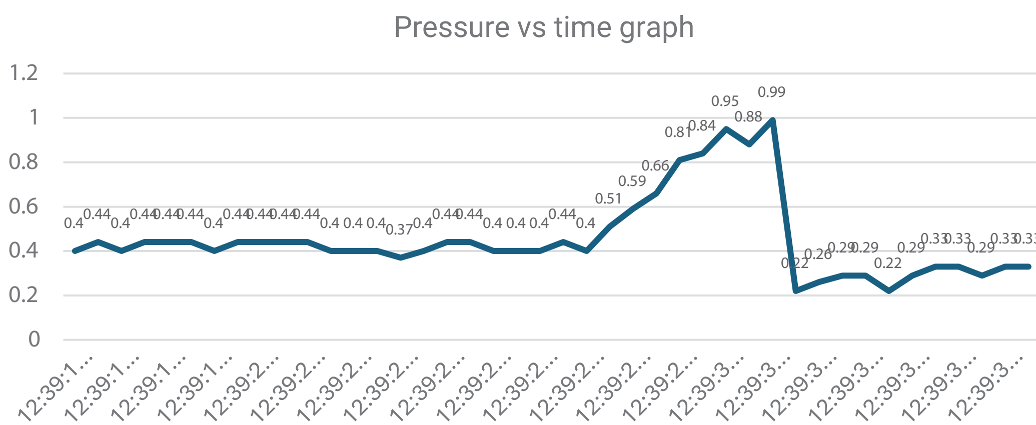


Figure 35: Pressure readings during the final break test set at 0.9 psi

Table 7: Steps taken and pressure applied to the cavity and pressure readings.

Steps	Pressure in psi	Pressure in pascal	Deflection in mm
1	0.3	2068.4	11 mm
2	0.35	2413	13 mm
3	0.4	2757.9	14 mm
4	0.5	3447.4	16 mm
5	0.7	4826.33	21 mm
6	0.88	6067	26 mm
6	0.9	6205.3	51 mm

The pressure readings were correlated with the deflection reading in the graph in Figure 36. The glass behaves elastically but as the pressure inside the cavity increases the cavity increases, the stiffness of the glass increases. This can be attributed to geometric non-linearity. The glass breaks at a pressure of 0.88 Psi or 6067 Pa and at a CGD deflection of 26 mm. After which the stiffness of the glass declines and the glass is held in place by the safety film and the CGD deflection increases up to 51mm.

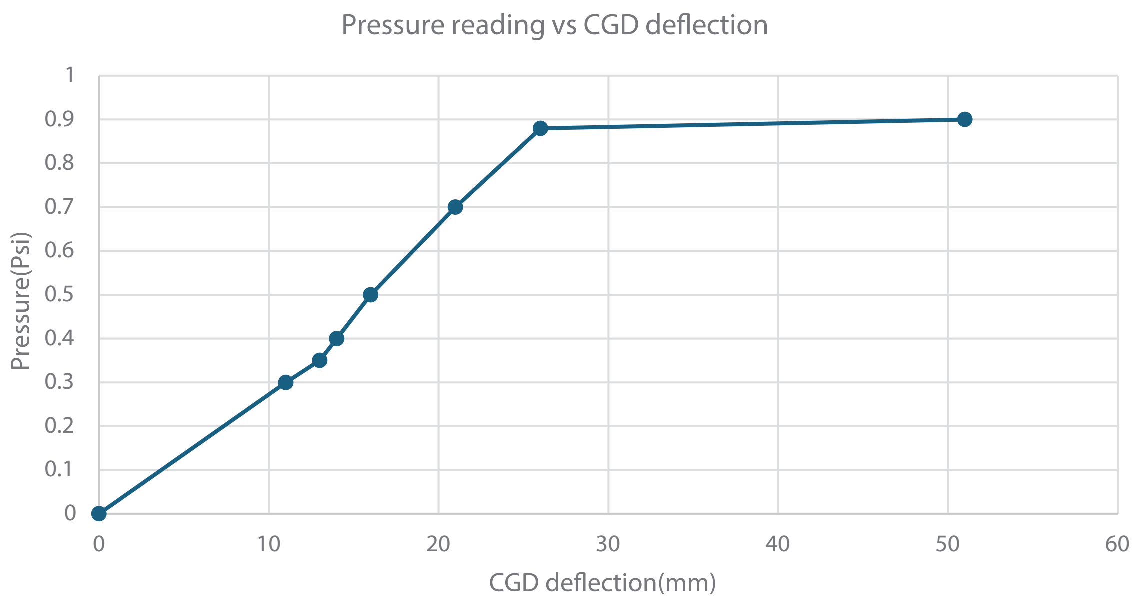


Figure:36 Stress vs strain graph from the break test performed. Stress measured in Psi and strain (CGD) measured in mm.

3.5 Validation using FEA

To validate the break test performed a finite element analysis was performed using Ansys. The IGU pane was modeled in Ansys modeler and simulated in the workbench environment. It was made of a simple plane of size 1467 mm x 972 mm. To simulate the support condition of the glass held in place during the experiment a pin support at the sides of the rectangular plate was preferred. Since Ansys doesn't support a pinned connection, the 4 edges of the plane were constrained in the Z axis and two corner points constrained in the X axis and one of the two points were constrained in the Y axis. The pressure was applied normal to the plane. The simulation was performed both in a Linear and Non-linear analysis. Fig 37-40 below shows images extracted from the linear and non-linear analysis. The results from the Ansys simulation were then compared with the readings taken from the break test.

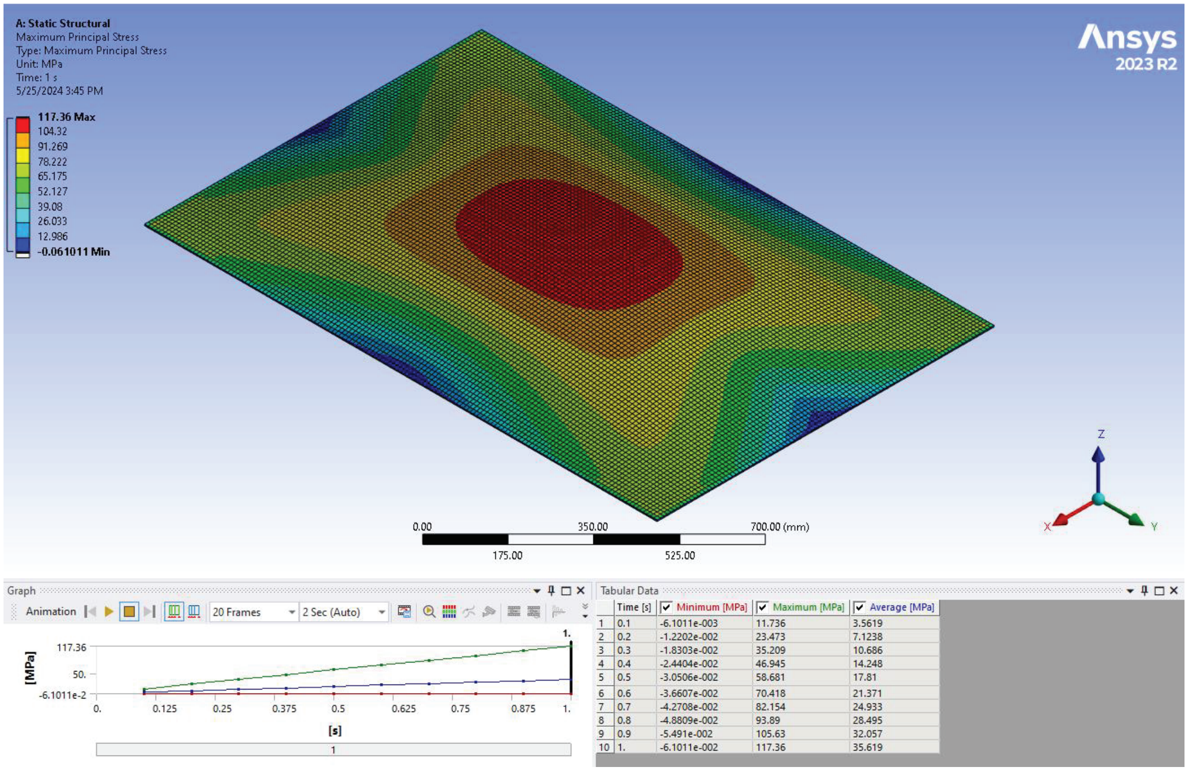


Figure 37: Linear analysis results of maximum principal stress

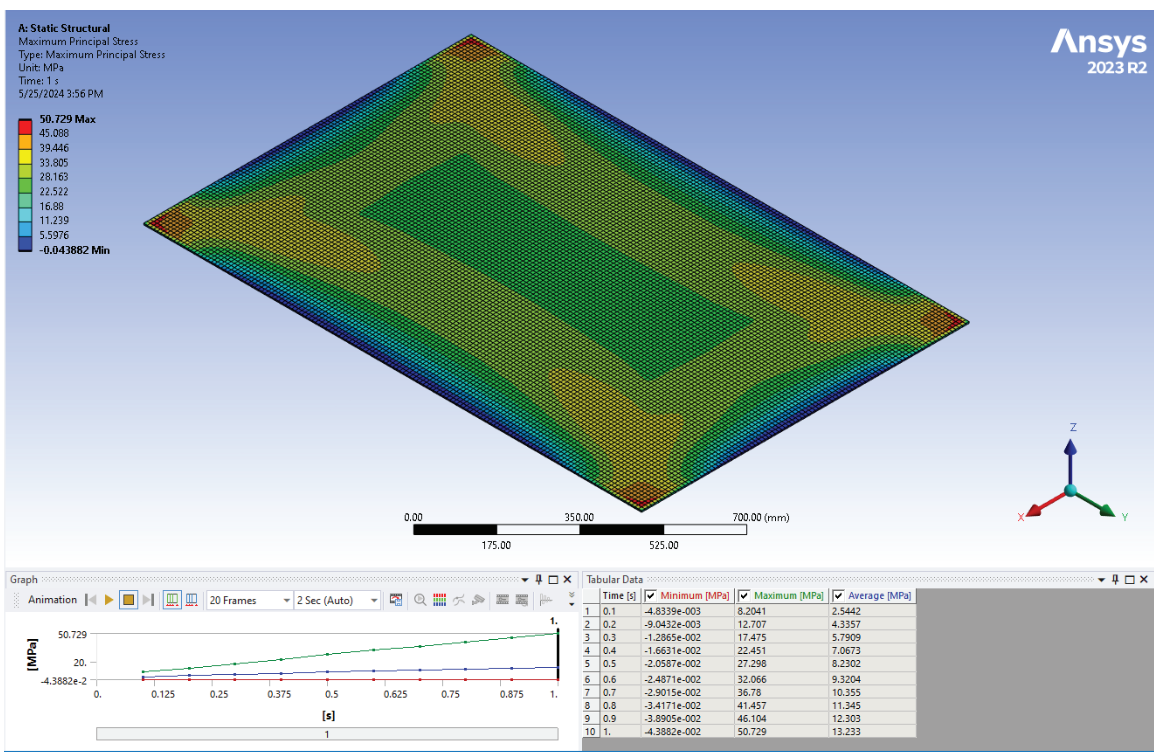


Figure 38: Non-linear analysis results of maximum principal stress

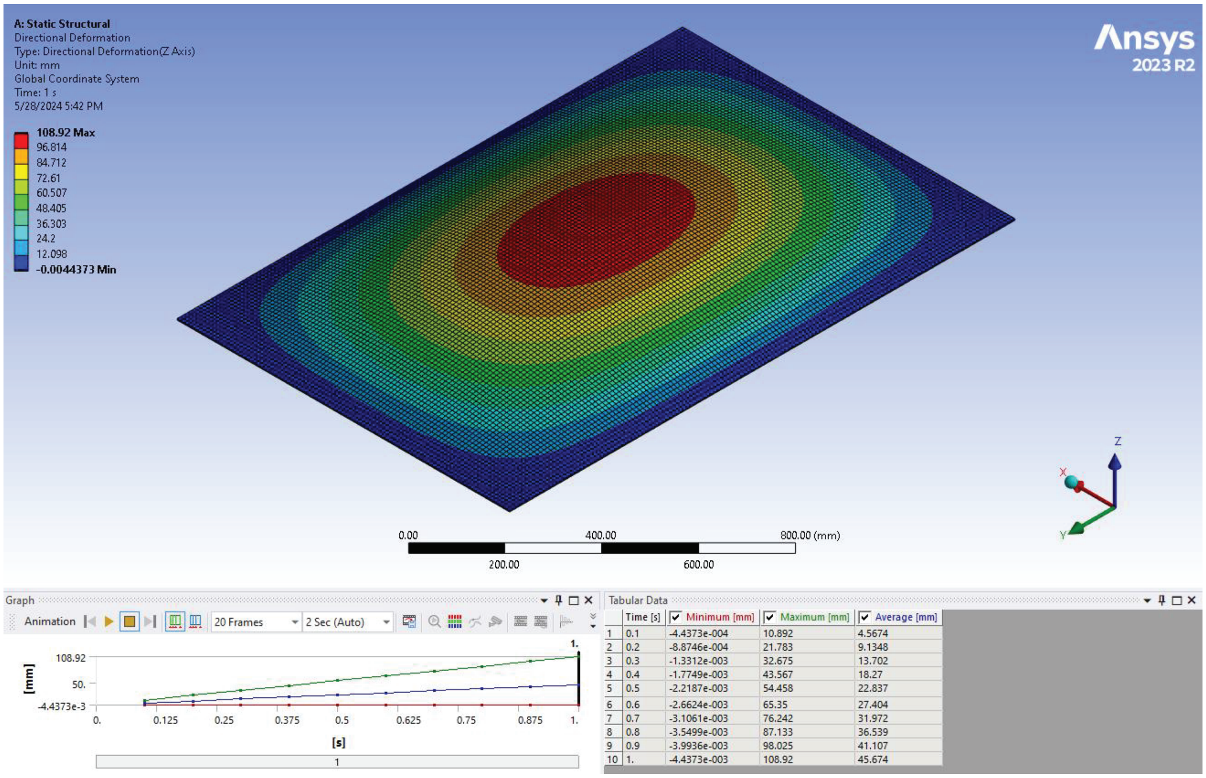


Figure 39: Linear analysis results of directional deformation

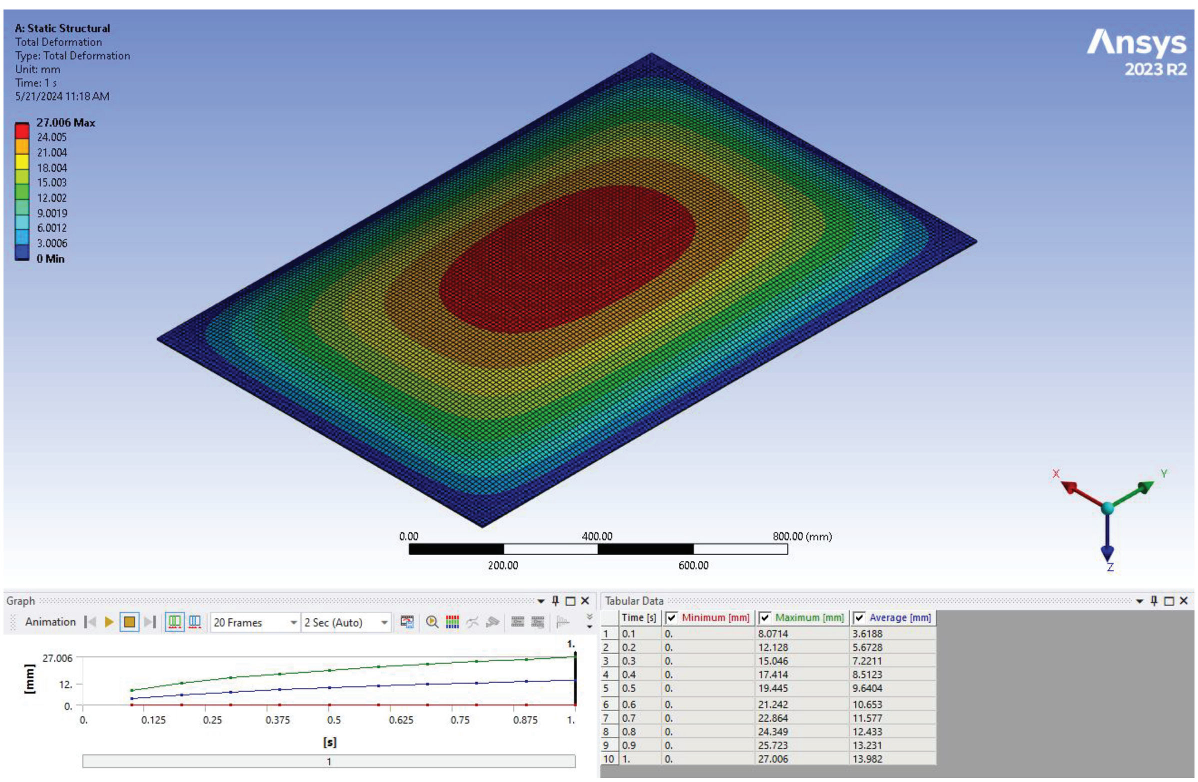


Figure 40: Nonlinear analysis of directional deformation

The linear analysis overestimates the deflection of the glass in relation to the results from the non-linear analysis are much closer to the readings from the break test. Table 7 and 8 and Figure 41 below compare the readings of the Linear analysis, non-linear analysis and the actual measurements. Beyond the breaking point of 6067 Pa, the graph of non-linear analysis deviates from the actual readings. For simulating the pressure build up in the cavity and its relation to center of glass deflection, a Non-linear analysis is preferred, especially when the glass is subjected to higher deflections.

Table 7: Results from the linear analysis in Ansys

Deflection(mm)	Pressure (Psi)	Pressure (Pascal)	Principal stress (MPa)
0	0	0	0
37.13	0.3	2068.4	58.679
43.32	0.35	2413	68.45
49.51	0.4	2757.9	78.24
61.89	0.5	3447.4	97.8
86.64	0.7	4826.33	136.92
108.92	0.88	6067	172.12
111.4	0.9	6205.3	176.04
136.15	1.1	7584.23	215.16
148.53	1.2	8273.7	234.72

Table 8. Results from the Non-linear analysis in Ansys.

Deflection(mm)	Pressure (Psi)	Pressure (Pascal)	Principal stress (MPa)
0	0	0	0
15.389	0.3	2068.4	32
16.645	0.35	2413	36.782
17.796	0.4	2757.9	41.461
19.862	0.5	3447.4	50.735
23.3	0.7	4826.33	69
25.96	0.88	6067	85.43
26.236	0.9	6205.3	87.249
28.758	1.1	7584.23	105.3
29.9	1.2	8273.7	114.3

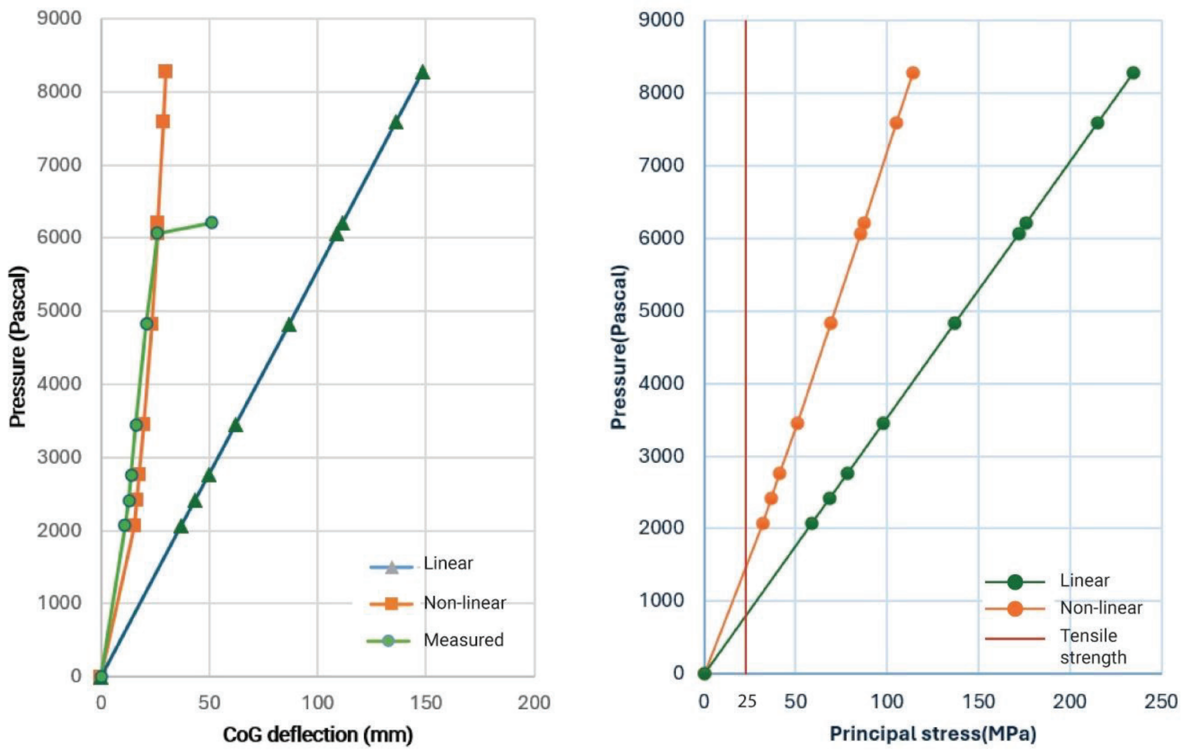


Figure 41: pressure vs deflection graph and pressure vs principal stress graph for comparison

Although the CGD deflections from the non-linear analysis have a similar curve with the actual measurements, the prediction of maximum principal stress developed in the glass might be an over estimation compared to the characteristic tensile strength of the annealed glass used in the break test. The Annealed glass characteristic tensile strength is 25 MPa and it is plotted with a vertical line on the graph in Figure 41.

The break test was performed for ensuring participants safety and to assess the risk if the glass was pushed beyond the limit. During the break test, the glass starts to deform elastically until it starts cracking near the center and the crack progresses to the edges. The FEA performed above demonstrates the maximum stress is indeed in the center of glass and it is the reason why the glass started shattering from a point closer to it. After the glass is shattered, it is held in place by the safety film. The pressure in the cavity momentarily continues to increase until the glass from the edge breaks loose and the pressure build up is released. The 3M S800 film has retained all the shards in place and the glass is kept attached to the sealant although it is totally broken. From this break test performed it has been concluded that the experiment is safe to continue with participants. The breaking pattern DGU can be seen in the following picture (Figure 42) after the test was concluded.

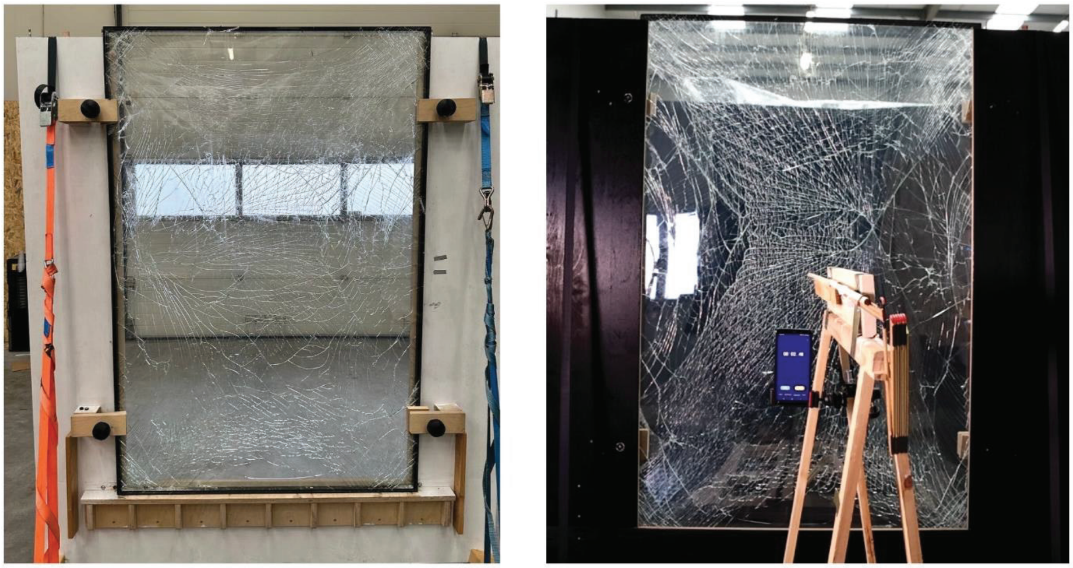


Figure 42: Breaking patterns observed after the break test

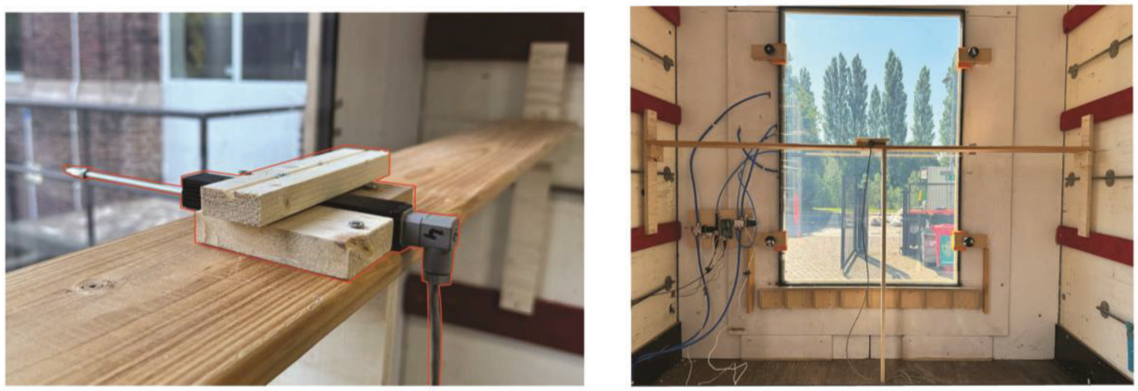
After the break test the second DGU which has the safety film applied on it is set up on the light van. As the nearest location to the outside for an outlet of the compressor in the basement of architecture is the wood workshop, the van was parked on the west side service entry of the faculty. The wood framings that hold the DGU in place were first assembled on the rear side of the van (Figure 43).

Figure 43: Setting up the framing on the van.

The DGU is then placed on the framing assembled and the electro-pneumatic system is installed. In this phase, the vacuum generators were placed as close to DGU as possible. The vacuuming performance decreases as the pipe that connects it runs longer. Two vacuum generators were used, and one was directly connected to a pipe leading to a hole in the cavity and the second vacuum generator was connected to the release valve of the 2-way solenoid. The pressure transducer was installed closer to the Arduino to decrease the length of the wires connecting to send back signal to the Arduino. The pressure transducer was then connected to a pipe leading to one of the 3 holes on the side of IGU. The DGU is held in place with a four-point connection, enough to keep it in place but not to put unnecessary pressure as the glass pushed on the connection points when it starts inflating.

Figure 44: installing the DGU in the van and routing the cables

For the experiment with participants the calibration of pressure inside the cavity to the center of glass deflection was done using a Linear variable differential transformer sensor (LVDT). The LVDT sensor measures deflection by converting the linear motion of an object into an electrical signal. It consists of a primary coil and two secondary coils wound around a movable core. When an AC voltage is applied to the primary coil, it induces a voltage in the secondary coil. As the core moves linearly in response to deflection, the induced voltage in the secondary coils changes proportionally. The difference in voltage between the two secondary coils is then measured, providing a precise and accurate measurement of the deflection. The voltage readings from the LVDT are recorded using a National instruments data logger and with the use of the software MP3, the voltage reading is converted into a deflection reading. For such a conversion, the LVDT is first calibrated to corelate deflection and voltage reading. The LVDT is set up inside the Lightvan and the rod is set close to the center of the glass pane (Figure 45).



A B

Figure 45: Deflection measurement and calibration with pressure

The frequency of readings from the LVDT are controlled to match the frequency of pressure readings from the pressure transducer. Both sensors were set to measure with a frequency of 5 Hz. But after exploring the data it was evident that the number of readings from each instrument in a given time interval does not match. This can be attributed to the differing methods the sensors use to read and record data.

The readings taken from the pressure sensors were interpolated to match the readings from the LVDT. The row of new interpolated readings were then removed from the list of data to only take the measured data to construct the correlation between deflection and pressure. Plotting the graph there are readings that are anomaly as they do not match the expected progression of the curve of deflection and pressure (Figure 46). The data is then filtered to remove anomalies and a new curve constructed.

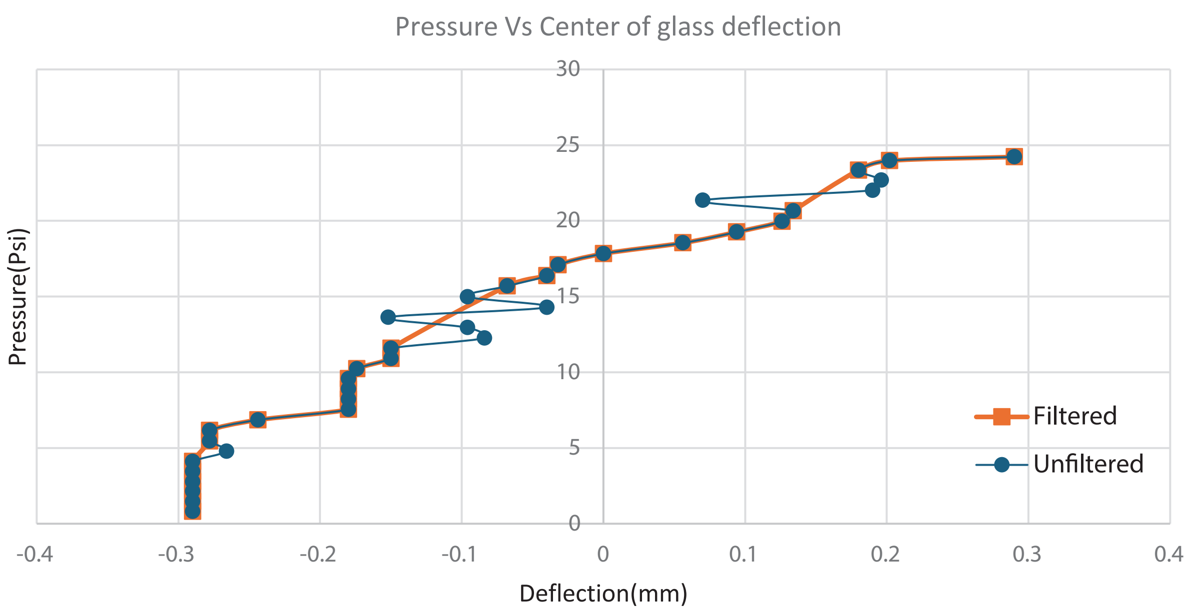


Figure 46: A plot of Pressure (psi) vs deflection(mm). The orange line represents filtered data removing anomalies and the blue line represents processed data without filtering.

As the glass cycles between a concave inflated state and a flattened or deflated position, it exerts pressure on the four fixing points. To prevent overstressing these points, the orange polyurethane foam was introduced (as shown in Figure 47, left). This foam is compressed to ensure that even when the vacuum pump creates a convex curvature by sucking air out of the cavity, the connections remain secure. The foam maintains the position of the double-glazed unit (DGU) by preventing the connections from loosening and releasing the glass.

Figure 47: Fixing mechanism on the van and vacuum generator

After completing the setup, the electro-pneumatic system was tested. It was discovered that placing the vacuum generators inside the van caused significant noise disruptions, potentially affecting the participants during the experiment. To mitigate noise as a confounding factor, the vacuum generators were relocated outside, and the piping system was reconfigured. Holes with a 10 mm diameter, matching the size of the air tubes, were drilled to reroute the pipes effectively. This adjustment aimed to minimize the amount of noise entering the room, ensuring a more controlled and accurate experimental environment.

3.6 Setting up the Lightvan

To conduct the experiment with participants, the Light Van was converted into a small office setup. It consists of two zones: the table closer to the DGU specimen is designated for participants and is aligned perpendicular to the glass, mimicking typical office seating arrangements. The table is positioned 125 cm away from the DGU, ensuring an appropriate distance for observing deflection effects.

Various cables run from the electronic board to facilitate data collection and control. A USB 2.0 M/M 5 m data transfer cable connects the Arduino controller to a laptop. The Arduino and solenoid are mounted inside the IGU frame. Ten-millimeter diameter pneumatic polyurethane pipes run from the solenoids to a hose and then to a connection point in the workshop within the architecture building. The hose is attached to a ball valve, which is connected to a splitter. This configuration allows air to be pumped into two separate pipes, each leading to one of the solenoids. The ball valve is situated close to the controller's table, serving as a manual switch to start and stop the experiment and as a backup safety switch in case the electronic systems fail.

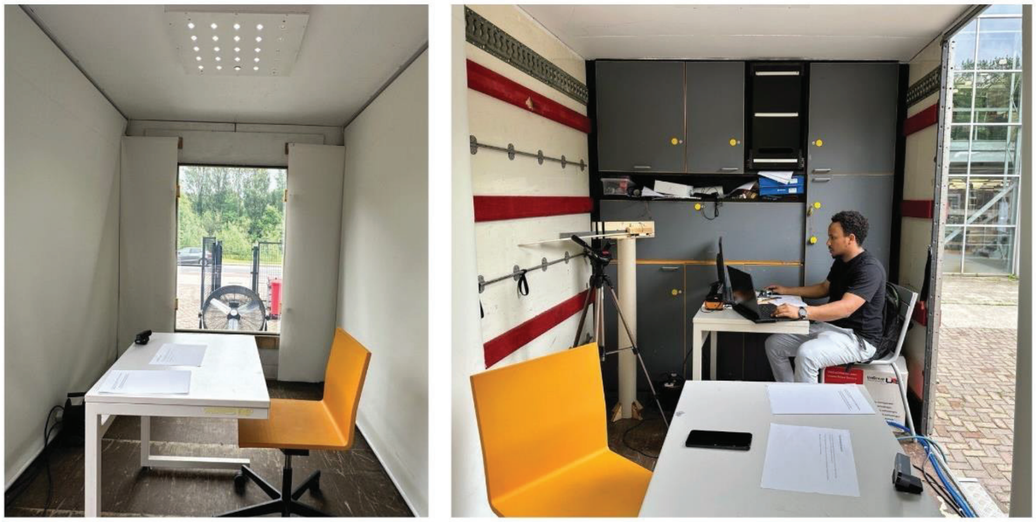


Figure 48: Interior view of the van after the setup was done. The left side showing participants zonae and right-side showing control zone.

A cable runs from the CPU to a camera positioned on the participants' table, aimed at capturing their facial expressions. To minimize visual bias for the participants, the cables and electronic systems near the DGU specimen are concealed behind wallpaper fixed 15 cm from the van's frame.

Power for the computers and the electronic system is supplied from an outlet near the workshop. The figure provided (Figure 49) illustrates the setup, showing the data cable outlined in green, the 10 mm diameter pipes, the air hose, and the power supply connections. This comprehensive arrangement ensures a controlled environment for the experiment, enabling data collection and analysis of participants' responses to glazing deflection.

Reading facial expressions

On the control side of the lightvan, a computer is set up to run OpenFace 2.0, which detects and analyzes the facial action units of participants. It enables automatic facial behavior analysis. The facial expression is represented using facial action units (AUs) (Figure 50) which objectively describe facial muscle activations. The participant's facial expression is recorded with a camera set on the participant's desk which was directed to their face. 17 facial action units are recorded with a range of 0-5 representing the intensity of activation.

The action units represent the movement of a specific part of the muscles on the face. The data from the facial action units is recorded in a csv and later processed to determine how the facial expressions of participants changed with the change in center of glass deflection. The methodology enables for an objective assessment of the experimental procedure proposed to correlate occupant's perception and acceptance to glazing deflection.

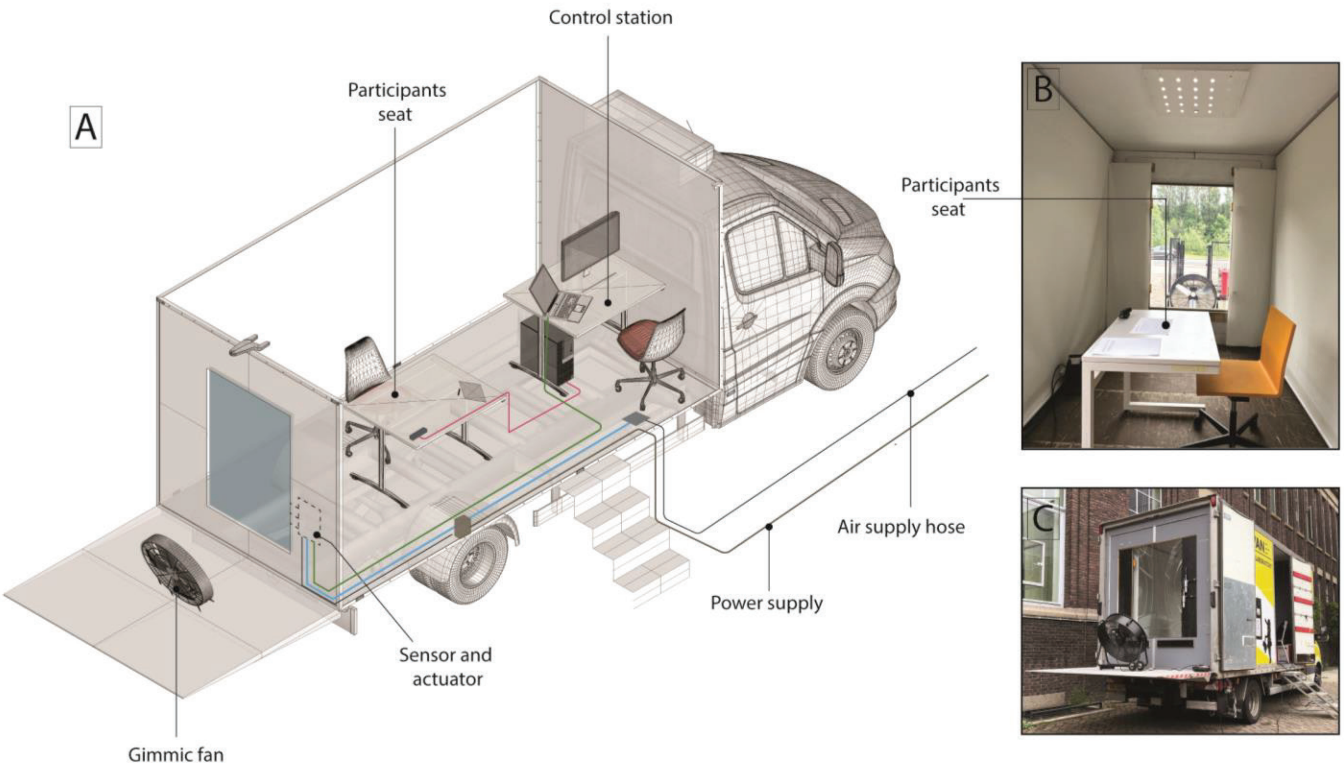


Figure 49: Experimental setup: a) schematics of experimental setup in the Lightvan; b) interior view of the Lightvan; c) exterior view of the Lightvan.

Figure 50: Facial action units and corresponding facial expressions. Baltrusaitis, T. (n.d.). OpenFace: Action Units. GitHub. Retrieved June 29, 2024, from https://github.com/TadasBaltrusaitis/OpenFace/wiki/Action-Units

3.7 Conclusion

The experimental design and methodology developed to simulate cyclic wind loading on glazing systems gave several key insights. This chapter has been an exploration of iterative refinement and practical problem-solving, ultimately leading to a replicable experimental setup.

One of the challenges encountered was in accurately mimicking the dynamic behavior of wind loads. Initially, controlling and synchronizing both the air intake and exhaust proved to be complex. The introduction of one-way and two-way solenoid valves enabled a more precise control of air pressure within the cavity. This step was important in achieving a simulation close to that of a wind load.

The need for scalability and stable airflow was apparent early on in setting up the experiment and the vacuum generator provided an effective solution. Safety considerations were a priority in the experiment. The application of safety films to the glass specimens and the adaptation of the ASTM Blast Arena Test were not merely procedural steps but vital measures to ensure participant safety.

The initial unreliability of the IR sensor, despite its promising specifications, highlighted the gap between theoretical performance and practical application. Adding a capacitor to stabilize the current improved the readings but did not fully resolve the issue. This led to the adoption of a simpler, mechanical gauge meter, which, while less sophisticated, provided the necessary reliability. The mechanical gauge was used during the break test but later on replaced by a more accurate sensor.

The use of a Linear Variable Differential Transformer (LVDT) for measuring deflection offers a more reliable reading. An LVDT can provide highly accurate and reliable measurements of deflection by converting mechanical displacement into an electrical signal. Integrating an LVDT into the setup enhances the precision of deflection measurements, offering a more robust solution compared to the mechanical method used. The LVDT's ability to deliver continuous, real-time data helps capturing the deflection patterns induced by cyclic loadings.

In terms of future implications, this experiment lays a foundation for further research into glazing systems and their behavior under cyclic loading. The methodology and findings can inform the design of better experimental setups to assess occupants' perception and acceptance to deflection, contributing to a method of empirically determining occupant satisfaction to glazing deflection. Additionally, the iterative process of refining the experimental setup offers valuable lessons for future projects, emphasizing the need for continuous improvement and adaptation.

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Survey design

4 Survey Design - Assessing Participant Perception and Acceptance of Glazing Deflection

4.1 Introduction

Understanding the perception and acceptance of occupants regarding glazing deflection is an important component of assessing the current serviceability limit. The goal of this research is to empirically assess how different levels of glazing deflection are perceived by individuals and inform design decisions aimed at optimizing material usage. To achieve this, a carefully structured survey was designed and implemented as part of the experimental methodology.

The survey aims to capture participants' subjective responses to varying degrees of deflection in glazing units subjected to cyclic loading. This chapter details the survey design, including the development of survey instruments, participant selection, data collection procedures, and the methods used to analyze the gathered data.

By examining the relationship between observed deflection and perception, the survey provides valuable insights into acceptable deflection limits from the perspective of building occupants. These insights are crucial for establishing guidelines that balance structural performance with user satisfaction, ultimately contributing to more efficient and sustainable building designs.

The following sections will elaborate on the specific aspects of the survey design, starting with the creation of the survey instruments and the rationale behind the chosen approach. This will be followed by a discussion on the procedure for administering the survey and the analytical techniques employed to interpret the results.

4.2 Identifying variables

To access the different layers of perception, participants were invited to the lightvan and the cyclic loading on the glazing unit was run. Participants were invited both during the day and the nighttime (Figure 51). After each observation an interview was conducted to collect their explanation of what is happening, and the changes noticed during the session. The collected information can be categorized as two. Some of the information is relevant for the perception of glazing deflection from outdoors looking at the façade of a building and others are relevant to perceiving deflection indoors. In both cases the noise coming from the compression and decompression of the cavity played a significant role and has been noted by all participants. Although the vacuum generator was later moved to the exterior, the noise the solenoid makes while switching between valves and releasing pressure still has an impact. To counter this, a noise canceling headset was used during the session conducted with participants.

In addition, to make the acoustical condition of the experiment similar throughout the sessions, the noise was pre-recorded and played over a speaker close to the original source of noise. Participants assessing the experimental design have noted that the glass deflection is particularly visible during the day from the outside as the reflection on the glass is clear. It has also been pointed out that lower levels of distortion are visible when the reflected image is linear, like the reflections of the brick wall. Nonlinear shapes like the reflections of the trees are less recognizable when their reflection is changing if the amplitude of deflection is low. From the interior looking outside, participants can sometimes see reflection when the sun is at a certain angle. During the night, the view of the outside is less discernible as the light intensity outside decreases and participants can clearly see the reflection of themselves and the room they are in on the glazing. As the DGU starts moving, participants have noted the change in reflection. Some have also mentioned the distortion of the view outside.

From the first impressions of participants four categories of perception and an additional parameter of disruption to activity and annoyance have been extrapolated.

Fig 51. Testing with preliminary participants

1. Perception of movement

Participants reported varying degrees of sensitivity to the physical movement of the glazing. This perception is influenced by the extent and frequency of deflection. The sensation of movement can impact occupant's satisfaction and sense of stability within the space, making it a critical factor in glazing design. Understanding this perception helps in setting appropriate deflection limits that minimize discomfort while maintaining structural efficiency.

2. Perception of change in reflection

Prior research has evaluated the influence of glazing a static deflection on view distortion. In the tests performed by Oke. (2023), it was observed that outdoor view was not perceptibly distorted. However, the effect on the reflections on the glass surface was clearly visible during glazing deflection (see Figure 52). As shown in Figure 52 and 53 respectively for the night and day conditions, deflections on glazing are visible from indoors at night because of the reflections, and from outdoor during the day because of outdoor reflections. The glazing unit was deflected under a cycling load. This was decided to include the additional disruption caused by high frequency movements under dynamic wind loading.

Preliminaray tests revealed participants observed distortions in the reflections of indoor elements, such as ceiling lights and furniture. These distortions can be distracting and may alter the experience of the interior space. Addressing this perceptual change is essential for studying the perception and acceptance of glazing movement.

Figure 52 Indoor view during the deflection of the glazing at night: a. condition with no deflection, b. condition with deflection 10 mm; c. condition with maximum deflection at 23 mm.

Figure 53 Outdoor view during the deflection of the glazing: a. condition with no deflection, b. condition with deflection 10 mm; c. condition with maximum deflection at 23 mm.

3. Perception of change in the view of the outside

While reflections were a primary concern, some participants also noted changes in the view of the outside through the glazing. The perception of change in view can be attributed to the interference of the distorted reflections observed on the glass while viewing outside. These changes are typically subtle but still significant for those sensitive to visual consistency and clarity. The perception of a distorted view can affect how occupants interact with their environment, potentially impacting their overall satisfaction with the view.

4. The Perception of safety

Perhaps the most critical perception was related to safety. Participants expressed concerns about the structural integrity of the glazing when they observed significant deflections. This perception of safety is key, as it directly influences the sense of security and well-being of the occupants.

5. Disruption to Activity and Annoyance

The perception of annoyance due to glazing deflection is a parameter explored in this research. Participants reported feeling irritated by the continuous or noticeable movement of the glass. This irritation was often linked to the frequency and amplitude of the deflections, with more frequent and larger deflections causing greater annoyance. This annoyance can influence the overall comfort and satisfaction of the occupants, making it an essential consideration for glazing design.

Participants also noted that the deflection of glazing could disrupt their activities. For instance, significant movements or changes in reflections could interrupt concentration or distract from tasks such as reading, working on a computer, or attending meetings. These disruptions can reduce productivity and negatively impact the overall functionality of the space.

Hypothesis:

The perception and acceptance of an individual to the amount of glazing deflection can be assessed experimentally.

There is a correlation between perception of movement in glazing and perception of safety

Information about glass property and impact of thin glass has a positive influence of the perception of safety.

Objectives:

Defining a set of scales to measure 4 sets of perception and creating a questioner to assess their change with the change of deflections. The survey design is to answer the following design questions:

1. What are the factors affecting occupant acceptance to deflection?
2. What is the effect of glazing deflection on user perception and acceptance?
3. What is the influence of information on the perception of safety?

Dependent, independent and confounding variables:

To answer the questions above the experiment was designed to include the following variables. The independent variable is the center of glass deflection, which refers to the extent to which the glass panes bend or flex due to applied pressure. This variable is manipulated to observe its effects on various dependent variables. The dependent variables include the perception of movement, perception of safety, and perceived annoyance and disturbance. These are the subjective responses of participants to the changes in glass deflection, reflecting how the deflection influences their sense of perception and acceptance of the overall experience within the space. Several confounding variables could potentially influence these perceptions and introduce bias. The biases include acoustical cues, lighting conditions, weather, indoor environmental quality (IEQ), prior knowledge of the participant, and age. These factors are not controlled by the experiment but can impact the participants' perceptions, thereby affecting the study's outcomes. Managing these confounding variables is important to ensure that the observed changes in dependent variables are primarily due to the manipulation of the independent variable, allowing for accurate assessment of the effects of glass deflection. A summary of the variables can be seen in table 9.

Table 9: Summary of variables used in the experimental setup in the lightvan experiment.

Independent	Dependent	Confounding
Center of Glass Deflection	Perception and acceptance of movement	Acoustical cues
Knowledge of glass		Lighting condition
	Perception and acceptance of change in reflection.	weather
		IEQ
	Perception of safety	view
		Prior knowledge
	Perceived annoyance and disturbance	Age

The confounding variables of age, weather condition and noise were recorded and the confounding variables of lighting condition inside a room and view of the outside were kept constant. To test the effect of knowledge of glass on the perception of safety, the sample population divided into two groups of 19 people making up a total of 38 participants. To better control prior knowledge as a confounding variable the participants were limited to post graduate students. Each experiment was conducted with 3 scenarios to test. The scenario tested are set to different deflection limits. Scenario A corresponds to 50 % below current serviceability limit set in the draft euro code of structural glass which come to 10 mm. Scenario B was set at the current serviceability limit of 19 mm and scenario C was set 30 % below the breaking pressure inside the cavity which corresponds to 23 mm. Table 10 summarizes the scenarios.

The experiment was designed as a repeated measured test to evaluate the influence of glazing deflection on participants perception and acceptance. Conversely, the impact of time of the day and previous knowledge was assessed by conducting between-subjects experiments. Participants were randomly exposed to the three levels of centre-of-glass deflection, either at day or at night conditions. In addition, knowledge on the safety of the glazing and the impact of material reduction on sustainability was provided to approximately half of the participants (detail numbers are reported in Table 10). The centre of glass deflection was controlled during the experiment by varying the air pressure in the cavity by means of a bespoke setup, which is described in section 3.3. However, a dummy fan was also placed outside the window and activated during the experiments to mimic the presence of wind in front of the façade. To reduce any potential bias from knowledge of the purpose of the experiment, participants were informed that the purpose of the experiments was to evaluate the performance of the glazing unit under the wind load induced by the fan. The laboratory was south oriented and shaded by the surrounding buildings, thereby ensuring that the participants were never exposed to direct solar radiation. The indoor artificial lighting was kept switched on during the whole experimental sessions, both during the day and the night. The overall scenarios and corresponding number of participants are described in Table 10.

Table 10: Tabulation of the 3 scenarios, time of day, condition of knowledge provided or not and number of participants in each repeated measure.

Glazing deflection at the centre of pane	Time of the day	Provided knowledge	Number of participants
Repeated measured in random order (38 participants)	**Between-subjects**		
10 mm (scenario A) 50% Below SLS	Day (20 participants)	Yes	8
		No	12
	Night (18 participants)	Yes	9
		No	9
19 mm (scenario B) SLS	Day (20 participants)	Yes	8
		No	12
	Night (18 participants)	Yes	9
		No	9
23 mm (scenario C) Above SLS	Day (20 participants)	Yes	8
		No	12
	Night (18 participants)	Yes	9
		No	9

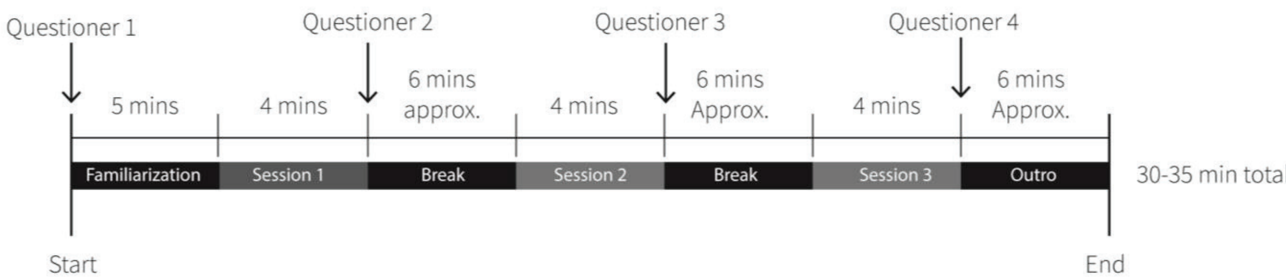

Figure 54: sequence of events on the experiment and the time taken by each event

Figure 54 shows the overall experimental procedure. Each experiment lasts for 30-35 minutes. At the start, participants were asked to sit at the desk to familiarise with the environment for approximately 5 min. During the familiarization time, participants were asked to fill in the consent form and the first questionnaire. This questionnaire contained questions regarding demographics, eyesight characteristics, personality, attitude towards sustainability, overall acoustic and thermal satisfaction, satisfaction with outdoor view, and self-reported sensitivity to surrounding movement while working. Each participant was then exposed to the three different levels of deflection in a randomised order, each lasting four minutes. During these four minutes, the glazing did not deflect during the first and last minute. To mask the noise of the pneumatic system, participants were also provided with noise cancelling headset, while the noise of the setup was kept constant even when the air pump was not activated to minimise any potential bias. During these test sessions, participants were asked to answer a set of questions based on the outdoor view from their seating position. After each test session, participants were then asked to fill out a questionnaire assessing their perception and acceptance of the deflection. The main parameters are reported in Table 11. Data on users' perception were collected regarding: (i) movement, (ii) change in reflection, (iii) distortion of their view of the outside and (iv) safety. It is also used to document their annoyance and disturbance to the different deflections tested. The questionnaires are included in the Supplementary Data of this report (Appendix 2). Tests were conducted at night with 20 participants and during daytime with 18 participants, for a total number of 38 participants. In addition, 17 participants out of 38 were then also provided with knowledge on the safety of the glass and on the impact of glazing stiffness on embodied carbon and sustainability.

Table 11: Main parameters measured during the experiment and related methodology

Domain	Parameter	Methodology
Visual environment	Outdoor illuminance on horizontal surface in proximity of Lightvan	Illuminance sensor Range: 0-50000 lx Resolution: ±100 lx
Acoustic environment	Noise level	Noise level meter
User response	Users' acceptance of glazing movement Users' acceptance of reflections on glazing User acceptance of view distortion Users' perception of glazing movement Users' perception of reflections on glazing User perception of view distortion User perception of safety in relation to glazing movement User annoyance during the experiment User self-reported impact of glazing movement on concentration during the task	Questionnaire, 5-point Likert scale.
Facial expressions	Facial action units	OpenFace software by means of webcam place in front of the user.
Glazing deflection	Pressure inside the glazing cavity. Centre of glass deflection	Pressure transducer, Linear variable differential transformer sensor

Research has indicated that people attach different personalities to different motion cues and hence interact with them differently. To capture participants' personality, an under 5 min personality test was used and consists of 10 questions of which 2 questions refer to one of the big 5 personalities.

The "Big Five" personality traits, also known as the Five Factor Model, provide a comprehensive framework for understanding human personality. These traits include Openness to Experience, characterized by imagination, creativity, and a preference for novelty, with high scorers being curious and inventive, while low scorers are more conventional and practical. Conscientiousness reflects organization, dependability, and discipline, with high scorers being reliable and goal-oriented, and low scorers being more spontaneous and careless. Extraversion encompasses sociability and assertiveness, with high scorers being outgoing and energetic, and low scorers (introverts) being more reserved and preferring solitary activities. Agreeableness involves compassion, cooperativeness, and altruism, with high scorers being friendly and empathetic, and low scorers being more competitive and skeptical. Finally, Neuroticism is characterized by emotional instability and anxiety, with high scorers experiencing more emotional distress and low scorers being more emotionally stable and calm. These traits capture the range of behaviors and attitudes that individuals exhibit in various situations, providing an overview of personality and have been included in the introduction survey.

The structure of the survey is illustrated in Figure 55. In summary, the introduction survey characterizes participants, the main surveys document their perception and acceptance of the different scenarios, and the outro captures the general acceptance of participants. The survey was developed in Qualtrics and can be found in appendix 2.

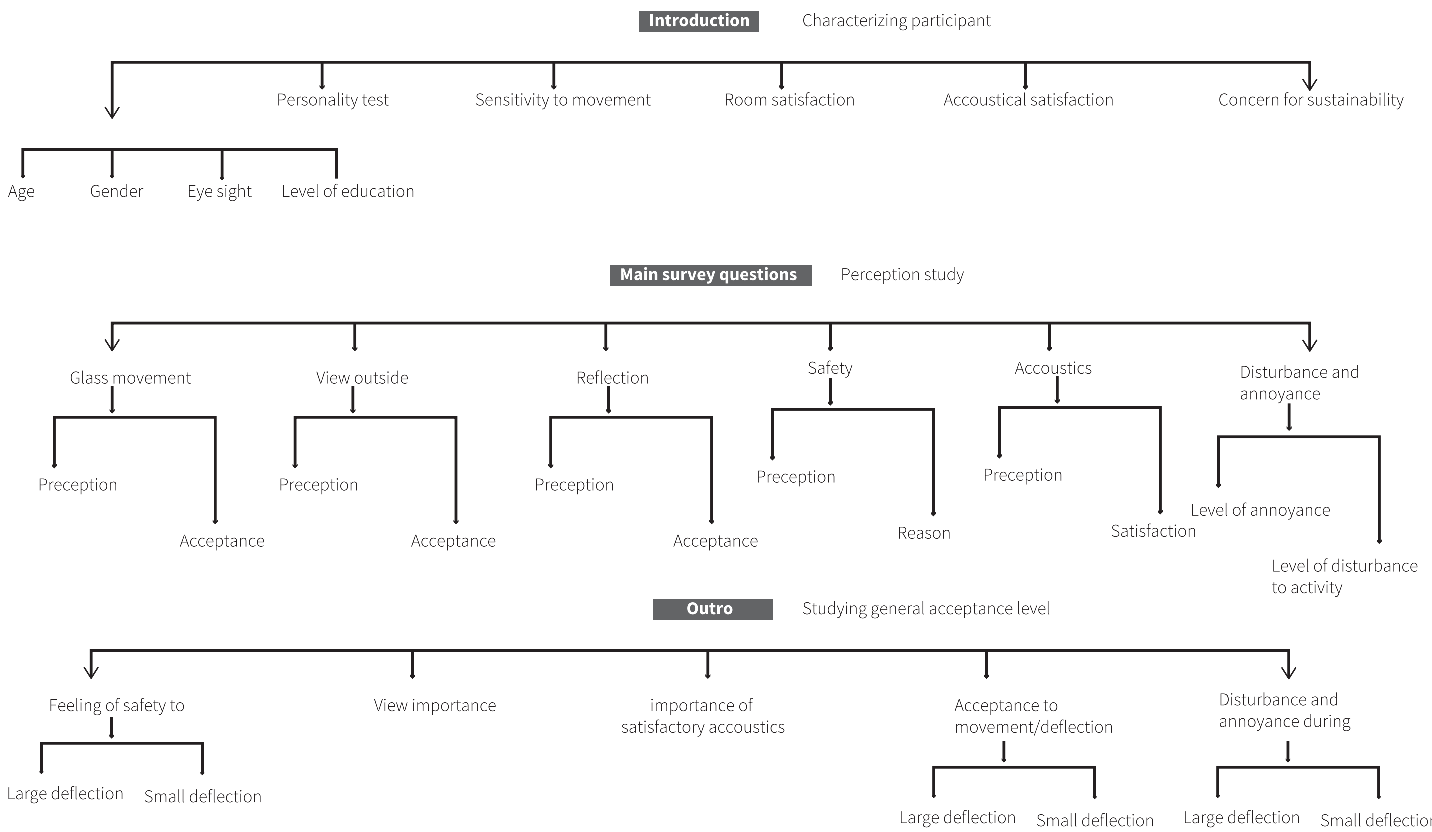

Figure 55: Structure of surveys. Introduction survey used tin the start of the experiment, main survey questions used in the 3 repeated measures and outro survey used to conclude the experiment.

4.3 Conclusion

This chapter has outlined the survey design and methodology used to assess occupant perception of glazing deflection. By capturing subjective responses to varying degrees of deflection under simulated real-world conditions, this study aims to provide insights that inform the optimization of material usage in building designs without compromising occupant satisfaction.

The methodology discussed in this chapter involved developing an extensive survey instrument, selecting a diverse group of participants, and implementing a rigorous data collection procedure. Participants were exposed to controlled deflection scenarios within a cyclic loading setup, and their perceptions were documented through a series of structured surveys. These surveys included introductory questions to gather demographic and background information, main scenario-based questions to assess perceptions and acceptance of deflection and concluding questions to capture overall impressions and acceptance levels.

The survey highlighted several key areas of perception: movement, changes in reflection, view distortion, safety, effect on concentration and annoyance. Participants' response to these factors can be documented with the questions in the main survey.

To ensure the reliability of the results, the study accounted for various confounding variables such as acoustical cues, lighting conditions, weather, and participant demographics. The randomization of deflection patterns further strengthened the validity of the survey by minimizing potential biases.

Additionally, the research explored the influence of information on perception, hypothesizing that educating participants about the properties and benefits of thinner glass positively impacted their perception of safety.

By employing a systematic approach to survey design, this chapter has provided a framework for assessing occupant perception and acceptance of glazing deflection. The empirical data collected through the surveys offers valuable insights into how different levels of deflection are perceived, highlighting the importance of considering occupant satisfaction in glazing design. These findings contribute to the broader goal of creating sustainable built environment, demonstrating the critical role of empirical assessment in informed design decision-making. As the field of building technology continues to evolve, the methodologies and insights from this study will serve as a valuable resource for future research and innovation in glazing system design.

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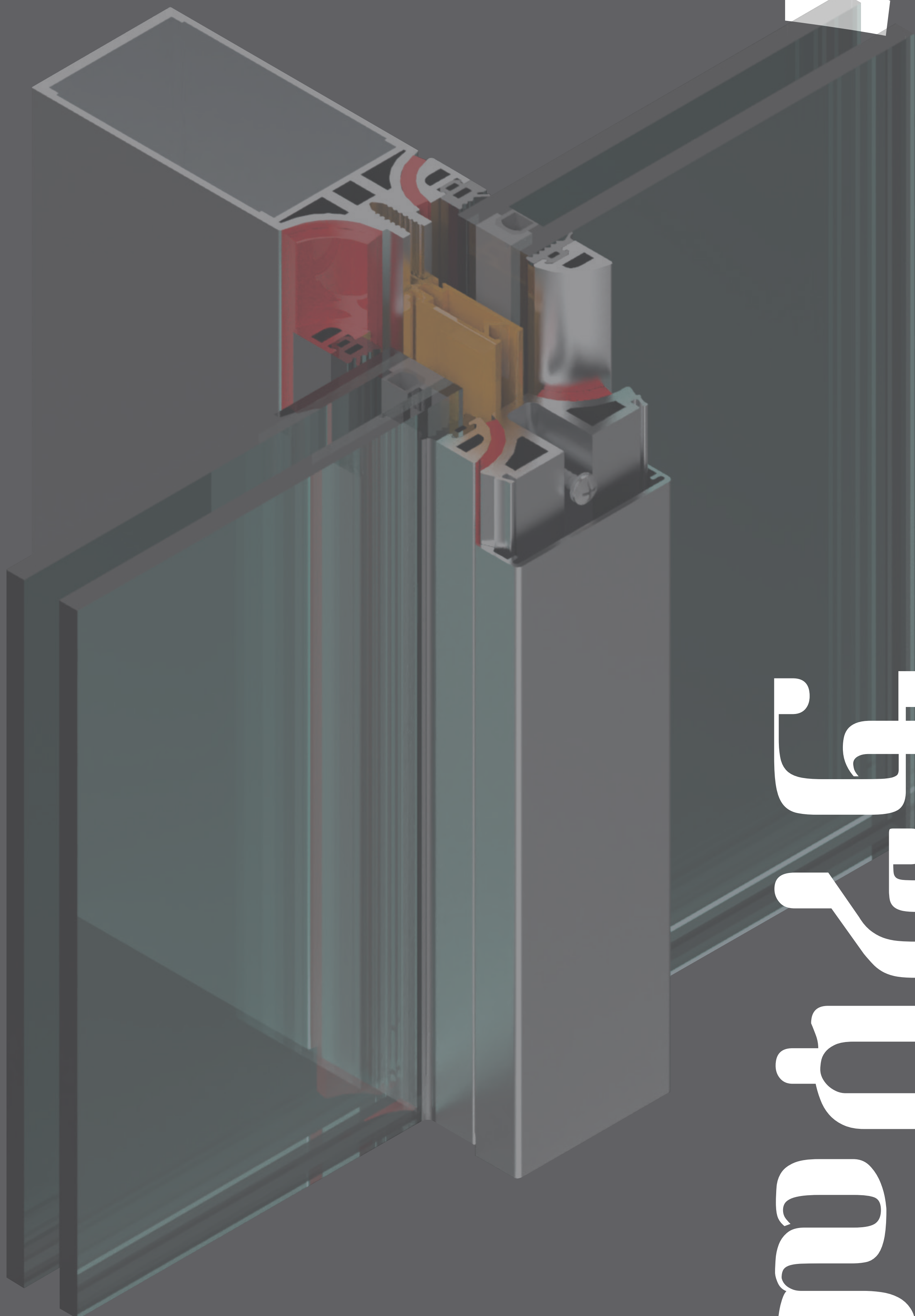


Results and implications

5 Results and implications

5.1 Introduction

An experimental campaign with human participants was conducted in May 2024 to capture occupant perception and acceptance of glazing deflections. The experiment was approved by the Human Research Ethics Committee of TU Delft and granted ethical approval. A total of 40 participants were recruited for the experiments and responses from the questionnaires were collected via Qualtrics. Participants indicated their preference for either daytime or nighttime sessions. The nighttime sessions, accommodating four participants each, were conducted from 21:00 to 23:30, while the daytime sessions began at 10:00, running eight experiments throughout the day. Participants age range between 21 and 39 years, consisting of 24 male and 14 female.

In this chapter, we combine the experimental design discussed in Chapter 3 with the survey design outlined in Chapter 4. The goal is to analyze the data collected from the experiments and surveys to answer the research questions in Chapter 1.

Of the 40 data sets collected, 38 were deemed usable. The data from the first participant was excluded because they played a critical role in refining the experimental duration, activities, and session timing. Additionally, the initial questionnaire was updated after the second session to enhance participant understanding and improve the clarity of the questions.

All survey data were compiled into a single database for analysis. This chapter details the analysis process and presents the findings, which address the research questions concerning occupant perception of glazing deflection, the factors influencing this perception, and the implications for design and sustainability in building technology.

The data collected from the surveys were compiled into a single, centralized database. This database included responses from the introductory survey, main scenario-based surveys, and concluding survey, providing a holistic view of each participant's experience and perceptions.

The analysis process involved several steps:

1. **Data Cleaning:** Ensuring the accuracy and completeness of the data, removing any anomalies or incomplete entries.
2. **Descriptive Statistics:** Demographic study and summarizing the data to identify general trends and patterns in participant responses.
3. **Inferential Statistics:** Using statistical tests to determine the significance of observed differences and correlations between variables.

The data collected from Qualtrics was analyzed using the statistical software SPSS. After cleaning and structuring the data, descriptive and inferential statistics was used to interpret the results. Levens homogeneity test was first performed. The participants were grouped by time of day (daytime and nighttime) and a linear mixed model analysis was performed to assess the influence of the different levels of deflection on the perception and acceptance of movement, view distortion and change in reflection.

The perception of safety was also checked and the effect of knowledge on the perception of safety has been tested.

5.2 Participants demographic

The demographic analysis of the participants provides insights into the diversity and representativeness of the sample used in this study. The data was collected through an introductory survey which captured various demographic and personality traits of the participants.

Age Distribution

The age distribution of participants ranged from 21 to 39 years, with the majority falling between 25 and 33 years. Specifically, the most represented age groups were 26-27 years and 28-29 years, each with a frequency of six participants. This indicates that the study primarily included young adults, which is reflective of the postgraduate student population targeted for this research.

Gender Distribution

The gender distribution was relatively balanced, with 25 male participants and 15 female participants. This gender ratio ensures that the perceptions of both male and female occupants are well-represented in the study.

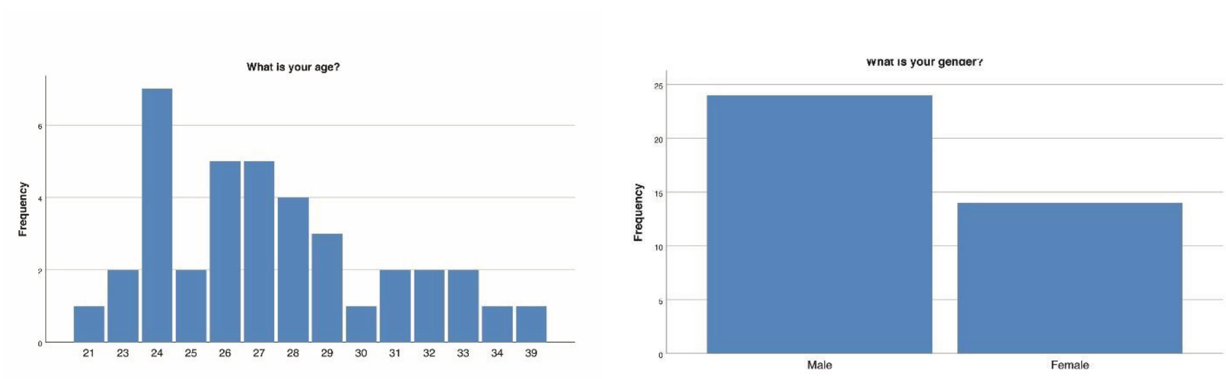


Figure 56: Demographics of participants Age and gender frequency plotted from spss.

Eyesight Correction

Regarding eyesight correction, the participants were divided into three categories: long-sighted, short-sighted, and no corrections. Most participants (approximately 20) reported no eyesight corrections, while the remaining participants were almost evenly split between long-sighted and short-sighted (Figure 57, left).

Sensitivity to Movement

Participants' sensitivity to movement varied, with responses ranging from noticing movements "every time" to "almost never." Most participants indicated that they notice movements "occasionally" or "almost every time," suggesting that a significant portion of the sample is attuned to changes in their environment, which is critical for assessing their perception of glazing deflection (Figure 57 right).

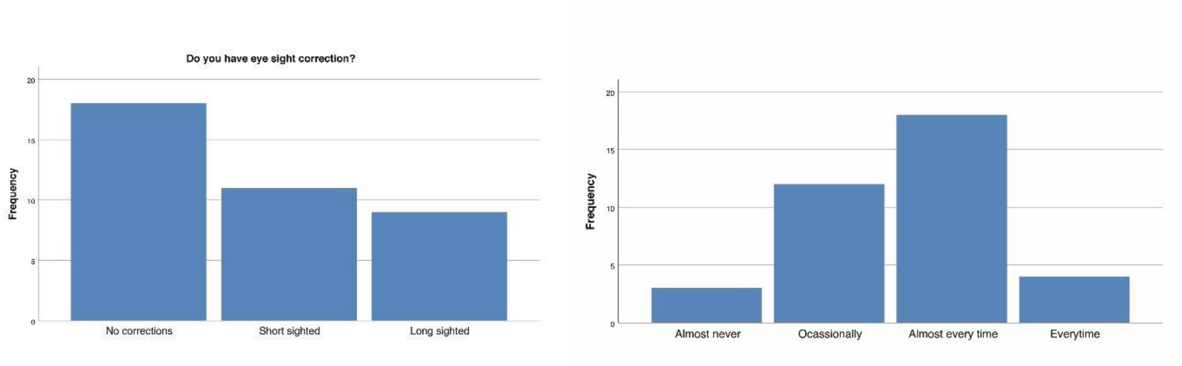


Figure 57: Demographics of participants: Type of eyesight (left) and level of sensitivity to movement (right) plotted from spss.

Personality Traits

The Big Five personality traits were measured on a scale from 1 to 5. The distribution for each trait was as follows:

Extraversion: The scores varied, with a notable number of participants scoring between 2.5 and 4.5, indicating a balanced mix of introverted and extroverted individuals (Figure 58, left).

Agreeableness: Scores were clustered around the mid to high range, with many participants scoring between 3.0 and 4.5, suggesting a generally cooperative and friendly sample (Figure 58, right).

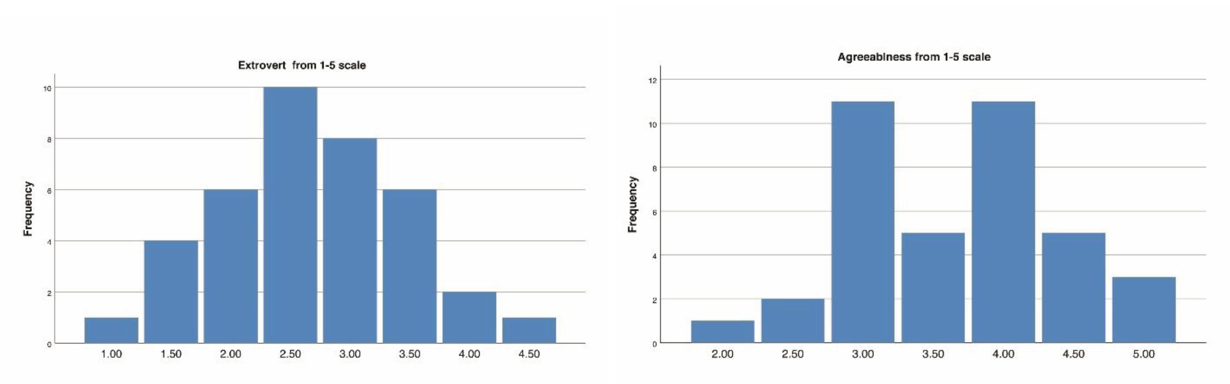


Figure 58: Frequency distribution of participants personality: Extroverts(right) and agreeableness(left) personality showing a normal distribution.

Conscientiousness: Participants showed a strong inclination towards being organized and reliable, with scores mostly ranging from 3.0 to 4.5 (Figure 59, right).

Neuroticism: The scores for neuroticism varied widely, with a significant number of participants scoring in the mid-range, indicating a moderate level of emotional stability (Figure 59, left).

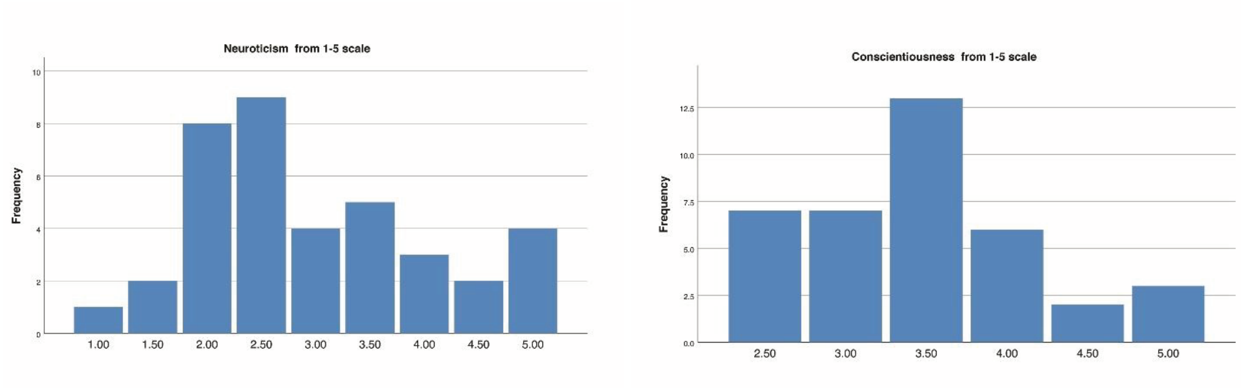


Figure 59: Frequency distribution of participants personality: Neuroticism and consciousness personality.

Openness to Experience

Participants demonstrated a wide range of openness, with scores spanning from 2.5 to 5.0, reflecting diverse levels of openness to experience (Figure 60).

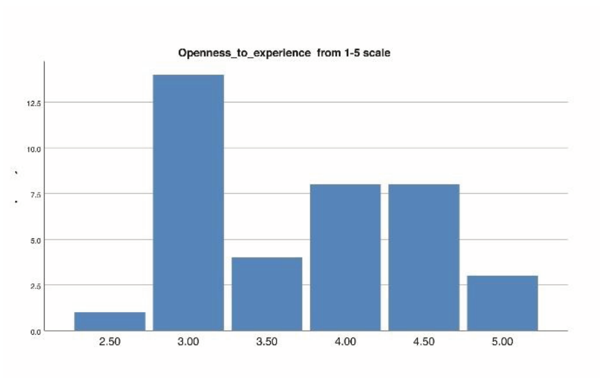


Figure 60: Frequency distribution of participants personality: Openness personality.

The demographic analysis highlights a diverse and representative sample in terms of age, gender, eyesight correction, sensitivity to movement, and personality traits. The balanced gender distribution and the wide range of personality traits are important for capturing a comprehensive understanding of how different individuals perceive glazing deflection, thus enhancing the reliability and generalizability of the research outcomes.

5.3 Satisfaction with indoor environment condition

The provided boxplot (Figure 61.) visualizes participant satisfaction with three environmental aspects of the room: acoustical quality, temperature, and the view outside the window. The satisfaction levels are rated on a scale from 1 (least satisfied) to 5 (most satisfied). Overall participants satisfaction of acoustical quality, temperature inside the room and view was above 3 meaning all were neutral, slightly satisfied or satisfied with the condition.

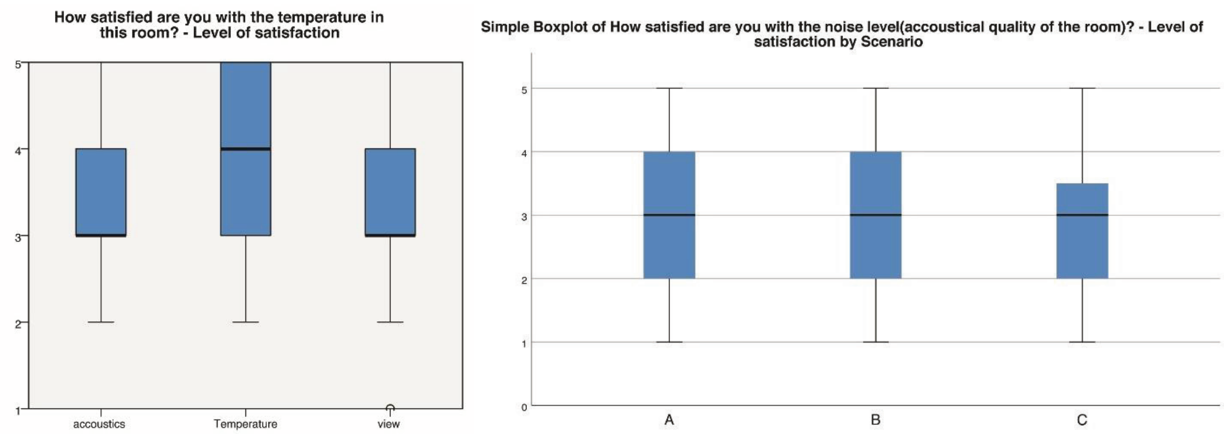


Figure 61: Box plot of response from participants regarding comfort: Satisfaction to the acoustical condition of the room, temperature of the room and View of the outside.

When comparing the acoustical conditions across different sessions, the median satisfaction levels are comparable to those captured in the introductory survey. The experimental design aimed to maintain consistent acoustical conditions throughout the sessions to minimize their confounding effect on perceived satisfaction. The graph shown on the right side of Figure 61 clearly demonstrates that the efforts to standardize acoustical conditions were successful, as evidenced by the consistent satisfaction ratings. This consistency ensures that variations in participant responses are more likely due to the experimental variables rather than differences in room acoustics.

5.4 Assessing perception and acceptance of participants

The surveys utilized a 5-point Likert scale to assess participants' perceptions and acceptance levels. For perception of movement, change in reflection, and change in view of the outside, the scale ranged from "strongly disagree" to "strongly agree." Acceptance of these perceptions was measured on a separate 5-point scale, ranging from "totally unacceptable" to "totally acceptable." Annoyance levels were evaluated using statements ranging from "annoyed" to "perceivable but not annoying." Concentration levels were assessed on a scale from "not aware at all" to "extremely affected." These metrics provided an understanding of how participants perceived and accepted the various conditions tested in the experiment.

Movement

Overall, the movement of the glazing was perceived by all participants both during the day and the night sessions, as shown in Figure 62. a. However, there was a significant difference in participants' perception during the day and the night sessions. At night, a larger number of participants perceived a movement of the façade to a greater degree. A similar difference between the day and night session was measured in terms of acceptance (Figure 62.b), where participants in the day session deemed the movement of the glazing to be significantly more acceptable than those in the night session. Nevertheless, almost none of the participants during night sessions perceived the glazing movement "Totally unacceptable", even for the largest deflection. Participants' acceptance is significantly lower at 23 mm than at 10 mm and 19 mm. In terms of perception of movement, there was no effect of the magnitude of the deflection, since there is no statistical difference between the scenarios with different deflection when comparing with in the day and nighttime sessions.

Furthermore, interviews revealed that frequent changes in reflection made the deflections more noticeable for some participants, while others were more attentive to the degree of change in reflection, resulting in a lower mean perception for condition B compared to A and C. The effect of frequency of perception is hence a factor to be explored by further research.

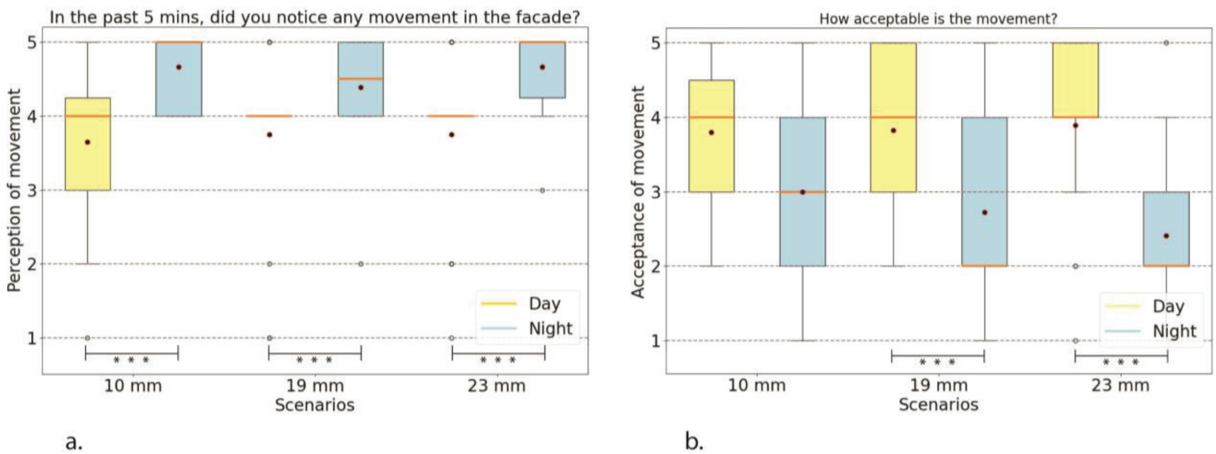


Figure 62: a. Participant perception of movement from 5 (Strongly agree: Absolutely: there was a significant movement in the facade) to 1 (Strongly disagree: I didn't noticed any movement of the façade), the "3" shows the neutral vote "I am unsure if there was any movement in the façade"; b. Participant acceptance of the movement: With a scale from 5 (Perfectly acceptable) to 1 (totally unacceptable), the "3" shows the neutral vote (Neither acceptable or not acceptable). The red dots show the means while the orange lines the median. The level of significance is shown as: "" p value < 0.05; "**" p-value < 0.01; "***" p-value < 0.001.*

Change in reflection

The mean perception of change in reflection during daytime sessions is generally lower than that during nighttime sessions, although both are within the highest range of ratings. We observed some outliers and extreme outliers in the data. The minimum score for condition A is 1, indicating that some participants did not notice any reflections at this level. Conversely, during the nighttime sessions for condition C, nearly all participants reported a significant change in reflection. This suggests that deflection and reflection changes are more noticeable and impactful in lower light conditions.

As shown in Figure 63.a, all participants strongly perceived changes in reflections during the deflection of the glazing. Only at 10 mm, did participants report a significantly lower perception of changes in reflections on the glazing (p-value < 0.05), but it was still noticed by participants. In terms of acceptance of changes in reflections, Figure 63.b, the acceptability of reflections during the day was much higher than at night, when the level of acceptability was low (mean acceptance close to slightly unacceptable). While during the day, the acceptance decreases with increasing deflection, at night the impact of magnitude of deflection on acceptance is negligible.

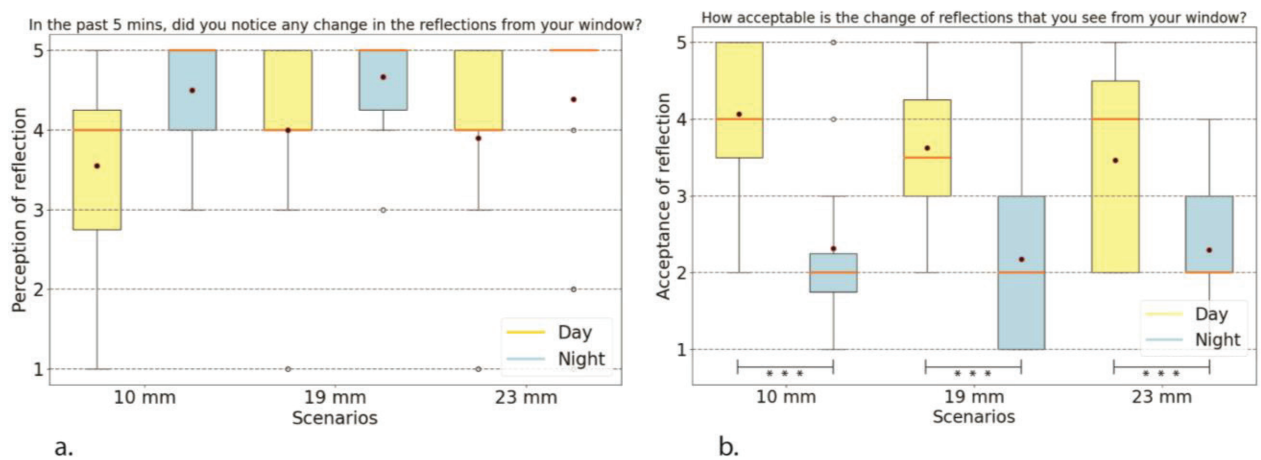


Figure 63: a. Perception of changes in reflection during day and night sessions; from 5 (Strongly Agree: There is a significant change in reflection.) to 1 (Strongly Disagree: There is no change in reflection.), the "3" shows the neutral vote " Neutral: I am unsure about the change in reflection.";: b. Acceptability of changes in reflection across the scenarios at day and night: With a scale from 5 (Perfectly acceptable) to 1 (totally unacceptable), the "3" shows the neutral vote (Neither acceptable or not acceptable).. The red dots show the means while the orange lines the median. The level of significance is shown as: "" p value < 0.05; "**" p-value < 0.01; "***" p-value < 0.001.*

Distortion of the view outside

In general participants did not perceive view distortion (Figure 64. a). Consequently, during the day and night the mean acceptability was either below the line of "Neither acceptable or not acceptable" or near "Perfectly acceptable"(Figure 64.b). This suggests that participants were less aware of distortion in the outside view at both times of day when compared to their awareness of changes in reflections on the glass. This indicates that the timing of the session had minimal impact on the perception of outside view distortion, and participants were more attuned to reflection changes than to any distortion in the view.

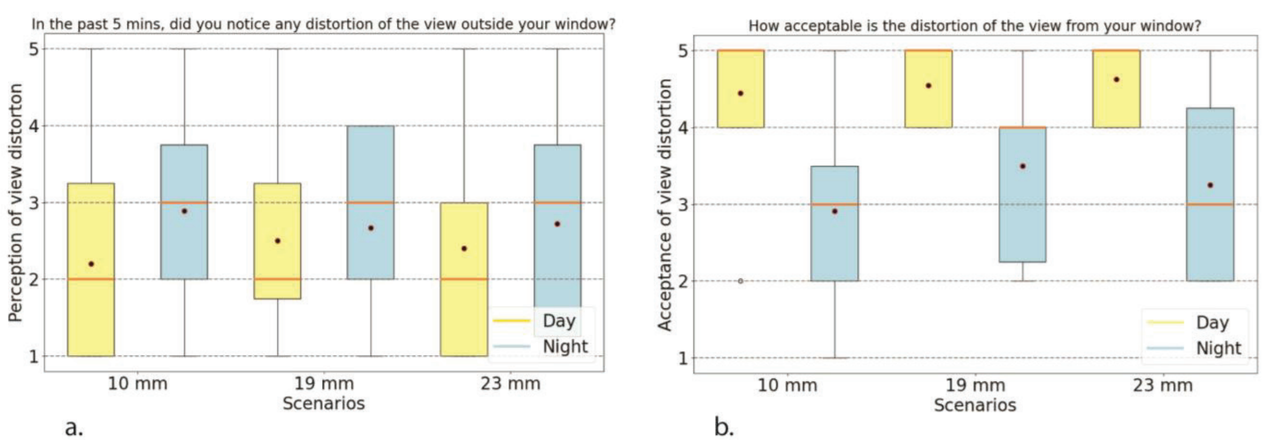


Figure 64: Perception and acceptance of view distortion: a. Perception of view distortion during the day and night; from 5 (Strongly Agree: There was a significant distortion in my view outside.) to 1 (Strongly disagree: There was no distortion in my view of the outside.), the "3" shows the neutral vote " Neutral:I am unsure about the change of distortion in my view of the outside."; b. Acceptance of view distortion during the day and night: With a scale from 5 (Perfectly acceptable) to 1 (totally unacceptable), the "3" shows the neutral vote (Neither acceptable or unacceptable). The red dots indicates the means while the orange lines the median. The level of significance is shown as: "" p value < 0.05; "**" p-value < 0.01; "***" p-value < 0.001.*

Perception of Safety

Participants were also questioned on their perceived safety while the glazing was moving. Figure 65.a shows the overall perceived safety. There is no significant difference between scenarios and day / night, except for the largest deflection, where perception of safety was slightly lower at night. However, the perception of safety is generally positive across all scenarios. Previous knowledge had no significant impact on the perception of safety (Figure 65.b).

Figure 67.a shows the main factors that contributed to user perception of glazing movement. Changes in reflections were the most perceptible and consequently the reason for the perceived loss of safety when glazing is moving. As shown Figure 66.a and 66.b, previous knowledge did not affect the acceptance of movement or the acceptances of changes in reflection.

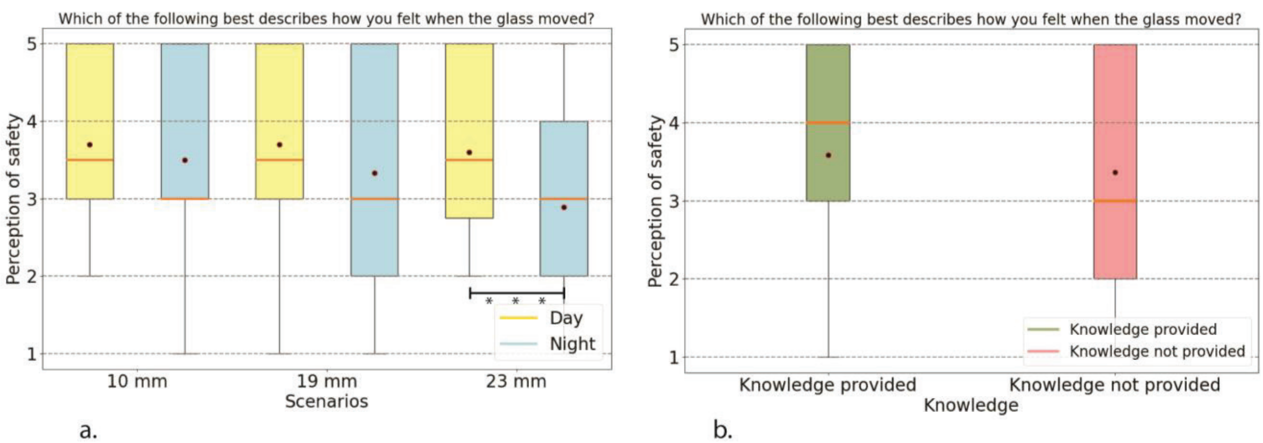


Figure 65: Perception of safety during glazing movement and impact of knowledge: a. Perception of safety while glazing is moving; from 5 (Safe.) to 1 (Unsafe.), the "3" shows the neutral vote " Neither safe or unsafe." ; b. Perception of safety while glazing is moving depending on previous knowledge of participants. The red dots show the mean while the orange lines the median. The level of significance is shown as: "" p value < 0.05; "**" p-value < 0.01; "***" p-value < 0.001.*

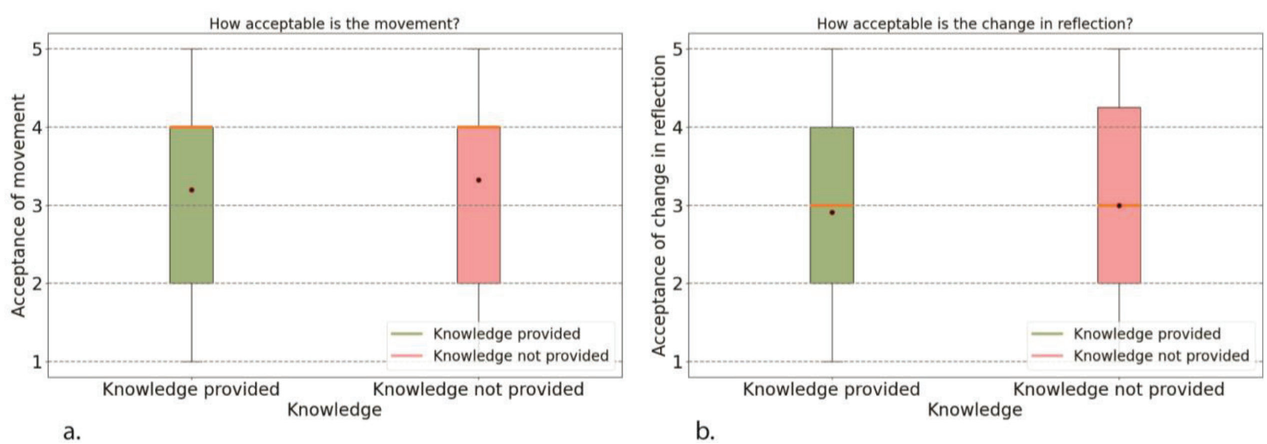


Figure 66: Impact of previous knowledge on participants acceptance: a. acceptance of glazing movement; b. acceptance of changes in reflections. With a scale from 5 (Perfectly acceptable) to 1 (totally unacceptable), the "3" shows the neutral vote (Neither acceptable nor unacceptable). The red dots show the means while the orange lines the median. The level of significance is shown as: "" p value < 0.05; "**" p-value < 0.01; "***" p-value < 0.001.*

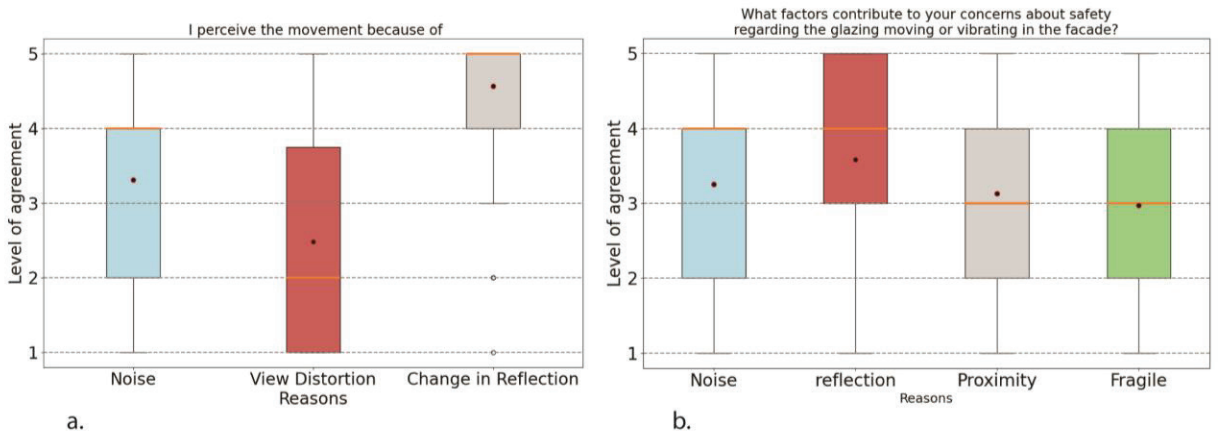


Figure 67: Factors contributing to perceive movement in glazing (a) and (b) factors contributing to concerns about safety when glazing is moving. from 5 (Strongly Agree.) to 1 (Strongly disagree.), the "3" shows the neutral vote. The red dots show the means while the orange lines the median. The level of significance is shown as: "" p value < 0.05; "**" p-value < 0.01; "***" p-value < 0.001.*

5.5 Assessing annoyance and effect on the concentration of participants

Participants reported less annoyance during the day compared to the night, with mean values remaining consistent across the three scenarios (Figure 68.a). From the interviews conducted after the experiment, it was revealed that the frequency of movement has an effect on participants, with more frequent movements leading to higher annoyance levels. During the day, the amplitude of the movement had a greater effect on participants, while at night, participants were more easily distracted, leading to higher overall annoyance. This suggests that both the frequency and amplitude of movements, along with the time of day, play crucial roles in influencing the level of annoyance experienced by participants.

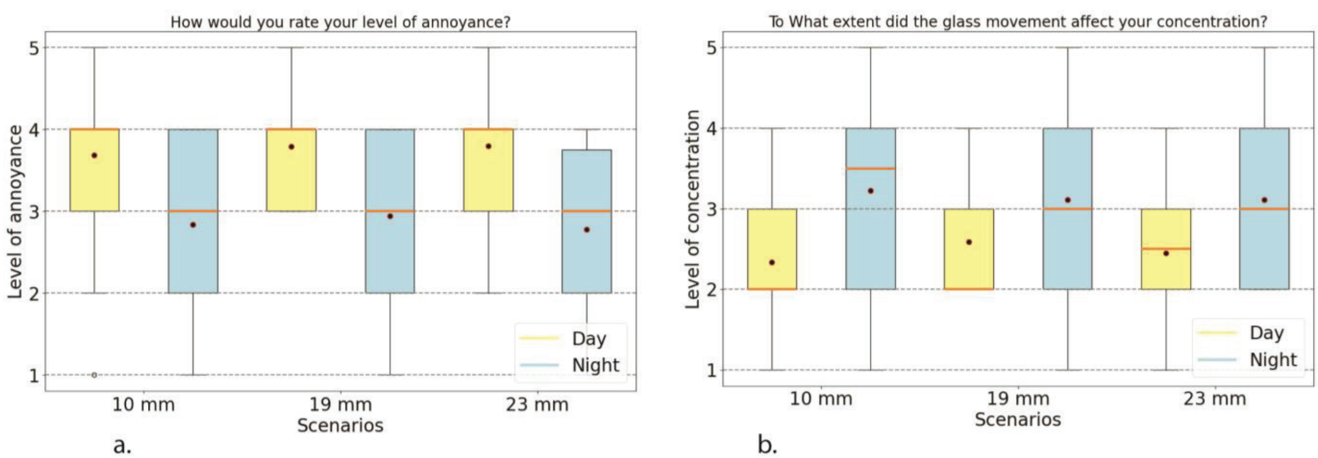


Figure 68: a. Annoyance from 5 (Unperceivable.) to 1 (Unbearable.), the "3" shows the neutral vote. The red dots show the means while the orange lines the median. Effect on concentration from 5 (Extremely affected.) to 1 (Not at all.), the "3" shows the neutral vote. The red dots show the mean while the orange lines the median. The level of significance is shown as: "" p value < 0.05; "**" p-value < 0.01; "***" p-value < 0.001 and b.*

5.6 Facial expression study

During the experiment conducted with participants, facial action units (AUs) were recorded. The record contains 17 AUs that correspond to specific facial expressions. AU activations are measured on a scale from 0 to 5, with the presence or absence of each unit captured as 0 (not activated) or 1 (activated). The data was processed using Python.

First, the CSV file was cleaned to remove unnecessary columns related to gaze analysis and facial landmark recognition. In future research, these records can be omitted by configuring OpenFace 2.0 to record only the action units. The readings were taken with timestamps corresponding to the computer used for the experiment. However, the time records were not accurate as the computer lacked an internet connection. To address this, the timestamps were remapped using the start and end times of each recording session, which were noted during the experiment.

Since the aim was to compare facial expressions during different deflection sessions, the data was further filtered to include only the rows corresponding to the periods of glass movement. Each session was then categorized based on the participants' deflection exposure patterns. The data collected from each participant was compiled to create a comprehensive database. Using this database, descriptive and inferential statistics were performed.

The box plot in Figure 69 shows the AUs categorized by scenario. A one-way ANOVA test revealed significant changes in most action units between the three scenarios, although the data contains considerable outliers, denoted by black circles.

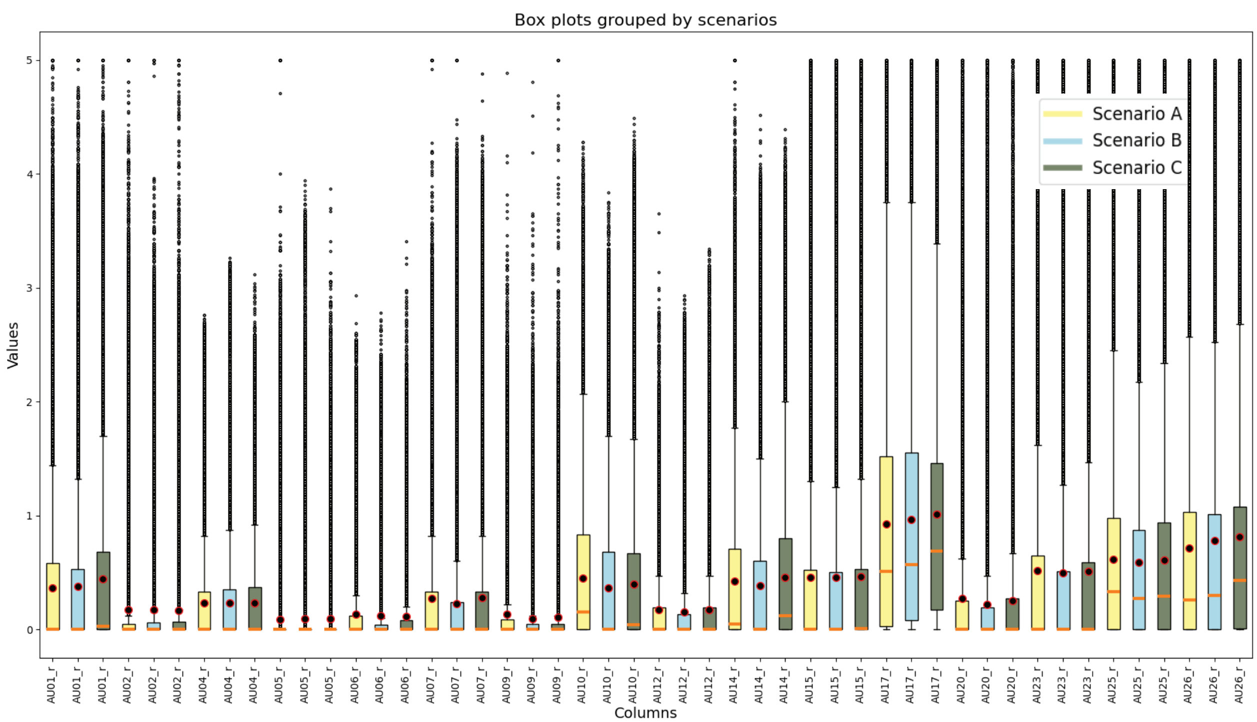


Figure 69: Box plot of facial action units (AU) of all participants. Each AU is plotted with the 3 scenarios of A (10 mm deflection), B (19 mm deflection) and C (23 mm deflection). The red dots denote the mean. The orange line denotes the median and the black circles denote outliers

The research speculates that the different activities participants were engaged in while the glass was moving might have influenced the varying results of facial action unit intensity. The database was filtered for a single participant to explore outliers. As shown in the sample box plot in Figure 70, there are still considerable outliers when examining the data at an individual level.

Nevertheless, it is noteworthy that documenting occupants' responses to glazing deflection is possible. However, confounding factors, such as changes in expression due to the activities participants are engaged in, could affect the recordings and must be considered.

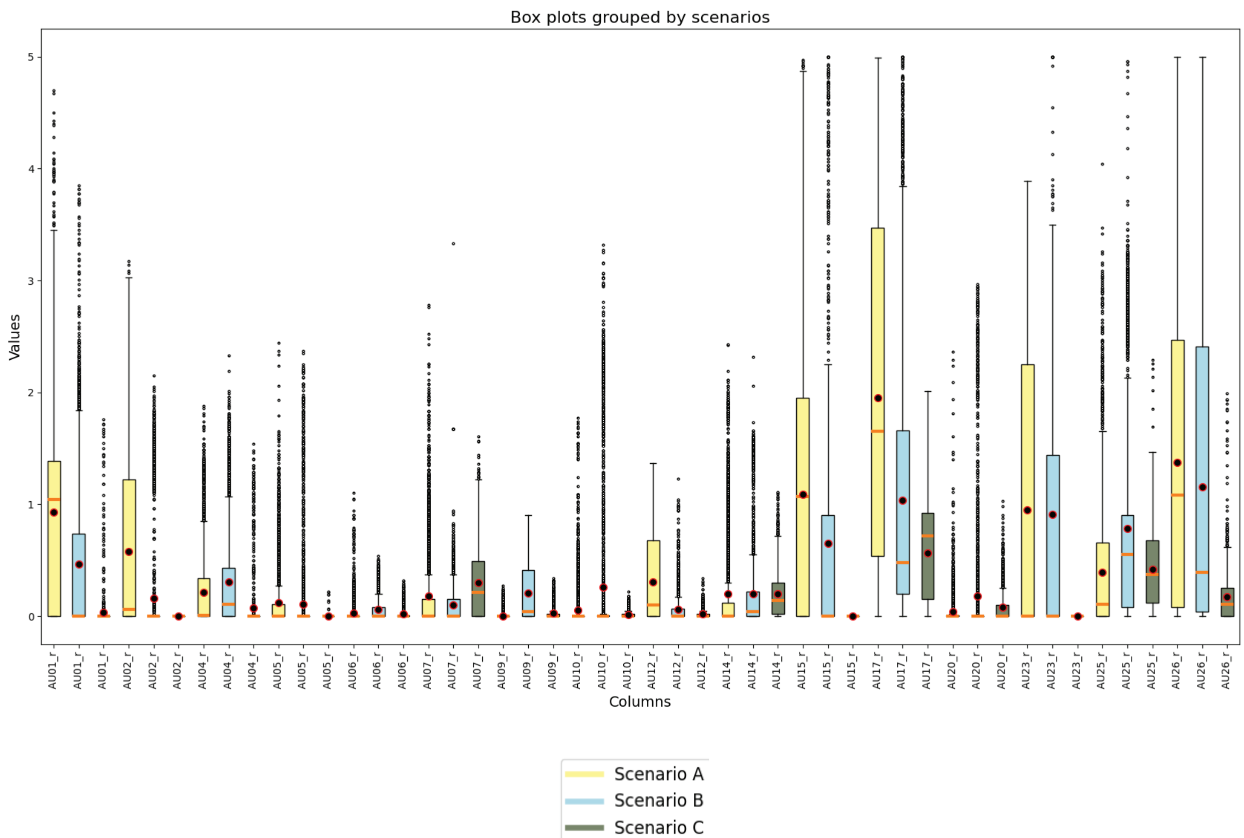


Figure 70: Box plot of facial action units (AU) of participant number 16. Each AU is plotted with the 3 scenarios of A (10 mm deflection), B (19 mm deflection) and C (23 mm deflection). The red dots denote the mean. The orange line denotes the median and the black circles denote outliers

5.7 Structural Implications

ANSYS

From the finding of relaxing the current serviceability limit explained previously in this chapter, a structural optimization was conducted on ANSYS to determine the potential material savings. The parameters used were

1. Thickness of the glass
2. The solid mass
3. Safety factor
4. Total deformation
5. Maximum principal stress

The analysis was conducted on considering geometric nonlinearity and the plane of size 972 mm x 1467 mm was subjected to the boundary conditions described in chapter 3. The range of thickness boundary was set between 2 mm and 8 mm. To determine the exact weight reduction, the possible thickness constraint due to manufacturing have not been considered. The optimization was started with the base glass thickness of 4 mm and the solution was iteratively determined with each step performing a static structural analysis and the results compared with the given constraint of total deformation. The first optimization was conducted with the constraint of 19 mm as the total deformation (Figure 71). This resulted in a glass thickness of 4.596 mm as the best candidate with a deflection of 18.965 mm. In other words, if the current serviceability limit was used to determine the thickness of the glass it would be required to be at least 4.596 mm which gives us the weight of 16.276 kg of glass weight (Table 10). A second experiment was conducted with the 23 mm as the constraint to the deformation (fig 66). This is a 4 mm increment in the deflection set by the current serviceability limit. The results are the minimum required glass thickness decreases to 3.823 mm with a weight of 13.538 kg (Table 12).

The change in thickness reduction comes up to about 16.8 %. This weight reduction doesn't account for the load sharing effect of glass and studies have shown that it contributed to 30 % less concentration in stress when compared to the structural analysis performed on a glass modeled as a simple plane. This means that the current estimation of potential material saving can be increased if advanced structural analysis was performed. To perform such an analysis, specialized tools like SJ Mapla can be used.

Table 12: Candidates of optimization study with 19 mm deflection limit. Result of optimization study in Ansys with the objective of achieving the minimum weight in in the limit of 19 mm.

	P1- thickness (mm)	P2- Solid mass (kg)	P3 –Safety factor minimum	P4-Total deformation maximum (mm)	P5- Maximum principal stress maximum (MPa)
Candidate points	4.596	16.276	0.39856	-18.965	48.179

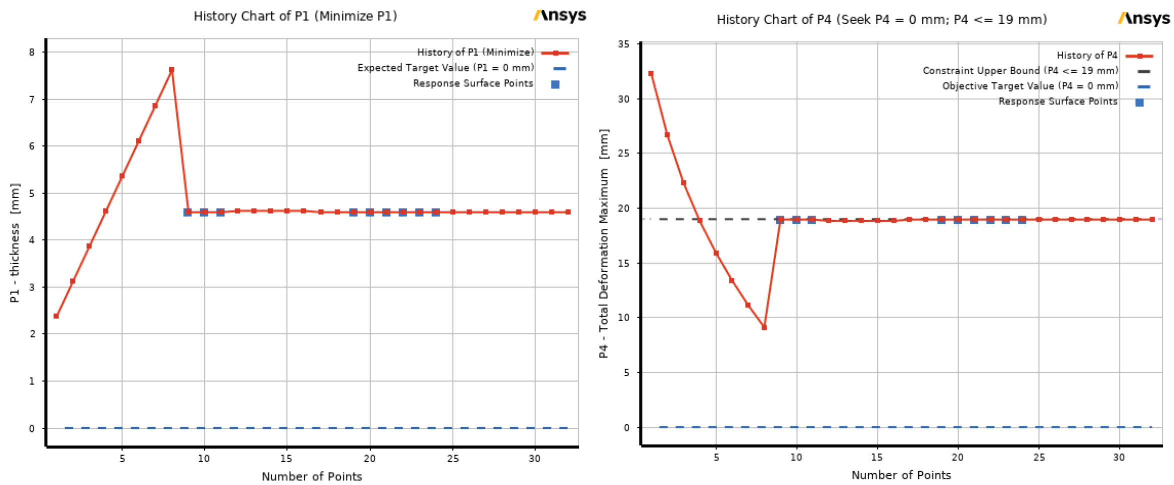


Figure 71: optimization steps of 19 mm deflection limit. Result of optimization study in Ansys with the objective of achieving the minimum weight in in the limit of 19 mm. Thickness iteration (left) and total deformation(right)

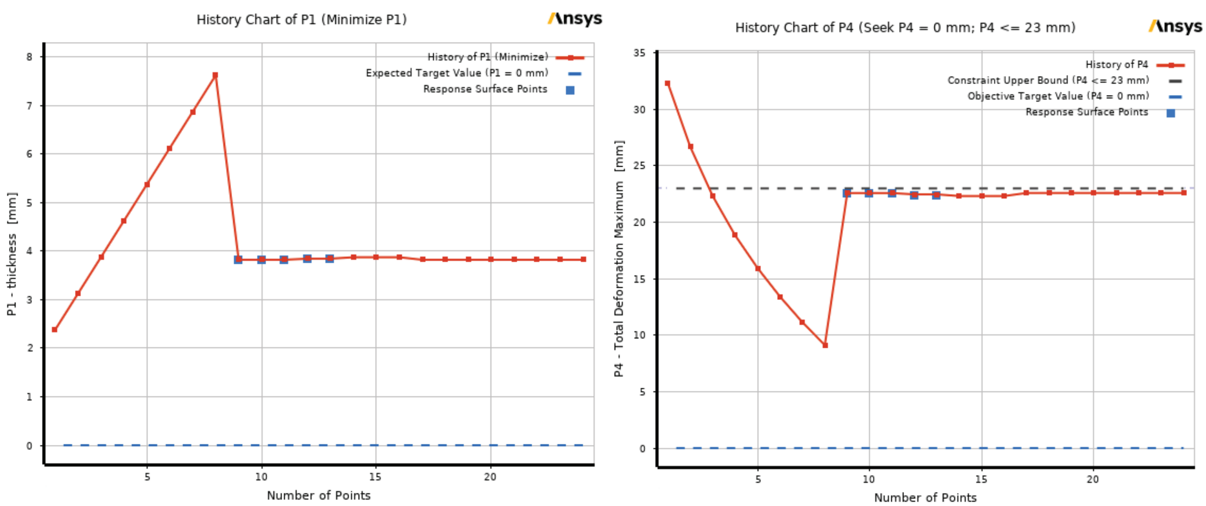


Figure 72: optimization steps of 23 mm deflection limit. Result of optimization study in Ansys with the objective of achieving the minimum weight in in the limit of 23 mm. Thickness iteration (left) and total deformation(right)

Table 13: Candidates of optimization study with 23 mm deflection limit. Result of optimization study in Ansys with the objective of achieving the minimum weight in in the limit of 23 mm.

	P1- thickness (mm)	**P2- Solid mass (kg)**	**P3 –Safety factor minimum**	**P4-Total deformation maximum (mm)**	**P5- Maximum principal stress maximum (MPa)**
Candidate points	3.823	13.538	0.30126	-22.595	64.021

SJ Mepla

The weight reduction estimations performed in ANSYS do not account for the load-sharing effect of the glass panes, as the model was simplified. If the load-sharing effect is considered, there is a potential for a 26-54% reduction in glass thickness compared to glass estimated using a rule-based approach (Heiskari et al., 2022). This estimation, proposed by Heiskari (2023), can be observed when comparing the thickness of the glass modeled in ANSYS versus the IGU model done in SJ Meple. For a given load, aspect ratio, size, and boundary condition of the glass, the analytical model in ANSYS overestimated the minimum thickness required to achieve the current serviceability check by 34% (Table 13).

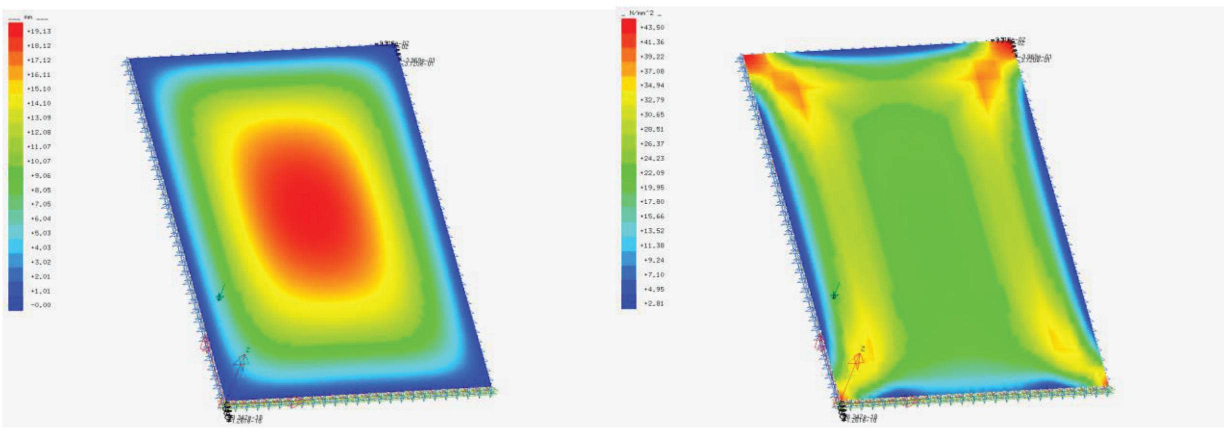


Figure 73: Structural analysis in SJ Mepla. Maximum deflection in the pane of glass the load was applied on(left) and maximum principal stress on the pane of glass the load was applied on (right).

Table 14: Tabulation comparing analytical model performed ANSYS and SJ Mepla. Similar boundary conditions were used and resulting minimum thickness required are compared.

	Glass type	Pressure(Pa)	SLS	Size of pane	Number of panes in the model	Air gap	Maximum principal pressure (MPa)	Minimum thickness of glass required
ANSYS	Fully toughened glass	4173 Pa	L/50=19 mm	1476mm x972 mm	1	N/A	48.18	4.596 mm
SJ Mepla	Fully toughened glass	4173 Pa	L/50=19 mm	1476mm x972 mm	2	16	43.5	3 mm

The IGU used in the experimental setup was modeled in SJ Mepla as a vertically installed simply supported glass with the bottom edge restrained from moving in the y axis. The glass was modeled with an air gap of 16 mm and with a material of fully toughened glass. The aim is to compare the effect of relaxing serviceability limit on weight reduction. The design load was applied normal to the pane of glass. The magnitude of load couldn't be the same as the one used in ANSYS as SJ Mepla couldn't arrive at a solution when determining the deflection of a glass below 3 mm. Hence, a glass with a higher thickness of 6 mm and a higher design load of 1.43 x e^{-2} Mpa was used. The pane of glass used to check the thickness and deflection is the one directly subjected to the load. The pane of glass on the opposite side of the applied load experiences less stress and deflection. The minimum required thickness to meet the two deflection limits was then iteratively calculated. For the results illustrated in Table 15, relaxing the current serviceability limit of L/50 to L/40 can potentially result in an 18% reduction in the amount of glass material used.

Compared to the material estimation in ANSYS of 16.8 %, the model in SJ Mepla predicts slightly higher material savings, with an approximate increase of only 1%.

Table 15: Tabulation comparing minimum thickness required based on deflection limit. The deflection limit compared are that of the current serviceability limit(L/50) and the relaxed serviceability limit of (L/40).

	Glass type	Pressure (Mpa)	SLS	Size of pane	Number of panes in the model	Air gap	Maximum principal pressure (Mpa)	Minimum thickness of glass required
SJ Mepla	Fully toughened glass	1.43 x e^{-2}	L/50=19 mm	1476mm x972 mm	2	16	51.47	6 mm
SJ Mepla	Fully toughened glass	1.43 x e^{-2}	L/50=23 mm	1476mm x972 mm	2	16	67.17	4.9 mm

5.8 Design implications

In addition to occupant's satisfaction, reducing glass thickness can affect the façade's performance in terms of air and water tightness. Transitioning from an L/50 to an L/40 serviceability limit or increasing the deflection limit from 19 mm to 23 mm, is feasible by increasing the thickness of EPDM gaskets. This adjustment could compensate for the movements of the glass pane when subjected to wind or climatic loads.

This design exploration in this subchapter considers a scenario involving a much more relaxed deflection limit, resulting in a more pronounced edge rotation. EPDM gaskets are designed to accommodate movements up to a certain percentage of their total thickness. Exceeding this limit risks compromising gasket performance, leading to direct contact between the glass panes and the aluminum framing. Such contact can create local stress points on the glass, potentially resulting in performance failures in air and water tightness or structural failure if the stress exceeds the glass's capacity.

The design shown in Figures 74-76 illustrates a façade profile engineered to accommodate movement. It features a hinge made of polyurethane, chosen for its durability and the range of flexibility that can be engineered into the material. This hinge is designed to be stiff enough to prevent unnecessary movement while remaining flexible enough to stretch and compress, accommodating edge rotation effectively.

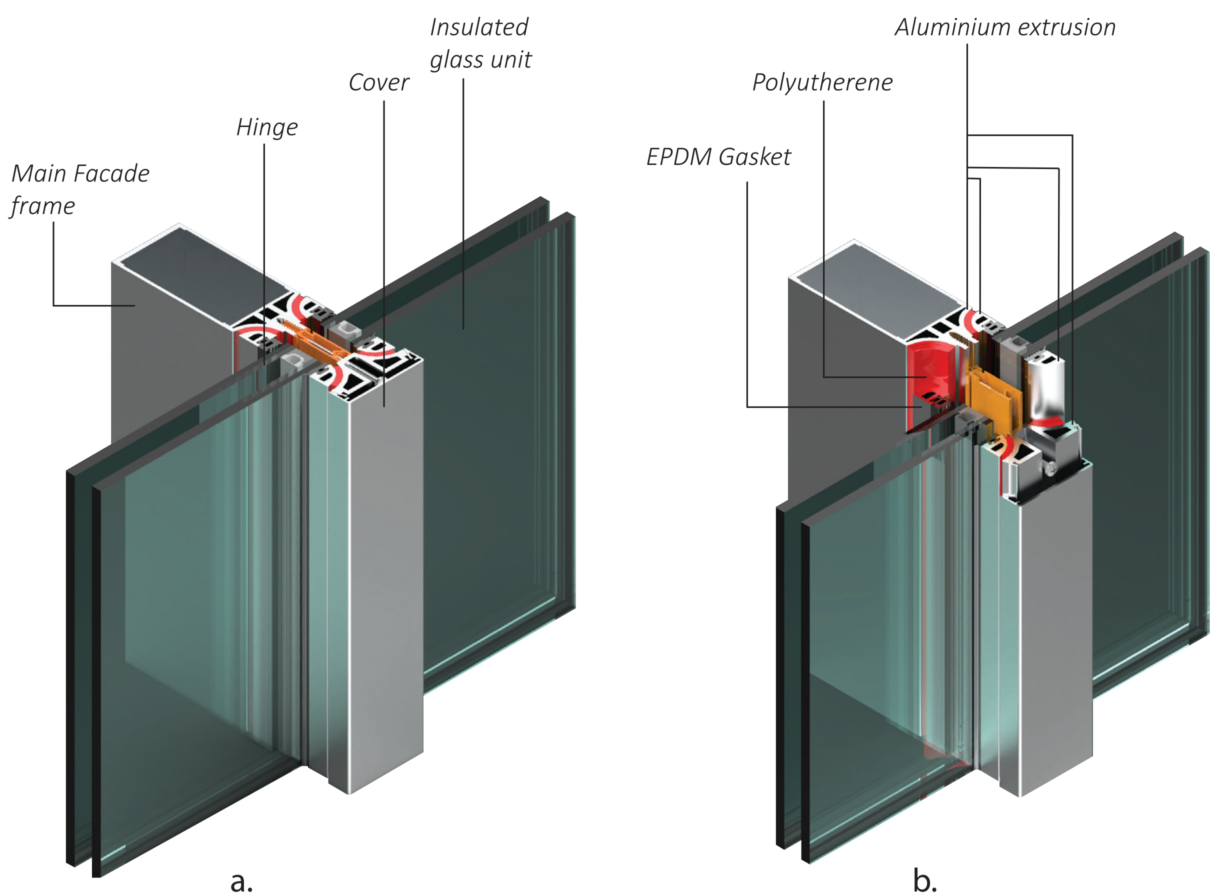
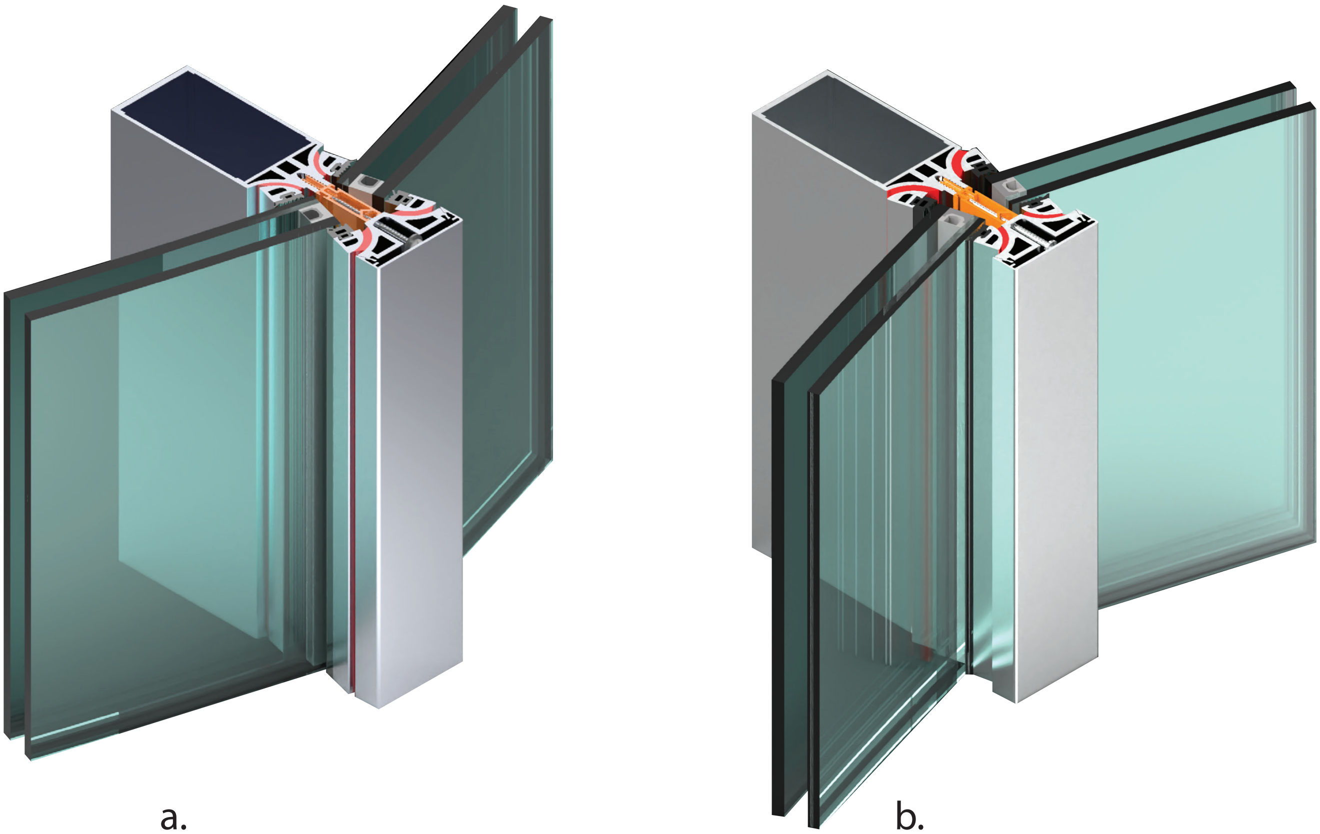


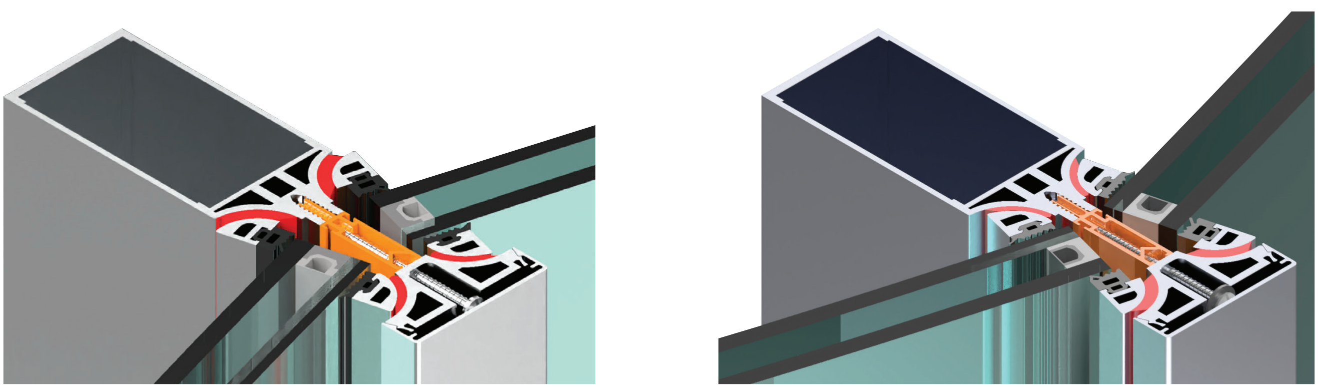
Figure 74: a. over all construction of proposed façade section to accommodate edge rotation. b. component break down showing the working of the hinge that accommodates edge rotation



a.

b.

Figure 75: a and b illustrate how the proposed section accommodates deflection of IGU.



a.

b.

Figure 76: a and b illustrate the workings of the polyurethane, compressing and stretching to accommodate for edge rotation that could potentially occur during higher defection caused by relaxing serviceability limit.

5.9 Conclusion

Chapter 5 has meticulously combined the experimental design discussed in Chapter 3 with the survey methodology outlined in Chapter 4 to analyze the collected data. By recruiting 40 participants and conducting sessions both during the day and at night, the research aimed at understanding how various factors influence the perception of glazing deflection and its implications for design and sustainability.

The demographic analysis revealed a balanced and diverse participant pool, encompassing a range of ages, genders, eyesight conditions, sensitivity to movement, and personality traits. This diversity is crucial for ensuring that the findings are robust and applicable to a broad audience. The balanced gender distribution and the variety of personality traits enriched the research understanding of different perceptions. It is worthy to note that all participants were from a technical background and further research with various participant's background would be beneficial to broaden the participant pool.

The overarching findings of this study indicates that it is possible to measure human response to glazing movement, which can in turn provide valuable evidence on human requirements for setting the serviceability limit. The experimental campaign conducted and the resulting occupant responses to glazing movement suggest there is room for questioning and relaxing existing serviceability limits. This provides opportunities for material efficiency, such as the use of thinner glazing solutions and a reconsideration of user perceptions and expectations of glass stiffness.

The proposed methodology effectively captures human responses to glazing movement. Participants noticed glazing movement throughout the experiment, with significantly higher perception during the night, irrespective of the magnitude of the movement. Acceptance of movement during the day is significantly higher than at night, particularly when maximum deflections are evaluated. However, user acceptance of movement does not decrease when existing serviceability limits are exceeded and remains above the "slightly unacceptable" level, similar to deflections within the serviceability limits.

Changes in reflection were the primary reason participants perceived glazing movements, with significantly lower acceptability at night and dependent on the magnitude of movement. This effect could be mitigated by installing anti-reflective coatings or films. Conversely, distortion of outside view had no significant impact. Overall, participants felt safe regardless of their prior knowledge about glass properties, and providing this information did not improve acceptance, which was already sufficiently high.

Future work and limitations include the need to consider the contextual impacts of the study, as it was conducted in a controlled environment with specific conditions. User expectations of glazing performance and environmental quality can vary based on context. For instance, the lab's ground-floor location may influence safety perceptions compared to glazing at height, and expectations of glazing performance in high-end office buildings might differ from those in a laboratory setting. These results are contextual, and generalizing the findings will require testing with larger populations in real office environments with different façade designs.

Additionally, the potential noise from the glazing movement generated in the experiment, may impact user acceptance and safety perceptions. The maximum deflection evaluated was approximately 23 mm; future studies should investigate larger deflection-to-span ratios. Larger deflections, well beyond the above-listed serviceability limits could have been accommodated during the experiment if a tempered glazing would have been tested.

Participants were in a relatively small spaces, maintaining a constant distance and orientation towards the façade. Future research should explore the impact of participants' angle of view and distances from the façade on their perception and acceptance of movement, reflections, and safety. The tasks performed by participants could also affect their perceptions; in this experiment, participants were specifically asked to look through the glazing, but their perception and acceptance might be more positive when focused on other tasks. Finally, human response was only captured from indoors, while outdoor perception of the façade's aesthetics can also be a significant consideration in enabling larger deflections. Further studies should therefore also assess user perceptions of glazing deflections from outdoors. That said, there is a clear incentive to relax the current serviceability limit, the change from L/50 to L/40 promises a potential material saving of 18%. Hence, a more relaxed limit ought to be explored in the future and the resulting effect on façade performance studied.

6 Reflections

1. Relation between the Graduation Project Topic, Studio Topic, Master Track, and MSc Program

The building technology master's program focuses on designing innovative and sustainable building components and integrating them into the built environment. Throughout my study, I have focused on façade design and sustainable structural design. The topic of my research "Empirical Assessment of Glazing Serviceability Limit: Exploring Occupant Acceptance" is concerned with material efficiency and façade performance. The aim is to find a balance of high-performance glazing with a reduced thickness without compromising the occupant's satisfaction. To achieve this the research has studied glass deflection, assessing the structural behavior of IGU under wind loading and the occupant threshold of acceptance of IGU under this cyclic deflection.

To effectively implement my research, I have chosen the discipline of two fields of study within the Building Technology track. The facade and structural design studios provided the necessary framework to combine the study of occupant's acceptance of IGU deflection and the potential thickness reduction in glazing thickness from relaxing the current serviceability limit.

2. Relevance of Graduation Work in the Larger Social, Professional, and Scientific Framework

Glass is one of the go-to materials for the façade of a building. It contributes to 26-60% of the overall embodied carbon of facades depending on their typology. We are at a time where the building industry ought to push for a better-performing building but also decrease the embodied carbon in the building. Glazing plays a crucial role and affects both the operational and embodied carbon footprint of the building.

Nonetheless, in regulations and codes governing the design of glass, there has been an absence of a clear threshold for human acceptance of deflections in glass. Hence, glazing thickness is typically determined with the assumption that humans have a low tolerance for glazing deflection. This leads to the glass being thicker than strictly necessary.

Recent technologies have enabled the production of thin glass. However, very thin glass panes are more susceptible to deflection. The research aim is to provide an empirical assessment of occupant's acceptance of glazing deflection to reduce the weight on high-performance IGUs.

Furthermore, the research emphasizes critical questioning of the current serviceability limit on glazing. As the need to reduce the weight of structures and our understanding of structural design advances, we should consider occupant level of acceptance as a means to design thinner structures with a lower environmental footprint without compromising the intended performance.

3. What is the relationship between the methodical line of approach of the graduation studio and your chosen method?

The façade and building products focus on a multi-dimensional approach to tackling the question of sustainability in the built environment. The research conducted is in line as it has explored multiple methods including an experimental design, survey design, statistical analysis and structural optimization to answer the main research questions. The first challenge to tackle was how to mimic cyclic loading on facades. For this, a 1:1 prototype of façade glass was equipped with sensors and pneumatic systems to get a controlled cyclic deflection. Moving further, the research has tackled the question of how to document the perception of an occupant and this included a survey design. To design the survey a preliminary assessment of the perception of glazing movement was conducted by inviting 8 PhD researchers and interviewing the experience from which the different forms of perception were extrapolated. An experiment was then conducted to study the correlation of different deflection limits to the perception and acceptance of occupants. The experiment was assessed with statistical tools to come up with a conclusion. Finally, from the information gained, structural analysis and optimization were performed to deduce the design and material-saving implications of the research.

An empirical assessment of glazing serviceability is a study that ranged from the study of the perception to material saving and it has benefited from the multidimensional approach of the studio of façade and building's product.

4. Impact of Research on Design/Recommendations and Vice Versa

The ecological impact of design has become one of the important considerations in the past decade. With the EU passing new laws to regulate the impact of constructions in the built environment, it is imperative to research different means of achieving sustainability. The question is, are we using more material than we should be? This research has taken an approach that does not develop a new technology but rather a methodology to reconsidering the current convention. The results will inform decision-making, particularly in the design of highly glazed buildings where glass can contribute up to 40% of the façade's weight. Glass material reduction will then have an impact not only on how we design façades but also on the main structure of the building, potentially having a secondary impact on material savings in the main structure.

5. Does the project contribute to sustainable development?

Indeed, the project contributes to sustainable development in several keyways. Firstly, by focusing on the empirical assessment of glazing serviceability limits and occupant acceptance of glazing deflection, the research directly addresses material efficiency. Reducing the thickness of glazing without compromising occupant satisfaction can lead to substantial material savings. Thinner glass panes mean less raw material usage, which directly correlates to a reduction in the embodied carbon footprint of building façades. This is crucial given that glass can contribute to 26-60% of the overall embodied carbon of façades depending on their typology.

Secondly, the project aligns with the broader goals of sustainability by aiming to balance high-performance building components with environmental impact. The shift from assuming low human tolerance for glazing deflection to empirically determining acceptable deflection limits can lead to a better informed and optimized use of materials. This approach not only minimizes weight but also promotes the consideration of occupant comfort when setting the limit.

Finally, by integrating occupant's satisfaction into the design criteria of glazing, the research ensures that sustainability does not come at the expense of building usability and satisfaction. This human-centered approach is essential for the long-term success and acceptance of sustainable building practices.

6. To what extent are the results applicable in practice?

The applicability of the results in practice depends on several factors, including the accuracy of the experimental setup, the representativeness of the test conditions, and the relevance of the findings to real-world scenarios as more considerations come into play.

It is essential to consider potential limitations such as the scale of the study, the assumptions made during the experiments, and external factors that were not accounted for. These limitations must be acknowledged and addressed when applying the results to practical scenarios.

Future work and limitations include the need to consider the contextual impacts of the study, as it was conducted in a controlled environment with specific conditions. User expectations of glazing performance and environmental quality can vary based on context. For instance, the lab's ground-floor location may influence safety perceptions compared to glazing at height, and expectations of glazing performance in high-end office buildings might differ from those in a laboratory setting. These results are contextual, and generalizing the findings will require testing with larger populations in real office environments with different façade designs.

To extend the applicability of this research in questioning the conventional limits, prolonged monitoring of the effects IGU deformation and influencing factors ought to be studied.

7. How does the project affect architecture / the built environment?

The empirical data generated from this research can influence building codes and standards related to glazing and façade design. Establishing clearer guidelines on acceptable deflection limits based on occupant's satisfaction can lead to a more rational and efficient use of materials, potentially driving changes in industry practices and regulatory frameworks.

The incentive for conducting this research varies depending on the stakeholder. For manufacturers, there is a drive to meet the growing market demand fueled by contemporary needs. Research such as this provides a foundational basis for developing new products that are lighter and have a lower carbon footprint, thereby aligning with industry trends towards sustainability and efficiency.

From a designer's perspective, the research offers insights into enabling the design of buildings that weigh less yet perform better and have a lower environmental footprint. It opens the potential for retrofitting heritage buildings with light weight and high-performance glass that can lead to improvements in building energy class.

Beyond the designer's realm and from a policymaker's perspective, the findings support the development of regulations and standards that promote material efficiency and occupant comfort. By understanding the benefits and implications of relaxing serviceability limits, policymakers can create guidelines that encourage the adoption of innovative solutions, ultimately contributing to reduced environmental impact and enhanced building sustainability.

8. Transferability of Project Results

The research methodology has been well documented, and it is just the beginning of the study of human perception and comfort regarding glazing deflection. The experimental setup will be stored properly, and the data collected from the survey archived to be studied further. The documented procedures and findings ensure that the project can be replicated or expanded upon by other researchers in the field.

Future studies can build on this research by using the same experimental setup and data to explore additional variables or refine the existing parameters. For instance, different types of glazing materials, various environmental conditions, or alternative locations could be tested to expand the applicability of the results.

9. What are the next steps to the research?

To achieve better control of glass movement, the experimental setup must be improved. This includes refining the control of airflow to regulate the frequency of movement across different scenarios and eliminating noise from solenoids switching to minimize distractions. Additionally, upgrading to a more accurate pressure sensor will enhance the reliability of the setup.

Further research should investigate factors influencing perception and acceptance, such as the angle of view, distance from the façade, and type of view. Long-term monitoring is essential to assess the effects over time and conduct a contextual study to evaluate how perception and acceptance vary across different building functions.

* **

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List of Figures

List of Tables

8 Appendix

Appendix 1

Product	Thick ness [µm]	Type of	filmTo use	Use Purpose	Classificatio n	Fire safety test*
S40	100	1-layer transparent	within	Protection against burglary and vandalism. Glass retention	EN12600:2B2	EN 45545-2: HL 1, 2, 3 DIN 54837: Pass DIN 5510-2: Pass
S70	175	1-layer transparent	within	Protection against burglary and vandalism. Glass retention	EN12600: Pass	EN 45545-2: HL 1, 2, 3 DIN 54837:
S80	200	2-ply, translucent	within	Protection against burglary and vandalism. Glass retention	EN12600: 1B1	DIN 5510-2: Pass
S140	325	3-ply, translucent	within	Protection against burglary and vandalism. Glass retention	EN356:P2A	
S600	150	multilayer	within	Protection against burglary and vandalism. Damage reduction in explosions. Glass retention	EN12600: 2B2	EN 45545-2: HL 1, 2, 3
S800	200	multilayer	within	Damage reduction in explosions. Glass retention	EN12600:1B1 EN356:P1A	
S40EX	100	1-layer transparent	outside / inside	Protection against burglary and vandalism. Glass that breaks spontaneously. Glass retention	EN12600: 2B2	
S70EX	175	1-layer transparent	outside / inside	Protection against burglary and vandalism. Glass that breaks spontaneously. Glass retention	EN12600: 2B2	

* Information on testing according to local regulations upon request

Appendix 2

Survey part	Q. No.	Question	Format	Choice options
Introduction	1	What is your ID number?	open	none
	2	What is your level of Education?	open	none
	3	What is your age?	open	none
	4	What is your gender?	Multiple choice	1.Male

				2.Female 3.Non-binary /third gender 4.Prefer not to say
	5	Do you have eyesight correction?	Multiple choice	1. No corrections 2. short sighted 3. Long sighted
	6	While you are working in your office, how sensitive are you at noticing movements in your surrounding? For example, movements in the surrounding such as the movement of automated blinds, people walking around the room, or a tree swaying outside your window	Multiple choice	5 Point Likert scale of: frequency
	7	How satisfied are you with the temperature in this room?	Multiple choice	5 Point Likert scale of: level of satisfaction
	8	How satisfied are you with the view from your window?	Multiple choice	5 Point Likert scale of: level of satisfaction
	9	How satisfied are you with the noise level (acoustical quality of the room)?	Multiple choice	5 Point Likert scale of: level of satisfaction
	10	How well do the following statements describe your personality? I see myself as someone who is reserved	Multiple choice	5 Point Likert scale of: level of agreement
	11	How well do the following statements describe your personality? I see myself as someone who is generally trusting	Multiple choice	5 Point Likert scale of: level of agreement
	12	How well do the following statements describe your personality? I see myself as someone who tends to be lazy	Multiple choice	5 Point Likert scale of: level of agreement
	13	How well do the following statements describe your personality? I see myself as	Multiple choice	5 Point Likert scale of: level of agreement

		someone who is relaxed and handles stress well		
	14	How well do the following statements describe your personality? I see myself as someone who has few artistic interests	Multiple choice	5 Point Likert scale of: level of agreement
	15	How well do the following statements describe your personality? I see myself as someone who is outgoing and sociable	Multiple choice	5 Point Likert scale of: level of agreement
	16	How well do the following statements describe your personality? I see myself as someone who tends to find fault in others	Multiple choice	5 Point Likert scale of: level of agreement
	17	How well do the following statements describe your personality? I see myself as someone who does a thorough job	Multiple choice	5 Point Likert scale of: level of agreement
	18	How well do the following statements describe your personality? I see myself as someone who gets nervous easily	Multiple choice	5 Point Likert scale of: level of agreement
	19	How well do the following statements describe your personality? I see myself as someone who has active imagination	Multiple choice	5 Point Likert scale of: level of agreement
	20	How conscious are you about sustainability in your daily life?	Multiple choice	5 Point Likert scale of: level of concern
Main survey	1	What is your ID number?	Open ended	None
	2	In the past 5 mins, did you notice any movement in the facade?	Multiple choice	5 Point Likert scale of: level of agreement
	3	How acceptable is the movement?	Multiple choice	5 Point Likert scale of: level of acceptance

	4	I perceive the movement because of the noise it makes when moving	Multiple choice	5 Point Likert scale of: level of agreement
	5	I perceive the movement because of the change in shape of objects in my view outside	Multiple choice	5 Point Likert scale of: level of agreement
	6	I perceive the movement because of the change in the reflected image on the glass	Multiple choice	5 Point Likert scale of: level of agreement
	7	I perceive the movement because of other reasons:	Open ended	None
	8	In the past 5 mins, did you notice any distortion of the view outside your window?	Multiple choice	5 Point Likert scale of: level of agreement
	9	How acceptable is the distortion of the view from your window?	Multiple choice	5 Point Likert scale of: level of acceptance
	10	In the past 5 mins, did you notice any change in the reflections from your window?	Multiple choice	5 Point Likert scale of: level of acceptance
	11	How acceptable is the change of reflections that you see from your window?	Multiple choice	5 Point Likert scale of: level of acceptance
	12	How would you rate your level of annoyance?	Multiple choice	5 Point Likert scale of:
	13	To what extent did the glass movement affect your concentration or focus (while engaged in activities such as viewing outside, writing or listening to the audio in your headset)?	Multiple choice	5 Point Likert scale of: level of annoyance
	14	Do you hear any noise from the glazing?	Multiple choice	5 Point Likert scale of: level of awareness
	15	How satisfied are you with the noise level (acoustical quality of the room)?	Multiple choice	5 Point Likert scale of:
	16	Which of the following best describes how you felt when the glass moved?	Multiple choice	5 Point Likert scale of: level of satisfaction

	17	What factors contribute to your concerns about safety regarding the glazing moving or vibrating in the facade? 1. Noise	Multiple choice	5 Point Likert scale of: level of safety
	18	What factors contribute to your concerns about safety regarding the glazing moving or vibrating in the facade? 2. Change in reflection	Multiple choice	5 Point Likert scale of: level of agreement
	19	What factors contribute to your concerns about safety regarding the glazing moving or vibrating in the facade? 3. Proximity to glazing	Multiple choice	5 Point Likert scale of: level of agreement
	20	What factors contribute to your concerns about safety regarding the glazing moving or vibrating in the facade? 4. The fact that I consider glass to be fragile	Multiple choice	5 Point Likert scale of: level of agreement
Outro	1.	What is your ID number?	Open ended	None
	2.	How important is it to have a satisfactory view from your window?	Multiple choice	5 Point Likert scale of: level of importance
	3.	How important is it to have a satisfactory acoustic environment in your room?	Multiple choice	5 Point Likert scale of: level of importance
	4.	To what extent do you agree to this sentence: I find large movements or deflections of the window glazing annoying while I am working	Multiple choice	5 Point Likert scale of: level of agreement
	5.	To what extent do you agree to this sentence: I find small movements or deflections of the window glazing annoying while I am working	Multiple choice	5 Point Likert scale of: level of agreement
	6.	To what extent do you agree to this sentence: I find large movements or deflections of the window glazing acceptable while I am working	Multiple choice	5 Point Likert scale of: level of agreement
	7.	To what extent do you agree to this sentence: I find small movements or deflections of	Multiple choice	5 Point Likert scale of: level of agreement

		the window glazing acceptable while I am working		
	8.	How safe do you feel when the glazing of the windows has a large deflections or movement?	Multiple choice	5 Point Likert scale of: level of agreement
	9.	How safe do you feel when the glazing of the windows has a small deflections or movement?	Multiple choice	5 Point Likert scale of: level of agreement

Appendix 3

```
const int pressureInput = A1;
const int pressureZero = 102.4;
const int pressureMax = 921.6;
const int pressureTransducerMaxPSI = 30;
const int baudRate = 9600;
const int sensorReadDelay = 250;
float pressureValue = 0;
int inflateValvePin = 9; // Pin for the valve used for inflation
int releaseValvePin = 10; // Pin for the valve used for releasing pressure

void setup() {
  Serial.begin(baudRate);
  pinMode(inflateValvePin, OUTPUT);
  pinMode(releaseValvePin, OUTPUT);
}

void loop() {
  // Read pressure value
  pressureValue = analogRead(pressureInput);
  pressureValue = ((pressureValue - pressureZero) * pressureTransducerMaxPSI) /
(pressureMax - pressureZero);

  // Perform actions based on pressure thresholds
  while (pressureValue < 0.28) {
    // Serial.println("Pressure is low. Pump air");
    Serial.println(pressureValue);
    // Call function to inflate
    controlValve(inflateValvePin, LOW); // Open inflation valve
    controlValve(releaseValvePin, LOW); // Close release valve
    delay(sensorReadDelay);
```

```
    // Update pressure value after delay
    pressureValue = analogRead(pressureInput);
    pressureValue = ((pressureValue - pressureZero) * pressureTransducerMaxPSI) /
(pressureMax - pressureZero);
  }

  // Close inflate valve when pressure reaches 0.2
  controlValve(inflateValvePin, HIGH); // Close inflate valve

  while (pressureValue >= 0.20) {
    // Release pressure until it reaches 0.1
    while (pressureValue >= -0.22) {
      // Serial.println("Releasing pressure");
      Serial.println(pressureValue);
      // Call function to release pressure
      controlValve(releaseValvePin, HIGH); // Open release valve
      delay(sensorReadDelay);
      // Update pressure value after delay
      pressureValue = analogRead(pressureInput);
      pressureValue = ((pressureValue - pressureZero) * pressureTransducerMaxPSI)
/ (pressureMax - pressureZero);
    }

    // After reaching 0.1, close the release valve
    controlValve(releaseValvePin, HIGH); // Close release valve
    // Break out of the loop and continue reading pressure
    break;
  }
}

void controlValve(int pin, int state) {
  digitalWrite(pin, state);
}
```

Appendix 4

Tests of Homogeneity of Variances

		Levene Statistic	df1	df2	Sig.
In the past 5 mins, did you notice any movement in the facade?	Based on Mean	.611	2	111	.544
	Based on Median	.594	2	111	.554
	Based on Median and with adjusted df	.594	2	109.093	.554
	Based on trimmed mean	.411	2	111	.664
How acceptable is the movement? - Level of acceptance	Based on Mean	.731	2	101	.484
	Based on Median	.545	2	101	.582
	Based on Median and with adjusted df	.545	2	91.172	.582
	Based on trimmed mean	.751	2	101	.475
In the past 5 mins, did you notice any distortion of the view outside your window?	Based on Mean	.298	2	111	.743
	Based on Median	.114	2	111	.892
	Based on Median and with adjusted df	.114	2	93.841	.892
	Based on trimmed mean	.271	2	111	.763
How acceptable is the distortion of the view from your window? - Level of acceptance	Based on Mean	3.067	2	54	.055
	Based on Median	2.147	2	54	.127
	Based on Median and with adjusted df	2.147	2	53.759	.127
	Based on trimmed mean	2.741	2	54	.073
In the past 5 mins, did you notice any change in the reflections from your window?	Based on Mean	.595	2	111	.553
	Based on Median	.350	2	111	.705
	Based on Median and with adjusted df	.350	2	101.448	.705
	Based on trimmed mean	.624	2	111	.538
How acceptable is the change of reflections that you see from your window? - Level of acceptance	Based on Mean	.594	2	93	.554
	Based on Median	.424	2	93	.656
	Based on Median and with adjusted df	.424	2	92.343	.656
	Based on trimmed mean	.608	2	93	.546
How would you rate your level of annoyance? - level of annoyance	Based on Mean	.863	2	109	.425
	Based on Median	.349	2	109	.707
	Based on Median and with adjusted df	.349	2	100.267	.707
	Based on trimmed mean	.861	2	109	.425
To what extent did the glass movement affect your concentration or focus (while engaged in activities such as viewing outside , writing or listening to the audio in your headset)? - on a scale of 1-5	Based on Mean	1.344	2	106	.265
	Based on Median	.498	2	106	.609
	Based on Median and with adjusted df	.498	2	76.435	.610
	Based on trimmed mean	1.308	2	106	.275

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
In the past 5 mins, did you notice any movement in the facade?	Between Groups	.333	2	.167	.160	.853
	Within Groups	115.947	111	1.045		
	Total	116.281	113			
How acceptable is the movement? - Level of acceptance	Between Groups	.501	2	.250	.140	.869
	Within Groups	179.961	101	1.782		
	Total	180.462	103			
In the past 5 mins, did you notice any distortion of the view outside your window?	Between Groups	.053	2	.026	.016	.984
	Within Groups	186.132	111	1.677		
	Total	186.184	113			
How acceptable is the distortion of the view from your window? - Level of acceptance	Between Groups	2.187	2	1.094	.732	.486
	Within Groups	80.690	54	1.494		
	Total	82.877	56			
In the past 5 mins, did you notice any change in the reflections from your window?	Between Groups	1.912	2	.956	.724	.487
	Within Groups	146.553	111	1.320		
	Total	148.465	113			
How acceptable is the change of reflections that you see from your window? - Level of acceptance	Between Groups	1.906	2	.953	.510	.602
	Within Groups	173.927	93	1.870		
	Total	175.833	95			
How would you rate your level of annoyance? - level of annoyance	Between Groups	.218	2	.109	.101	.904
	Within Groups	118.211	109	1.085		
	Total	118.429	111			
To what extent did the glass movement affect your concentration or focus (while engaged in activities such as viewing outside , writing or listening to the audio in your headset)? - on a scale of 1-5	Between Groups	.183	2	.092	.077	.926
	Within Groups	125.376	106	1.183		
	Total	125.560	108			

Multiple Comparisons

Dependent Variable		(I) Scenario for the case	(J) Scenario for the case	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
In the past 5 mins, did you notice any movement in the facade?	Tukey HSD	A	B	.079	.234	.939	-.48	.64
			C	-.053	.234	.973	-.61	.50
		B	A	-.079	.234	.939	-.64	.48
			C	-.132	.234	.841	-.69	.43
		C	A	.053	.234	.973	-.50	.61
			B	.132	.234	.841	-.43	.69
	Scheffe	A	B	.079	.234	.945	-.50	.66
			C	-.053	.234	.975	-.63	.53
		B	A	-.079	.234	.945	-.66	.50
			C	-.132	.234	.855	-.71	.45
		C	A	.053	.234	.975	-.53	.63
			B	.132	.234	.855	-.45	.71
	Bonferroni	A	B	.079	.234	1.000	-.49	.65
			C	-.053	.234	1.000	-.62	.52
		B	A	-.079	.234	1.000	-.65	.49
			C	-.132	.234	1.000	-.70	.44
		C	A	.053	.234	1.000	-.52	.62
			B	.132	.234	1.000	-.44	.70
How acceptable is the movement? - Level of acceptance	Tukey HSD	A	B	.106	.324	.942	-.66	.88
			C	.169	.322	.859	-.60	.93
		B	A	-.106	.324	.942	-.88	.66
			C	.063	.317	.979	-.69	.82
		C	A	-.169	.322	.859	-.93	.60
			B	-.063	.317	.979	-.82	.69
	Scheffe	A	B	.106	.324	.947	-.70	.91
			C	.169	.322	.871	-.63	.97
		B	A	-.106	.324	.947	-.91	.70
			C	.063	.317	.981	-.72	.85
		C	A	-.169	.322	.871	-.97	.63
			B	-.063	.317	.981	-.85	.72
	Bonferroni	A	B	.106	.324	1.000	-.68	.89
			C	.169	.322	1.000	-.61	.95
		B	A	-.106	.324	1.000	-.89	.68
			C	.063	.317	1.000	-.71	.83
		C	A	-.169	.322	1.000	-.95	.61
			B	-.063	.317	1.000	-.83	.71
In the past 5 mins, did you notice any distortion of the view outside your window?	Tukey HSD	A	B	-.053	.297	.983	-.76	.65
			C	-.026	.297	.996	-.73	.68
		B	A	.053	.297	.983	-.65	.76
			C	.026	.297	.996	-.68	.73
		C	A	.026	.297	.996	-.68	.73
			B	-.026	.297	.996	-.73	.68
	Scheffe	A	B	-.053	.297	.984	-.79	.68
			C	-.026	.297	.996	-.76	.71
		B	A	.053	.297	.984	-.68	.79
			C	.026	.297	.996	-.71	.76
		C	A	.026	.297	.996	-.71	.76
			B	-.026	.297	.996	-.76	.71
	Bonferroni	A	B	-.053	.297	1.000	-.77	.67
			C	-.026	.297	1.000	-.75	.70
		B	A	.053	.297	1.000	-.67	.77
			C	.026	.297	1.000	-.70	.75
		C	A	.026	.297	1.000	-.70	.75
			B	-.026	.297	1.000	-.75	.70
How acceptable is the distortion of the view from your window? - Level of acceptance	Tukey HSD	A	B	-.448	.382	.475	-1.37	.47
			C	-.337	.410	.690	-1.33	.65
		B	A	.448	.382	.475	-.47	1.37
			C	.110	.406	.960	-.87	1.09
		C	A	.337	.410	.690	-.65	1.33
			B	-.110	.406	.960	-1.09	.87
	Scheffe	A	B	-.448	.382	.508	-1.41	.51
			C	-.337	.410	.714	-1.37	.69
		B	A	.448	.382	.508	-.51	1.41
			C	.110	.406	.964	-.91	1.13
		C	A	.337	.410	.714	-.69	1.37
			B	-.110	.406	.964	-1.13	.91
	Bonferroni	A	B	-.448	.382	.739	-1.39	.50
			C	-.337	.410	1.000	-1.35	.68
		B	A	.448	.382	.739	-.50	1.39
			C	.110	.406	1.000	-.89	1.11
		C	A	.337	.410	1.000	-.68	1.35
			B	-.110	.406	1.000	-1.11	.89
In the past 5 mins, did you notice any change in the reflections from your window?	Tukey HSD	A	B	-.316	.264	.457	-.94	.31
			C	-.132	.264	.872	-.76	.49
		B	A	.316	.264	.457	-.31	.94
			C	.184	.264	.765	-.44	.81
		C	A	.132	.264	.872	-.49	.76
			B	-.184	.264	.765	-.81	.44
	Scheffe	A	B	-.316	.264	.490	-.97	.34
			C	-.132	.264	.883	-.79	.52
		B	A	.316	.264	.490	-.34	.97
			C	.184	.264	.784	-.47	.84
		C	A	.132	.264	.883	-.52	.79
			B	-.184	.264	.784	-.84	.47
	Bonferroni	A	B	-.316	.264	.700	-.96	.32
			C	-.132	.264	1.000	-.77	.51
		B	A	.316	.264	.700	-.32	.96
			C	.184	.264	1.000	-.46	.82
		C	A	.132	.264	1.000	-.51	.77
			B	-.184	.264	1.000	-.82	.46
How acceptable is the change of reflections that you see from your window? - Level of acceptance	Tukey HSD	A	B	.283	.342	.688	-.53	1.10
			C	.318	.345	.628	-.50	1.14
		B	A	-.283	.342	.688	-1.10	.53
			C	.035	.339	.994	-.77	.84
		C	A	-.318	.345	.628	-1.14	.50
			B	-.035	.339	.994	-.84	.77
	Scheffe	A	B	.283	.342	.712	-.57	1.13
			C	.318	.345	.655	-.54	1.17
		B	A	-.283	.342	.712	-1.13	.57
			C	.035	.339	.995	-.81	.88
		C	A	-.318	.345	.655	-1.17	.54
			B	-.035	.339	.995	-.88	.81
	Bonferroni	A	B	.283	.342	1.000	-.55	1.12
			C	.318	.345	1.000	-.52	1.16
		B	A	-.283	.342	1.000	-1.12	.55
			C	.035	.339	1.000	-.79	.86
		C	A	-.318	.345	1.000	-1.16	.52
			B	-.035	.339	1.000	-.86	.79
How would you rate your level of annoyance? - level of annoyance	Tukey HSD	A	B	-.108	.242	.896	-.68	.47
			C	-.046	.241	.980	-.62	.53
		B	A	.108	.242	.896	-.47	.68
			C	.063	.241	.963	-.51	.63
		C	A	.046	.241	.980	-.53	.62
			B	-.063	.241	.963	-.63	.51
	Scheffe	A	B	-.108	.242	.905	-.71	.49
			C	-.046	.241	.982	-.64	.55
		B	A	.108	.242	.905	-.49	.71
			C	.063	.241	.967	-.53	.66
		C	A	.046	.241	.982	-.55	.64
			B	-.063	.241	.967	-.66	.53
	Bonferroni	A	B	-.108	.242	1.000	-.70	.48
			C	-.046	.241	1.000	-.63	.54
		B	A	.108	.242	1.000	-.48	.70
			C	.063	.241	1.000	-.52	.65
		C	A	.046	.241	1.000	-.54	.63
			B	-.063	.241	1.000	-.65	.52
To what extent did the glass movement affect your concentration or focus (while engaged in activities such as viewing outside , writing or listening to the audio in your headset)? - on a scale of 1-5	Tukey HSD	A	B	-.079	.258	.949	-.69	.53
			C	.015	.253	.998	-.59	.62
		B	A	.079	.258	.949	-.53	.69
			C	.094	.255	.928	-.51	.70
		C	A	-.015	.253	.998	-.62	.59
			B	-.094	.255	.928	-.70	.51
	Scheffe	A	B	-.079	.258	.954	-.72	.56
			C	.015	.253	.998	-.61	.64
		B	A	.079	.258	.954	-.56	.72
			C	.094	.255	.934	-.54	.73
		C	A	-.015	.253	.998	-.64	.61
			B	-.094	.255	.934	-.73	.54
	Bonferroni	A	B	-.079	.258	1.000	-.71	.55
			C	.015	.253	1.000	-.60	.63
		B	A	.079	.258	1.000	-.55	.71
			C	.094	.255	1.000	-.53	.71
		C	A	-.015	.253	1.000	-.63	.60
			B	-.094	.255	1.000	-.71	.53

Appendix 5

Correlations

*. Correlation is significant at the 0.05 level (2-tailed).
**. Correlation is significant at the 0.01 level (2-tailed).

How acceptable is the movement? - Level of acceptance	I perceive the movement because of - The noise it makes when moving	I perceive the movement because of - The change in shape of objects in my view outside	I perceive the movement because of - The change in the reflected image on the glass	In the past 5 mins, did you notice any distortion of the view outside your window?	How acceptable is the distortion of the view from your window? - Level of acceptance	In the past 5 mins, did you notice any change in the reflections from your window?	How acceptable is the change of reflections that you see from your window? - Level of acceptance	How would you rate your level of annoyance? - level of annoyance	To what extent did the glass movement affect your concentration or focus(while engaged in activities such as viewing outside ,writing or listening to the audio in your headset)? - on a scale of 1-5	Do you hear any noise from the glazing?	How satisfied are you with the noise level(accoustical quality of the room)? - Level of satisfaction	Which of the following best describes how you felt when the glass moved?	What factors contribute to your concerns about safety regarding the glazing moving or vibrating in the facade? - Noise	What factors contribute to your concerns about safety regarding the glazing moving or vibrating in the facade? - Change in reflections	What factors contribute to your concerns about safety regarding the glazing moving or vibrating in the facade? - Proximity to the glazing	What factors contribute to your concerns about safety regarding the glazing moving or vibrating in the facade? - The fact that I consider glass to be fragile
-0.038	-0.117	0.147	-0.111	-0.140	-0.011	-0.278	0.188	-0.010	-0.051	-0.180	-0.309	-0.152	-0.009	-0.175	0.085	-0.095
0.844	0.509	0.408	0.534	0.392	0.952	0.091	0.312	0.952	0.769	0.279	0.087	0.362	0.969	0.413	0.692	0.764
33	34	34	34	38	20	38	31	37	38	38	38	38	24	24	24	24
0.390	0.168	-0.016	0.043	0.108	.563*	-0.183	0.249	0.011	-0.231	0.248	-0.150	0.112	.482*	-0.142	-0.153	-0.094
0.102	0.267	0.928	0.808	0.520	0.010	0.271	0.177	0.949	0.175	0.133	0.383	0.501	0.017	0.508	0.476	0.768
33	34	34	34	38	20	38	31	37	38	38	38	38	24	24	24	24
0.061	0.039	0.034	-0.127	-0.104	0.000	-.382*	0.302	0.281	-0.322	-0.088	0.042	-0.200	-0.079	0.124	0.304	0.333
0.734	0.825	0.846	0.473	0.534	1.000	0.018	0.098	0.092	0.055	0.601	0.807	0.228	0.713	0.564	0.149	0.112
33	34	34	34	38	20	38	31	37	38	38	38	38	24	24	24	24
-.443*	0.046	-0.110	-0.087	-0.157	-0.184	-0.038	-.427*	-0.194	0.307	0.139	-0.072	0.002	-0.046	-0.303	-0.121	-0.204
0.011	0.797	0.543	0.632	0.352	0.469	0.814	0.018	0.250	0.072	0.411	0.680	0.989	0.839	0.160	0.583	0.351
32	33	33	33	37	20	37	30	37	35	37	35	37	23	23	23	23
-0.324	0.310	.367*	0.110	0.058	-.527*	0.000	-0.271	-0.174	0.161	0.016	0.219	0.117	0.053	0.348	0.122	0.111
0.065	0.074	0.036	0.537	0.737	0.017	1.000	0.140	0.304	0.366	0.926	0.199	0.484	0.805	0.242	0.570	0.604
33	34	34	34	38	20	38	31	37	38	38	38	38	24	24	24	24
.388*	0.036	0.172	0.109	0.113	-0.154	0.104	0.301	0.083	-0.003	-0.036	-0.015	0.090	0.287	0.014	0.002	0.366
0.026	0.840	0.330	0.539	0.498	0.517	0.536	0.100	0.627	0.986	0.580	0.932	0.590	0.207	0.950	0.994	0.079

End.

End

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