Graduation Plan: All tracks

Submit your Graduation Plan to the Board of Examiners (Examencommissie-BK@tudelft.nl), Mentors and Delegate of the Board of Examiners one week before P2 at the latest.

The graduation plan consists of at least the following data/segments:

Personal information	
Name	Sagar Oke
Student number	5578752

Studio		
Name / Theme	Building Technology: Façade Design	
Main mentor	Alessandra Luna Navarro	Façade Design
Second mentor	Mauro Overend	Structural Design
Argumentation of choice of the studio	An important aspect of a building façade is the structural role it has to perform, to resist wind and climatic loads, while maintaining air tightness and insulation. The more roles it has to play, the more carbon intensive a glass façade becomes. Glass contributes a significant amount to the embodied carbon a building's façade. Hence, in order to provide solutions for a more material efficient façade design without compromising its performance, this studio at the intersection of Façade and Structural design was chosen.	

Graduation project	
Title of the graduation project	Human-centered appraisal of façade design for serviceability
Goal	
Location:	Not Applicable at this stage
The posed problem,	Facades play an important role in reducing the operational carbon in a building's life cycle. But, in doing so, they contribute to around 30% of embodied carbon in buildings (Arup & SGG, 2022; Hartwell et al., 2021). Out of this, it has been estimated that around 26-60% embodied carbon is the contribution of glass (Arup & SGG, 2022). Lowering of carbon footprint of glass can be achieved through strategies of either reuse, recycle or reduce. Though reuse and recycle are theoretically feasible, there

	are many practical constraints which are difficult to overcome at the moment (Arup, 2018; Zaccaria, 2022). But through material efficient design, it is possible to reduce the input carbon footprint in new construction. Material efficiency in glass can be achieved by optimization of glass thickness. Companies such as AGC are able to manufacture thin glass (0.5mm to 2.0mm) in large sizes using float lines. Apart from being more flexible, the glass also has a higher compressive strength, scratch resistance and quality of finish, which makes it a potential alternative to soda-lime glass (AGC, 2020). A disadvantage of thinner glass is it displays relatively higher deflections under wind and climatic loads. The level of acceptance of higher deflections in glass has not been defined in the past. A standardized guidance for glass design had been lacking, and there is still time for a final Eurocode for glass to be published (Coult & Overend, 2022). In the draft guidelines, serviceability of glass pertains to deflection limits based on criteria that do not take into account occupant comfort parameters, such as perception of safety, visual disturbances, etc (European Committee for Standardization, 2021). Further, literature related to comfort performance of facades under deflection is also lacking. If human-centered criteria are considered, there is a chance that higher deflections may be within the acceptable threshold. There is a need to first define a comprehensive set of criteria for serviceability and then set limits based on each. For technical criteria, this can be done through analytical or experimental methods, but for human-centered criteria, there is a need to develop and perform experiments to gather empirical data.
research questions and	Research Question: What are acceptable deformation limits of facades for durability and occupant acceptance during service life? Sub Questions: 1. What are the existing serviceability criteria and methods for defining limits of façade deformation?

	2. What are the additional criteria for which serviceability limits of facade deformation must be defined? 3. What are the available lightweight glazing options and their potential applications? 4. What is the level of human acceptance towards façade deformation under wind load or climatic loads? 5. How can defining human-centered serviceability limits influence the design of facades? 6. What is the impact on embodied carbon of facades due to change in serviceability limits?
design assignment in which these result.	An important contribution of the thesis is the identification of a comprehensive set of criteria for façade serviceability, which includes human-centered criteria. This research will then result in the design of an experiment to assess the level of acceptance of deflections in glass among users. The aim of the experiment is to collect empirical data related to human response to deflections in glass. The data thus gathered will be analyzed in order to arrive at an acceptable threshold of glass deflection, as one of the serviceability limits.

Process

Method description

1. **Gathering state of the art information – Literature review, Industry Survey, Interviews.**

The research relies primarily on the state of the art in terms of standards and practices in decision making in design of glazing. While literature review was a necessary method for understanding standard limit state design practices and effects of glass deflection on the performance of glazing; industry practices are not always found in literature. Therefore, another step in gathering information is by means of a of professionals from façade design and related companies. Further, interviews with selected professionals will be conducted to gain detailed information pertaining to certain serviceability criteria.

2. **Research through Experiment – Human response to façade movement.**

To fill the knowledge gap in literature and (possibly) the industry about human acceptance of façade deformation, an experiment has been proposed. The experiment will be conducted either in a physical set-up or using virtual reality and simulations. In both cases, volunteers would be required to comment on their perception of safety,

comfort, disturbance, etc. in the scenario that glass in the façade is deforming. The set-up will replicate an office environment and volunteers will be expected to conduct a reading or writing task for a limited time (5-10 minutes) while and adjacent glass deforms under controlled conditions. The responses of volunteers will be recorded by means of a survey they would fill out at the end of stages of the experiment and by means of a facial action unit (using a webcam) that numerically records facial expressions. The privacy of the volunteer will be maintained as per standards recommended by TU Delft.

Depending on whether the experiment is in physical set-up or in VR, certain parameters will change. However, some of the general parameters that would be decided for the experiment are – glass size, position and orientation of the volunteer with respect to glass, amount and frequency of distortion, limiting the effect of other factors that may affect comfort (e.g. noise, temperature and daylight variations, etc.). Relevant information to best assess the responses will be gathered, such as age, background, sex of the volunteer, time of the day and weather conditions, prior knowledge of volunteer about capacity of thin glass, prior knowledge about benefits of material efficient design of glass, etc.

The results from the experiment will be analyzed and used to formulate a general understanding of human perception of glass deflections. This knowledge will be quantified to gain insight into the general patterns, levels and limits of acceptance of glass deflections. The framework of the experiment will be open for future modifications, based on type and depth of information intended to be gathered. It is envisioned that this experiment provides a much needed insight into the open-ended question of acceptance of glass deformation.

The planning and timeline of the research process is given in ‘Appendix B – Timeline’.

Literature and general practical preference

The literature review was conducted to gather information on specific sub-topics, namely a. impact of glass on embodied carbon of a building, b. limit state design criteria and c. effects of deformation of glass on glazing performance (thermal and optical performance, durability, etc.). The full list of references has been attached in as an Annex. While most of the literature is journal articles and conference papers, other types of literature such as reports from the industry, standards and guidelines, company brochures and student theses were referred. Further, an industry survey is being conducted to gather data on practices followed to determine glass thicknesses and deflection limits.

Impact of glass on embodied carbon of a building,
For the state of the art information on contribution of glass in typical facades, reports from (Arup & SGG, 2022) were referred to. Relevant information was also found from research conducted by (Zani et al., 2021), for design methodology to achieve zero carbon building targets. Further, the research by (Hartwell & Overend, 2019) was useful to formulate an industry survey, which is an important step in this research.

Limit state design criteria
While journal articles and papers refer to limit state design criteria, the most extensive information and guidelines are available in the standards. Since there are no standards for glass yet, important information was found in EN 1990:2002, FprCEN/TS 19100, ASTM 1300E. Information in these standards was compare with guidelines from Switzerland (Wuest & Luible, 2020) and Hong Kong (Buildings Department Hong Kong, 2018).

Effects of deformation of glass on glazing performance
Effects on mechanical properties, the thermal, acoustical and optimal performance of glazing, durability of IGUs and comfort performance were targeting in the literature search. As anticipated, there enough research was not found for some topics, such as acoustic and comfort performance. However, interesting insights were gained from research on mechanical properties (Datsiou & Overend, 2016; Galuppi & Royer-Carfagni, 2020; Quaglini et al., 2020); thermal performance (Hart et al., 2012; Respondek, 2018, 2020) and durability (Besserud et al., 2012; Starman et al., 2020). For optical performance, specific papers were not found, but papers on relevant topics, such as mechanical performance provided some information.

Reflection

1. **What is the relation between your graduation (project) topic, the studio topic (if applicable), your master track (A,U,BT,LA,MBE), and your master programme (MSc AUBS)?**

This topic of research falls at the intersection of the domains of Façade Design and Structural Design, specifically in the context of glass. The focus of the Façade and Structural design research groups at the Faculty of Architecture are aligned towards

the larger vision of sustainable construction, while maintaining or improving the quality of the built environment.

In the wake of a rising material crisis, it is imperative to reduce the use of new materials in construction. The objective of the thesis is to identify barriers in the way of reduction of glass thickness, and to critically assess the standards and industry practices that can be better designed to optimize the use of glass. At the same time the objective is to consider occupant comfort in terms of façade deformation, for which hard data or literature is lacking. A scientific approach towards the issue of human interaction with facades is at the core of this research topic.

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

Glass has been used in our buildings for centuries. A glass façade provides humans with the much needed connection between the inside and the outside, while sheltering us from the elements. Over the years, technology has evolved, and we are able to manufacture glass of very high quality and in various sizes and forms. We have, for the longest time imagined glass to be a rigid, yet brittle material. Hence, the perception of glass in society has been shaped by the conventional form in which we have always seen it.

However, with the innovation in ultra-thin glass, we have glass which is flexible, and can be produced on float-lines like conventional, soda-lime glass. But the social perspective of glass as a rigid material seems to be a barrier in the use of thinner glass in facades. The graduation thesis explores ways in which deflections in façade glass are perceived by humans, and what role does the prior knowledge of the material play in the acceptance of a new form of glass. Thus, the graduation topic closely has a social relevance.

Further, the decision makers in the industry have had to rely on certain norms which have not been standardized, since in most countries, there is no codified guidance for structural design of glass. One of the exercises in the graduation thesis is to conduct an industry survey to gather knowledge no available in literature, to understand practices. Thus, the thesis has a strong professional relevance.
Further, a scientific approach towards problem solving can no longer be restricted to numerical or analytical methods. Especially in the domain of buildings, experiments which are more human-centric have to be conducted in order to realistically assess the impact of technology. Thus, a human-centered approach to scientific research has been chosen for the topic which is so closely related to human interaction with facades.