Graduation Plan

Master of Science Architecture, Urbanism & Building Sciences

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	Sanguk Ryu
Student number	

Studio		
Name / Theme	Building Technology Graduation Studio	
Main mentor	Mauro Overend	Structural Design
Second mentor	Eleonora Brembilla	Climate Design
Argumentation of choice of the studio	Architects, including myself, have a strong interest in using glass in architectural design. Responding to this demand, glass technology has advanced rapidly, with thin glass emerging as a revolutionary material. Its lightweight, material efficiency, and flexibility open new possibilities for architectural applications, overcoming the limitations of conventional glass products. I aim to contribute to realizing architectural visions previously constrained by material limitations, while addressing challenges through integrative technological solutions. To address this, the studio focuses on Structural Design and Climate Design, the two most critical aspects of glass innovation. Structural research ensures thin glass meets mechanical and durability requirements, while climate design addresses solar control and energy efficiency.	

Graduation project	
Title of the graduation project	Cold-Bent Thin Laminated Glass with New Geometries and Solar Integration
Goal	
Location:	The OWO Pavilion, Whitehall, London, UK
The posed problem,	Despite the potential of thin glass to achieve both material efficiency and structural stiffness through curving, their application remains rare due to fabrication challenges and the complexities of analysing the geometric nonlinearities of double-curved shells.

research questions and	How can thin glass be cold-bent and laminated into double curvature forms for architectural applications, while integrating solar protection mechanisms?
design assignment in which these result.	1. Establishment of boundary conditions and deformation (buckling) mechanism design for the following cold-bending geometries: i) single curved sinus curvature ii) parabolic sinus curvature 2. Cold-bending shape optimization in terms of strength and stiffness 3. Design of an effective solar transmittance control mechanism applicable to double-curved glass using computer simulation 4. Design of manufacturing method for cold-bent glass, including lamination and solar protection method, to use it as a roofing element 5. Experimentation of the capacity and post-failure behaviour of the fabricated glass units 6. Inspection of surface quality and solar transmittance performance of the end-product

Process

Method description

1. State of the art information – Literature & industry supplier interview

A literature review was conducted based on keywords such as *cold-bending, lamination, and solar control* of *thin glass (glass)*. This process provided valuable insights that contributed to establishing the foundational knowledge and boundary conditions for the product design. Through this review, research gaps could be found to supplement areas that required further investigation through my own research.

Given the complexity and diversity of glass manufacturing methods, selecting an option is crucial as it determines the feasible processes for the subsequent steps. The applicable processes can vary significantly depending on the specific product being produced, making it essential to consult closely with manufacturers to ensure feasibility. To gain professional information regarding a specific product, meetings are planned with AGC for information related to thin glass production, and with HB Fuller Kömmerling to obtain details about adhesives used for lamination.

2. Glass buckling behaviour testing

Before directly handling the brittle and challenging material, a more manageable substitute such as plexiglass or acrylic plates will be used to study deformation under specific load conditions. This approach allows for physical verification of hypotheses while minimizing risks. The process will begin with designing a force-application device using 3D printing, followed by testing to observe how the plate deforms under applied loads. The aim is to identify areas of high stress, such as unexpected wrinkles or deformations, and gather insights into the material's buckling behaviour.

3. Numerical simulation – FEA & irradiance simulation

Finite element modelling (FEM) and analysis will be conducted based on the actual dimensions of the end-product. Applying the load conditions of the pre-deformation on the glass so that it becomes a prestressed system is crucial because it affects the glass behaviour and the entire results. Additionally, this stage allows to simulate the required glass thickness to withstand specific loads, identify areas of maximum stress, and predict potential points of structural failure. Detailed design optimisation will be carried out by adjusting simulation variables. Properly replicating the boundary conditions of the manufactured product within the FEM framework and accurately interpreting the simulation results are critical. Furthermore, an impact load test will be simulated in the FEM to measure the structural capacity of the manufactured product. The derived results will enable comparisons with the actual experimental outcomes.

The climate data for the OWO Pavilion will be applied to the optimized glass geometry. Then, the baseline irradiance level of the control group, which has no solar protection, will be measured. For the experimental group, frit patterns of varying shapes and density will be employed to the curved glass product. Through this simulation, the relationship between the frit patterns and solar transmittance is expected to be established in case of complicated double curvature glass geometry.

4. Fabrication and real performance testing

The roof panel module, designed at a 1:1 scale identical to that of the OWO Pavilion, is planned to be fabricated and assembled in collaboration with Octatube. If conditions permit, an impact test will be conducted to assess the structural capacity and post-failure behaviour of the manufactured panel.

Additionally, zebra board testing and 3D scanning will be carried out to evaluate the surface quality of the completed product. For solar transmittance validation, data will be collected at specified points using an illuminance device.

Literature and general practical references

I referred to literature that provides basic background knowledge about glass, including Wurm (2007), Schittich et al. (2007), and Belis et al. (2019). The in-depth literature review related to my research topic was divided into three sub-topics: cold-bending, lamination, and solar control. Most of the literature consulted consisted of

journal articles and conference papers, along with NEN standards, company specification sheets, and student theses. The literature referenced in this section has been included in a separate appendix.

Cold-Bending

While the hot bending process, a higher degree of double curvature can be achieved (Fildhuth & Knippers, 2012), the cold bending process most easily produces shapes with single curvature, as explained by the thin flat plate theory (Galuppi et al., 2014). Synclastic double-curvature can also be achieved through cold bending by stiffening two or more plate edges or vertices, but this approach has curvature limitations, and high-strength thin glass is essential for structural applications (Galuppi & Riva, 2022). The cold deformation limit depends on factors such as glass thickness, support conditions, and the geometry of the glass (van Herwijnen et al., 2004; Nehring & Siebert, 2018; Silveira et al., 2018). While greater cold warping generally increases plate stiffness, significant warpage can intentionally result in a loss of stiffness in certain cases (Bensend & Zaccaria, 2024). Cold bending deformation may create unwanted ripples on the surface, which can affect distorted reflection and surface quality (Datsiou & Overend, 2016).

Lamination

To calculate and predict the performance of the multi-layered sections of the thin glass layers, the Enhanced Effective Thickness formula is being proposed (Galuppi & Royer-Carfagni, 2012; Galuppi & Royer-Carfagni, 2015). While double curvature cold-bent laminated glass is achievable, it induces high membrane stresses, and the behavior of the interlayer is highly dependent on both time and temperature (Galuppi & Royer-Carfagni, 2014). Differences between adhesive interlayer types and methodologies to mitigate shear stress concentration are discussed in Galuppi & Royer-Carfagni (2015). As an alternative interlayer type, epoxy is categorized by a wide range of viscosities and formulation types, with each offering specific advantages and disadvantages depending on the application (Gross, 2002). Volakos et al. (2021) introduced a manufacturing method to produce a flat laminated glass unit using a single-part epoxy product. Additionally, Pannetier et al. (2020) presented a methodology for prototyping curved laminated thin glass as architectural elements.

Solar Control

Jiang et al. (2020) analyses the impact of various roof geometries regarding solar radiation on the roof surface. One method to control solar transmittance is ceramic frit patterning on glass (Wilson & Elstner, 2018). While enamel coating has been shown to negatively affect the strength of glass (Bergers et al., 2016), this approach is highly adaptable to localized contexts and climates (Monticelli et al., 2013; Lau et al., 2024). Simulation methods that encompass both qualitative and quantitative aspects of solar control have been discussed by Roudsari & Waelkens (2015).

Company Collaboration

The collaboration with Octatube as part of my graduation internship provides basic information about the OWO pavilion project, opportunities to discuss with engineers from Octatube and access to facilities for conducting final manufacturing and experiment phase. To support the development of the end-product, I have arranged

meetings with AGC and HB Fuller Kömmerling to receive practical guidance on selecting and producing thin glass and lamination products.

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)?**

The topic of this research aligns closely with the interdisciplinary engineering field of my master track (BT) and integrates structural and climate design perspectives. Glass faces significant challenges due to its brittleness, which limits its structural potential as an architectural element, however, is being used due to its transparency. This research addresses these challenges not by increasing the thickness of the glass—an approach that would lead to a cycle of increased self-weight and additional structural reinforcement—but by exploring efficient material use. Specifically, the goal is to uncover the geometrical potential of thin glass, providing architects with new design possibilities that combine efficiency and sustainability. By doing so, this study aims to establish a new design language for glass. In addition to addressing structural concerns, the research also considers the balance between daylight harvesting and maintaining comfortable interior illuminance. The unique geometry of the new glass product can lead to unforeseen solar effects, and this study seeks to propose sustainable and effective methods to manage such challenges.

This topic aligns well with the studio theme and master program, as it integrates the two important interdisciplinary fields of glass in architecture: structural design and climate design. Architects often lack specialized knowledge of glass manufacturing processes and are limited in their ability to envision challenging designs due to this knowledge gap. Conversely, engineers prioritize safety and sustainability, thus tend to focus on improving existing properties. By bridging the gap between architectural design and engineering knowledge, this research highlights the unexplored geometrical potential of synclastic thin laminated glass, addressing a niche yet significant field that has the potential to redefine sustainable innovative architectural applications.

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

The safe and aesthetically pleasing application of glass in architecture involves a highly intricate manufacturing process carried out in sequential stages. Due to the material's inherent complexity, most research focuses on one aspect of the glass. However, this segmented approach often overlooks the interdependencies between processes, which can lead to issues such as reduced performance of the final product, process incompatibility, or excessively high production costs. This study takes a holistic approach by considering the interconnected processes involved in working with thin glass, including cold bending, lamination, frit patterning, and the selection of materials for each step. By ensuring compatibility from start to finish, the

research aims to avoid the unintended consequences that often arise when changes to one process negatively affect subsequent stages. Therefore, this study establishes a research framework that provides a more complete and integrated answer to the challenges of thin glass in architecture.

Furthermore, since existing studies rely on bending or twisting for cold deformation, the introduction of buckling deformation as a new methodology for achieving smooth and nature-driven sinus curvature is the novelty of this research. Because of the restricted shape deformability of glass, buildings are typically designed from the whole to the parts by dividing a large final shape into panels of the maximum manufacturable glass size. However, if the high-curvature, free double-curved shapes tested in this study can be achieved through thin glass cold-bending, it will enable the creation of a completed 3D form within their individual glass panel. This breakthrough could shift the design paradigm, allowing glass buildings to be designed from the parts to the whole, offering new possibilities.