BUCKLE BENDING COLD LAMINATED THIN GLASS WITH SOLAR CONTROL INTEGRATION

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REFLECTION

1. **What is the relation between your graduation project topic, your master track, and your master programme?**

The topic of this research aligns closely with the interdisciplinary engineering field of my master track (Building Technology) and integrates structural, climate design, and façade fabrication & manufacturing perspectives. Glass faces significant challenges due to its brittleness, which limits its structural potential as an architectural element. However, it continues to be widely used for its transparency. This research addresses these challenges not by increasing its thickness—which would lead to a cycle of added self-weight and reinforcement—but by exploring more efficient material use. Specifically, the goal is to uncover the geometrical and structural potential of thin glass, providing architects with new design possibilities that combine efficiency and sustainability. In addition to addressing structural concerns, the research also considers the balance between daylight harvesting and maintaining interior comfort. The unique deformed geometry of the new glass product can lead to unforeseen solar effects, so this study seeks to propose sustainable and effective methods to manage such challenges. Beyond computational analysis, the research translates digital designs into physical prototypes. Through a series of iterative experimental fabrication processes, the study moves toward a realizable construction solution. This hands-on approach allows for continuous refinement and correction of errors encountered during production, ultimately leading to an applicable prototype that bridges the gap between conceptual innovation and practical implementation.

This topic aligns well with the studio theme and master program, as it integrates the three important interdisciplinary fields of glass in architecture: structural design, climate design, and manufacturing detailing. 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. By bridging the gap between architectural design and engineering knowledge, this research highlights the unexplored geometrical potential of double

curved thin laminated glass cold bent, addressing a niche yet significant field that has the potential to redefine new fabrication methods for 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, cold lamination, frit patterning, and material selection at each stage. 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, while existing studies rely on bending or twisting for cold deformation, this research introduces *buckle bending* as a novel method to achieve smooth, organically inspired sinusoidal curves. This represents the main innovation of the study. Because of the restricted shape deformability of glass, glass buildings are typically designed from the whole to the parts by subdividing the overall shape into smaller flat panels. If the high-curvature and complex geometries explored in this research can be accurately defined and reliably produced, the findings may open up new possibilities for cold-bent 3D glass architecture.

3. **How did your literature review inform your research question, and how did your findings influence the design process and final outcome?**

Glass differs from many other architectural materials in both its physical behaviour and how it is perceived, prompting extensive academic and practical research into the possibilities and limitations of cold bending. Thin glass and chemical toughening have introduced new mechanical potentials, but most recent studies still rely on established methods, particularly cylindrical single curvature, simply adjusting the degree of deformation.

This led me to ask: could alternative boundary conditions unlock new and unexplored cold bending geometries? While literature frequently highlights the difficulty of achieving double curvature through cold bending—leading to a focus on single curvature or out-of-plane twisting—very few studies have examined more complex forms or investigated the specific causes of failure in such attempts. I found limited numerical validation of why double curvature with chemically toughened thin glass is so challenging, which revealed a research gap.

Although the early numerical results did not align with my initial expectations—which were based on a hopeful outlook regarding the feasibility of double-curved glass—I refined the approach step by step without abandoning the original concept. This iterative process produced both encouraging outcomes that challenged conventional assumptions, and results that reaffirmed existing limitations—particularly the increased residual stress and reduced structural capacity associated with double-curved geometries, as compared to single-curved ones.

When this understanding was applied to the OWO Pavilion's specific rhombus geometry, additional constraints became apparent that had not surfaced during generic simulations or fabrication trials. These challenges made it unfeasible to implement the original benchmark design. However, by thoroughly analysing the reasons for this infeasibility, I was able to propose a more realistic yet still innovative design solution that responded to the constraints while preserving the design intent.

4. **Does the project contribute to sustainability in the built environment?**

Rather than relying on the conventional strategy of increasing material thickness to ensure safety, this research re-evaluates what are typically considered limitations—such as flexibility—and turns them into strengths. The project demonstrates that even thin, chemically toughened glass, often dismissed due to its lack of rigidity, can provide both structural stiffness and visual elegance when its inherent flexibility is strategically utilized through cold-bent geometries. In this way, a perceived weakness was not merely mitigated but actively transformed into a functional and aesthetic advantage.

Furthermore, the fabrication process was designed to eliminate the need for energy-intensive thermal treatment and custom moulds, significantly reducing material use and energy consumption. By addressing the entire production workflow from the outset, the project ensures that the proposed method supports sustainability not only through the structural performance and material efficiency of the glass itself, but also by enhancing overall manufacturing efficiency and reducing environmental impact.

5. **How do you assess the value of your way of working?**

The strength of my approach lies in treating the research problem much like a complex architectural design challenge—by grounding it in a real architectural context and resolving it through iterative testing and problem-solving. Rather than viewing the topic solely through a design or engineering lens, I was able to bridge both disciplines, ensuring that decisions were informed by necessity and validated through both computational analysis and physical experimentation.

This integrative methodology—beginning with numerical structural and solar performance analysis, defining and solving optimization problems, and validating the results through hands-on testing—was central to the project's depth and credibility. A key milestone was the development of a full-scale prototype using actual glass, which tested not only technical feasibility but also the real-world relevance of the design approach.

Managing interdisciplinary communication, coordinating with collaborators, and scheduling fabrication processes were all integral parts of the workflow. The project brought together diverse competencies—design thinking, engineering precision, computational modelling, material prototyping, and project management—without compromising the depth of inquiry in any single area. I believe it is this holistic yet technically rigorous way of working that gives the project its enduring value.

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

This research presents a complete methodology for addressing a specific architectural design problem, covering the full process from concept development to fabrication. By following the workflow outlined in the thesis, it is feasible to produce a cold-laminated sinusoidal half-paraboloid roof element—within defined size and boundary constraints—making the results directly applicable to real-world construction scenarios.

However, achieving an expressive degree of double curvature requires the use of square panels with limited dimensions, due to both structural and manufacturing limitations. While the proposed system is suitable for applications such as greenhouses or uninhabited pavilions, it is not yet compatible with insulated glass units (IGUs), which are standard in most contemporary buildings.

Although fritting was explored as a visual and solar-control feature, its mechanical impact was not analysed, nor was it physically integrated into the prototype.

The fixture system used to induce buckling deformation shows potential for use as a permanent secondary structure—minimizing spring-back and contributing to sustainability by eliminating the need for additional support systems. However, while the study proposes a conceptual strategy for integrating such a system, further development is required to resolve the detailed engineering and on-site fabrication aspects necessary for real-world construction.

In summary, while the core methodology has clear practical potential within certain constraints, further development and technical refinement are necessary for broader architectural application.

7. **How do you asses the value of the transferability of your project results?**

This project spans multiple disciplines and includes a wide range of experiments, all of which have been thoroughly documented. The methodologies and results—both numerical and experimental—are clearly recorded, making replication by others feasible.

However, differences in material parameters—such as the type of glass or specifics of the cold lamination process—may influence outcomes, as these factors directly affect material behaviour. Similarly, variations in structural numerical modelling—such as whether secondary sandwich components (e.g., edge seals) are included, how the sandwich panel itself is modelled, the type of connection with edge supports, or how the interlayer is represented before and after curing—may lead to minor differences in the results.

Despite these sensitivities, the optimisation workflows developed in this research—particularly those for computing flattened pane geometry for efficient structural analysis and designing fritting patterns—constitute original contributions. These methods are not only transferable to other glass-related design challenges but can also serve as a foundation for future research.

In addition, a custom-developed method for experimentally measuring relative solar transmittance, along with a logic for determining the measurement area, was used to validate the digital twin simulation. This involved designing a consistent measurement setup and a systematic approach for comparing digital and physical performance under varying solar angles. The clarity and replicability of this methodology make it valuable not only for this study, but also as a potential tool for other researchers working on solar-responsive façade systems, glass performance analysis, or digital-to-physical validation frameworks.

8. **What are the next steps to the research?**

Future research could explore whether alternative geometries—beyond the sinusoidal half-paraboloid investigated in this study—might offer greater potential for cold bending thin, chemically strengthened glass. While this appears less likely based on current findings, it remains an open question, particularly in combination with different boundary or loading conditions. A more promising direction would be to expand the current methodology to multi-layered insulated glass units (IGUs), applying buckle-bent cold lamination techniques to more complex glazing assemblies and investigating how different cold-deformed geometries behave under structural and environmental loads.

In parallel, investigating the feasibility of using sheet-based interlayers such as PVB or SGP—instead of the liquid-based CIP interlayer used in this study—could broaden the applicability of the buckle bending method in façade systems. Closely related to this is the need for more accurate simulation models of residual stress development during the curing process. As the cold-bent interlayer transitions from liquid to solid state, time-dependent molecular rearrangement and stress relaxation occur, which significantly influence final performance. Capturing this behaviour would improve the predictive reliability of digital twin simulations.

Another important research avenue involves the use of ceramic fritting. While it was explored visually in this study, its mechanical implications—especially potential chemical interactions between the frit and interlayer materials during lamination, and its effect on strength under elevated temperatures and loads—remain untested. In this context, further investigation is needed into how ceramic fritting influences both structural behaviour and manufacturability.

Additionally, solar control strategies could be significantly improved by integrating more comprehensive simulation criteria, including glare, light convergence, and indoor illuminance, alongside traditional transmittance metrics. The development of new solar control methods specifically tailored for double-curved laminated glass roofs could align optical performance with structural efficiency and environmental comfort.