Challenging Glass Conference Proceedings – Volume 10 – June 2026 – Louter, Bos & Belis (Eds.)
International Conference on the Architectural and Structural Application of Glass
Challenging Glass Conference 10 – 15-17 June 2026 – TU Delft – The Netherlands

Cold-Bent Thin-Glass IGUs: Lightweight and Optically Superior Curved Glazing with a High Curvature Range

Koen van Deurzen [a], Mauro Overend [a], Marcel Bilow [a]

a Department of Architectural Engineering & Technology, Delft University of Technology,
The Netherlands, kcvandeurzen@gmail.com, m.overend@tudelft.nl, m.bilow@tudelft.nl

Abstract

Recent developments in thin glass technology and flexible edge spacers present an opportunity to address notable fabrication challenges in conventional curved insulated glazing units, namely the undesirable visual distortions arising from hot bending the glass and the limited curvatures allowed by the glass strength. This study investigates the structural feasibility of flexible insulated glazing units (IGUs) incorporating chemically strengthened thin glass and a flexible spacer system, with the objective of enabling higher cold-bending curvatures than those achievable with conventional glass façades. And in doing so, the curvature imposed on the thin glass also provides the necessary stiffness to resist loads without excessive deflections. A combined methodological framework was adopted in this study, comprising finite element modelling to predict stress–strain behavior under controlled single-corner bending, alongside experimental validation through prototype fabrication and destructive testing. With additional material-scale mechanical tests to improve the accuracy of the numerical models. It was found that thin-glass IGUs can achieve a curvature ratio of 0.112, representing a 420% improvement on fully tempered IGUs with standard thickness glass. This demonstrates that thin-glass assemblies are capable of accommodating substantial geometric flexibility without compromising mechanical integrity, thereby reducing reliance on hot-bent glass in architectural applications.

Keywords

Thin-glass, Cold-bending, IGU, Chemically strengthened glass, flexible spacer

Article Information

- Digital Object Identifier (DOI): 10.47982/cgc.10.672
- Published by Challenging Glass, on behalf of the author(s), at Stichting OpenAccess.
- Published as part of the peer-reviewed Challenging Glass Conference Proceedings, Volume 10, June 2026, 10.47982/cgc.10
- Editors: Christian Louter, Freek Bos & Jan Belis

1. Introduction

Curved glass façades are increasingly used in contemporary architecture due to advances in computational design and fabrication technologies. However, the production of curved glass remains resource-intensive, particularly when hot bending is required. Hot bending relies on custom molds and high-temperature processing, resulting in high energy consumption, long lead times and limited design adaptability. Cold bending, in which flat glass units are elastically deformed on site, offers a more sustainable alternative but is constrained by the limited curvature capacity of conventional glass panes.

Recent developments in chemically strengthened thin glass, primarily driven by the electronics industry, present new opportunities for architectural applications. Thin glass exhibits increased flexibility while maintaining sufficient strength, suggesting potential for significantly enhanced cold bending performance. This paper explores whether thin glass can be effectively applied in insulated glass units to increase achievable curvature while maintaining structural integrity and optical performance.

2. Methodology

A combined numerical and experimental methodology was adopted to investigate the cold bending behaviour of thin-glass IGUs. The research focused on a single-corner cold bending configuration, as this method enables relatively high deformations while maintaining controllable boundary conditions.

A finite element model was developed using ANSYS to simulate the cold bending process. The models incorporated detailed representations of the glass panes, spacer, primary adhesive and secondary sealant. Particular attention was given to accurately modelling the mechanical behaviour of the spacer and sealant materials, which play a critical role in accommodating deformation. Where material data was unavailable, experimental testing, including uniaxial tensile and double-lap shear tests, was conducted to derive input parameters.

To validate the modelling approach prior to thin-glass testing, a plexiglass IGU prototype was constructed and tested. Plexiglass was selected due to its lower brittleness, allowing extensive testing without fracture risk. Strain gauges were applied to critical locations on the pane surfaces, and measured strains were compared with numerical predictions. The numerical model was fitted according to the plexiglass model. Following validation, the plexiglass panes were replaced with chemically strengthened thin-glass panes and identical testing procedures were applied.

3. State of the Art

Curved glass façades are increasingly used in contemporary architecture, driven by advances in computational design and fabrication. Two principal methods exist for producing curved glass: hot bending and cold bending. Hot bending allows high curvatures but requires moulds, high temperatures, and bespoke fabrication, resulting in high costs and long lead times. Cold bending, in contrast, shapes flat glass panels on site, offering economic and logistical advantages, but is limited by the structural capacity of glass and edge components.

Previous research has shown that the structural behaviour of cold-bent glass plates is governed by geometric nonlinearity and instability. Galuppi and Royer-Carfagni (2014) demonstrated that cold-bent plates subjected to corner displacements exhibit buckling phenomena, transitioning from anticlastic to monoclastic shapes at relatively low deformations. Staaks (2003) observed similar snap-through behaviour during cold twisting, highlighting the sensitivity of deformation paths to plate thickness and boundary conditions.

To increase achievable curvature, several studies investigated edge stiffening strategies. Young (2019) introduced GFRP edge profiles to monolithic glass plates, achieving limited curvature enhancement but still encountering instability. Van Driel (2021, 2022) extended this approach to insulated glass units (IGUs), demonstrating that rigid edge systems significantly restrict curvature and that anticlastic cold bending of IGUs remains impractical.

The use of thin glass has emerged as a potential solution to overcome curvature limitations. Zhang et al. (2021) showed that reducing glass thickness substantially increases bending capacity, while lamination has limited influence on elastic bending behaviour but improves post-fracture safety. However, most architectural applications still rely on glass thicknesses of 4–8 mm, and research on thin glass in IGUs remains scarce.

In addition, the mechanical behaviour of spacers, adhesives, and sealants has been identified as critical in cold-bent IGUs. Studies by Fedoseeva et al. (2015) and van Driel (2022) showed that spacer stiffness and sealant shear behaviour strongly influence stress redistribution and failure mechanisms, yet these components are often simplified in numerical models.

Overall, existing research indicates that cold bending of IGUs is limited primarily by glass thickness and edge stiffness. Bending glass plates into an anticlastic (double curved) shape has been proved nearly impossible, at most only to a very small extent, therefore this research will focus on monoclastic, developable (single curvature) shapes. While thin glass offers clear potential to increase curvature, its integration into flexible IGUs, supported by experimental validation and detailed numerical modelling, has not yet been comprehensively explored.

4. Material selection & prototype fabrication

To enable large cold-bent deformations, the insulated glass unit (IGU) was designed using highly flexible components. The glass panes consisted of chemically strengthened Glanova thin glass (NSG Pilkington) with a thickness of 1.1 mm. All panes were cut to 800 × 800 mm, a size selected to balance handling constraints with representative structural behaviour. In total, 10 thin-glass sheets were used.

A flexible warm-edge spacer was required to accommodate bending without edge stiffening. The Edgetech Triseal spacer was selected, consisting of silicone foam with an integrated polyisobutylene (PIB) primary sealant. The spacer has cross-sectional dimensions of 20.2 mm × 7.3 mm, and a total length of 99 m was supplied. The relatively wide spacer was chosen to prevent glass-to-glass contact during extreme deformation.

For the secondary seal, a two-component silicone sealant (Kömmerling Ködiglaze S) was used. Although not specifically developed for cold-bent IGUs, its post-curing flexibility and laboratory availability justified its use. The sealant was applied using an Airflow One pneumatic dispenser with a controlled 10:1 mixing ratio. After assembly, all panels were cured for a minimum of 3 days.

IGU assembly was performed manually by bonding the glass panes to the spacer under distributed clamping pressure, followed by complete cavity sealing. In total, six IGU prototypes were fabricated: one PMMA (plexiglass) IGU, two standard thin-glass IGUs, two laminated thin-glass IGUs, and one blackened thin-glass IGU for optical evaluation.

A single-corner cold-bending test rig was constructed to match the panel dimensions (800 × 800 mm). Three corners were rigidly clamped, while the fourth corner was displaced out of plane using a threaded steel rod. Polyethylene foam was placed between clamps and glass to reduce local stress concentrations.

5. Numerical modelling

A finite element model was developed to simulate the mechanical behaviour of cold-bent thin-glass insulated glass units (IGUs) subjected to single-corner out-of-plane deformation. The numerical analysis aimed to (i) capture the stress and deformation response during large elastic bending and (ii) support interpretation and extrapolation of experimental test results.

The IGU was modelled as a multilayer system consisting of two chemically strengthened thin-glass panes separated by a flexible spacer and sealed along the perimeter. The glass panes were represented by linear elastic shell elements, as stresses remained within the elastic regime up to fracture. Geometric nonlinearity was included to account for large deformations during cold bending. Perfect bonding between glass, spacer, and sealant was assumed.

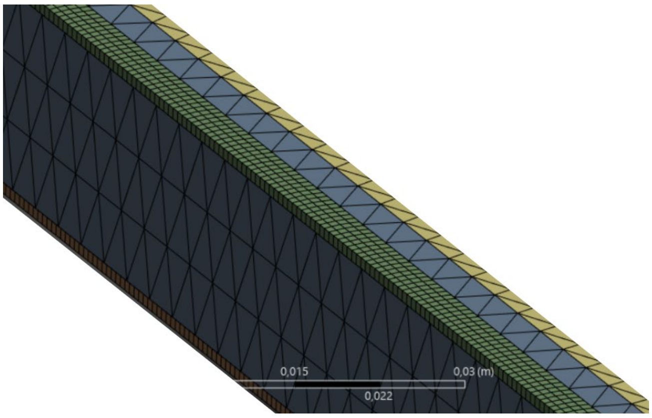

Fig. 1 and 2: FEM model of the spacer, including the PIB strip and the sealant (own work, 2025)

Particular attention was given to the mechanical behavior of the spacer system, as its flexibility governs deformation compatibility and stress redistribution within the IGU. Due to limited manufacturer data, the spacer material was experimentally characterized using uniaxial tensile and double-lap shear tests. The resulting stress–strain data were used to calibrate a first-order Yeoh hyperelastic material model, enabling realistic representation of large-strain behavior. The primary adhesive and secondary sealant were modelled with reduced elastic stiffness, reflecting their limited contribution to global bending resistance while allowing shear deformation along the panel edges.

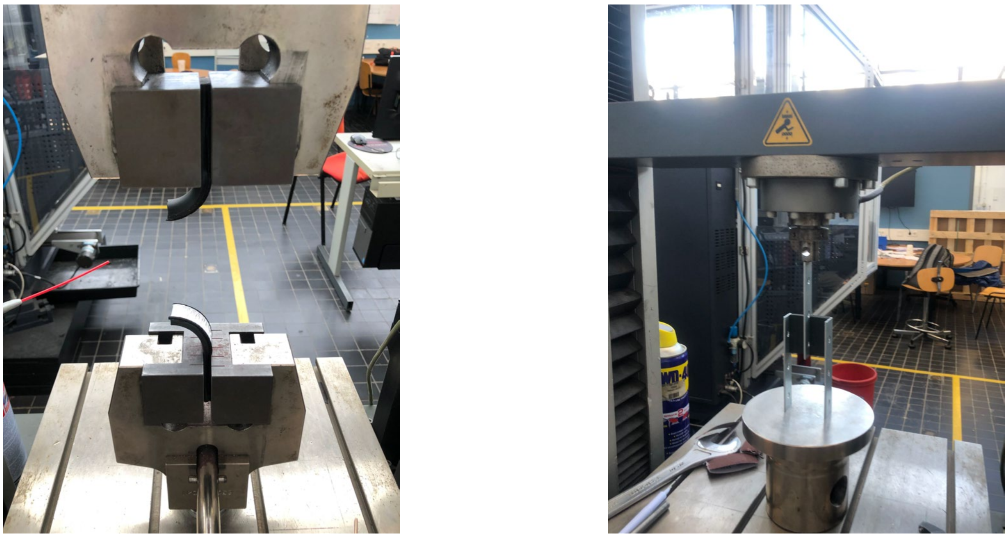

Fig. 3 and 4: result of the tensile test (left) and double-lab shear tests with a piece of spacer between three metal strips. (own work, 2025)

Boundary conditions were defined to replicate the experimental single-corner bending configuration. Three corners of the panel were restrained against out-of-plane displacement, while the fourth corner was subjected to a prescribed vertical displacement. In-plane translations and rotations at the supports were constrained to reflect the clamping conditions used during testing. Contact effects and geometric nonlinearity were included to ensure numerical stability at large displacement levels.

Model validation was performed by comparing numerical predictions with experimental measurements from strain-gauged IGU specimens. Good agreement was observed in global deformation behavior and strain development within the tested displacement range. The model consistently predicted stress concentrations near restrained edges and at transitions between clamped and free regions, corresponding closely to observed fracture locations in the physical tests.

Numerical results indicate that single-corner cold bending of thin-glass IGUs predominantly results in single-curved deformation. The limited stiffness of the flexible spacer system restricts the development of anticlastic shapes, causing stresses to localize near the panel edges rather than being distributed over the surface. Following experimental validation, the model was used to extrapolate stress development beyond experimentally accessible displacements, supporting the conclusion that chemically strengthened thin glass enables substantially higher cold-bending curvatures than conventional architectural glass types.

6. Physical testing

Mechanical performance of chemically strengthened thin-glass insulated glass units (IGUs) was evaluated through a series of single-corner cold-bending experiments. Three separate thin-glass IGUs (800 × 800 mm) were tested under increasing out-of-plane corner displacement, while the remaining three corners were clamped. Strain gauges were applied to the glass surface to record local strain development, and results were compared against finite-element simulations to validate the numerical model. In addition, a displacement gauge was positioned at the rear of the panel to record out-of-plane deformation at a fixed reference point, ensuring repeatability across multiple tests. The set-up of the tests can be seen in Figure 4.

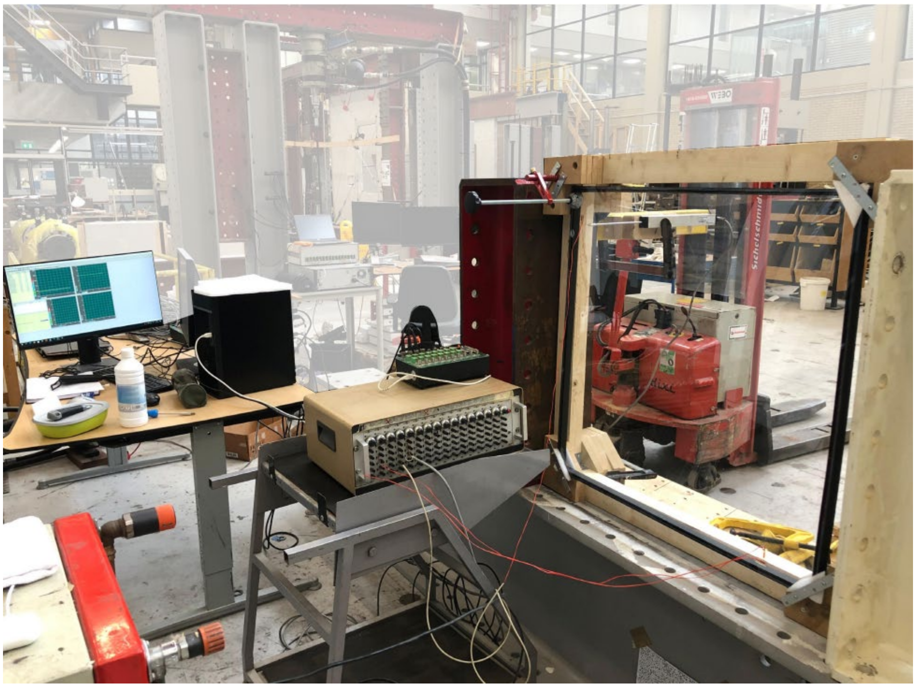

Fig. 4: Setup of the single corner bending tests (own work, 2025)

Fig. 5 and 6: Scheduled Setup of the single corner bending tests (left), and the displacement gauge at the back of the IGU (right) (own work, 2025)

In **Test 01**, insufficient clamping resulted in premature and non-representative failure, highlighting the sensitivity of thin glass to boundary conditions and motivating refinement of the test setup.

Test 02 employed improved clamping and three strain gauges, yielding reproducible strain–deformation behaviour. Measured strains showed good agreement with numerical predictions up to the simulation limit (~110 mm corner displacement). Linear extrapolation of the maximum principal stress indicated that failure would occur near 300 MPa, suggesting slightly loose clamping still influenced the measured response.

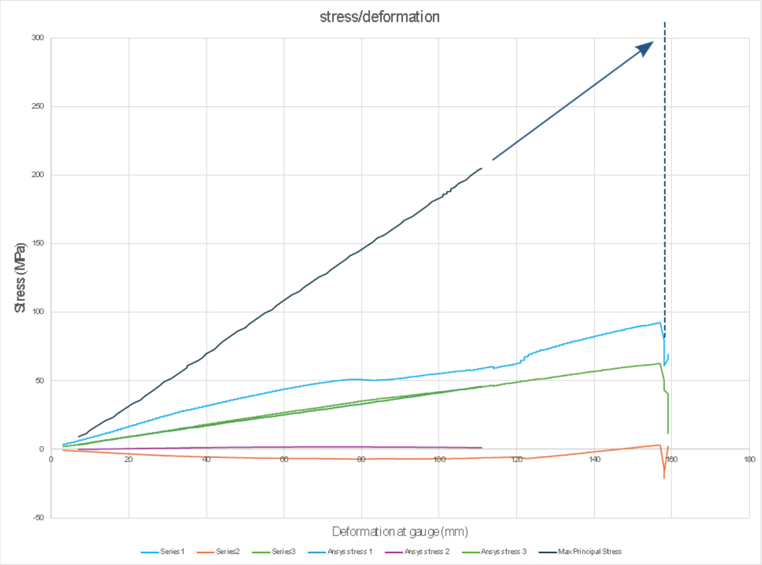

Fig. 8: Thin-glass test 02 strain gauge stress results against numerical model, including maximum measured stress in model (own work, 2025)

Test 03 : Clamp positions were further improved by moving the clamps closer to the panel centre, increasing edge restraint. Although only one strain gauge was available, the test reached a corner displacement of 163 mm, at which point fracture occurred on the concave (tensile) side of the glass. Extrapolation of the numerically predicted stress–deformation relationship indicated failure at approximately 260 MPa, corresponding closely to the known tensile strength of chemically strengthened thin glass and validating the numerical model.

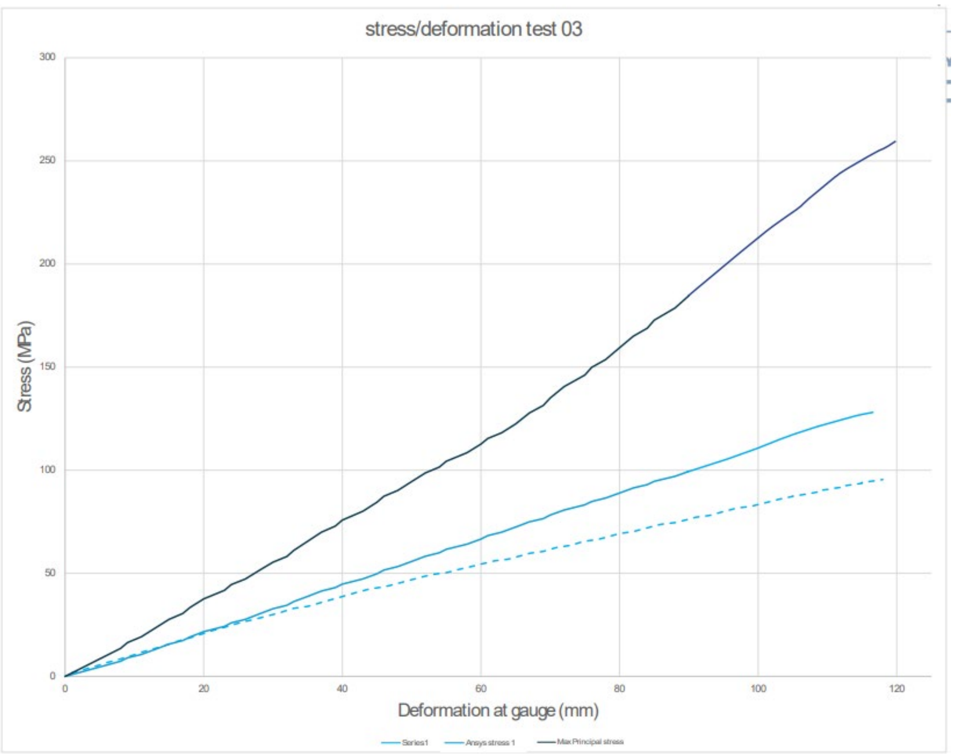

Fig. 9: Thin-glass test 03 strain gauge stress results against numerical model, including maximum measured stress in model (own work, 2025)

Across the validated tests, failure occurred at corner displacements between 16.3 cm and 18.5 cm, demonstrating a substantial improvement over conventional glass types. Compared to annealed, heat-strengthened, and fully tempered glass, the thin glass panels exhibited bending capacities approximately 5.25×, 2.76×, and 2.2× higher, respectively.

The results confirm that chemically strengthened thin glass can tolerate large elastic deformations under cold bending, provided that edge constraints are carefully designed to avoid stress concentrations and premature edge failure.

7. Optical quality Assessment

The optical performance of the cold-bent thin-glass IGUs was evaluated to assess surface distortions introduced during extreme bending. Optical quality was examined using a visual reflection test with a zebra-striped pattern, a commonly applied qualitative method for detecting surface waviness, ripples, and local distortions in glass panels during forming processes.

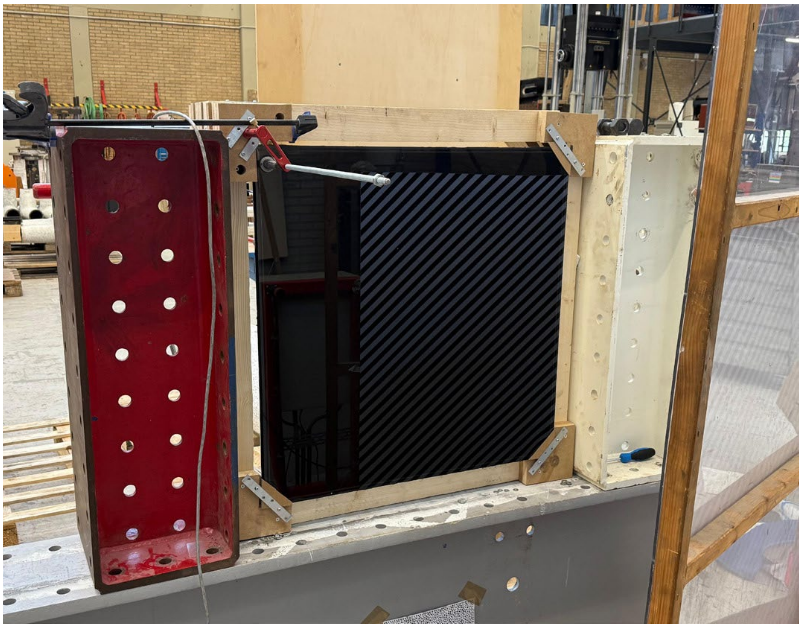

Fig 10: Set-up of the optical quality test. (own work, 2025)

Observations were made before, during, and after single-corner cold bending at large displacement levels. Throughout the bending process, the reflected zebra pattern remained largely continuous and undistorted across the central area of the panel. No significant surface ripples or localized optical defects—often associated with hot-bent glass—were observed. Minor deviations in the reflected lines occurred primarily near the panel edges and corners, corresponding to expected geometric distortions induced by the cold-bending deformation rather than material imperfections.

Due to the lack of specialized optical measurement equipment, a quantitative surface quality classification could not be performed using established assessment frameworks. Nevertheless, the visual reflection test indicates that cold bending chemically strengthened thin glass preserves high optical quality, even at large deformation levels. In contrast to hot-bent glass, where thermal processing frequently introduces permanent surface waviness, the cold-bent thin glass panels exhibited smooth reflective behaviour dominated by global geometry rather than local surface defects.

These findings suggest that cold-bent thin-glass IGUs are well suited for architectural applications where optical clarity and surface quality are critical, such as façade elements with visible reflections or high visual exposure. Figure 10 and 11 show a case study whereby the initially hot-bent glass panels on the roof of the Fenix are replaced by cold bent thin-glass IGU's.

Fig. 11: Potential difference in optical surface quality between hot bending (left) and cold bending (right) (own work, 2025)

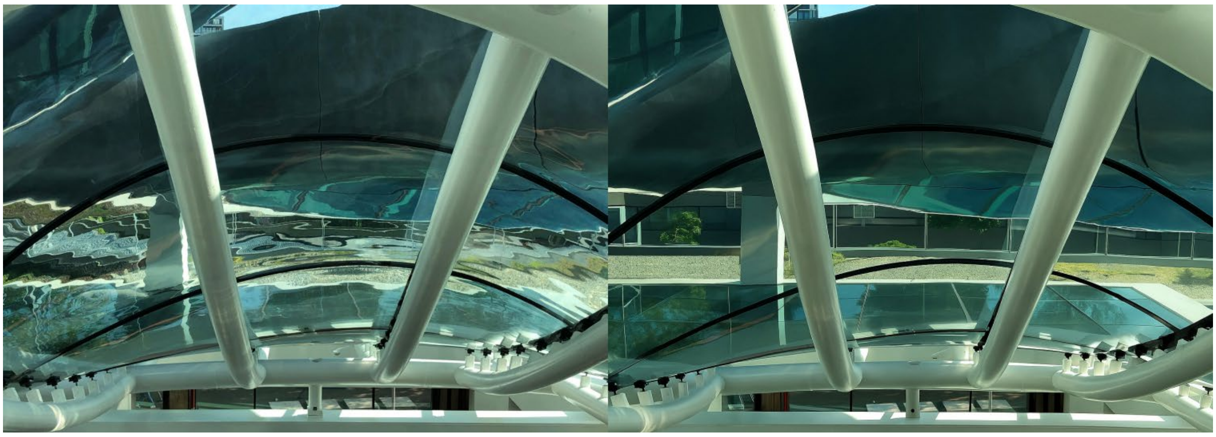

Fig. 12 Potential difference in optical surface quality between hot bending (left) and cold bending (right) (own work, 2025)

8. Conclusions and future work

This research demonstrates that the application of chemically strengthened thin glass significantly increases the achievable curvature of cold bent insulated glass units (IGUs) compared to conventional architectural glazing. Through a combination of numerical modelling and experimental testing, the study confirms that thin-glass IGUs can sustain substantially higher corner deflections while maintaining structural integrity, marking a notable performance improvement over annealed, heat-strengthened, and fully tempered glass units.

Despite these promising results, several limitations must be acknowledged. First, glass failure remained the governing limit state in all tests, indicating that while higher curvatures are achievable, the system operates close to material limits. As a result, the proposed configuration requires careful validation before application in practice. In particular, the absence of lamination in the tested panels limits post-fracture safety and does not yet align with standard façade safety requirements. Although previous studies suggest that lamination has limited influence on bending capacity, its interaction with extreme cold bending, thin glass, and flexible spacers remains insufficiently understood.

The accuracy of the numerical model proved adequate in capturing global structural behaviour and strain trends, but discrepancies between measured and simulated values highlight the sensitivity of the system to boundary conditions and material properties. The mechanical behaviour of sealants, spacers, and cushioning materials played a critical role in both experimental and numerical outcomes. Further refinement of material characterisation, particularly for hyperelastic and time-dependent components, would improve predictive reliability.

From an application perspective, the results suggest that thin-glass cold bending offers a viable alternative to hot bending for moderately sized façade panels, combining high curvature potential with reduced fabrication complexity and cost. However, long-term performance under sustained stresses, environmental exposure, and repeated loading remains unverified. Additionally, this study focused on single-corner cold bending; alternative geometries and loading scenarios may exhibit different structural and optical behaviour.

Overall, the research establishes thin-glass IGUs as a promising direction for curved façade design, while underscoring the need for further investigation into lamination, durability, and large-scale implementation.

Acknowledgements

I want to thank Rory Back, Arai Daichi and the rest of the team at Pilkington/NSG who were willing to provide chemically strengthened thin-glass sheets. I also want to thank Roger Kahlen from Edgetech/Superspacer for providing their Triseal flexible spacer, which was crucial to this research project. Lastly I would like to thank the entire team at the Stevin labs for helping me set up my testing rig and measurement instruments.

References

Galuppi, L., & Royer-Carfagni, G. (2014). Buckling phenomena in cold-bent glass plates. *Engineering Structures, 60*, 75–88. https://doi.org/10.1016/j.engstruct.2013.12.030

Staaks, D. (2003). *Cold twisting of glass plates* (Doctoral dissertation). Delft University of Technology, Delft, The Netherlands.

Young, B. (2019). Cold bending of glass plates with stiffened edges. *Glass Structures & Engineering, 4*(1), 25–38. https://doi.org/10.1007/s40940-019-00084-5

van Driel, T. (2022). *Investigations on the cold bending behaviour of a double glazing unit with a rigid edge spacer frame* (Master's thesis). Delft University of Technology, Delft, The Netherlands.

Zhang, X., Liu, Y., Bedon, C., & Zhang, H. (2021). Experimental and numerical investigation on the bending behaviour of thin and laminated glass. *Construction and Building Materials, 269*, 121270. https://doi.org/10.1016/j.conbuildmat.2020.121270

Fedoseeva, A., Schneider, J., & Santarsiero, M. (2017). Mechanical behaviour of spacers and sealants in insulating glass units under combined loading. *Glass Structures & Engineering, 2*(2), 135–150. https://doi.org/10.1007/s40940-017-0044-1

Overend, M., & Jin, Q. (2016). The strength and fracture of structural glass elements. *Construction and Building Materials, 114*, 18–30. https://doi.org/10.1016/j.conbuildmat.2016.03.138

Challenging Glass Conference Proceedings – Volume 10 – June 2026 – Louter, Bos & Belis (Eds.)
International Conference on the Architectural and Structural Application of Glass
Challenging Glass Conference 10 – 15-17 June 2026 – TU Delft – The Netherlands

CGC 10

Platinum Sponsor

SAINT-GOBAIN

Gold Sponsors

EASTMAN

kuraray

NorthGlass®

sedak

seele

Silver Sponsors

DOW®

octatube

PERMASTEELISA GROUP

SEEN

Organisation

TU Delft

Technische Universität München

GHENT UNIVERSITY