Adaptive and composite thin glass concepts for architectural applications

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Thin glass – such as commonly applied for displays and touchscreen on electronic devices like smartphone and tablets – offers interesting characteristics for architectural applications. Due to its high strength and small thickness the glass can easily be bent in architecturally appealing curvatures, while the small thickness of the glass offers a significant weight reduction compared to traditional window glazing. This paper explores the potential of thin glass for architectural applications and reports on two thin glass concepts that are currently under investigation at TU Delft. The first concept concerns flexible and adaptive thin glass panels that can change their shape in response to external parameters. The second concept concerns thin glass composite panels in which thin glass facings are combined with (3D printed) core elements to create strong, stiff yet lightweight glass façade panels. From initial design explorations and prototyping, it can be seen that both concepts are very promising and viable for further in depth investigations.

Key words: Thin glass, composite, adaptive

1 Introduction

Thin chemically strengthened alumino-silicate glass is predominantly applied in the electronics industry for displays on smartphones, tablets and other devices. For such applications, its high strength, scratch resistance, impact resistance, optical quality and small thickness thus low weight are favoured. These are interesting characteristics which could also be exploited for novel glazing solutions in the building industry [Schneider, 2015]. Due to its small thickness (e.g. 0.1 – 2 mm) and high bending strength (indicative range 200–1000 MPa [Schneider, 2015]) such thin glass can easily be cold bent in architecturally appealing curvatures, which provides an opportunity for creating curved and deformable building skins. Furthermore, due to its small thickness a significant weight reduction in comparison to regular window glazing (typically ≥ 4 mm) can be obtained.

The architectural application of thin glass is a novel domain and to date only a few precedent studies have explored its potential. In those studies, a variety of concepts for the architectural application of thin glass are explored, some of which are briefly highlighted here.

Firstly, hybrid thin glass concepts are proposed in which high strength thin glass facings are laminated to a thicker polymer or glass core ply [Lambert and O'Callaghan, 2013; Overend et al. 2014; Weimar and Andrés López, 2018]. Benefit of such hybrid solutions is that they can offer reduced weight and enhanced pre- and post-fracture structural performance compared to conventional laminated glass units.

Secondly, concepts are proposed in which curved thin glass surfaces are created by means of cold-bending techniques thereby taking advantage of the flexibility of thin glass [Lambert and O'Callaghan, 2013; Mainil, 2015; Simoen, 2016; Datsiou, 2017; Schlösser, 2018]. Benefit of doing so is that curved glass surfaces with relatively tight radii and high optical quality can be created by on-site bending or by autoclave lamination bending without the need for energy intensive and cost intensive hot-shaping techniques.

Thirdly, concepts for considering thin glass as a transparent fabric are proposed [Lambert & O'Callaghan, 2013; Ottens, 2018]. This offers an opportunity for creating thin glass membrane structures.

Finally, movable and adaptive thin glass structures and building envelopes are proposed [Hundevad, 2014; Neugebauer 2015; Neugebauer et al. 2018]. In such concepts, full benefit is taken of the flexibility of the thin glass for the creation of structures and building skins that can change their shape depending on external conditions and requirements.

In addition to these design explorations, some research projects investigate the strength of thin glass, e.g. [Cervio, 2018; Spitzhüttl et al., 2014; Maniatis et al. 2016; Neugebauer, 2016; Oliveira Santos et al. 2018]. Due to its high strength and flexibility, conventional glass testing procedures are not always suitable for thin glass and thus new testing procedures are being proposed.

The current paper contributes to the design explorations with thin glass. It reports on the thin glass design concepts and small-scale prototypes that have recently been developed at TU Delft in a series of MSc thesis projects. Two main concepts are proposed and reported in this paper, namely the creation of *adaptive thin glass panels* as presented in Section 2 and the creation of *composite thin glass panels* as presented in Section 3.

2 Adaptive thin glass panels

2.1 ***General concept***

The first proposed concept makes use of the high flexibility of thin glass for the creation of adaptive glass façades. The general idea is that such façades can repetitively change their shape in response to external parameters. For instance, by bending the thin glass, ventilation openings can be created to provide an airflow through the cavity of a double-skin façade. Moreover, the curvature of thin glass façade panels could be adjusted so to better resist increased wind loading or to continuously optimize the orientation of thin film photovoltaic cells that may be added to the thin glass layer.

The following sections report on the concepts that were studied and the prototypes that were produced in a series of MSc thesis projects executed at TU Delft.

2.2 ***Adaptive thin glass façade panels***

In the works of Ribeiro Silveira [Ribeiro Silveira, 2016] [Ribeiro Silveira et al., 2018] and Topcu [Topcu, 2017], the first steps regarding the development at TU Delft of adaptive thin glass façades were made. After initial design explorations, see e.g. Figure 1, final design proposals were elaborated and proof of concepts were presented through prototyping.

In the work of Ribeiro Silveira [Ribeiro Silveira, 2016] a design and prototype of a double-skin adaptive thin glass façade was made. The design consists of thin glass panels with a central scissor guide that can move outwards, thereby curving the glass towards the exterior, see Figure 2. The thin glass is framed along the long (vertical) edges of the glass and pin-connected to a rail system at the top and bottom. This allows the glass panel to curve and, if desired, to adopt a different curvature at the bottom and top of the panel. A 500 x 800 mm mock-up was produced to provide an initial proof of concept, see Figure 3. In the mock-up, the scissor guides were replaced by chain drive actuators with a stroke of 250 mm which could push the glass outwards to a bending radius of 106 mm. A monolithic chemically strengthened aluminosilicate glass panel with a thickness of t = 2 mm was used for the mock-up. The end result of the mock-up was very satisfactory as it demonstrated the overall feasibility of the concept.

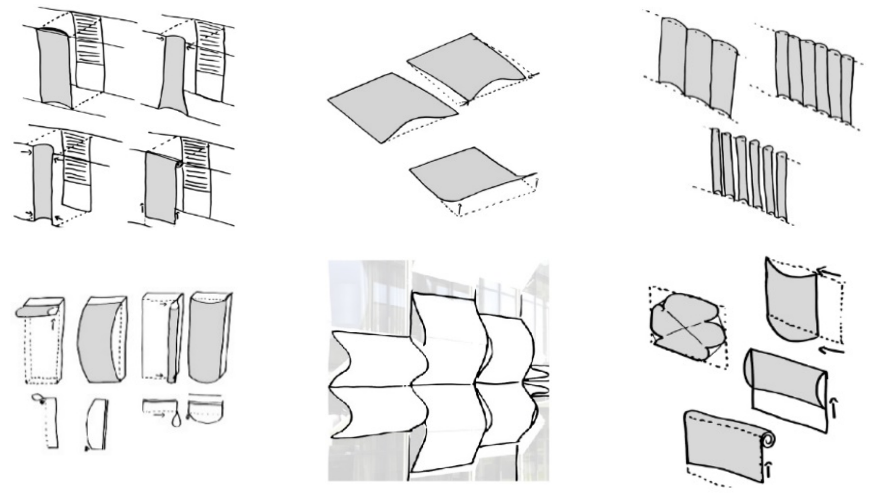


Figure 1: Sketches of adaptive thin glass façade concepts [Ribeiro Silveira, 2016]

Figure 2: Renderings of the proposed adaptive thin glass façade [Ribeiro Silveira, 2016]

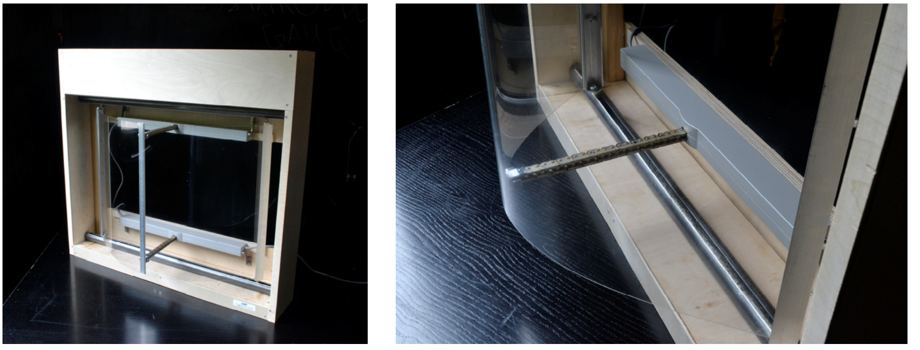


Figure 3: Mock-up of the proposed adaptive thin glass façade [Ribeiro Silveira, 2016]

The work of Topcu [Topcu, 2017] further explored the adaptive thin glass façade concept and focused additionally on possibilities for creating water- and airtightness of the façade in its closed condition. Different design solutions were explored, see Figure 4, such as (a) adding a magnetic strip along the perimeter of the glass which would seal the panel in the closed condition, similar to a refrigerator door, (b) applying a bi-directional tensile force on the glass panel in its closed condition to prevent outworks movement and thus to provide a tight closure of the panels, and (c) to add an elastic (stretchable) fabric along the curved sides of the glass to continuously seal the panel along its long sides.
The concept of the magnetic strip was considered most feasible and demonstrated in a 500x800 mm mock-up, see Figure 5. The mock-up, in which magnetic strips were provided along the perimeter of the panel, demonstrated the proper functioning and feasibility of the system. Finally, the concept was further exemplified in a case-study design in which the existing façade of the AGC Technovation Centre was replaced by an adaptive thin glass façade solution, see Figure 6.

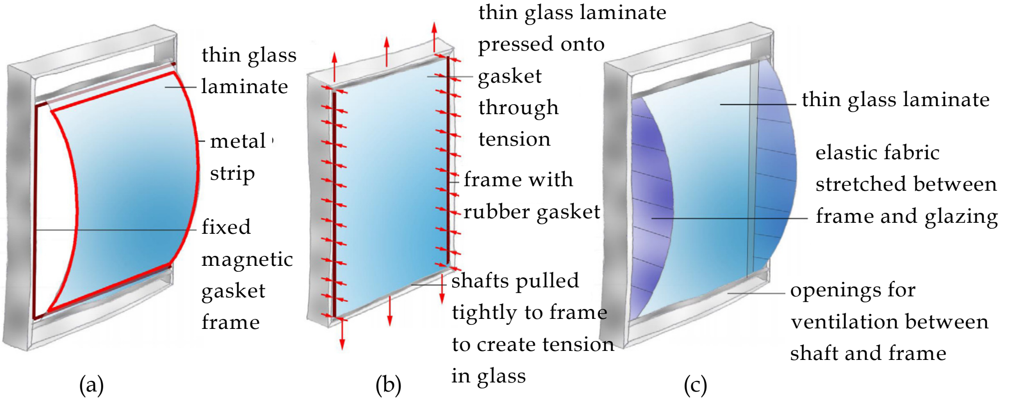


Figure 4: Design solutions for water and airtightness of an adaptive thin glass façade [Topcu, 2017]

Figure 5: Mock-up of adaptive thin glass façade with magnetic sealing at the edges [Topcu, 2017]

Figure 6: Rendering of case-study design of the proposed adaptive thin glass façade [Topcu, 2017]

2.3 *Adaptive thin glass façade panels with shape memory alloy wire actuation*

The concept of adaptive thin glass façades has been further explored in the work of Miri [Miri, 2018]. In this work the actuation of thin glass by means of shape memory alloy (SMA) is investigated. Basic concept is to integrate a thin wire SMA in the thin glass window configuration. When the SMA wire is heated, e.g. by means of solar radiation or by applying an electric current, the wire will shorten and thereby pull and bend the thin glass façade panel. In the study, different configurations have been explored, see Figure 7.

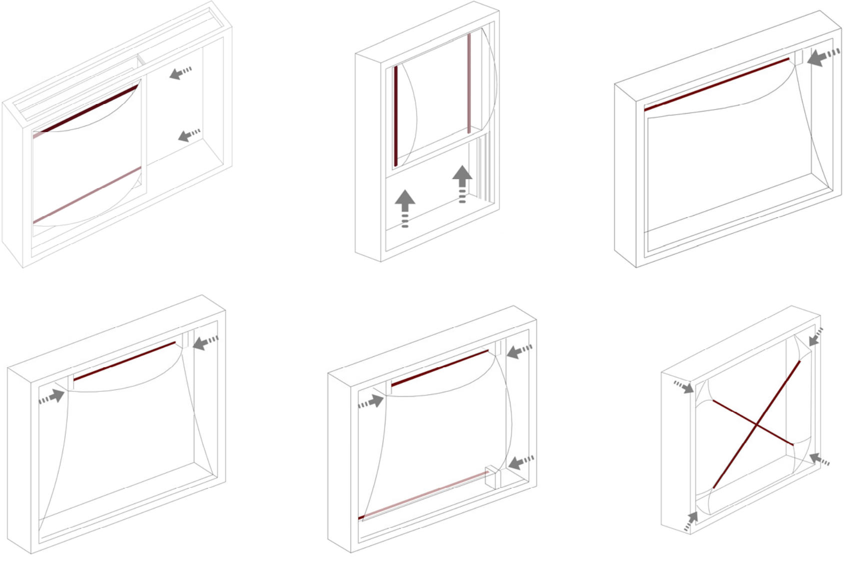


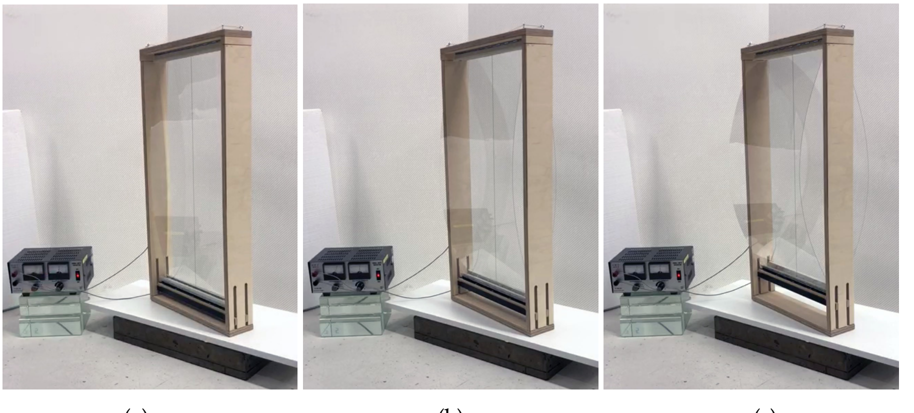
Figure 7: Design explorations for adaptive thin glass façades with shape memory alloy actuation [Miri, 2018]

As a proof of concept, a 500 x 800 mm mock-up has been made, see Figure 8 and Figure 9. In this mock-up, chemically strengthened aluminosilicate thin glass panels with thickness t = 0.55 mm and dimensions 360 x 710 mm are actuated by means of a 0.51 mm Flexinol® SMA wire. The SMA wire is placed in the cavity between two thin glass panels and is extended into the top part of the window frame. By the application of an electric current (~10V, ~1.2A), the SMA wire heats up, shortens and lifts the bottom of the thin glass. The SMA wire is able to lift 3.65 kg [Miri, 2018] and has a stroke of about 5% which translates into 70 mm over its applied length of 1400 mm. This results in a bending radius of the thin glass of about 415 mm. The response time for opening/curving the window is about 20 seconds. The mock-up successfully demonstrated the feasibility of the concept.

The concept is further exemplified in a case-study re-design for the Genzyme Center; a twelve-story building located in Cambridge, Massachusetts, see Figure 10. In the case-study re-design the adaptive thin glass concept with SMA wire is applied as a double-skin façade system, allowing for ventilation of the façade cavity by curving the thin glass. Although the current design shows two layers of thin glass, the concept is also applicable as a single layer adaptive thin glass façade.

(a) (b)

Figure 8: Schematic representation of the adaptive thin glass façade concept with shape memory alloy actuation [Miri, 2018]



(a) (b) (c)

Figure 9: Mock-up of the adaptive thin glass façade concept with shape memory alloy [Miri, 2018]

Figure 10: Case-study re-design of adaptive thin glass façade for the Genzyme Center [Miri, 2018]

2.4 *Adaptive thin glass façade panels with soft pneumatic actuation*

The work of Zha [Zha, 2018] focused on the actuation of an adaptive thin glass façade by means of soft pneumatics actuators. The basic idea is to adhesively bond a series of soft polymer air chambers on the thin glass façade panel and to bend the glass through inflation of the air chambers, see Figure 11. The soft polymer air chambers will, due to the inflation, expand like a balloon and will start to touch each other thereby exerting a compressive force between the air chambers. Since this compressive force acts at a distance from the thin glass to which the air chambers are bonded, a bending moment is exerting on the thin glass which causes the glass to bend.

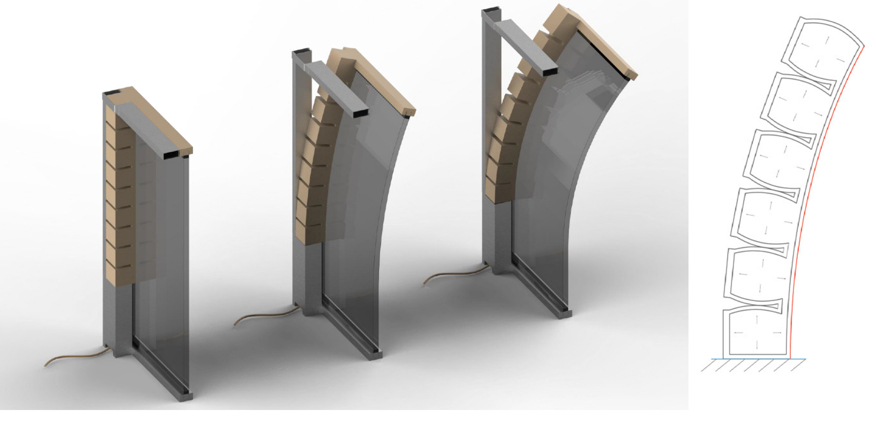


Figure 11: Concept of adaptive thin glass façade panels with soft pneumatic actuators [Zha, 2018]

As a proof of concept, a 300 x 300 mm mock-up of an insulating adaptive thin glass panel with soft pneumatic actuators was made, see Figure 12 and Figure 13. The mock-up consisted of two 300 x 300 mm chemically strengthened aluminosilicate thin glass sheets with nominal thickness t = 0.55 mm and a series of soft rubber air chambers which were bonded to the glass by means of double-sided acrylic tape. To allow bending of the overall insulating glass panel, a flexible foam spacer was applied (Edgetech Super Spacer), which was for the sake of simplicity bonded to the glass also by means of the double-sided acrylic tape. The air chambers were interconnected by means of silicone tubes. By manual air pomp inflation the overall panel could be bend. Due to air leakage the glass panel could not be bend to its full potential, but the mock-up successfully demonstrating the feasibility of the concept.

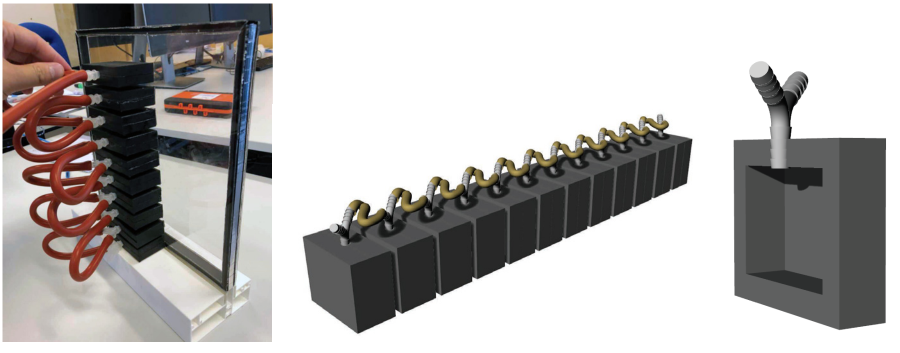
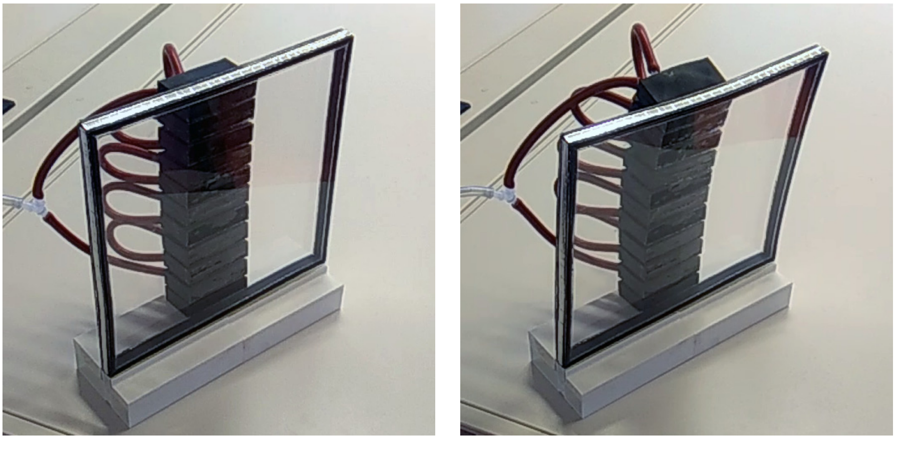


Figure 12: Configuration of air chambers applied in the adaptive thin glass mock-up [Zha, 2018]



(a) (b)

Figure 13: Images of the mock-up in (a) flat position and (b) slightly curved position [Zha, 2018]

3 Composite thin glass panels

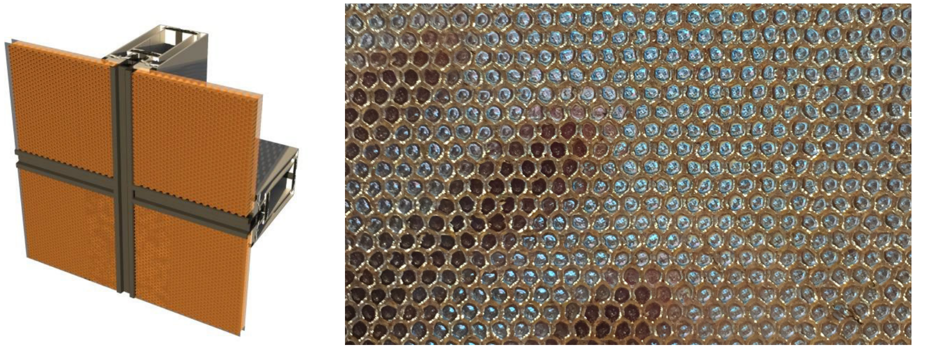
3.1 General concept

The second proposed concept is the creation of strong, stiff yet lightweight composite thin glass panels. Thin glass is typically too flexible to replace flat conventional window glazing on a one-to-one basis. The application of thinner glass, without additional measures, would result in too much deformation of the window glazing thereby exceeding the serviceability limit state requirements. Although this may not pose a direct safety treat, the large(r) deformation and potentially associated vibrations and optical deformations may cause discomfort and nuisance for building occupants. To prevent such large deformations, the here proposed concept makes use of core materials to stiffen thin glass panels. More specifically, a composite consisting of thin glass outer facings that are adhesively bonded to an inner stiffening core is generated. Benefit of doing so is that very lightweight yet strong and stiff façade panels are created. It should be noted that instead of combining thin glass with solid core materials such as e.g. polycarbonate [Weimar and Andrés López, 2018], the current study uses hollow core patterns to further optimize the weight of the panel. Although these opaque or translucent core patterns on the one hand may compromise the overall transparency of the panel, it could on the other hand contribute to the architectural expression and daylighting characteristics of the panel. The following subsections report on the concepts that were studied and the prototypes that were produced in a series of MSc thesis projects executed at TU Delft.

3.2 Thin Glass Panels with Honeycombed Core

In the work of Van der Weijde [Van der Weijde, 2017], the first steps regarding the development at TU Delft of thin glass composite panels are taken. In this MSc thesis project a thin glass composite panel with honeycombed core material is developed, see Figure 14, targeting for a lightweight yet stiff and strong glass façade panel. The panels show some similarities with the glass sandwich panels of the entrance canopy of the Berkeley Hotel in London [Teixidor, 2016]. However, rather than an aluminium honeycombed core, as used in the Berkeley Hotel entrance canopy, the study of Van der Weijde makes use of an aramid honeycombed core which was considered promising because of its low weight and low thermal conductivity. The latter especially contributes to the thermal insulating performance of the overall (façade) panel by minimizing the thermal bridging between the glass outer facings through the honeycombed core.

To demonstrate the potential of thin glass composite panels, a small 80 x 350 mm thin glass composite panel with a honeycombed aramid core was made at TU Delft. Chemically strengthened, aluminosilicate thin glass outer facings of thickness t = 2 mm and a honeycombed aramid core with thickness t = 10 mm and a cell size of 5 mm were used. SentryGlas (SG) interlayer sheets of t = 1.52 mm were found to be most suitable for bonding the thin glass with the honeycombed core [Van der Weijde, 2017]. Lamination was done by means of a controlled oven lamination cycle. Even though this does not comply with an industrial autoclave lamination cycle, the production results were satisfactory. During the lamination process the SG interlayer has partially molten into the cells of the aramid honeycomb creating filleted surfaces inside the cells. Due to this, the view through the cells is not fully transparent, but partially distorted, see Figure 14.
The resulting specimen was submitted to a load of 1.5 kN in a 3-point bending test, see Figure 15. The test demonstrated a satisfactory structural interaction between the thin glass and the honeycombed aramid core through the SG interlayer, providing a stiff thin glass composite panel.



(a) (b)

Figure 14: Thin glass composite panel with honeycombed aramid core (cell size on photo is 5 mm)

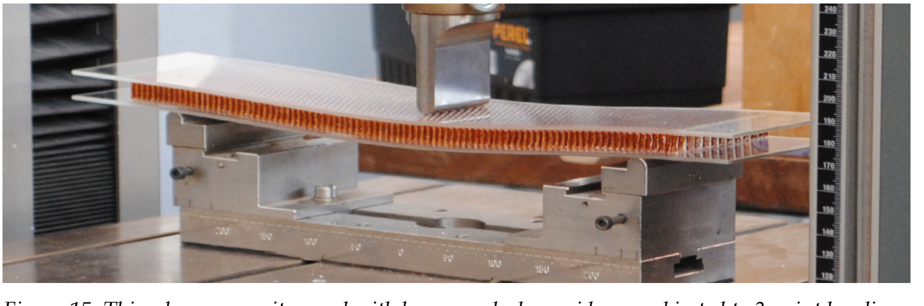


Figure 15: Thin glass composite panel with honeycombed aramid core subjected to 3-point bending

3.3 *Thin glass with 3D-printed trussed and hypar core patterns*

The work of Akilo [Akilo, 2018], which was done in collaboration with University of Bologna, focuses on the development of a thin glass composite with a 3D-printed polymer core. Instead of a closed-cell honeycomb core such as used in the work of Van der Weijde [2017], the study of Akilo explores the possibilities of 3D printing an open-cell pyramidal trussed core and a hypar-shaped core that stiffen the thin glass composite panel. The trussed core provides an optically more open structure than the previously investigated honeycomb core, whereas the hypar-shaped core provides a translucent and textured appearance. Through additional small perforations in the hypar-shaped core a certain degree of transparency is provided to the panel.

To demonstrate the principle and to explore its feasibility, 210 x 297 mm thin glass composite panels were constructed at TU Delft, applying either a trussed core or a perforated hypar-shaped core, see Figure 16, Figure 17 and Figure 18. Single layers of chemically strengthened aluminosilicate thin glass of thickness t = 0.7 mm were used for the outer facings of the composite panel. The 11 mm thick core was printed from polyethylene terephthalate glycol-modified (PETG) filament by means of Fused Deposition Modelling (FDM) technique using a Leapfrog's "Creatr HS" printer for the trussed core and a Kossel XL printer for the hypar-shaped core, see Figure 19. Due to size limitations of the printers, the trussed core was printed in 4 parts and the hypar-shaped core in 2 parts, which were afterwards adhesively bonded. To bond the glass and the PETG core and to bond the individual pieces of the PETG core a transparent two-component epoxy-based adhesive was selected (VersaChem's 5 Minute Epoxy System).

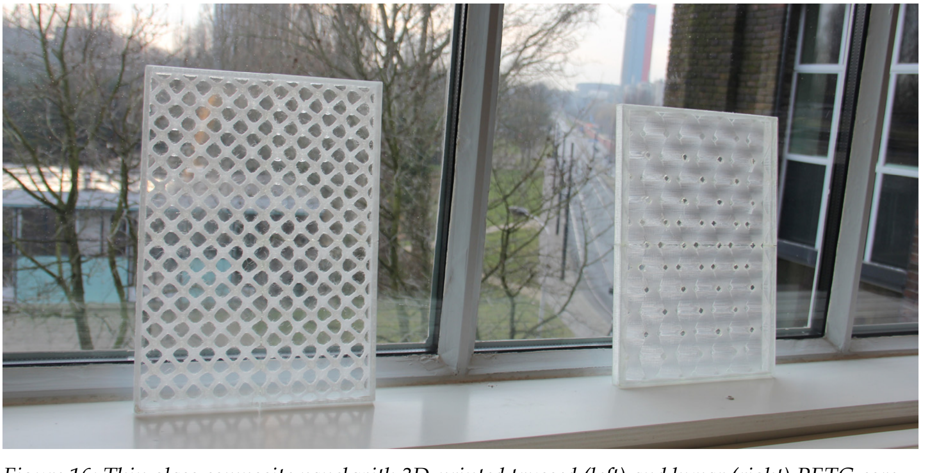


Figure 16: Thin glass composite panel with 3D-printed trussed (left) and hypar (right) PETG core

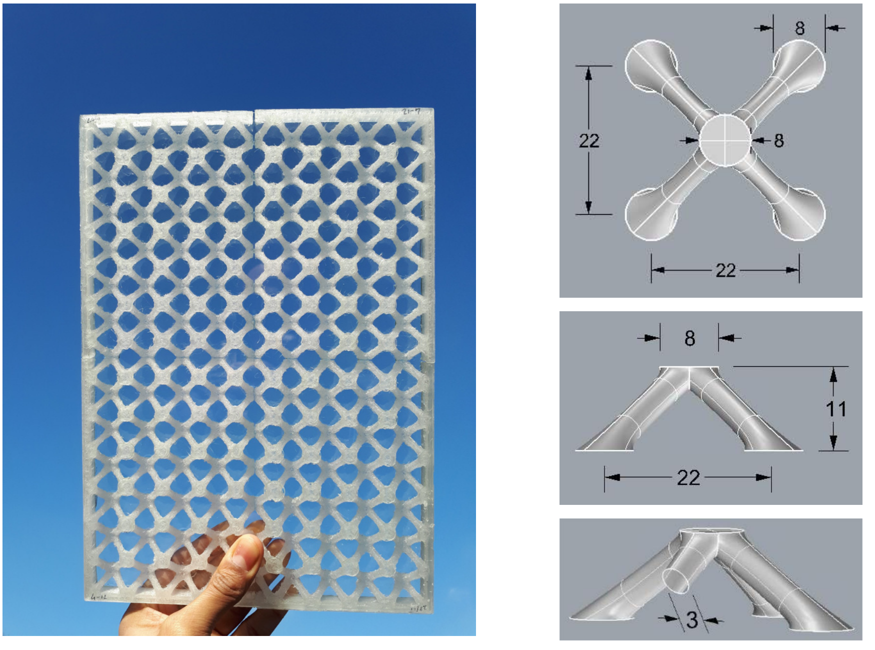


Figure 17: Overview of the thin glass composite panel with 3D printed trussed core [Akilo, 2018]

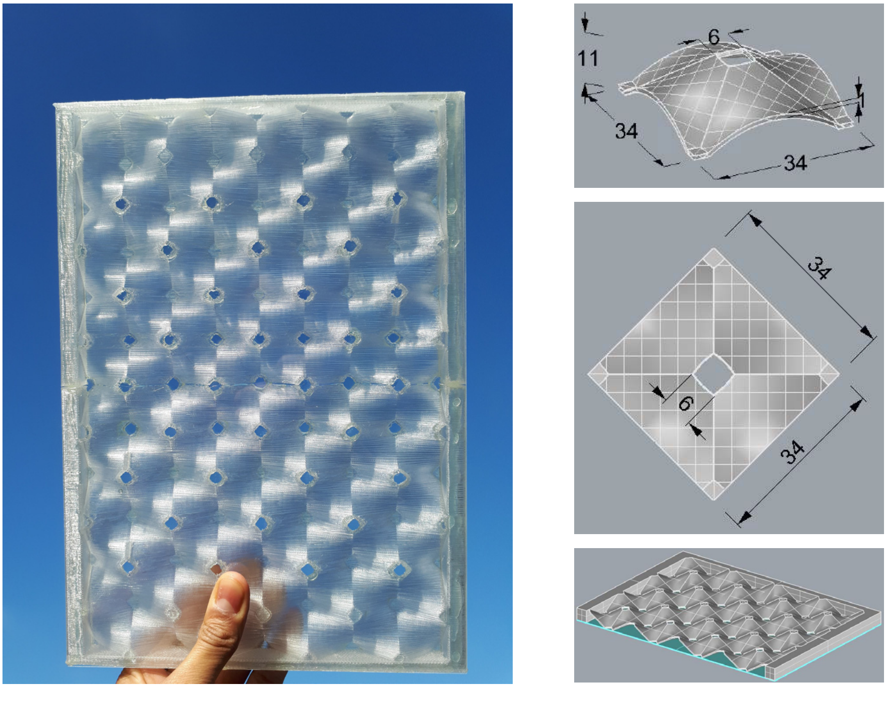
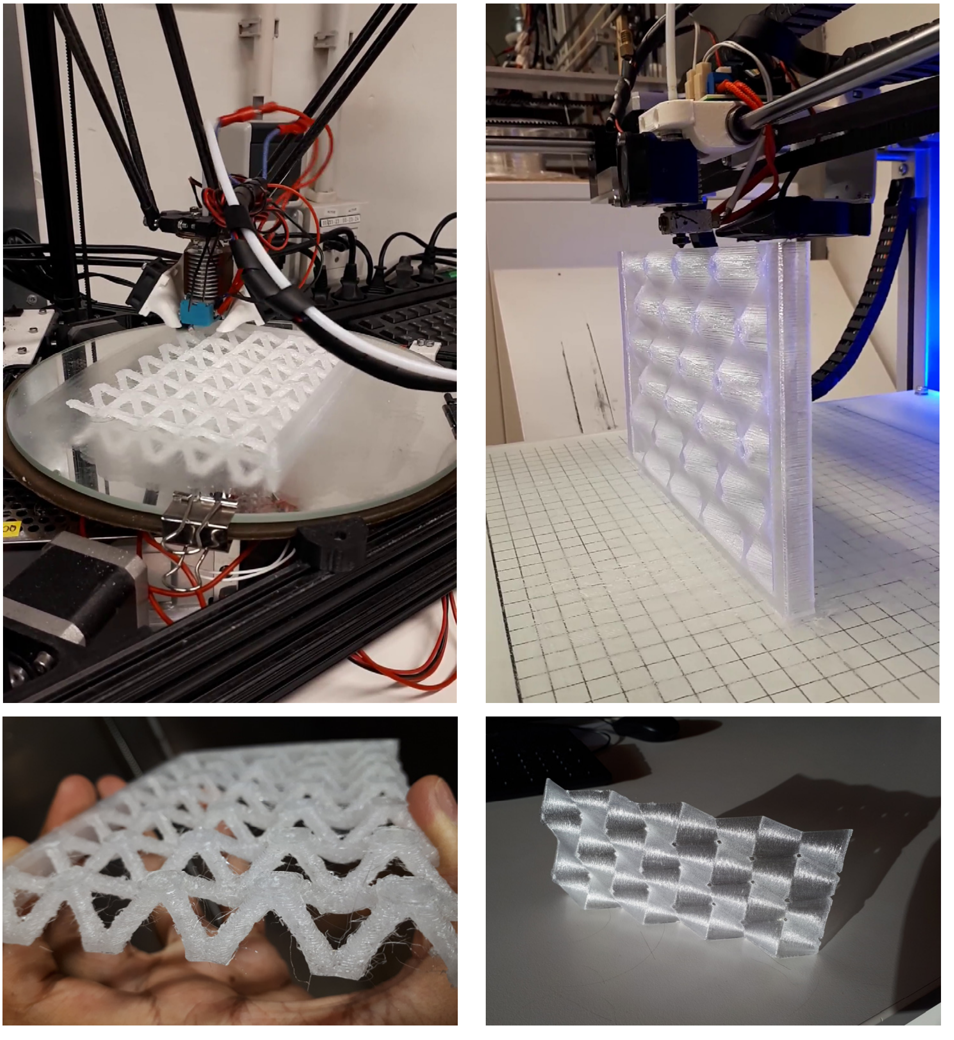


Figure 18: Overview of the thin glass composite panel with 3D printed perforated hypar-shaped core [Akilo, 2018]



(a) (b)

Figure 19: 3D printing strategy applied for (a) the trussed core, and (b) the perforated hypar-shaped core [Akilo, 2018]

The small-scale panels showed the architectural expression and implications of the concept and proofed to be structurally efficient in a 3-point bending test. Furthermore, their structural stiffness was successfully predicted using Allen's sandwich theory [Akilo, 2018].

3.4 *Thin glass with 3D-printed Voronoi core pattern (generation 2)*

The concept of 3D printing a polymer core for the creation of a thin glass composite panel has been further exploited in the work of Neeskens [Neeskens, 2018]. In this work the investigated strategy was to create a structurally optimized core pattern by applying core material only where structurally most efficient, so to safe material and weight. To do so, a Voronoi pattern was applied of which the precise geometry was generated through topology optimization. Through a parameter study, the effects of changing boundary conditions and targeted pattern density was investigated.

To demonstrate the principles and the practical feasibility, small scale 150 x 300 mm thin glass composite panels were produced, see Figure 20. The panels consist of the 3D-printed PETG cores with a nominal thickness of t = 8 mm and two outer facings of chemically strengthened aluminosilicate glass each with a thickness of t = 1 mm. To connect the 3D-printed Voronoi core pattern to the outer glass layers, either a TESA 51966 PET tape with acrylic adhesive layer or a Delo Photobond UV curing acrylic adhesive was used.

The small-scale prototype panels showed the architectural expression and implication of the concept. Also, in a 3-point bending test the structural efficiency of the system was successfully demonstrated. However, it was seen that the interaction between the outer thin glass panels and the polymeric core was insufficiently guaranteed by the PET tape, but highly efficient for the acrylic adhesive [Neeskens, 2018].

Figure 20: Thin glass panels with 3D-printed PETG Voronoi core patterns [Neeskens, 2018]

4 Discussion and conclusion

The projects that are reported in this paper demonstrate the potential of applying thin glass for architectural applications in the form of either *adaptive* or *composite* thin glass panels. Benefit of the adaptive thin glass panels is that such panels can be exploited for the realization of glass envelopes that can adjust their shape depending on external parameters. Benefit of the composite thin glass panels, using e.g. honeycombed or 3D-printed polymer cores, is that such panels could offer a reduced weight and enhanced strength and stiffness compared to conventional laminated glass units. Although the presented projects are merely exploratory, they all yield architecturally appealing and structurally promising results.

It should, however, be noted that the presented prototypes are still at a rather small scale and that further upscaling is needed to demonstrate the full feasibility of the adaptive and composite thin glass concepts. In this respect, also further upscaling of the available thin glass sheet sizes is needed to conform with the dimensions needed for architectural applications, but the glass industry is quickly advancing in this respect.

Furthermore, regarding the presented adaptive thin glass prototypes it should be noted that these are currently executed in monolithic glass, whereas in building practice often laminated glass is required. Since lamination of two or more thin glass layers would result in a stiffer panel, the implications of such lamination for the flexibility and thus the adaptiveness of the thin glass panel needs further studies. To facilitate the bendability, such lamination should preferably be done with low stiffness interlayers, which may need to be custom developed for this purpose. Also, the effects of repetitive bending and potential delamination risks need to be investigated.

Moreover, regarding the composite thin glass panels it should be noted that the presented 3D printed core patterns could be further developed to take full benefit of the 3D shaping possibilities. The here presented core patterns are still rather regular and could also be produced using conventional production methods. For instance, the Voronoi patterns could also be obtained through (laser-jet or water-jet) cutting these from a polymer sheet. Full advantage could thus be taken from the 3D printing technique to produce patterns that are further optimized for structural, thermal and optical performance and which may as a result deviate significantly from the here presented patterns.

Finally, it can be concluded that both adaptive and composite thin glass panels offer promising opportunities for architectural applications and that further studies are needed to develop its full potential.

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