Dynamic Bending of Thin Glass to Control Surface Roughness of Building Facades

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Abstract. This paper describes the development of a research prototype for a kinetic transparent facade panel. Previous research has indicated the potential for kinetic facades to modulate airflow around buildings. With the ascent of thin glass and its application as kinetic building component, this project sought to further explore that potential with a transparent design. The project was undertaken as a design and making process, where knowledge is created through the collaborative engagement with the prototype. In its final state, the prototype, which used polycarbonate as a placeholder for thin glass, was used to visually assess the qualities of the transparent panel in motion. The project has led to a working mechanical scheme that creates a visually dramatic effect through distorting reflections. Analysis has shown that airflow can be modulated using this scheme, with possible applications for natural ventilation of buildings.

Keywords: Open Track, Kinetic Facade, Thin Glass, Prototyping, Research by Design.

1 Introduction

As we are progressing into the Anthropocene, the built environment is subject to global phenomena that increasingly disrupt the familiar rhythms of change. Human-induced climate change has been linked to more extreme weather patterns (Seneviratne et al., 2021) and is likely to lead to more viral events such as the 2019 coronavirus outbreak (Daszak et al., 2020; Marani et al., 2021). The impact of such tendencies on society and the built environment should make building designers consider a wider range of future exposure and use scenarios to make lasting buildings. Design that addresses the disruptive scenarios may include diverging strategies of resistance or adaptation. Where some seek solutions in greater inertia in buildings to weather the storms of the future, others promote buildings with agility and a capacity for change. And buildings can tend towards impermeability that strictly separates what is in and what is out, or form more ambiguous environments that embrace the natural phenomena they are exposed to. Often these strategies are not exclusive, but an adaptive and open approach is the basis of the work described in this paper.

Kinetic adaptive facades as architectural tectonic systems have predominantly been relying on extensive supplemental mechanical parts to move discrete and rigid components. Examples are the *Al Bahr* twin towers in Abu Dhabi, where linear actuators and hinges between individual panels are systematically applied throughout the façade (Armstrong, 2013; Oborn, 2013). Or the southern facade of the *Institut du Monde Arabe* in Paris that was recently renovated, where electric motors in full view drive a complex mechanism of multiple adjustable diaphragms (Goulet, 1982; Durand, 2015). Developments in material technology have led to experiments and building projects that employ wood, bi-metals, ETFE and GFRP to create movement in the facade material itself with no additional actuators at all, or with them moved to the fringes where they are out of sight and easy to maintain. The addition of polycarbonate and thin, strengthened glass to that list of materials enables building designers to generate kinetic transformations in the transparent material of the envelope (Louter, 2019; Neugebauer et al., 2019; Mulder, 2022). The impact of such systems in tectonic terms can be both functional and aesthetic.

This paper takes the starting point in a system proposed by Lignarolo et al. (2011), that applies shape-changing materials to alter the roughness of a building facade and that consequently manipulates the airflow around a building. The paper describes an explorative study that was performed to develop the system by Lignarolo et al. with an outer facade materialisation of kinetic thin glass. Maintaining a transparent appearance, the facade would actively manipulate wind friction and drag with the potential to change overall wind loading on the building, affect convective heat exchange, and create pressure zones to drive natural ventilation. Taking a design-based approach, the study comprised of the development of a physical prototype (fig. 1). Because of practical constraints, polycarbonate was used in the physical prototype as a placeholder for the potential use of thin glass in an actual building facade. Computational analysis was performed using Butterfly with OpenFOAM in Grasshopper to assess the effects of the deformed geometry on airflow. Large deformation and stress analysis were performed in Karamba3D and Ansys, for both thin glass and its placeholder material in the prototype. The prototype served as a design integrator and was used to assess in outline the feasibility of the proposed kinetic drive and control systems. In its finished state it was used to perform a qualitative visual assessment of the different morphological states and of the material in motion.

Figure 1. Kinetic prototype developed in this study. Source: authors.

2 Methodology

The approach for this study is rooted in the idea of design as a form of research. *Research by design* has been championed and clarified by Johan Verbeke as a mode of knowledge creation that is specifically suited for the designing disciplines, such as architecture (e.g., Verbeke, 2013). Jonathan Hill suggests that the explorative practice of architecture is performed as a triptych: "Studying the history of architecture since the Italian Renaissance, it is evident that researching, testing and questioning the limits of architecture occur through drawing and writing as well as building" (Hill, 2013, p. 19). In fact, the study described in this paper relies on the design and production of a physical prototype. A prototype as such, has been described by Michael Speaks as a form of production that drives change, where “the product is not so much the prototype as it is the innovations that occur as a result of thinking with and through the prototype” (Speaks, 2002, p. 6). More concretely, the prototype has acted, before and during its production, as a design integrator that facilitated collaboration in the research team. During and after production of the prototype, it served as a demonstrator of the kinetic performance and allowed for qualitative assessments of the visual qualities of the deforming material.

In order to engage in a productive and focussed process, a design objective was set for a prototype of a close-to 1:1 kinetic transparent facade panel that could be assessed qualitatively. The design and production of the prototype would then satisfy the other research objectives of investigating the structural performance and airflow around a building with similar kinetic panels and developing a reliable kinetic scheme to drive the motion.

The design development can be understood to exist of the following parts, however it should be noted, as is common in design, that these parts have been informing each other throughout and that the order therefore is somewhat arbitrary (see also fig. 2).

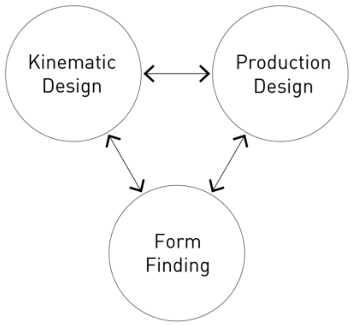

Figure 2. Process diagram. Source: authors.

1. The kinematic design of the panel included establishing the type of deformation, and following that, the motion paths of the supports, the required degrees of freedom, the actuator types, and the control infrastructure including the back-end code and graphical user interface.
2. The production design included layout, sizing, production, and assembly of the elements of the prototype, the selection of material and thickness of the panel, the translation of the kinetic requirements in a physical bracket detail, selection, and assembly of linear actuators, and wiring of the motors, drivers, and control circuits.
3. The form finding and analysis process included assessing the deformation and stresses in the transparent materials. Analyses for both thin glass and polycarbonate were performed to address the potential future building and the practical prototype scenarios. And

analyses of outdoor airflow were performed to compare difference configurations of the kinetic panels on buildings.

For design and production purposes a range of software was used including SolidWorks for 3D layout and preparing the machining of parts, Karamba3D and Ansys for structural analysis, Rhino Grasshopper with Butterfly for the use of openFOAM, and Arduino and Processing for controlling the actuators from a computer-based graphical user interface.

3 Results

During the ideation phase, various kinetic schemes were considered that would induce roughness to the facade. For reasons of perceived feasibility in a building context, and after confirming with initial structural and airflow analysis that the proposed setup could offer the sought performance, a scheme was adopted that would position a panel in portrait mode and actuate it from four corners. In its starting position, the panel would be slightly curved so that pushing the corners sideways and inwards along the face of the facade would lead to increasing curvature, bending the panel. Because the vertical edges of the panel would not be stiffened, the deformation would be in two directions—a dominant barrel-like curvature along the short direction of the panel, and additional curvature along the long direction due to plate stiffness, most pronounced along the edges. By actuating different combinations of corners of the panel, different shapes can be generated (fig. 3).

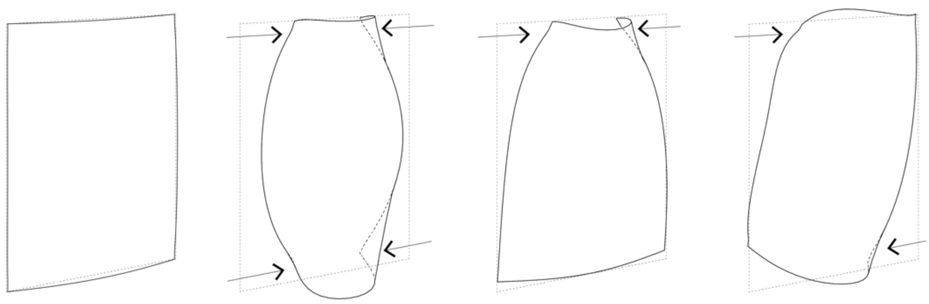

Figure 3. Different combinations of actuation give rise to a variety of shapes.
Source: authors.

Assessments of the material had been made with initial form-finding exercises in Karamba3D and stress analysis of the deforming shape in Ansys. Even though the expected shape changes would not differ significantly, important structural differences and design considerations exists between polycarbonate and thin glass. Youngs modulus is 2.35 GPa for polycarbonate and 70 GPa for thin glass, yield and breaking strengths are in the range of 60 MPa and 300 MPa respectively. Higher forces are therefore required to bend thin glass in the same way as polycarbonate, and higher stresses are expected to occur as a result. The bent shapes were also assessed in various configurations in a CFD model to compare a flat facade with the bent shapes of the transparent panels. With individually controlled elements endless variations of deployed and flat panels can be made, allowing potential real-time modulation of airflow (fig. 4). Figure 5 shows two configurations of a square and a circular plan building with deployed and flat panels and the different flow patterns as a result on either side.

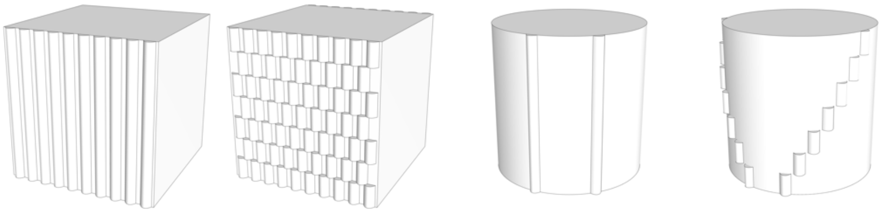

Figure 4. Example configurations of panel deformation across a façade. Source: authors.

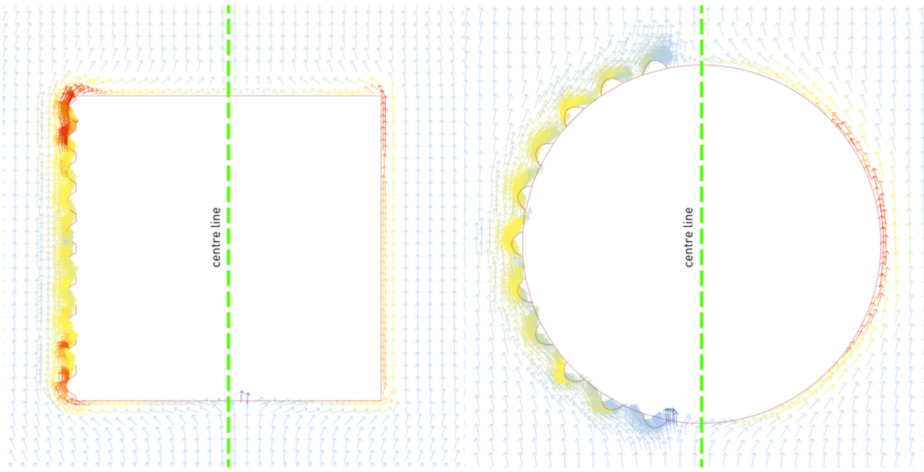

Figure 5. Air flow around square and circular plan building. Red indicates faster flow and offsets from the centre line are clearly visible. Source: authors.

Holding the transparent material in place, and introducing forces to bend it, requires careful detailing of a custom bracket. Where the polycarbonate of the prototype may be more forgiving because it can yield without breaking, glass is sensitive to local stress concentrations that could cause a single material imperfection to form a crack. Similar to a design in glass therefore, the brackets in the prototype would be rubber padded and hold the material by clamping it from the outside. The design also aimed to avoid stress build-up from unnecessary constraints. Vertical movement was therefore unconstrained at the bottom corners to accommodate displacements due to the panel's secondary curvature, and due to skewing of the panel in some states of the actuators. Rotations around the Y and Z-axes were also kept free to allow bending and skewing. Translation in X direction was controlled by the linear actuator (fig. 6).

This led to the design of two different brackets to connect the panels to the linear actuators. The rotational freedom in Z direction was accommodated by a rotary bearing, and in Y direction by a hinge. To allow vertical movement of the brackets at the bottom, an additional rotary bearing was introduced, creating a short arm. 4mm of 65 Shore A neoprene was used in the clamps that were produced as laser cuts from 5mm steel plate.

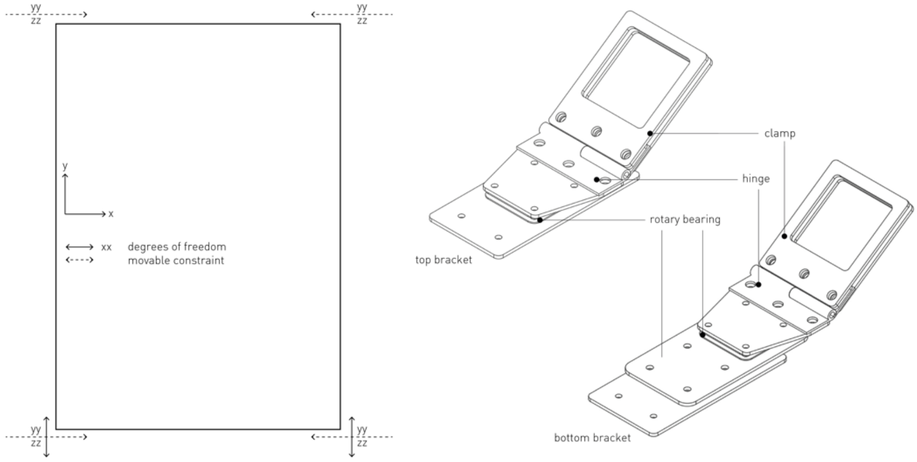

Figure 6. Degrees of freedom and corresponding bracket designs. Source: authors.

A modular aluminium truss structure was used as a base frame to mount the actuators on. The applied linear actuators were 500mm OpenBuilds C-beams with a lead screw drive, powered by NEMA 17 stepper motors, which allowed for approximately 350mm travel. A carriage would facilitate the mounting of the bracket. The four motors were driven from a single Arduino board with four motor drivers. Scripts were developed for Arduino and Processing to allow control of the motors from a graphical user interface on a laptop. Manual control of individual motors and presets for motor combinations could be managed in this way. The transparent panel that was implemented was a 2 × 1.4m sheet Exolon polycarbonate of 3mm thickness and light transmission of 88%. Figure 7 shows various states of the prototype in operation.

Figure 7. Stills from a video of the prototype movement. Source: authors.

The structure was positioned near a window so that views could be taken through the facade during and in between movements. Various observations were made. First, the sound of the motors was quite noticeable. This was a clear signal that the panel was moving. Without the sound, the slow movement of the panel would have been more in the background, and less pronounced. As a second skin, it is expected that actuator sound would be dampened by the inner skin. Second, even at strong curvatures, there was very little distortion of the views through the panel. Only at the edges of the panel and close to the brackets, some distortion was noticeable when specifically looking for it. The implication is that the material was almost invisible in some conditions. Third, not looking through, but at the glass, the movements can be seen to have a dramatic effect on reflections. Depending on the lighting conditions, this effect is visible from inside and outside (fig. 8). Reflections may move and transform, depending on the panel movement, which is a very particular effect that can be employed as an aesthetic feature in building design.

Figure 8. Photographs showing distorted reflections. Source: authors.

4 Discussion

The initial intention of the project was to build a kinetic prototype that was as close as possible to a thin glass panel for implementation in a building. Design decisions were made with that in mind—one of the key drivers of kinetic building design in engineering practice is simplicity, because the conditions for mechanical systems on buildings are often harsh. Along the way however, several practical solutions had to be implemented in order to move the prototype project along and some concessions were made. This does not take away however from some valuable insights that were gained during the project.

The mechanical principle that was applied to drive motion in the panel was simulated and then tested on the large-scale panel of the prototype. Because of the four-dimensional complexity of kinetic systems, there is often a discrepancy between theory and practice. In this case the motors in the prototype were underpowered, leading to some slip at the extremities of the motion range. Otherwise, the drive system was sound, including the performance of the bracket assemblies, leading to smooth deformations of the panel shape.

The effect of the shape change on airflow has been demonstrated and might lead to further investigations on how this can be made productive. A first step is to further quantify the results with CFD and possibly scaled wind-tunnel testing, and then develop use scenarios that harness the natural flow of air. It seems less likely that shape changes will reduce the codified load on a building, but controlling the pressure along the facade could optimise the conditions for natural ventilation in a building.

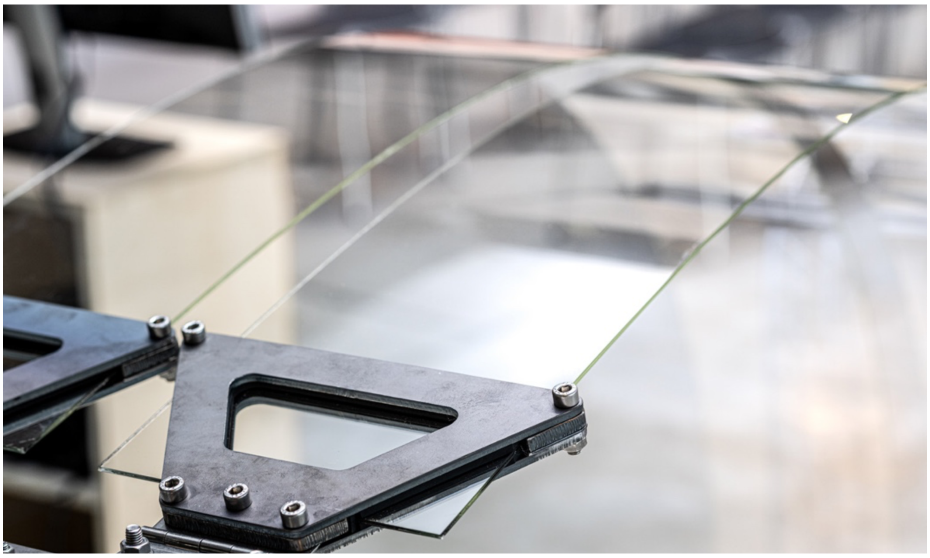

Figure 9. Kinetic thin glass installation. Source: Hugo Mulder, 2022.

Visually, the kinetic panel confirmed the aesthetic relevance of this line of work. Assessing these qualities on a large-scale object is significant because scale models, nor simulations bring the same immersion and fidelity. The visible speed of movement, combined with the dramatic distortion of the reflections indicate what a conspicuous feature this could be in a building context, whilst maintaining transparency of the facade. On a building scale, the effect can be leveraged by using repetition and patterning.

There are important differences to consider however, between the prototype and a potential implementation at scale, in a building. For example, the prototype setup with four actuators for a single panel may not be economic in a building context, but sharing of actuators and reduced degrees of movement can be feasibly achieved.

The use of polycarbonate as a placeholder for thin glass works visually, but structurally the materials are different in important ways. Polycarbonate is ductile, and will yield before breaking, whereas glass is brittle. Thin glass is chemically toughened and would be laminated to ensure a safe breaking condition, which makes the material prone to significant creep at large deformations. The potential to actively bend laminated thin glass has been explored (fig 9. reference withheld for review), and further investigation is ongoing to develop safe, sustainable, and practical applications for buildings.

5 Conclusion

The paper presents an explorative study for a novel approach to kinetic facades, with kinetic transparent materials. Such facades and materials might contribute to buildings that are sustainable and resilient in conditions of weather and public health that are anticipated to become more extreme. Thin glass is currently being investigated as a flexible facade material for application in adaptive facades. The ability of a flexible facade to modulate external airflow can contribute to naturally ventilated buildings, by directing pressure zones to specific areas of the facade. The quantification of this principle is the subject of further study.

The tectonic considerations of building designers for choosing glass over other materials include their aesthetic qualities. The dynamics of distorting reflections are a dramatic feature of flexible glass and polycarbonate that can be emphasised through repetition and patterning across the facade.

This study has led to a working prototype of a single panel in polycarbonate that could be experienced as a full-size building element. To confirm the workings of the mechanical principles, and to assess its visual qualities, the material was an adequate placeholder for thin glass. Further work is required and ongoing to transition the developed system to thin glass, given the structural differences between the materials.

References

Armstrong, A., Buffoni, G., Eames, D., James, R., Lang, L., Lyle, J., & Xuereb, K. (2013). The Al Bahar Towers: Multidisciplinary Design for Middle East High-Rise. (D. Brown, Ed.) *Arup Journal*, *2/2013*, 60–73.

Daszak, P., Amuasi, J., das Neves, C. G., Hayman, D., Kuiken, T., Roche, B., Zambrana-Torrelio, C., Buss, P., Dundarova, H., Feferholtz, Y., Földvári, G., Igbinosa, E., Junglen, S., Liu, Q., Suzan, G., Uhart, M., Wannous, C., Woolaston, K., Mosig Reidl, P., … Ngo, H. T. (2020). *Workshop Report on Biodiversity and Pandemics of the Intergovernmental Platform on Biodiversity and Ecosystem Services*. IPBES secretariat, Bonn, Germany.

Durand, L. (2015). *IMA: Ingénierie de Restauration des Moucharabiehs APD*. Avignon.

Goulet, P. (1982). Concours pour l'Institut du Monde Arabe. In *L'Architecture d'aujourd'hui* 219, février 1982: 81-90.

Hill, J. (2013). Design Research: The First 500 Years. In M. Fraser (Ed.), *Design Research in Architecture: An Overview* (pp. 15–34). Ashgate Publishing, Ltd.

Lignarolo, L., Lelieveld, C. M. J. L., & Teuffel, P. (2011). Shape morphing wind-responsive facade systems realized with smart materials. In *Proceedings of the International Adaptive Architecture Conference*.

Louter, C. (2019). Thin Glass Concepts for Architectural Applications. In *Conference Proceedings. All eyes on smarter glass. Glass Performance Days 2019. June 26-28, 2019, Tampere, Finland*. Tampere: Glass Performance Days.

Marani, M., Katul, G. G., Pan, W. K., & Parolari, A. J. (2021). Intensity and frequency of extreme novel epidemics. *Proceedings of the National Academy of Sciences, 118(35)*, e2105482118.

Mulder, H. M. (2022). Kinetic Thin Glass Building Envelope. In *Structures and Architecture A Viable Urban Perspective?* (pp. 297-299). CRC Press.

Neugebauer, J., Wallner-Novak, M., Wrulich, C., Baumgartner, M. & Kalteis, S. (2019). Adaptive Facade Systems made from Thin Glass. *In Conference Proceedings. All eyes on smarter glass. Glass Performance Days 2019. June 26-28, 2019, Tampere, Finland*. Tampere: Glass Performance Days.

Oborn, P., Heathcote, E., Denison, E., & Ormsby, E. (2013). *Al Bahr towers: the Abu Dhabi investment council headquarters*. Wiley.

Seneviratne, S.I., X. Zhang, M. Adnan, W. Badi, C. Dereczynski, A. Di Luca, S. Ghosh, I. Lewis, F. Otto, I. Pinto, M. Satoh, S.M. Vicente-Serrano, M. Wehner, and B. Zhou. (2021). Weather and Climate Extreme Events in a Changing Climate. In *Climate Change 2021: The Physical Science Basis*. (pp. 1513–1766). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Speaks, M. (2002). Design intelligence: or thinking after the end of metaphysics. *Architectural Design*, *72*(5), 4–6.

Verbeke, J. (2013). This is Research by Design. In M. Fraser (Ed.), *Design Research in Architecture: An Overview* (p. 312). Ashgate Publishing, Ltd.