Kinetic Omni-Stable Structural Forms Using Ultra-Thin High-Strength Glass for Envelope Applications

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The aim of this paper is to establish the feasibility and to explore the potential of thin and strong glass for kinetic all glass structures which have direct application for adaptive envelopes. Ideas will be tested on a full-scale prototype of reclining and twisting arches, a concept adaptive pavilion developed by Hugo Mulder. The concept is structurally innovative as it takes into account the omni-stable nature of twisting arches. The paper will combine a number of innovative ideas at the forefront of developments in thin, strong glass as well as kinetic structures with direct applications in adaptive building envelopes. The main technical challenges discussed in this paper will be the methodology of establishing forces and strains in the glass interlayer that occur when the structure moves. Digital design allows us to experiment with different glass thicknesses and strip aspect ratios, providing direct structural feedback for every change. The study will be concluded with a summary of how these ideas may be used in real life practical application.

Keywords: thin glass, adaptive, envelope

1 Introduction

Kinetic structures that have multiple states of stability are attractive for building facades because of the lack of framing or folding gear and moving parts that are typically needed. Omni-stable systems eliminate the need for multiple moveable parts, which tend to have a detrimental effect on their appearance, but also on other important aspects such as system maintenance and durability. Adaptive envelopes of this omni-stable type have been explored before and have been used in building envelopes. In this paper the feasibility will be explored of the structural principles for successfully utilizing thin glass as kinetic omni-stable structure. A concept prototype for an adaptive kinetic pavilion has been developed at the IT University of Copenhagen.

1.1 Multi-Stable Kinetic Structural Forms

In this section four innovative reference projects that employ kinetic multi-stable forms are discussed. HygroSkin, Bloom, and Movable Thin Glass Canopy are projects developed in an experimental context, whereas One Ocean Pavilion was realised as a permanent building.

1.1.1 HygroSkin

The project HygroSkin–Meteorosensitive Pavilion [1] explores a novel mode of climate-responsive architecture. While most attempts towards environmental responsiveness rely heavily on technical equipment superimposed on inert material constructions, HygroSkin uses the responsive capacity of the material itself. The dimensional instability of wood in relation to moisture content is exploited and a meteoro-sensitive architectural skin is designed that autonomously opens and closes in response to weather changes. This system does not require the supply of operational energy, nor any kind of mechanical or electronic control. A wooden skin is designed and produced utilizing the self-forming capacity of initially planar plywood sheets to form conical surfaces based on the material's elastic behaviour. Within the deep, concave surface of each robotically fabricated module, a weather-responsive aperture is placed. Materially programming the humidity-responsive behaviour of these apertures opens up the possibility for a strikingly simple yet truly ecologically embedded architecture in constant feedback and interaction with its surrounding environment. The responsive wood-composite skin adjusts the porosity of the pavilion in direct response to ambient changes. Relative humidity triggers the silent, material-innate movement of the wooden skin.

1.1.2 Bloom

Bimetals are not a new invention – the tight coils used inside most household thermostats for the past century are bimetals. Sung [2] proposed new uses for the material, creating tessellated skins comprising small geometrically fitted tiles that react to the sun. Exposed to the sun's radiation, the tiles curl or unfold in response to temperature fluctuations. The main idea is that building skins which will follow this principle can significantly decrease the need for air-conditioning. In addition to the bimetal skins, Sung researched window systems that sandwich bimetal patterning between double-glazed panels, which would allow windows to regulate the quantity of sunlight and heat entering the building. Both the window systems and the skins remain in a conceptual phase, due to the cost associated with fabrication and relatively small return of initial investment. The key goal of her research is to develop materials that respond to the environment with the objective of creating sustainable architecture.

1.1.3 One Ocean Pavilion

The thematic pavilion One Ocean, was one of the major buildings for the Expo 2012 in Yeosu, Korea, designed by SOMA architects. The building has two main facades, both illustrating the theme of the Expo "The Living Ocean and Coast" [3]. The waterfront façade is designed as a reference to pebbles, whereas the kinetic façade with the main entrance facing the Expo area symbolizes the gills of a fish. More than one hundred individually moveable louvers can be set to respond to changing sunlight conditions. The façade can also perform according to a predefined choreography or react to individual events. The louvers are made of fiber reinforced polymer and have one stiff and one thin edge. With actuators placed both at the top and bottom, they are capable of asymmetrical bending, to allow light to radiate in and out of the building as well as to afford views both ways.

1.1.4 Movable Thin Glass Canopy

One of the very first practical applications of thin glass was a deployable canopy developed by Neugebauer [5]. The concept was presented at the Glastec fair of 2015. The canopy is retractable and this was only possible with the large flexibility in combination with the very high ultimate bending strength of chemically strengthened glass of 0.7 mm thickness. To achieve all safety demands the glass was laminated. The roof weight of approximately 3.5 kg per square meter, can be called ultra-light. The canopy is designed as an arch, while the segments of the arches were connected with hinges. A special system of motors, drives the flexible system to open and close.

1.2 Thin Glass

Thin and super thin glass are new developments in glass technology, fuelled by progress in smart phone and flat TV technology. Potential applications in the construction industry have been researched by [4], [8], AGC, Schott, Corning, and others with a handful of practical applications already constructed. Raw glass is stronger than classical annealed glass due to the manufacturing technology that can reduce surface flaws. In addition, chemical toughening can further increase body strength beyond the strength of high grade steel. However, glass edges are significantly weaker due to the edge processing, as well possesing inherent vulnerability to accidental breakage. Another point to watch is shear strength, mode II failure mechanisms and flaking. High stiffness of the interlayer can introduce relatively high shear forces at the interfaces which may trigger glass failures. High flexibility could be an advantage in the forming process of more complex geometrical forms, but geometrical stiffening needs to be considered to resist variable loads and meet serviceability code requirements. Local and global buckling checks need to be carefully carried out if compression force or lateral torsional instability are expected.

2 Concept Prototype Envir()nment

Envir()nment is the title of a research prototype that was developed in the context of a larger academic project. The installation challenges current ideas about building intelligence, pointing to a new conceptual position on artificial intelligence in buildings, based on theories of cognitive enaction [6]. The title of the work is a reference to the environments produced from the mid – 1950s until the mid – 1970s by kinetic artists investigating movement in art [7].

2.1 Concept

The installation responds to the speculative question: what if a building was not made of traditional building materials, but was made of movement? The installation therefore locates movement not anywhere in particular, but all around the observer. Movement itself creates a sense of space. The distinctive feature of the prototype is an array of eight transparent arches that are formed from thin strips, bent over a square floor plan. The arches are raised, creating a space underneath, high enough to stand in. The strips may seem delicate and frail, or hard and reflective, depending on the light conditions they are encountered in. The arches are kinetic. Each arch support is a turntable, driven by a stepper motor and controlled centrally. The strips perform two types of movement. One is purposeful and calculated, driven by motors, and controlled from within the installation. The other is undetermined, generative, and driven by wind forces, external to the installation.

Figure 2-1 The Pavilion.

In wind, the strips wobble, creating wave patterns that are most prominent where the strips deflect the most: at the apices of the arches. The arches also move in a more controlled manner, driven by the motors at their base. The simultaneous rotations of both footings, in opposite directions, make the arches twist and bend sideways. The controlled movement is slower, but more purposeful than the wind driven motion. The movement is also synchronised between arches, allowing them to move along predefined patterns. As the strips twist and bend, they become less sensitive to deformation from airflow.

2.2 Numerical analysis

The initial step in the structural analysis of thin glass is to develop analysis models predicting behaviour of the glass laminate at the forming process. Two possible methods of forming arches are theoretically possible: forming during lamination, or in situ cold bending technique. The former will put less stress in the glass, however relaxation in the interlayer may cause a geometrical instability challenge. The latter will increase stress in the glass as the assembly is stiffer and will permanently shear the interlayer. Due to the transportation limitations, we opted for the cold bending option. Finite element analysis was carried out to calculate initial stress in the glass due to this on – site bending. Glass and Interlayer was modelled using volumetric elements. Material properties of the interlayer was considered as linear elastic however upper and lower bound of stiffness was considered to capture time-temperature depending behavior of the material and . Peak stress of 82 MPa corresponds to the analytical stress of 75 MPa following the Euler – Bernoulli theorem.

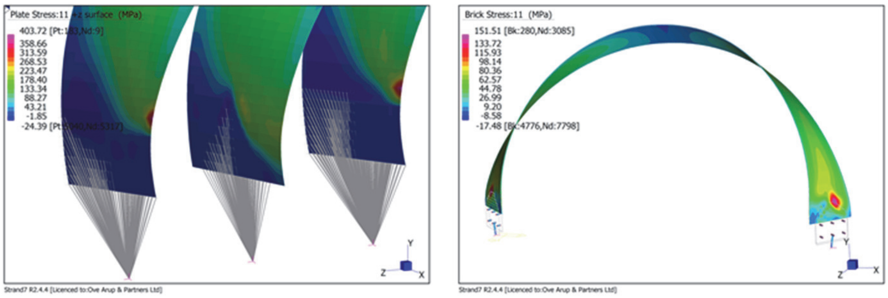

Figure 2-2 The Pavilion numerical analysis, forming process.

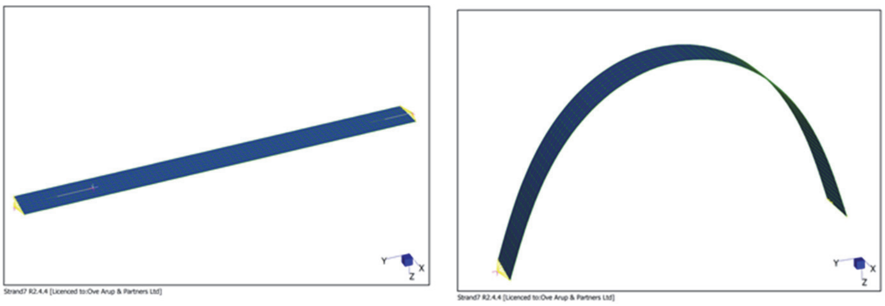

Figure 2-3 The Pavilion numerical analysis support rotation.

The next step in the verification workflow was the transient (dynamic) geometrically non-linear analysis which calculated stress and deformation of the pavilion due to the rotation of supports. A parametric study of the shape of the end plate, as well as relative stiffness was carried out to optimise stress intensity and distribution. As presented in the figure 2-3, the shape of the end plate influences stress distribution, where shapes that avoid stressing glass at edges are clearly beneficial due to the lower glass strength. With further optimization of the connection stiffness, where all components contributing to the load path were explicitly modelled, glass stress due to the support rotation was reduced to 151 MPa. Total stress of about 230 MPa is within safe limit of chemically tempered glass. The next step will be to investigate failure scenarios, risks and consequences of such failure. This is due to the fact that stored energy is relatively high. A possible failure mechanism can be geometrical instability, leading to the progressive collapse linked to the burst of glass dust and small particles.

3 Future application

The potential of kinetic glass structures, as discussed in previous sections, could be applied in fully glazed double skin facades. The outer skin of a double skin facade could be formed from the glass sheets that can be deformed and breath; release heat from the cavity when required. This deformation can be triggered either by the movement introduced in the supports or spontaneously by lamination of glass with different absorptivity, or thermal expansion. Another alternative is that glass surface coating may increase glass temperature locally. Geometrical stiffness shall be carefully treated in the design to ensure system behaviour meets specifications when subjected to typical loads such as wind. Possible arrangements of glass geometries are presented in the figure below.

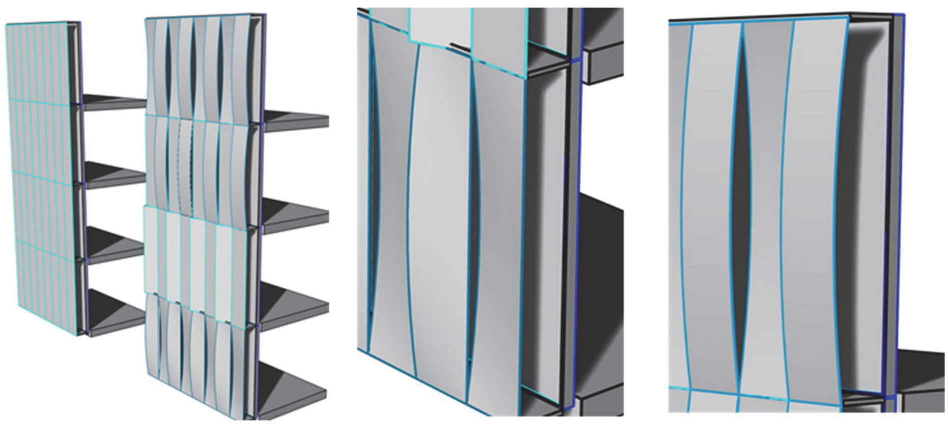

Figure 3-1 Double skin façade.

Conceptually, we investigated how the whitening effect, a well-known material behaviour of plastics, can be used to our advantage. When plastic materials are strained beyond a certain limit, transition between fully transparent and opaque material occur. This is illustrated in the diagram for one of most recent DOW product – TSSA below. Glass deformation could be tailored to increase strains in the interlayer. This will activate the above effect, where translucency will spread from the glass panel ends where the shear in the interlayer is highest. Together with the previously discussed concept of heat release, building occupants may benefit from dynamic shading while keeping a clear vision zone to enjoy spectacular views.

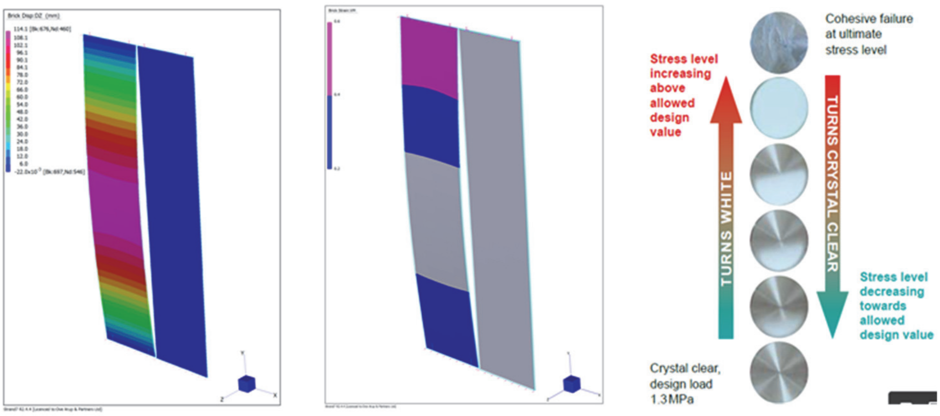

Figure 3-2 Whitening of the interlayer.

4 Conclusion

At the beginning of this paper we reviewed current research and projects related to adaptive envelopes. We narrowed our focus in ideas of naturally occurring movements based on a simple physical phenomenon such as temperature and moisture variation. In the second section we briefly summarized a concept pavilion with movable transparent strips, a collaboration with IT University in Copenhagen led by Hugo Mulder, where a thin glass structure and a concept of adaptive movements were explored. We developed structural analysis models predicting the behaviour of glass laminate at the forming process as well as dynamic nonlinear analysis predicting stresses and deformations of the pavilion in use. As part of this project, we have engaged with manufacturing partners and presented our ideas and concepts. However, after a promising start of a collaboration, development slowed due to production restrictions. We are positive that after overcoming production challenges we will be able to continue this project. In the final section we outlined some of our ideas about how gained knowledge from this research could be applied to the full scale double skin facade. We strove to improve building performance which goes hand in hand with providing occupants a healthier environment to enjoy.

5 Acknowledgment

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