Movable Thin Glass Elements in Façades

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Façades play an important role in the control of energy flow and energy consumption in buildings as they represent the interface between the outdoor environment and the indoor occupied space. The option of regulating internal and external conditions acquires great relevance in new approaches to sustainable building solutions. Studies on climate adaptive façades show a very high potential for improved indoor environmental quality conditions and energy savings by moveable façades. A number of movable façades were realized in the past, but the use of thin glass with a thickness of 0.5 mm to 3 mm opens a brand-new field, that allows for playing with the geometry of the outer skin and the opportunity to make it adaptive by movement. Thin glass requires for curved surfaces in order to gain structural stiffness in static use. In kinetic façades the high flexibility of thin glass allows for new options for changes in size and position by bending of elements rather than implementing hinges in a system of foldable rigid panels. The geometry is based on the known theory of developable surfaces for keeping a low stress-level during movement. This allows for façades created from cold bent thin glass or curved laminated safety glasses produced by laminating of thin glass plies which provide better sealing, greater simplicity in construction and robustness and durability of moveable components which may be actuated autonomously. Some concepts based on the before mentioned theories were created to explain some principles and discuss their principles and applicability.

Keywords: Thin Glass, Developable Surfaces, Movable Systems, Actuators

1. Introduction

In 2016 a research center, "Josef Ressel Center for Thin Glass Technology for Structural Glass Applications", was launched and deals, for example, with the topics of the determination of the ultimate bending strength of thin glass, explores new fields of applications for thin glass or creates new design possibilities for architects. Another aim of this research center is to systematically gather existing knowledge about general moveable structures in buildings and apply this expertise to façades made from thin glass as for example climate adaptive building shells. Based on experiences with prototypes both at model scale and real size, computer models were carried out and tested in terms of kinematics of bending using Rhinoceros 3D with Grasshopper and other plugins from the Rhino environment.

As a key point the real size model of a movable canopy presented at the Glasstec 2014 in Düsseldorf, Germany, as shown in figure 1 below, was an excellent demonstrator for the potential that lies in the utilization of thin glass in moveable structures. This canopy was also the initial point for the application for the research project mentioned above. Several prototype models were first studied in computer models to evaluate their feasibility and subsequently built as cardboard-models or transparent synthetic models to gradually optimize the system to finally build the real-life application.

Fig. 1 Skin folding canopy at Glasstec 2014 in Düsseldorf.

The basic idea of the canopy comes from a paper lantern which can be found at the most birthday celebrations for children. One can buy such a lantern as a piece of flat, folded paper and it can be opened. In the open position the flat paper is forced to a conical geometry. The same principle was used for the canopy, but instead of paper, thin glass

was used. In addition, instead of a whole circle only half of a circle was designed. With this, a static system of an arch was achieved. The flat laminated safety glass consists of two 0.7 mm chemically pre-stressed glass forced into a conical geometry, which is a stable structure (Neugebauer, 2015)

2. Developable surfaces

A developable surface is a smooth surface with zero Gaussian curvature. It is a surface that can be flattened onto a plane without distortion that means without stretching or compressing of the mid-surface of the glass. Conversely, it is a surface which can be made by transforming a plane by bending.
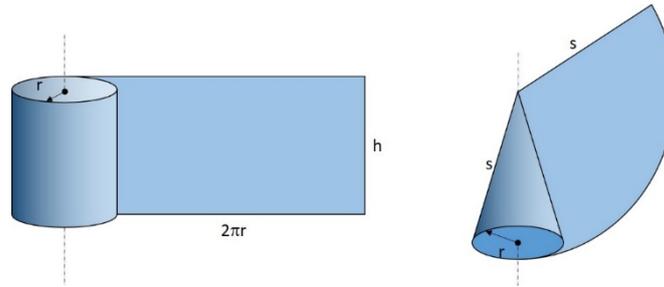
Fig. 2 Principle of Developable surfaces, cylinder and cone.

The developable surfaces which can be realized as members of a special family of solids that develop their entire surface when rolling down a flat plane can for example be the following kinds:

- Cylinders and cones, as shown in figure 2 above;
- The oloid (sphericon) is the convex envelop made by placing two linked congruent circles in perpendicular planes, see in figure 3 a.) and developable orbs are, as shown in figure 3 b.) c.) and d.).
- Tangent developable surfaces; which are constructed by moving and rotating the tangent lines along a spatial curve, as shown in figure 3 e.).
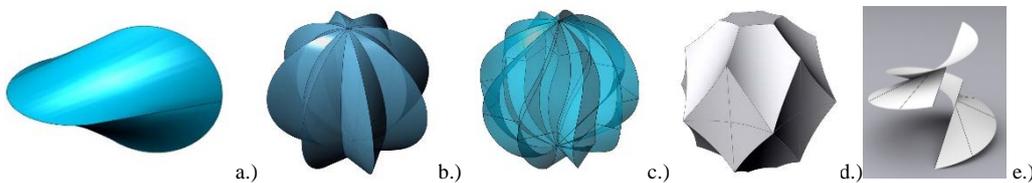
Fig. 3 Oloid a.), Developable orbs b.), c.) and d.), tangent developable surface e.).

For the characterizing of a surface regarding whether the surface is a developable surface or not, the analysis of the Gaussian curvature has to be done.

3. Gaussian curvature

At any point on a surface, we can find a normal vector that is at right angles to the surface; planes containing the normal vector are called normal planes. The intersection of a normal plane and the surface will form a curve called a normal section and the curvature of this curve is the normal curvature, as shown in figure 4. For most points on most surfaces, different normal sections will have different curvatures; the maximum and minimum values of these are called the principal curvatures, designated with κ_1, κ_2. The Gaussian curvature K of a surface at a point is the product of the principal curvatures, κ_1 and κ_2, at the given point and can be determined with the following equation (1).

$$K = \kappa_1 \cdot \kappa_2 \tag{1}$$

For example, a sphere of radius r has Gaussian curvature of $K=1/r^2$ everywhere on the surface. A flat plane, a cylinder or a cone have Gaussian curvature of $K=0$ everywhere on the surface. The Gaussian curvature can also be negative, as such in the case of a hyperboloid.
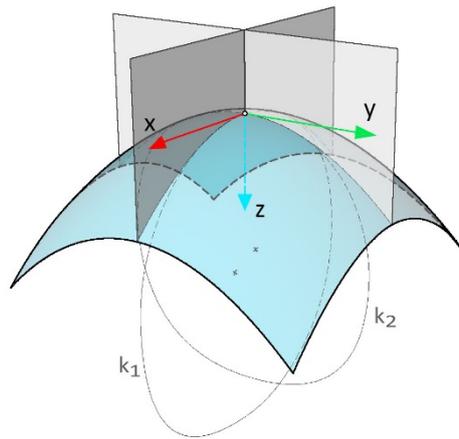
Fig. 4 Principle of Gaussian Curvatures.

The sign of the Gaussian curvature can be used to characterize the surface. If both principal curvatures are of the same sign K > 0, then the Gaussian curvature at this point is positive, as can be seen in figure 5 a.). At such points, the surface will be dome like. All sectional curvatures will have the same sign. If the principal curvatures have different signs K < 0, as can be seen in figure 5 b.) then the Gaussian curvature at this point is negative. At such points, the surface will be saddle shaped. Because one principal curvature is negative. If one of the principal curvatures is zero K = 0, as can be seen in figure 5 c.) the Gaussian curvature is zero and the surface is developable.

a.) positiv   *b.) negativ*   *c.) zero*
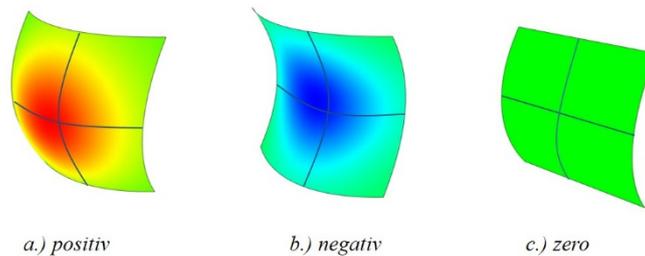
Fig. 5 Types of Gaussian Curvatures a.) positive, b.) negative and c.) zero.

4. Bending Strength of Thin Glass

For investigation of developable surfaces for example with the help of finite element programs it is helpful to know the value for the expected result of the stress due to bending. One approach is to determine the stress using equations (2) and (3). The bending moment can be calculated with equation (2) based on the differential equation of bending theory and with the section modulus the stress can be computed easily with equation (3). This approach neglects the influence of the Poisson's ratio.

$$E \cdot I \cdot w'' = -M; or \ E \cdot I \cdot \kappa = -M \tag{2}$$

$$\sigma = M/W \tag{3}$$

E Young's modulus

I modulus of inertia

w'' curvature κ

M bending moment

W section modulus

With the characteristic value given such as for chemically pre-stressed glass as $\sigma=150 \, MPa$ (EN 12337), the minimum radius depending on the thickness of the glass can be determined, as shown in table 1 below.

Table 1: Minimum radii depending on thickness of glass.

Thickness of Glass [mm]	Minimum Radius [mm]
0.5	116
1.0	2334
2.0	466
3.0	700

5. Movable Systems

All these before described principles of a developable surface and the discussion of the Gaussian curvature are basics for the design, development and investigation of movable surfaces.

5.1. Principles

In the design process, the geometry of movement of structural elements is generally aimed at leading to the lowest degree of complexity for simple and, therefore, robust and durable constructions. The movement of the geometry of thin glass may be realized one-dimensional by shifting along a line or a curve in plane or in space, two-dimensional by rotating around one axis or translation along two or more curves or three-dimensional by a combination of translation and rotation.

In façade elements, common types of movement are linear translation or rotation about one axis. Linear translation of elements is found either in a horizontal direction as in sash windows and sliding doors or in a vertical direction as in lifting panels and lifting façades. Rotation of elements is generally about a vertical axis, as in side-hung windows and conventional doors, or about a horizontal axis, as is the case in top-hung windows and pivot windows. These common types of movement are used for rigid elements. In the case of flexible or foldable façade parts the same types of movement are found with the additional task of storage by either rolling (roller shutters), gathering (venetian blinds) or folding (bi-fold hangar doors).

In the design of thin-glass-façades the full potential of structural behavior may be obtained by curved geometries, which are generally built from one or more developable surfaces. However, the bending of such curved surfaces leads to more complex kinematics.

The general design process of moveable structures can be split into the following four steps displayed in figure 6: starting from a kinematically determined structure, one constraint is released a.), rails, hinges or other mechanical elements are then used to guide the movement so that the position of all elements is determined at any time b.), actuators are used to propagate the movement c.). Finally, when a desired position is reached, the structure is again constrained by the means of locks in order to withstand loads d.).

a.)　　　　　b.)　　　　　c.)　　　　　d.)
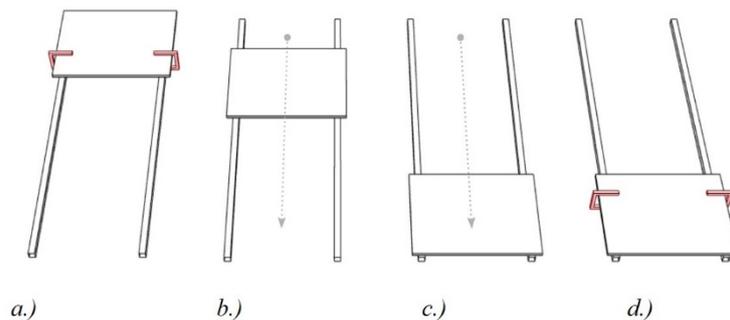
Fig. 6 Steps of a moving Structure

The initial design process of moveable elements in architecture usually involves the sole geometry of movement – kinematics. Figure 7 shows the construction of element positions of a bi-fold door during movement as well as the movement lines.
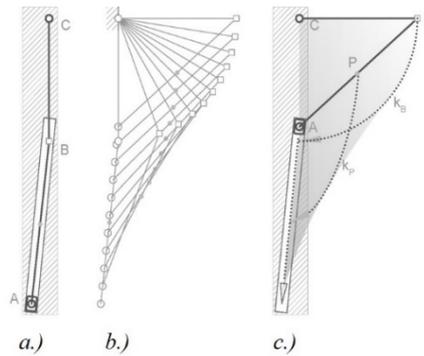
Fig. 7 Kinematics of a Bi-fold Door a) closed Position, b) Construction of folding Geometry, c) open Position with Envelope and Movement paths of two Points

With thin glass involved, kinematics become more complex as the basic geometry in resting positions is already curved. In order to build curved surfaces with cold bending, developable geometry is preferred. Surfaces are developable if at any point one of the two Gaussian curvatures vanish. Examples for developable surfaces are cones and cylinders. Starting from a developable geometry, deviations from developable shapes during movement may be allowed only to a certain extent. The magnitude is governed by the stresses in the glass panels, but the possible curvature is higher for thin glass elements.

In the following a small extract of possibilities for movable structures are displayed. The described movable systems can be used such as for shadowing, air ventilation or an openable separator between indoor and outdoor.

5.2. Sun shades

The idea behind this model is a ring-shaped hexagon with a central hole that may be opened and closed like in an enlarged camera aperture. In the example shown, the opening area in a closed state measures about 40% of the one in an open state. The kinematics involved are translations about concentric lines. The thin glass elements are bent from lower to higher curvature keeping their conical shape, see in figure 8. Simple linear rails and slotted links may be used as a guide. As active actuators, gears on a tooth rail may be used or as an alternative, a passive temperature sensitive actuator may be involved.
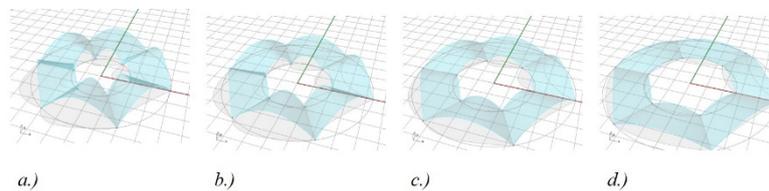
Fig. 8 Steps of a moving Structure

5.3. Opening elements for air ventilation

Vertical conical elements overlap like pantiles of a roof. By moving the end points of the lower base curve of any of the truncated cones closer? together, the rise of the curve is increased, as shown in figure 9. This leads to an opening in the horizontal plane to enable an air ventilation. Kinematically, the endpoints move along a straight line. The glass surfaces stay conical during their movement. As a guide small rails at the curve ends may be used. Either two synchronized active actuators such as motorized jackscrews may be used for each cone base as an actuator or passive actuators with crank mechanisms may be employed.
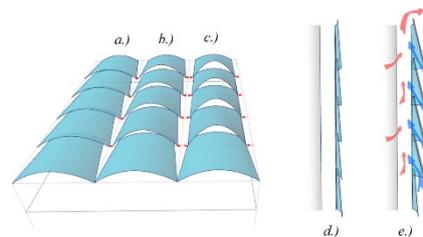
Fig. 9 Steps of a moving Structure

5.4. A curtain made as a folding systems

This folding systems can be used as an openable façade element such as in a double skin façade. The kinematically the elements move along a straight line and enable an open or closed situation in the façade, see in figure 10 a.). Due to the special arrangement of the thin glass elements, as shown in figure 10 b.), a curvature in the glass is achieved. In the open position the thin glass elements a nearly plane, as shown in figure 10 c.). During the closing process of the opening in the façade these elements become more and more curvature and therefore more and more stiffness.

a.)   b.)   c.)
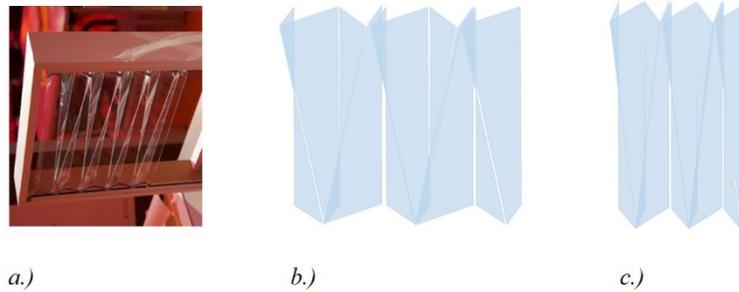
Fig. 10 Folding system

A signal, an information or an environmental impact is needed to actuate a movement and mechanical components are needed to fulfill the movement. These elements were described in the following two chapters.

6. Actuators

Current applications are based on actuation that is carried out either manually or mechanically either by a system of electric switches and or, as is increasingly the case, by sensors. This system of actuators may be referred to as active actuators as they require a control system in contrast to passive actuators that act autonomously. Passive actuators support the concept of simplicity in building solutions and are more durable and robust and therefore recommended for façades. Examples for such actuators are hoist cylinders filled with expansion materials, shown in figure 11 c.), that elongate when the temperature changes, composites of bi-layered wood or similar hygromorphic composite that bend when there is a change in moisture, displayed in figure 11 a.) and b.), level or bi-metals that also bend when there is a change in temperature. Another temperature sensitive element is an artificial muscle from a fishing line. While the hub of common temperature sensitive cylinders is limited to 25 mm, the elongation capacity of the artificial muscle elements made of woven fishing line is relatively high as is the tension capacity, see in figure 11 d.). This is due to the fact that the actuation elements are tension elements.

a.)   b.)   c.)   d.)
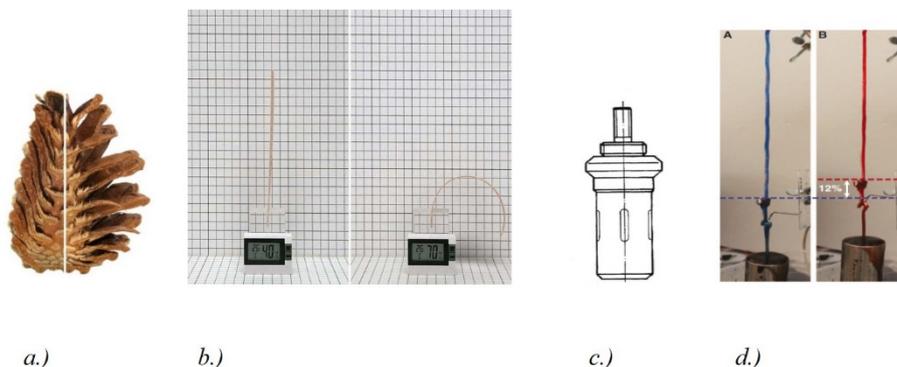
Fig. 11 a.) example of a natural hygromorphic cone, (Holstov 2017) b.) bi-layered wood composite, (Holstov 2017) c.) thermos fluid actuator (ACS, Thermo Fluid Control) d.) artificial muscle made of fishing line (Carter 2014).

7. Mechanical Components

The Mechanical components for guide and actuation may be chosen from a library of seven types: pressure driven gears, tension gears, wheel gears, screw gears, crank mechanisms, curve gears and locks, as shown in figure 12 below. In current moveable façades tension gears in the form of ropes and chains for manual actuation are in use, chains and wheel gears are usually used for electrical actuation. Sometimes screw gears are used in façades in the form of jackscrews or toothed racks and cog wheels. More rarely, crank mechanisms are also applied in façades.
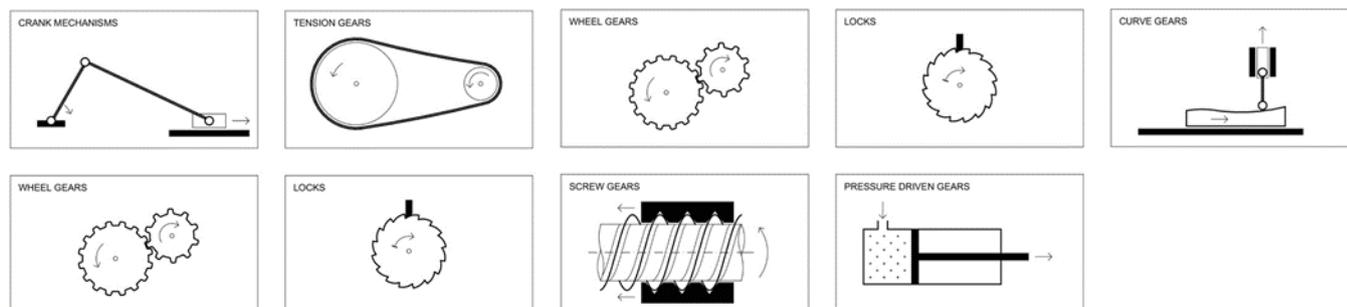
Fig. 12 Gear library.

8. Conclusion and Outlook

The aim of this research work is to find new fields of application for thin glass in buildings. One kind of new application is the field of movable and adaptive systems. Due to the high flexibility of thin glass, new design options for example of facades become feasible in comparison to regular thicknesses of glass. Based on the known theory of developable surface new kinds of "organic" facades can be designed. With cold bend glass or curved laminated safety glass produced by laminating glass plies, very interesting elements in the facades can be achieved. Possibilities of movement, with the meaning of a permanent bending of thin glass, for example for elements of the façade which can be opened and closed, creates new tools for the design process of architects.

The research work in future will explore new fields of application for thin glass. These new applications should be categorized according to their concept, for example, the theory of developable surfaces or curved folding. Based on the two basic types of movement - translation and rotation and their combination – new "lively" systems of thin glass structures will be developed

Acknowledgements

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