Flexible Transparency With Smart Materials

A study on adaptive thin glass façade developed with SMA

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Abstract

Owing to the rapid development of construction materials in building industry, a tendency towards smart and light design solutions using modern architectural principles is growing noticeably. The ultra-thin glass is a relatively new material which could be replaced with the thicker glasses in traditional windows to create a new concept for the building. Its promising prospects due to its low weight and its ability to be bent could develop a novel adaptive glass panel concept as a breathing skin in the building. Adaption can be implemented using smart materials capable of inherently sensing and responding to environmental changes with a type of actuation action. In this research study, the advancements of smart material technologies have been elaborated, together with the feasibility of these materials in adaptive architecture aspect. In the end, a novel adaptive glass panel concept has been offered by means of shape-memory alloy (SMA) cables in order to create a breathing skin for façade. The panel has been placed as an inner and outer skin in the selected case study. Its validation has been assessed through Finite-element numerical studies and experimental tests. The structural efficiency of the panel is evaluated by analyzing several glass laminate configurations under bending for inside and outside the situation and taking into account the effects of ordinary wind pressures for the outside condition. Based on the current investigation, it is expected that valuable design proposals can be derived for this novel design concept.

Keywords: Ultra-thin glass, Shape Memory Alloy, Flexinol, Breathing Façade, Adaptive façade, Finite-element numerical modeling, Experimental test

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1 Research Framework

This chapter will give an overview of the outline of the research project which includes a short introduction of the project, problem statement, research objectives and research questions. The research approach and methodology will be explained in order to answer the research questions.

1.1 Introduction

The building envelope is considered one of the important elements in construction, given it has a considerable effect on users' interaction with the surrounding environment; energy efficiency and the indoor environmental quality performance of a building.

The development of kinetic breathing façade technologies has evolved to adapt to worldwide climate change. These facades are capable of adapting to changing outdoor and indoor environments to supply maximum environmental quality and comfort.

While the façade has the important role related to energy performance and interior function of a building, it is an elegant component that helps to define the unique architectural aesthetics of the building. Glass is one of the common materials which is selected for façade elements as the architects desire to attain a transparent envelope. This challenges engineers and architects to discover new inventive ideas to be executed into the built environment.

The growing trend in alternative glass applications is leading to the advancement of ultra-light and smart design solutions for façade elements. The ultra-thin glass is a light transparent innovative material that could reduce the amount of raw material being used, while also harboring the potential for flexibility. Due to these characteristics, this material, which is currently applied in electronic devices such as laptops or smartphones, also opens utterly new viewpoints in glass design for architecture that would be impossible by the use of regular glass.

Thin glass special potential owing to its flexibility and its excellent optical properties, makes the possibility of combining two different concepts into one credible. Creating a bendable thin glass façade which could be used as a breathing skin for a building would not only increase the user comfort but also create a light and energy efficient façade element.

In order to satisfy the requirements for the design of innovative façade panel, Shape-Memory Alloy (SMA) wire is used as an efficient actuator system for bending thin glass and creating a breathing element. Shape-Memory Alloys (SMAs) are a class of metal materials with two special properties; superelasticity and shape memory effects. Taking advantage of their shape memory effect, several SMA actuator wires have been offered in the engineering industry.

In this research study, the feasibility of a novel design concept of Flexinol wires, a class of SMA materials, as an actuator for creating a breathing thin glass element for building envelope is proposed. The design has been essentially evaluated by means of Finite- Element investigations, and experimental methods. Accordingly, the design could be proposed as a possible innovative technique for the enhancement and optimization of traditional windows use. Based on the achieved outcomes, it is expected that useful design recommendations and ideas can be derived from this novel design concept.

1.2 Problem Statement

From the past, glass has been used in buildings to provide light, transparency, and appearance. In modern architecture, the trend for transparency in building facades is growing due to plenty of aspects. The increasing demand for use of glass facades steers designers towards the minimization of frameworks, substructures, and supports, looking for "lighter" and "smarter" optimized design and technological solutions based on the use of frameless glass panels in wide dimensions. (Ultra) thin glass with high strength and small thickness is a new material with the high potential to be used in the built environment.

By considering the characteristics of this new material, it is possible to demonstrate the potential of thin glass and especially its flexibility as a building material which is used in façade. One of the main challenging aspects in the use of thin glass in the facade is its lack of stiffness. Lateral forces and the most important ones, wind load, is an important factor which has a great impact on the design of such a thin material for façade.

Apart from the issues with the thin glass itself, there are also challenges related to the applying of thin glass in adaptive breathing façade. An adaptive breathing envelope in the building is one that responds to the climate in an optimal way, providing the highest user comfort and indoor environmental quality. A significant challenge at this point is the selection of the most appropriate technique to bend the thin glass, keep the façade lightweight and creating a kinetic skin. The other important aspect is finding the suitable design and control strategy of an adaptive façade according to the building typology and the climatic location.

It should be also considered if the actuator could completely move actively or it should be integrated with external inputs such as electricity and fluid. One of the important aspect that restricts the use of active and smart actuators in façade applications can be the relatively high cost of their production techniques. Additionally, it should be remarked how to achieve maximum transparency in façade by implementing opaque actuators. So, in designing the façade panel, the placement of the actuator should be evaluated.

The last challenge that also plays an important role in the design of adaptive thin glass façade is a lamination of thin glass. Glass facades not only provide a view and light transmittance but also has important safety requirement. Most of the researches which have been so far done on bending of thin glass are only with the focus on a single layer of glazing, which is not applicable in public spaces due to safety concerns.

1.3 Research Objective

The main objective of this thesis is a demonstration of the potential of thin glass in an adaptive breathing skin.

The following sub-objectives also are considered to define the project more:

- To explore the possibilities to create a breathing façade element featuring a bendable thin glass panel
- To investigate the application of advanced material technologies whereby adaptation will be established
- To analyze the most suitable actuator system to bend the glass with attention to its structural behavior
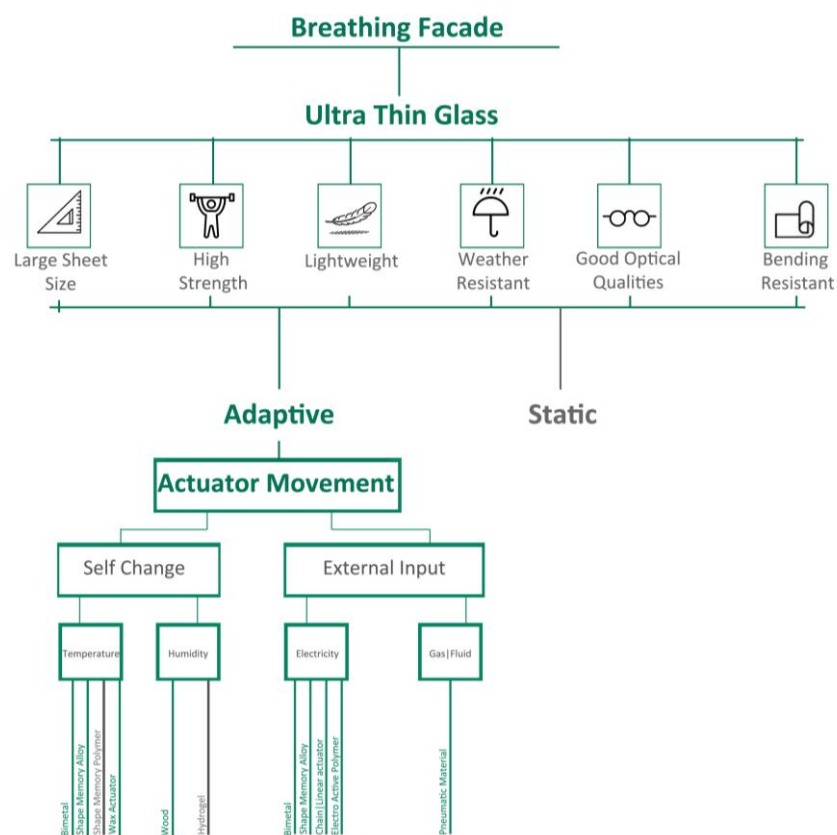
Figure 1, Breathing Facade System

1.4 Research Question

How can a thin glass skin be applied as an adaptive façade developed by smart materials?

1.4.1 Sub Questions

- What is the main purpose of using thin glass in façade?
- What is the reason for making an adaptive panel?
- What are the possibilities of movement for the thin glass panel?
- Which technologies could be used for bending the thin glass?
- Is Bi-Metal or any other smart materials capable of bending the thin glass?
- What is the most suitable technology for bending thin glass panel?
- Could the glass be adapted completely actively?

- Is the actuator capable of improving the structural performance of thin glass toward lateral forces (wind)?
- How much force is needed to bend the thin glass in different situations?
- How does bending influence the stress generation in thin glass panel?
- How to attach the actuator to the panel of glass?

1.5 Research Methodology

The first phase in the development of this research paper is focused on understanding the thin glass properties, chemical composition and its differences with regular glass. Additionally, at the same time, another literature study has been done based on adaptiveness of thin glass and with the aims of investigating the principles of breathing façade, comparing different types actuators, exploring possible movement and the impact of geometry in glass structure in order to select the most suitable method for bending the glass and creating breathing façade. These questions are addressed by comparing several case studies in double and single skin facade and in different shapes, types of support, actuator attachment, and exploring possible alternatives relying on the knowledge from literature. In general the

In the next phase, the research will be specified more by finalizing the actuator type and apply it to a specific case study. As a result, a number of possible options will be modeled in terms of attachment of the actuator to the glass and its types of movement and support for more details. The numerical models will be also analyzed structurally and according to the design principles and subsequently, most suitable concept will be selected. After evaluation of numerical models, the selected design will be developed more to create a final product include technical detail drawings and a physical mock-up.
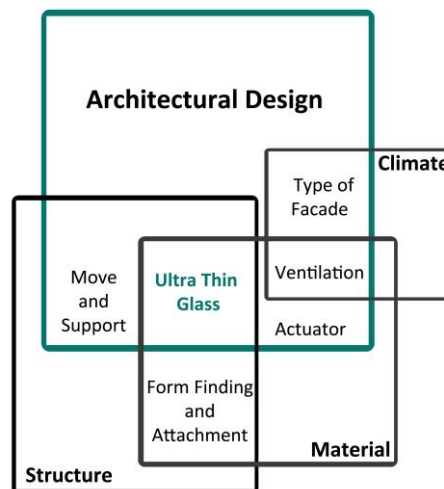
Figure 2, Research focus

The brief research method of the thesis is illustrated in Figure 3.

Literature Study

Regular | Thin Glass

History

Chemical Composition

Material Properties

Production Techniques

Online Production | Offline Production

Mechanical Processing

Pre-stressing of Glass

Lamination

Coating

Bending Glass

Current application of Ultra-Thin glass

Breathing Facade

Adaptiveness

Thin Glass Deformation

Actuator

Self- Change	External Input
Bi-Metal	Bi-Metal
Shape Memory Alloy	Shape Memory Alloy
Wood	Pneumatic Material
Wax	Electro active Polymer
	Chain|Linear Actuator

Thin Glass Movement

Structural Analysis
Possible Movements
Possible attachment of actuator
Possible types of support

Selecting the most suitable actuator for bent thin glass and creating breathing facade

Design

Case Study

Numerical Models

Structural Analysis	Feasibility
Deformation analysis	Types of movement
Types of support	Ventilation
Evaluation of Initial bending stresses	Attachment of actuator
Evaluation of actuation stress	Conceptual detail design
Stability under wind load	Materialization
Testing	
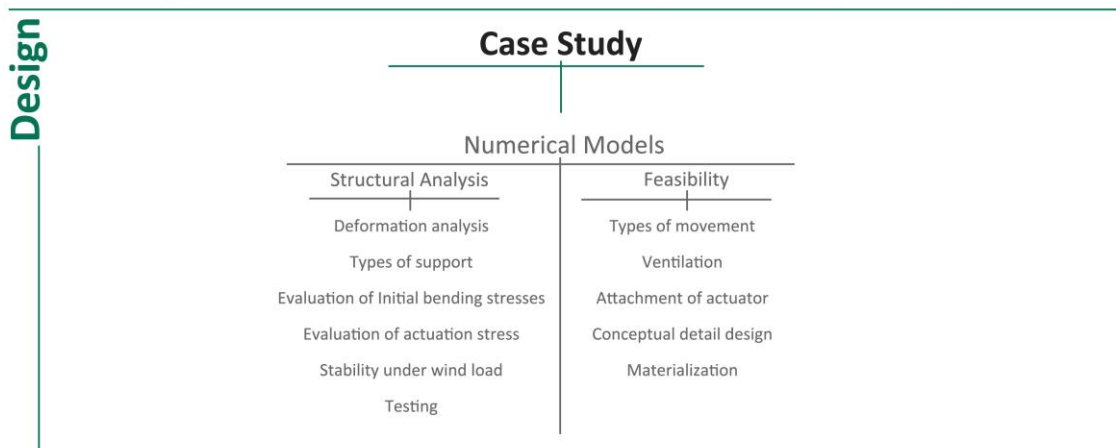
Selecting the most appropriate concept

Detailing

Selected Concept

Technical detail drawing | Physical mock-up design
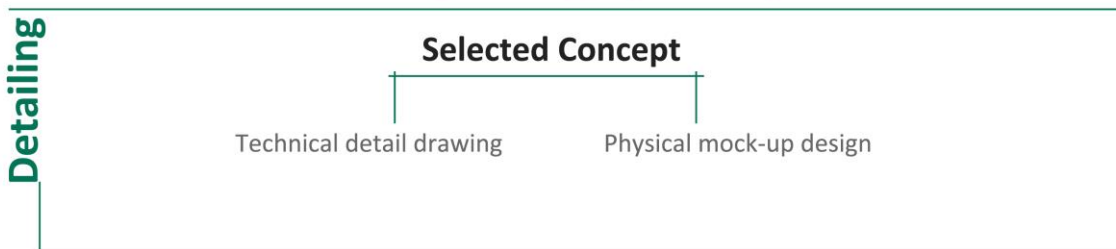
Results and Discussion

Figure 3, research method

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1.6 Relevance

The tendency to build dynamic building envelopes that respond to climate and provide high comfort and indoor quality has been increasing considerably over time. Due to this crucial role, investigation of new technologies and methods to move facades in the building has been the subject of numerous studies and research in recent years.

The relevance of this research begins by following the development of thin glass as an innovative material in the built environment and apply it in a breathing skin by using its flexibility property while it provides maximum transparency for the users. Furthermore, thin glass can diminish the impact on the environment because of the reduction in the use of raw materials compared to regular glass, and on the other hand, it creates a potential for more economical constructions and degrade the total embodied energy of the building due to reducing the weight of the façade and the supporting structures. The emphasis of this research project lies in the investigation of the application of advanced material technologies to bend the thin glass and create a breathing façade.

Thin glass has a huge potential for adaption but the current research progress in this field is not enough for the product to be applied to buildings. Previous researches for its application in façade mainly focus on its safety, water tightness, stiffness and structural stability in a static façade. There are just few research studies with a focus on adaptive thin glass façade by traditional mechanism but a bendable breathing façade panel with use of advanced materials such as SMA wires in which thin glass is applied is not developed yet. So, this research aims to enhance the knowledge on the use of adaptive bendable thin glass for breathing façade and at the same time, focus on the special potential of the Flexinol wire, a class of SMA materials. The design proposal can serve as a foundation for examples and data for feasible future smart applications and research over this new material.

1.7 Graduation plan

	Week number	Course Week	Ultra Thin Glass	BI-Metal	Other Techniques	Selecting the suitable actuators	Exploration	Analyse case study	Define criteria	Numerical Model	Testing Physical Model	Structural Analysis	Climate Analysis	Implementing of Actuator	Final Structural Detail	Final Drawing	Physical Model	Final Presentation	
			Literature Study				**Case Study**			**Design Development**				**Detailing**		**Final Design**		**Reflection**	
November	45	1.10																	
	46	2.1																	**P1**
	47	2.2																	
	48	2.3																	
December	49	2.4																	
	50	2.5																	
	51	2.6																	**P2**
	52	-																	
January	01	-																	
	02	2.7																	
	03	2.8																	
	04	2.9																	
	05	2.10																	
February	06	-																	
	07	3.1																	
	08	3.2																	
	09	3.3																	**P3**
March	10	3.4																	
	11	3.5																	
	12	3.6																	
	13	3.7																	
April	14	3.8																	
	15	3.9																	
	16	3.10																	
	17	4.1																	
May	18	4.2																	
	19	4.3																	**P4**
	20	4.4																	
	21	4.5																	
	22	4.6																	
June	23	4.7																	
	24	4.8																	
	25	4.9																	
	26	4.10																	**P5**
July	27	4.11																	

2 Literature Review

This chapter will describe three main concepts of the research study. First, the concept of breathing façade and its performance will be defined. Then, a general overview of the material glass and the more recently developed thin glass, with consideration of its basic properties, chemical composition, production and application will be discussed. At the end, Different types of actuation systems will be explored in terms of materialization, movement and performance.

2.1 Breathing system

The multiple environmental and climatic features of the area are different parameters, while those concerning internal comfort in buildings are extremely static; this is the reason of using large amounts of energy to pump heating or cool, ventilate and light the buildings between quite well-defined limits, while external environmental factors can change considerably. The concept of breathing architecture, based on environmental parameters, is a solution to save energy for ventilation, cooling, and heating while it concentrates on improving the indoor air quality of a building. "The concept of breathing architecture is based on the meaning of the word "air" and is formed as follows: 1. Anthropocentric perspective: Air→ Breath→ Life, 2. Environmental perspective: Air→ Oxygen→ Indoor Air Quality. The word "air" has a multi-dimensional meaning, and the concept of "breathing architecture" aims to enable the spaces to "breathe". " [1] The promotion of indoor air quality, the decrease of air pollutant concentrations, and the conservation of suitable atmospheric oxygen levels have attracted broad scientific interest in recent years. Immense efforts to decrease outdoor atmosphere pollutants and setting air quality limits by environmental organizations obviously demonstrates the importance of good air quality. Thus, not only good air quality of outdoors but also indoors where people spend most of their lives is essential. [1] The breathing architecture could be achieved by using the concept of adaptiveness in façade of buildings.

2.2 Adaptiveness

"Adaptation is the evolutionary process whereby an organism becomes better able to live in its habitat or habitats" [2]. The building envelope is the connector between exterior environmental factors and the interior requisition of the occupants. [3] An adaptive building envelope is one which contains the abilities to change its properties and flexibly control the variant parameters of a building envelope

responds to changing interior and exterior environmental conditions. Adaptive architectural envelopes should have adaptation strategies to forecast exterior environmental difference as well as interior activities and their interactions with inhabitants. [4] In the concept of breathing architecture, adaptive façade deals with air flow, velocity, direction, temperature, and several other parameters that aid the analysis and comprehension of the movement and behavior of air masses.

In summary, the adaptive breathing skin provides natural ventilation for the building by moving the skin which results in achieving thermal comfort. Then, and indoor air quality can be improved by optimizing air exchange rates. These conditions may steer to appropriate oxygen concentration levels, which contribute to the improvement of good health and pleasant living environment for the inhabitants. "Therefore, the architectural synthesis of a building or space, as well as the use of high technology and technical expertise to achieve high-quality indoor atmosphere, enables the ability of the building or space to "breathe"." [1]

2.2.1 Levels of Adaption

The different levels of adaptive architecture are based on the technological and advancements which displays a specific character and indicates complexity. It begins with flexible architecture in which the building components are changeable and activated externally by human power, and finished with smart architecture which has the ability to grow, evolve, adapt and learn and shows self-initiative and has learning capabilities. Figure 4 demonstrates the levels of adaption in a building. [5]
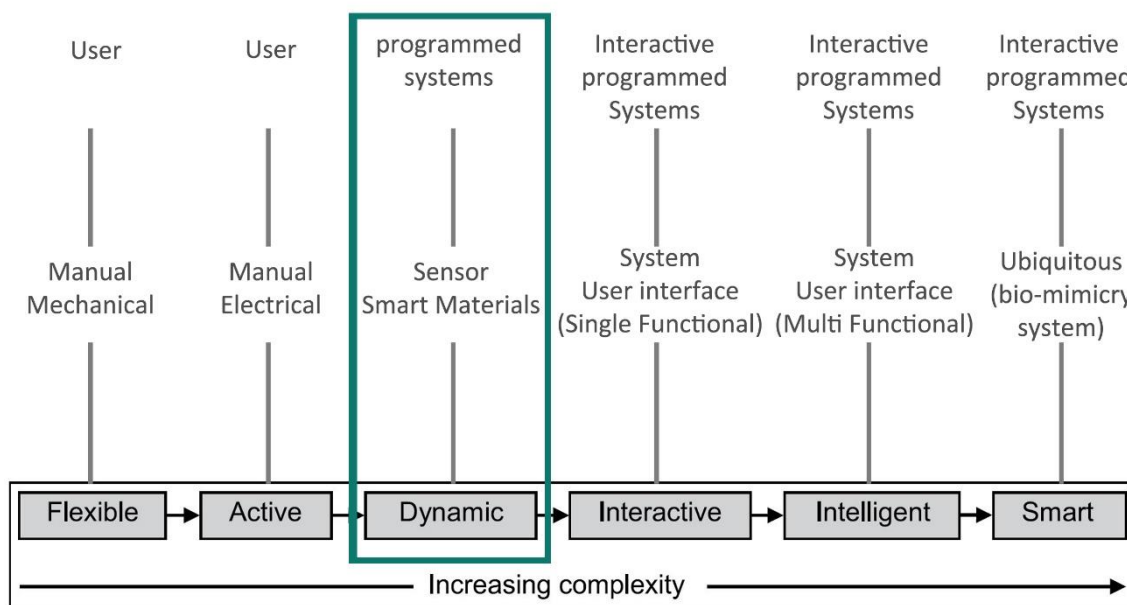
Figure 4, Levels of adaptation in order of sophistication

The system which is chosen in this project is dynamic with use of a sensor or smart material. The dynamic architecture has the ability to change its configuration without manual control of the user. When the building component detects a certain change, it reacts accordingly according to programmed systems while it is confined in a framework in advanced.

The sensor which is used in the dynamic system for breathing envelope should easily control indoor air quality. The chosen sensor in this project is BME680 from Bosch which is a digital 4-in-1 sensor with

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gas, humidity, pressure and temperature measurement based on proven sensing principles. It is produced in small dimensions and low power consumption. [6]
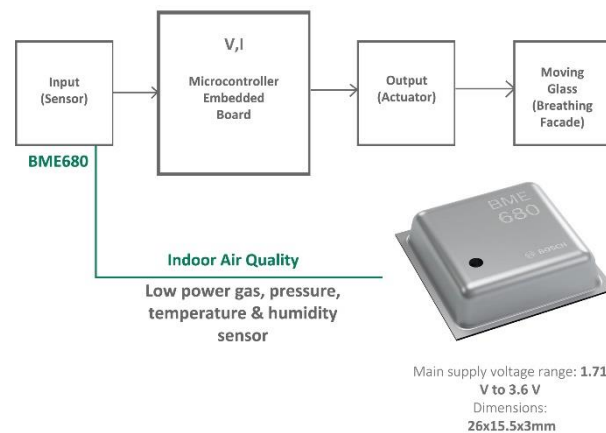
Figure 5, Dynamic system

2.3 Glass

The increasing trend for transparency in building facades steers designers towards the maximum use of glass in building envelope. (Ultra) thin glass with particular specifications is a new material with the high potential to be used in the built environment to make it "lighter" and "smarter". Regarding the special characteristics of this new material, it is possible to demonstrate the potential of thin glass and especially its flexibility as a skin which is used in breathing adaptive façade system.

This part will describe a general overview of the material glass and the more recently developed thin glass, with consideration of its basic properties, chemical composition, production, and application.

2.3.1 History

The first glass was developed in the Middle East, possibly as an extension of the production of glazes (*5000 BCE). [7] At that time, faience which is actually an intermediate material between a glaze and glass was produced by employing different techniques to create a glaze layer over a silica core.

Different manufacturing processes ranged from using blowpipes and cylinder blow-molding techniques to the crown-glass method resulted in small quantities and small window panes, which were almost exclusively used in stained glass windows in churches. One of the examples is the windows of the Notre Dame Cathedral in Paris in 1260. During the seventeenth century, glass demand increased because, in addition to using glass in church windows, builders of castles and stately townhouses realized the possibility of using glass to enclose spaces. During the 18th century, the addition of soda to the composition of glass dropped the production cost of the material considerably and resulted in spreading the use of higher quality glass; windows of Victorian houses in England on the 18th century is a goof-proof for this issue. [7]

Figure 6, Notre Dame in Paris [8]

Figure 7, Victorian House [9]

For a long time, glass utilization was only limited to creating a transparent panel, providing daylight and view. However, in the 19th century, glass started to be applied to different functions such as structural element; this is one that formed the appearance of contemporary architecture. The early 19th century greenhouses in England by Joseph Paxton is one of the first contemporary glass construction. For the first time, a composition of iron frames and glass panels were used as load-bearing structural elements which fulfilled the desire of cultivating exotic plants under controlled conditions. In the 20th century, Glass production become industrialized when glass plates beyond the dimension of 2 meters began to be mass produced on a large scale using the Lubbers and Foucault methods. The dimensions of glass plates increased along time by the development of the production technologies and results in using the newly available products to produce innovative solutions in architecture. The Glass Pavilion Bruno Taut in 1914 shows several potential uses of glass in roof, walls, stairs, bricks and other elements. In the following years, the modernist movement by Mies van der Rohe and several architects gave significant importance to the glass. The production of even bigger glass plates at the beginning of the 21st-century leaded architects and engineers to new solutions.
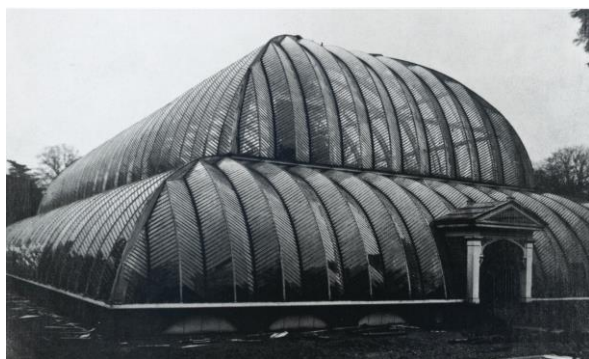
Figure 8, Joseph Paxton, Large Greenhouse at Chatsworth [10]
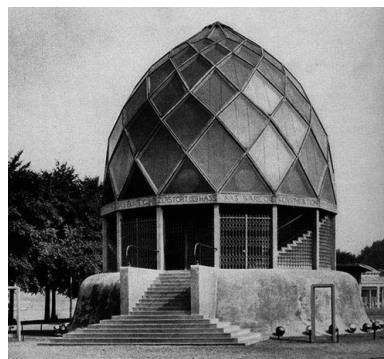
Figure 9, Glass pavilion of Bruno Taut [11]

In the past few decades, the use of glass in buildings has considerably increased. As a result, several transparent buildings have been constructed, in which the materials have almost disappeared. Also, by the growth of innovative technologies, unusual shapes, as well as sustainable products, can be produced with glass. Development of curved glass panels is among the growing glass trends across the globe. The curved glass curtain MAS (Museum Aan de Stroom) in Belgium designed by Neutelings Riedijk can be seen as a new interpretation of the material glass which is used in a more free-form way and gives it quite some emotion. [12]

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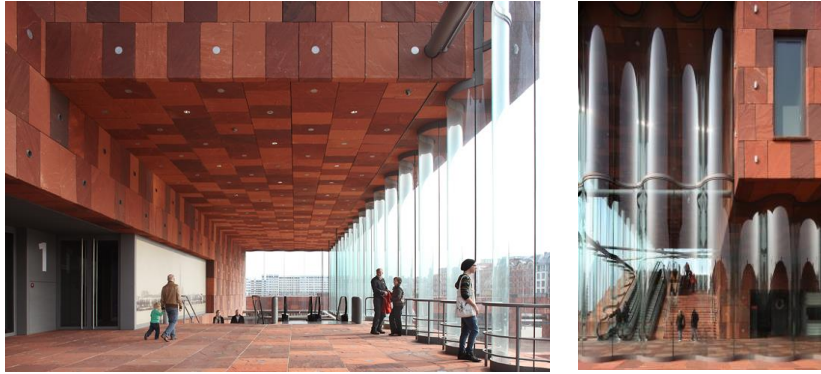
Figure 10, Museum Aan de Stroom [13]

2.3.1.1 Chemical Composition

"In the scientific sense, the term "glass" refers to a frozen, supercooled liquid that has solidified without crystallization." [14] Glass is made up of many different types varies depends on their properties, appearance, uses, and compositions, but generally, all types of glass are composed of silica or quartz sand (SiOz) as the main element combined with soda (NanO), lime (CaO). Although quartz on its own could make excellent glass, it has a very high melting temperature (~1700°C). So, other elements are combined to reduce the melting point and also to improve the hardness and chemical resistance of the glass. Glass is formed when silica together with the numerous impurities are melted at a high temperature then rapidly cooled, preventing crystallization. [15] Glass is hence considered as non-crystalline or amorphous material without a symmetry and periodicity in its network. In other words, glass is a solid material with the structure of a liquid. It is rigid and brittle at room temperature while sorely plastic when heated. [16]
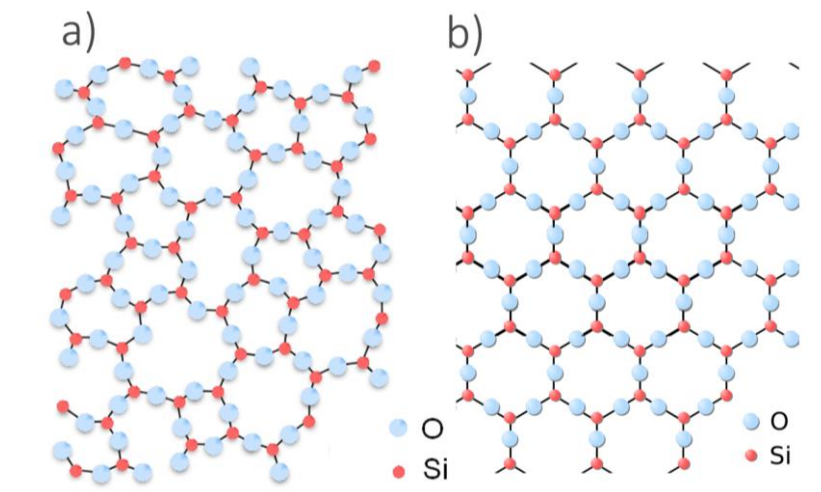
Figure 11, irregular atomic structure glass (a) and regular atomic structure quartz (b) [17]

The most common glass in use today is soda-lime glass, made of mostly silicon dioxide ($SiO2$), sodium oxide ($Na2O$) and lime (CaO). Small amounts of other components also exist in the mixture. The ratio of each component has been standardized. The advantage of the soda-lime type is mainly because of the cheapness and abundance of its raw materials.

(Ultra) thin glass can be produced with either soda lime or aluminosilicate glass, but aluminosilicate glass is more commonly used for thin glass products because of its suitability for the chemical toughening process. The most considerable difference in soda-lime glass and aluminosilicate glass type is the percentage of aluminum oxide in their compositions. [18]

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Table (1) indicates the chemical composition of both types.

Element		Composition of Aluminosilicate glass	Composition of Soda-lime glass
Silicon dioxide	SiO2	62%	73%
Calcium oxide	CaO	8%	5%
Sodium oxide	Na2O	1%	17%
Aluminum oxide	Al2O3	17%	1%
Boric oxide	B2O3	5%	-
Magnesium oxide	MgO	7%	4%

Table 1, Composition of soda-lime glass [19]

2.3.1.2 Material Properties

Transparency and fragility are considered as the most important properties of glass. The transparency is due to the atomic structure and non-crystalline nature of the glass while its tendency to sudden failure, which characterizes glass as a typical brittle material, can be traced back to the high proportion of silicate.

It impossible to predict failure in glass because its maximum elongation at failure is around 0.1%, Moreover, glass behaves as an ideal elastic material, which means, it does not undergo a plastic deformation before reaching its marginal strength and can form back to its initial shape after unloading. Furthermore, the glass deformation does not depend on load duration [14]. Figure 12 clearly shows the comparison of the stress-strain behavior of glass to steel and wood.
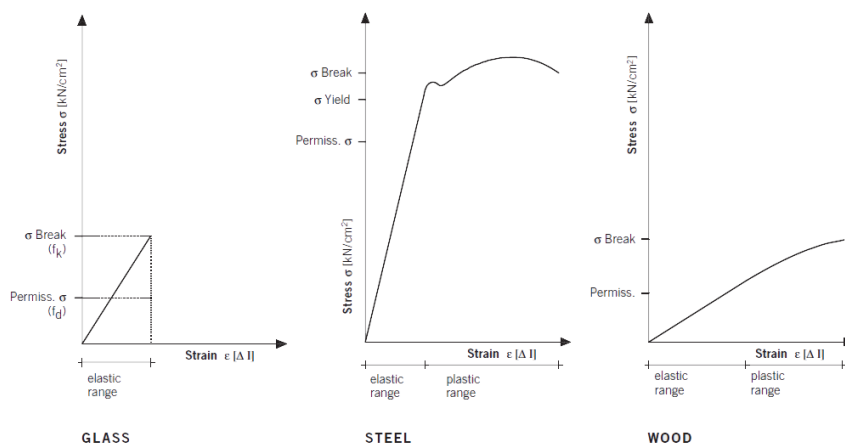
Figure 12, stress-strain graphs of glass, steel, and wood [20]

When considering the strength of the glass, it is important to emphasize not only the material properties but also the physical condition of the sheet glass. The surface flaws of the glass results in a distinction between the theoretical and the practical tensile strength of the sheet. The theoretical value for the tensile strength of a sheet of glass will in practice be reduced considerably because of surface flaws, notches, and cracks. So, in summary, the strength of glass is not a constant value and it is influenced by duration of load, size, and age of pane, glass type and Surrounding medium (air moisture content). [12]

However, the compressive strength of the glass sheet is regardless of any surface flaws. In both theory and practice, it has a very high compressive strength value comparing to concrete.
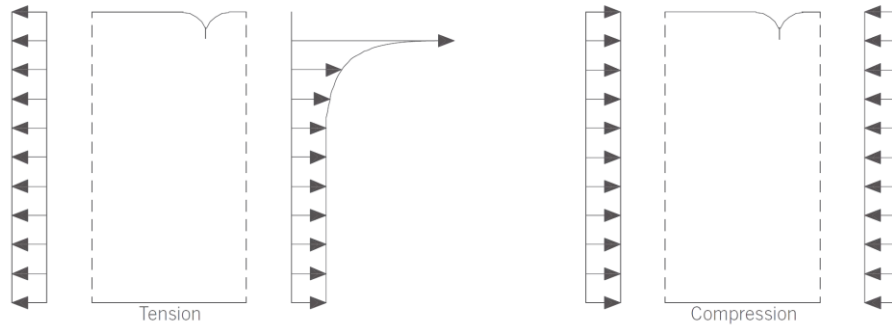
Figure 13, Stress distribution over the cross-section of surface-damaged glass: Stress peaks occur as a result of the notch effect. Under compressive stress the notches are compressed, resulting in no stress peaks. [12]

Plus the good surface hardness of glass, it also expresses excellent properties with respect to chemical resistance and long-term durability due to the silicate basis which is a good corrosion resistance. In general, glass is durable in acids and alkalis except for hydrofluoric acid, which is used for etching glass surfaces. Glass also has high resistance to water, but ponding on glass surfaces in long-term can exhibit white stains on its surface that leads to corrosion. [14] Table (2) clearly shows various mechanical and thermal properties of soda-lime glass compared with those of another brittle material (concrete) and two tough materials (wood and steel). [12]

	Steel S 235	Softwood S 10	Concrete C20/25	Glass Soda-lime glass
Refractive index η	–	–	–	1.5
Density ρ [kN/m³]	78.5	6	22	25
Modulus of elasticity E [kN/cm²]	21 000	1 100	2 900	7 000 (like aluminium)
Tensile strength $f_{t,k}$ [kN/cm²]	24 (yield strength)	1.4	0.22	4.5
Elongation at break ε in %	25	0.7	–	0.006–0.17
Compressive strength $f_{c,k}$ [kN/cm²]	23.5	II 1.7–2.6 ⊥ 0.4 –0.6	2	approx. 50
Limiting tensile stress $σ_{Rd}$	21.8	0.9	(~0.1)	1.2/1.8
Safety factor γ	$γ_M = 1.1$	$γ_M = 1.3$	1.8	2.5
Breaking length σ/ρ [m]	2 800	1 500	(45)	480/720
Thermal conductivity [W/m x K]	75	II 0.5 ⊥ 0.2	1.6	1
Thermal shock resistance ΔT [1/K]	–	–	–	40
Coefficient of thermal expansion $α_T$ [1/K]	12 x 10⁻⁶	II 5 x 10⁻⁶ ⊥ 35 x 10⁻⁶	10 x 10⁻⁶	9 x 10⁻⁶ 60 K ≈ 0.5 mm/m

Table 2, Properties of Steel, Wood, Concrete, GLass [12]

2.3.1.2.1 Thin Glass

Glass with a thickness of 0.55 mm up to 2.0 mm can be defined as thin glass and as ultra-thin glass when the thickness is lower than 0.1 mm. [21]

"Typical glass types used for thin glass are borosilicate glass, aluminosilicate glass, and the well-known float glass." [22]. However, aluminosilicate glass has far primarily been used in thin glass production due to its noticeable properties such as comparatively high Young's modulus, hardness, fracture toughness, chemical durability, lower coefficient of thermal expansion and reduced electrical conductivity. [23] Thin glass has a surface with higher quality, with an almost flawless result and more

scratch- and impact resistant, stronger and surprisingly, flexible due to its different chemical composition, production process and pre-stressing method. Remarkable surface quality and higher strength of thin glass results in having a high resistance to bending stresses and allowing it to bend in a smaller radius. Thin glass thickness is directly related to its minimum radius of bending. In general, thinner glass sheets could bend in smaller radius without breaking. One of the other characteristics of aluminosilicate thin glass is related to the vacancy of iron in its composition which tends to have a higher optical quality compared to the soda- lime glass. The edges of this glass do not present the usual green tone of soda lime glass which happens because of containing the iron in the composition. [24]

Ultra-thin glass manufacturing companies such as ACG, Corning, and Schott produce thin glass sheets which are available in a wide range of compositions, thicknesses and dimensions for different applications. Table briefly shows the general material properties of different types of glass.

Properties			Any producer	Schott	Corning	AGC
			soda lime	xensation	gorilla glass	leoflex
Mechanical	Density	g/cm3	2.5	2.477	2.39	2.48
	Youngs modulus	GPa	73	74	71.7	74
	Shear Modulus	GPa	30	30	29.7	30
	Poisson's Ration		0.21	0.215	0.21	0.23
	Vickers Hardness, before CT		527	617	625	595
	Vickers Hardness, after CT		580	681	674	673
Thermal	CTE		85	?	?	98
	Tg	°C	550	615	?	604
	Softening Point	°C	733	880	852	831
	Annealing Point	°C	554	635	613	606
	Strain Point	°C	511	?	563	556
	Expansion coefficient	(10-6 1/K)	9	?	?	9.8
Optical	Energy transmission	%	91.1			91.6
	Refraction Index	Nd	1.52	1.51	1.51	1.51

Table 3, Material properties of different types of glass [25]

Bending radius of the thin glass

One of the most important properties of (ultra) thin glass is its bending resistance which results in producing it for curved shapes. There is a relation between the thickness of the glass and its maximum bending radius. In general, "the thinner the glass the more it can be curved". Figure 14 demonstrates the stress generated in the top layer of glass pane which is caused by bending different glass thicknesses and in different radii. [24]
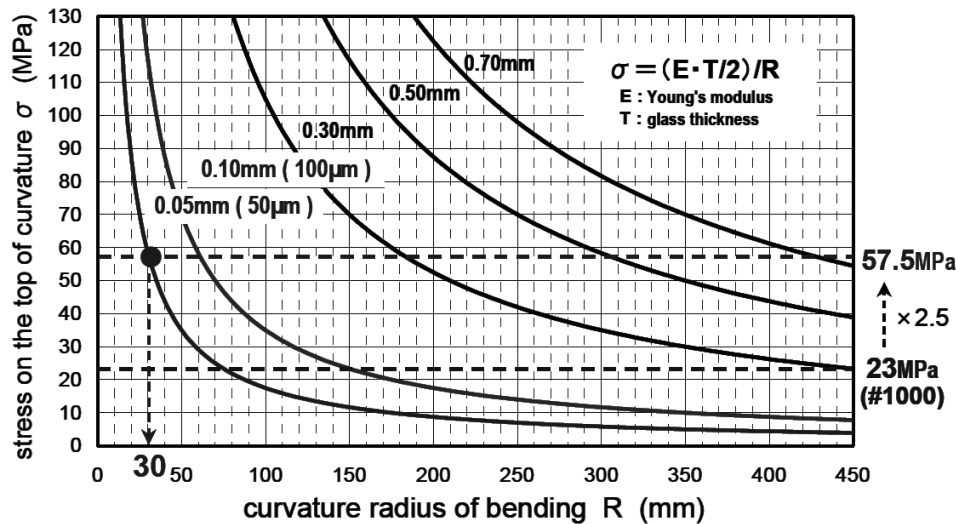
Figure 14, comparison of stress generation by bending different glass thicknesses

2.3.2 Production Techniques

The production of glass contains two main parts: the on-line and off-line production. The different production techniques are clarified in the following sections.

2.3.2.1 On-line Production

There are different phases of the glass production industry. The online production phase is the actual manufacturing of the glass sheet which is followed by offline production processes. The separate techniques for regular glass and thin glass are clarified in the sections below.

2.3.2.1.1 Regular Glass

There are three main techniques for manufacturing of flat glass sheets: float glass rolled glass and drawn glass process. The float glass technique is the most basic used method for production of flat glass in batches and only around 10 percent of the manufactured glass is drawn or rolled. [12] Compared to the two other methods, the float glass technique, developed by the British Pilkington company between 1952 and 1959, produces glass with a remarkable surface quality without the need for any additional treatment. [14]

The production consists of several phases. During the first phase, a homogenized mixture of raw materials is melted in a large furnace at a temperature of about 1550°C to form molten glass. In the next phase, the molten glass floats over the surface of a bath of molten tin at 1050°C where the glass spreads out evenly over the surface of the tin bath which has a higher density of the glass.

The molten glass flows onwards while its thickness is specified by the speed of the pulling rollers on both sides of the bath. The temperature decreases from 1050°C to 600°C by flowing from one side of the bath to the other side gives the glass sufficient inherent strength to be lifted onto rollers. Then the glass is gradually cooled in the annealing lehr further down to 100°C. At this phase, the glass has obtained its optimum flatness and solidity. During the next phase, it is inspected with an optical laser to check for any flaws while it is cooled to room temperature. Then, the glass will be cut in the desired sizes (maximum size of 6.00x3.21 m). Thicknesses can be achieved following the float glass technique are 0.5-25 mm, while the most common thicknesses range between 2-19mm. [14]
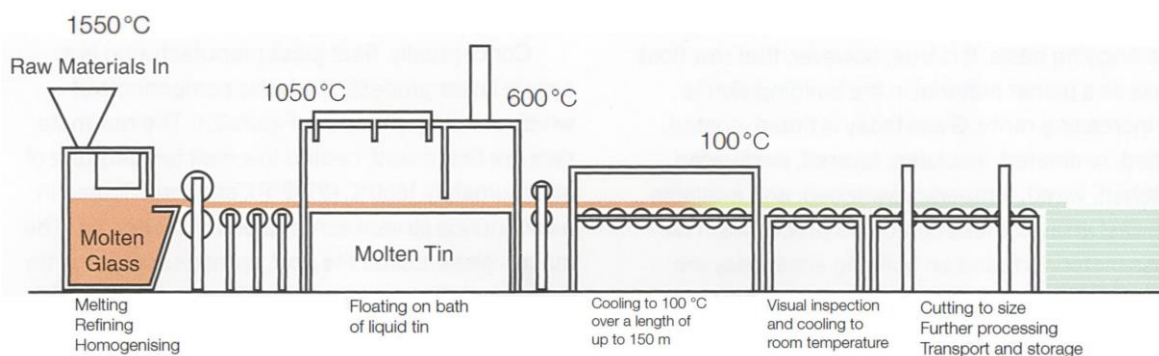
Figure 15, Float glass production

2.3.2.1.2 Thin Glass

Thin glass sheets, less than 2 mm thick has different production technique than regular glass. In general, there are three different processes for thin glass production: the micro-float process, the overflow-fusion process, and the downdraw process.

The micro-float process is similar to a regular float process while it can produce glass sheet thickness down to approximately 0.7 mm. The maximum width is determined by the production equipment same as the float process. [26]

The overflow-fusion process conceived by Corning in 1964 as a system for manufacturing automotive windshields. The new demand for thin glass which is used in LCD screens has led to the further development of this technique in the '80s. The process starts the same as the floating process by melting and mixing of the raw materials and producing molten glass. The molten glass is then poured into a V-shaped bath until it is filled and overflows its capacity by both edges. The molten glass flows down to the sides of the V-shaped bath and the two flows join each other combine to one flow at the bottom. The final molten glass streams down vertically by gravity while it cools down without contacting any surface. The plate will be ready for cutting and storing after it is sufficiently cooled and stiff enough. [27]

The downdraw process, inspired by elder techniques, has been already patented in the 1970s. However, like the overflow-fusion process, this technique was later developed for the production of thin glass. The process is very similar to the overflow-fusion process. The main division is that the molten glass is pulled down out of a furnace through an orifice and not streaming down because of the gravity. After passing through the orifice, the glass strip is already annealed and is ready for the cutting phase. The down draw process has the possibility to create thin glass rolls that have a length of over 100 m. [22]
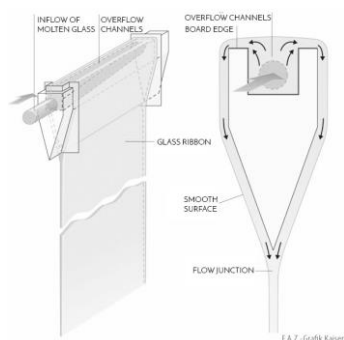
Figure 16, Overflow-fusion process [24]
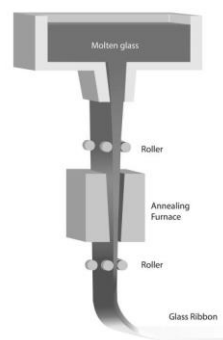
Figure 17, Down draw process, [28]

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At the moment, there are several glass manufacturing companies capable of producing thin glass sheets with different dimensions. Table 2.3 demonstrates different dimensions of thin glass types compared to a regular soda lime sheet.

Properties			Regular soda lime	Schott Xensation	Corning Gorilla glass	AGC Leoflex
Size	thickness	mm	12.0, 10.0, 8.0, 6.0, 4.0	2.0, 1.5, 1.0, 0.7, 0.55	2.0, 1.5, 1.0, 0.7, 0.55	2.0, 1.5, 1.0, 0.7, 0.55
	maximum panel size	mm	3210 x 6000	1150 x 950	1250 x 900	1220 x 737

Table 4, Producers of thin glass and their production sizes [25]

2.3.3 Offline production techniques

The glass sheet products are often processed after manufacturing to meet the desired shape, performance and appearance. This is called post-production processing or off-line processing and carried out in several stages: mechanical processing, pre-stressing, lamination, coating, and bending.

2.3.3.1 Mechanical Processing

Mechanical processing contains cutting, sawing, drilling, edge- and surface grinding which is usually done by CNC-controlled equipment these days.

Zero-cut is the first process that the newly produced sheet glass undergoes. The glasses available in ribbon or standard dimensions can be cut into stock sizes by trimming 5 to 10 centimeter of all edges ensuring the sheet to have the right angle. [12] Float glass sheet is normally cut by scoring and then snapping the material, less frequently with the help of diamond-tipped saws with an accuracy of up to 0.1 millimeters. [14] Cutting of cyclical and conical countersunk holes is often done with a water jet. [12] Very thin glasses can also be cut with lasers. [14]

A variety of finishing of the edges techniques may be done in order to eliminate the irregularities caused by the cutting. The edges of glass remain with irregular surfaces until they chamfered or polished according to its future use. When the edge of the glass sheet is placed within a frame, the simplest, normal cut edge, is only enough. Otherwise, the sharp edges of the glass sheet could be dangerous. The edges should be grounded and/or polished in all other applications. [29] Edges that are ground to the desired dimensions still have flaws in the edge surfaces. Further polishing of the ground edges makes transparent edges again with the highest edge quality. [14] Grinding and polishing the cut edges are carried out using metal tools. These processes are performed in several phases with decreasing grain sizes until the desired mechanical and optical properties are achieved. The accuracy of edge treatment determines the strength of the glass. [30]
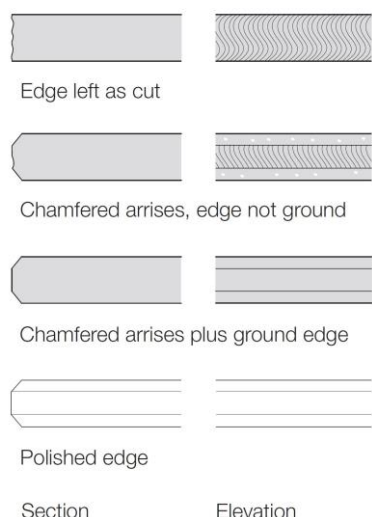
Figure 18, diagrams of edge forms [14]
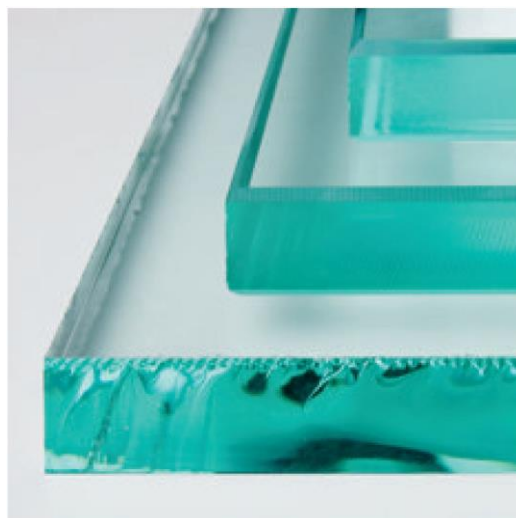
Figure 19, Float glass with an edge left as cut (bottom), ground edge (middle) and polished edge (top) [14]

2.3.3.2 Pre-stressing of Glass

The glass is a strong material with special characteristics such as its optical properties, good hardness, light-fastness, thermal stability and resistance to radiation and chemicals. However, it has a low tensile strength, dependent on the surface properties, and brittle fracture behavior with the high risk of injuries. The technology of pre-stressing of glass is developed a long time to improve the strength and failure behavior of this material. The glass with no pre-stress is called annealed glass. Pre-stressing creates a tensile stress in the core and compressive stress in the surfaces. The core is resistant to the residual tensile stresses because it does not contain flaws. The compressive stress in the surfaces decreases the imperfection sensitivity of the glass; the tensile stress in the surface should overcome the residual compressive stress before the cracks can grow.

Three techniques can be used to pre-stress the glass: toughening, heat strengthening and chemical strengthening.

2.3.3.2.1 Thermally Toughening

Toughened glass or tempered glass is the oldest technique of toughening glass first developed in the 19th century in France. This method consists of heating the basic glass product to about 650 °C, which is approximately 100 °C above its transformation point, and then cooling it down rapidly. consequently, the outer surfaces of the glass are cooled down below the transformation point and getting stiffer, while the internal hot core is still expanding which results in generating internal stresses in the glass pane. The final result is that the external surfaces of the glass get the desired compressive stresses on the glass surface that is in equilibrium with the tensile stresses at the core of the glass.

Thermally toughened glass will split into a large number of small fragments upon failure. However, it will suddenly fall as one whole piece containing the fragments adhering to the interlayer when it is laminated which results in its restriction in use in heights above head level. [14]
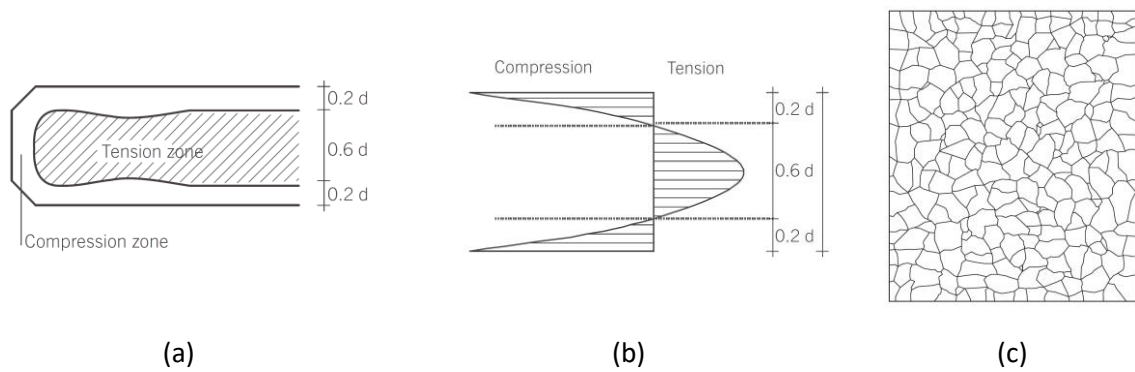
Figure 20, (a), Compression and tension zones in tempered glass cross- section [12], (b), Stress distribution over the thickness of toughened glass [12], (c), Fracture pattern of Toughened safety glass [14]

2.3.3.2.2 Heat-Strengthened Glass

Heat strengthened glass technique is similar to tempered glass method, except that the cooling process is slower which results in less stress generation in the material. This obvious distinction between toughened safety and heat-strengthened glass is in their fracture pattern. In contrast to thermally tempered glass heat-strengthened glass exhibits large fragments rather than small ones in breakage. Heat- strengthened glass suitability for further processing to form laminated glass is a crucial advantage which causes the glass large fragments to interlock and resist a certain amount of compressive forces, while the interlayer is taking the tensile stress. Another important not is that heat-strengthened glass is usually only produced in thicknesses up to 12 mm by considering the fact that the maximum and minimum dimensions depend on the manufacturer. [14]
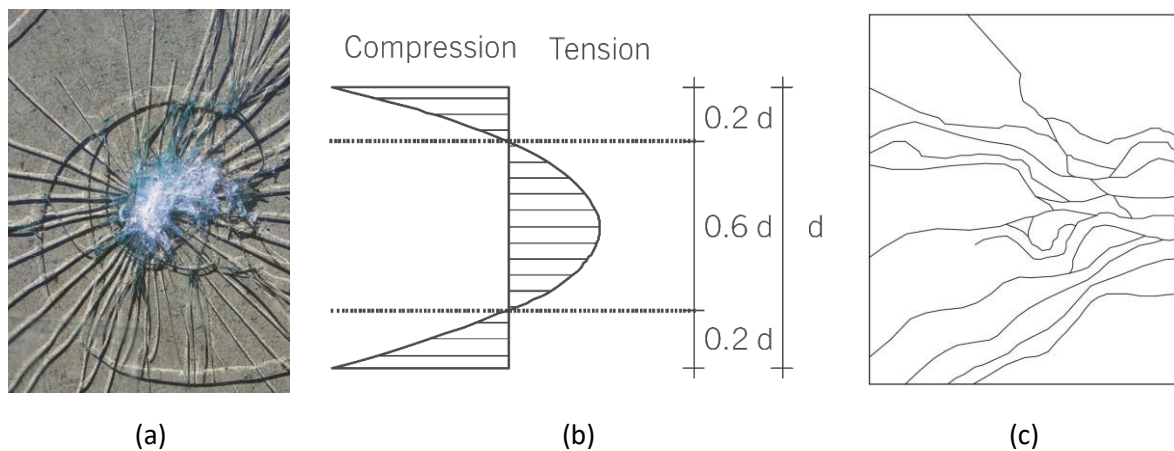
Figure 21, (a) Fracture pattern of Heat-Strengthened Glass [14], (b) Stress cross-sectional diagram of Heat-Strengthened Glass [12], (c) Fracture pattern of Heat-Strengthened Glass [14]

2.3.3.2.3 Chemically Toughening

Chemical strengthening technique is suitable for glass sheets with a smaller thickness. This technique contains a process of ion exchanging instead of thermal shock. The pre-stressing is achieved by placing a glass panel in a hot bath of salt (containing KNO3 and NaNO3) with an approximate temperature of 500°C and then results in a replacement of the ions on the glass surface by other ions with a larger radius.

In a salt bath, the Li-ions of Aluminosilicate glass will be exchanged with Sodium (Na) ions, which are bigger in volume. In case the Aluminosilicate glass contains Sodium (Na), these Na-ions will be replaced by Potassium (K) ions in the bath. The new and bigger volume of the exchanged ions in the glass surface creates a compressive stress layer. [31] Although the surface compression in this technique

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(minimum of 230Mpa) is higher than the thermally toughened glass (90Mpa) or heat-strengthened glass (40Mpa), it extends only a very short distance into the material. The fracture pattern is similar to the float glass. The chemically toughened glass is usually used in the automotive industry and for optical applications. [14]

| (a) | (b) | (c) |
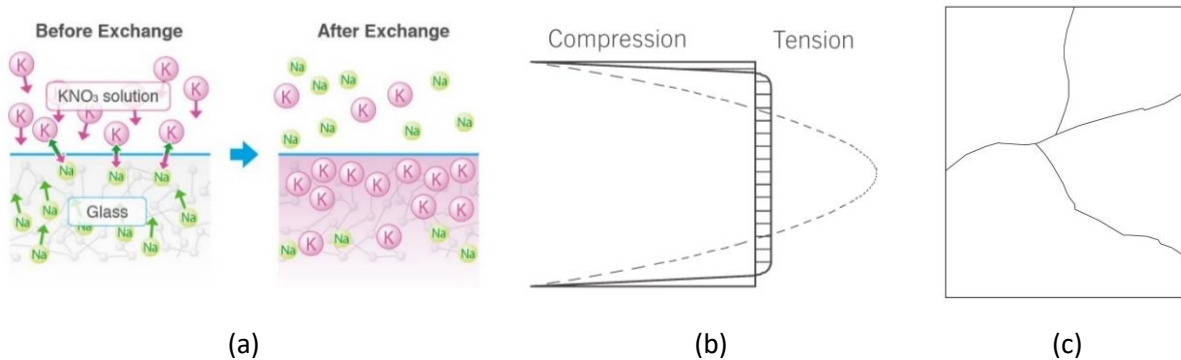
Figure 22, (a), Chemical strengthening process [32], (b), Stress cross-sectional diagram of chemically strengthened glass [12], (c), Fracture pattern of chemically strengthened glass [14]

2.3.3.3 Comparison of the methods

All three mentioned post-production methods improve the strength and failure behavior of glass. However, they result in different material property in the glass pane. Table 5 demonstrates the different properties resulted in chemically and thermally tempered (toughened) glass. Heat-strengthened glass is not considered in this comparison because it serves another purpose due to the importance of its residual capacity after failure.

		Unit	chem. tempered (Leoflex)	thermally tempered
Physical Characteristic	Minimum thickness limit	MM	0.55	3.2
Mechanical Characteristics	Strength / Marginal Stress	MPa	260	80
	Young's modulus	MPa	74000	70000
	Poission ratio	-	0.23	0.20
	Density	g/cm³	2.48	2.50
	Vickers Hardness	-	673	527
Optical Characteristics	Energy transmission rate	%	91.6	91.1
Thermal Characteristics	Expansion coefficient	1/K	9.8×10^{-6}	9×10^{-6}
	Strain point	°C	556	500

Table 5, Comparison of chemically and thermally tempered glass [21]

2.3.3.4 Lamination

The laminated glass contains minimum two layers of glass bonded by adhesive interlayers. The common types of interlayers used in lamination are polyvinyl butyral (PVB), cast-in-place resin (CIP), ethylene vinyl acetate (EVA) and SentryGlas Plus (SGP) from Dupont. [33]

Lamination of glass is developed at the beginning of the 20th century, with the objective of making glass sheets safer in structural applications. With laminated glass, one panel can fail while the other(s) still remain and maintain residual structural integrity. In case of breakage, the interlayer retains the fragments, which eliminate the risk of injury due to glass shards.

The process of producing laminating glass starts by cleaning the individual glass panes in a washing plant to remove any remaining grease, oil, and dust that is attached to the surface. Then the cleaned glasses are placed and the interlayer is positioned in between them to form a sandwich. The pre-lamination process can be done by using the roller process. In case of production of glass laminates with a high curvature, the vacuum bagging process could be used. It is then put into the autoclave under high pressure and raises the temperature to 140℃. So, the adhesive bonds completely attach to the glass sheets and in case of conducting the process correctly, the interlayer will become fully transparent. [12]

Positioning and layering   Prelamination by calender   Autoclave   Finished laminated safety glass
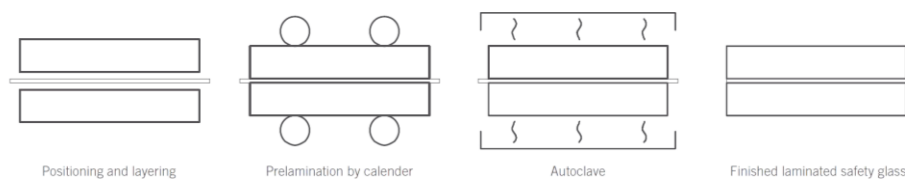
Figure 23, Manufacturing of laminated glass [12]

Combination of the interlayer with a viscoelastic and glass with linear-elastic behavior in a sandwich results in a composite material, where the different layers cooperate mechanically under bending load. This cooperation is directly related to the selection of the component layers, their sequence, thicknesses, positions.

The thickness and Young's modulus of the interlayer determine the bending strength of a laminated glass sheet. In other words, the stiffer and thicker the interlayer, the smaller the resulting deflections.

Secondly, the location of the interlayer within the stressed cross section is related to its load-bearing capacity. "With outer layers of equal thickness in a symmetrical laminated section, the interlayer lies at the neutral axis and in an intact system is subject to shear stresses only." [12]

Figure 24 clearly demonstrates the bonding effect in the cross-sectional stress diagram of a glass panel which is exposed to a lateral load.

A with no interlayer bond/loose

B with flexible interlayer bond

C with stiff interlayer bond
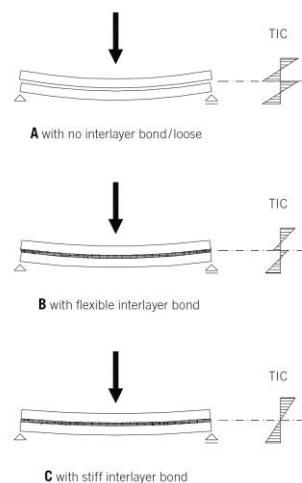
Figure 24, Interaction between glasses and interlayer [12]

2.3.3.4.1 Post-breakage behaviour

One of the main reasons for the use of laminated glass is the safety aspect. Lamination of the glass enhances the post-breakage behaviour of the glass which itself is a brittle material and failing without plastic deformation. The mechanical behaviour of a laminated glass in failure can be described in three stages. (Figure 25)
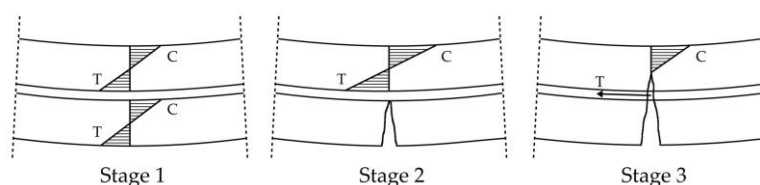
Figure 25, Post-breakage stress distribution, T=tension, C=compression

Both glass sheets are intact in the first phase. In the next phase, the bottom glass panel is fractured and the top panel is carrying all the loads. In the third phase, the top sheet is also fractured; the interlayer is in tension and the glass pieces stick together in compression. [34]

There is a risk for so-called dropouts in phase three when both glass plies have broken and the interlayer is carrying the load. The glass panel may then separate from the support and fall down. Since the risk of dropouts is higher for laminated glass units made of fully tempered glass, it is better to eliminate using fully tempered glass in a laminated glass. [35]

Therefore, choosing the right type of glass and interlayer in designing laminated glass as a structural element is considered important because the remaining load-bearing capacity is dependent on these. [34]

2.3.3.5 Coating

Many types of coating can be applied to improve the optical, thermal and electrical performance of typical glass sheets. In general, three common coating techniques can be applied to soda lime silica glass: hard coating, semi-soft coating and soft coating. Hard coatings are usually done by using a chemical vapour deposition and are positioned on the exterior of the glass, and they are resistant to mechanical and heat damages which results in the possibility for further processing after application., solar control, Low-emission, mirrors, non-reflective glass and self-cleaning can be developed by hard coatings. Soft coatings can be applied by different techniques such as dipping and chemical or physical vapour deposition and they should only be implanted between two sheets of laminated glass or in insulated panels. Soft coatings are applied to produce low-emission, solar control and dichroic (multicoloured) glass. Semi-hard coatings are developed in a vacuum process with three various processes: cathode evaporation, thermal evaporation and magnetically reinforced vacuum metallizing. [12]

The development of coating techniques for soda lime glass has been very promising for the thin glass facade panel. So far, only anti-reflection, anti-fingerprint and the Low-E coating have been successfully applied to thin glass. Unfortunately, except these, no other coatings have yet been tested on thin glass, although it seems like it is technically possible to apply any coating. [25]

2.3.3.6 Bending Glass

Curved glass can be applied in an interesting way in facades and canopies, overhead glazing or several other applications due to their unique architectural expressions. However, since this technique is energy and time consuming and consequently relatively expensive it is usually applied in more ambitious projects. Annealed, thermally or chemically tempered elements are the type of glazing

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which could be used for bending. Generally, there are two techniques for curving the glass: cold- and hot-bending which are produced with different post-processing methods.

2.3.3.6.1 Hot Bending

The hot-bending technique involves reheating the glass plate at a temperature of about 600 C till it can be formed in the desired shape. This is carried out either in by being placed into a mould or using the gravity bending method in the case of smaller batches. [14] The bent Glasses with this technique are shaped in the viscous state and therefore will be free of permanent bending stresses. Hot-bending provides extreme glass curvatures with a maximum bending angle of 90°. [18] However, besides several advantages of hot bending technique, the process is relatively expensive. [18] Museum aan de Stroom in Antwerp, Belgium and Elbphilarmonie in Hamburg, Germany are two examples with the use of the hot bending technique in their façade. The glasses which are used in the façade for Museum aan de Stroom are bent to make a geometrically stable form. Apart from structural purposes, also double curvatures are possible with a hot-bending method for architectural purposes. The double curved glass façade of Elbphilarmonie is produced with hot bending technique.
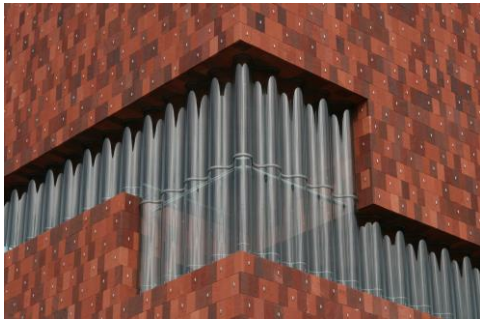
Figure 26, Museum aan de Stroom [13]
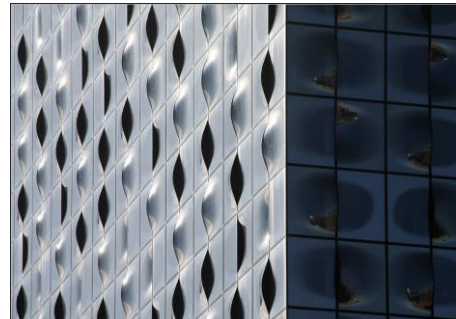
Figure 27, Elbphilarmonie [36]

2.3.3.7 Cold-Bending

Glass can be mechanically formed in the cold state due to its linear elastic deformation behaviour. This technique is much cheaper than hot bending because of the elimination of the need for a mould, and removal of high amounts of energy to soften the glass plates. However, this method can only be used for single curved surfaces with lower bending angle. Also, the stresses which are implied to the glass plates reduce the final structural capacity of the panel.

The cold-bending method could be done in two different processes: cold bending over the rigid framework and cold bending during lamination. In the method of cold bending over a rigid framework, a flat glass plate is forced by clamps or point fixings to get a curved shape. The thicker and stiffer glass sheets can be curved less. [12] The cold bending in lamination process is done by bending the panes of a glass before laminating and then laminating them with the new bent geometry. "The finished laminated pane retains its bent shape after autoclaving without the need for a supporting framework." [18]
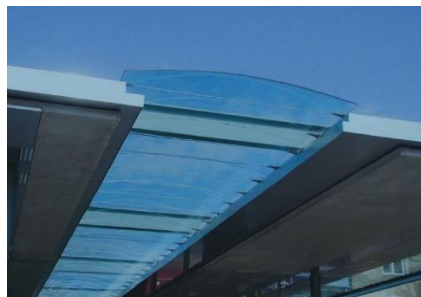
Figure 28, 2 m x 4 m cold bent glass elements functioning as a skylight, Main Bus Station, Heidenheim [12]

2.4 Actuator Systems

In this part, the actuator material selection for the adaptive breathing building skin is presented. A smart material analysis is conducted in order to achieve insight into the performance of shape-morphing smart material systems. On the other hand, the actuator types with external input such as electricity and gas are also studied in order to select the most suitable technology to move the thin glass façade.

The material properties and performance parameters of the actuators are analyzed in relation to the design requirements. It should be considered that the smart materials could not make a complete breathing skin which is at the same time sensitive to temperature, humidity, oxygen level and so on. They are sensitive to just one parameter, so, in case of using smart materials in breathing skin, they could actively move the façade in one parameter such as temperature, and the other parameters such as humidity and oxygen level could be controlled by sensors and the external input such as electricity. As a result, they make a semi-active breathing skin.

2.4.1 Movement and shape relation

There are different types of movement in actuators relating to their texture (rigid or deformable) and to their dimensionality (1D, 2D or 3D shape).

Figure 29 contains the movement and shape of deformable elements as classified by Schumacher et al. [37]
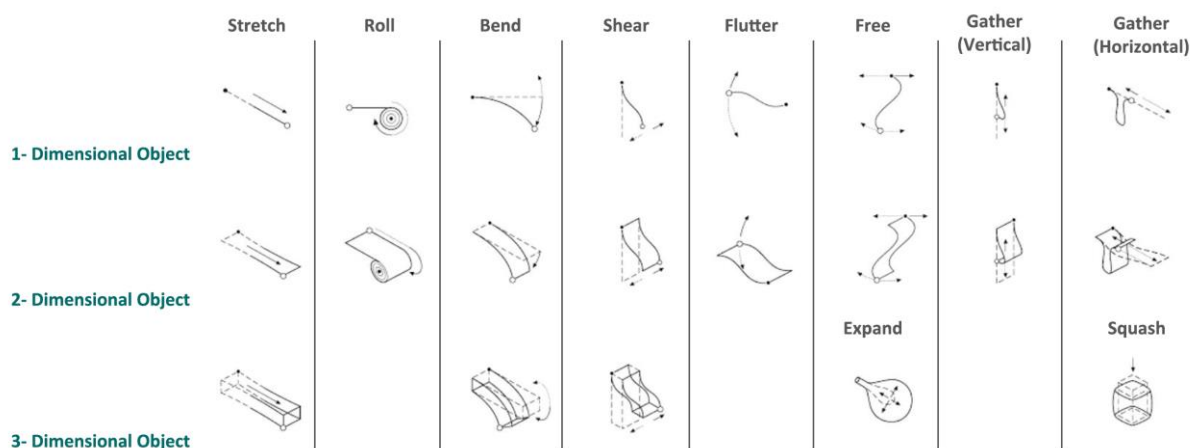
Figure 29, Relation between movement and shape of deformable building elements

2.4.2 Actuator movement type

The movement in facade could be made by a material deformation in the actuator, meaning a change of the original shape of the element which is classified in two different categories: by the reaction of the material to the change of the environment (self-change); or by an external input.

Self-change actuators with kinematic behaviours can deform responding to changes in the environment and as a result, they have a high potential to reduce energy consumption according to the environmental issues. The main research directions on these materials are based on temperature and humidity change.

The actuator can also deform based on an external input, such as electricity, a fluid or gas. As it was mentioned before, some self- change materials such as Bimetal and shape memory alloys could also consider in this part and make semi-active skin in order to fulfil the requirement of breathing façade.

Figure 30 demonstrates the different types of materials in the category of self- change and external input. The green materials are the ones which are studied more in detail and are suitable to be used for the actuator of adaptive breathing façade.
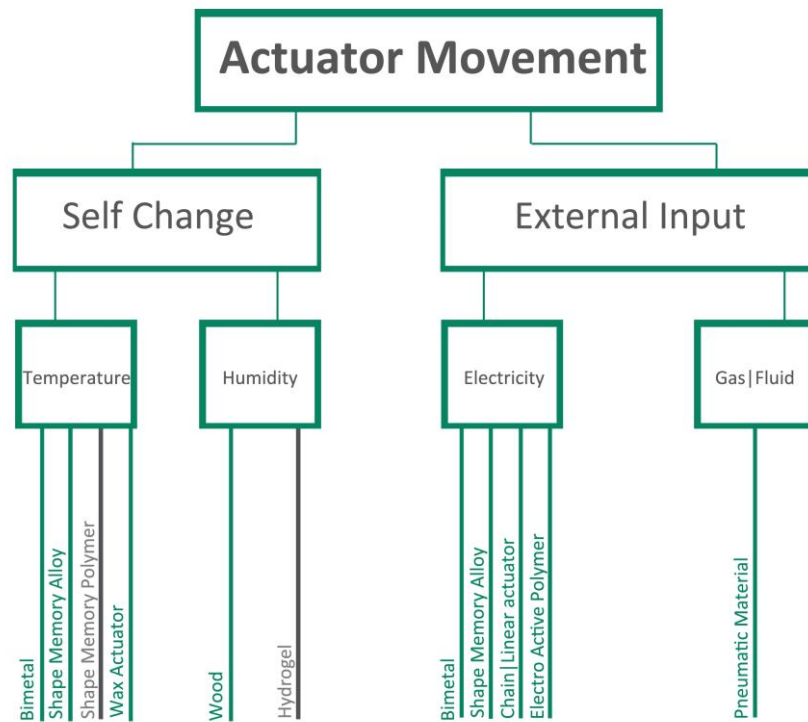
Figure 30, Actuator movement

2.4.3 Self-Change Temperature- Bi-Metal

Bimetal refers to an object that is composed of bonding two different layers of metals with different thermal expansion coefficients. By heating these strips, their length will change differently according to their expansion properties. As a result, the strip with the higher thermal expansion will be prevented from expanding at its natural rate by the opposite strip with lower thermal expansion. Avoiding this dynamic effect results in curving the thermostatic bimetal. Figure 31 shows expansion and deflection process by increasing the temperature in a thermostatic bimetal. [38]
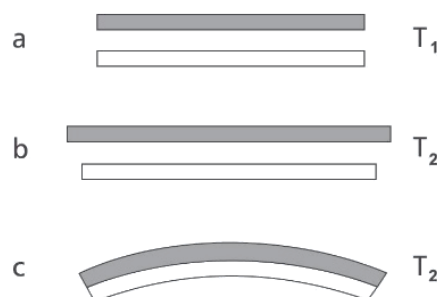
Figure 31, Expansion and deflection by a change in temperature in Bimetal [38]

2.4.3.1 Application

2.4.3.1.1 Architecture

The Thermostatic bimetals are mostly used as a shading system in the field of architecture. The most famous project in this field in the Bloom pavilion by Doris Sung in 2012. This pavilion contains thousands of "bimetallic panels in which two laminated sheets of metal expand and contract at different rates when exposed to heat, in this case, direct sunlight." Furthermore, "the bimetallic panels are thermally very sensitive, with almost real-time defection when exposed to solar heat." [39] According to the talk which is done with Doris Sung the material she used can curl starting at about 80˚F. Depending on the many choices of alloys, this temperature can be controlled. Much also depends on the thickness of the material and the geometry that it is cut.
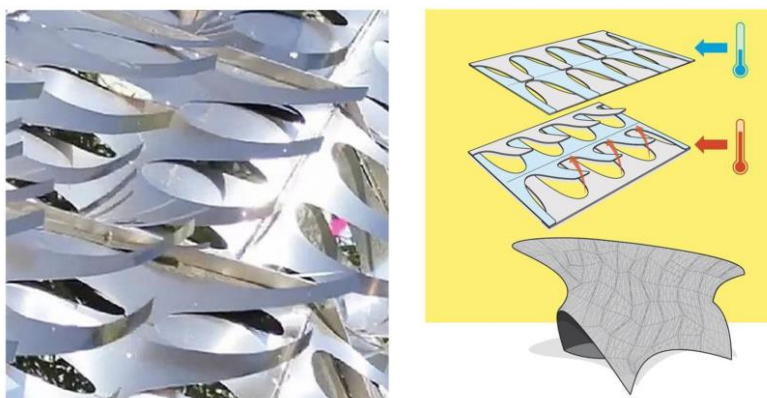
Figure 32, Bloom pavilion [39]

2.4.3.1.2 Engineering

Thermostatic bimetals are used in several engineering application such as motor protection switches and miniature circuit-breakers in the field of Electrical Engineering, temperature compensation and temperature plotters in the field of measuring technology, heating system controls and steam traps in the field of thermal engineering and so on.

2.4.3.2 Application of Thermostatic bimetals in breathing façade

One of the presumptions of this project is creating a berating adaptive façade by attaching the thermostatic bimetal to the thin glass. The thermal force due to the change in temperature or small current could curve the thin glass and open the windows.

The design criteria that should be considered in the application of thermostatic bimetals in this project are their deflection, size (length, width, thickness), material combinations, weight, permissible force, reacting temperature range (20°-35° C), type of support and specific thermal curvature.

For further analysis, the selected temperature range is from 25°C to 35°C and it is considered that the bimetals actively curve the thin glass. Without a doubt, by applying the electricity, the temperature range could be increased and results in a higher thermal force.

It is assumed that the Bimetal strip is covered by a longer fire resistant fabric while the fabric provides enough space for elongating the bimetal which is subjected to the current or increasing of temperature. The fabric included the bimetal strip is glued the bimetal on the edge in order to keep the maximum transparency in façade.
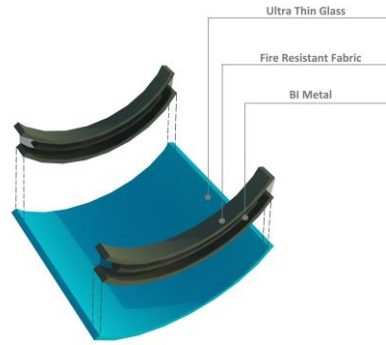
Figure 33, Bimetal attachment to glass

2.4.3.2.1 Types of Bimetal

Among the several Thermostatic bimetals producers all around the world, "Engineering Material Solutions" and "Auerhammer Metalwork" from "Wickeder Group" are considered the most notable ones. By comparing the most active material available from these two companies, it can be concluded that the bimetal form Auerhammer Metallwek Company is more suitable. It should be mentioned that the most active bimetal for Auerhammer Metalwork is "TB 230/110" in the catalog but it is not available yet. [40] [41]
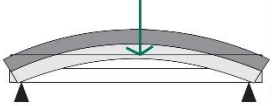
	Engineered Materials Solutions *Wickeder Group*	Auerhammer Metallwerk *Wickeder Group*
Location	USA	Germany
Minimum order quantity	100 KG	2 KG
Shipping Cost	19 €/kg	-
Most active material available	P675R	TB 208/110
Composition	Mn,Cu,Ni / Fe,Ni	Mn,Cu,Ni / Fe,Ni
Specific Thermal Curvature(K)	38X 10-6 (mm/mm)/°C	39X 10-6 (mm/mm)/°C
Useful Deflection Temperature Range	-70 to 260 °C	-70 to 250 °C
Recommended Max. Temperature	430 °C	350 °C
Electrical Resistivity (24°C)	1.18 µΩ	1.10 µΩ
Density	7.61 g/cm³	7.7 g/cm³
Modulus of elasticity	131 GPa	145 GPa
Price	360 €/kg	350 €/kg
Evaluation	☒	☑

Table 6, Comparison of P675R and TB208/110

P675R and TB 208/110 could be compared in thermal force and deflection by using the Bimetal calculators which are given by two companies. In this case, the temperature range is around 25°C-35°C and the size is chosen due to the size of glass mock-up. Also, both types of Bimetals are simply supported. According to the table 7, TB 208/110 has better performance compared to the same size of P675R. As a result, further calculations for this project are done with TB 208/110.
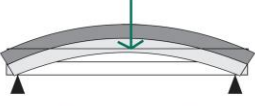
Simple Supported Beam	Engineered Materials Solutions (Wickeder Group)	Auerhammer Metallwerk (Wickeder Group)
	P675R	**TB 208/110**
Thickness	5mm	5mm
Width	100mm	100mm
Active Length	710mm	710mm
Temperature range	25-35 °C	25-35 °C
Thermal Deflection	49mm	52mm
Thermal Force	90.37 N	624 N
Evaluation	☒	☑

Table 7, Structural comparison of P675R and TB208/110

TB 208/110 Types of support

TB 208/110 Bimetal roll is produced in the thickness range of 0.115- 2.000 mm and width of 3.0- 250 mm. It structurally could act either as a cantilever beam or simply supported beam. The thermal deflection of the cantilever case is considerably higher (four times more) while the thermal force is noticeable (two times more). According to TB Calculator, the lower thickness is used, the higher thermal deflection and lower thermal force will be achieved. Also, the active length of the bimetal is one of the key role in determining the thermal deflection but the total weight should also be considered. In this case, the length is selected according to the mock upsize. Table 8 determines the different performance of a bimetal in two types of support.

TB 208/110	Simple Supported Beam	Cantilever Beam
Thickness	5mm	5mm
Width	10mm	10mm
Active Length	710mm	710mm
Temperature range	25-35 °C	25-35 °C
Thermal Deflection	52mm	208mm
Thermal Force	62 N	108 N
Weight	2.733 KG	2.733 KG

Table 8, the Different performance of bimetal in various types of support

2.4.4 Self-Change Temperature- Shape Memory Alloy

Shape-Memory Alloys (SMAs) are a class of shape memory materials (SMMs) with two main characteristics, shape-memory effects, and superelasticity. They are considered as a class of smart materials which have the ability to 'memorize' or recover their original shape from a plastic deformation when subjected to certain stimuli such as magnetic variations or thermomechanical. Also, they have great superelasticity characteristic which happens when SMAs deformed above Austenite finish temperature. In this condition, it shows a large reversible elastic deformation (up to 10%) as a result of stress-induced martensite transformation.

These unique properties result in using SMA actuator wires and plates in robotics, automotive, and biomedical engineering. [23] This technology was first discovered in 1932 but further research was not conducted until 1962. [42]

2.4.4.1 Chemical composition

The three main types of shape memory alloys are the copper-zinc-aluminium-nickel, copper-aluminium-nickel, and nickel-titanium (NiTi) alloys but SMA's can also be created by alloying zinc, copper, gold, and iron. Table 6 shows different types of shape memory alloys with their transformation temperatures.

Alloy	Transformation Composition	Transformation Temp. Rang (°C)	Hysteresis (°C)
Ag-Cd	44/49 at % Cd	-190 to -50	~15
Au-Cd	46.5/50 at % Cd	30 to 100	~15
Cu-Al-Ni	14/14.5 wt %Al, 3/4.5 wt %Ni	-140 to 100	~35
Cu-Sn	~15 at % Sn	-120 to 30	–
Cu-Zn	38.5/41.5 wt % Zn	-180 to -10	~10
Cu-Zn-X (X=Si,Sn,Al)	few wt % X	-180 to 200	~10
In-Ti	18/23 at % Ti	60 to 100	~4
Ni-Al	36/38 at % Al	-180 to 100	~10
Ni-Ti	~49/51 at % Ni	-50 to 110	~30
Fe-Pt	~25 at % Pt	~-130	~4
Mn-Cu	5/35 wn % Cu	-250 to 180	~25
Fe-Mn-Si	32 wt % Mn	-200 to 150	~100

Table 9, Shape memory alloy composition and properties [43]

The ability of SMAs to retain their original shape after being deformed is basically because of the forward and reverse change between two state phases on the atomic level. There is a low-temperature phase which is called martensite. By increasing the temperature the atomic alignments change into another phase named austenite or parent phase.
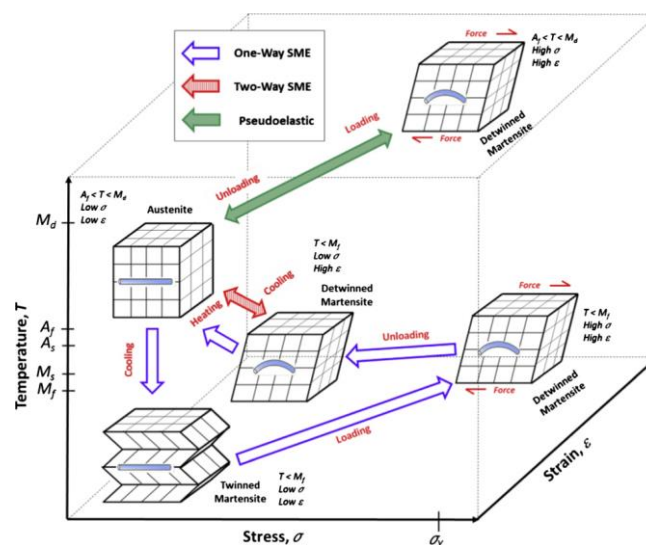
Figure 34SMA phases and crystal structures [43]

Ms = Starting temperature of the martensitic phase

Mf = Finishing temperature of the martensitic phase

As = Starting temperature of the austenite phase

Af = Finishing temperature of the austenite phase
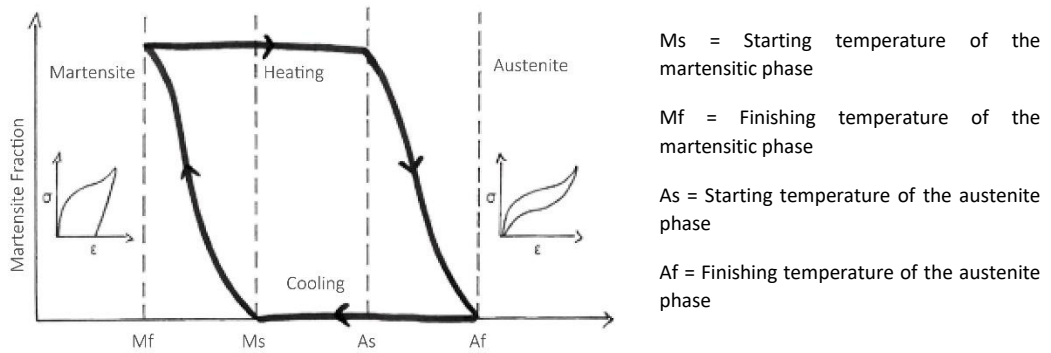
Figure 35Variation of the martensite fraction in alloy with temperature

2.4.4.2 Pseudo-Elasticity

One of the special property of shape memory alloy is its superelasticity. In the austenite phase, by stressing the material, it could be forced to the martensite phase and by removing the stress, it transforms to austenite phase or its original shape. [44] High deformations, on the order of 5–8%, can be achieved in this phase. For the superelasticity phenomenon, changes in the external temperature environment are not required.

One of the examples for use of this property is the frame of reading glasses. The frames of reading glasses have been made of shape memory alloy as they can undergo large deformations in their high-temperature state and then instantly revert back to their original shape when the stress is removed.
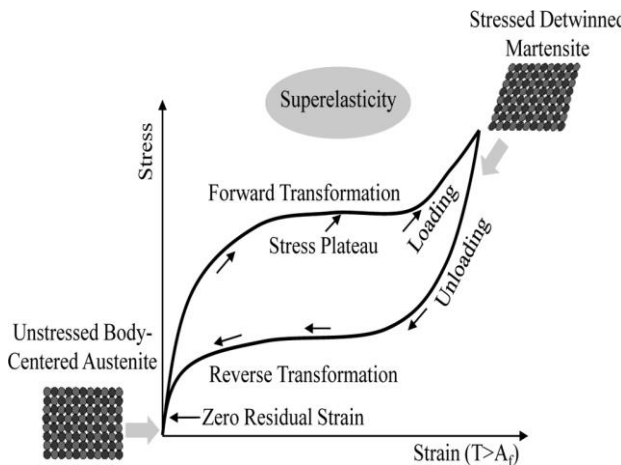
Figure 36, Stress and strain curve for superelastic SMA [45]

Figure 37, SMA Glasses frame [46]

2.4.4.3 Application

2.4.4.3.1 Aircraft

Boeing, General Electric Aircraft Engines, Goodrich Corporation, NASA, and All Nippon Airways developed the Variable Geometry Chevron using shape memory alloy that reduces aircraft's engine noise.

Also, SMAs could also be used as wires in the wing of airplanes to replace the actuator. Electric pulses sent through the wires allow for accurate movement of the wings, as would be needed in an aircraft. This reduces the need for maintenance, weighs less, and has less cost. (Figure 38)

25
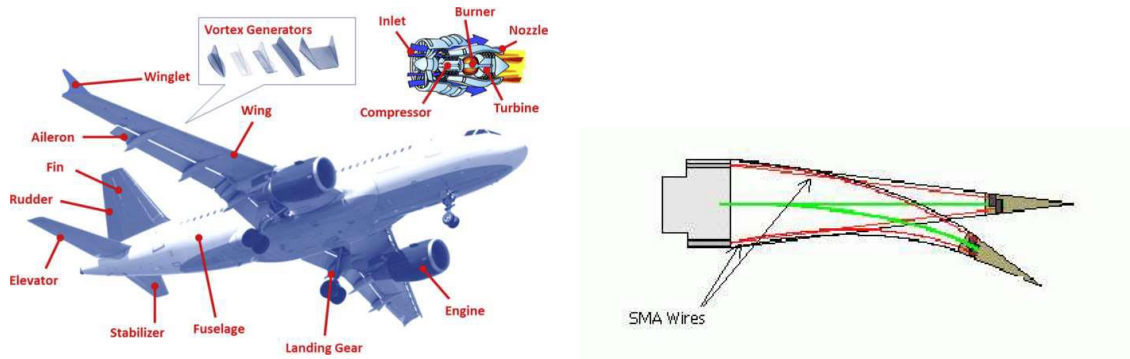
Figure 38, existing and potential SMA applications in the aerospace domain [47]

2.4.4.3.2 Robotics

There have also been limited studies on using these materials in robotics (such as "Roboterfrau Lara"), as they make it possible to create very light robots. Weak points of the technology are energy inefficiency, slow response times, and large hysteresis. [48]
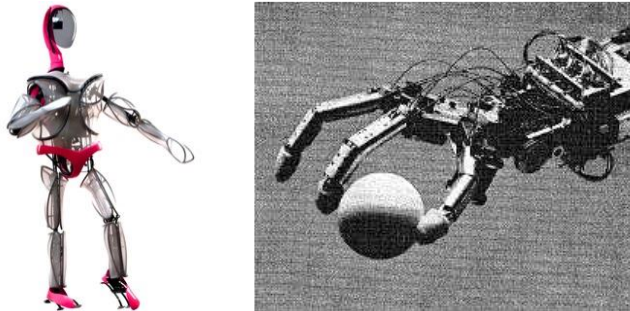
Figure 39, Lara robot [48]

2.4.4.3.3 Medicine

Shape memory alloys are applied in medicine, for example, as fixation devices for osteotomies in orthopedic surgery, in dental braces to exert constant tooth-moving forces on the teeth and in-stent grafts where it gives the ability to adapt to the shape of certain blood vessels when exposed to body temperature.
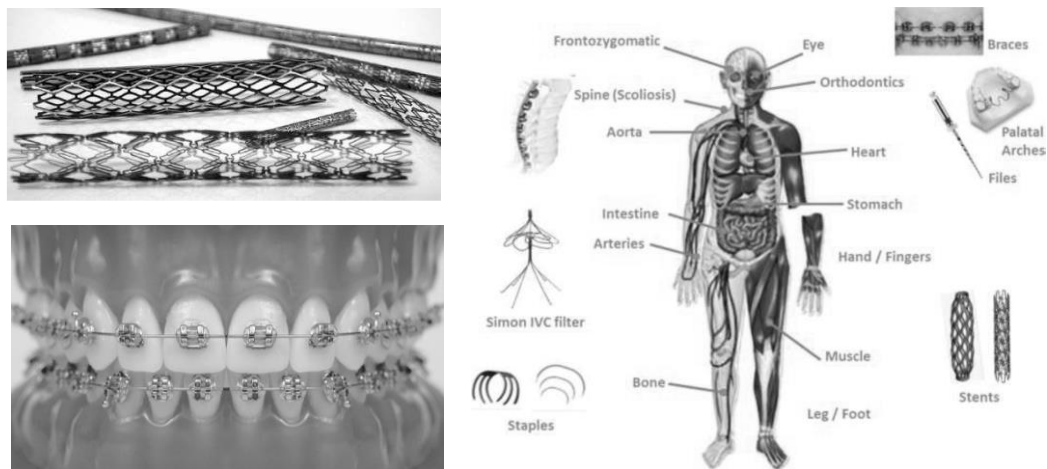
Figure 40, existing and potential SMA applications in the biomedical domain [47]

2.4.4.3.4 Structural application

Unique physical and mechanical features of SMA makes it a successful candidate to be used in structural engineering applications. Among them, SMA braces for frame structures, SMA damping elements for bridges, SMA connectors, and structural reinforcement for earthquake retrofit could be named. [49] Recently, Filipe Amarante dos Santos and Chiara Bedon could reinforce glass panels by SMA in two separate works and as a result, provide a higher stiffness and resistance to large size traditional laminated glass panels and minimize the possibility of glass failure in wind. [50] [51] Filipe connected the SMAs behind the glass panels and by changing the numbers and positions of them, could minimize the displacement of the glass in wind force. On the other hand, Chiara placed the SMAs between the gap of two glazing in a window panel and by changing the distance between SMAs could reinforce the window panel in wind. In both projects, after applying the current, the SMA wires deflection confront the displacement by wind pressure.
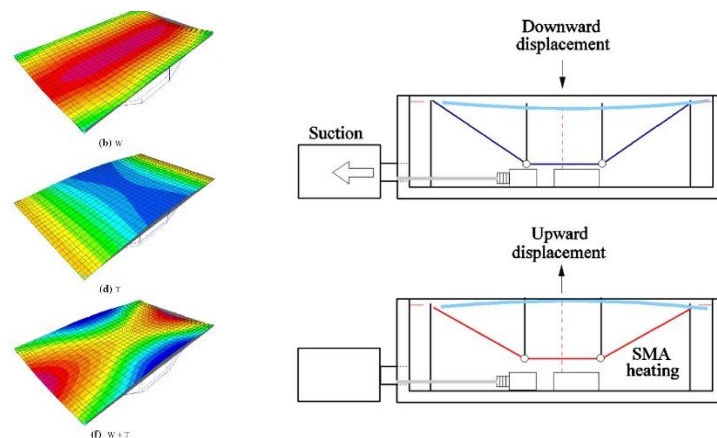
Figure 41, Glass deflection, b: wind, d: Temperature, f: wind + temperature [50]

In Chiara project, the interesting part is that when the LG elements are subjected to ordinary temperatures, the SMA wires provide a moderate stiffness contribution by pre-stressing the panel and make the possibility to have more stability even without applying any current. In contrast, an increase of temperature leads to the activation of the SMA wires, and as a result, providing a certain level of additional stiffness and resistance to the glass panes. [51]
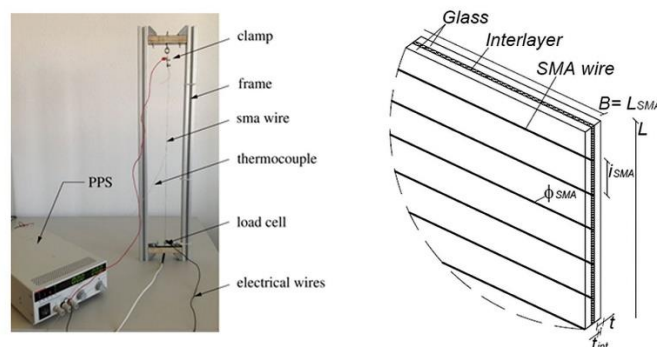
Figure 42, SMA-reinforced laminated panel concept [51]

Table 10 indicates the effect of SMA wires in a glass panel in different distances when the panel subjected to short-term wind load. In normal temperature, the existing SMA decreases the maximum deflection in glass caused by wind. [51]

		SMA net		Panel geometry		Loading condition	
		ϕ_{SMA} [mm]	i_{SMA} [mm]	B [mm]	L [mm]	T [°C]	q [kN m^{-2}]
No SMA	M1-0	0	3 000	1 000	3 000	30, 40, 50, 60	1 (3 s)
SMA wires	M1-1	4	650				
	M1-2		450				
	M1-3		250				

			Max. deflection in the glass		Max. stress in the glass panes		Max. stress in the interlayer
			w_q [mm]	R_w (Eq. 1) [%]	σ_q [MPa]	R_σ (Eq. 1) [%]	$\sigma_{int.q}$ [MPa]
30°	M1-	0	3.300	–	7.405	–	0.0358
		1	2.805	−15.0	7.089	−4.3	0.0553
		2	2.646	−19.8	6.877	−7.1	0.0419
		3	2.574	−22.0	6.803	−8.1	0.0416
40°	M1-	0	3.851	–	8.229	–	0.0304
		1	3.151	−18.2	7.678	−6.7	0.0575
		2	2.881	−25.2	7.269	−11.7	0.0389
		3	2.855	−25.9	7.263	−16.7	0.0371
50°	M1-	0	4.549	–	10.190	–	0.0238
		1	3.571	−21.5	8.495	−16.6	0.0605
		2	3.294	−27.6	7.993	−21.6	0.0378
		3	3.173	−30.2	7.809	−23.4	0.0305
60°	M1-	0	5.852	–	13.730	–	0.0109
		1	4.249	−27.4	9.712	−29.3	0.0352
		2	3.837	−34.4	8.863	−35.4	0.0308
		3	3.660	−37.5	8.490	−38.2	0.0258

Table 10, Comparative results for the panel subjected to short-term wind loads, under the effects of temperature variations in different distance of SMA [51]

2.4.4.4 Material Properties

According to the diagram, the shape memory alloy in austenite phase has a higher module of elasticity in the martensite phase and as a result, it is stiffer. This property is one of the most characteristics of SMA which could be used in this project.

Figure 43, Elastic modulus evolution vs. martensite fraction [52]

2.4.4.5 Shape memory alloys behavior

Two common effects of shape memory alloy are one-way and two-way shape memory.

2.4.4.5.1 One-way shape memory effect

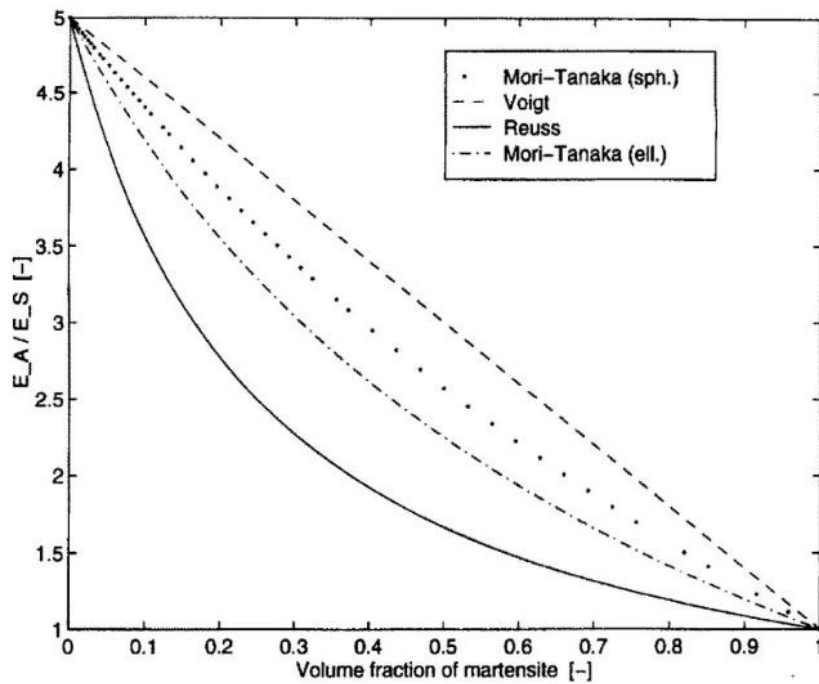A type of shape memory alloy which can be deformed at martensite phase only by applying an external force rather than automatically. Generally, when a shape memory alloy is in its cold state, the metal can be bent or stretched and will hold this shape until heated above the transition temperature. Upon heating, the shape changes to its original. When the metal cools again, it will remain in the hot shape until deformed again. In this case, cooling from high temperature does not cause macroscopic shape change. The most common one-way shape memory alloys are Cu- Al- Ni Alloy and Ti51Ni49.

Figure 45 briefly shows the process for one way shapes memory alloy. According to the figure, it is clear that the triggers for Martensitic Transformation (MT) are both temperature and stress. [42]
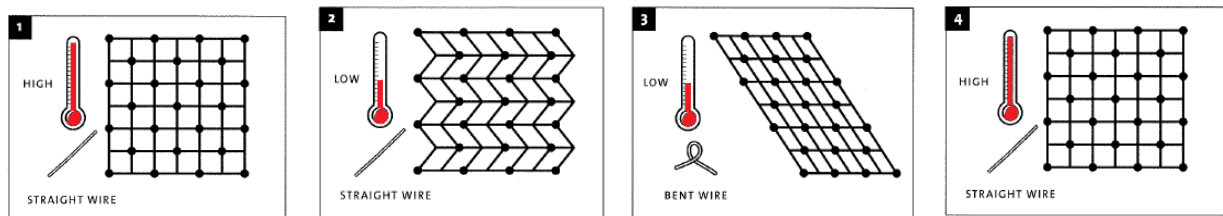
Figure 45, 1.Austenite Phase: High Temperature, The atoms arrange themselves in their "permanent" shape, 2. Martensite Phase: Low temperature, the Cubic structure becomes folded or twined, 3. deform the Wire, and It remains in its Martensite Phase, 4. Austenite Phase: Heat the wire above the transition temperature, It moves back to its original form [47]

SMA Spring

SMA springs are one of the common types of one way shape memory alloy which is also suitable for this project. As it was mentioned before, one way shape memory alloy needs temperature difference and applying a load in order to remember its shape again. In this case, by carrying the load of the glass and its panel, the SMA spring could be deformed and after rising the temperature naturally or by a small current, it could be contracted and carry the load of the frame and glass due to its higher module of elasticity (Figure 44).
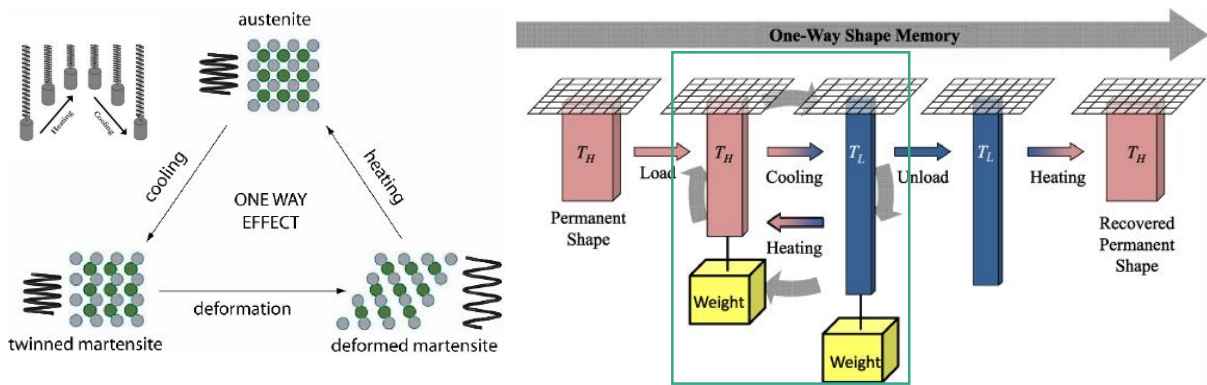
2.4.4.5.2 Two-way shape memory effect

A type of shape memory alloy which remembers two different shapes: one at low temperatures, and the other at the high-temperature. It is based on the repeatable shape changes without application of an external force when subjected to a cyclic thermal load. In this type, the only trigger for Martensitic Transformation is temperature. The most common composition type of two way SMA are Ni-Ti and Copper. Although NiTiHf is also common because of its high transformation temperature range, since it is more expensive than NiTi, it has been disregarded in this case.

According to Table 11, Ni-Ti is more corrosion resistant which is necessary for window application and also has more recoverable strain than Copper base SMA. So, Ni-Ti has been selected for deeper studies for this project.

| Ni-Ti based SMA	Copper based SMA
Recoverable strain(8%)	Recoverable strain(4-5%)
Shape change temperature range (- 50 to +110 C)	Shape change temperature range (-200 to +150 C)
High resistance to corrosion Consist of 50% Ni and 50% Ti	Low resistance to corrosion.
Expensive material and highly controlled Fabrication process.	Consist of 80% Cu and 20% Zn+Al.
	Less expensive material and Metallurgical process.

Table 11, Comparison of Ni-Ti and Copper based SMA

Nitinol

Nickel Titanium shape memory alloy is a unique type of SMA alloy with superelasticity, low modulus of elasticity, good resiliency, corrosion resistance, simple training mechanism advantages while it can be controlled by a low electrical current. On the other hand, its poor cutting efficiency, poor resistance to fracture compared to stainless-steel are among the disadvantage of this material. It should be also considered that NiTi does not show signs of fatigue before fracture and, it breaks after 720 degrees of rotation. In addition, highly controlled fabrication process required (1% change in composition results in 20° C temperature variation) for this type of material.

The important point which should be considered in Nitinol is its low transformation temperature. The average activation temperature starts at 50° C, and also in the temperature of more than 110° C, it

will lose its shape memory effect and will be deformed permanently. So, in case of application in windows for hot climate location, SMA could become hot by solar radiation and actively open the windows and it is not possible to keep the windows closed according to the user preference. For this situation, we should consider a shading system in order to avoid overheating and also control the adaptiveness of the panels.

Table 12 shows a brief comparison between Nitinol and stainless steel. [54]

Properties	Nitinol Martensite(M)| Austenite(A)	Stainless Steel
Recovered Elongation	8%	0.8%
Biocompatibility	Excellent	Fair
Elastic Modulus	40GPa(M)- 75GPa(A)	193GPa
Torqueability	Excellent	Poor
Density	$6.45g/cm^3$	$8.03g/cm^3$
Electrical Resistivity	76 μΩ.cm(M)- 82 μΩ.cm(A)	72 μΩ.cm
Magnetic	No	Yes
Thermal Expansion	$6.6 \, 10^{-6}/°C$ (M)-$11 \, 10^{-6}/°C$ (A)	$17.3 \, 10^{-6}/°C$
Thermal Conductivity	18 W /m.°C	16.3 W /m.°C

Table 12, Comparison of Nitinol and Stainless Steel [54]

Nitinol could be produced in four types of wire, board, stick, tube. Jinhua Ruipu Titanium Industry is one of the Nitinol producers in China which manufacture Nitinol in two different transformation temperature range of 20 °C- 40 °C and 45 °C- 90 °C. Depends on thickness and shape, the price is between 30-200 $/KG.

Product	Ti-Ni shape-memory wire	Color	Light
Size	Dia: 0.05mm-6mm	Manufacturing Process	Finishing
international standard	ASTM F2063-2012	Surface	Polished
Domestic standards	GB24627-2009	Density	$6.5g/cm^3$

Product	Ti-Ni shape-memory board	Color	Light
Size	Ply: 0.08mm-10mm	Manufacturing Process	Finishing
international standard	ASTM F2063-2012	Surface	Polished
Domestic standards	GB24627-2009	Density	$6.5g/cm^3$
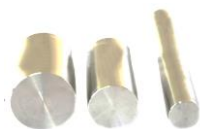
Product	Ti-Ni shape-memory stick	Color	Light
Size	Dia: 6mm-L	Manufacturing Process	Finishing
international standard	ASTM F2063-2012	Surface	Polished
Domestic standards	GB24627-2009	Density	$6.5g/cm^3$

Product	Ti-Ni shape-memory tube	Color	Light
Size	OD:0.70mm-6.00mm WT:0.08mm-2mm	Manufacturing Process	Finishing
international standard	ASTM F2063-2012	Surface	Polished
Domestic standards	GB24627-2009	Density	$6.5g/cm^3$

Table 13, Types of Nitinol [55]

Flexinol

Flexinol (muscle wire) which is a trade name for shape memory alloy wire, is the linear actuator made of Nickel and Titanium. These types of wires with very small diameters can be contracted around 5% of their length in higher temperature and can be easily stretched out again as they cool back to room temperature. The wire can be heated by solar radiation, ambient temperature or electricity.

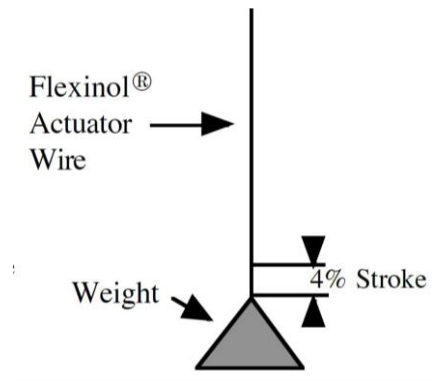
Figure 47, Flexinol wire [56] *Figure 48, Dead weight Bias [56]*

"The movement occurs through an internal "solid state" restructuring in the material that is silent, smooth, and powerful." [56] Depends on the diameter of the wire, it can have a considerable pull force in heating, while it needs one-third of the pull force as a cooling deformation to come back to its original length in cooling. As you can see in Table 14, the Heating pull force is based on 25,000 psi (172 MPa) and the cooling deformation force is based on 10,000 psi (70 MPa).

Diameter Size inches (mm)	Resistance ohms/inch (ohms/meter)	Pull Force* pounds (grams)	Cooling Deformation Force* pounds (grams)	Approximate** Current for 1 Second Contraction (mA)	Cooling Time 158°F, 70°C "LT" Wire *** (seconds)	Cooling Time 194°F, 90°C "HT" Wire *** (seconds)
0.001 (0.025)	36.2 (1425)	0.02 (8.9)	0.008 (3.6)	45	0.18	0.15
0.0015 (0.038)	22.6 (890)	0.04 (20)	0.016 (8)	55	0.24	0.20
0.002 (0.050)	12.7 (500)	0.08 (36)	0.032 (14)	85	0.4	0.3
0.003 (0.076)	5.9 (232)	0.18 (80)	0.07 (32)	150	0.8	0.7
0.004 (0.10)	3.2 (126)	0.31 (143)	0.12 (57)	200	1.1	0.9
0.005, (0.13)	1.9 (75)	0.49 (223)	0.20 (89)	320	1.6	1.4
0.006 (0.15)	1.4 (55)	0.71 (321)	0.28 (128)	410	2.0	1.7
0.008 (0.20)	0.74 (29)	1.26 (570)	0.50 (228)	660	3.2	2.7
0.010 (0.25)	0.47 (18.5)	1.96 (891)	0.78 (356)	1050	5.4	4.5
0.012 (0.31)	0.31 (12.2)	2.83 (1280)	1.13 (512)	1500	8.1	6.8
0.015 (0.38)	0.21 (8.3)	4.42 (2004)	1.77 (802)	2250	10.5	8.8
0.020 (0.51)	0.11 (4.3)	7.85 (3560)	3.14 (1424)	4000	16.8	14.0

Table 14,Flexinol Types [56]

2.4.5 Self-Change Humidity- Wood

Wood is a traditional material with the properties of hygroscopicity and anisotropy, which convert wood into a humidity reactive material. "Wood is a cellular structure and always seeks to reach equilibrium moisture, thus continuously responding to changes in the relative humidity by adjusting the bound water content, resulting in constant dimensional movement." [57]

One example is Conifer cones which have a repetitive opening and closing cycles as the humidity responsiveness. Conifer cones are biological examples of humidity reactive systems with responsive capacity in the structure of the material itself. [57]
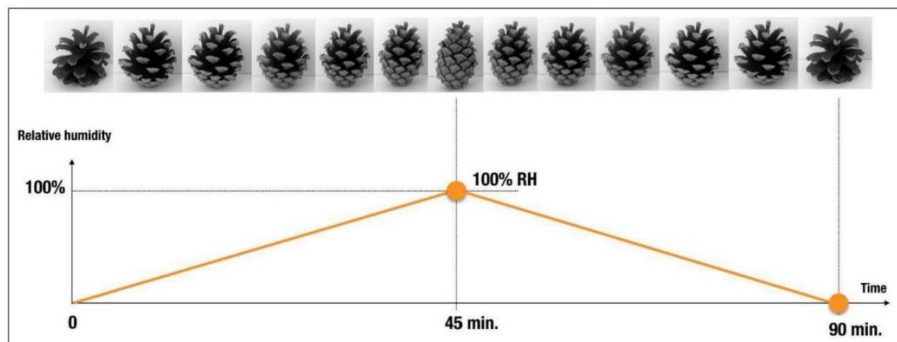

Figure 49, opening and closing movements in conifer cones due to humidity level changes [57]

HydroSkin Pavilion, by the Institute for Computational Design (ICD), is a climate responsive architecture which is based on hygroscopic properties of wood in relation to moisture content. In other words, it relies on bending thin planar plywood sheets which are responsive to relative humidity changes within a range from 30% to 90% (equals the humidity range from bright sunny to rainy weather in a moderate climate). Thin layers of plywood develop a meter sensitive architectural skin that opens and closes in response to climate changes with no need for any technical equipment or a supply of external energy. [58]
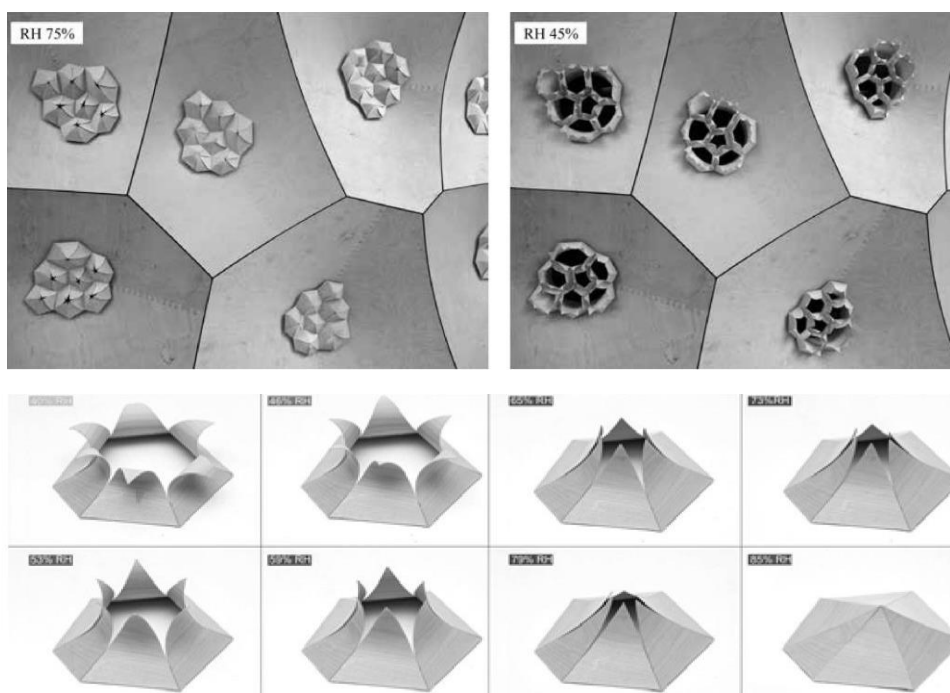

Figure 50, use of wood's active bending behavior and hygroscopic actuation of the material in HydroSkin Pavilion [58]

Wood could be used as an active material by attaching to the glass in a breathing façade and bend the thin glass by its movement related to change in humidity. But, complex production technique prevents using wood as an active actuator in this project. In addition, the small thickness of plywood is another obstacle for using it as an actuator because it could be broken or damaged very easily while it is applied to move the glass.

2.4.6 External input Gas- Pneumatic Material

The inflatable material could be used either as a special connection to move the glass or a strip which is attached to the panel to change the form.

2.4.6.1 Soft pneumatic Actuator

Soft robotic devices are obtaining high popularity because of their customization compliance, strength, flexibility and ease of fabrication compared to the traditional actuators. These types of actuator mainly contain chambers made by a highly compliant elastomer, such as silicone rubber, which results in a large deformation when a pressure is applied to the chamber. By customizable fabrication such as molding, the form of the actuator and then the resulting motion can be sewed to the requirements of a special application. "If the comparatively slow response time, which can be in the order of seconds to one minute, of soft pneumatic actuators is acceptable, then their low weight, and resulting high power-to-volume ratio, makes them a viable alternative to conventional actuators." Table 15 indicates pros and cons of using soft pneumatic actuator in a façade system. [59]

+		−	
	Good thermal stability		Relatively high cost
	The constancy of properties over a wide temperature range (e.g. −100 to 250°C)		Some grades have poor hydrocarbon, oil and solvent resistance
	Excellent resistance to oxygen, ozone, and sunlight, water, acids		complex manufacturing processes limit the complexity of robotic geometry and design freedom
	Resistance to damage		Time-consuming manufacturing
	Low chemical reactivity		Large compressors, valves, and tubing all →larger mass that must be carried by the structure
	Low toxicity		Slow response time
	Different types of movement with one actuator due to the number of chambers		Large robots: -Slow locomotion speed due to the flow rate of air into the actuators - Higher weight → -Larger numbers of robots Or -Smaller glass pane
	Good electrical insulation		

Table 15, Advantages and disadvantages of soft pneumatic actuators

This type of actuator has been used in creating "The Adaptive Solar Facade (ASF)" in ETH Zurich. ASF is an architectural facade composed of photovoltaic (PV) elements, which act simultaneously as a conduction for natural lighting and shading, as well as solar power generation. In this case, the soft

pneumatic actuators contain three inflatable chambers and are capable of orienting a PV cell in two degrees of freedom. This is a principal component for maximum power production of the ASF. [60]
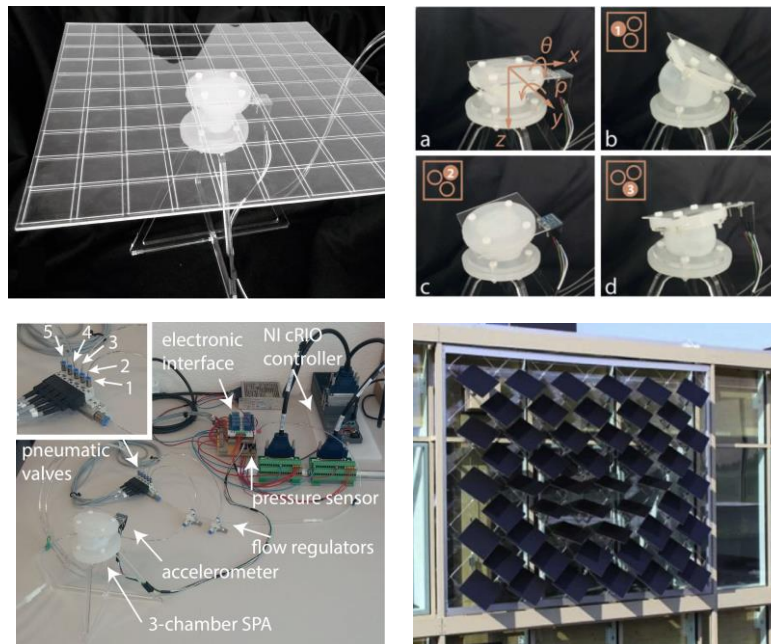

Figure 51, ASF soft pneumatic actuator [59] [60]

2.4.7 External input Electricity- Electroactive Polymer (EPC)

Electroactive polymers or EAPs are polymers that exhibit a change in their volume when subjected to an electrical current, while their expansion and contraction are based on the electrical impulses. A common example of electroactive polymers (EAP) is dielectric elastomers composed of a layer of either acrylic or silicon, coated with conductive graphite on each side. The arising electric field causes a slimming in thickness and an enlargement of the area of the membrane due to condensation of the polymer layer. The efficiency between inputted electric energy and the output in mechanical energy is around 70 %. Activating EAPs needs a very high voltage more than 1KV, and these types of polymers work in dry condition. [61]
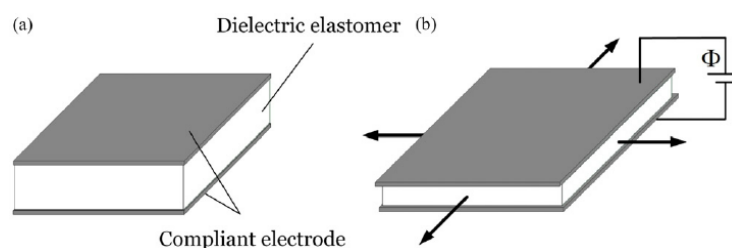

Figure 52, Principal of dielectric elastomer [62]

Decker Yeadon used this effect to create a solar shading system where a pattern of dielectric elastomers between window panes provide for shade by unfolding the dielectric elastomers.
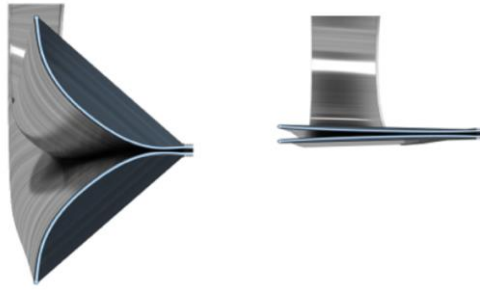
Figure 53, Decker Yeadon EAP solar shading [61]

2.4.7.1 Ionic polymers (IPMC)

Ionic polymers metal composites (IPMC) is another type of electroactive polymers. As an electric current is applied to IPCM, it curves instead of a change in the size of the polymer. In contrast to Electroactive polymers, IPMCs' deforming can be achieved at a very low voltage, less than 5V. IPMC is composed of two electrodes made out of a highly conductive metal and an ionomer polymer between these two layers.
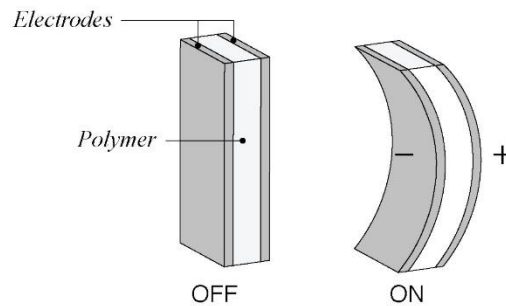

Figure 54, Principal of IPCM [62]

IPMC is a very strong electroactive polymer which is referred to as an artificial muscle; while in some cases it has the capacity to lift 20 times its own weight. It is operated in wet condition as an electrolyte is required. It should be considered that the electrochemical reactions for IPCM'S actuation might shorten its lifetime and lengthen the response time. [61]

2.4.7.2 Comparison of EPC and IPCM

Table 16 indicates the advantage and disadvantage of each type of polymer. Although EPC needs a higher voltage for operating, its larger actuation force and operation condition make it more suitable than IPCM in this case.

EAP Type	Pros and Cons		Applications
Electronic EAP	**+**		

☑	• Rapid response within milliseconds
	• Can hold strain under DC activation
	• Large actuation forces
	• High mechanical energy density
	• Long operation time
			• Actuators
			  ○ Haptic feedback for portable consumer electronics
			  ○ Over ear headphones
			• Sensors (disposable ones, pressure, percolation)
			• Energy harvesting and generation (wave energy)

	-		
	• High voltage requirements (~100MV/m) – recent R&D ~20MW/m in ferroelectric EAP • No effect of voltage polarity		
Ionic EAP	**+**		
☒	• Bi-directional actuation depending on voltage polarity • Low voltage requirements (1-5V) • Bi-stability (in some)		• Catheters • Automotive devices • Prosthetic devices • Active noise and vibration • Reduction materials • Peristaltic pumps
	-		
	• Must be operated in wet state, electrolyte required • Encapsulation/barrier layer required • Low electrochemical coupling efficiency • Do not hold strain under DC voltage • Slow response (fraction of a second) • Relatively low actuation force (bending EAPs) • Electrolysis in aqueous systems at >1.23V		

Table 16, pros and cons of IPCM and EPC

2.4.7.3 EPC feasibility

Table 17 compares SMA and EPC performances and properties. The SMA properties are based on its activation temperature and not with the use of electricity. This is the reason for lower reaction speed of SMA compared to EPC. According to this table, although the actuation strain of EPC is higher while it has a lower density, its actuation force on the same size glass pane is considerably lower (700 times less) than SMA. The low actuation force of EPC compare to SMA prevents conducting more investigation on this type of material for this study.

Property	EAP	SMA
Actuation strain	>10%	<8% short fatigue life
Force (MPa)	0.1 – 3	about 700
Reaction speed	μsec to sec	sec to min
Density	1- 2.5 g/cc	5 - 6 g/cc
Drive voltage	2-7V/ 10-100V/μm	-
Fracture toughness	Low	High

Table 17, EAP vs. SMA [61]

2.4.8 External input Electricity- Chain or Linear Actuator

One of the easiest and cheapest methods to curve the thin glass in a breathing façade is using chain or linear electric window openers.

Linear Actuator   Chain Actuator

Figure 55, Linear vs. Chain actuator [63]

Table 18 compares Chain and linear actuators. According to the table, the linear actuator has much higher actuation force which is considered a key role in adapting the glass skin. So, for more analysis, linear actuator has been selected.

Properties	Chain actuator	Linear actuator
Push/Pull force	250N	600 N- 1000 N- 1500 N
Sandblast oxidative surface treatment	No	Yes
Low noise optional	No	Yes
Waterproof and dustproof	No	Yes
Max current	1.0 A	1.5- 1.5- 2.5 A
Working Temperature	-20 ~ +65	-20 ~ +65

Table 18, Linear vs. Chain actuator [63]

2.4.9 Self-Change Temperature- Wax Actuator

The last type of actuators in this study is Wax actuators with phase change performance behavior. They made of waxes or fluids in a sealed container which can allow large volume expansions or contractions by increasing temperature. Wax actuators are smart and their performance relies on the expansion of a fluid material resulting in a deformation without using any external input. These types of actuator are very similar to the electric linear actuator in attachment and curving the glass frame. [5]

Figure 56, auto vent greenhouse window openers [64]

One of the common applications for this types of actuators is in greenhouses. They act as an automatic roof vent openers while it provides adequate ventilation for the greenhouses. This metal piston contains a mineral wax are attached to the window frames and allow them to open and close automatically. They mainly function in the warmer months when temperatures are high inside and outside the greenhouse. Some types of super unit wax actuator are guaranteed to lift a total vent weight of 31 kg. In addition, their opening temperature range **is** adjustable between 15°C to 25°C while the Maximum opening could be achieved at around 50°C. [64]

The main disadvantage of this type of actuator which prevents further study in this report is its very low reaction time due to the sealed container and the thermal conductivity of the material. In addition, it is not possible to apply external input such as electricity in order to accelerate the process or opening the windows for other reason except the high temperature

3 Design Exploration

In this chapter, different design options on thin glass are presented with the use of more suitable actuators mentioned in the previous chapter. The designs and ideas are based on the available thin glass for mock-up in size of 71mm*36mm in three different thickness of 2mm, 1.1mm and 0.55 mm.

3.1 Bimetal

3.1.1 Glass Deformation by use of BI Metal

In this cases, it is assumed that two strips of bimetal are attached to the edges of the glass. The glass deformation by bimetal in simple and cantilever type of support are like figures 57 and 58.
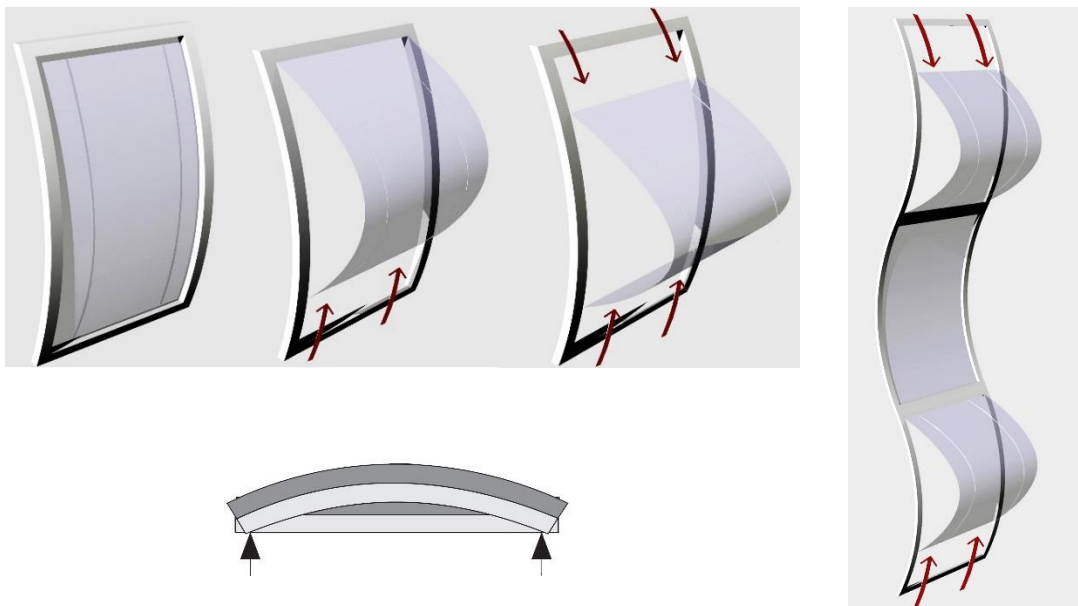

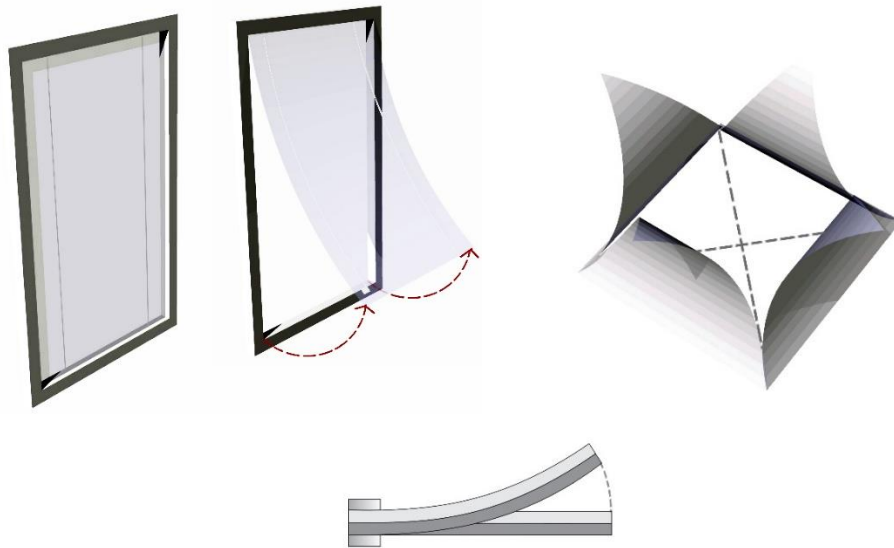*Figure 57, Simple support glass deformation by the bimetal*

Figure 58, Cantilever support glass deformation by the bimetal

3.2 Shape memory alloy

3.2.1 One way SMA spring

In this case, the one way SMA spring could be placed in the frame of the window. At low temperature, the spring is fully stretched due to the weight of the glass. While at a High temperature or by applying a small electric current, the spring will contract and return to the austenite phase and carry the load. A normal Nitinol spring could easily carry 8.5 kg weight.
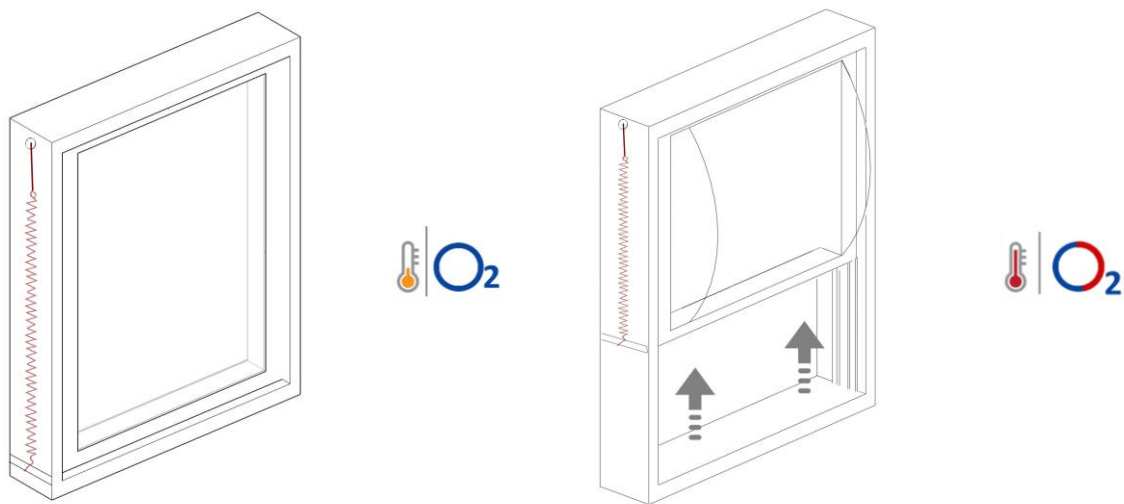

Figure 59, one way shape memory alloy spring

3.2.2 Two way Nitinol shape memory alloy

3.2.2.1 Single Glazing Concept

Nitinol springs as a two way shape memory alloy could be attached to the window while it is not necessary to carry the load of the panel to get deformed. Single glazing windows are assumed for this situation.
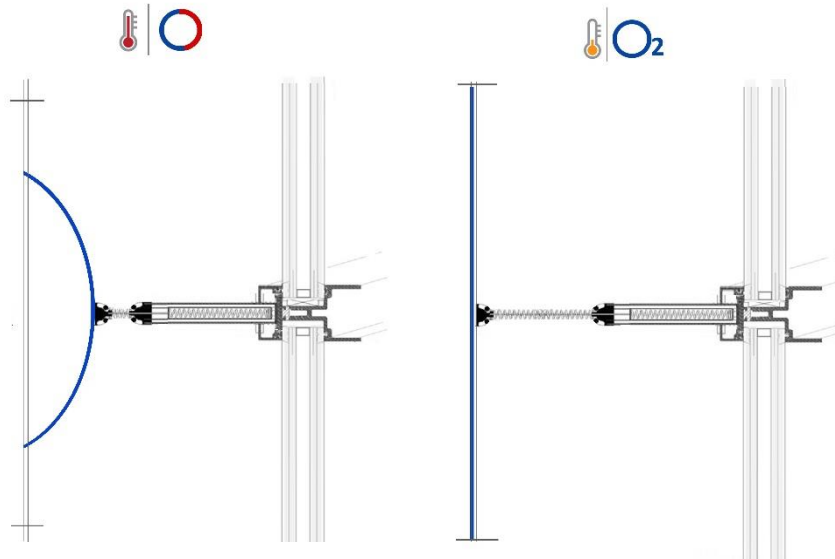
41

Figure 60, Nitinol two way shape memory alloy spring

It is also possible to use two-way shape memory Nitinol tube or wire which is attached to the frame of the glass window, and by changing the temperature, it could get two different shapes.
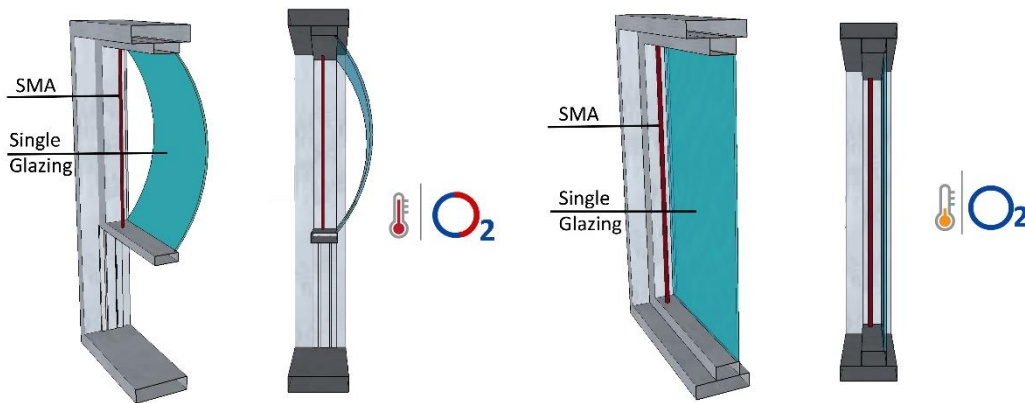

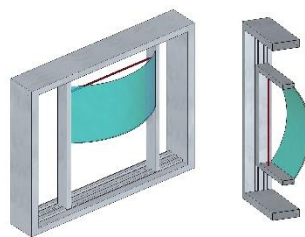*Figure 61, Nitinol two way shape memory alloy wire or tube*

Figure 62, Other possibilities of opening by Nitinol two way shape memory alloy wire or tube

3.2.2.2 Double Glazing Concept

Two-way shape memory Nitinol wire could also place between the gap of two layers of thin glass in a double glazing panel. Nitinol SMA within the interlayer of double ultra-thin glazing panel could not only make the adaptiveness effect in a breathing façade but also has structural Improvement for the thin glass panel. As a result, it makes the possibility to have larger glass pane due to controlling and minimizing the maximum deformations in the glass even in normal temperature, while by Increasing temperature or electrical current: Enhance Stiffness and resistance in panels subjected to lateral

forces such as wind. The Consideration Criteria, in this case, is the thickness of SMA, shape of SMA and number of SMA.
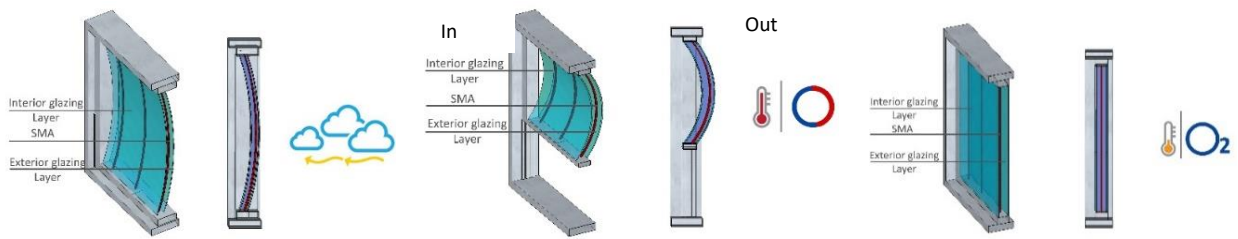

Figure 63, Nitinol two way shape memory alloy wire effect in temperature and wind

Several shapes could be achieved by heating the SMA Nitinol. The other possibility is twisting the thin glass while Nitinol wires are placed between two glazing and attached to the frame.
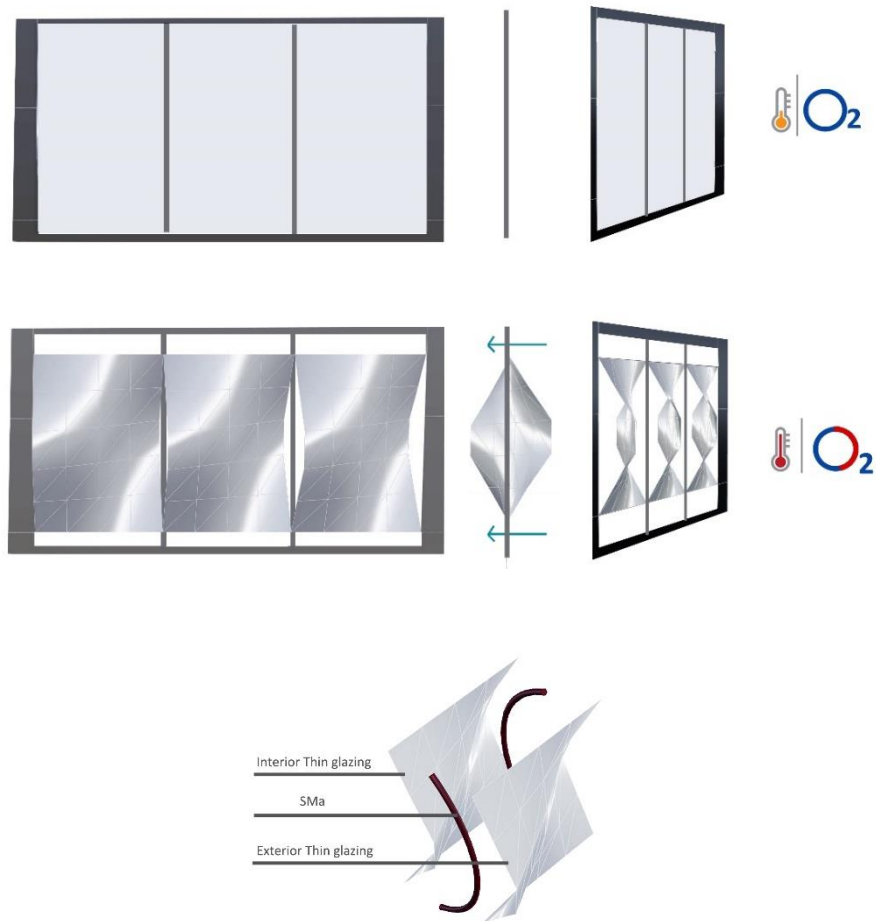

Figure 64, Twisting the glass by Nitinol two way shape memory alloy wire

3.2.3 Flexinol

Flexinol can place behind the glass pane, between two glazing, or in the frame. The only difference is that it has the determined linear motion as an actuator and there is no need to train it before using.
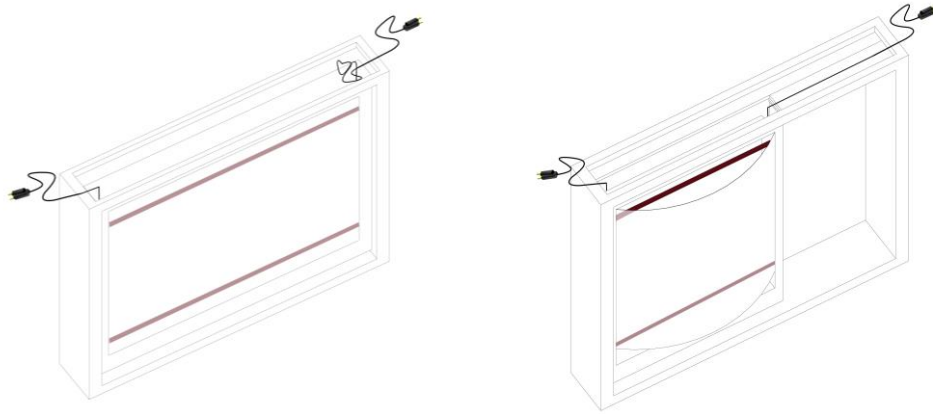
Figure 65, bending the glass by placing flexible behind it

3.3 Soft pneumatic actuator

A similar type of soft robotic actuator in ASF project with three chambers could attach in the middle of thin glass pane as a special connection to bend the glass and create breathing façade. Programmable logic controllers could adjust the indoor air quality and send the order to the pneumatic actuator system for opening or closing the windows.
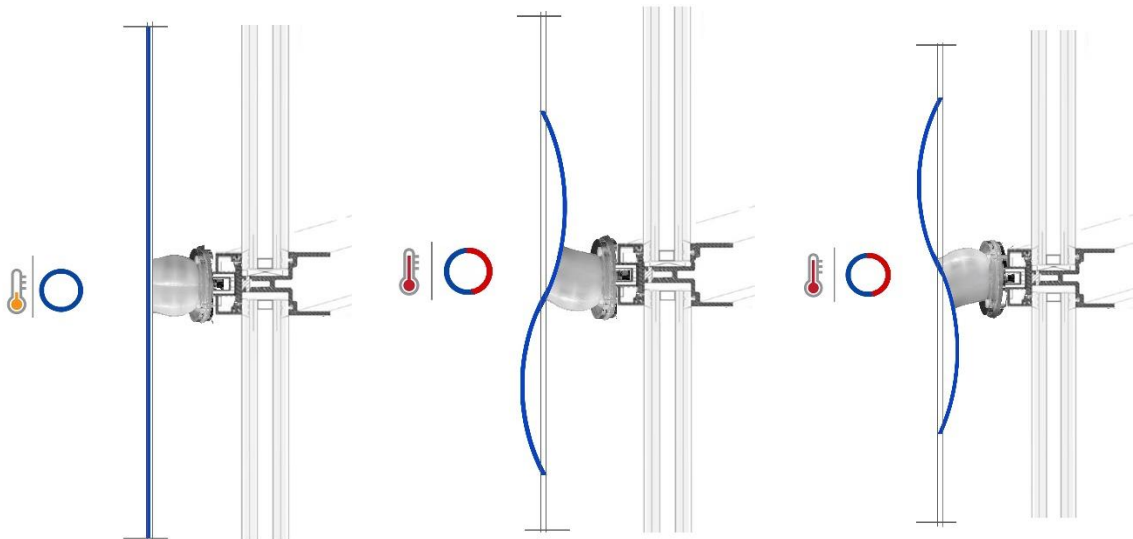

Figure 66, a soft robotic actuator as a three chamber connection

As it was mentioned before, the pneumatic actuator could be also attached to the glass as a thin plane. Figure 67 clearly shows this type of actuator and its effect on a thin glass. The consequence is same as attaching a closed plastic plane to a paper and inflating it to deform the sheet.
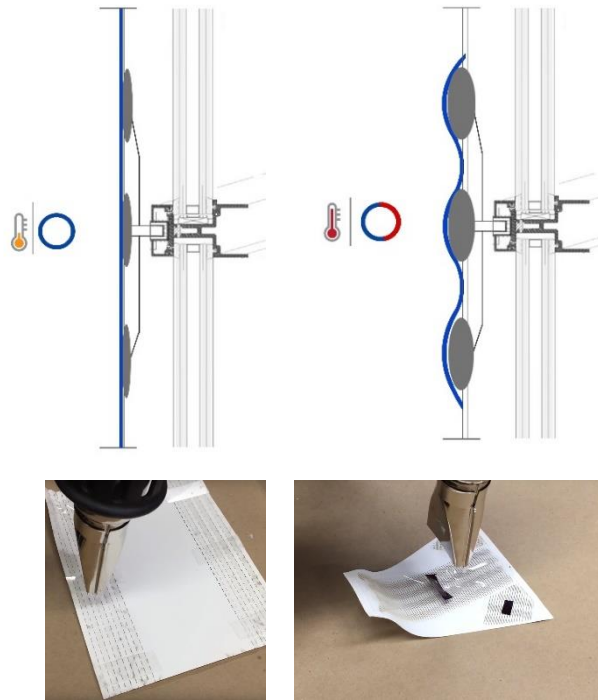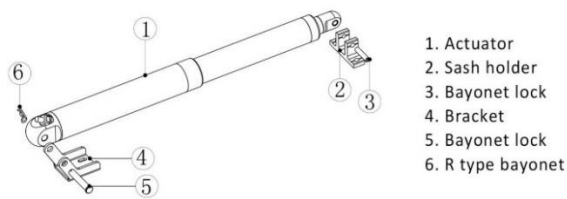
Figure 67, Pneumatic plane and its effect on glass [65]

3.4 Linear Actuator

"LinkAyle" is a famous electric linear window opener with following specifications. [63]

1. Actuator
2. Sash holder
3. Bayonet lock
4. Bracket
5. Bayonet lock
6. R type bayonet

Specification	Unit	Technical Data
Working Voltage	V	DC24
Max. Current	A	1.5/1.5/2.5
Push/Pull Force	N	600/1000/1500
Travel Distance	mm	50 ～ 600
Travel Speed	mm/s	8 / 4 / 5
Protection Class	IP	67
Working Temperature	℃	-20～+65
Dimension	mm	Φ38*352(372)～902(922)

Figure 68, Linear actuator elements [63]   *Table 19, Linear actuator specification [63]*

For the application in berating façade, the electric linear actuator could be attached to the window frame and with use of air quality sensors, the actuators could open and curve the thin glass when it is needed. The figure shows two different options for attaching the linear actuators while they could create the same curvature in the glass.
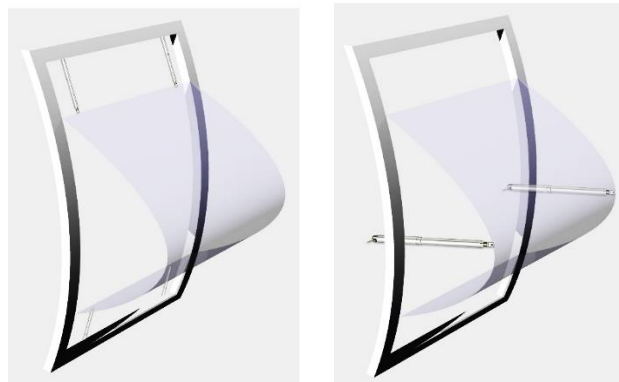

Figure 69, Different types of attachments for the electric linear actuator

3.5 Selected Actuator system

Table 20 briefly compares all types of actuators which are studied in this report. As it was before, wood could not be a suitable actuator for creating breathing façade due to it complex production technique and its fragility. In addition, both wood and wax actuator have very low reaction speed while there is no possibility to use external input such as electricity to accelerate the process. EAP actuators could not also be considered as a promising type of actuator because of their very low actuation force compare to SMA actuators. On the other hand, electro linear window openers are one of the easiest and cheapest methods to curve the glass in a breathing façade, but they are not considered as a new technology for creating an adaptive façade, and there is no challenge for the application of them in thin glass window panels. Furthermore, they do not have a high potential for creating various shapes and curvatures in the adaptive thin glass façade.

Pneumatic actuators without doubts could be assumed as one of the most suitable technology for adapting thin glass in a breathing skin. Its high strength, flexibility, ease of fabrication and low weight compared to the other analyzed actuators make them an appropriate alternative for bending the thin glass and opening the window. The main disadvantage of them is that large area on each floor should be considered for placing a large pressurized air tank for inflating the pneumatic actuators. In addition, their high cost is another negative point for this type of actuator.

One of the main challenges in using ultra-thin glass for façade is the impact of wind on such a thin material and restraining its resulted deflection on a large glass pane. The only reason for assuming SMA as the first option same as pneumatic actuators is its structural properties. As it was mentioned before, placing SMA behind the glass or between two glass panes could improve the structural properties of the glass by reinforcing it, and as a result, even when there is no current, the glass has more stability in wind. This property could results in having larger and thinner glass panes whit no deflection in wind pressure. SMA has lots of other advantages such as strength and resistance but its density is much higher than pneumatic actuators and the suitability of its actuation force and performance is in doubt. Also, there are not enough research studies on the properties of this material which makes it really difficult to apply it as a façade actuator for this project.

Bi-metal could also consider as the next option after SMA and Pneumatic actuators for adapting the thin glass in a breathing façade. Its cost and density is much higher than the other two options and in addition, it does not have high corrosion resistance, the important factor for façade application. Same as SMA, since it is a very new material, there are not many research studies conducted on this material.

	BIMetal +Electericity	SMA +Electericity	Wax	PLywood	Electro Linear	EAP	Pneumatic
Density (g/cm^3)	7.7	6.45	0.92	0.79	0.70	1.75	0.25+0.001
Cost	Very High	Medium	Low	Low	Very Low	High	Very High
Production Technique	Difficult	Difficult	Easy	Extremely Difficult	Very Easy	Difficult	Difficult
Structural application	✗	✓	✗	✗	✗	✗	✗
Energy Storage	Batteries	Batteries	-	-	Batteries	Batteries	Large Air Tank
Force	High	High	High	Very Low	High	Low	Very High
Reaction Speed	Fast	Fast	Very Slow	Slow	Fast	Fast	Slow
Strength	High	High	High	Low	High	Very Low	High
Smart	✓	✓	✓	✓	✗	✗	✗
Variety in adaptiveness	High	Very High	Very Low	Low	Very Low	Low	High
Corrosion resistant	Low	High	High	High	High	High	High
Resilient	✓	✓	✓	✗	✓	✓	✓
Average Drive Volatge	3 V	2.5 V	-	-	24 V	>1kV	-
Possibility of external input	✓	✓	✗	✗	✓	✓	✓
New Technology	✓	✓	✗	✓	✗	✓	✓
Result	2	1	✗	✗	3	✗	1

Table 20, Actuator brief comparison

3.6 Possible Applications

3.6.1 Single skin facade

The panel could be considered as a single skin façade with double glazing layer. In this case, thinner glazing Layer (0.55mm each layer) and a Lamination Layer (PVB) could be applied to the frame. The thin glass which is used in this case could be smaller in thickness because of having two glass panes in one panel. The window becomes opened when the oxygen level is low or the temperature gets higher.
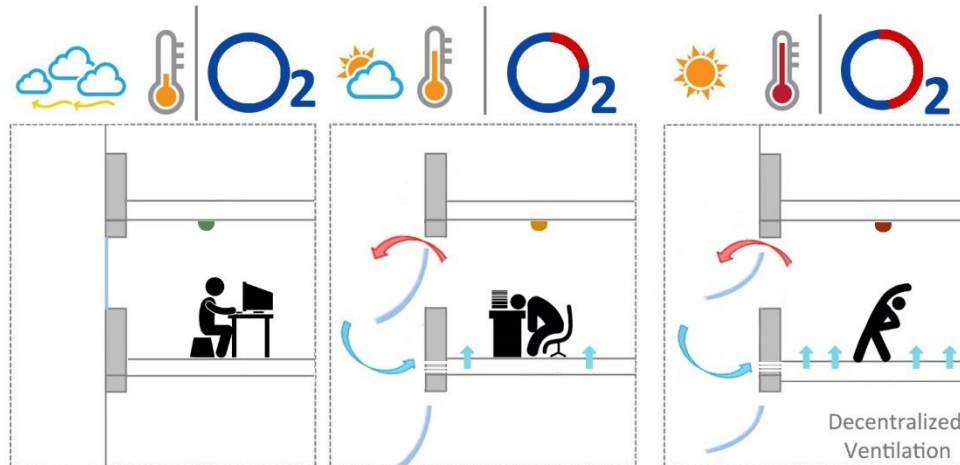

Figure 70, Single skin façade

Table 21 shows the requirement for single skin façade.

Requirements	
Thermal Insulation	☑
Stiffness for wind load	☑
Transparency	☑
Safety	☑
Natural Ventilation	☑
Airtightness	☑
Watertightness	☑
Acoustic Insulation	☑

Table 21, the requirement of single skin facade

3.6.2 Double skin façade (Outer skin)

The other possibility is placing the breathing panel on the outer layer of a double skin façade. Then the air quality in the cavity could be controlled and also by placing the opening of decentralized ventilation in the cavity, the indoor air quality of the building could be adjusted without opening the inner window. In this option, the outer layer is a single glazing with a higher thickness (1.1 mm) and Lamination Layer (PVB).
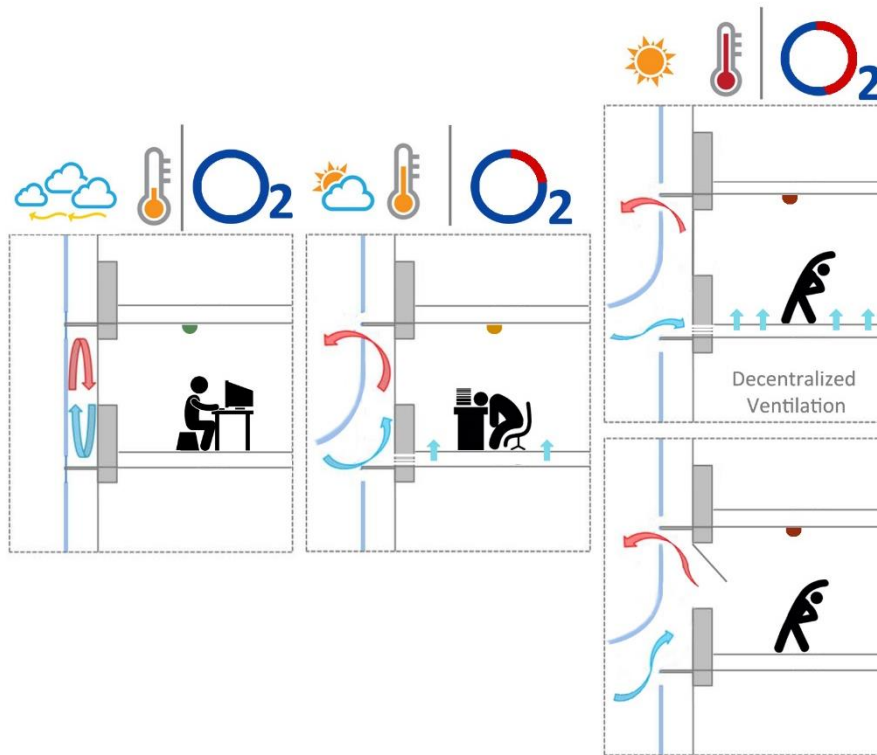
Figure 71, Double skin façade (Outer skin)

The requirements for the outer layer of double skin façade are brought in table 22.

Requirements	
Thermal Insulation	❌
Stiffness for wind load	☑
Transparency	☑
Safety	☑
Natural Ventilation	☑
Airtightness	❌
Watertightness	❌
Acoustic Insulation	❌

Table 22, Requirement of the outer layer of double skin façade (Outer layer)

3.6.3 Double skin façade (Inner skin)

The last option is placing the breathing façade as an inner layer in a double skin façade. In this case, the panel will be protected from the wind by the outer layer.
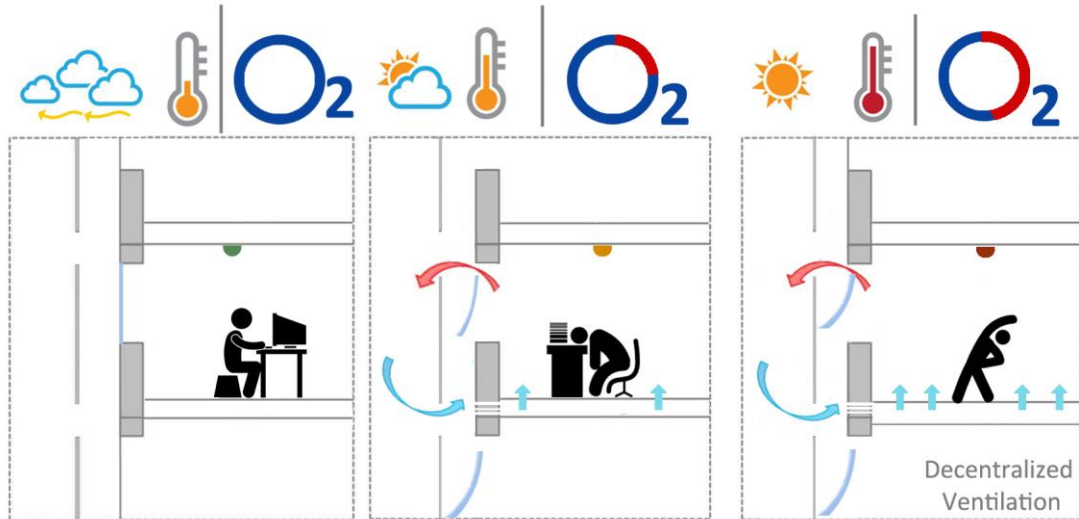
Figure 72, Double skin façade (Inner skin)

Requirements	
Thermal Insulation	☑
Stiffness for wind load	☒
Transparency	☑
Safety	☑
Natural Ventilation	☑
Airtightness	☑
Watertightness	☑
Acoustic Insulation	☑

Table 23, Requirement of the outer layer of double skin façade (Inner Layer)

3.6.4 Selected application

For initial analysis, option three has been chosen. Since the application of the SMA (selected actuator) in adaptive façade is completely new, there is no proof from the beginning which shows it can bend the thin glass easily. As a result, it is logical to first analyze its application in a frame which is protected from the wind in the beginning, in order to reduce the challenges in large and thin glass panes such as deflection by wind pressure and focus mostly on the possibility of using new technologies for creating breathing adaptive façade. In this case, as the first step, the panel is considered as an inner layer of a double skin façade, but at the end of the research study, the wind will be also considered as an extra option.

4 Material Analysis

This Chapter has a deeper view on the selected actuator system, Shape Memory Alloy in terms of materialization. The most suitable type of SMA will be chosen and defined with regards to its operation techniques and properties. Finally, a type of movement for the panel will be selected after drawing several sketches based on the linear motion of the wire which could bend the thin glass

4.1 SMA Selection

According to chapter two, shape memory, alloy actuators can be classified into three main types: one way SMA, two way SMA and Flexinol. Two way and one-way SMA can have a wide range of movements, while Flexinol can also have the linear motion. On the other hand, Flexinol needs no training because they have predetermined memory, but the other two types of wire need to be annealed and trained to get shaped. By considering all criteria, Flexinol has been chosen for further analysis. The predetermined motion that it has, could save time and energy in this project. Also, annealing the wires need special equipment such as a furnace to heat up the material to approximately 500°C.

4.1.1 Flexinol properties

Flexinol is considered promising actuators; if they are used in the right conditions, they can have the repeatable motion for tens of millions of cycles. "If higher stresses or strains are imposed, then the memory strain is likely to slowly decrease and good motion may be obtained for only hundreds or a few thousands of cycles. The permanent deformation that occurs in the wire during cycling is heavily a function of the stress imposed and the temperature under which the actuator wire is operating. Flexinol® wire has been specially processed to minimize this straining, but if the stress is too great or the temperature too high, some permanent strain will occur." [56]

According to Table 1424, the largest diameter of Flexinol has been selected in this project. This wire can easily pull 35N while it became heated. It should be considered that "higher-diameter wires have lower resistance and draw more power. Thus, they are more likely to overheat and lose its original contraction abilities. Wires that are 0.006" or smaller can be kept on constantly without fear of

overheating." [66] Based on this fact, the selected wire should be well insulated in the final case and analyzed carefully for risk of overheating.

Diameter Size inches (mm)	Resistance ohms/inch (ohms/meter)	Pull Force* pounds (grams)	Cooling Deformation Force* pounds (grams)	Approximate** Current for 1 Second Contraction (mA)	Cooling Time 158°F, 70°C "LT" Wire *** (seconds)	Cooling Time 194°F, 90°C "HT" Wire *** (seconds)
0.020 (0.51)	0.11 (4.3)	7.85 (3560)	3.14 (1424)	4000	16.8	14.0

Table 24, Selected Flexinol [56]

As it was mentioned before, Flexinol can be heated by ambient temperature, solar radiation or electricity. Depends on the application of the wire, the activation temperature is different. If the wire is supposed to be heated by the sun, it should be placed behind or between two glazing. While if it is going to be heated by electricity, it is better to be placed in the frame in order to be insulated better. Of course, there is another situation that the wire can work with both electricity and sun. In this case, the wire which is placed behind or between two glasses can be activated by solar radiation in sunny days, and by electricity as a backup option in cold and cloudy days.

In this case, the wires are considered to be heated only by electricity as the first step because by use of electricity the more accurate results can be achieved. In case of further analysis, the attained results from using electricity can be generalized to the solar radiation application.
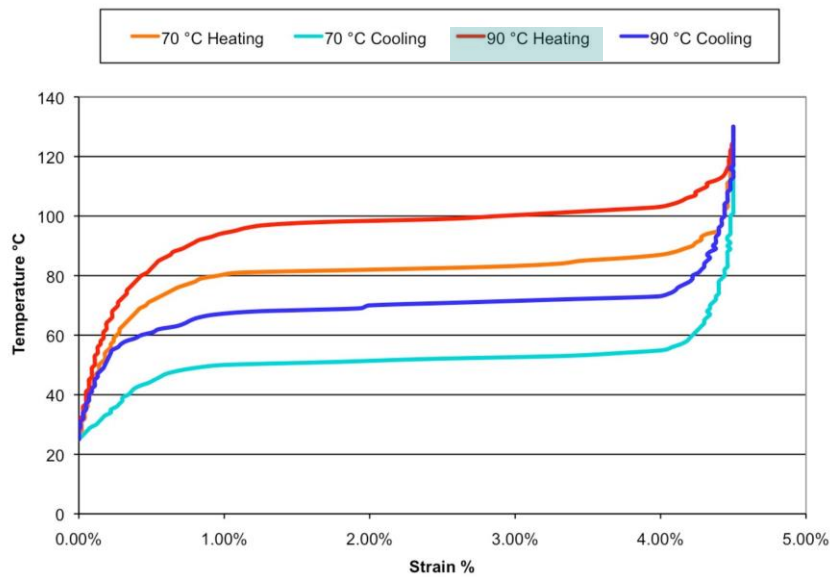

Figure 73, Typical Temperature vs. Strain Characteristics for Flexinol [56]

As it was mentioned before, higher diameter wires have longer off times; it means it takes longer for the wire to return to its original. Based on this fact and according to the chart 75, the selected Flexinol in order to be activated by electricity is 90°C heating. In order to cool the wire faster and reduce the chance of overheating, the highest activation temperature wire has been chosen. In this case, because of the higher difference between ambient and wire temperature, the Flexinol wires get cold faster.

4.1.2 Operation Criteria

There are several ways to avoid the risk of overheating. Running the wire through a small diameter rubber tubing is one of the ways to cool the wire faster. In fact, the tube insulates the wire as it heats, allowing faster heating and thus less time power is applied, and the rubber acts as a heat sink to help the wire cool faster.

Also, it should be considered that overheating the wire (with too much power, or with power for too long) is not the only case that damage the wires. Asking the wire to exert too much force, stretching it too much when applying the bias force, bending the wire beyond its bend radius can destroy the wire permanently.

4.2 Type of movements

In this stage, different types of linear motion of wire which could cause bending the glass and making an opening for fresh air has been considered. Figure 74 shows different types of movements of the glass which could happen by use of Flexinol and its linear motion.
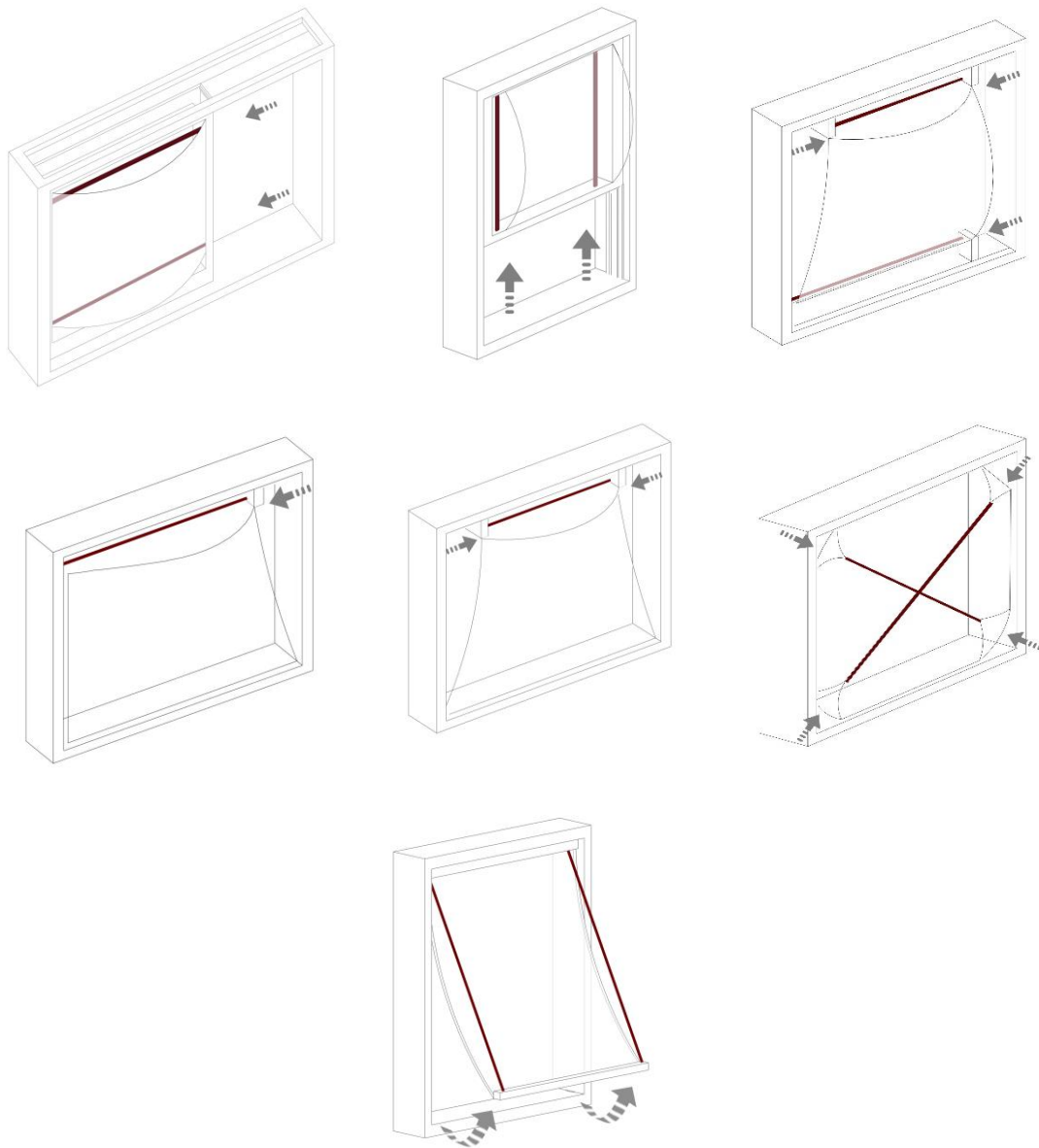
Figure 74, Types of movement by linear motion of Flexinol

There is also another option to bend the glass not only with use Flexinol wire but also with help of other types of actuators. Figure 75 and 76 display different possible movements of glass by use of combined actuator systems. In figure 75, the adaptiveness has been created by use of scissor actuator and Flexinol wire. In figure 76, the glass can be bent by contraction of Flexinol wire and movement of the telescopic tube.
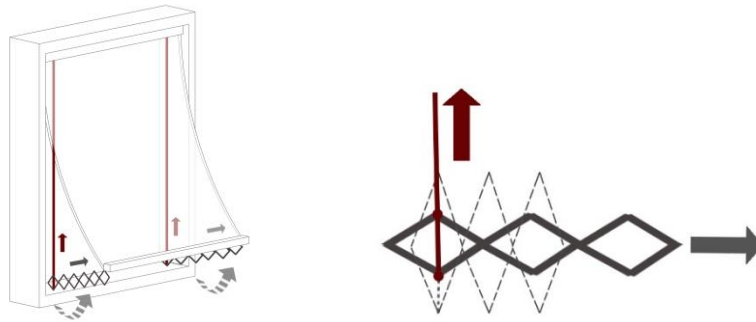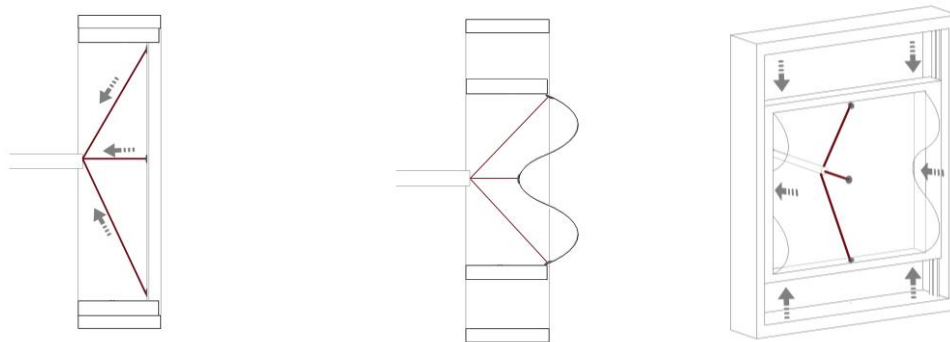

Figure 75, Combination of scissor actuator and Flexinol wire

Figure 76, Combination of telescopic Tube and Flexinol wire

4.2.1 Selected Movement

Due to the complexity of the system, the simplest type of movement has been selected in this step for further analysis. The panel can be placed horizontally or vertically.
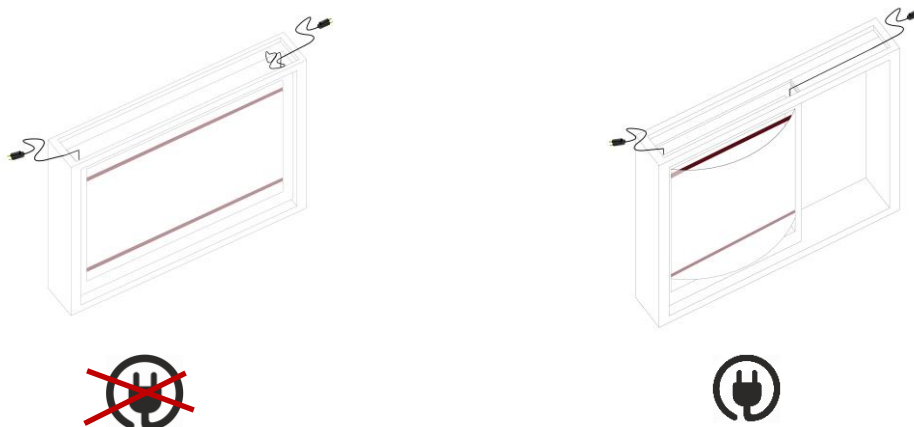
Figure 77, selected movement

4.3 Stroke

As it was mentioned before, the Flexinol wire can be contracted between 3-5% of its total length. But depends on the application of the wire, it is possible to convert this small stroke into movements over 100% of the wires' length. [56] Adjusting curvature idea, is one of the options to have the stroke of 110%. In this case, the wire is attached to a flexible surface such as thin glass, the surface and wire from one side get fixed while the other side can be moved by contraction of the wire. The wire can make a stroke of 110% by changing the curvature direction.
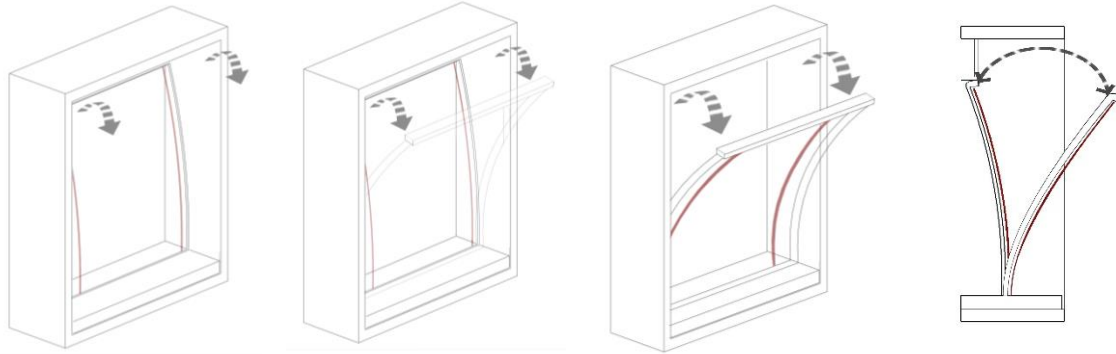
Figure 78, Adjusting curvature concept

The other possibility to have more stroke is using longer wire. The wire can pass through a ring while it is fixed from one side, to make the stroke of double or more.
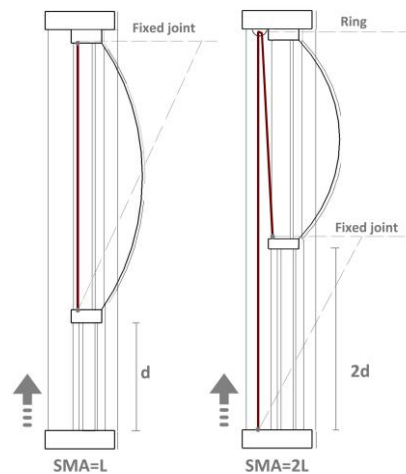
Figure 79, Double stroke

In figure 81, the size of the frame is same, while the length of the wire becomes double; as a result, the total contraction of the new wire will be twice.

Figure 80, briefly shows the effect of length of the wire in having a different stroke.
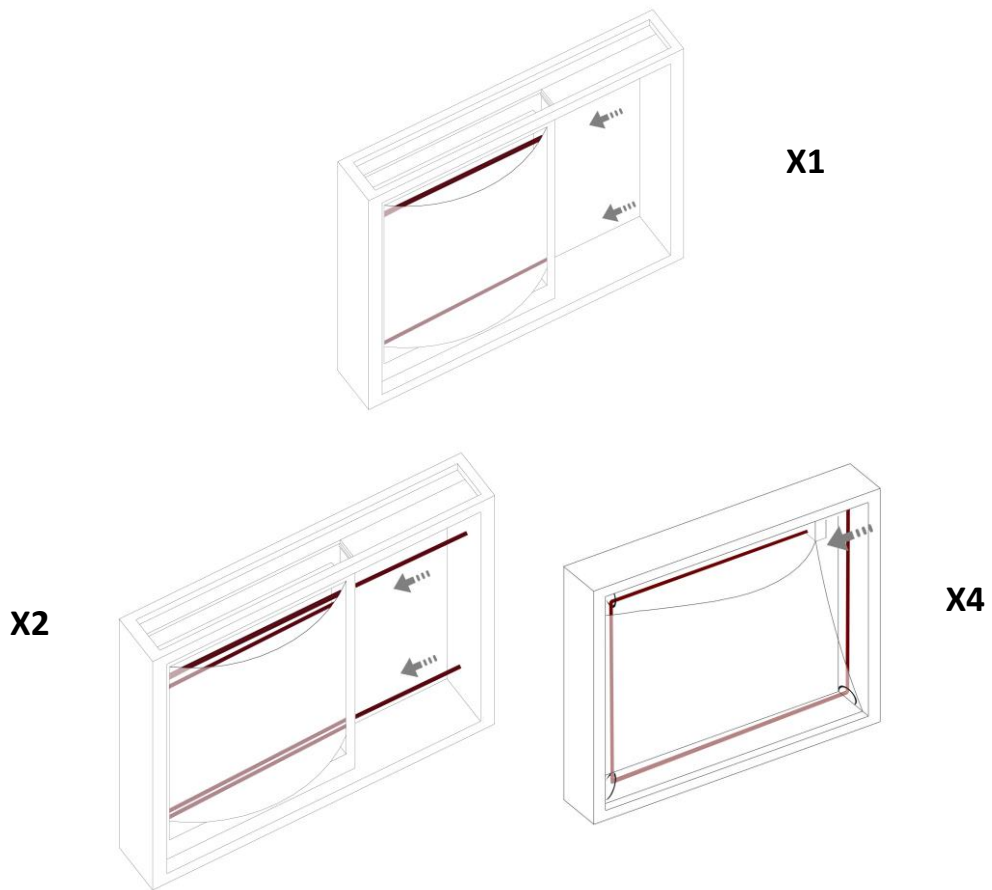
X1

X2

X4

Figure 80, Different types of stroke

5 Practical Feasibility

After narrowing the scope of the research and selecting the type of movement with muscle wire, there is the necessity of understanding the possibility of using Flexinol as an actuator to bend the thin glass and create breathing façade. For this reason, several computer FEM simulations were developed to simulate different scenarios. And then based on their results, several practical experiments have been done in order to prove the feasibility of the concept. At the end, two physical models have been made based on the same concept but different positions of SMA wires.

5.1 Structural Analysis

5.1.1 Thin Glass

In this step, the structural analysis on the thin glass in Abaqus has been done based on the available thin glass for mock-up in size of 710mm *360mm with different thickness of 0.55mm, 1.1mm, and 2mm.

Availability

Standard thicknesses	Standard tolerance	Typical max sheet size
0.5 mm	+/-0.05 mm	1245*3210 mm
0.7 mm		1350*3210 mm
0.9 mm		
1.1 mm		1480*3210 mm
1.3 mm		
1.6 mm	+/- 0.1 mm	1600*3210 mm

Figure 81, Available thin glass [21]

Also, It is also important to mention that the glass pane is not placed in the frame entirely flat, a small initial radius has been made to allow for the simulation to be made, to bend the glass in the physical model with lower required force, to guide the bending movement into the desired direction and to create extra stability in glass. The models included a displacement of 10 mm in the center for further simulations.
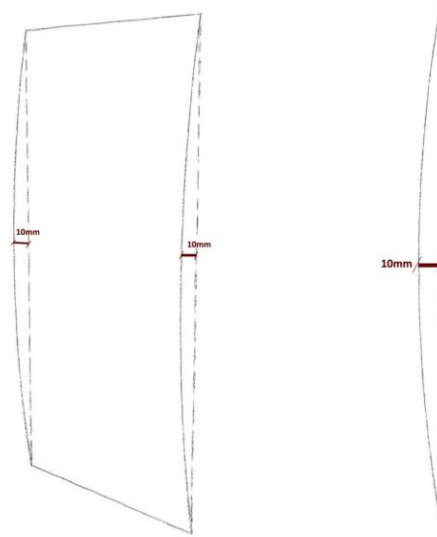

Figure 82, Initial bending of glass

5.1.2 FEM Analysis

The first step in developing models is done by modeling several structural analysis in Abaqus in order to clarify the feasibility of using Flexinol actuator for the thin glass to make the adaptive breathing building skin.

The simulations were first developed in the Karamba software, plug-in for Grasshopper; but the results were not satisfying. Karamba was not a proper structural engineering tool for non- linear analysis in the shell structures. As an alternative to Karamba, Abaqus software which is commonly used for crash simulation was selected mainly due to the reliability of the results.

5.1.2.1 Single Glass

5.1.2.1.1 Degrees of Freedom

In the first step, the aim is to compare the behavior of the panel according to the number of degrees of freedom of the supports by removing rotation. In the first case, the supports on both sides are free to rotate, while in the second one, one degree of freedom (rotation) is removed for the supports. In both cases, one line support along 360 mm edge is considered to be fixed, whereas the other one has freedom for translation in one direction (x-axis) on the other edge with the same length.
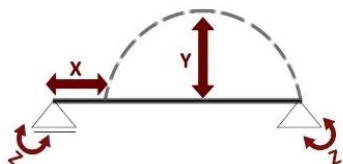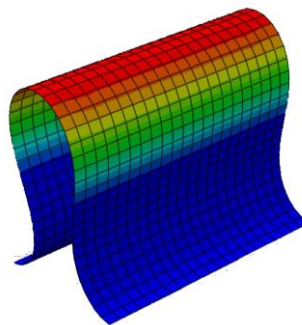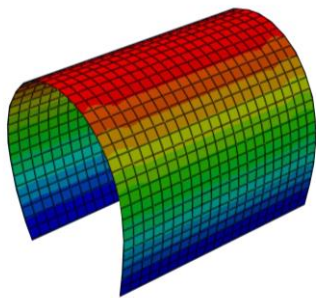
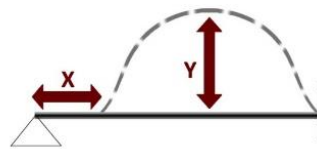*Figure 83, Case one with a degree of freedom for rotation*   *Figure 84, Case two without a degree of freedom for rotation*

For the geometry of both models, a 2D planer shell has been modeled in the size of 710mm* 360mm in three different thicknesses. Shell elements are used to model structural elements in which two dimensions are much greater than the third one. As a result, the change of the analyzed feature across this third direction can be neglected. The advantage of the use of shell elements compared to the solid elements is reducing the number of finite elements and solving the equation faster.

In the next step, the properties of thin glass as an isotropic material have been written according to the AGC catalog. [21] Approximate global size of 0.017 has been selected for the mesh size in a metric system as a maximum number of nodes in the student version of the software (Student edition is restricted to 1000 nodes).
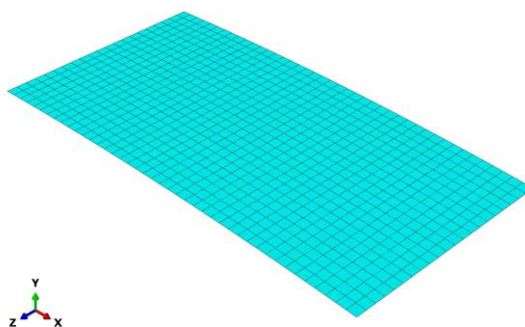

Figure 85, Global seeds

In the first case, the support along the 360mm edge is pinned (U1=U2=U3=0) and on the other side, U1 along X-axis can translate 160mm while U2=U3=0. Both supports can rotate freely.

In the second option, the supports are placed at the same location. They are assumed to be encastré (U1=U2=U3=UR1=UR2=UR3=0) on one side and have the translation of 160mm and U2=U3=UR1=UR2=UR3=0 on the other side.
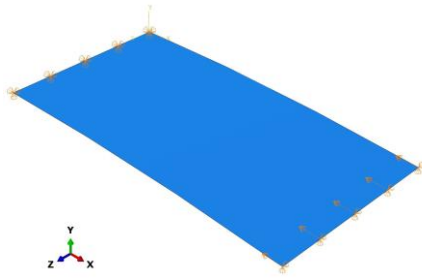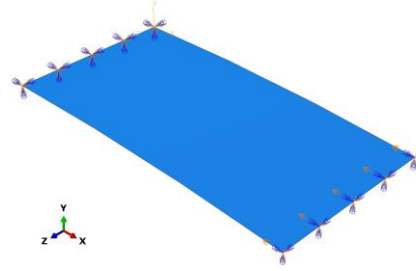
From the sum of the reaction forces in the X direction of 22 nodes on the edge with X translation in different time, it is possible to draw the chart of displacement to Force for each analysis.
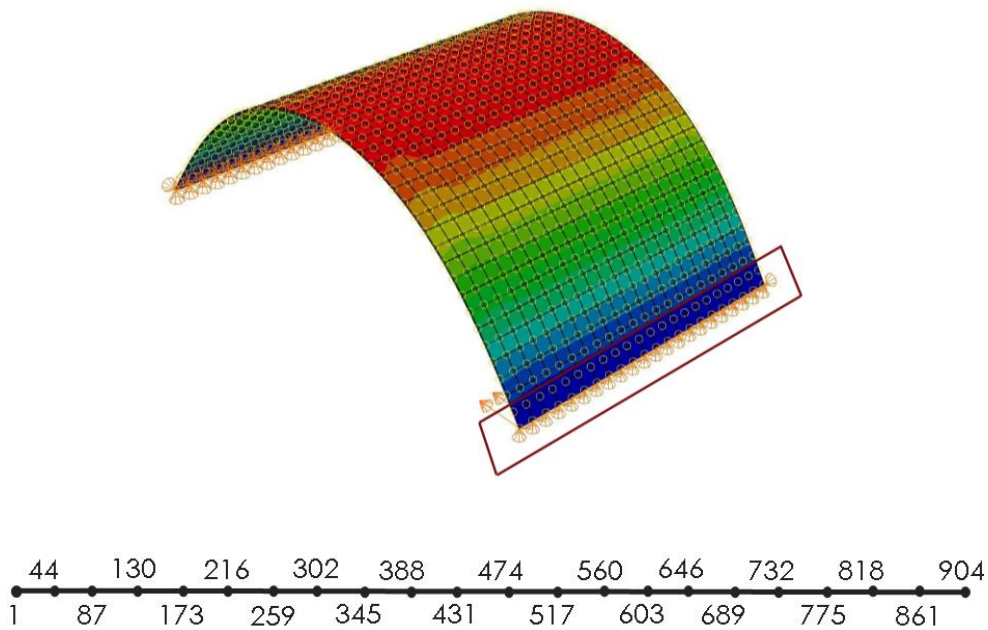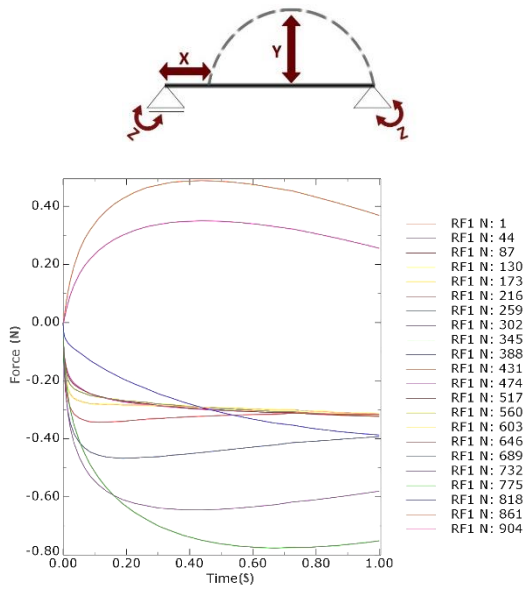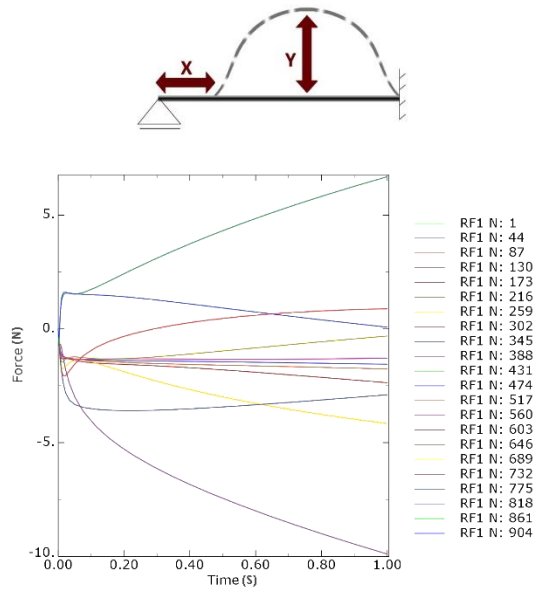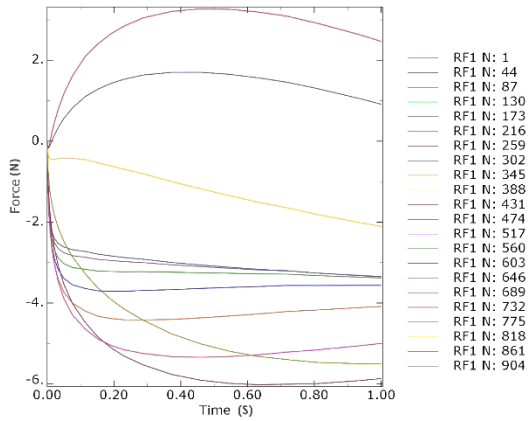

Figure 88, 22 considered nodes on the moving edge

Figure89 shows the reaction forces (RF1) of 22 nodes during the time the glass is moving in both situations.
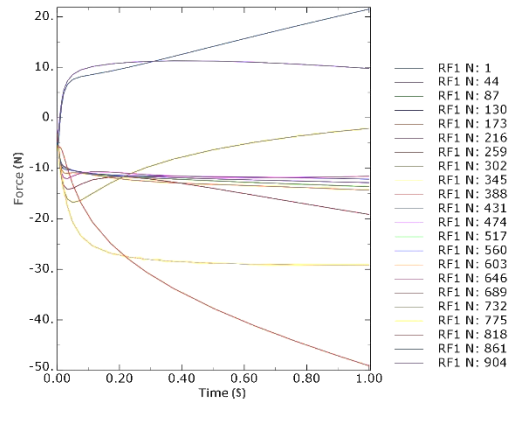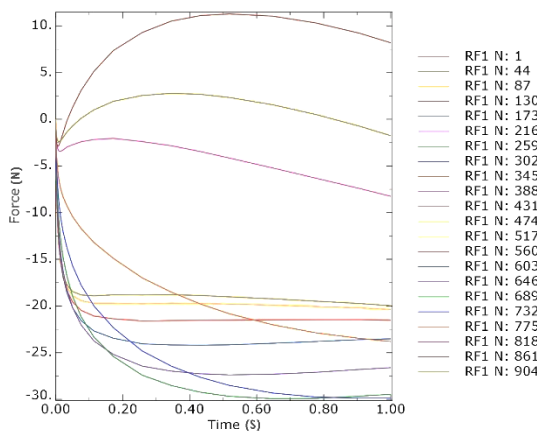
60

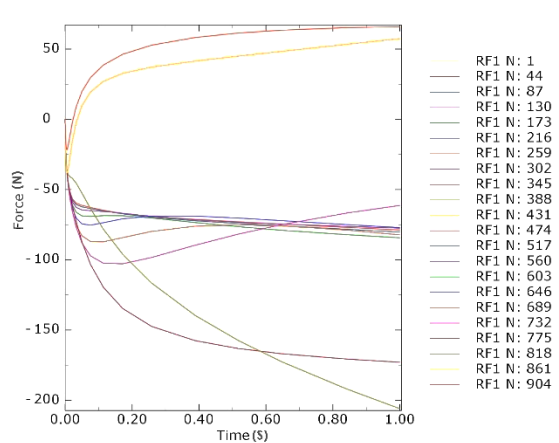Glass thickness:0.55mm — Glass thickness:0.55mm

Glass thickness:1.1mm — Glass thickness:1.1mm

Glass thickness:2mm — Glass thickness:2mm

Figure 89, Reaction forces of 22 nodes in 2 situations

In the charts below, the applied force needed to move the glass in the X direction is displayed in two different situations.
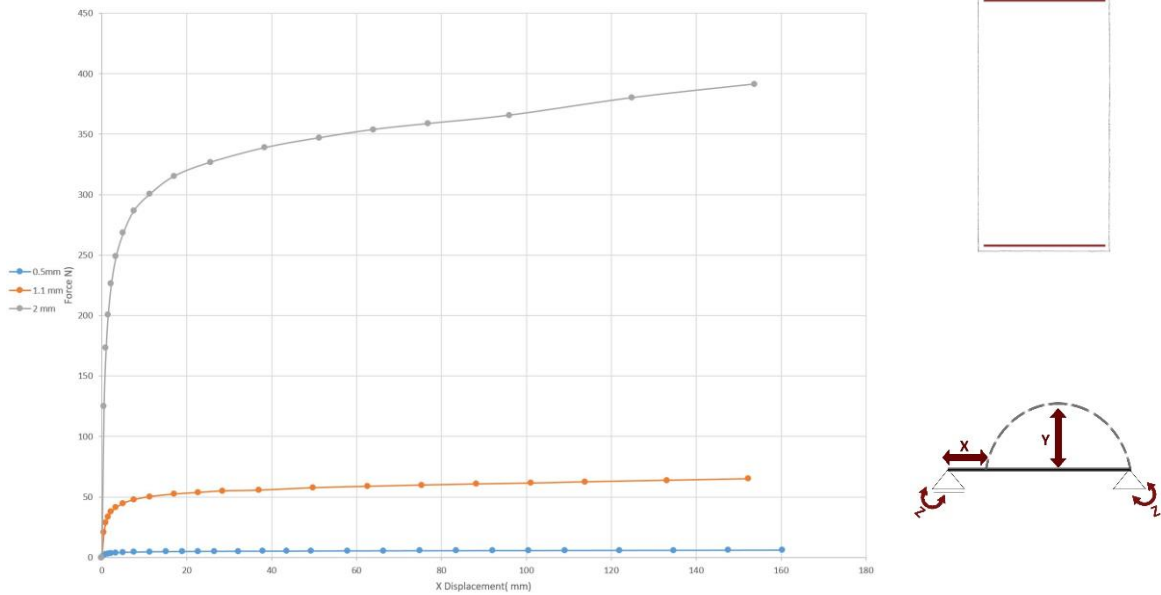

Figure 90, applied force vs. Horizontal displacement with a degree of freedom for rotation of supports
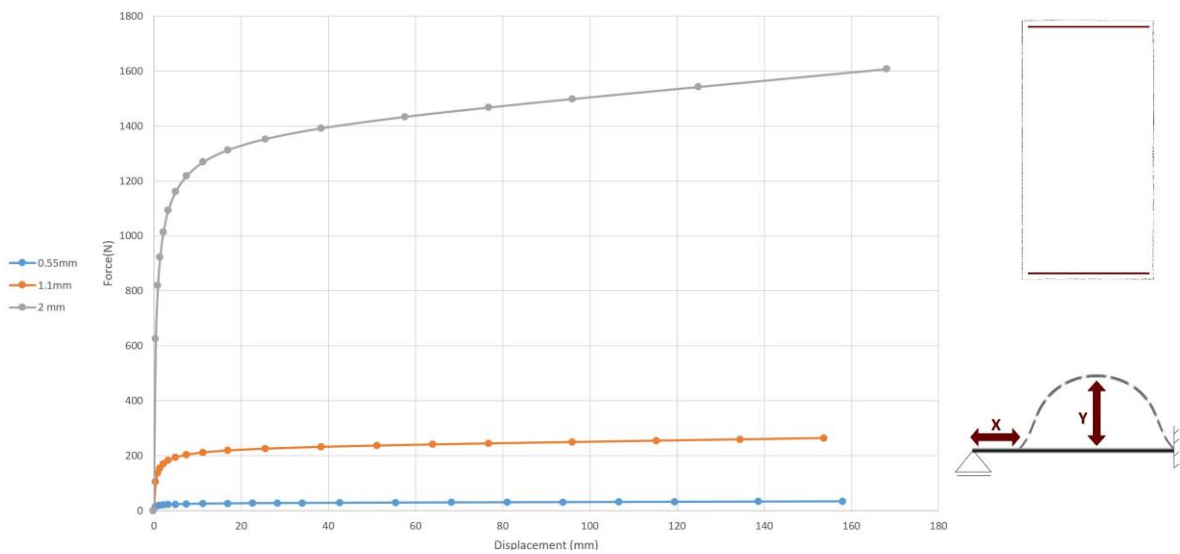

Figure 91, applied force vs. Horizontal displacement without a degree of freedom for rotation of supports

Due to the noticeable difference of the applied forces in two situations, option one has been selected for further analysis. The glass with the supports that can rotate freely needs much less force to be bent compared to the one with no degree of freedom for rotation.

5.1.2.1.2 Structural Analysis of selected frame

Figure 93 shows the chart for maximum principal stress on the top layer of glass to X displacement in different thicknesses. To achieve the chart, the principal stress on the top layer of the middle element in the glass was chosen and considered during the time the glass moves (figure 92).
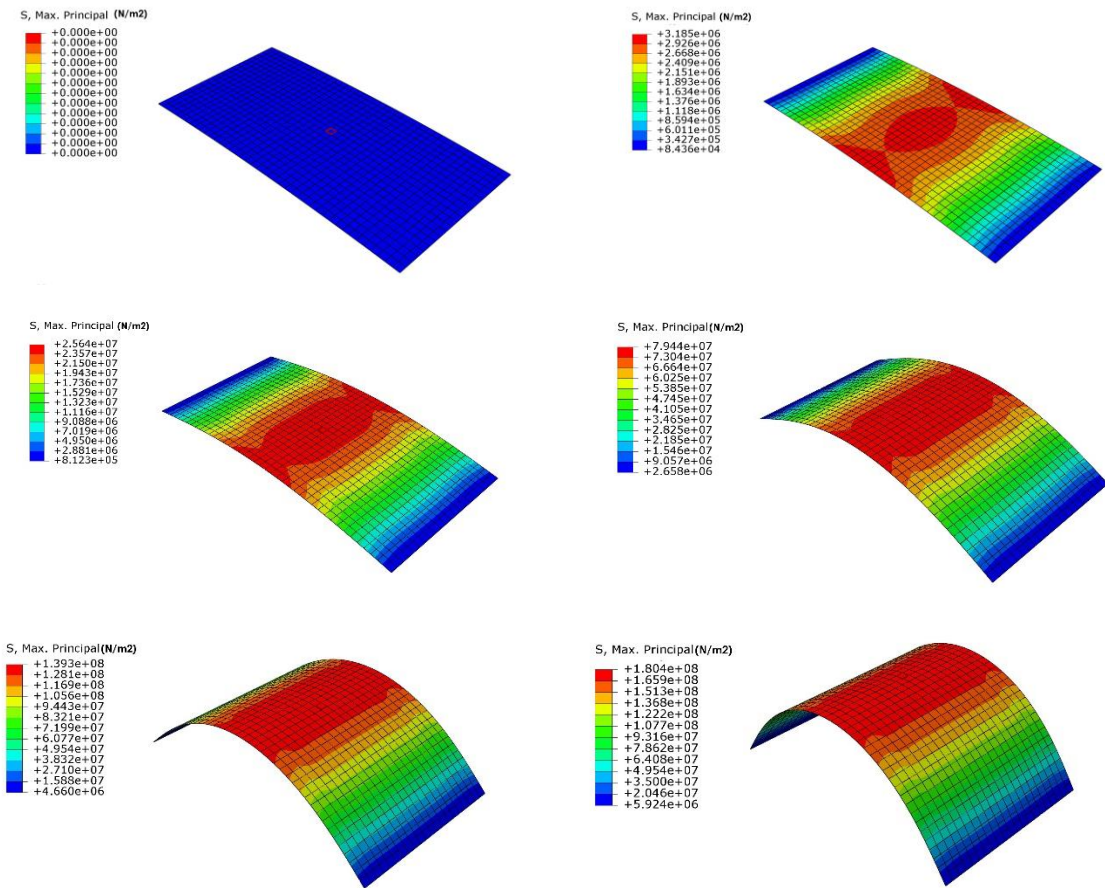
Figure 92, Maximum principal stress on the top layer of the middle element during the time for 160mm X displacement for a glass thickness of 1.1mm
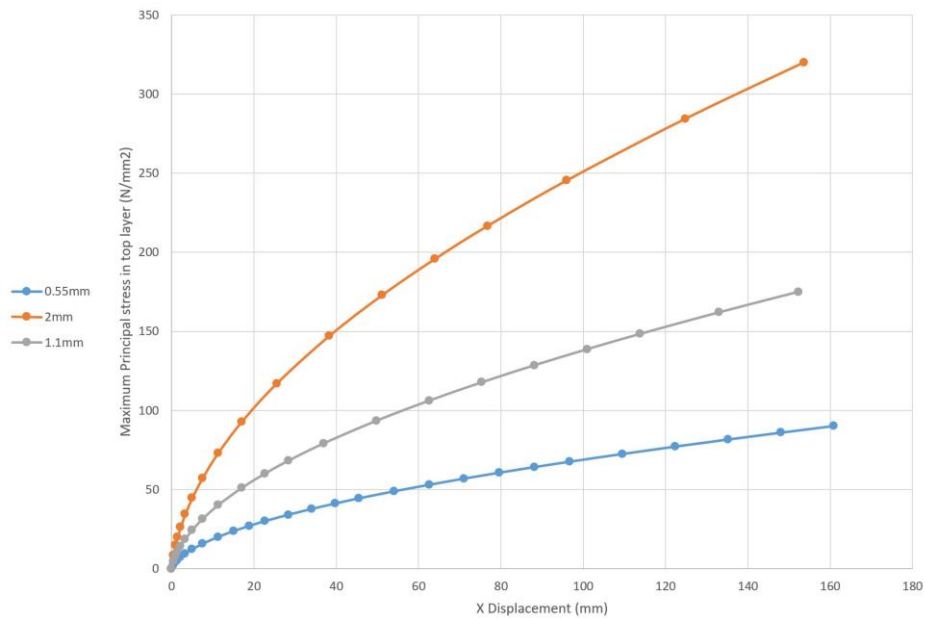

Figure 93, Maximum principal stress on the top layer in function of X displacement for different thicknesses

63

5.1.2.1.3 The orientation of the frame

In this step, the thickness of the thin glass panel for the following phases of the research has been defined based on the structural analysis. After analyzing the influence of the thickness of the glass to its principal stress, applied force, and displacement, the thickness of 1.1mm has been selected in case of using single glazing panel. Although 0.55mm plate can be easily moved by a small applied force, it showed very low resistance to lateral forces due to its very low bending stresses. On the other hand, 2mm plate with great resistance has considerably higher bending stresses which limit its movement. For having a small displacement in the plate, the wires should have a much higher applied force compared to the other two situations. As a result, the 1.1mm plate has been chosen since it has been demonstrated a good balance between bending stresses and lateral resistance in case of having single glazing panel. The following charts show Y to X displacement of the panel and its degree of rotation along the Z axis in specified X displacement for the 1.1mm thickness of the glass.
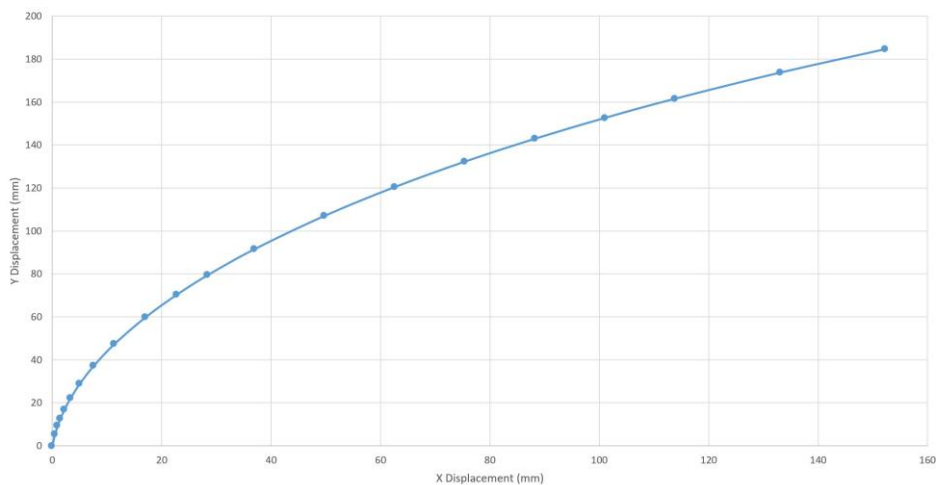
Figure 94, Y to X displacement

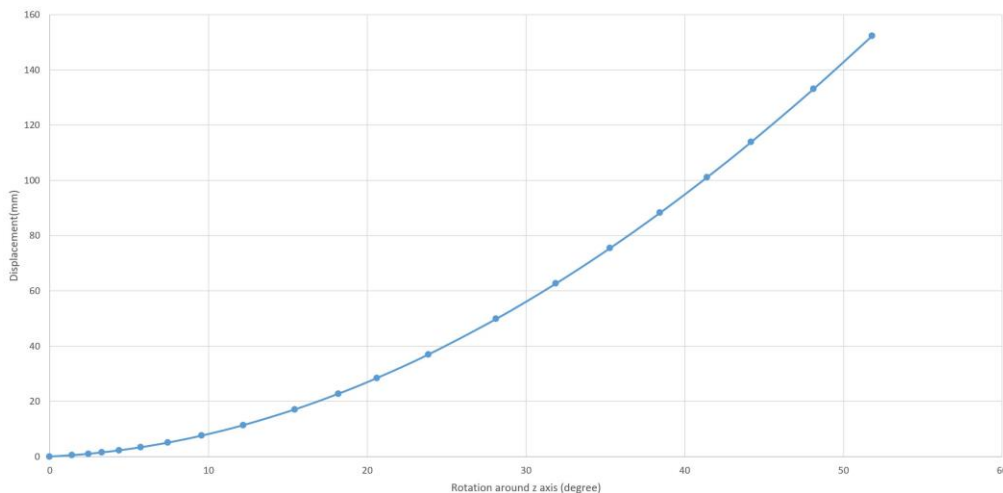*Figure 95, Rotation to X Displacement*

Figure 96 briefly shows the force and as a result the number of wires which are needed for different displacements in the plate. The specific displacements are selected based on the size of the frame and length of the wire. 5% of the length of the wire with 710mm is 35mm and depends on the stroke which will be selected, this displacement can be doubled or more.
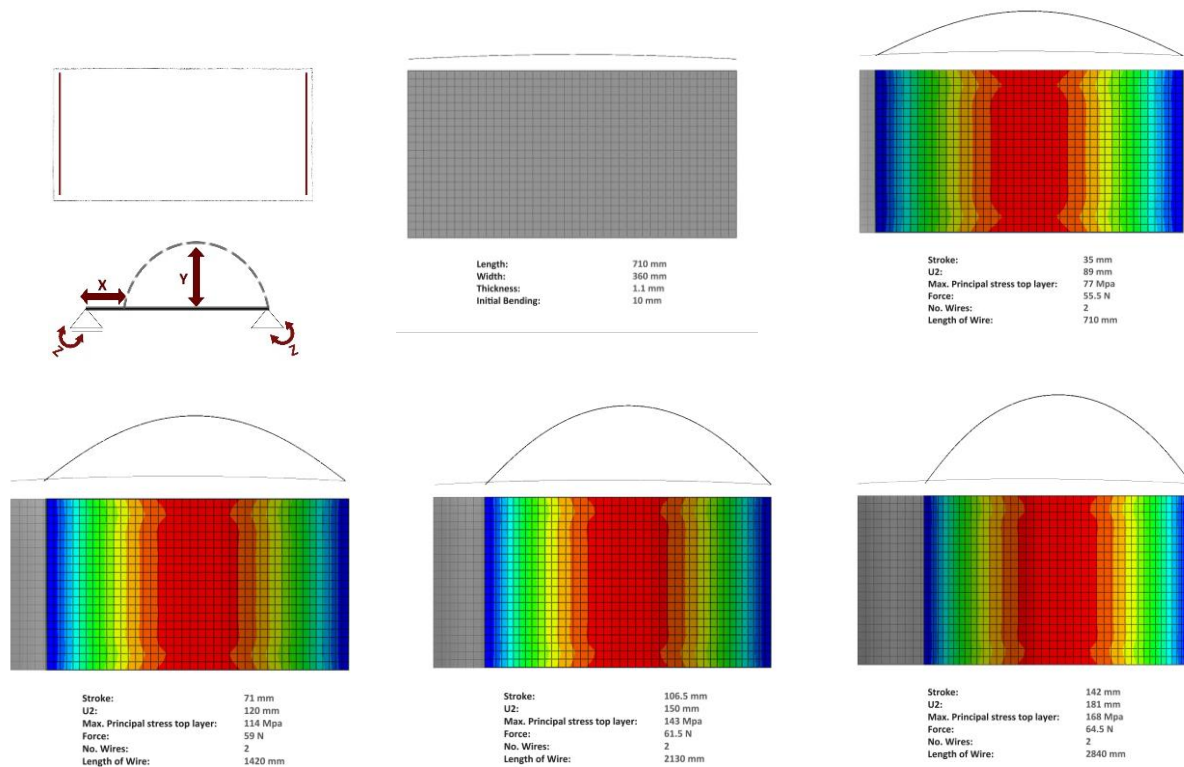
64

Figure 96, the Structural analysis of different displacement for 1.1mm glass

Depends on the orientation of the frame, the applied force of the wire will be different. Based on figure 97, the most suitable orientation for the frame has been chosen for the mock-up.

In option 1, the wire should also carry the load of the glass during phase change. The weight of the glass can be calculated as below:

M glass= Density x Area x Thickness

M glass= 2.48g/cm3 x 36x71x0.11= 0.7kg

W glass= 0.7 x 10= 7N

F total= F displacement + W glass

In this case, the weight of the glass is small compared to the force which is needed for bending; so, this option can be suitable for the following analysis.

In option2, although the wire should not carry the load of the glass during the phase change, the upper frame has a downward force toward the glass due to its weight even when the wires are relaxed and the window is closed. So, it might prevent that the window remains completely closed. As a result, this option is not applicable for further development.

In the third case, the wires do not carry any extra load related to the weight of the frame or glass. In addition, the weight of the frame does not have any effect on the glass. The mentioned points make this option as the safest and most suitable choice for further analysis.
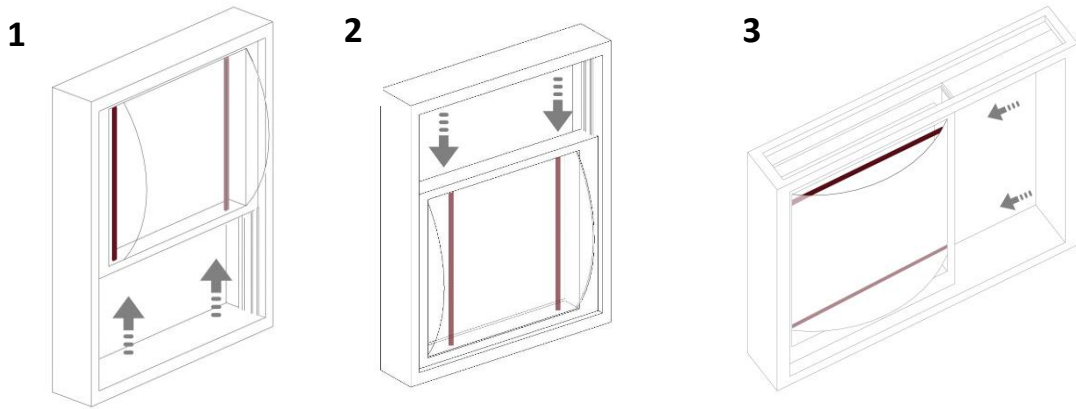
65

Figure 97, Orientation of the frame for Mock-up

5.1.2.2 Double layer laminated glass

Due to the structural and safety reasons, typical glass elements should be stiffened by lamination in the built environment. According to Ozhan Topcu research study [18], Five PVB layers with various stiffnesses have been shown in table 25. The selected glazing layer for mock-up type consists of two glass panes with a thickness of 0.55 mm bonded by E5 lamination configuration in two different thicknesses of 0.38 mm and 0.76mm. In this case, the softest PVB type has been selected and as a result lower number of SMA wires is needed to bend the panel compared to using the other PVB types. It should be mentioned that the young modulus of E5 PVB type has been changed from 0.3 to 30 in the numerical analysis because the small value of young modulus led to convergence errors.

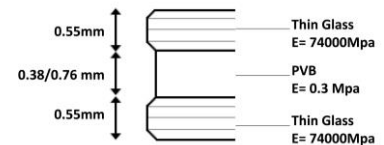| PVB Type No.	Young's Modulus E [MPa]	Shear Modulus G [MPa]	PVB Type	Temperature [°C]	Load Duration
E1	2030	700	Trosifol Extra Stiff	10	3 sec
E2	1450	500	Trosifol Extra Stiff	10	5 min
E3	943	325	Other Stiff PVB	20	3 sec
E4	435	150	SentryGlas	20	1 d
E5	0.3	0.1	Trosifol PVB	30	1 mo

Table 25, PVB Types [18]

5.1.2.3 Structural Analysis of Laminated Mock-up glass

In Mock-up case, the aim of structural analysis is to find out how much force and consequently how many wires are needed in case of replacement of single 1.1mm thin glass to the laminated glass.

In this analysis, a composite layup has been made with three different plies. The approximate global size of the mesh has been increased to 0.025 due to the increased number of layers. The figure shows the chart for the applied force to X displacement for the selected glass pane with two different thicknesses of lamination layer.
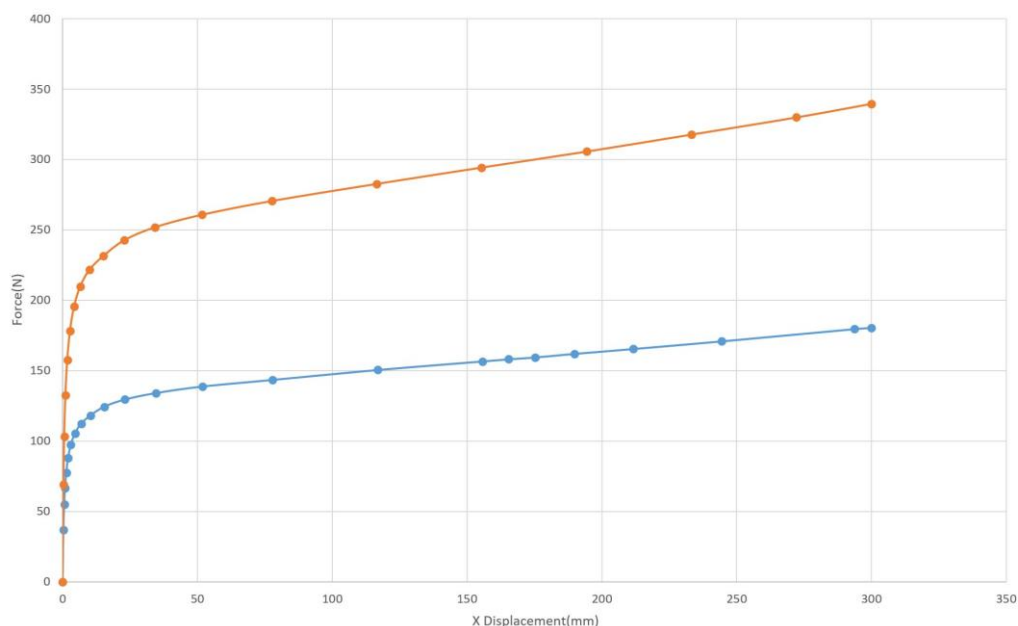
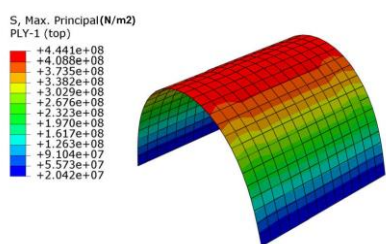*Figure 98, Force vs X displacement in laminated glass for Mock-up*

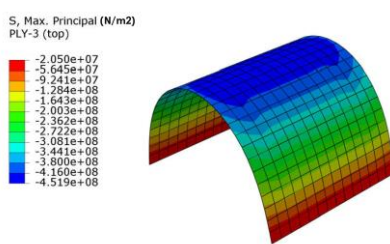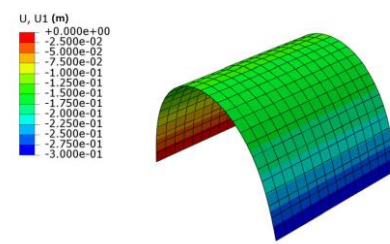*Figure 99, Max. Principal stress on top and bottom layers in 300 mm X displacement*　　　*Figure 100, X Displacement*

5.2 Electrical Analysis

As it was mentioned before, Flexinol wires are supposed to be heated by electricity in this project. Before making the physical model, all the considerations for applying electricity to the frame have been done.

First of all, since temperature is directly related to current density passing through the wire, care should be taken to heat, but not overheat, the actuator wire. According to the catalog, the recommended current which should be passed through the 0.5mm wire in one second is 4A. Based on the resistance of the wire, the voltage which is needed for activation for each wire can be calculated as according to the simple Ohm's law:

V=RI   R=4.3 ohm/meter   L= 710mm

R= 4.3 x 0.71= 3 ohm   V= 3 x 4= **12 v**

5.2.1 PWM Module

The current seems to be so high, and it also should be considered that this amount is only for one wire. According to the structural analysis, for bending a single glass pane of 1.1mm in mock-up size, more than two wires are needed. For applying 8A current, the special Adjustable Power supply is needed to control Voltage and current at the same time. Of course, PWM modules can be adjusted and control the contraction speed and save energy. According to the figure 101, the system is coded

based on the activation time for each wire. Based on this system, the electricity is applied to one wire while the other one is in its relaxing period. So, instead of applying 8A to two wires, 4A is applied in pulses in different duration to two wires.
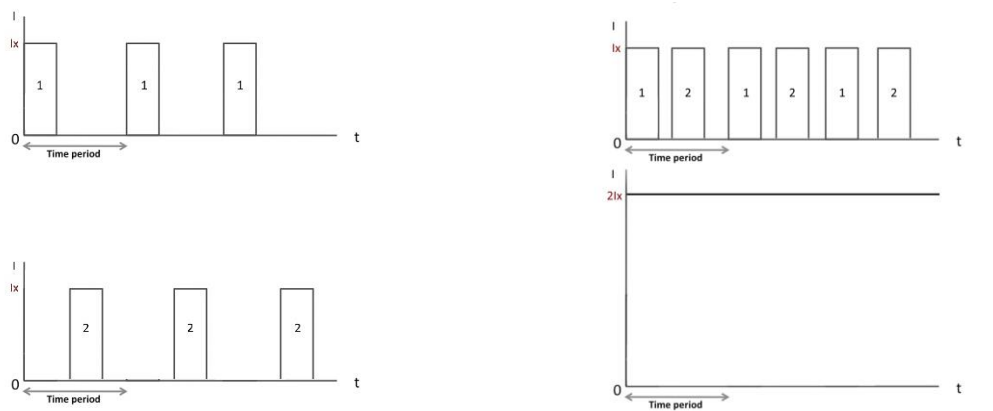
Figure 101, PWM Module

Although PWM module can make the applied current half, still 4A for the applied current is considered high. It should be counted that the 4A recommended in the datasheet is for a 1-second contraction, a lower current can be used to contract the wire slower. Decreasing the contraction time can cause increasing the power input to achieve the same amount of energy in Joules. It should be also mentioned that, in slower contraction, the waste of energy will be higher especially for not insulated wires.

5.2.2 Pulley concept

A pulley concept has been recommended as a strategy for applying the lower current in situations by having more than one wire. In this concept, a single wire is passed around the feature it pulls on which doubles the effective pull force of the wire and doubles the voltage requirement while the current requirement remains the same (see figure below). So, It is possible to have a very long single wire of a smaller diameter passed through several features many times to achieve the desired pull force with a low current if each strand is electrically isolated. For example, 6 strands of 0.31mm Flexinol actuator wire can pull more with more force than 2 strands of 0.51mm wire and need only 1.5A vs 4A.

According to the structural analysis, one glass in size of mock-up and thickness of 1.1mm needs two wire for 50mm stroke. In this case, instead of having two wires and applying 4A to each wire and 8A in total, it is possible to have a long wire with the double-length while it is passed through a feature and apply 4A in total to it.
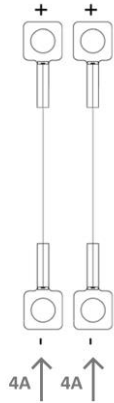
Figure 102, Normal situation for two wires
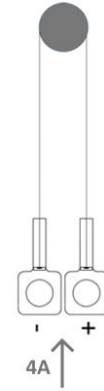
Figure 103, Pulley option

This case works exactly like a pulley system. It makes the force double while the displacement becomes half. The current requirement remains the same while the voltage becomes double.

Figure 104, Perspective of Pulley option

Figure 105, Pulley system

By passing the wire through a ring, and at the same time applying the pulley system, double force can be archived while the stroke will be doubled.
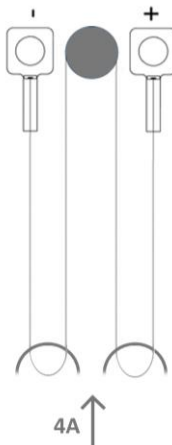
Figure 106, Combination of a pulley system and double stroke option

Based on the previous studies, the mock-up panel with one glass can have a long wire with one pulley system instead of having two separate wires and achieve the same force and stroke.
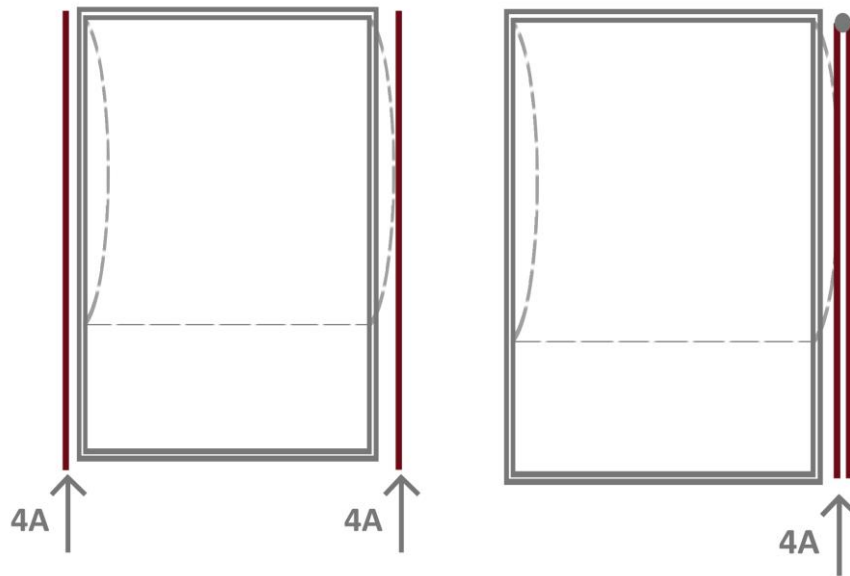
Figure 107, Strategy for low current for one panel

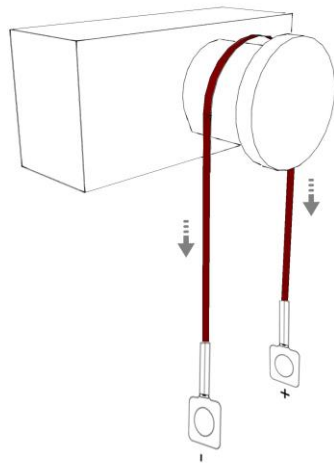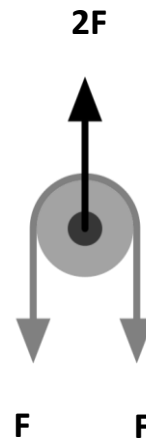In case of having two panels and 16A with four separate wires, four times longer wire can be applied to get same force and contraction while applying one forth current and four times more voltage.
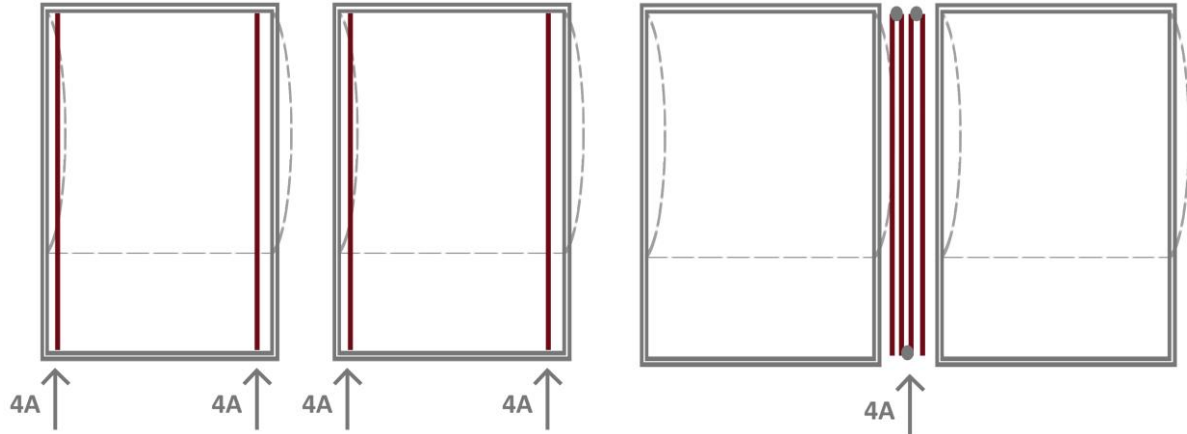
Figure 108, Strategy for low current for two panels

Applying the long wire just in one side of the frame might unbalance the frame in both sides. In order to keep the balance on both sides of the frame, another option has been developed. In this case, the wire has been moved around the frame, while the pulley system can be also applied by passing the wire several times depending on the force which is needed. The longer wire can makes the stroke more than double.
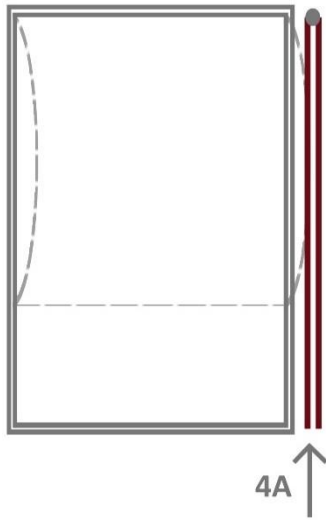
Figure 109, unbalanced option
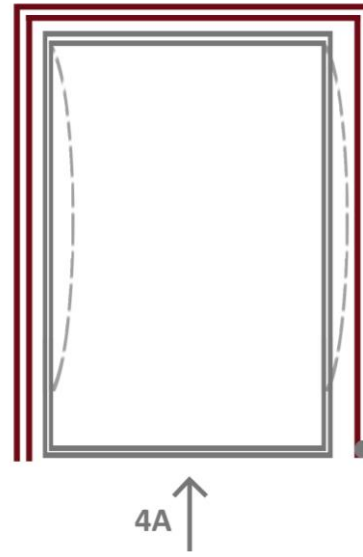
Figure 110, Balanced Option

In should be considered that the stroke in the balanced option can be different depends on the attachment of the wire. In figure 111, both ends of the wires are moving. So, the stroke has been divided by two into both ends. On the other hand, in figure 112, since one end is remained fixed, the stroke on one side could be doubled. Moving the wire only on one side might affect the balance in the frame. Figure 113 is an alternative for one end free concept. In this case, the balance has been kept but because of having two separate wires, the current should be double.
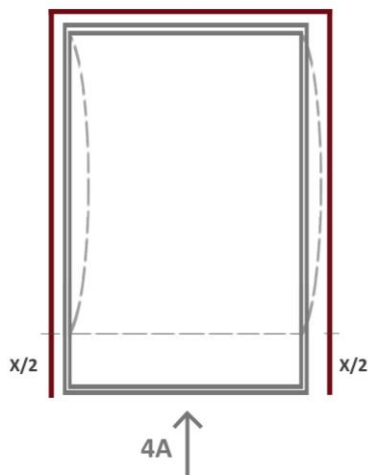
Figure 111, Two ends free
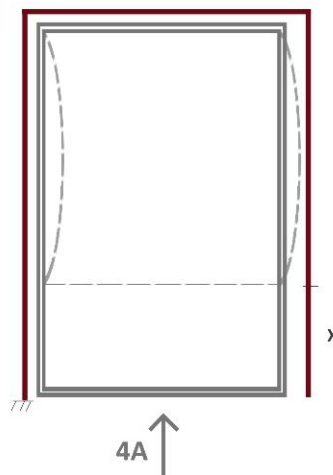
Figure 112, One end free
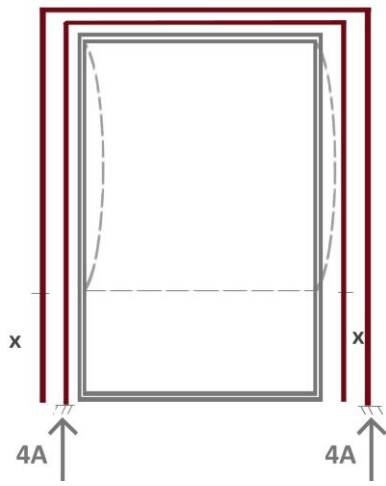
Figure 113, Balanced one and end free

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5.3 Experimental Setup

In the following tests, it has been aimed to look at the performance of the Flexinol wire step by step.

5.3.1 Test 1- 150mm wire

In this step of the experiment, a short wire of 15cm has cut to be tested in different voltages and currents in order to find the optimum situation based on the reaction time.
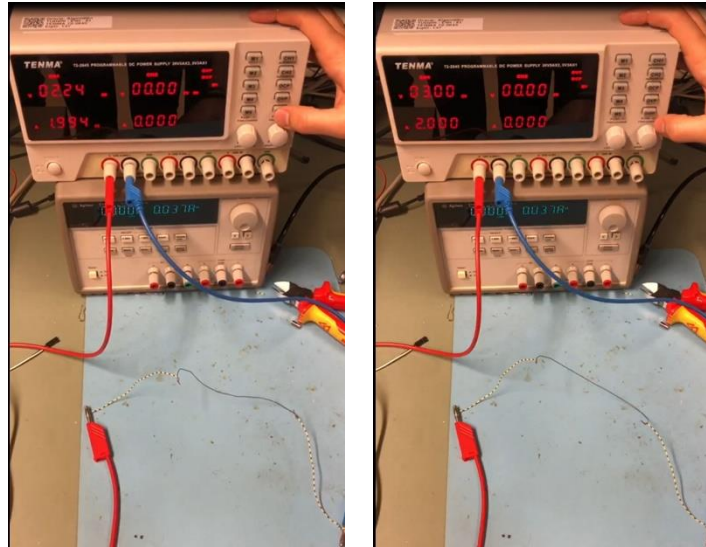
Figure 114, 15cm wire voltage and current test

Base on Ohm's law, the voltage in one second that should be applied to the wire can be simply calculated.

V=RI   R=4.3 ohm/meter   L = 150mm

R= 4.3 x 0.15= 0.6ohm   V= 0.6 x 4= **2.4 v**

According to table 26, it can be seen how the wire reacted to the current lower than 4A. The wire, it should be noticed that the wire does not work in very low current such as 0.5A.

I	V	Performance	
0.5	12		X
0.85	20		X
2	4	1 sec	✓✓ ✓
2	2.4	4 sec	✓ ✓✓
2	3	2 sec	✓✓✓
2	1.6	10 sec	✓✓
1.5	1.6	14 sec	✓
1.2	1.6	17 sec	✓
1	1.6		X
1.2	1		X

Table 26, Performance of 150mm wire

5.3.2 Test2-stroke and Force

In this step, the percentage of the stroke and the amount of pull force have been tested for the wire with the length of 710mm. As a start point, the Voltage of the wire has been calculated for one second as before.

V=RI   R=4.3 ohm/meter   L = 710mm

R= 4.3 x 0.71= 3ohm   Stroke= 0.05 x 71= 35 mm   Force= 35N

V= 3 x 4= **12 v**

In this experiment, one side of the wire has been fixed on the top of the wooden plate, while the other side can be moved in the gap. The first part of the test has been done without carrying the weight, and in the second part, the weight of 3.5kg has been applied as the maximum weight that the wire can carry based on the data sheet.

Figure 115, Test 2 setup

Table 27 shows the performance of the wire with 710mm length.

I	V	Performance		
4	12	1 sec	✓✓ ✓	
0.5	2	X		
1.4	5.4	11 sec	✓✓	
0.9	4	120 seconds ✓		

Table 27, Performance of 710mm wire

Figure 116 shows how the wire becomes contracted by applying electricity while it is carrying 3.5kg weigh. The wire can have a stroke of more than 5% but it should be avoided because it might damage the wire.
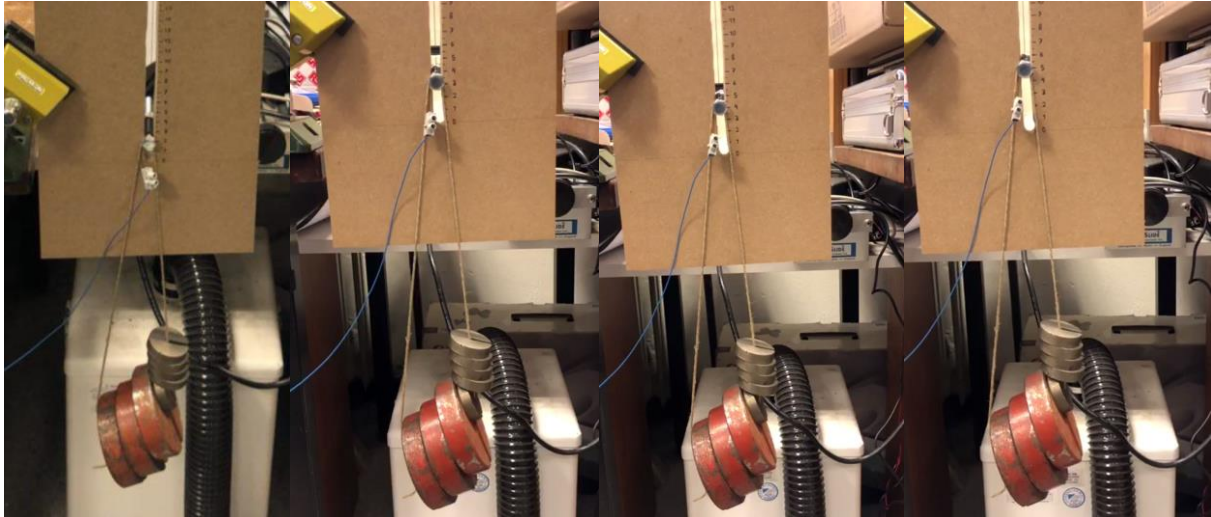
Figure 116, Stroke of 710mm wire

5.3.3 Test3-Double Stroke

In this test, the percentage of the stroke double length wire with the length of 1420mm has been studied. The following calculations are the recommended voltage and current for the wire which should be applied in one second.

V=RI   R=4.3 ohm/meter   L = 1420 mm

R= 4.3 x 1.42= 6ohm   Stroke= 0.05 x 1420= 70mm   Force= 35N

V= 6 x 4= **24 v**

A wire with a double length has been fixed to the wooden plate while it has been passed from a wheel on top. The wire is free to move at the end through the gap in the plate. The aim is to investigate the amount of stroke which could be achieved by having a longer wire placed in the same size frame. Same as the previous test, the wire was first tested without the weight and then the weight of 3.5 kg was applied to its end.

Figure 117, Test 3 setup details

Figure 118, Test 3 setup

Table 28 shows the performance of the wire with 1420mm length. The reaction time of the wire is much higher with use of same voltage and current because of using a double length of it. In order to achieve the same reaction time in the same current, the voltage should be doubled.

I	V	Performance	
4	24	1 sec	✓✓ ✓
1.4	5.4	300 sec	✓
1.4	10	13 sec	✓✓

Table 28, Performance of 1420mm wire

The contraction of the wire with double length and stroke could be seen in the figure.
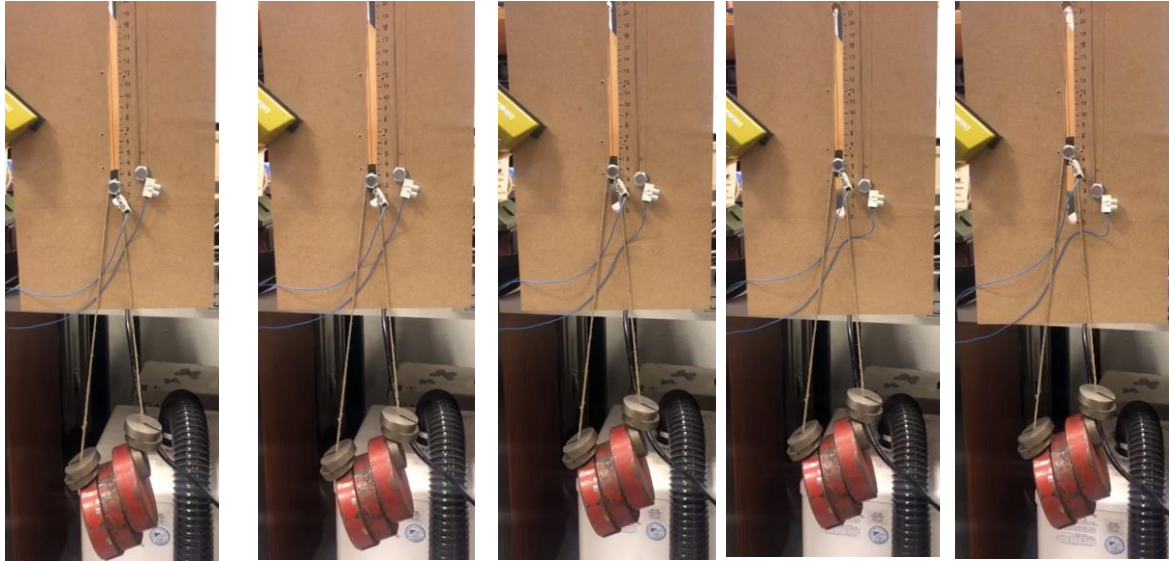
Figure 119, Stroke of 1420mm wire

5.3.4 Test 4- Mock-up

In this project, three Mock-up have been made. The first two were made to compare placing the wires between two glasses or in the frame, and in the last one, the selected option has been made professionally and more accurate.

Before making the mock-ups, the final decision for the panel should be made. It has been decided to attach two glasses to one frame and bending them at the same time. (Figure 120)

Figure 120, Mock-up concept
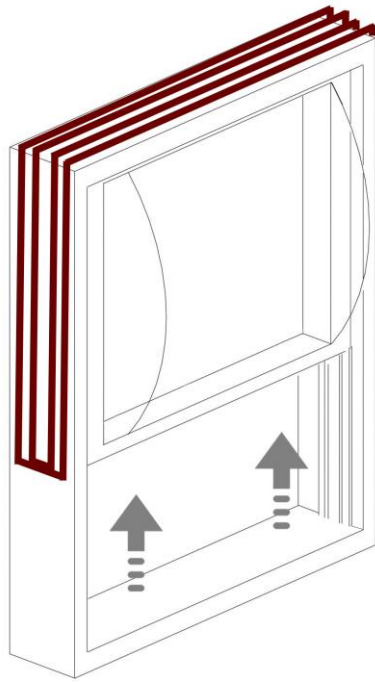
Figure 121, Mock-up 1 configuration   *Figure 122, Mock-up 2 configuration*
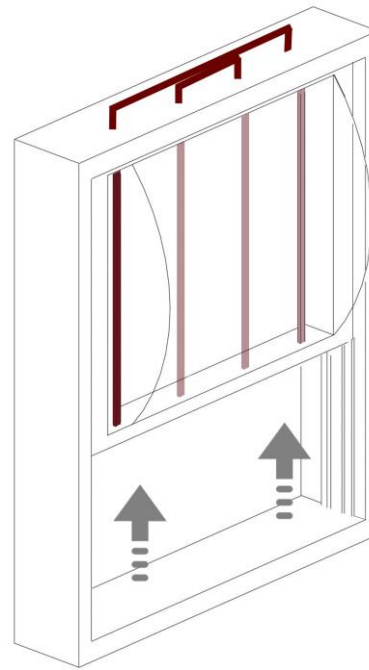
5.3.4.1 Mock-up I

In the first mock-up, the wires are placed in the frame. The thickness of the glasses in this option is 1.1mm. In order to bend two glasses vertically in the frame, four wires are needed. Based on the previous research studies, the balanced option has been selected for further analysis. So, a long wire should pass around the frame four times in order to move the glass five percent of its length. In this case, the stroke can be calculated like below:

Length of the wire in one turn: 1840mm   Total length:7360mm

Stroke:5/100 x 1840 x1/2 = 46mm

The stroke is divided by two because both ends of the wire are supposed to move.

Based on the Ohm's law, the voltage which is required for one second in 4A current can be calculated.

V=RI   R=4.3 ohm/meter   L one turn = 1840mm

R= 4.3 x 1.84= 7.9ohm   Stroke= 46mm   Force= 35N

V one turn =7.9 x 4= 31.6 v   V total= 31.6 x 4= 126.4

The calculated voltage for a long wire seems so high, and the available power supply for testing could not supply with that high amount of voltage. So by splitting the wire into two parts, the required voltage became half (V=63.2V), while the total current convert to 8A for one-second phase change. Before making the mock-up, the details have been drawn.

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Figure 123, elevation details of mock-up 1

Figure 124, mock-up 1, Perspective view of details

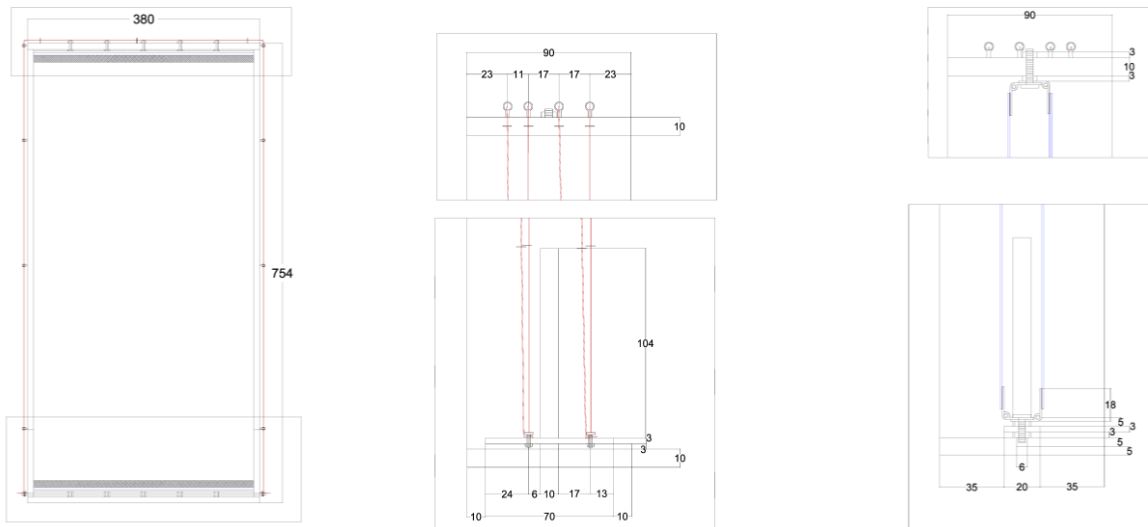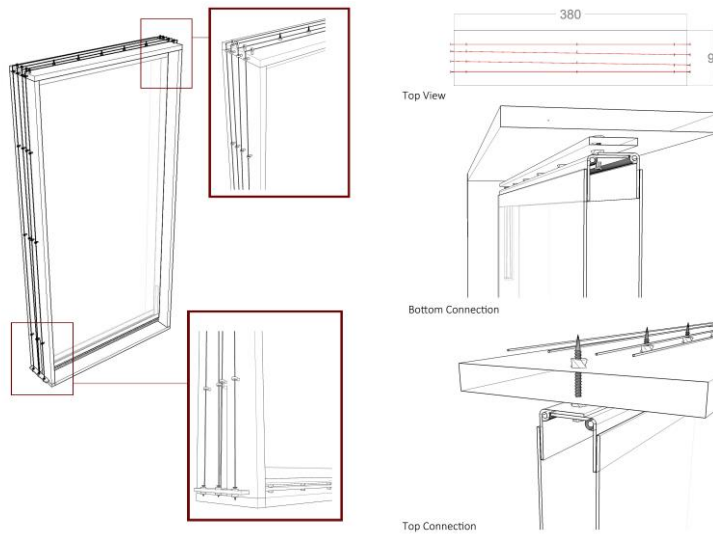Rotating connections are made by overlapping two piano hinges in the top and bottom parts. The glasses can go up and down through two sliders which are attached by a circular pin to the bottom frame part of the frame. Also, the wires are guided by ring screws which are attached to the base.
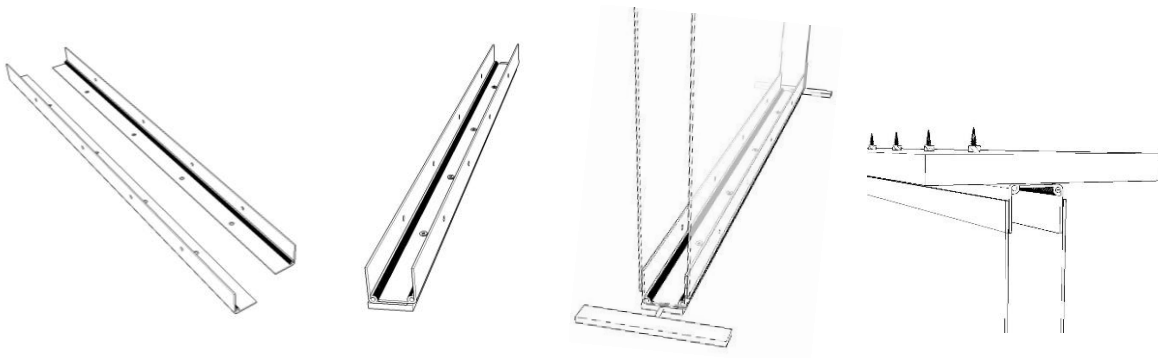
Figure 125, Rotating Connections

In the first step of the test, the wires are attached to the system and the frame has been tested by electricity without the glasses. The electricity is applied to four ends of the wires on one side, while the wires are connected to each other by creating a short circuit on the other side of the sliders.

Table 29 shows the performance of the wire with different voltage and current.

I	V	Performance	
2.8	25	10 sec	✓ ✓ ✓
1.7	17		X
2.4	23	15 sec	✓ ✓
2.2	22	25 sec	✓✓
2	20	60 sec	✓

Table 29, Performance of first concept

Figure 126, Mock-up 1, frame set-up 1

As you can see in figure 127, the siders cannot push the frame up in balance. The reason is that they cannot move smoothly in the gap.

Figure 127, Mock-up 1, frame test without glass

In the second step, the glasses have been attached to the hinges one by one with use of double-sided tape. The wires could push the first glass up hardly. (Figure 128) But after attaching the second glass, the sliders couldn't move the frame. The reason is related to the connections of the sliders. The circular pin which connects the slider to the frame is rotating while the wires become activated and spinning the frame instead of moving it up.

Figure 128, Mock-up 1, one glass test

A new connection has been made in order to prevent the rotation of the sliders. In this case, the sliders are attached under the frame.
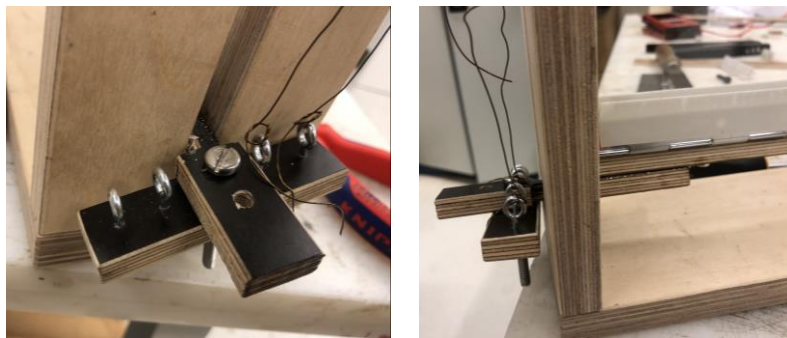
Figure 129, Mock-up1, new connections for sliders

The new sliders could move two glasses easily, but they still had enough space for rotation. The glasses could easily be moved up, but at they couldn't be pushed down when the wires get relaxed. The sliders rotated at the end and did not let the frame to move down.

Figure 130, Mock-up 1, frame setup with new connections

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Figures 132 and 133 show the new connection error before and after the wire stroke. The rotated sliders got stuck in the gap and prevent moving the frame down after the SMA wires got relaxed.
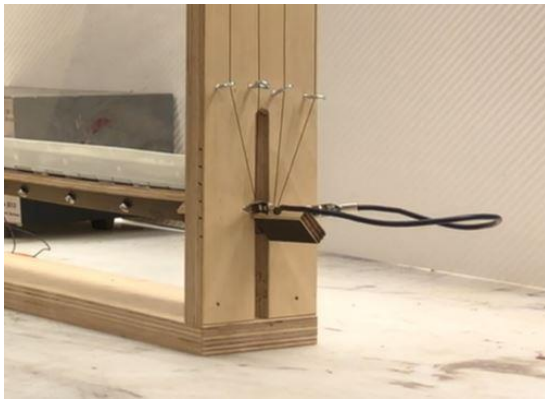
Figure 131, rotated sliders with active wires
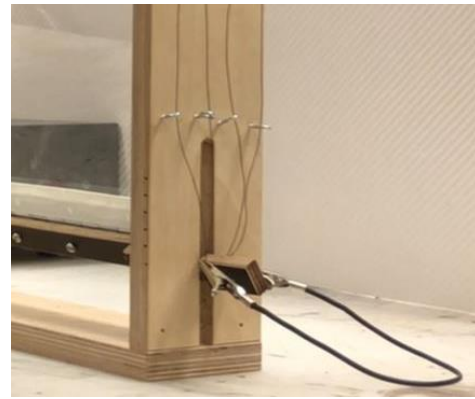
Figure 132, Trapped sliders with relaxed wires

In the next step, the final connections for the sliders have been made. In this case, a long wooden strop has been placed vertically under the frame. The strip does not have enough space to rotate, so it can just move the frame up and down smoothly.

Figure 133, Mock-up 1, final connections

Figure 134 shows all the details for the final mock-up 1.
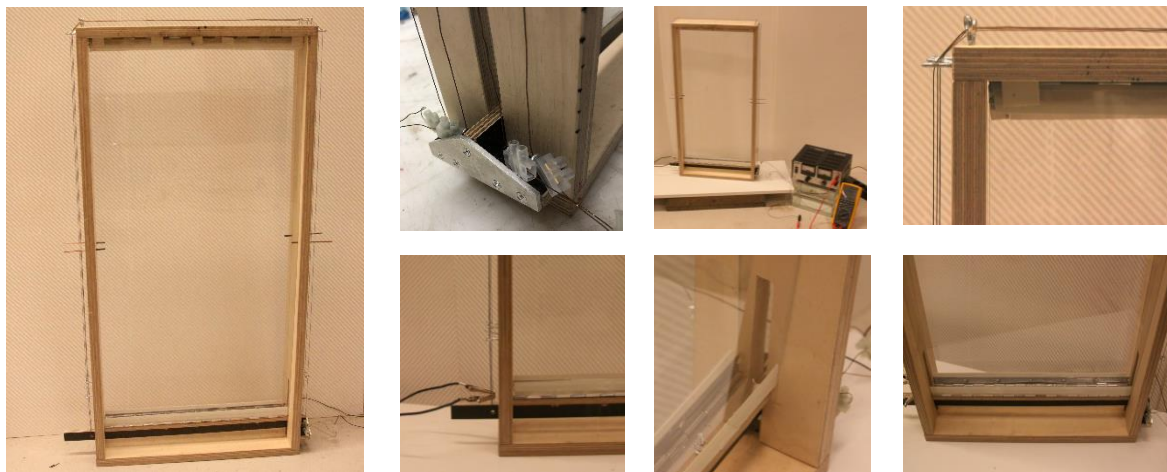
Figure 134, Mock-up 1, final frame

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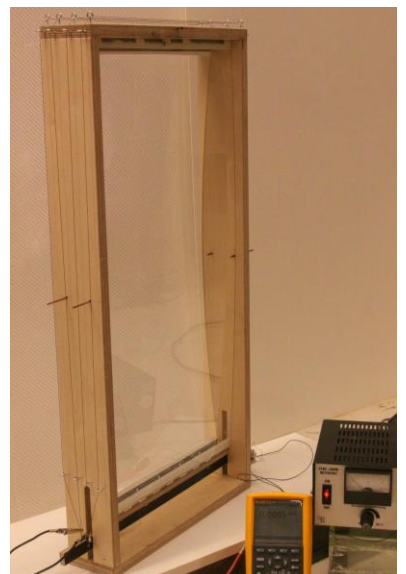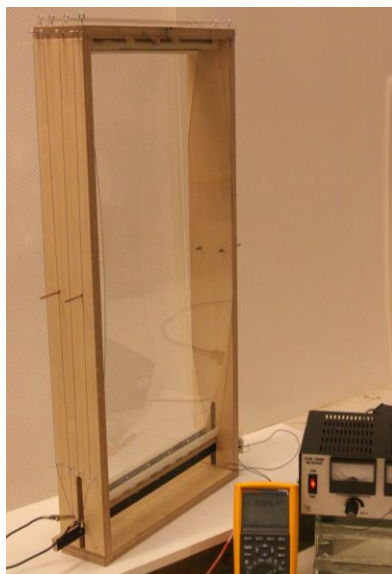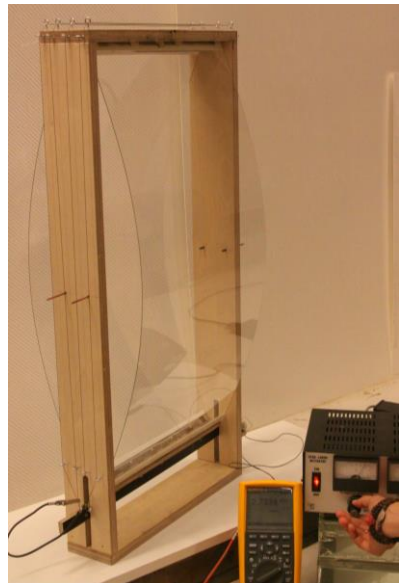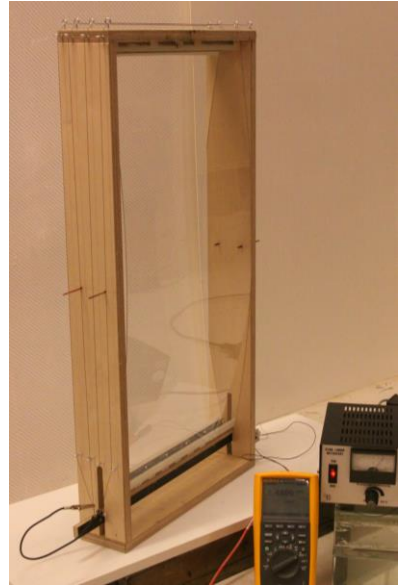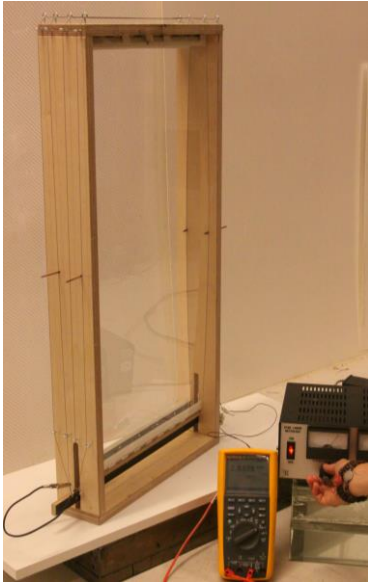
Figure 135, mock up 1 perspective view
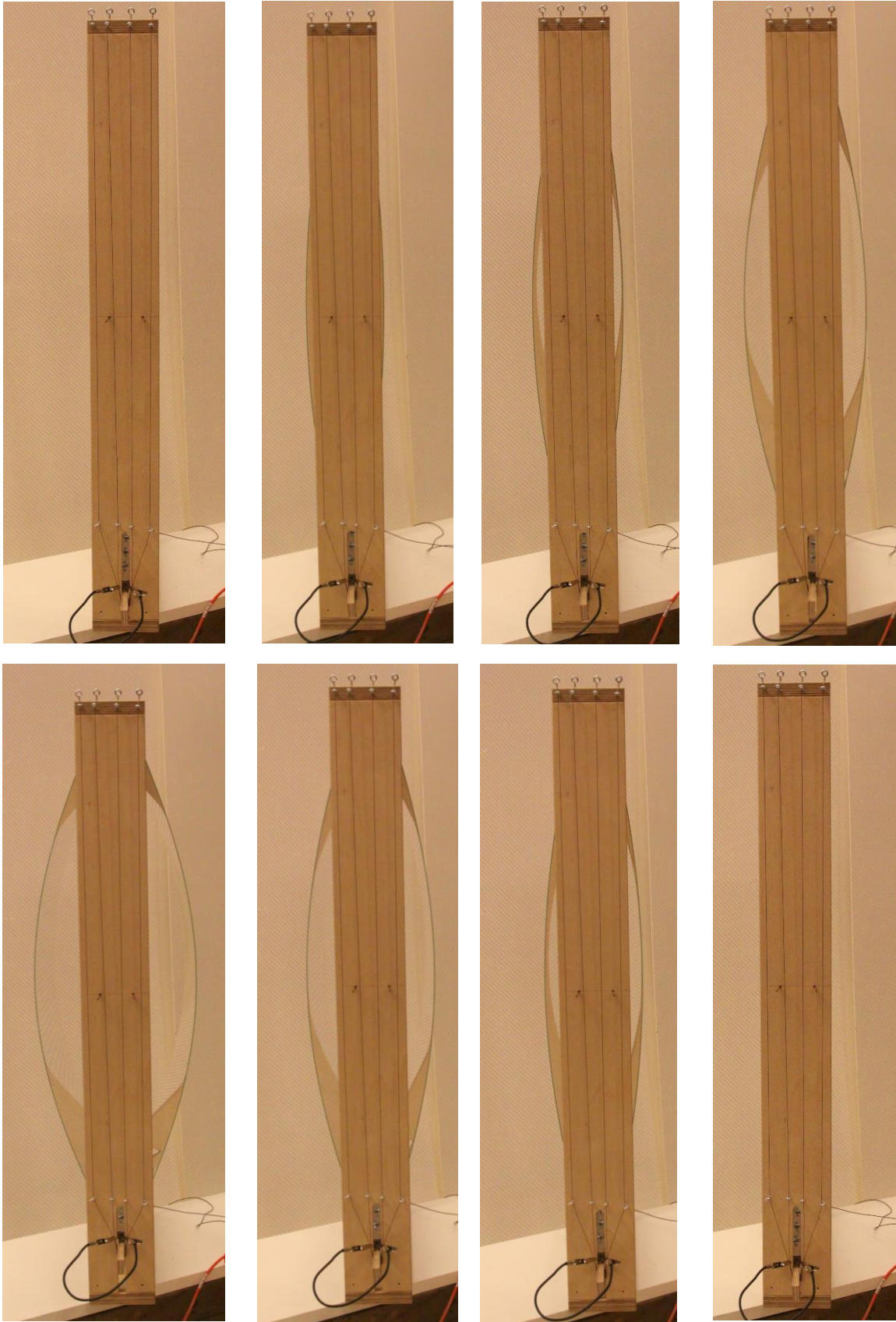
Figure 136, Mock-up 1 side view

5.3.4.2 Mock-up II

As it was mentioned before, the difference between mock-up one and mock-up two is the location of the wires. In the second mock-up, the wires are placed between two glazings. In this case, since there is no need for extra space for attaching the wires to them, the final frame could be smaller on sides. Also, it could be mentioned that in this case, the wires can also be activated by solar radiation.

For the second mock-up, the thickness of 0.55 mm has been chosen for the glasses. According to the analysis, one wire is enough for moving two glasses with mentioned thickness.

The main challenge is how to make the stroke higher while there is one wire. The figure has been proposed as an alternative for increasing the stroke from the wire.
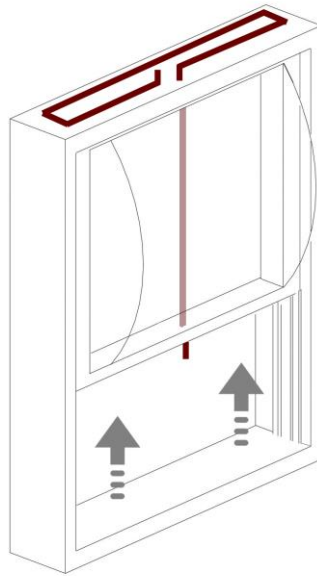
Figure 137, Mock-up2, alternative for more stroke

In this case, the required voltage for one second can be calculated based on the Ohm's law when the current is considered to be 4A.

Length of the wire: 1430mm

V=RI	R=4.3 ohm/meter	R= 4.3 x 1.43= 6.1ohm
V= 6.1 x 4= 24.4	Stroke= 71 mm	Force= 35N

The mock-up has same details and connections except for the slider part. Figure 138 shows the details of this alternative.
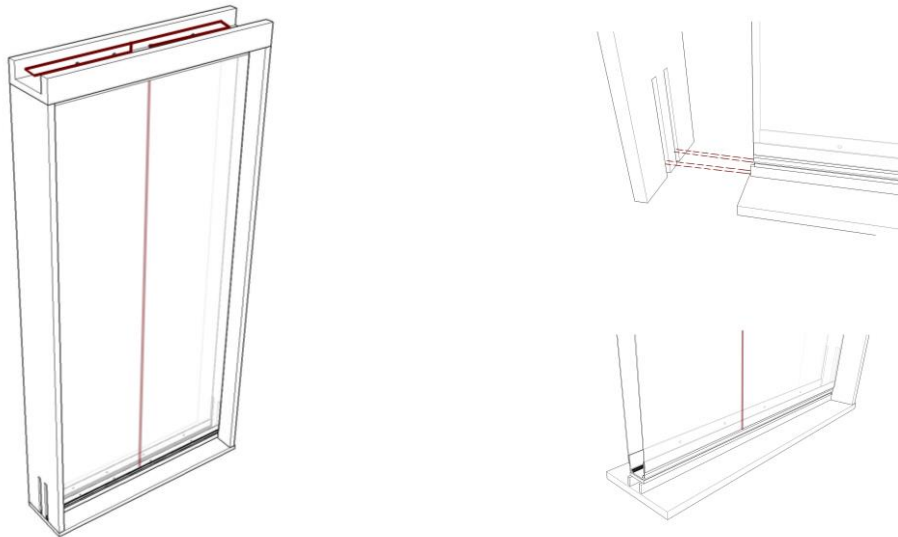
Figure 138, Mock-up 2, Perspective view of details

Same as the previous mock-up, the wire has been attached to the frame first and activated without glasses. The adaption worked well. The frame with wire in middle moved a bit imbalanced but the problem was solved by attaching the glasses. The weight of the glasses keeps both sides of the frame symmetric in adaption.
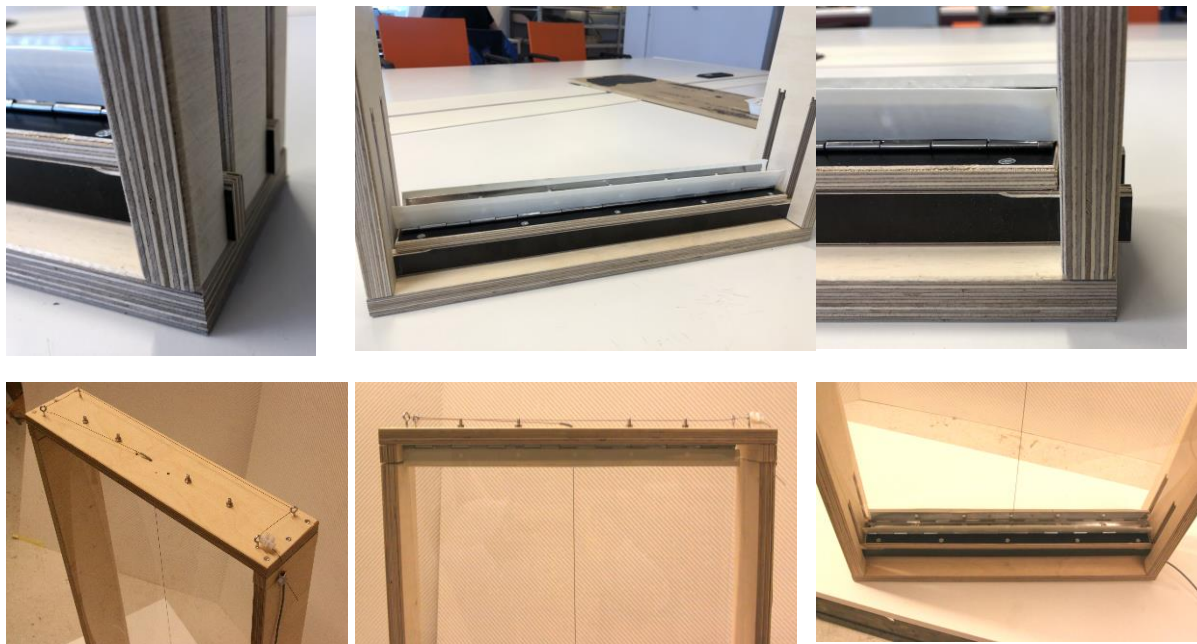
Figure 139, Mock-up II details

Table 30 shows the performance of the wire in different current and voltage.

I	V	Performance		
4	24	1 sec	✓✓✓	
1.4	5.4	300 sec	✓	
1.4	10	13 sec	✓✓	

Table 30, Performance of the wire in concept II

Figures 140 and 141 show the adaption of the frame while the electricity is applied.

Figure 140, Mock-up II perspective

Figure 141, Mock-up II side view

5.3.4.3 Conclusion

The development of each mock-up made it possible to continue the detailing into final products. In this step, both models are compared to each other and their advantages and disadvantages are investigated.
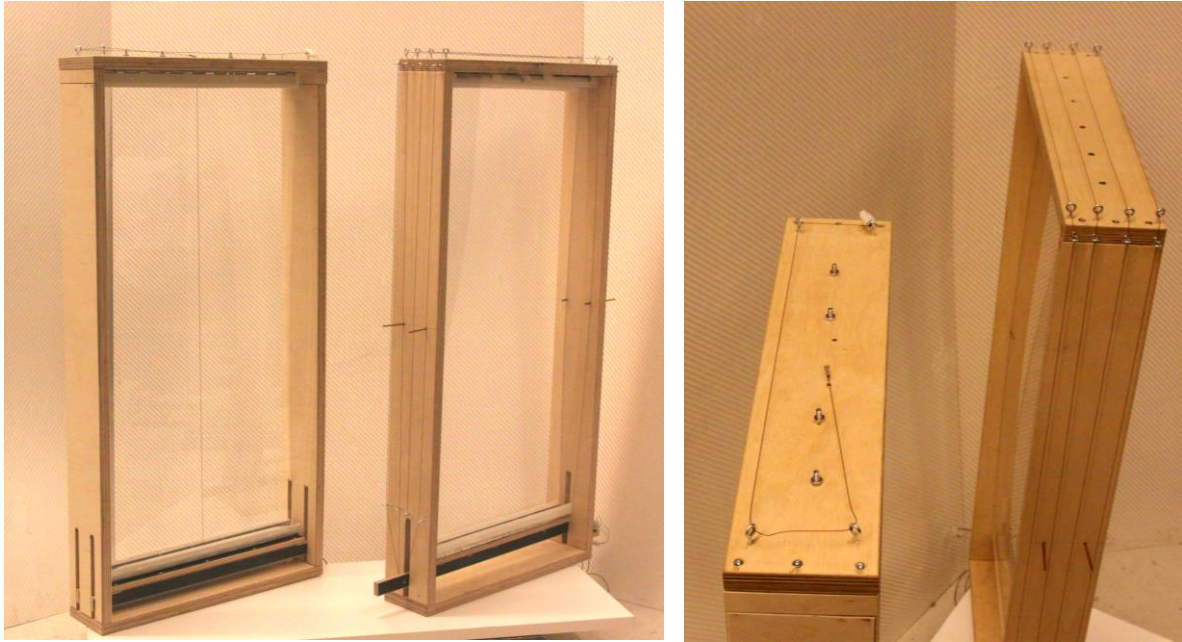
Figure 142, two concepts

In concept one, the wires are placed inside the frame. So the frame can protect the wire from dust and rain. On the other hand, the frame should be larger to place the wire inside and guide it through. Guiding the wires around the frame requires longer SMA wires and as a result higher power consumption for wire activation. Furthermore, the longer the SMA wire is, the slower the reaction time becomes. Placing the wires inside the frame provides the possibility of having a single glazing layer instead of two layers on sides. However, in the second concept, since the wires are placed between two glazing layers, removing one layer makes the wires completely exposed to the outside from one side and creates the chance of burnt and damages. In the second concept, the wires are shorter and subsequently, the reaction time is faster and the power consumption is lower. The frame becomes smaller especially from left and right sides and it makes the system simpler. Applying the wires between to glasses and exposing them to the sun provides the possibility of activating them by solar radiation while the whole system could be visible through the glasses.

Each concept has its own pros and cons and they could be selected depends on their application and location in the building. The second concept with two glasses has been chosen for further study as it was studied and analyzed for the mock-up.
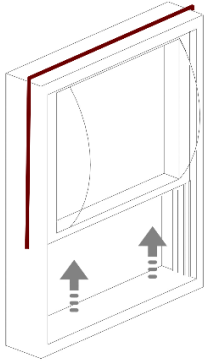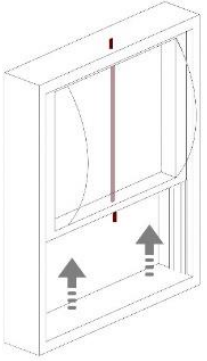
+	-	+	-
The possibility of insulating the wires	Long wires	The possibility of activation by solar radiation	Impracticality of insulation
Wire protection	Thick frame	Short Wires	Impossible for single glazing layer
Applicable for single glazing layer	Complex system	Thin Frame	
	High power consumption	Simple system	
	Slow reaction time	Visibility of the system	
		Low power consumption	
		Fast reaction time	

Table 31, Comparison of two concepts

6 Case Study

The mock-up frames clearly show that the proposed system can work well. As a result, the same analysis could be done for a frame which is applied in façade. As it was mentioned before, the adaptive skin can be placed in either a double façade (inner or outer skin), a single skin façade or an inner window. According to the case study, two options will be developed later. For both cases, the size of the glass is considered to be 1000mmx 3000mm. Same as mock-up concept, the supports are supposed to be placed along the shorter edge (1000mm) while the longer edge (3000mm) could be bent.

6.1 Design Overview

The chosen case study for this project is Genzyme center, a twelve-story building located in Cambridge, Massachusetts.

Figure 143, Genzyme center [67]

The glass is used in the façade to a great extent. Forty percent of the building's exterior facade is a double façade which is divided by an accessible four-foot loggia space. The building consists of operable windows from inside and outside that are automated for providing natural ventilation and reducing the building's dependence on cooling and heating systems. Moreover, an atrium in the middle of the building distributes light and ventilation through 12 stories during temperate seasons. The loggia of the building creates a temperate buffer zone through the use of solar heat radiation and

ventilation flaps. It also covers a substantial amount (32%) of the exterior with a double facade of glass. [67]
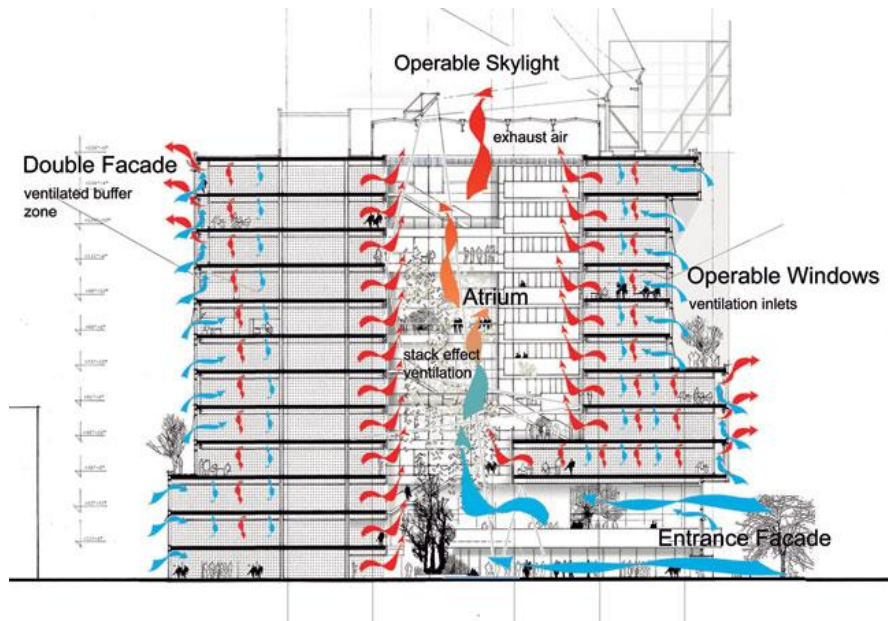
Figure 144, Genzyme center section

The idea is to replace the operable windows which are used as the inner windows for the atrium and the outer skin of the double skin façade with the designed breathing windows.
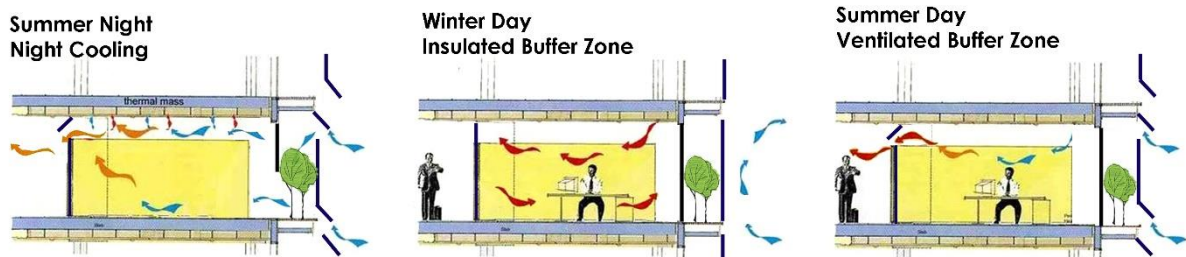
Current situation of operable windows
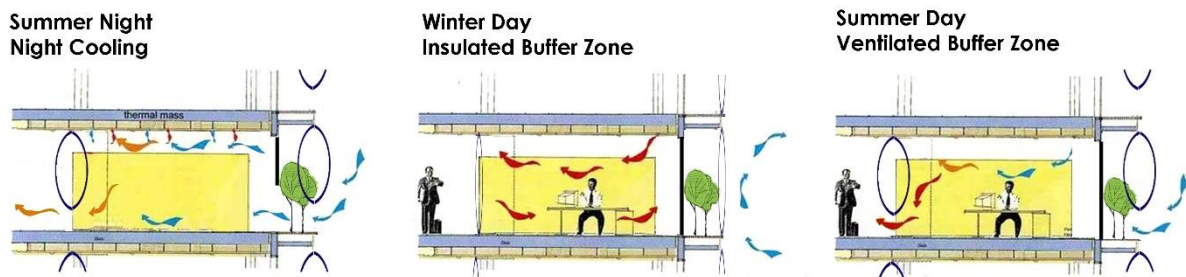
The proposed situation for the windows

Figure 145, Current and proposed situation for the building windows

6.2 Structural Analysis

6.2.1 Atrium glazing

The same FEM structural analysis for mock-up has been done for the new size of the glass. Chart 146 shows the force which is needed for different displacements. As you can see, the required force in the same displacement for 3000mmx1000mm glass is much lower compared to the glass with 360mmx710mm. This issue could be simply proved by Euler's column law. According to Euler column formula, buckling of columns under critical load can be calculated like below:

$$F = n\,\pi^2\,E\,I\,/\,L^2$$

F = allowable load (N)   n = factor accounting for the end conditions

E = modulus of elasticity (Pa (N/m^2)   L = length of column (m)

I = Moment of inertia (m^4)

According to the formula, the longer the panel is, the lower force is needed to bend it.
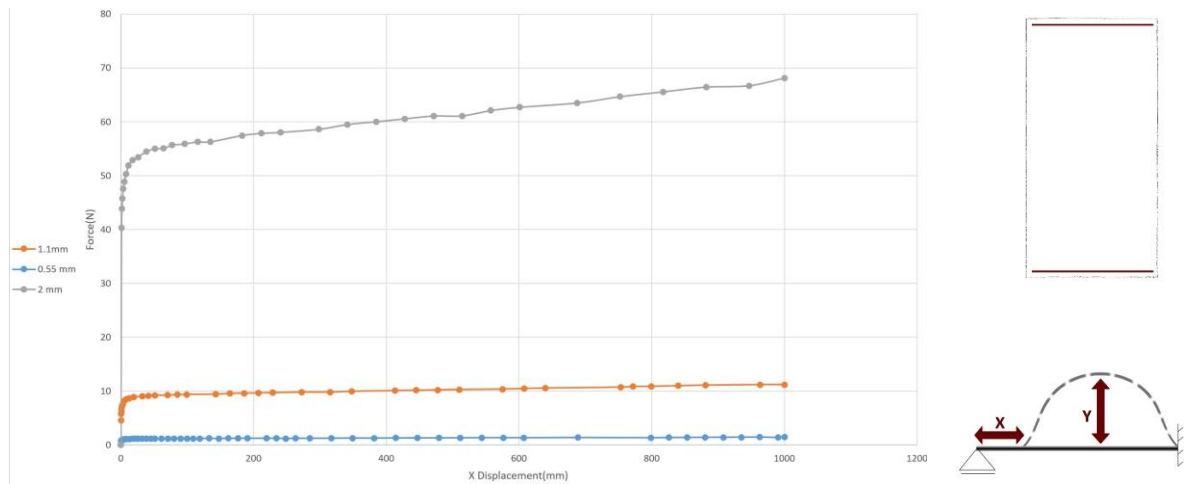
Figure 146, applied force vs. Horizontal displacement

The maximum principal stress of the glass panel with three different thicknesses in different displacement is like chart 147.
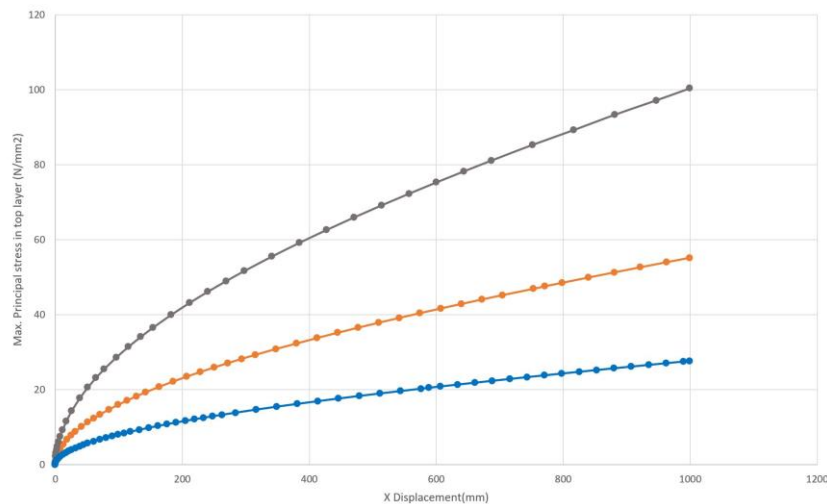
Figure 147, Maximum principal stress on top layer vs. X displacement

6.2.1.1 Single Glass

In case of applying the panel as the outer or inner skin of a double skin façade, the glass with a thickness of 1.1mm has been selected. The charts below show the structural analysis for this thickness of the glass.
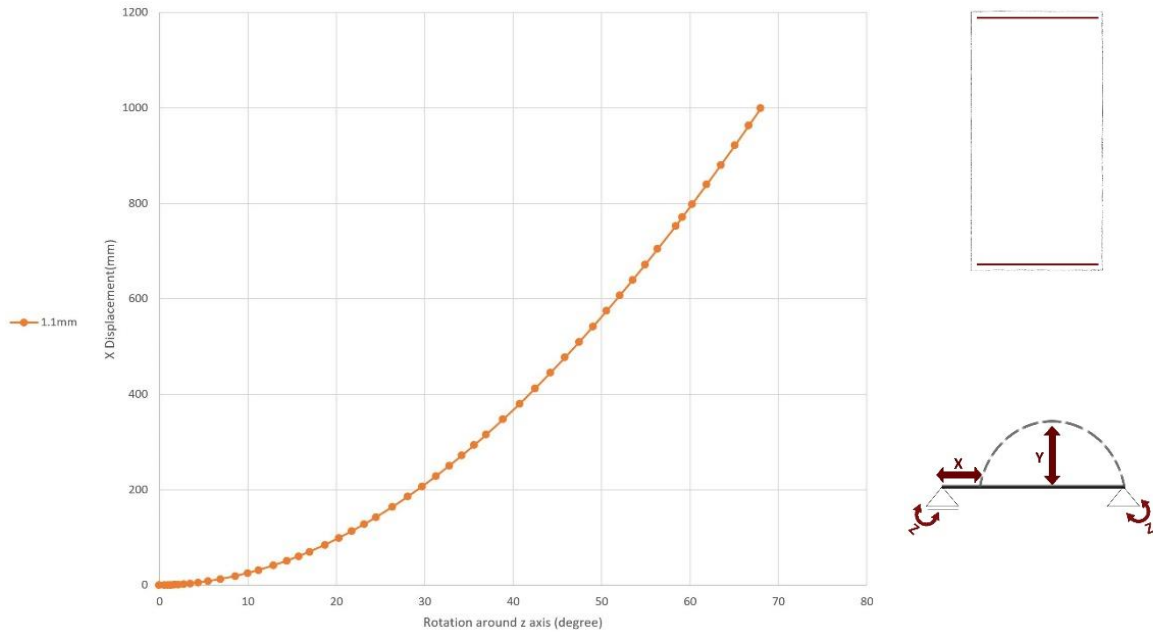
Figure 148, X displacement vs. rotation around z axis
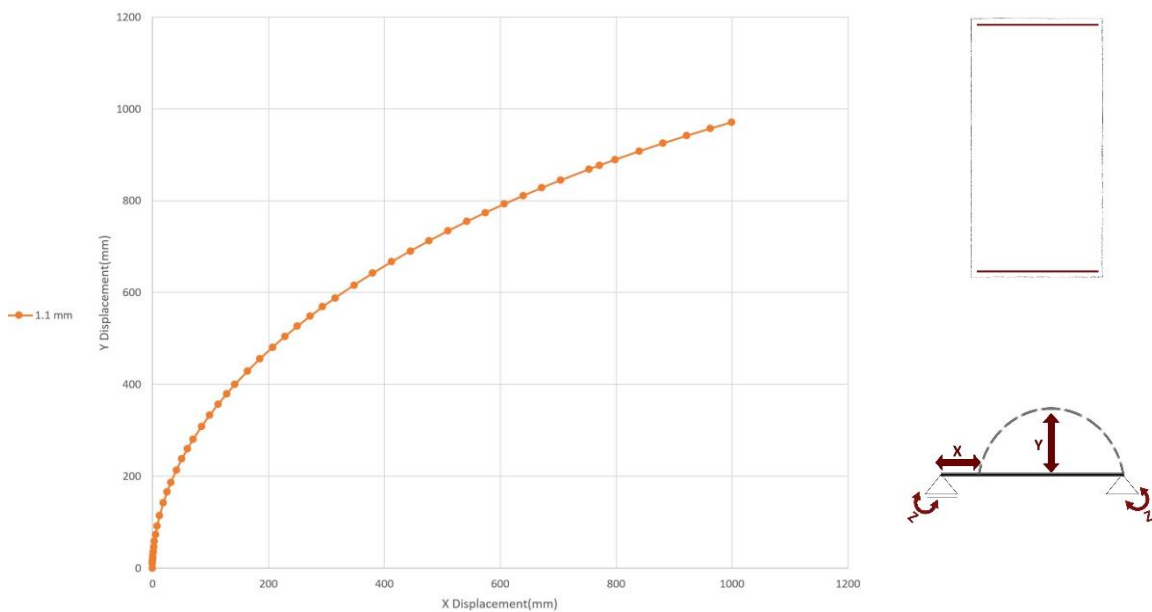
Figure 149, Y displacement vs. X displacement

Figure 150 shows the number of wire which is required for different displacement of the panel.

Length:	3000 mm
Width:	1000 mm
Thickness:	1.1 mm
Initial Bending:	10 mm

Stroke:	150 mm
U2:	410 mm
Max. Principal stress top layer:	20 Mpa
Force:	9.4 N
No. Wires:	1
Length of Wire:	3000 mm

Stroke:	300 mm
U2:	570 mm
Max. Principal stress top layer:	28.5 Mpa
Force:	9.7 N
No. Wires:	1
Length of Wire:	6000 mm

Stroke:	450 mm
U2:	692 mm
Max. Principal stress top layer:	35 Mpa
Force:	10.1 N
No. Wires:	1
Length of Wire:	9000mm
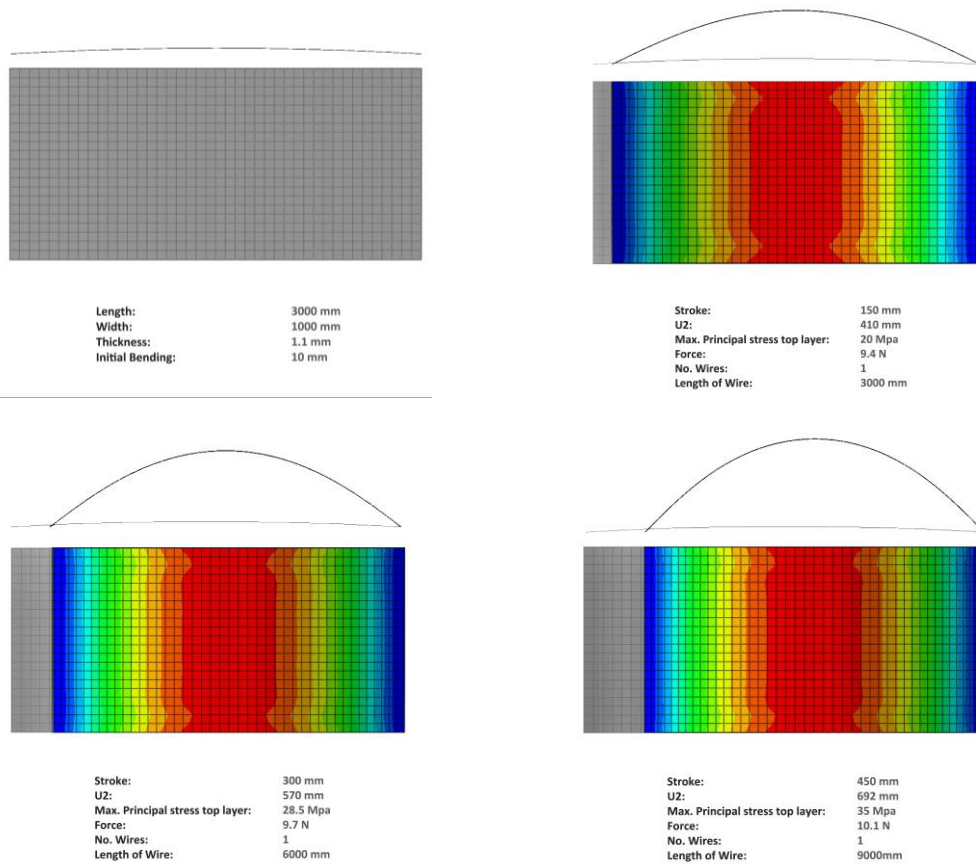
Figure 150, Structural analysis of single glass

As it was mentioned before, the applied force of the wire will be different based on the orientation of the frame. According to figure 105 in the page (), option one and three are selected for further analysis. The weight of the glass should be calculated in case of using option one and added to the force of displacement to get the total force.

M glass= Density x Area x Thickness

M glass= 2.48g/cm3 x 100x300x0.11= 8kg

W glass= 8 x 10= 80N

F total= F displacement + W glass

6.2.1.2 Double layer laminated glass

As it was mentioned before, typical glass elements should be stiffened by lamination in the built environment because of the structural and safety reasons. The type of lamination for the case study is different from the mock-up. The strategy for the determination of the most suitable configuration is based on the force which is needed for bending the panel. In this case, the glass panel is bigger and it is easier to bend it. The most suitable lamination is the one which makes the panel stronger under the wind and at the same time doesn't add to the number of SMA wire. The chosen glazing layer is made up of two glass panes with a thickness of 0.55 mm bonded by E3 lamination configuration in thicknesses of 0.38 mm. The selected configuration is strong enough to withstand wind loads and still as flexible as possible. Also, according to the chart below, the reaction force of the panel in different X displacement is still under 35N and lower than the maximum force that one wire can exert. So, one wire is still needed to bend the panel in different x displacement.

PVB Type No.	Young's Modulus E [MPa]	Shear Modulus G [MPa]	PVB Type	Temperature [°C]	Load Duration
E1	2030	700	Trosifol Extra Stiff	10	3 sec
E2	1450	500	Trosifol Extra Stiff	10	5 min
E3	943	325	Other Stiff PVB	20	3 sec
E4	435	150	SentryGlas	20	1 d
E5	0.3	0.1	Trosifol PVB	30	1 mo

0.55mm — Thin Glass E= 74000Mpa
0.38/0.76 mm — PVB E= 943Mpa
0.55mm — Thin Glass E= 74000Mpa

Table 32, PVB Types [18]

Charts 151 and 152 show the required force and maximum principal stress on top layer 1 of laminated glass in different displacements.
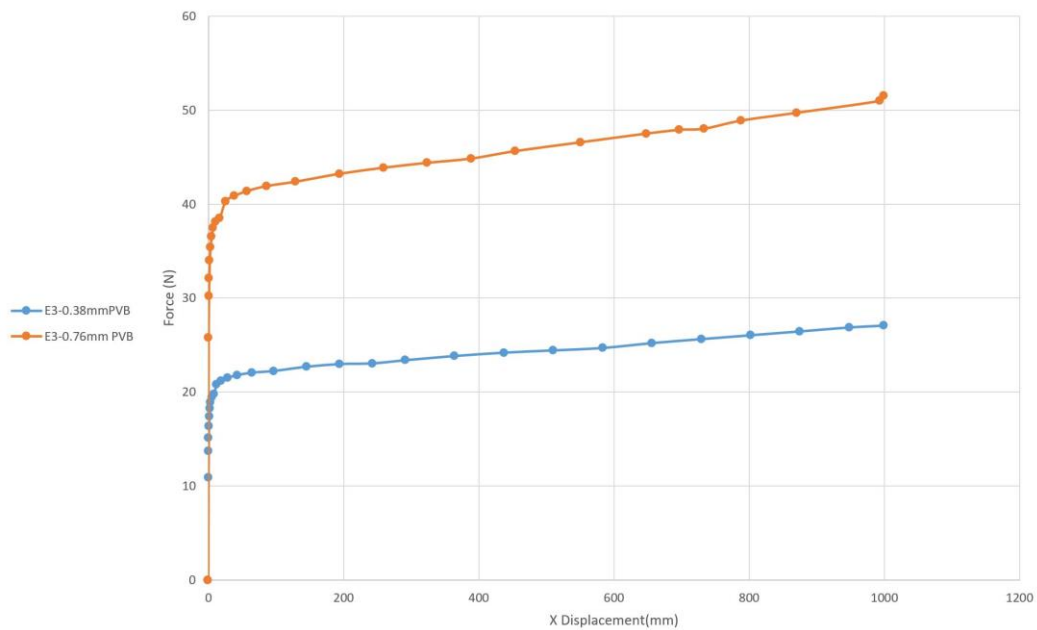
Figure 151, Force vs. X displacement of laminated glass
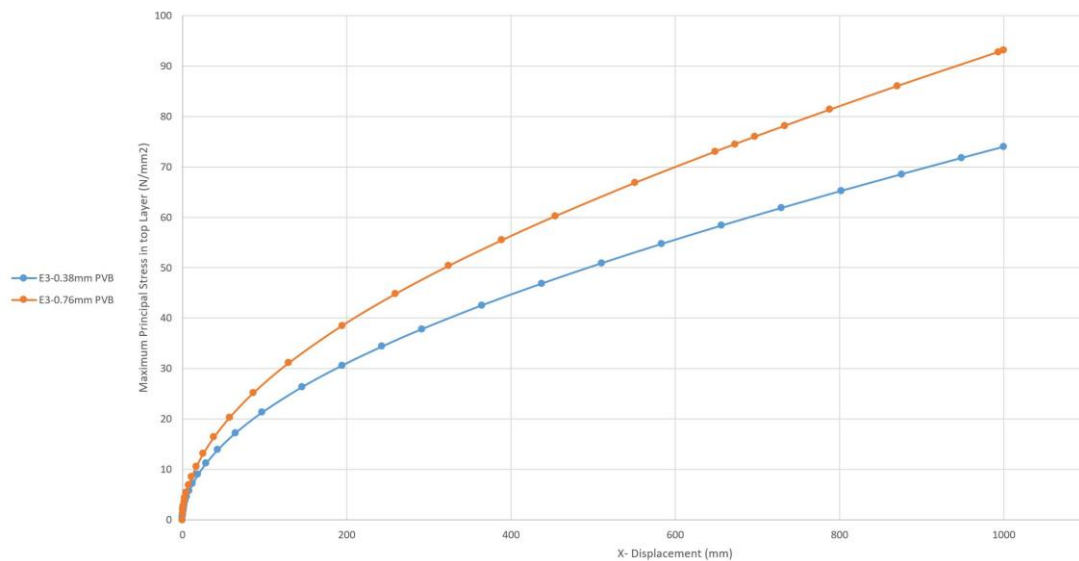
Figure 152, Maximum principal stress in the top of layer 1 vs. X displacement

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Figure 153 shows the structural analysis to get the number of wire for laminated glass in case of using 0.38mm PVB.

Length:	3000 mm
Width:	1000 mm
Thickness:	
Thin Glass 1:	0.55 mm
PVB:	0.38 mm
Thin Glass2:	0.55 mm
Initial Bending:	10 mm

Stroke:	150 mm
U2:	410 mm
Max. Principal stress top layer:	27 Mpa
Force:	22.8 N
No. Wires:	1
Length of Wire:	3000 mm

Stroke:	300 mm
U2:	570 mm
Max. Principal stress top layer:	39 Mpa
Force:	23.5 N
No. Wires:	1
Length of Wire:	6000 mm

Stroke:	450 mm
U2:	692 mm
Max. Principal stress top layer:	48 Mpa
Force:	24.3 N
No. Wires:	1
Length of Wire:	9000mm

Figure 153, Structural analysis of laminated glass
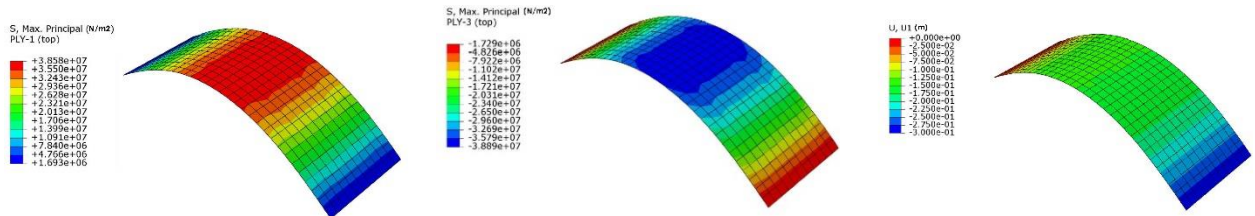
Figure 154, Max. Principal stress on top and bottom layers in 300 mm X displacement   *Figure 155, X Displacement*

6.2.2 Exterior Glazing

In case of applying the window in a single skin façade or the outer skin of double skin façade, the wind load is a crucial factor which should be taken into account. For the FEM analysis, a suction of 1 KN/m² for wind is assumed.

6.2.2.1 Magnet

The wind load can easily bend and move the glass panel which is free to move along the x-axis. As a result, it is supposed to have a magnet strip on the edges of the frame to withstand wind load. So the magnetic force makes the thin glass window closed when it is subjected to the wind pressure. Different types of magnets are analyzed in table 33 in order to select the most suitable one for this case.

Permanent Magnet	Mechanically Switchable Magnet	Electro Magnet	Electro-Permanent Magnet
Extra force from the actuator for opening the window	Switchable Magnet force	Thin	Temporary electric current
	Expensive	several strips need one switch	Low electricity consumption rate
	Thick	High electricity consumption rate	Thin
	Each strip needs one switch	Permanent electric current	several strips need one switch
	Failure in Curved geometry		
X	X	X	✓

Table 33, Magnet types

According to the table 33, Electro-permanent magnet type has been selected for further analysis. These types of magnets do not need a permanent electric current to keep the window closed; A very short power is only required once for the switching. [68] So, they could save electricity compared to the electromagnets and at the same time, there is no need for the extra force from the SMA wires for opening the windows because the magnetic force could be turned off with electricity.

The electro-permanent magnet type is selected from ThyssenKrupp Magnettechnik Company. This type of magnet has an adhesion area of 30 mm x 90 mm with a holding force of 4.6 N/mm.
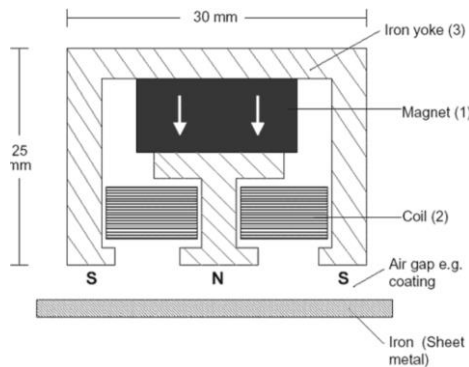
Figure 156, Electrically settable permanent magnets [68]

Two steps of analysis have been done to get the required magnetic force. In the first step of the analysis, the wind is applied while the frame can move from one side along the x-axis and then the frame get fixed on the edges in order to get the required force for the magnet.
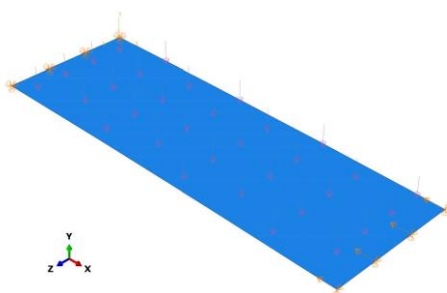
Figure 157, the first step of wind analysis
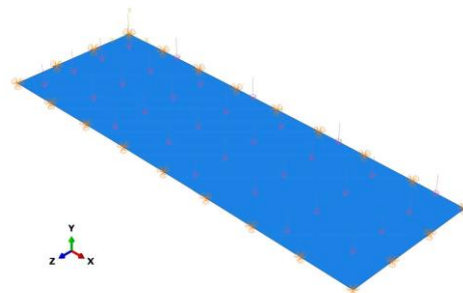
Figure 158, the second step of wind analysis

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6.2.2.2 Single Glass

The wind load can easily bend and move a single glass in size of 1000mmx 3000mmx 1.1mm whose shorter edge could move freely along the long edge. Figure 160 shows that the wind can move the glass panel 1m in the x-direction.
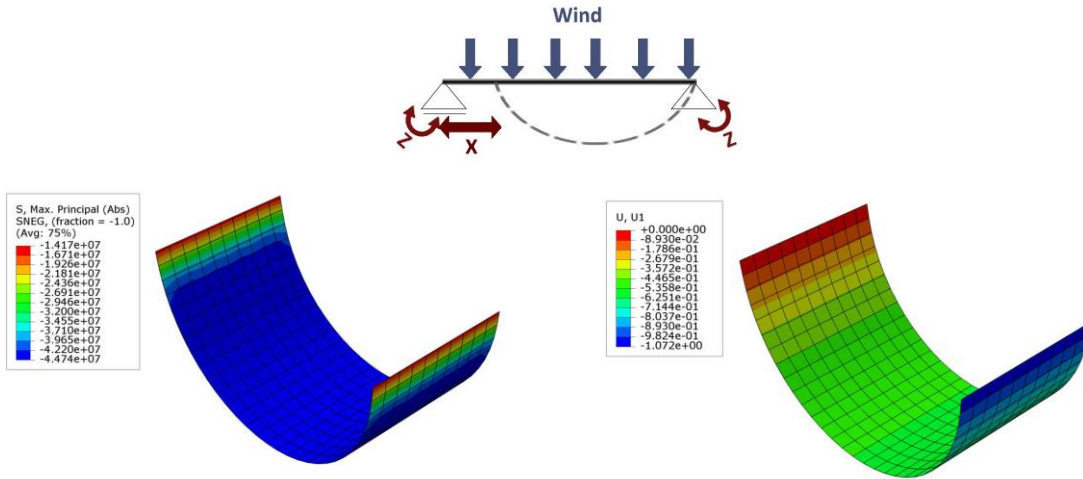
Figure 159, Max. Principal Stress on top Layer in wind   Figure 160, X displacement in wind

By fixing the frame on the edges, the magnetic forces on three free edges could be achieved. Figure 161 shows the behavior of the panel while it is fixed on four edges.

Max. Principal Stress on top Layer   X Displacement

Y Displacement   Z Displacement
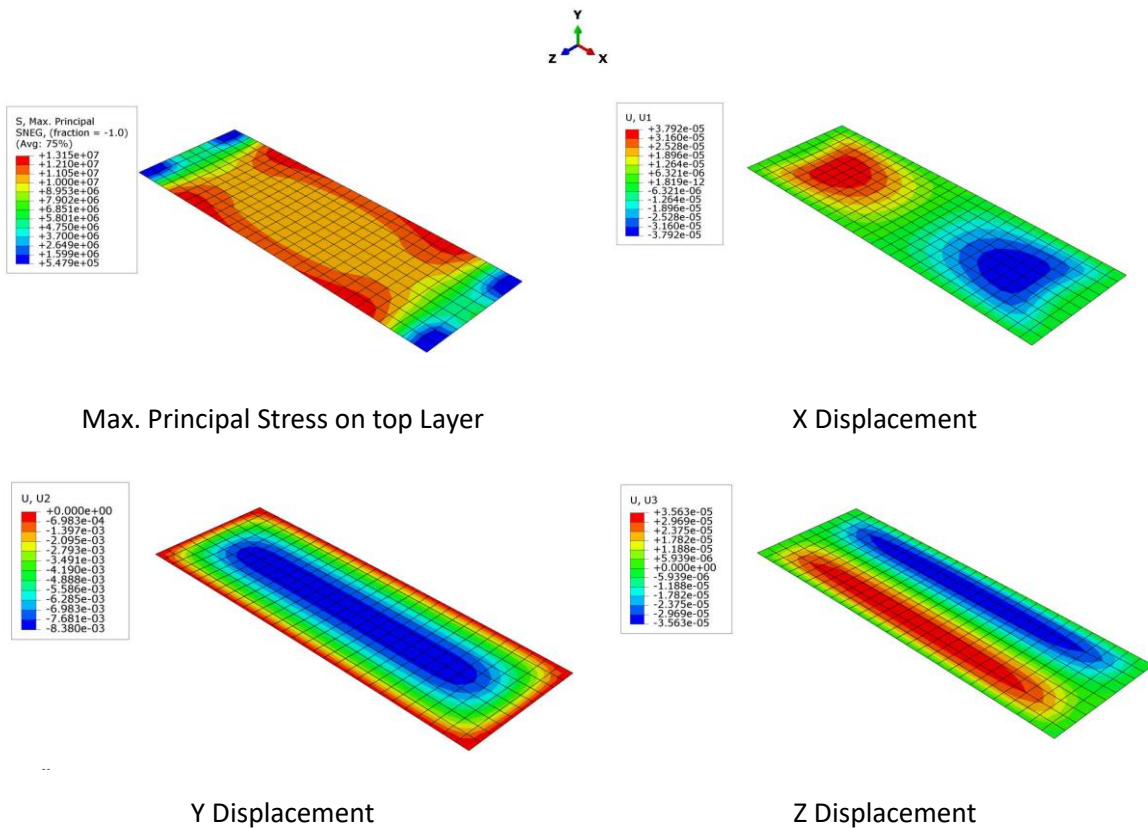
Figure 161, Structural analysis of a fixed panel of 1.1mm

The sum of the reaction forces of the nodes on each edge shows the required magnetic force on that edge to fix the panel.

F1= 4899N= 4.9 N/mm
F2= 1357N= 0.452 N/mm
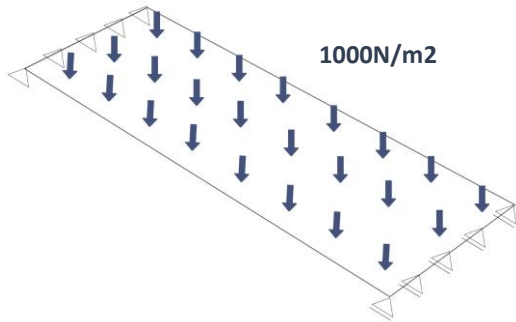
Figure 162, Free edges in wind   *Figure 163, Magnetic forces in wind*
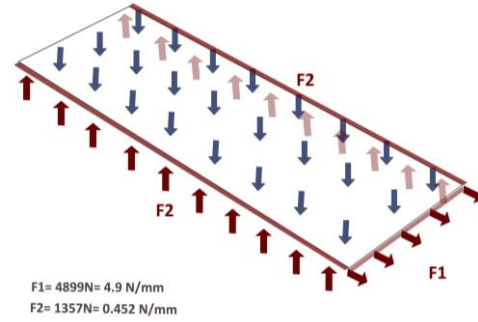
The magnetic force on long edges should be in Y direction while on the shorter edge it is in the X direction. The sum of reaction forces in the other directions are almost zero. F2 force in longer edge could be neglected due to its small amount compared to the shorter edge. It should be also considered that placing the magnet along the long edge which should be bent is problematic and affect the movement of the panel. A simple structure has been placed behind the long edges of the glass in order to prevent the glass to be bent toward inside while the shorter edge is fixed by magnetic force. Figure 164 shows the schematic diagram of the window while it is closed.

F1= 4899N= 4.9 N/mm
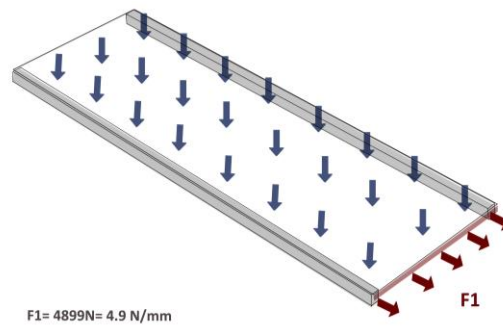
Figure 164, closed window with one glass

6.2.2.3 Double layer laminated glass

The same analysis has been done for the panel with two glass of 0.55mm thickness and PVB interlayer of 0.38mm.

Figure 165 shows that the wind load can move the glass panel around 1m from its free edge.

a   b   c
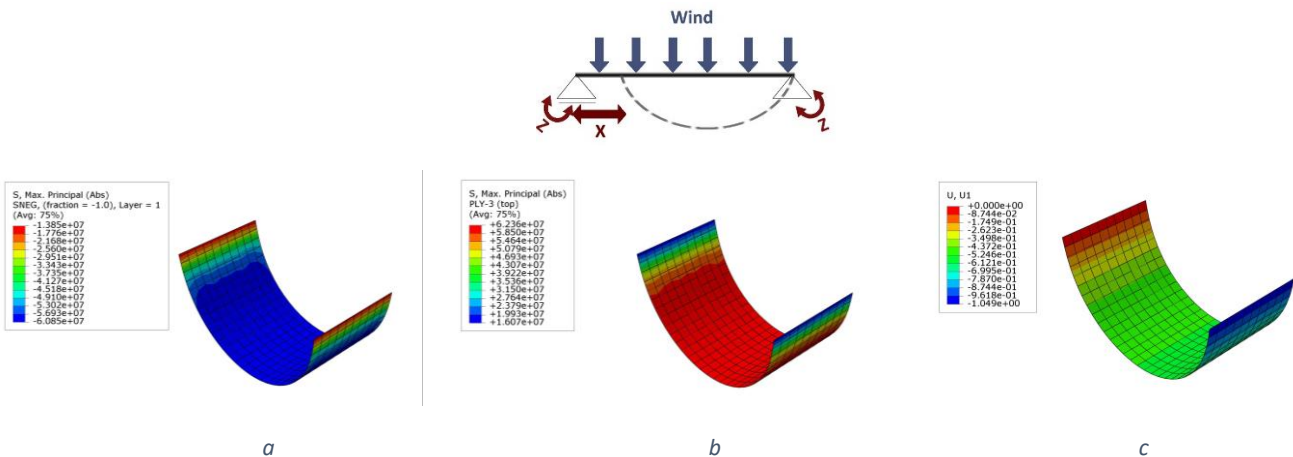
Figure 165, (a), Max. Principal Stress on top Layer 1, (b), Max. Principal Stress on top Layer 2, (c), X displacement

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Figure 168 shows the behavior of laminated glass while it is fixed on four edges.

Max. Principal Stress on top Layer 1

Max. Principal Stress on top Layer 3

X Displacement

Y Displacement

Z Displacement
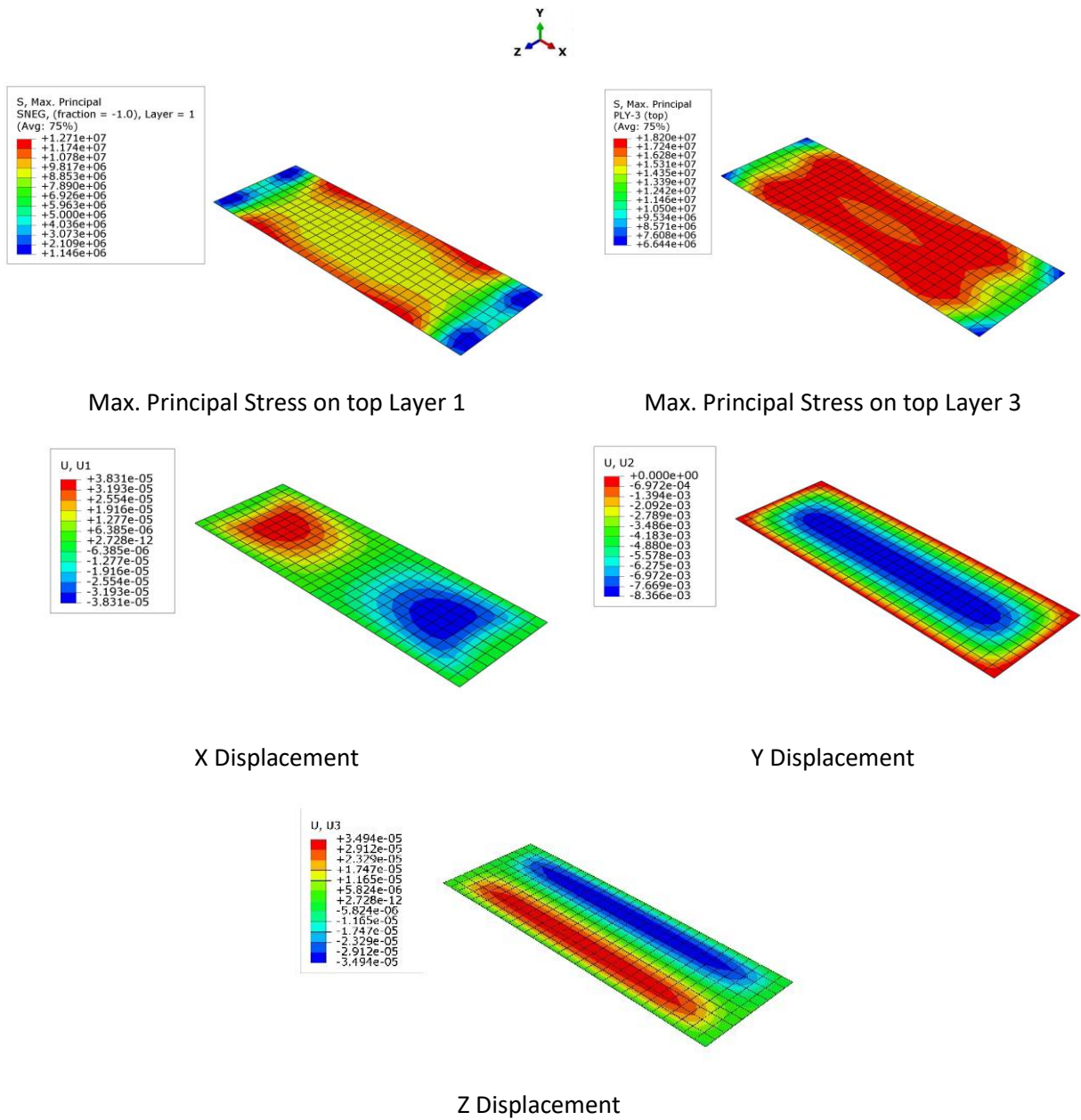
Figure 166, Structural analysis of fixed laminated panel

The same analysis has been done to get the magnetic force in each free edge.

1000N/m2

F2

F2

F1

F1= 4654N= 4.6 N/mm
F2= 1498N= 0.5 N/mm
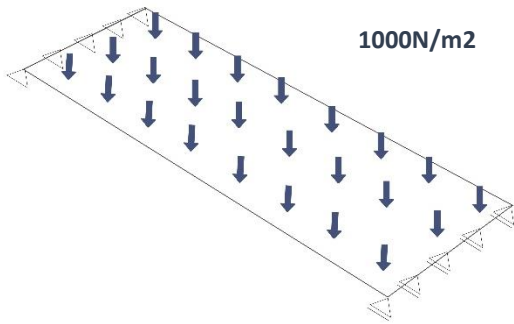
Figure 167, Laminated glass, Free edges in wind   *Figure 168, Laminated glass, Magnetic forces in wind*
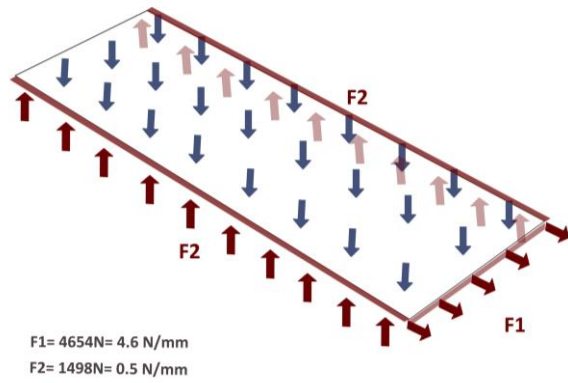
The magnetic forces are smaller due to laminating of glasses. The force F1 is exactly same as the force that the selected magnet could provide. F2 could be neglected as it was discussed before. The schematic diagram of the closed laminated wind under wind is like figure 171.

F1= 4654N= 4.6 N/mm   F1
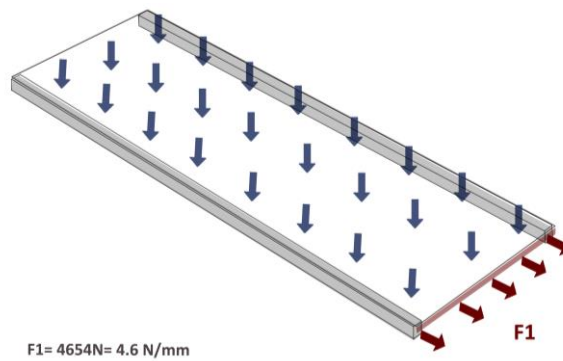
Figure 169, closed window with laminated glass

6.3 Climate Analysis

One of the main reasons for creating an adaptive façade is to create a breathing façade by making openings for fresh air.
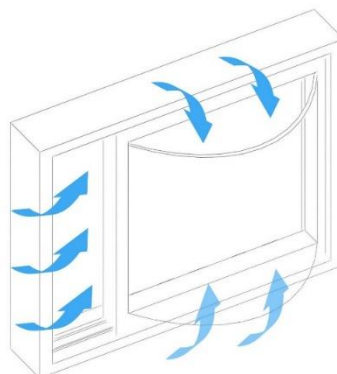
Figure 170, breathing façade

Depend on the length of the SMA wire and its stroke, the opening area for fresh air could be calculated. The air flow rate could be also calculated according to ASHRAE standards.

Area of Panel: 1000mmx3000mm   Q= air flow rate   V air= 0.1 m/s

Q= V air x Area opening
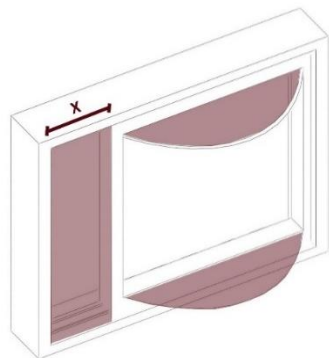
X= 15cm
2x 8116 cm^2
1x1500 cm^2

17732 cm^2
Q= 177320 cm^3 / s

X= 45cm
2x 12589 cm^2
1x4500 cm^2

29678 cm^2
Q= 296780 cm^3 / s

X= 30cm
2x 10815 cm^2
1x3000 cm^2

24630 cm^2
Q= 246300 cm^3 / s

Figure 171, air flow rate in different displacements

6.4 Details

Before drawing and selecting the details for the case study, the details of both concepts have been drawn. As it was mentioned before, there are two alternatives for placing the wires in the panel. They could be placed in the frame or between two glasses. The details of both alternatives have been drawn separately to investigate the pros and cons of each concept later.
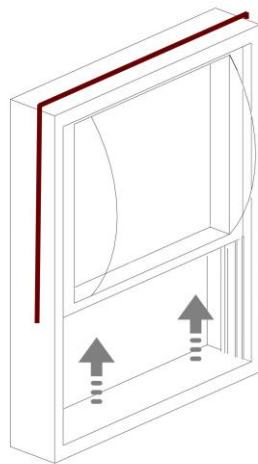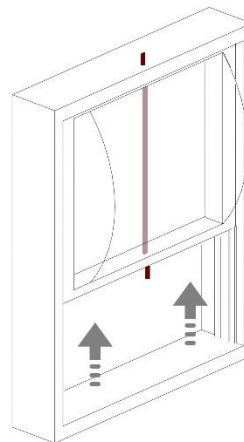
Figure 172, Option I   *Figure 173, Option II*

6.4.1 Number of Glazing

Before drawing the details, the number of glazing in each unit should be specified. Table 34 is a short comparison between the single glazing and double glazing concept. The single glazing concept is lighter, and as a result, less and shorter wires are needed for bending the glass. Consequently, the unit consumes lower electricity and has faster reaction time. On the other hand, in case of placing the wire behind the glass, it will be exposed to the outside and should be covered by a type of insulation. The wire becomes hot and carries electricity in activated status, so it should be protected from users in order not to make safety problems. It should be considered that in case of covering the wire, it cannot be activated by solar radiation. Furthermore, having two glasses which are placed symmetrically could improve the balance of the window while the wire becomes activated and opens the window. Placing one glass in the frame might create balance disorders. In the second concept, two glasses are placed

in such a way that air flows in the intermediate cavity. Depends on the width of the cavity, there is a possibility to create a higher airborne sound insulation for the unit. Also, by adding a second glass pane, the insulating value of the fenestration product glass alone becomes doubled. As the additional glass increases the insulating value of the assembly, it also diminishes the visible light transmission and the solar heat gain coefficient. Moreover, the increased weight due to the extra glass makes mounting and handling more difficult and transportation more expensive.
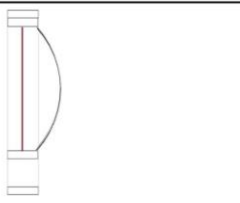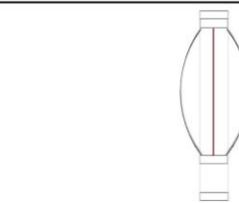
+	-	+	-
Less wire	Balance disorders	Improved balance	Extra wires for bending
Lower Electricity consumption	Covering the wire	Possibility of activation by solar radiation	Higher Electricity Consumption
Fast reaction time		Wire protection	Slower reaction time
		Higher airborne sound insulation	Occupy more space from inside
		Higher Thermal Resistance	Heavier

Table 34, single glazing unit vs. double glazing unit

The details are drawn based on the tests which have been done on two mock-ups. Same as mock-up design, each frame consists of two layers of glass which could be bent from the bottom. Of course, there is a possibility to have one layer of glass with the same details in case of not having enough space from inside.

6.4.2 First Sketches

In the initial design, the details are similar to the ones that traditional windows have. The aim was to make a male and female connections for two glass panels in a way to create a watertight and airtight panel when the window with two glasses on the side is closed.
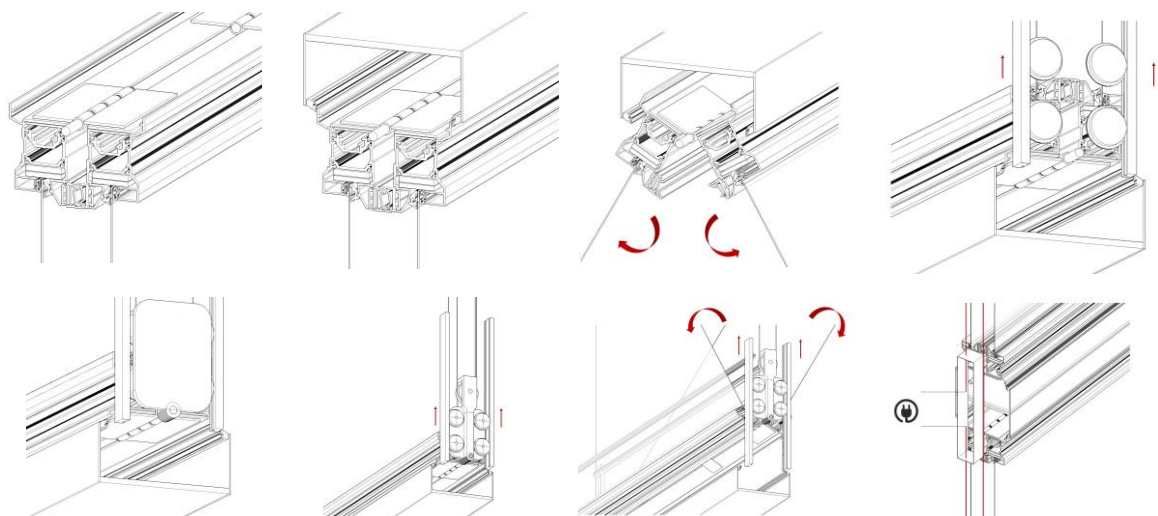
Figure 174, Initial detail design

It should be noticed that although the details make an entire watertight and airtight frame, they are so complicated and heavy for a frame with a very thin glass. So, the details are not considered for further analysis.

6.4.3 Detail development

The first element that should be analyzed individually is the edge profile of the glass which is connected to the middle hinge and is same on top and bottom of the frame. The profile should be designed in a way to have maximum space for bonding the glass. The dimension of the extension is based on 3M VHB structural glazing tape data sheet and selecting G23F with the maximum width of tape which is 35mm. [69]
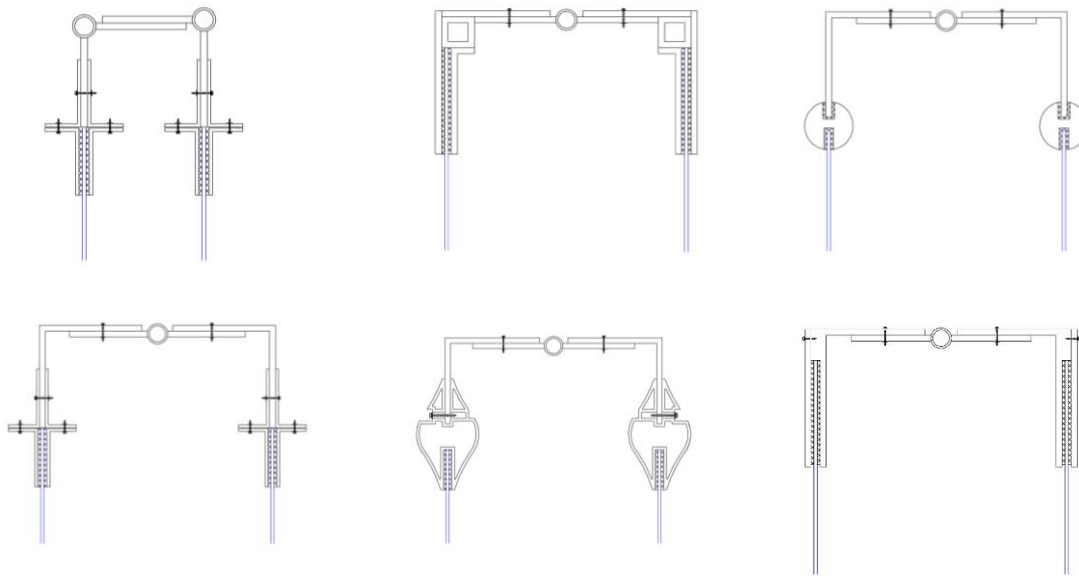
Figure 175, Profile alternatives
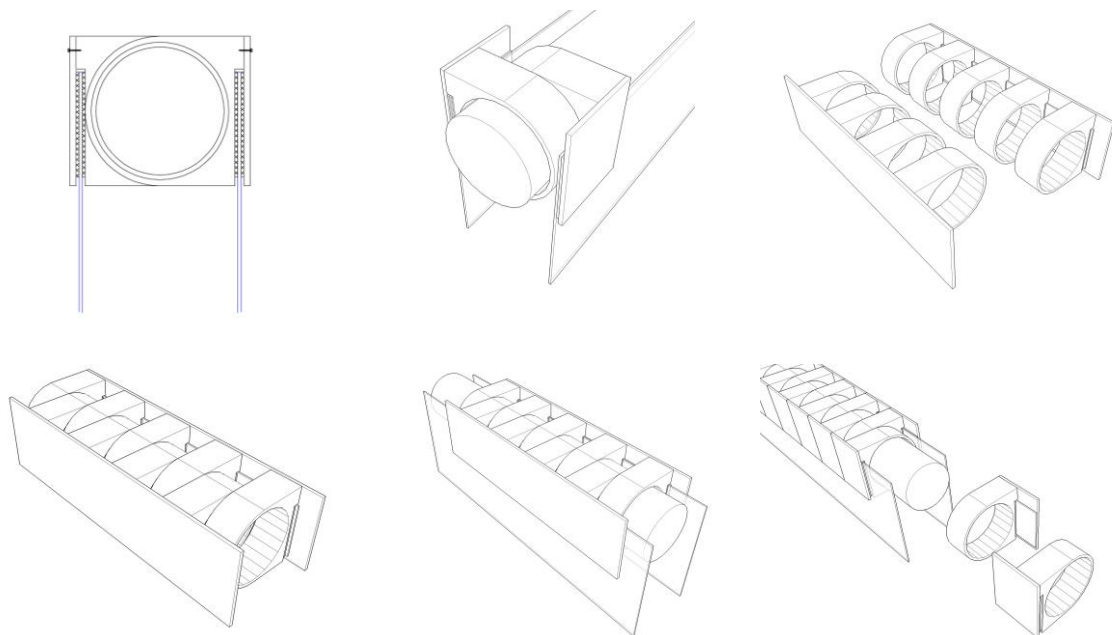
Figure 176, Interlocking profile

Alumium Profile
3M VHB Structural Glazing Tape
3M VHB Structural Glazing Tape
Alumium Cap
Selft Tapping Screw
Thin Glass
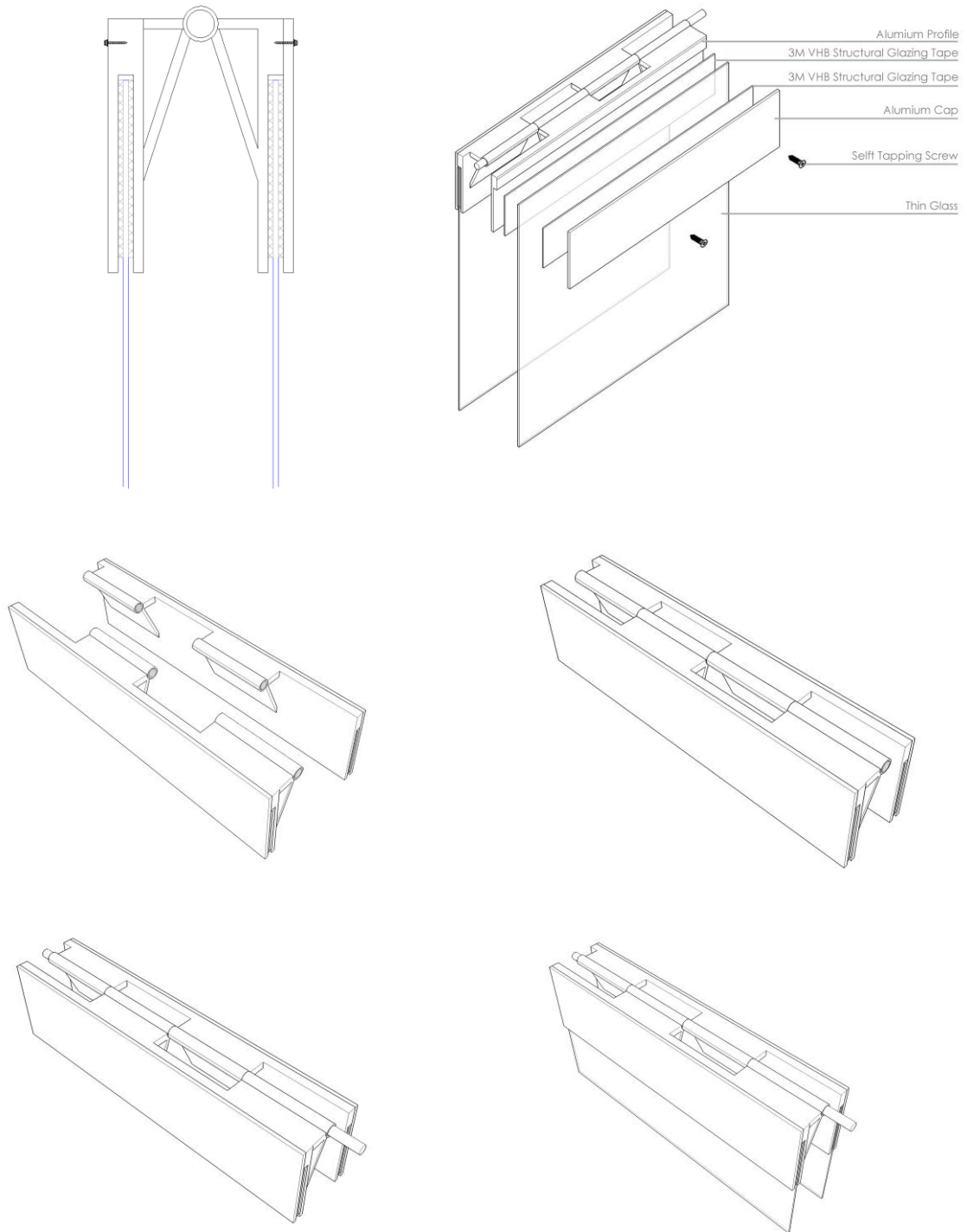
Figure 177, Interlocking profile 2

6.4.4 Final Detail

For further analysis, a type of profile similar to the mock-up has been designed.

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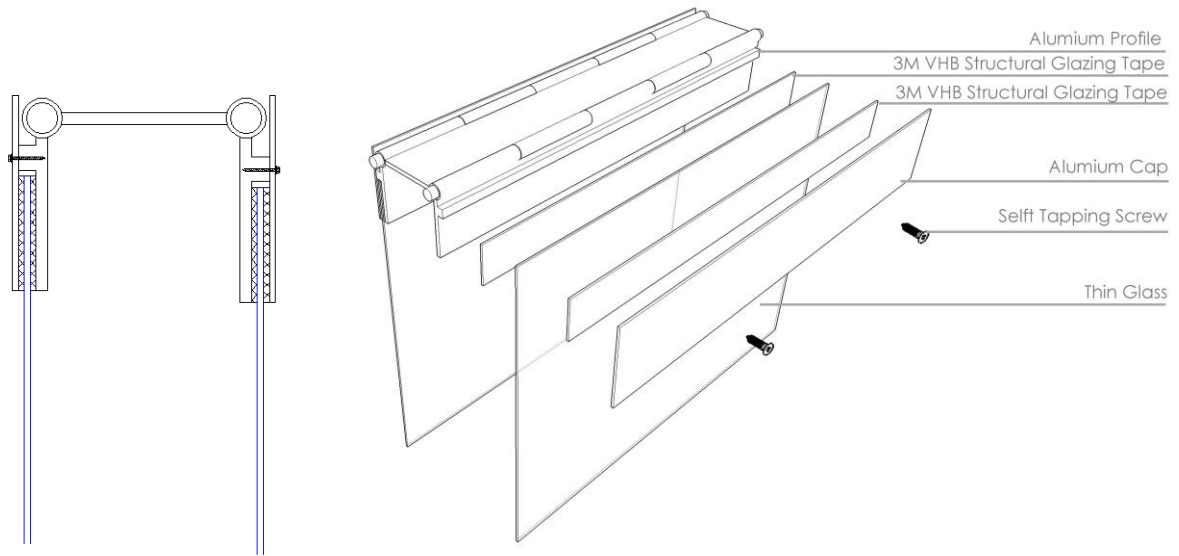
Figure 178, selected profile

Figure 179 shows the setup procedure for the final profile.
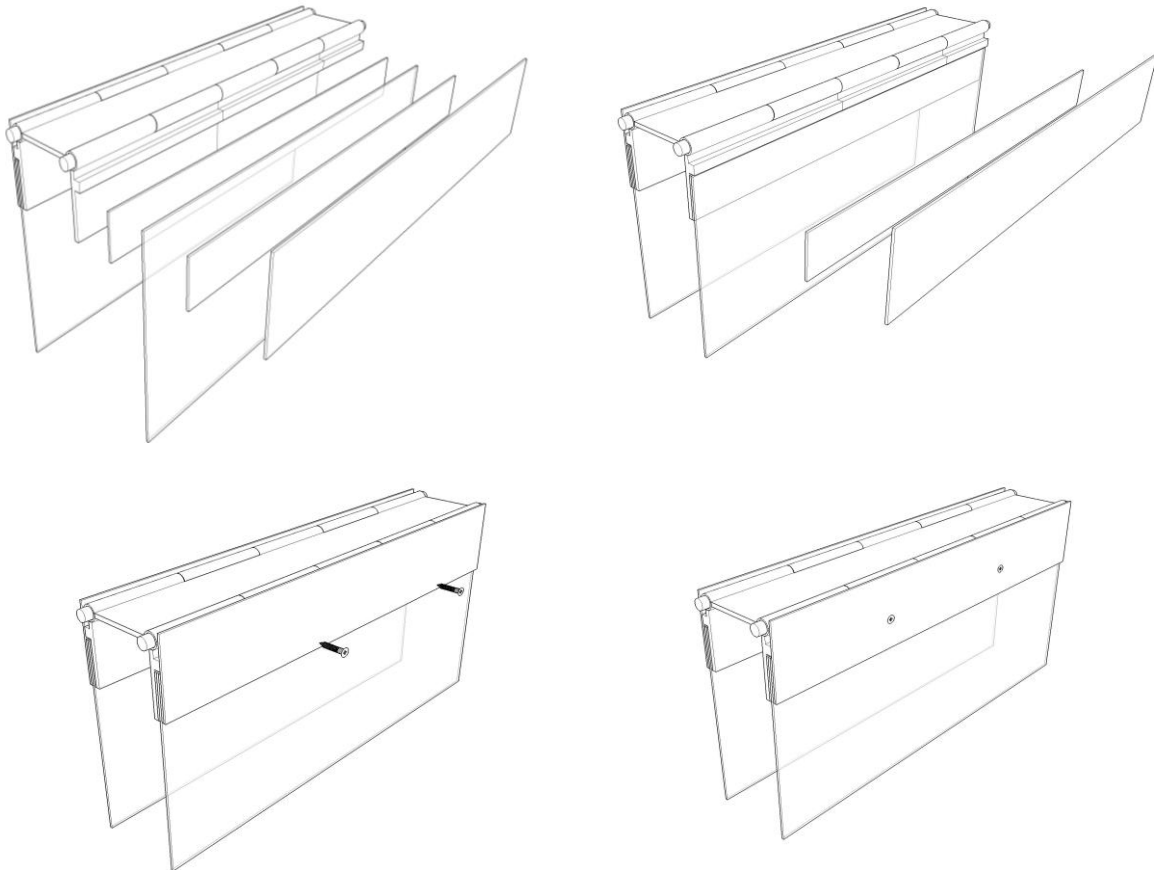
Figure 179, Final profile setup

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6.4.4.1 Concept I

In concept I, the details are drawn in a way to guide the SMA wires around the glass and inside the frame. For the bottom part of the window in outside situation, a magnet with mentioned dimensions is placed under the frame for keeping the window closed in wind.
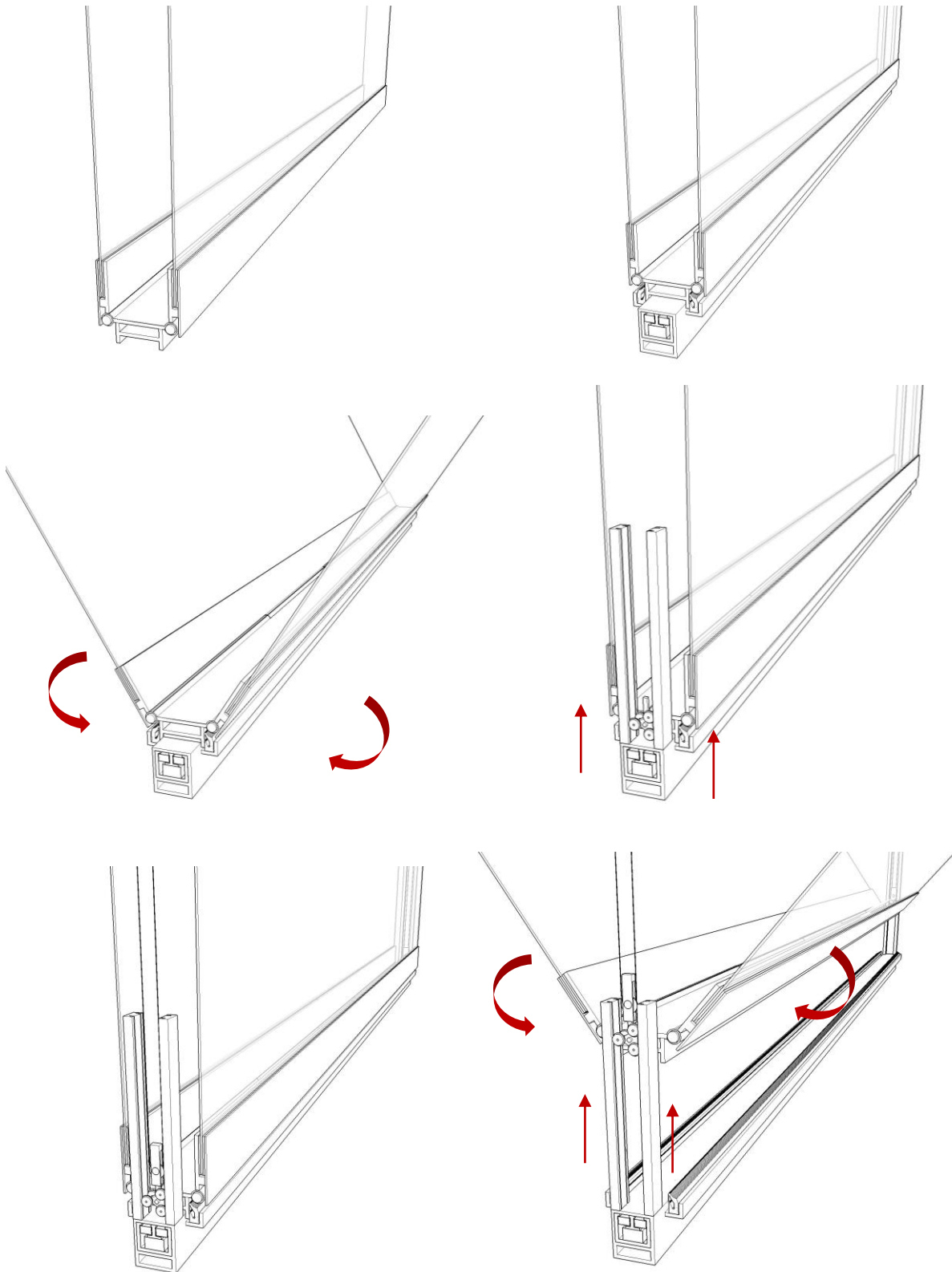
Figure 180, Concept I final window setup

The SMA wire can move and rotate smoothly around the frame with the use of several wheel guides which are placed on top of the frame.
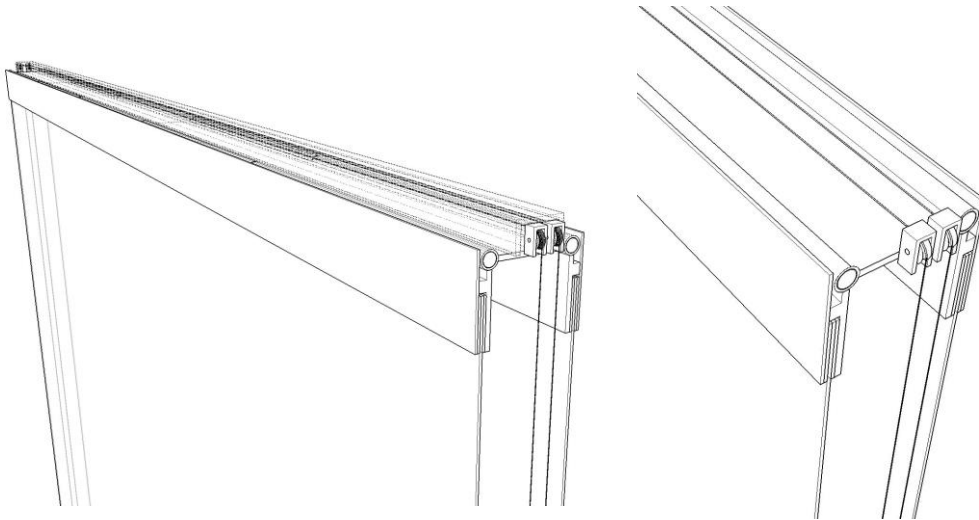
Figure 181, Wheel guider concept I

Both ends of the SMA wire are connected to the electricity from one side of the frame while on the other side, the wire just passes through the wheel guider.
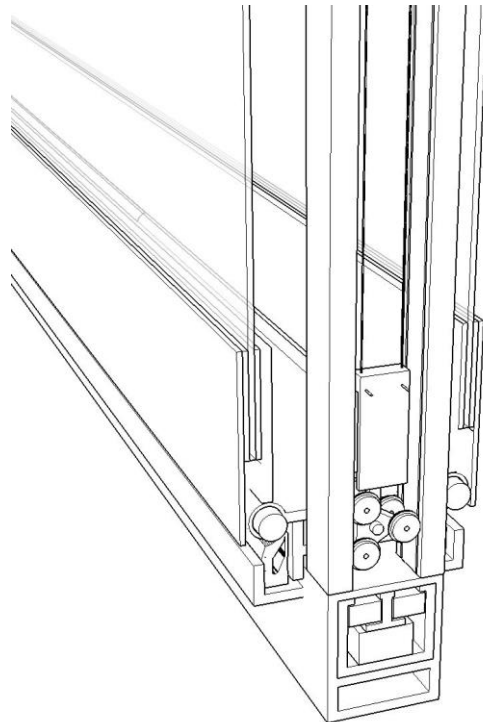
Figure 182, free end SMA wire side

Three elevations of top and bottom of the frame are shown in figure 183.
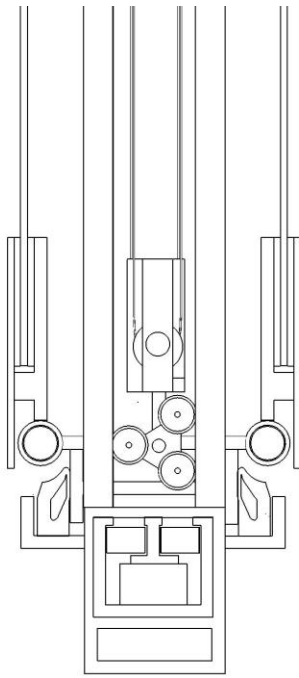
Bottom Connection 1   Bottom Connection 2
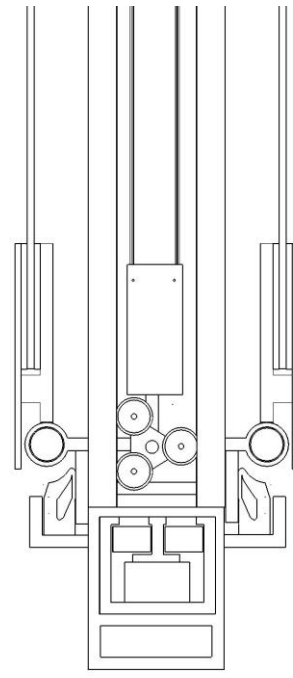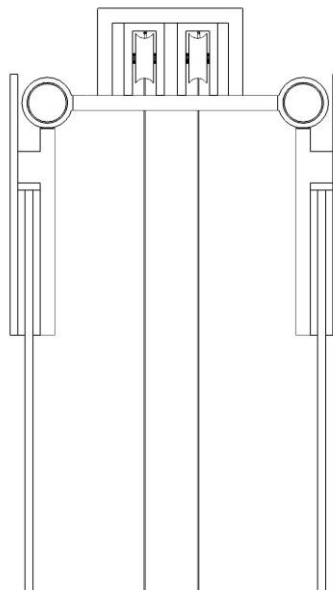
Top connection

Figure 183, Side views of concept I

6.4.4.2 Concept II

The details of the second concept are same as the first one except for the part for connecting the SMA wire. In the second concept, the wires are placed between two glasses and there is no need for extra guiders in the frame.
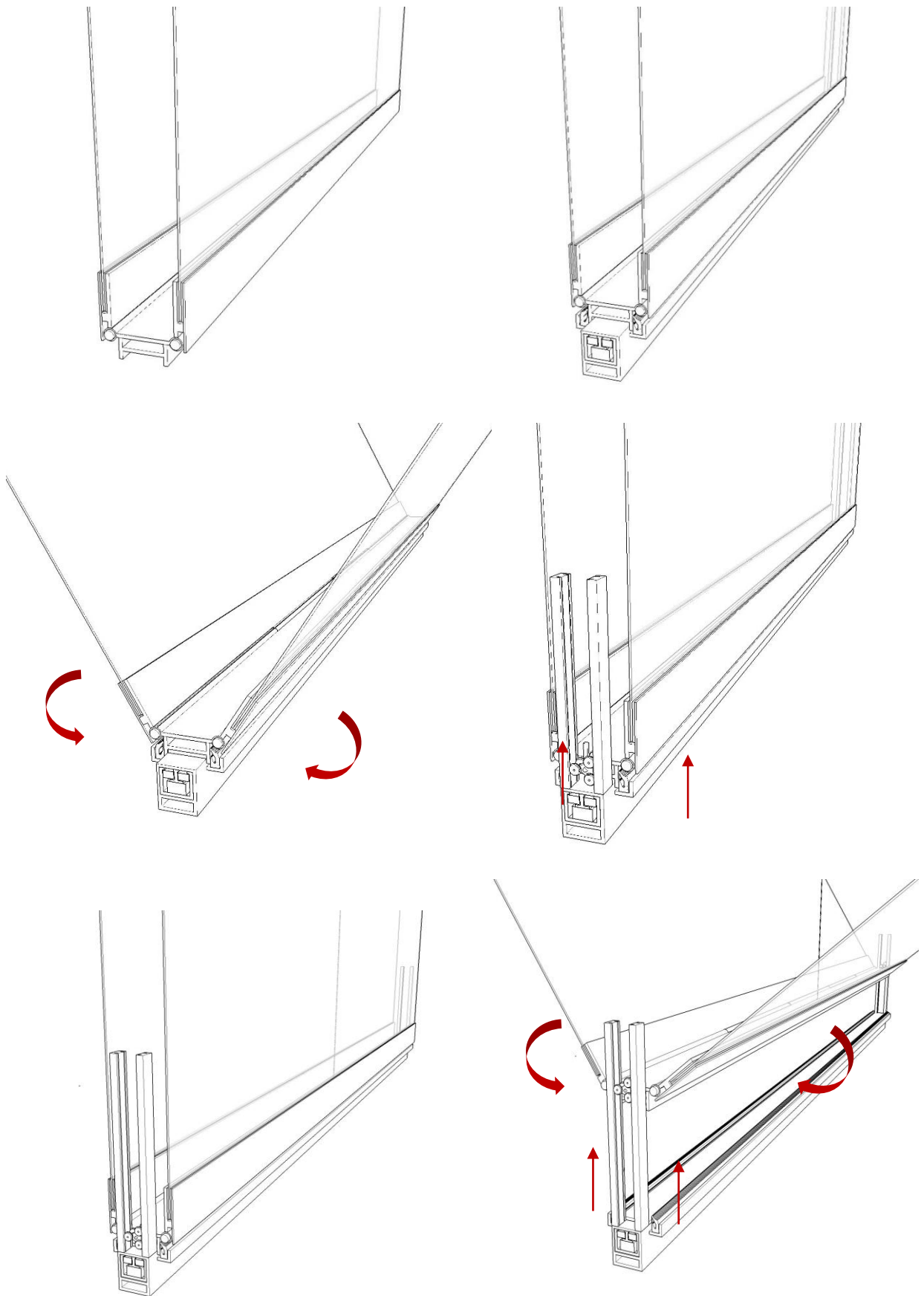
Figure 184, Concept II final window setup

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Figure 185 shows the side views of the second concept window in the top and bottom parts.

<table>
<tr><td>Top connection</td><td>Bottom connection</td></tr>
</table>
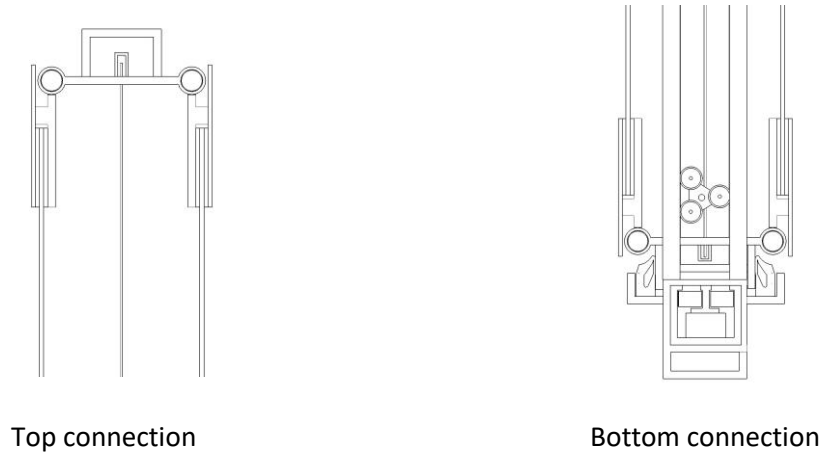
Figure 185, Concept II side views

6.4.5 Case study Details

The breathing windows are replaced with both inner and outer windows. The second concept with the wire between two glasses has been selected as its frame is thinner and the percentage of the transparency is higher. The size of the new thin glass windows is 1000mmx3000mm with different thicknesses based on the position of the window.

6.4.5.1 Atrium Window

The operable inner windows could be replaced by two layers of 0.55mm laminated thin glasses. There is no need for placing the magnet in the frame because the window is protected by the atrium and it's covering on top.
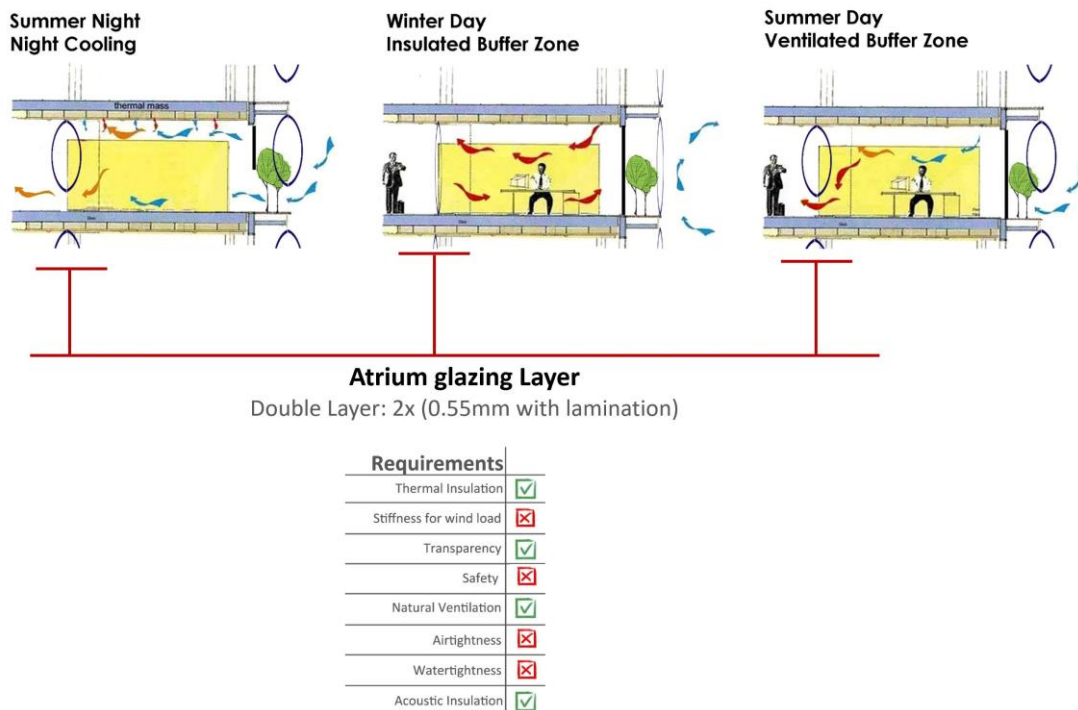
Figure 186, Requirements of atrium glazing layer

6.4.5.1.1 Atrium Window Details

The details are same as the ones in Figure 185. The frame is smaller because the magnet is removed.
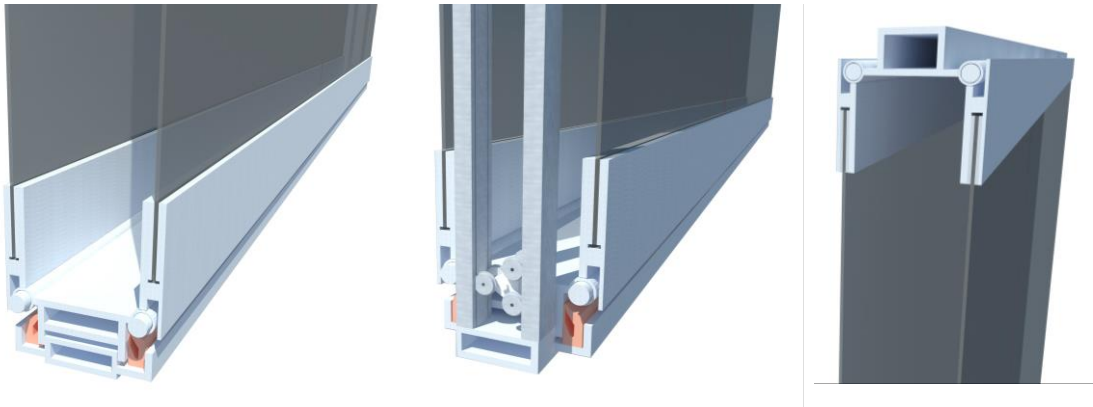
Bottom Connection from middle   Bottom Connection with rail   Top connection

Figure 187, 3d views of the details of the Atrium window
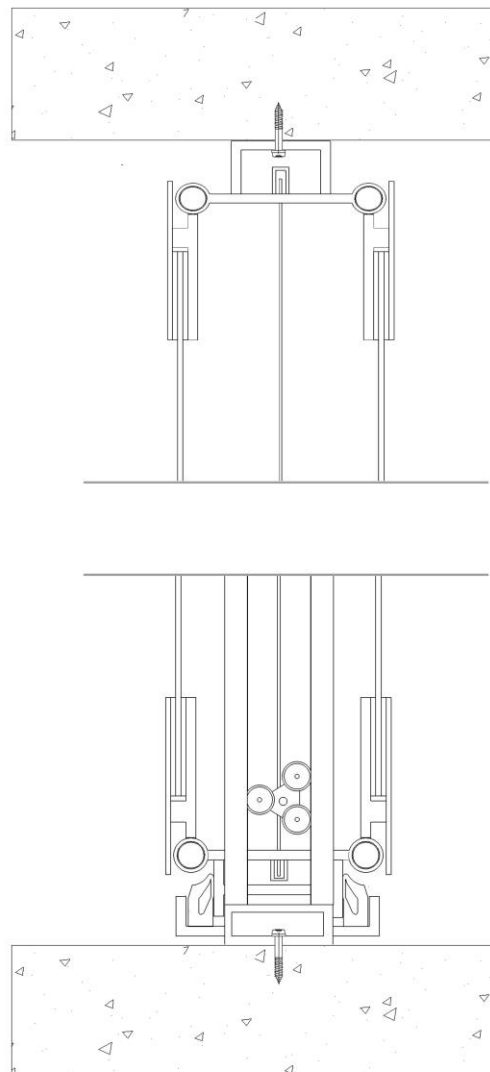
Figure 188, Section of the Atrium window
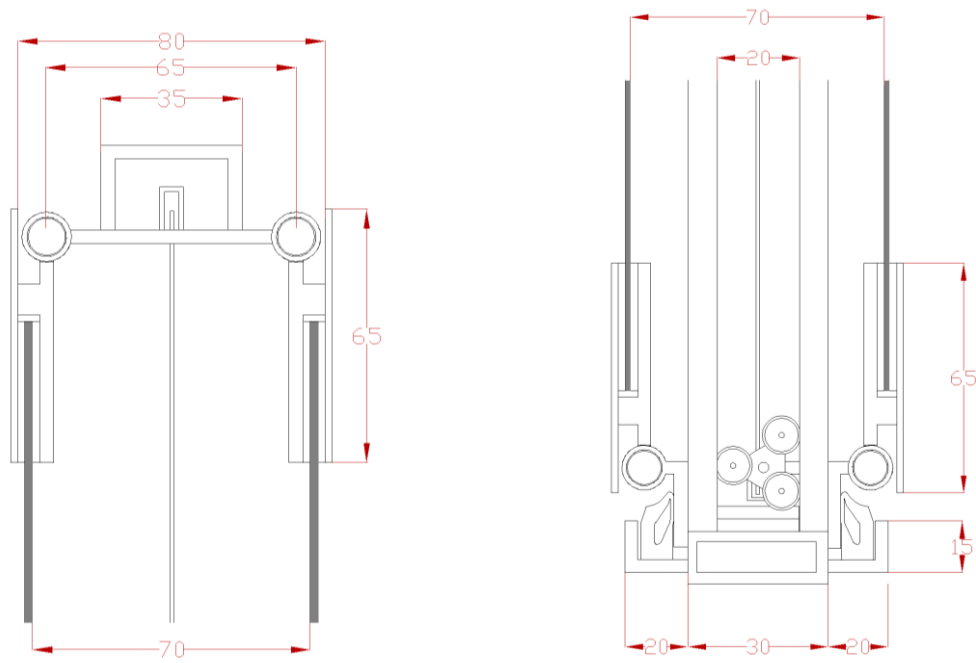
Figure 189, Details of the inner window

6.4.5.1.2 3d views of interior facade
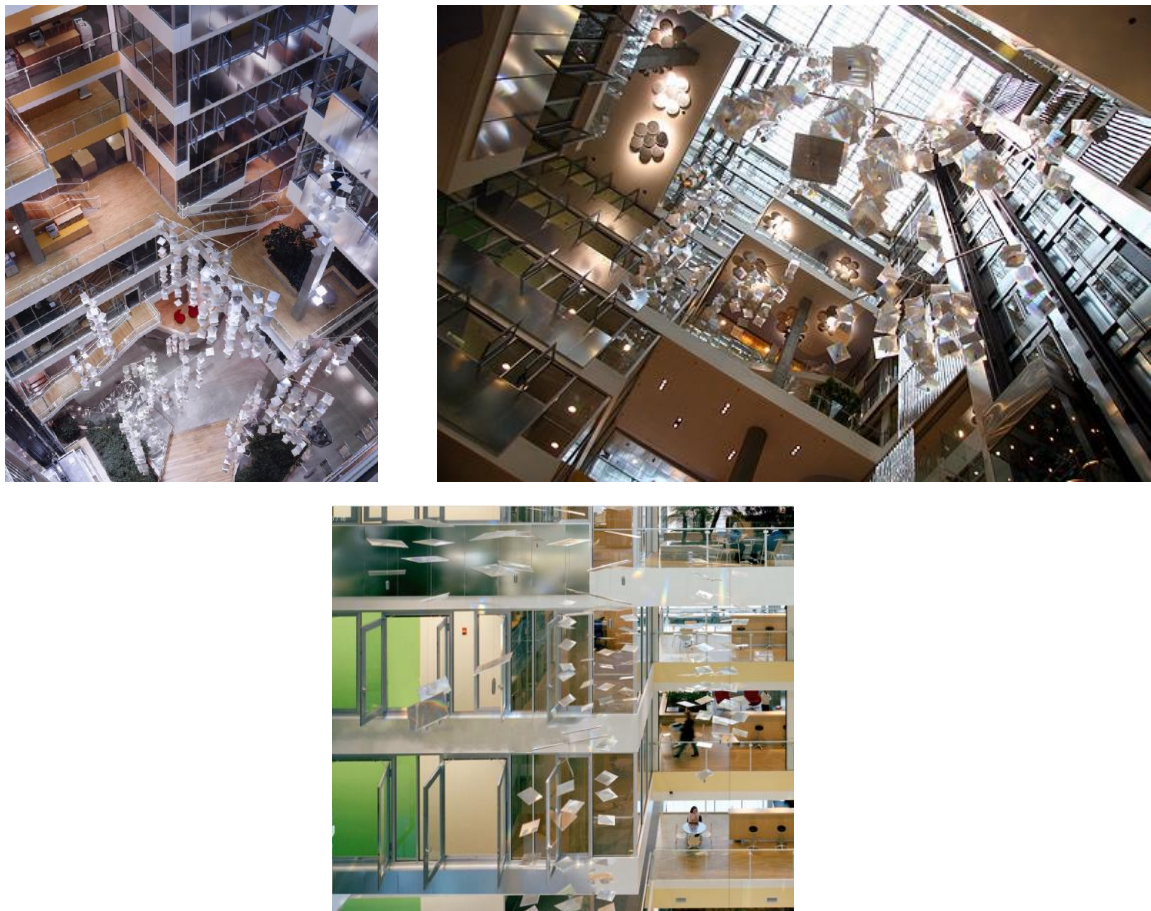
Figure 190, Current situation of the inner windows
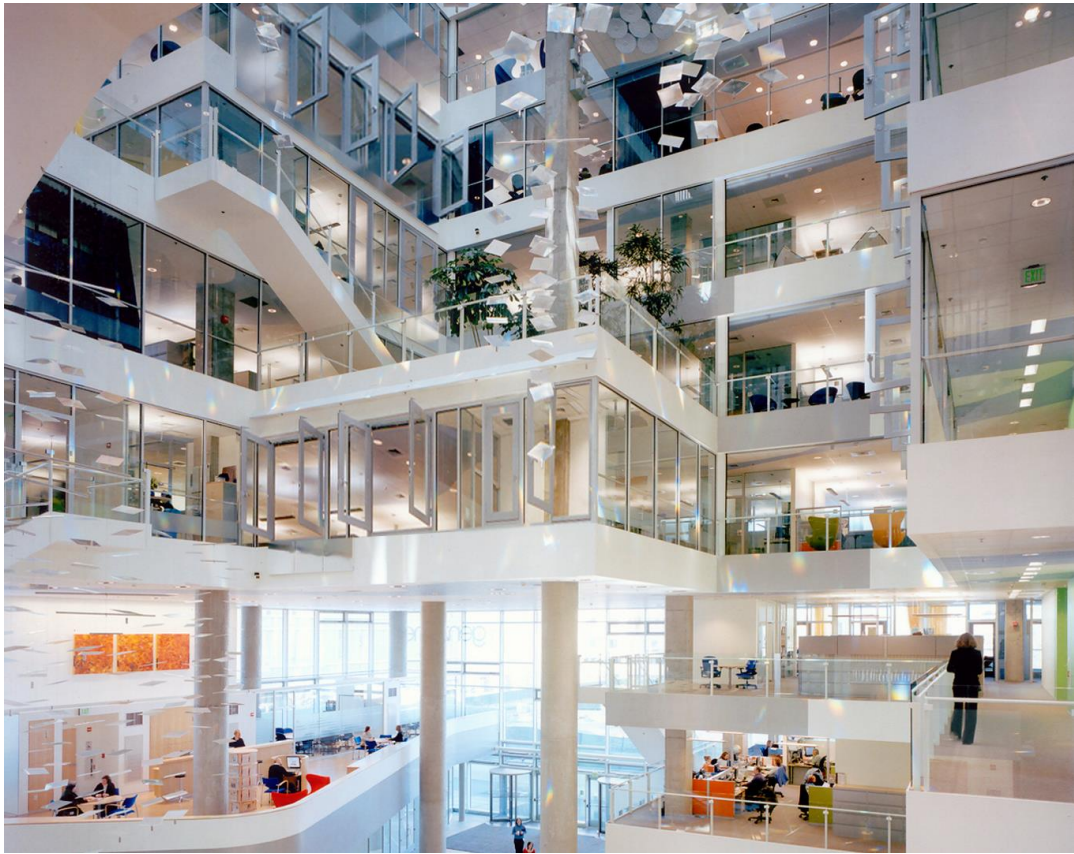
Current situation

Proposed situation

Figure 191, existing interior window vs. proposed interior window

Relaxed SMA Situation
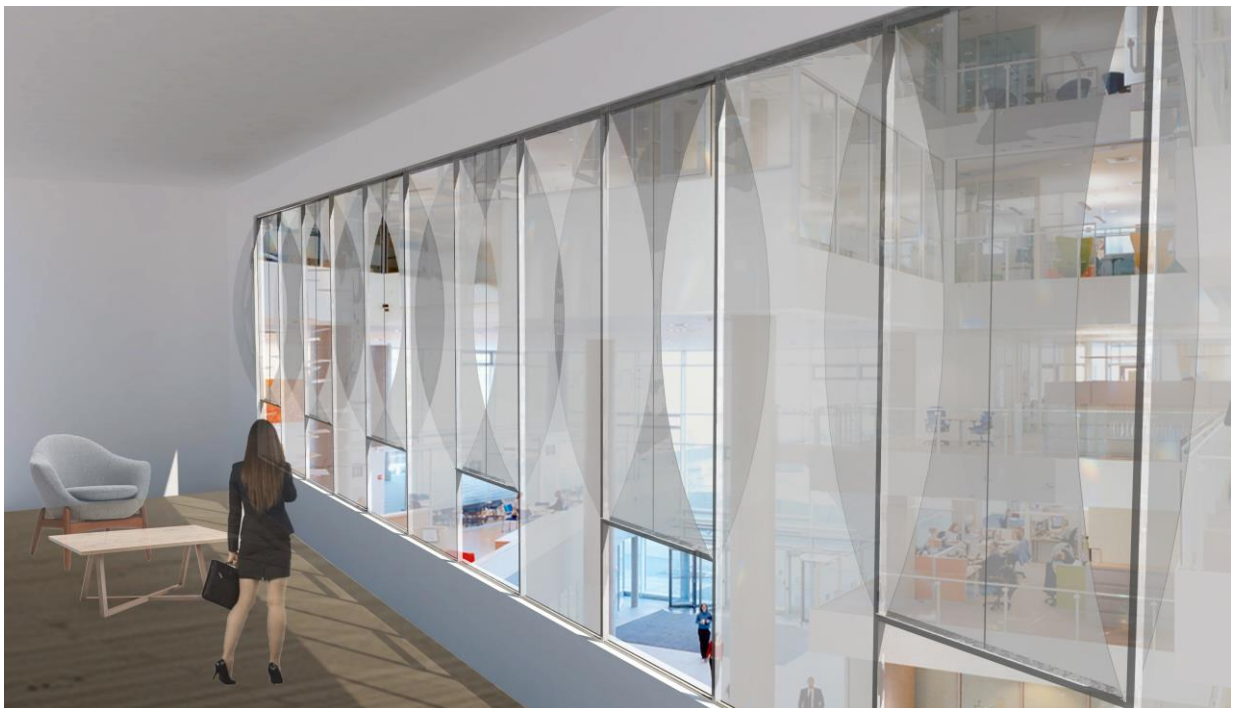
Activated SMA Situation
Figure 192, Proposed interior window system

6.4.5.2 Exterior window

The breathing façade could be also replaced with the second skin of the double skin façade in the building. In this case, a magnet with the mentioned details is placed under the frame to keep the window closed in wind. The window could contain either a single layer of 1.1mm laminated glass or two sheets of double glazing layer with 0.55mm thickness and lamination between.

Summer Night
Night Cooling

Winter Day
Insulated Buffer Zone

Summer Day
Ventilated Buffer Zone
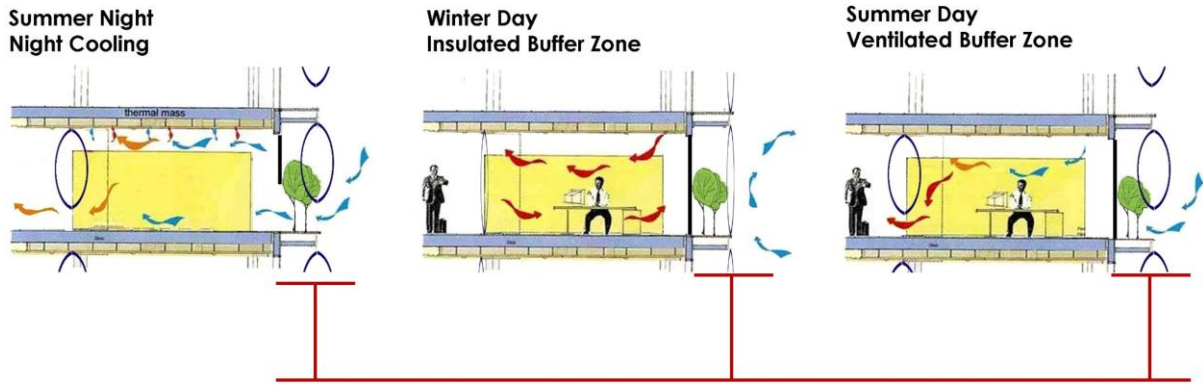
Outer glazing Layer
Double Layer: 2x (2x 0.55mm with lamination between)
Single Layer: 1x (1.1 mm and Lamination Layer)

Requirements	
Thermal Insulation	☒
Stiffness for wind load	☑
Transparency	☑
Safety	☑
Natural Ventilation	☑
Airtightness	☒
Watertightness	☒
Acoustic Insulation	☒

Figure 193, Requirements of the outer glazing layer

6.4.5.2.1 Exterior Window Details

The profile is made in the Aluminum extrusion process. The details are same as the ones in Figure 185 for concept II.

Inner Ultra Thin Glass

Outer Ultra Thin Glass

Shaft for SMA wires
Metal Sheet

Aluminium Profile
Electro-Permanent Magnet
Shaft for Magnet wires
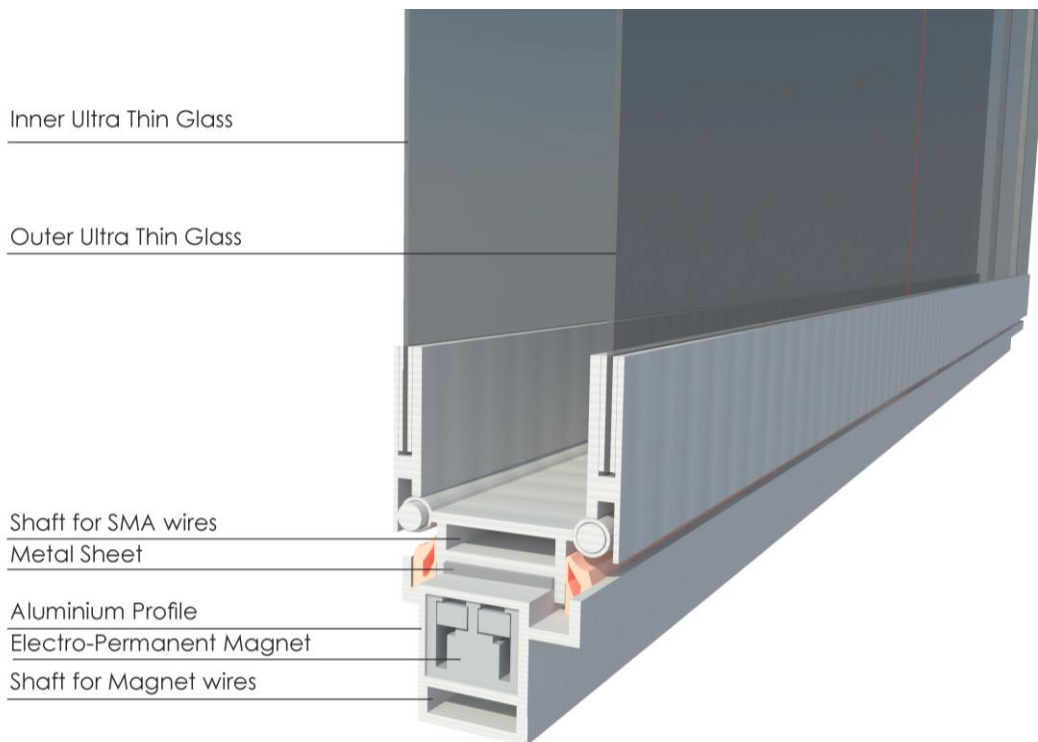
Figure 194, 3d views of the details of the outer window

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In general, the panel is supposed to be placed in the building with the unitized system. Each unit consists of an adaptive thin glass layer on top and a fixed single glass in the bottom part. The fixed single glass is placed in front of the thickness of the floor while it contains insulation.
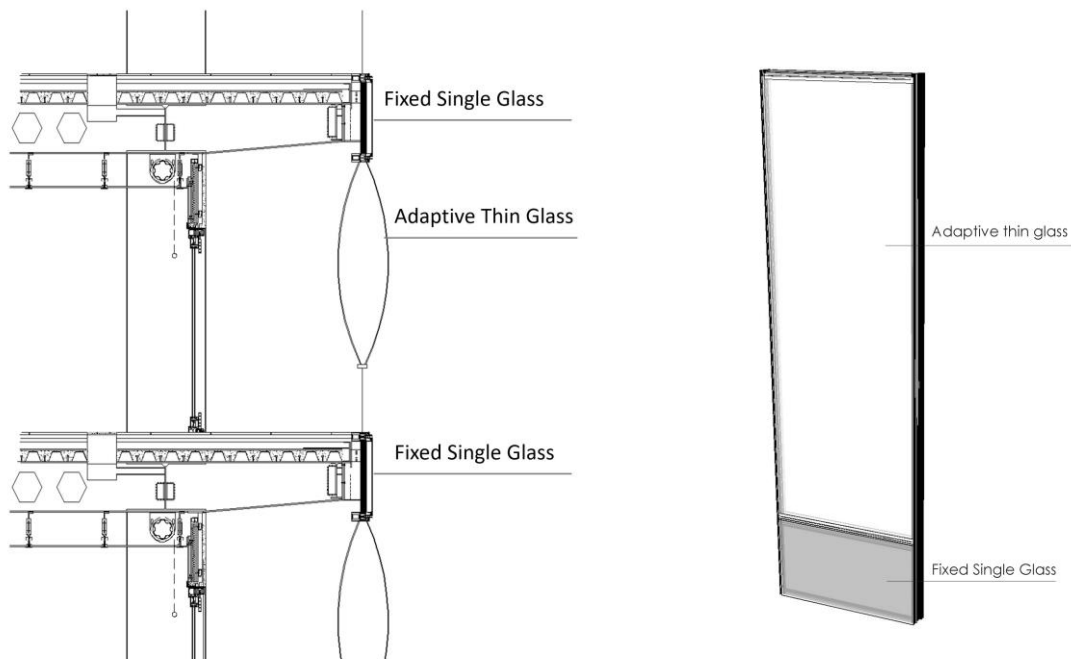
Figure 195, new concept panel

In order to assemble the façade in the unitizing system, the details are designed based on CW 86-SG, a unitized structural glazing Aluminum profile, from the Reynaers producer. [70] The details for the fixed single glass is similar to the mentioned profile while the part for adaptive thin glass is designed in a way to match with the other half.
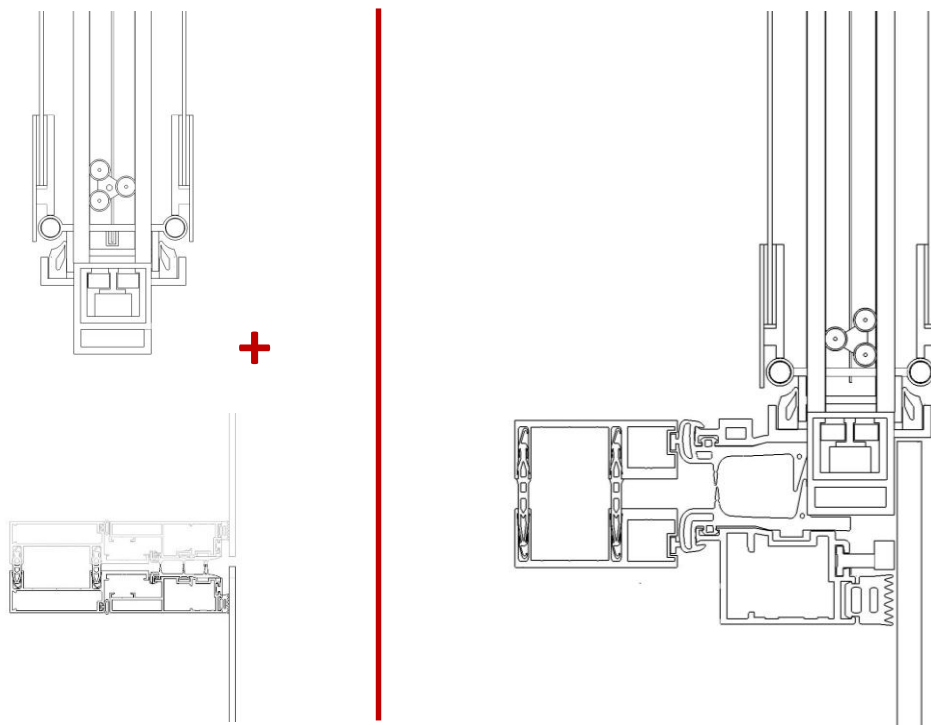
Figure 196, the proposed profile for unitized facade

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Inner Ultra Thin Glass

Outer Ultra Thin Glass

Rail

Wheel

Electro-Permanent Magnet

Aluminium Mullion

Sandwich Panel(Fire rated Rockwool Insulation)

4mm Tinted Reflective Glass
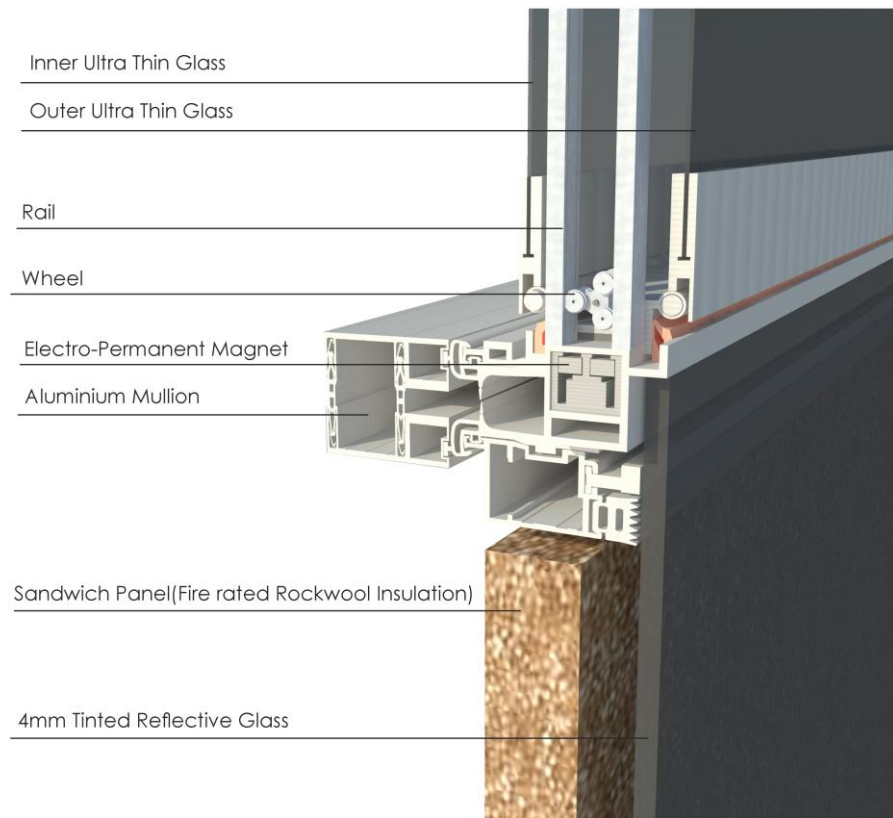
Figure 197, 3d view of the proposed profile for unitized façade

As it was mentioned before, one of the important targets of the proposed window panel is to design it in a way to have maximum transparency from outside. The Designed mullion for the panel is placed in the wheel system for moving the glass in one of its shafts while the glass could be extended to the T shaped part.
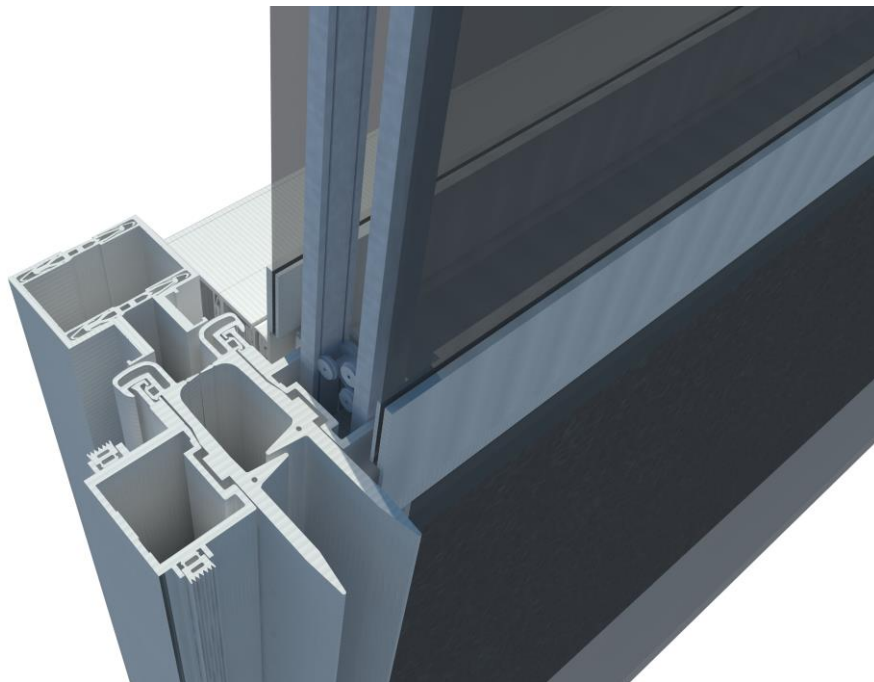
Figure 198, proposed mullion for unitized facade

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Figure 199 shows more details of the proposed panel.
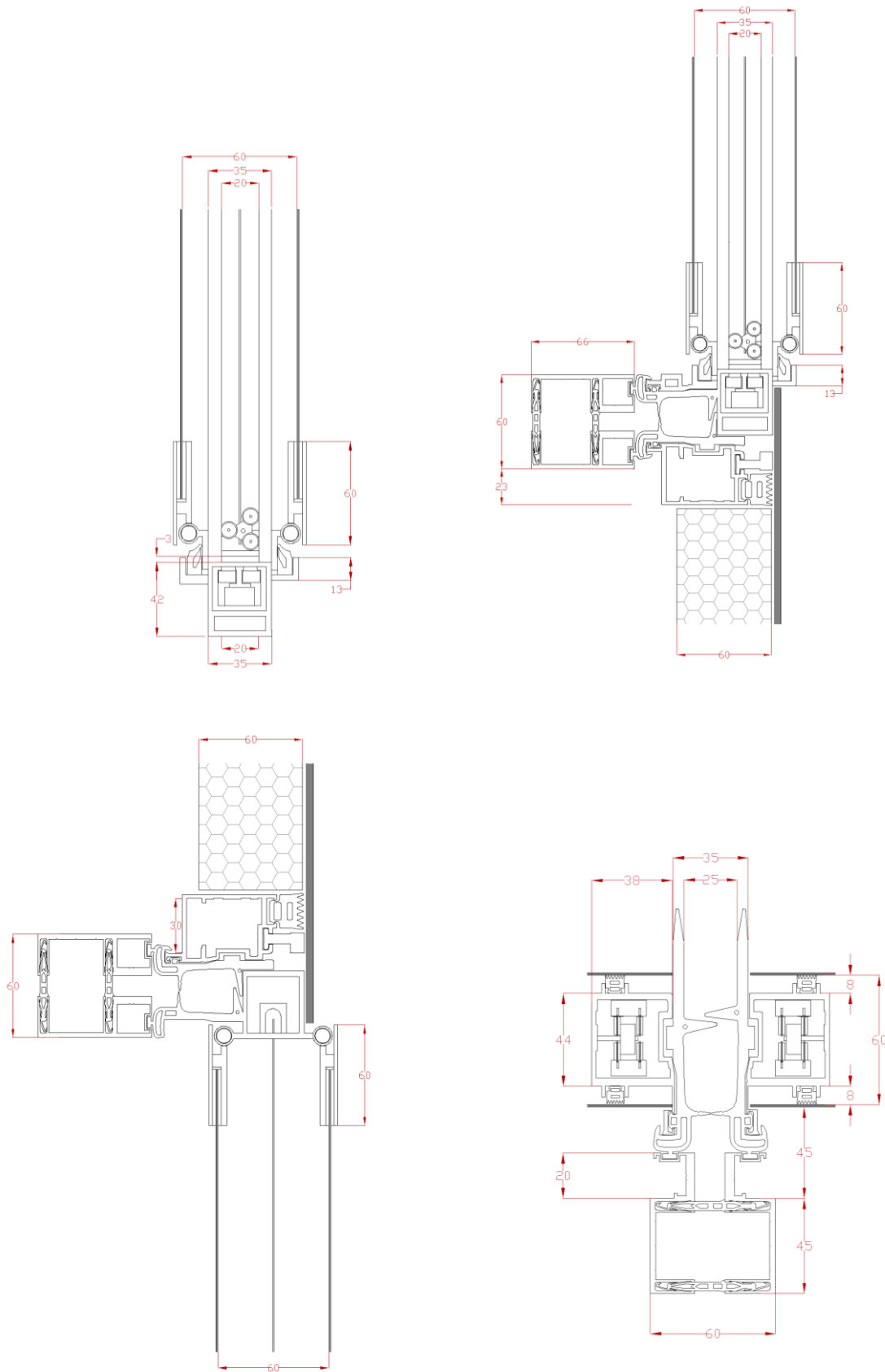
Figure 199, Side views of the proposed unitized façade

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6.4.5.2.2 Assembly

The unitized façade system is so common due to its fast and easy assembly. In general, the process consists of 1) Transportation, 2) Anchorage and connection provision, 3) Installation arrangement, 4) Final fixing and inspection. During the installation, the curtain walls are suspended from above with the aid of tie rods. The following diagrams show the assembly of the curtain wall panels in the selected case study.
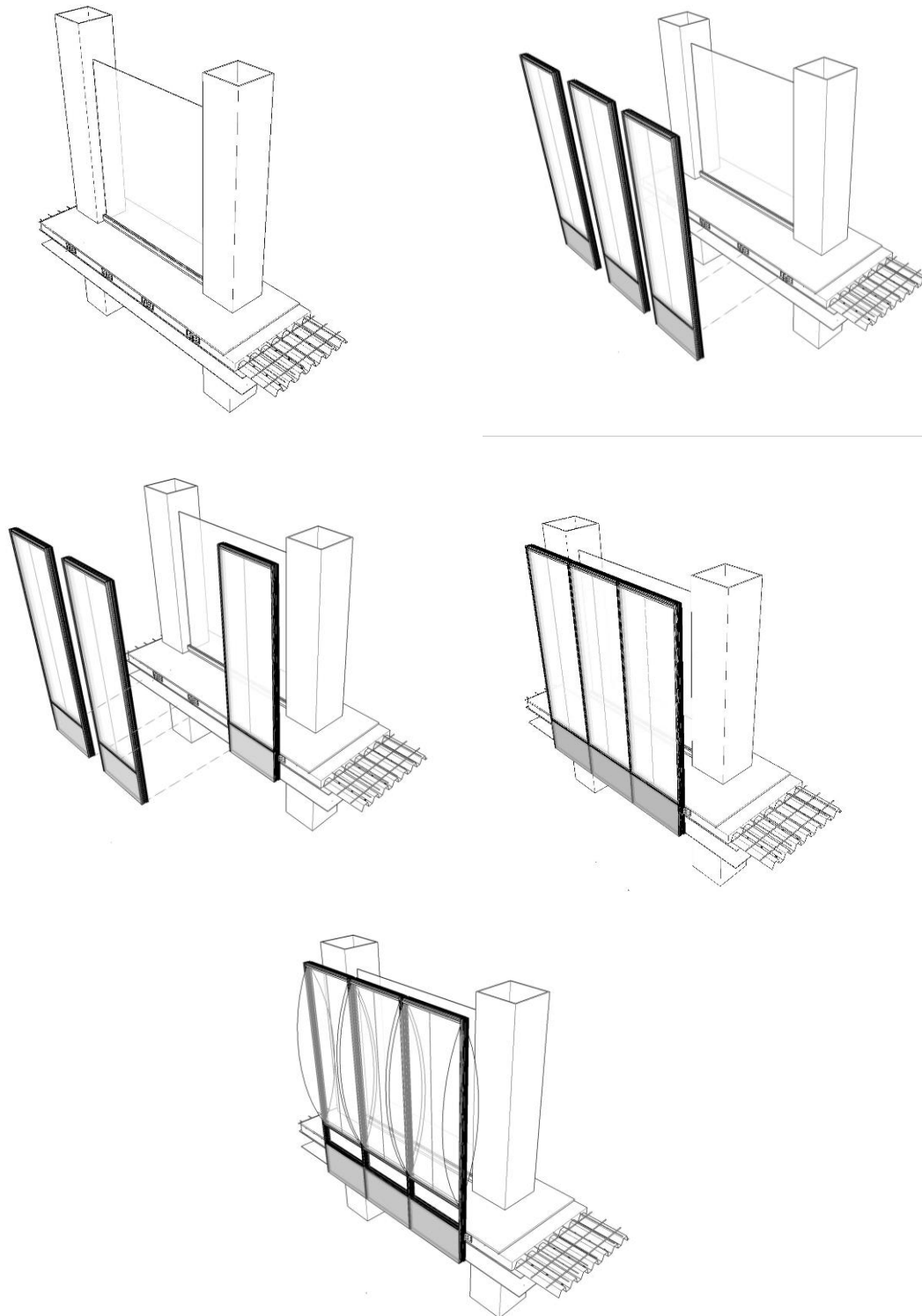
Figure 200, Assembly process

120

The selected bracket has been placed on the edge of the concrete slabs. The channels are cast into the concrete frame of the structure, to which façade brackets can be connected by using special T-head bolts. The system provides an ideal method for the connection of façade systems. The HCW-ED bracket has been chosen for this project according to its proper characteristics. [71]This type of bracket has a tolerance in three different directions. The brackets are designed to support both vertical and horizontal loads.
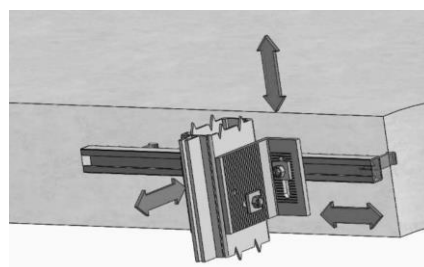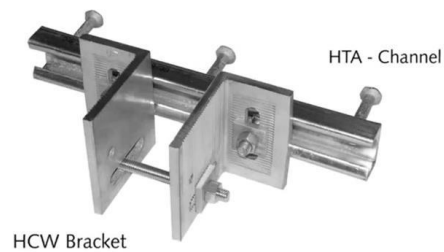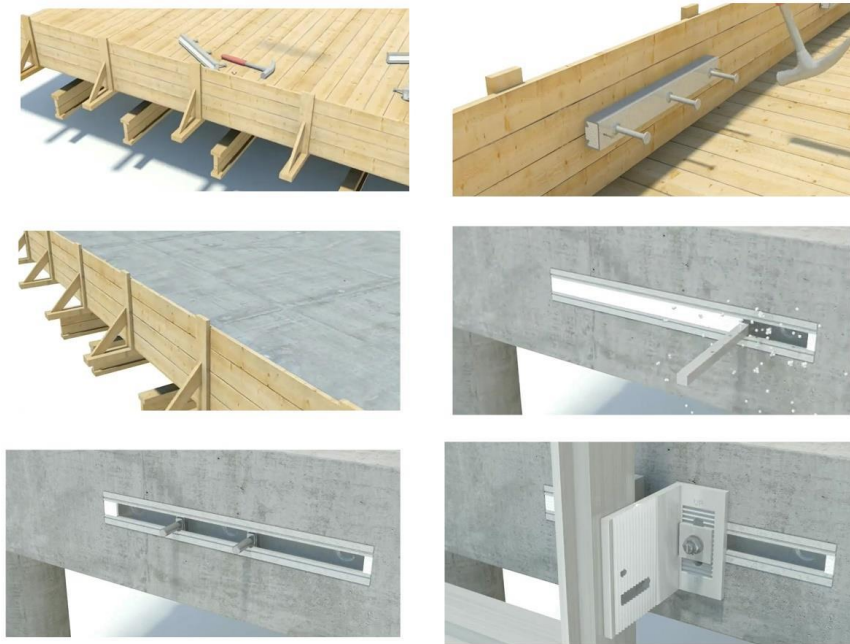
Figure 201, Bracket system [71]

121

6.4.5.2.3 3d views of exterior facade
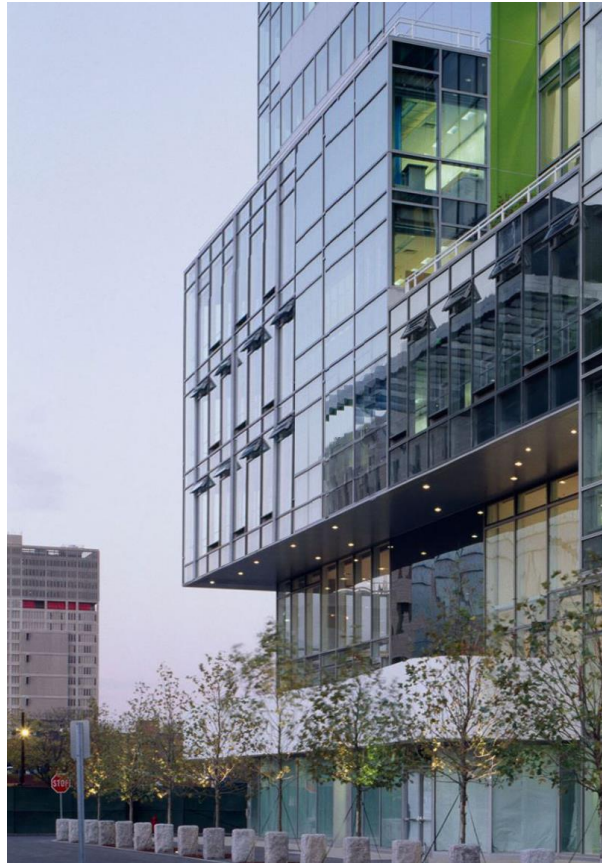
Figure 202, Current situation of the outside windows vs. proposed situation of exterior windows

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Relaxed SMA Situation
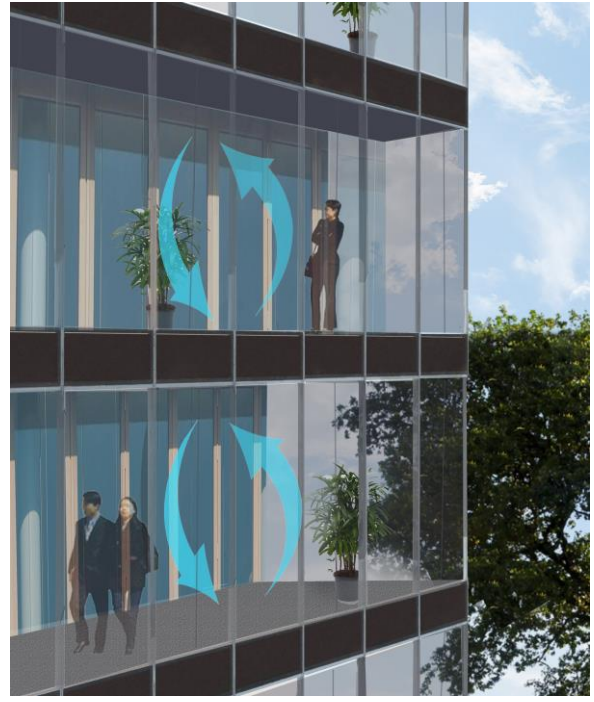
Insulated Buffer Zone

Activated SMA Situation

Ventilated Buffer Zone

Figure 203, Proposed Exterior windows in different conditions

Figure 204, Natural Ventilation situation

7 Conclusion

This chapter presents the general conclusions of the research by looking into the research questions. At the end, the chapter will also look at the recommendations for further development together with several suggestions for using the concept for other applications or different shapes.

In this research study, a novel design concept of Shape- Memory Alloy (SMA) as an actuator to move and bend thin glass panel in facade has been fundamentally assessed by means of Finite- Element investigations, and experimental methods. Consequently, the design could be proposed as a possible innovative technique for the enhancement and optimization of traditional windows use.

In order to answer the main research question, the sub-questions should be tackled individually. As a result, the findings will be discussed briefly, addressing the suggestions for further analysis based on the findings developed in this study.

What is the main purpose of using thin glass in façade?

Although common glass panels are widely used in the building industry, in the form of facades and roofs, they have major restrictions in design due to their weight and the amount of raw material and energy they need for production. Bonding two or more glass plates with interlayers enables large surface coverage; therefore, preventing large deflections with increased stiffness and safety. Thin glass as a new innovative material has been selected as an alternative to more traditional glass plates to solve the challenges and problems currently facing glass design. Thin glass could result in a reduction of raw material and energy while it also diminishes the loads in main structures of buildings.

What is the reason for making an adaptive panel?

The main reason for making the adaptive panels is to create a breathing skin. The breathing envelope can control the different parameters of a building envelope, responding to the changing interior and exterior environmental conditions by improving indoor air quality in the building and the user's comfort.

What are the possibilities of movement for the thin glass panel?

One of the most important features of thin glass which is mainly focused on this research study is its potential for flexibility. This feature creates the possibility of making a bendable adaptive thin glass panel for the facade. Bending the glass not only exhibits one of the main potentials of this new material but also makes the panel stiffer when lateral forces are applied.

Which technologies could be used for bending the thin glass?

As a first step, the purpose of using thin glass as a façade element has been investigated whereby the most suitable innovative technologies have been selected to create the breathing façade. Different types of actuator systems with internal and external input have been explored in the first chapter and their material properties and performance parameters are analyzed in relation to the design requirements.

Is Bi-Metal or any other smart materials capable of bending the thin glass?

In order to be sure about the feasibility of the actuators for bending thin glass, their active force should be considered not only in theory but also in practice. The active forces for different actuator systems have been calculated in chapter one and also in some cases, the materials were tested. For instance, the experimental tests on Bi-metal show that the material does not have enough bending force for moving the glass although, in theory, the force is enough for the mentioned application.

What is the most suitable technology for bending thin glass panel?

Based on the design proposals, structural analysis, and experimental tests, Shape memory alloy has been selected as the most suitable and innovative technology for bending thin glass and creating a breathable façade. This material could be produced in different types, but Flexinol is chosen as a most promising type for further developments.

Could the glass be adapted completely actively?

Although SMA wires could be activated by temperature, the panel could not be made based on ambient temperature to create a zero energy system. In order to increase the indoor air quality, all of the effective criteria should be considered in the system. Increasing the indoor temperature is only one of the reason for opening the windows. Other principles such as the levels of gas, humidity, and pressure should be monitored by sensors with windows being opened with electricity in case of necessity through a semi-active panel.

Is the actuator capable of improving the structural performance of thin glass toward lateral forces (wind)?

Thin glass can be easily bent in lateral forces. Although applying SMA wires to the thin glass plates could provide a stiffness and resistance contribution especially in case of activation of the wires, there is a need for the extra force for keeping the window closed in wind. This force could be supplied by use of an electro-permanent magnet in the frame.

How much force is needed to bend the thin glass in different situations?

The amount of force which is needed for bending the thin glass in different thicknesses and designs has been calculated by means of FEM analysis. Shell simulations in Abaqus software provide the data for activation force in each panel. These analyses are highlighted in Chapter 5.

How does bending influence the stress generation in thin glass panel?

The same FEM analysis has been done in chapter 5 in order to get the influence of bending in a thin glass panel. The maximum principal stresses are calculated in different cases and are compared for different thicknesses.

How to attach the actuator to the panel of glass?

There are different possibilities for attaching the actuator to thin glass. In the first chapter, general ideas and designs have been proposed for different types of actuators. While in the second chapter and after selecting the most suitable technology as an actuator, various types of attachment are considered for Flexinol wire. In the end, two different concepts have been selected for further analysis and tested individually.

Main Question: How can a thin glass skin be applied as an adaptive façade developed by smart materials?

It is possible to analyze the main question and provide its answer after looking into all the sub-questions.

In this research study, the feasibility of an adaptive thin glass facade built up of SMA wires has been explored, by taking into account some configurations for thin glass applications. Flexinols are a class of metallic materials from SMA classification that exhibits outstanding features when activated. Of course, there are several different systems which could be replaced with Flexinol for bending the thin glass; Flexinol as an innovative material that shows special characteristics which is favorable to consider it as a feasible actuator system for further developments in façade systems.

The research focuses on the material behavior analysis of the actuator systems and at the same time thin glass structure to the considerations into the detailing of the panel. In general, the process to make a thin glass panel adaptive is related to all the mentioned sub-questions. After specifying the purpose to have an adaptive window with the use of thin glass, several actuator systems have been analyzed. The initial geometry of the panel and its movement was defined based on the selected actuator system while various structural FEM analysis identified details such as the degree of freedom, type of supports and movements for the breathing panel. The experimental models have certified the feasibility of the system and created the possibility to apply the system in the selected case study.

Recommendations for further development

Without a doubt, extended research studies are required for a full optimization and development of this novel design concept. Nevertheless, due to the promising results, it is expected that the current outcomes could depict a logical and useful background for the development of further design recommendations and refinements.

One advanced development in this research would be to create an insulating bendable thin glass panel in a single skin unit which is watertight and airtight. One of the main challenges is to find an efficient solution to have the optimum number of SMA wires of reduced length. On the other hand, different types of attachments of the SMA wires to the panel could be another issue which needs further developments. In this research study, the two simplest solutions have been selected for the wire connections. Now that the feasibility of the system has been proved, different types of connections and details could also be considered.
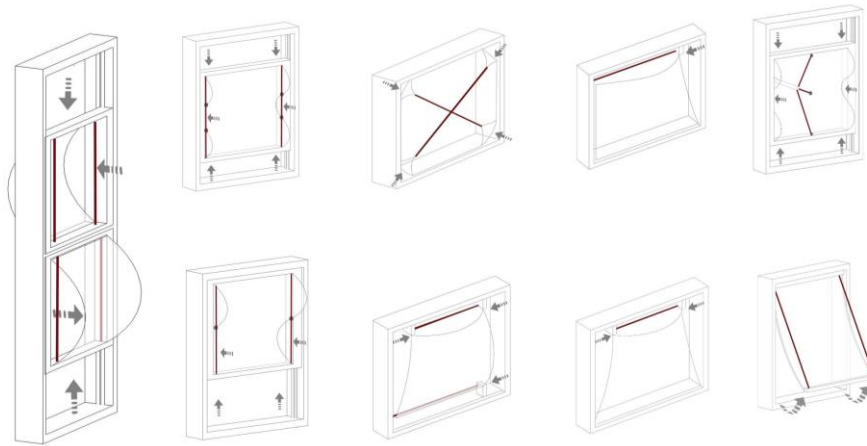
Figure 205, alternatives for different shapes of bent glass with linear motion

Besides, the amount of the stroke could be increased if the SMA system is combined with another actuator system such as scissor actuators. This can save energy consumption as the length of the SMA wire is shortened.
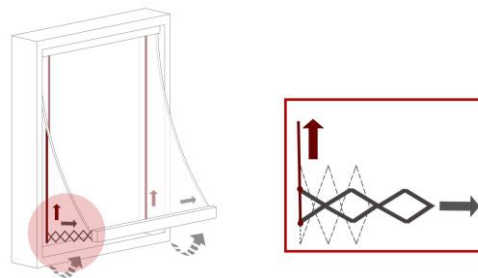
Figure 206, Scissor Mechanism

Another idea in noticeably reducing electricity consumption is designing the system in a way to use electricity just for activating the SMA wire to open the windows and not for keeping the window open. The window will be kept open by being locked in a fixture while the SMA wires become relaxed. The next activation of the wire would unlock the window and close it. As a result, there is only a need for electric pulses to activate the wires for less than one minute.
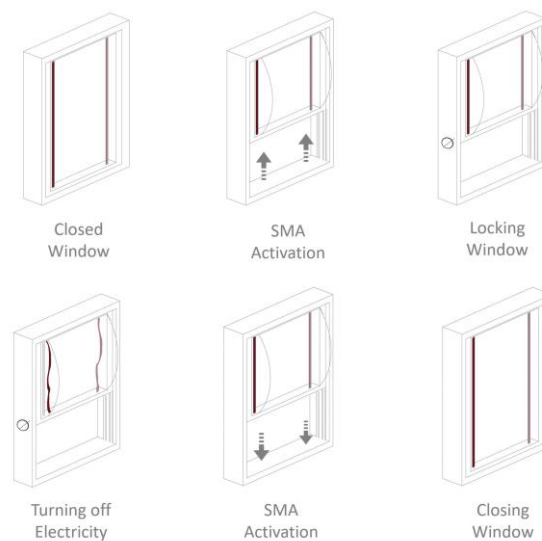
Figure 207, Concept for reducing electricity consumption

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Last but not least, investigating other possible architectural applications of adaptive bendable glass could increase the demand for this product in the building industry, which in turn might decrease the price of the final product. The proposed concept can be used to increase the stiffness of the thin glass panel under the wind. The glass can be bent under the wind and the window could still remain closed with use of an elastic fabric. Adaptive solar façade or canopy could be another application for the proposed concept. Thin glass can be laminated by flexible PV cells and based on the solar radiation angle, can be bent differently in order to provide maximum efficiency for the solar panels. Also, the system can be replaced by the existing auto vents in the greenhouses and create a simpler and lighter system as an adaptive skin.

Closed Window

Activation of SMA
Bending the Glass
Increasing Stiffness

Integration with
elastic fabric

Increasing stiffness under wind

14° angle
Winter

38° angle
Spring/Autumn

62° angle
Summer

Adaptive solar facade

Adaptive solar canopy

Auto vent greenhouse
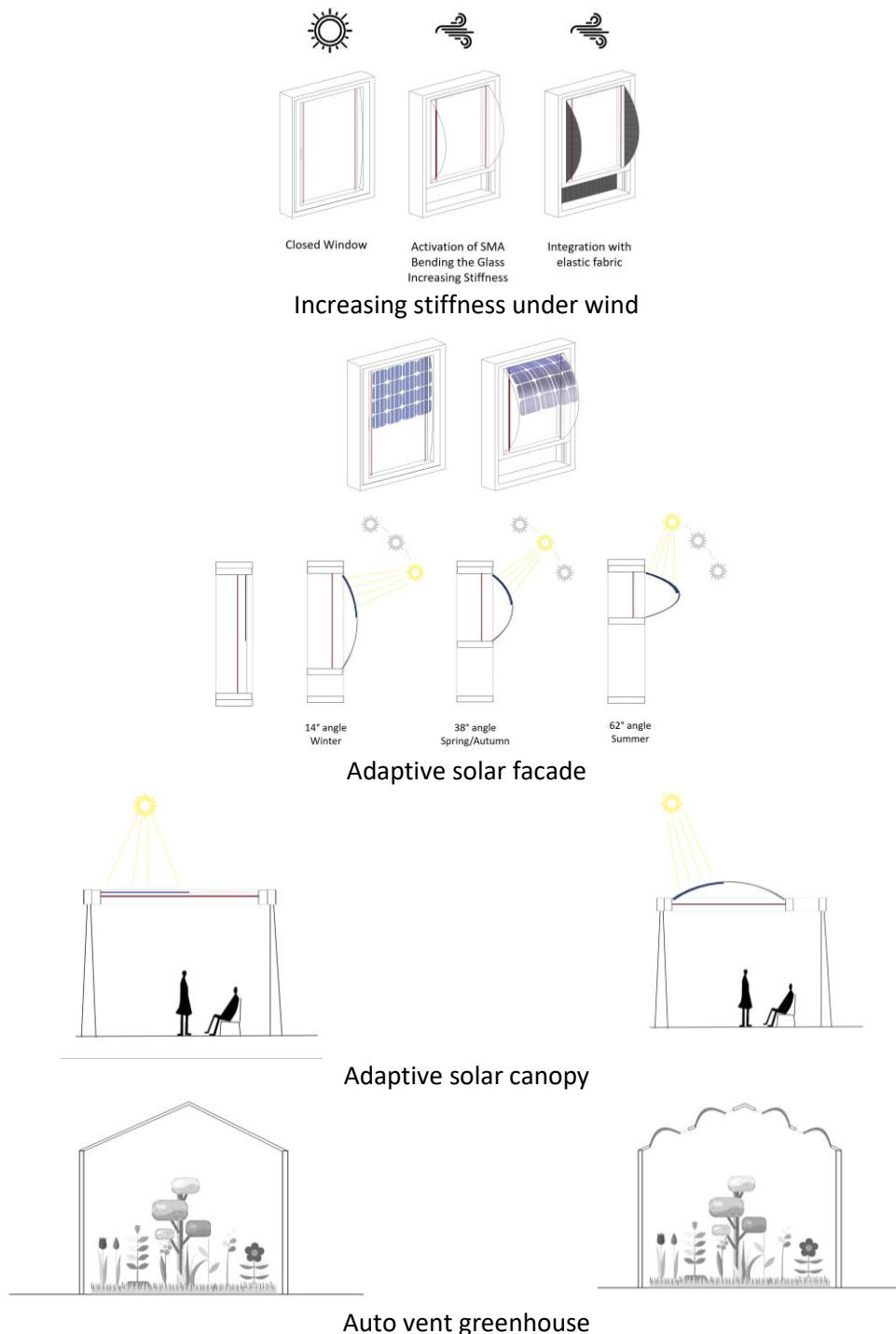
Figure 208, Different architectural Application for the concept

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8 Reflection

This reflection concentrates on motivation and attitude as well as challenges and restrictions towards this research project and the gained results.

This research is divided into two main parts; Looking into the thin glass for façade application, and at the same time, exploring for smart materials as an actuator for the system. The aim of both parts is to investigate new materials and using them as a new function. Each part has its own challenges and constraints.

8.1 Thin Glass

Nowadays, Ultra-thin glass is regularly used in the electronics industry and practically non-existent in architecture. On the other hand, there is a lack of existing research studies and information on the thin glass, especially on material properties. This aspect is one of the main constraints which made us spend too much time looking for a possible reference material.

The other issue is to find the most suitable software for accurate structural simulations. Since the thin glass panel is considered to be adaptive and deflected by the smart actuator, the force for moving the panel should be exactly calculated in order to find a correct number of wires needed as an actuator. This part is so important because if the calculated force is wrong and the wires are asked to exert too much force, they will completely lose their shape memory effect. In this research, first we used Grasshopper to analyze but the results were not satisfying since Grasshopper is not a proper software for non- linear analysis in the shell structures. As an alternative to Grasshopper, we chose Abaqus software which is commonly used for crash simulation. There is the unavailability of tutorials of the software in the faculty of architecture as the software is so professional. So it took me time to learn the software by the online tutorial and get the right results.

8.2 Smart Material

The first phase of the research study is to find a type of smart material with enough potential as an actuator for the panel. This process has been done paralleled to exploring information for thin glass. For selecting the most suitable smart material, several materials were considered. The main obstacle is that most of them are new, and nobody is sure about the feasibility of them in practice. In theory, they might have the capability to move the glass, but in practice, sometimes you get different results.

As an example, the Bimetals from Wickeder group in Germany have a very high thermal force in theory, but in practice, they are so fragile and not usable as an actuator.

In the second phase, the Shape memory alloy has been chosen for further analysis. Shape memory alloy could be produced in three different types of one way SMA, two way SMA and Flexinol in the market. The two-way shape memory alloy seemed to have a lot of potential for this study at the beginning, but it turned out to have some limitations. Mainly, training the material is needed, which needs specific equipment such as a furnace to heat up the material to approximately 500°C. Because of the lack of equipment and also time, we considered Flexinol for further analysis. Although Flexinol has only linear movement, it saved lots of time as it didn't need annealing.

The third phase is to test Flexinol. One of the main limits is providing electricity and the power supply. The selected diameter wire needs 4 A/second, and finding a power supply with high current was time-consuming and challenging. On the other side, applying a high current especially in case of using more than one wire for just moving a very thin glass does not seem so logical. An alternative to this approach is to apply a lower current in a longer duration to save electricity. The problem with this approach is that the wire does not work in a lower current and a longer span of time. Unfortunately, there is no research study on this material and its application in different current and voltage with different reaction time. So, everything had to be tested carefully in order to find the optimum performance of the wire.

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10 Appendix

10.1 AGC

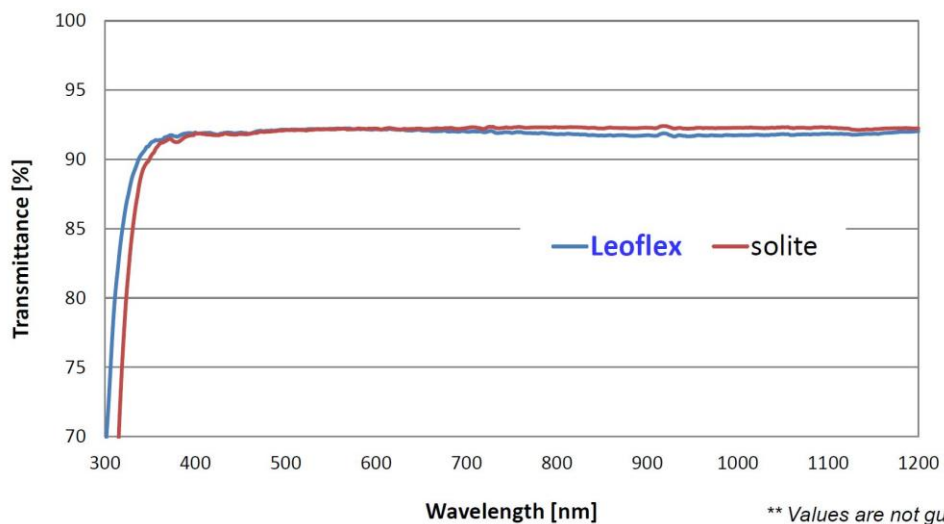

Transmittance (Leoflex 0.85t, Solite 3.2t)   **AGC**

Leoflex / SOLITE Transmittance (no coating)

** Due to embossed surface of SOLITE, both SOLITE and Leoflex surface are specially treated.

Leoflex shows the same transmittance as SOLITE.

Performances

Properties	Substrate	Parameters	1.6 mm	0.5 mm
Optical properties	Clear soda-lime	LT (D65,2°)	90.7	91.5
		ET (ISO 9050)	89.2	91
		Refractive index (visible)	1.52+/-0.005	
		Photoelastic constant	26.9 nm/cm/MPa	
	Extra-clear soda-lime	LT (D65,2°)	91.7	91.8
		ET (ISO 9050)	91.3	91.8
		Refractive index (visible)	1.52+/-0.005	
		Photoelastic constant	26.9 nm/cm/MPa	
	Alumino-silicate	LT (D65,2°)	91.6	92.1
		ET (ISO 9050)	91.5	92.1
		Refractive index (visible)	1.515+/-0.005	
		Photoelastic constant	27.2 nm/cm/MPa	
Mechanical properties	Soda-lime and alumino-silicate	Density	~2.48 g/cm³	
		Young's Modulus	71-73 GPa	
		Poisson's Ratio	0.22	
Chemical strengthening properties	Soda-lime	Depth of Layer	> 20 μm	
		Compressive Stress	> 350 MPa	
	Alumino-silicate	Depth of Layer	> 40 μm	
		Compressive Stress	> 500 MPa	
Thermal properties	Soda-lime	Tg	~555°C	
		Coefficient of thermal expansion	87.10^{-6}	
	Alumino-silicate	Tg	~565°C	
		Coefficient of thermal expansion	90.10^{-6}	
Chemical resistance	Soda-lime	Hydrolytic class	3	
	Alumino-silicate	Hydrolytic class	2	

Processing options

Safety	Toughening (chemical)
Cutting	Straight or circular
Shaping and edge finishing	Edge grinding, drilling
Special treatments	Anti-warping
	Silkscreen printing
	Bending (thermo-forming and cold-bending)
	Acid etching (single or double)
	Anti-reflective coating
	Wet coating application (anti-fingerprint/hydrophobic coating)
	Safe foil application
	UV gluing

Availability

Standard thicknesses	Standard tolerance	Typical max sheet size
0.5 mm	+/-0.05 mm	1245*3210 mm
0.7 mm		1350*3210 mm
0.9 mm		
1.1 mm		1480*3210 mm
1.3 mm		
1.6 mm	+/- 0.1 mm	1600*3210 mm

Other thicknesses, dimensions or specific properties (flatness, parallelism, roughness, cutting tolerance, etc.) are possible upon agreement between the customer and AGC.

AGC GLASS EUROPE, A LEADER IN FLAT GLASS

AGC Glass Europe is the European branch of AGC, the world's leading flat glass producer. Its baseline, Glass Unlimited, reflects its core assets: innovative strength in advanced glass technologies, a global sales network and an industrial presence stretching from Spain to Russia. AGC Glass Europe has representatives worldwide.

AGC
GLASS UNLIMITED

01/2017

10.2 Flexinol

FLEXINOL®

Section 1. Movement

The movement or stroke of Flexinol® actuator wire is measured as a percentage of the length of the wire being used and is determined, in part, by the level of stress one uses to reset the wire, or to stretch it in its low temperature phase. This opposing force, used to stretch the wire, is called the bias force. In most applications, the bias force is exerted on the wire constantly, and on each cycle as the wire cools, this force elongates it. If no force is exerted as the wire cools, very little deformation or stretch occurs in the cool, room temperature state and correspondingly very little contraction occurs upon heating. Up to a point the higher the load the higher the stroke. The strength of the wire, its pulling force and the bias force needed to stretch the wire back out are a function of the wire size or cross sectional area and can be measured in pounds per square inch or "psi". If a load of 5,000 psi (34.5 MPa) is maintained during cooling, then about 3% memory strain will be obtained. At 10,000 psi (69 MPa), about 4% results, and with 15,000 psi (103 MPa) and above, nearly 5% is obtained. However, there is a limit to how much stress can be applied.

Far more important to stroke is how the wire is physically attached and made to operate. Dynamics in applied stress and leverage also vary how much the actuator wires move. While normal bias springs that increase their force as the Flexinol® actuators contract have only 3-4% stroke, reverse bias forces which decrease as the actuator wires contract can readily allow the wire to flex up to 7%. Mechanics of the device in which it is used can convert this small stroke into movements over 100% of the wires' length and at the same time provide a reverse bias force. The stress or force exerted by Flexinol® actuator wires is sufficient to be leveraged into significant movement and still be quite strong. Some basic structures, their percent of movement, and the approximate available force they offer in different wire sizes are as follows:
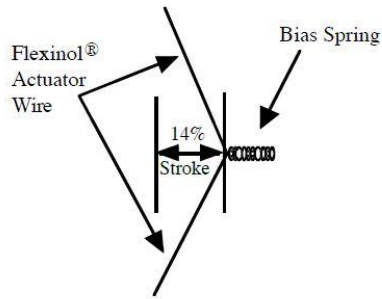

Normal Bias Spring

Flexinol®
Actuator
Wire

Spring

3% Stroke

Dead Weight Bias

Flexinol®
Actuator
Wire

Weight

4% Stroke

Leaf Spring Bias

Leaf Spring
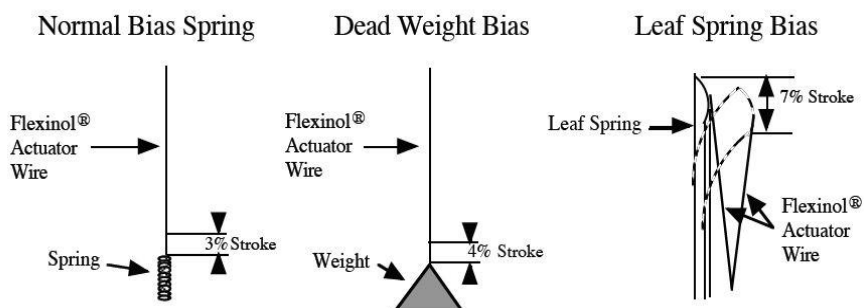
7% Stroke

Flexinol®
Actuator
Wire

APPENDIX

Right Angle Pull

Simple Lever
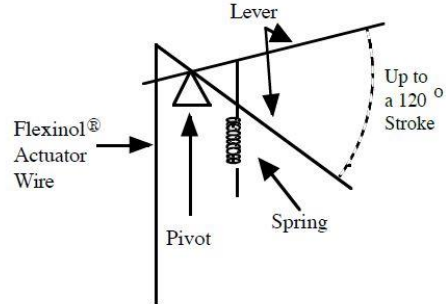
Adjusting Curvature
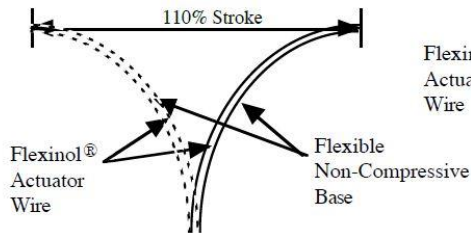
Clam Shell
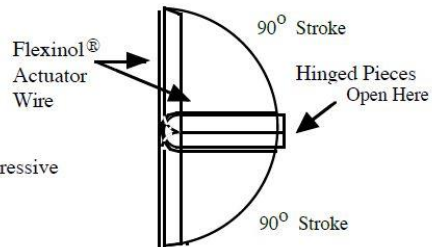
Stroke and Available Force Table

	Approx. Stroke	0.003" Wire (0.076 mm)	0.006" Wire (0.15 mm)	0.010" Wire (0.25 mm)
Normal Bias Spring	3%	0.18 lb (80 g)	0.73 lb (330 g)	2.05 lb (930 g)
Dead Weight Bias	4%	0.18 lb (80 g)	0.73 lb (330 g)	2.05 lb (930 g)
Leaf Spring Bias	7%	0.18 lb (80 g)	0.73 lb (330 g)	2.05 lb (930 g)
Right Angle Pull	14%	0.04 lb (20 g)	0.18 lb (83 g)	0.51 lb (232 g)
Simple Lever (6:1 ex)	30%	0.024lb (11 g)	0.10 lb (47 g)	0.29 lb (133 g)
Adjusting Curvature	110%	0.006 lb (3 g)	0.026 lb (12 g)	0.075 lb (34 g)
Clam Shell	100%	0.007 lb (3.2 g)	0.028 lb (13 g)	0.082 lb (37 g)

10.3 Magnet

Electro Magnets

A simple electro magnet shown (fig.1) incorporates a coil of N turns wrapped around a ferromagnetic steel horseshoe.

Direct current is applied to the coil which creates a magnetic force perpendicular to the coil.

Magnetic flux passes through the poles of the horseshoe which will then influence any ferromagnetic material that comes within the field area.

Electro magnets can be very powerful, more turns on the coil and or more current generates more force: MMF = I x T.
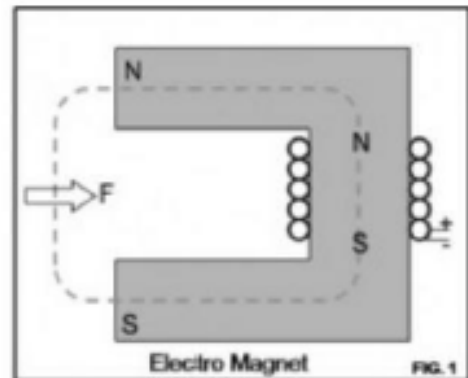

Electro Magnet   FIG. 1

The magnetic field is removed from the poles the moment the current is removed from the coil.

Permanent Magnets

In the case of a simple permanent magnet design, the horseshoe is interrupted with a permanent magnet.

The permanent magnet material would likely exhibit high coercivity (difficult to demagnetize), Rare-Earth, for example.

As its name suggests, magnetic flux is always flowing from north to south. The horseshoe allows the flux to concentrate over the pole areas and influence any ferromagnetic material that comes within the field area.

Permanent Magnet   FIG. 2
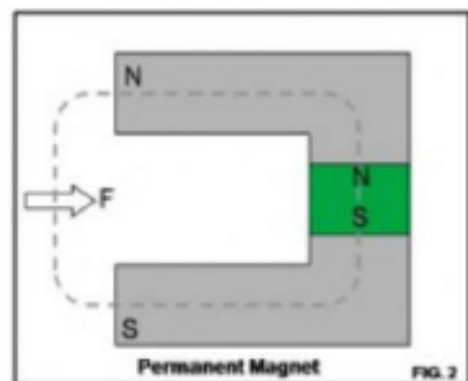
With permanent magnets, MMF is increased as the magnetic length of the raw material is increased.

In this illustration the magnetic field is always present and cannot be removed*. A high-coercive permanent magnet is very difficult to demagnetize, therefore, if we want to make it switchable, we need some method of redirecting the flux away from the pole surfaces.

Switchable Permanent Magnets

In Fig. 3 we have introduced a second permanent magnet of equal proportions into the circuit. This has the benefit of providing twice the amount of flux which increases the density of the field, creating an even greater attractive force when in the ON condition.

More important, the second magnet is free to rotate which changes the overall state of polarity.

As can be seen in Fig. 4, when the second magnet has been rotated, the flux emanating from both raw magnets has a better route to travel from one pole to the other, and is now diverted away from the pole surfaces placing the unit in an OFF condition.

Switchable permanent magnets can be very powerful and have the benefit over electro-magnets of better safety since there are less external factors that can affect performance*. However, there comes a point when the physical friction of moving a magnet becomes impractical and expensive to solve. Permanent-electro magnets combine the benefits of both electro and permanent magnet technology.

Switchable Permanent Magnet   FIG. 3

Switchable Permanent Magnet   FIG. 4
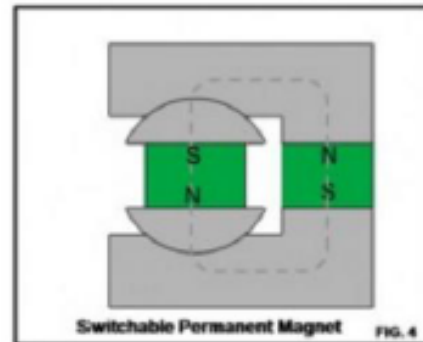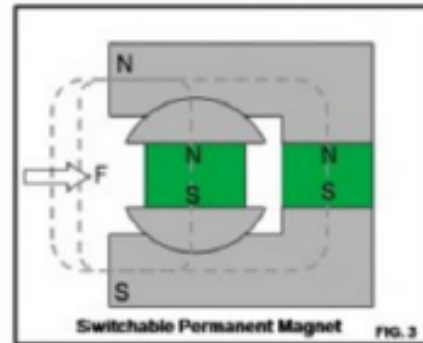
Permanent-Electro Magnets

In Fig. 5 we have replaced the moving magnet with a static low coercive one.

By placing a coil around this magnet and using a short electromagnetic field, this magnet can be energized fully.

In the ON condition, as with the previous permanent magnet, flux from both magnets are combined and directed through to the poles surfaces. In the OFF Condition, the coil is re-energized in the opposite direction, thus re-magnetizing the magnet to opposite polarity.

Magnetic flux from both magnets is now re-routed internally leaving the pole surfaces free of magnetism.

Permanent-electro magnets, require electricity only for the switching process (<0.5 secs). They can be very powerful, they don't generate heat and have no moving parts.

Permanent-Electro Magnet   FIG. 5

Permanent-Electro Magnet   FIG. 6
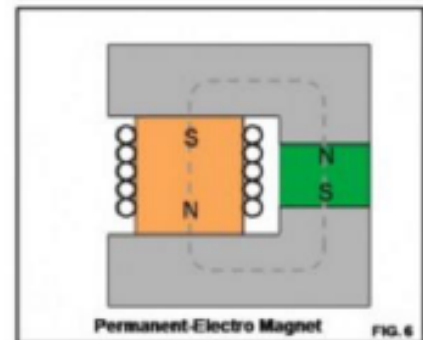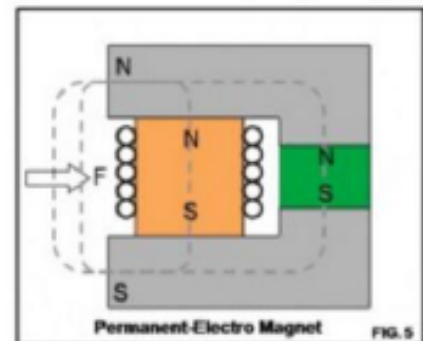
High Coercive magnets can be influenced externally, either by high temperatures and/or by influence of high electro-magnetic fields.

10.4 Sensor

Key features

- Package   3.0 mm x 3.0 mm x 0.93 mm metal lid LGA
- Digital interface   I²C (up to 3.4 MHz) and SPI (3 and 4 wire, up to 10 MHz)
- Supply voltage V_{DD} main supply voltage range: 1.71 V to 3.6 V
  V_{DDIO} interface voltage range: 1.2 V to 3.6 V
- Current consumption   2.1 µA at 1 Hz humidity and temperature
  3.1 µA at 1 Hz pressure and temperature
  3.7 µA at 1 Hz humidity, pressure and temperature
  0.09–12 mA for p/h/T/gas depending on operation mode
  0.15 µA in sleep mode
- Operating range   -40–+85 °C, 0–100% r.H., 300–1100 hPa
- Individual humidity, pressure and gas sensors can be independently enabled/disabled
- The product is RoHS compliant, halogen-free, MSL1

Key parameters for gas sensor

- Response time ($\tau_{33-63\%}$)   < 1 s (for new sensors)
- Power consumption   < 0.1 mA in ultra-low power mode
- Output data processing   direct indoor air quality (IAQ) index output

Key parameters for humidity sensor

- Response time ($\tau_{0-63\%}$)   ~8 s
- Accuracy tolerance   ±3% r.H.
- Hysteresis   ±1.5% r.H.

Key parameters for pressure sensor

- RMS Noise   0.12 Pa, equiv. to 1.7 cm
- Offset temperature coefficient ±1.3 Pa/K, equiv. to ±10.9 cm at 1 °C temperature change

APPENDIX

Table 3: IAQ system parameter specification[3]

Parameter	Symbol	Condition	Min	Typ	Max	Unit
Accuracy status[4]	AX_{IAQ}	Android compatible	0		3	
IAQ Resolution	IAQ_{rs}			1		
IAQ Range	IAQ_{rg}		0		500	
Sensor-to-sensor deviation[5]	IAQ_{S2S}	All operation modes|		±15% ±15		
Durability to siloxanes[6,7,8]	IAQ_{S2S}	Sensor-to-sensor deviation		±15% ±15		
	IAQ_{drift}	Drift at low & high concentrations		±1% ±4		

Table 4: Indoor air quality (IAQ) classification and color-coding[9]

IAQ Index	Air Quality
0 – 50	good[10]
51 – 100	average
101 – 150	little bad
151 – 200	bad
201 – 300	worse[2]
301 – 500	very bad

Table 5: bVOC mixture with Nitrogen as carrier gas

Molar fraction	Compound	Production tolerance	Certified accuracy
5 ppm	Ethane	20 %	5 %
10 ppm	Isoprene /2-methyl-1,3 Butadiene	20 %	5 %
10 ppm	Ethanol	20 %	5 %
50 ppm	Acetone	20 %	5 %
15 ppm	Carbon Monoxide	10 %	2 %

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[3] IAQ parameters only apply for the combination of BME680 together with the Bosch Software Environmental Cluster (BSEC) solution (available separately, see Chapter 4)
[4] The accuracy status is equal to zero during the power-on stabilization times of the sensor and is equal to 3 when the sensor achieves best performance
[5] Tested with 0.6–90 ppm of EtOH at 5–40 °C, 20–80% r.H. and atmospheric pressure. Condition is valid after the calibration period of the BSEC algorithm.
[6] Siloxanes are present in a typical indoor environment and can in principle perturb the metal-oxide-based gas sensor performance.
[7] 220 hours of 700 mg/m³ of octamethylcyclotetrasiloxane (D4) in ambient conditions (i.e. 20 °C and 50 % r.H.) simulates the amount of siloxanes in a typical indoor environment over more than 10 years.
[8] Tested with 0.5–15 ppm of b-VOC at 20 °C and 50% r.H. using continuous operation mode for 220 hours of 700 mg/m³ of octamethylcyclotetrasiloxane (D4).
[9] According to the guidelines issued by the German Federal Environmental Agency, exceeding 25 mg/m³ of total VOC leads to headaches and further neurotoxic impact on health.
[10] The BSEC software auto-calibrates the low and high concentrations applied during testing to IAQ of 25 and 250, respectively.

APPENDIX

1.3 Humidity sensor specification

Table 6: Humidity parameter specification

Parameter	Symbol	Condition	Min	Typ	Max	Unit
Operating Range[11]			-40	25	85	°C
			0		100	% r.H.
Full accuracy range			0		65	°C
			10		90	% r.H.
Supply Current	$I_{DD,H}$	1 Hz forced mode, temperature and humidity measurement		2.1	2.8	µA
Absolute Accuracy	A_H	20–80 % r.H., 25 °C, including hysteresis		±3		% r.H.
Hysteresis[12]	H_H	10→90→10 % r.H., 25°C		±1.5		% r.H.
Nonlinearity[13]	NL_H	10→90 % r.H., 25°C		1.7		% r.H.
Response time to complete 63% of step[14]	$\tau_{0-63\%}$	N_2 (dry) → 90 % r.H., 25°C		8		s
Resolution	R_H			0.008		% r.H.
Noise in humidity (RMS)	N_H	Highest oversampling		0.01		% r.H.
Long-term stability	ΔH_{stab}	10–90 % r.H., 25°C		0.5		% r.H./ year

APPENDIX

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[11] When exceeding the operating range (e.g. for soldering), humidity sensing performance is temporarily degraded and reconditioning is recommended as described in Section 7.7. Operating range only for non-condensing environment.
[12] For hysteresis measurement the sequence 0→10→30→50→70→90→70→50→30→10 % r.H. is used. The hysteresis is defined as the maximum difference between measurements at the same humidity up / down branch and the averaged curve of both branches.
[13] Non-linear contributions to the sensor data are corrected during the calculation of the relative humidity by the compensation formulas described in Section 3.5.
[14] The air-flow in direction to the vent-hole of the device has to be dimensioned in a way that a sufficient air exchange inside to outside will be possible. To observe effects on the response time-scale of the device an air-flow velocity of approximately 1 m/s is needed.