Designing Architectural Morphing Skins with Elastic Modular Systems

Chin Koi Khoo, Flora Salim and Jane Burry

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Abstract

This paper discusses the issues of designing architectural skins that can be physically morphed to adapt to changing needs. To achieve this architectural vision, designers have focused on developing mechanical joints, components, and systems for actuation and kinetic transformation. However, the unexplored approach of using lightweight elastic form-changing materials provides an opportunity for designing responsive architectural skins and skeletons with fewer mechanical operations. This research aims to develop elastic modular systems that can be applied as a second skin or *brise-soleil* to existing buildings. The use of the second skin has the potential to allow existing buildings to perform better in various climatic conditions and to provide a visually compelling skin. This approach is evaluated through three design experiments with prototypes, namely *Tent*, *Curtain* and *Blind*, to serve two fundamental purposes: *Comfort* and *Communication*. These experimental prototypes explore the use of digital and physical computation embedded in form-changing materials to design architectural morphing skins that manipulate sunlight and act as responsive shading devices.

1. RESPONSIVE KINETIC SKINS

The term "Responsive architecture" was coined by Nicholas Negroponte in the mid seventies when spatial design problems were beginning to be explored through digital technologies [1]. In recent examples, responsive and kinetic architectural design can primarily be found in building envelopes or skins. These approaches to designing architectural skins comprise the adoption of kinetic mechanisms for environmental adaptation and responsiveness. The term "Kinetic architecture" was introduced by William Zuk and Roger H. Clark in the early seventies when dynamic spatial design problems were explored in mechanical systems [2]. This concept differs from responsive architecture since it investigates a building's capacity of motion with less consideration of response to environmental conditions. Kinetic architecture often focuses on expensive and complicated kinetic and mechanical systems as well as physical control mechanisms for actuation and structural transformations. The responsive kinetic skin of L'Institut du Monde Arabe at Paris designed by French architect Jean Nouvel in 1987 is a significant precedent which is known for its mechanical failure. A decade ago, dECOi attempted to integrate responsiveness and kinetic skins to create and investigate responsive architectural facades and installations, such as the Aegis Hyposurface [3], by using high-tech mechanical solutions, such as multiple piston components to actuate transformation [4]. However, solutions involving such mechanical components require designers to deal with the high energy cost and complex mechanisms. In the Aegis Hyposurface, piston components were found to be prone to fatigue-failure, causing gaskets leakage from the piston [4]. Such a *'hard'* mechanical approach often produces brittle and vulnerable kinetic systems. Thus, reliability and longevity factors of the system are the main challenges for kinetic architectural skins to become a more widely adopted approach in architectural design. How to design kinetic architectural skins with fewer mechanical operations? New *'soft'* architectural components like elastic silicone polymer and other active form-changing materials offer new possibilities for designing kinetic, responsive skins. In this paper, we describe a 'soft' approach, which integrates digital and physical computation with elastic materials to embed responsive and kinetic morphing abilities into architectural skins. This 'soft' approach has the potential to address the brittleness of the hard mechanical components.

Although *'soft'* architecture is a concept introduced during 60s and 70s, there is still limited progress in this domain [5]. In order to pursue this vision, further exploration with kinetic materiality is needed. This research explores the use of *'soft'* elastic form-changing materials for constructing kinetic and responsive architectural models. The purpose of this investigation is to address performance and aesthetics demands in designing soft responsive architectural skins. We propose that a more organic approach with less mechanical operations can harness material properties to produce transformations on architectural morphing skins. Omar Khan's Gravity Screens provides a novel active response where surface form results from gravity's effect on the elastic material patterning. These elastic mutable screens provide possibilities for responsive space that can mutate from circulation corridors to room clusters [6]. However, Khan's work just provides a starting platform for the soft responsive architectural idea and there is still unexplored territory to expand from the *'hard'* to the *'soft'* approach.

Current researchers attempting to address this *'soft'* approach include Tristan d'Estrée Sterk and Kas Oosterhuis with the use of pneumatic muscles in their projects. Sterk designed a responsive architectural structure by applying tensegrity (or tensional integrity) components actuated by pneumatic muscles [7]. Oosterhuis used pneumatic muscle as an architectural membrane to respond to various spatial conditions [8]. The members in a tensegrity structure are segregated into those which carry only compressive and those which carry only tensile forces in a way that obviates the need for direct contact between adjacent compressive members, giving them the appearance of floating in space. The recently completed Media-ICT building designed by Cloud 9 Architects in Barcelona is an example of a highly energy efficient building, achieved through the implementation of the *'soft'* approach to kinetic architectural skins. The complex façade made of ETFE (Ethylene Tetrafluoroethylen) protects the interior by moderating direct sunlight in a way that is responsive to changing conditions [9]. The project *ShapeShift* is taking another approach using kinetic membranes with EAPs (electro active polymers) and "parametric paravent", prototypes of robotically fabricated room-dividers [10]. Beyond the described examples, work that investigates the porosity and permeability of *'soft'* architectural envelopes that respond to environmental and communication inputs is largely unknown at this stage.

In this study, we are using passive and active design strategies to create kinetic prototypes that minimise the need for complex mechanical actuations as the basis of *soft kinetic* systems. All the experimental models that have been prototyped in smaller scale through this study combine material explorations, digital and physical computing techniques, as discussed in section 3. The main idea behind deploying *soft kinetic* systems for designing morphing skins is the integration of an exoskeleton structure, and a surface as the actual actuator. Hence, *soft kinetic* systems do not require mechanical joints, parts, or motors. The kinetic actuation also takes place in the overall modular system with the use of form-changing materials and little use of mechanical components. This concept is inspired by the soft mechanical approaches in aerospace engineering especially morphing wing technology [11]. In the field of engineering, the word morphing is used when referring to continuous shape change i.e. no discrete parts are moved relative to each other but one entity deforms upon actuation [12]. For example, on an aircraft wing this could mean that a hinged flap would be replaced by a structure that could transform its surface area and camber without opening gaps in and between itself and the main wing [13]. This fascinating concept of morphing skin as an emerging aerospace technology has inspired aircraft wing design but it has remained unexplored territory in terms of architectural morphing skins.

The study presented in this paper aims to develop prototypes of architectural morphing skins, since the elastic nature of these structures is able to accommodate responsive mechanisms with passive elastic memory while minimising the energy and weight required for actuation. Although the research encompasses consideration of energy use and the cost of maintenance, these are not part of the scope of this paper. We argue, as an early hypothesis, that elastic modular systems can provide designers with a mix of passive and active design strategies to manipulate architectural morphing skins. We test this argument through design experiments with small-scale models. The paper describes and discusses the development of a new repertoire of responsive architectural morphing skin ideas using accessible *'soft'* components, such as elastic materials integrated with contemporary sensor devices. These ideas are developed using parametric design tools.

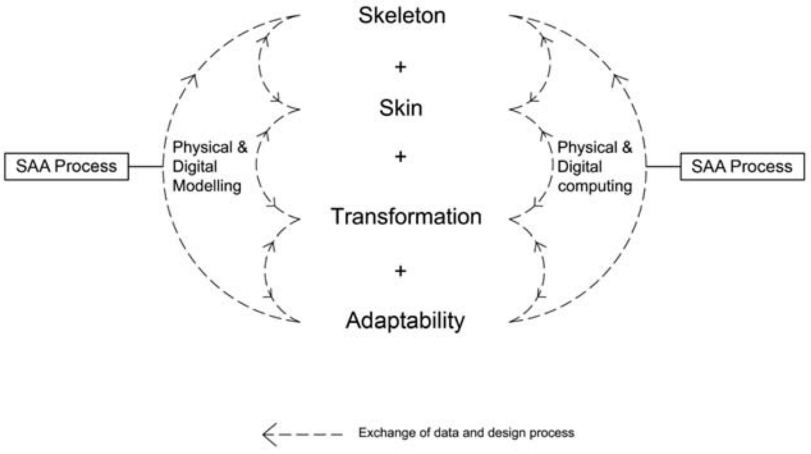
2. PROPOSAL: ELASTIC MODULAR SYSTEMS

Modular systems are not uncommon in architectural design. Their use has largely been concerned with reducing cost and the materials needed to construct full-scale architecture. In contrast to existing kinetic systems, for instance, the Aegis Hyposurface and L'Institut du Monde Arabe projects, Elastic Modular System (EMS) offers movement and change in response to material properties rather than changes in mechanical components such as actuated motors and gears based on the concept of *soft kinetic* systems as discussed in section 1. This shift challenges the notion of kinetic structure relying on external actuation. This approach, although similar to *soft* mechanical approaches in aerospace engineering such as the morphing wing design, has not liberated the transformable skin from the requirements of a sturdy structure [14]. Modular components of the skin act as a lightweight structural support and a spatial envelope at the same time.

The purpose of the development process presented in this section is to design architectural morphing skins using the soft approach in a simple yet efficient way. The design process requires iterations of physical and digital modelling, electronic prototyping and fabrication. Through each stage of the development process, *Skeleton*, *Skin*, *Transformation* and *Adaptability*; the data is exchanged between digital and physical models (Figure 1).

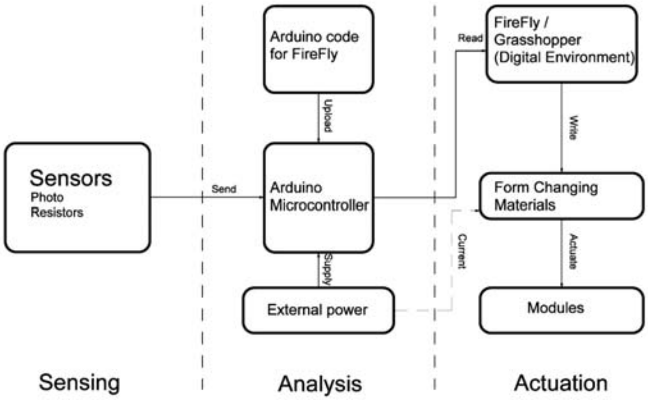
The four stages for the process of designing EMS as discussed in this paper include:

1. *Skeleton* - the first stage of the design requires modular components of skeleton to be sketched, modelled, and fabricated. They are represented in the form of parametric digital and physical tensegrity modules (tetrahedra) as part of experimentation process.
2. *Skin* - the second stage investigates accessible elastic and form-changing materials such as silicone rubber, nylon coated stainless steel string and SMAs (shape memory alloys) for physical implementation.
3. *Transformation* - the third stage focuses on the new possibilities of the elastic and form-changing materials to emulate simple transformable mechanisms like joints, actuators and hinges that could become an alternative toolkit to conventional mechanical components.
4. *Adaptability* - the last stage of the system discusses the adaptability of models in order to achieve morphing skins that display elastic properties, able to respond to digital and physical stimuli, and facilitate a feedback loop to the system.



◀ Figure 1: The process of designing Elastic Modular System (EMS).

The overall design process conforms to a Sensing-Analysis-Actuation (SAA) system diagram that is general to the responsive set-up within the EMS in all three of the design experiments that are discussed in subsections 3.1-3.3. Firstly, the sensors receive the analogue data that is sent to an Arduino microcontroller with Arduino code for processing. Then, the FireFly plug-in embedded in the Grasshopper program reads the processed data and produces the values that activate the form-changing materials for actuation. The contraction and expansion of the actuated form-changing materials produce kinetic movement in the models as they respond to the external stimuli (Figure 2).



► Figure 2: The generic system diagram of SAA process.

Virtual parametric models can be associated with real time data from sensors, which stream data from the physical environment, as input to drive the parametric variations in the model [15]. The Sensing – Analysis-Actuation process is a way of working that has been called form fostering, which enables interoperation and integration of digital, physical modelling and computing through associative design [15]. Form fostering facilitates the parametric model to be the platform for simulating the behaviours of the elastic modular systems in the early design stage.

The process of designing EMS requires research to be performed in three distinct but overlapping areas: *elasticity*, *tensegrity*, and *form-changing materials*.

Elasticity refers to the ability of a body that has undergone deformation caused by applying force to return to its initial size and shape once the distorting force is removed [16]. Elasticity is a result of the chemical bonds between the atoms that a material is made of [17]. During deformation potential energy is stored within the material which activates the acceleration back to its original state. This offers potential new forms of flexibility, adaptability and deformation using the memory effect in architectural skins. Despite this obvious potential, such material systems have not found widespread application: architects have tended to shy away, cowed by questions of liability and lack of experience [16].

The term *tensegrity* coined by Buckminster Fuller by combining the words tensional and integrity is a structural principle based on the use of isolated components in compression inside a net of continuous tension, in such way that the compressed members do not touch each other and the pre-stressed tensioned members delineate the system spatially[18]. Thus, the tensegrity structural approach reduces the friction between mechanical joints and achieves a lightweight structure which is particularly interesting when considering the development of responsive systems. Due to the interdependent nature of all the compressive elements, a slight change in any of their parameters can result in a significant form transformation [19].

For these reasons the tensegrity structure was chosen as part of the EMS and for its flexibility and lightweight components.

There are several *form-changing materials*, such as those shown in Table 1. However, there has been little investigation into the use of these materials as an actuator for structural adaptation and transformation in the architectural context. In this paper, an experiment with form-changing materials will be presented in subsection 3.3.

Form-changing materials (electrical and heat stimuli)	Commercial	Electrical stimuli	Actuation	Transformation
Shape memory alloy	Yes	Yes	Strong	Large
Shape memory polymer	No	Yes	Weak	Large
Elastic polymer	Yes	No	N/A	Large
Piezoelectric crystals	Yes	No	N/A	Small
Dielectric electro active polymer	No	Yes	Medium	Large
Ionic electro active polymer	No	Yes	Strong	Large
Paraffin wax (liquid)	No	No	Strong	Large

◄ Table 1: The comparison of form-changing materials driven by electrical and heat stimuli.

The concept of EMS is explored through implementation in three different prototyped design experiments: *Tent*, *Curtain* and *Blind.* These modular design experiments served as the methods of inquiry. They focus on the research areas: *elasticity*, *tensegrity*, and *form-changing materials*. Each experiment is conceived to achieve individual goals for the overall design process as set out in Table 2.

Design experiments	Goal	Research areas	Implementation focus
Tent	Flexibility with 'memory'	Elasticity	Architectural skin
Curtain	Transformation	Tensegrity	Structure
Blind	Actuation	Form-changing materials	Actuator

◄ Table 2: Design experiments' goal, research areas, and implementation focus.

These design experiments are conceived as analogue proof of concept for the early architectural morphing skins effects already simulated by computational methods. These early concept models explore active and passive modes of response to changes in the environment. They consider both environmental *comfort* and use of responsive skins for *communication.*

3. DESIGNING ARCHITECTURAL MORPHING SKINS

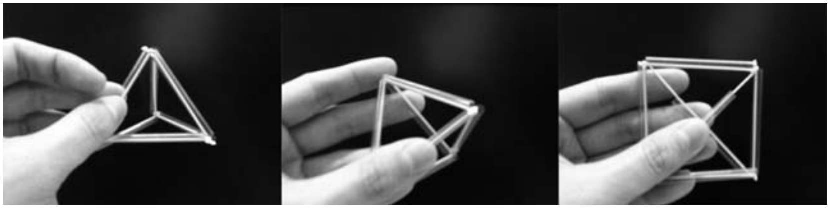
This section describes the design process for three design experiments using the Elastic Modular System (EMS). The Sensing-Analysis-Actuation (SAA) process discussed in section 2, is integral to these experiments *Elasticity*, *Tensegrity* and *Form-changing materials* in the context of designing responsive morphing skins.

The first experiment explores the area of *Elasticity* by using an assembly of passive tetrahedral elastic modules to represent the morphing architectural skin. It investigates the performance, capacities and behaviour of this system under external actuation. A second and subsequent experiment develops the elastic modules of the first prototype to minimise the number of components and reduce the weight of the module in the assembly of the *Tensegrity* exoskeleton of the morphing skin. The third and last experiment emulated an implementation of *Form-changing materials* to become the actuator as well as the skeleton structure of the morphing skin. These exploratory design experiments test the hypothesis discussed at the beginning of this paper that elastic modular systems can provide designers with a mix of passive and active design strategies to manipulate architectural morphing skins.

3.1. Design Experiment 1: Elasticity-*Tent*

Tent is a responsive elastic architectural skin assembled by series of elastic tetrahedral modules. It contracts and expands without mechanical components such as motors or pistons. It is a kinetic tent-like skin which changes shape to meet various needs and environmental conditions.

The initial idea of the elastic experiment was to demonstrate the ability of the structure to reconfigure itself to allow physical change to respond and adapt to inputs. However, this idea needs further exploration especially in terms of energy and weight. This section describes how the experiment *Tent* addresses the issues of energy and weight by using lightweight, simple elastically-transformable modules which respond to stimuli by changing their form. It aims to test on one module: 'elastic tetrahedron' the central hypothesis that elastic modular systems can provide designers with mix of passive and active design strategies to manipulate architectural morphing skins (Figure 3).



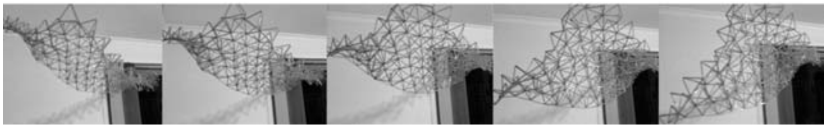
► Figure 3: Elastic tetrahedron module is formed by elastic string and plastic hollow straws for their lightweight and flexible purpose.

The intention of this experiment was to discover general directions to apply to future *'soft'* solutions to responsive design and weight issues. The elastic experiment focussed on the new possibilities of elasticity for architectural morphing skins in the following areas:

- *Elasticity as structure*- The structural, architectural components for architectural skins that can expand and contract.

- *Elasticity as membrane*- A *'soft'* architectural surface will be explored through harnessing elastic polymer properties. This tests aspects of the feasibility of implementing passive amorphous building membranes that respond to external environmental stimuli.
- *Elasticity as actuation*- The novel application of elastic material as an actuator. It excels for its light weight and for the possible substitution for the use of mechanistic joints and pistons. An example is pneumatic balloons or muscles for global actuation, that reduce weight and fiction between parts compared to equivalent mechanical systems.

These were the lines of inquiry for the experiment *Tent*. First, the assembly skeleton components of *Tent* included using accessible, basic materials such as elastic string as a primary material and hollow straws to fabricate the elastic tetrahedron module used as supportive and expendable structure (Figure 4). Second, the skin of *Tent* is the inflatable elastic polymer in *'balloon'* form that serves as actuator and skin simultaneously. The approach created novel effects that mimic '*organic*' movement and behaviour. The skin itself is elastic and expandable and achieves a high degree of flexibility and adaptability.

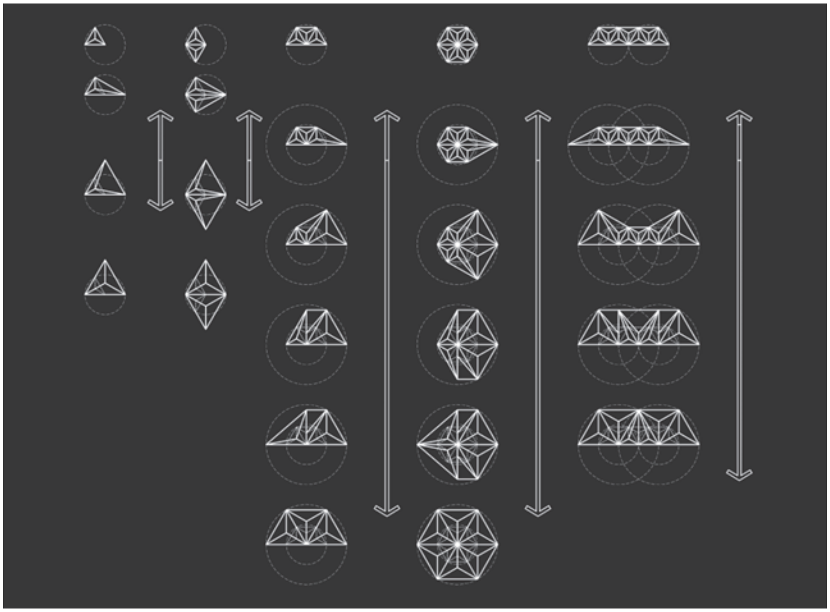


◀ Figure 4: Initial test of *Elastic Space-Frame* as skeleton that perform as contract and expendable skeleton.

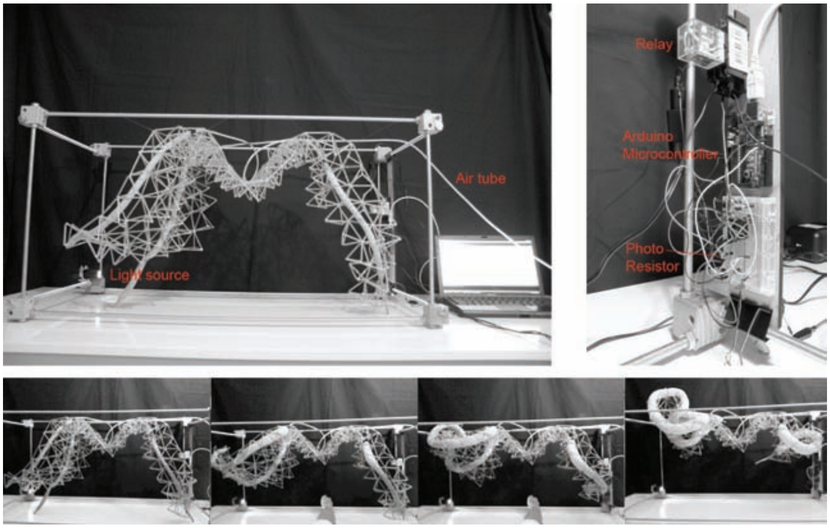
The third area used the pneumatic actuation through the skin to trigger the general morphological transformation of the *Tent*. Through expansion and contraction, the combination of individual tetrahedral modules forming the *Elastic Space-Frames* perform complicated morphing behaviour that can thus be envisaged at full scale (Figure 5). This experiment – the responsive *Tent* - is mimicking a simple living organism that responds to proximity to form the responsive *Tent*.

The initial *adaptability* test of *Tent* assessed its response to proximity. This test used pneumatic *'balloons'* to actuate the flexible contraction and expansion of the surface. A microcontroller controls this process to drive change between various states while force is applied, and return the surface to the original state if the force is released (Figure 6). This set up minimised the energy that would otherwise have been needed for local actuation. It aims to develop a low-technological approach to performance structures that possess adaptive and evolutionary personality related to environmental stimuli using the SAA process discussed in section 2.

► Figure 5: The various configurations of *Elastic Space-Frame* as skeleton structure of '*Tent*'.



► Figure 6: Top: The set-up of overall *Tent* included Arduino microcontroller, solid state relay, air pump, photo resistor and torch light. Bottom: *Tent* contracts and expands, responding to the proximity of humans using the pneumatic *'balloon'* as elastic actuator.

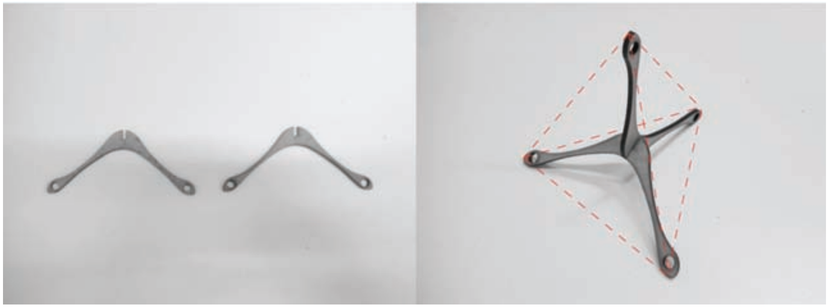


3.2. Design Experiment 2: Tensegrity-Curtain

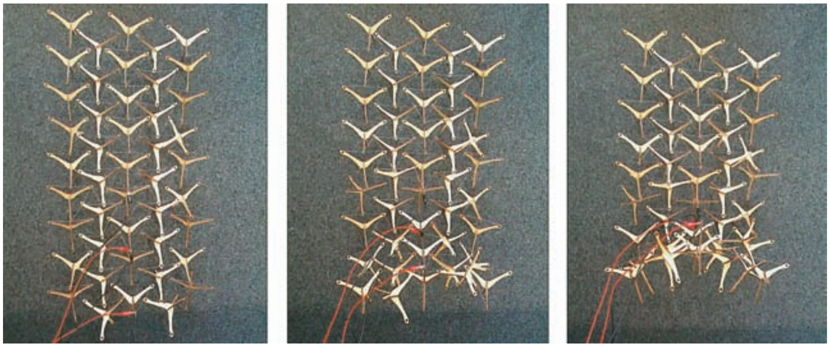
Experiment 1 demonstrated the *'organic'* kinetic behaviour of a modular *elastic* tetrahedral structure. It also started to integrate the actuator and skin, engendering a new idea for implementing them as one entity. Thus, Design Experiment 2, *Curtain* was conceived. This section reports on work to investigate how architectural skins can move and morph while minimising intricate mechanical components. This investigation will demonstrate the early physical and digital modular experiment focusing on actuated *Tensegrity* skeletal structures and surface prototypes. *Curtain* is a design proposal for integration of skin and structure as *brise-soleil* intended to improve the interior spatial conditions of existing buildings and to allow us to attain a representation of the concept of *'tensegrity'* discussed in section 2.

The assembly of *Curtain* included a series of modular tetrahedral components that form the overall design framework. In general, the design framework of *Curtain* consists of four parts as listed in section 2.

The main structural intention of *Curtain* is to fabricate a simple, flexible and lightweight skeleton. It is to eliminate or minimise the complicated and heavy mechanisms such as joints and actuators in order to produce a highly flexible structure. The tetrahedral modules form a tensegrity space frame (Figure 7). The integration of lightweight components such as MDF board and fishing string makes the physical model easy to construct (Figure 8).



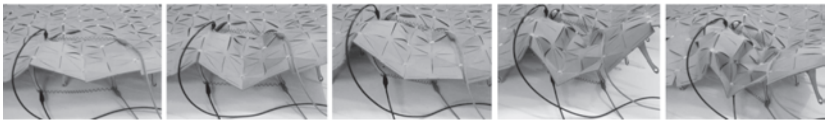
◀ Figure 7: Simple 'Inverted' tetrahedral module formed the basic backbone of the skeleton of the *Curtain*.



◀ Figure 8: Physical tetrahedral module formed the basic tensegrity space frame as skeleton of the *Curtain* and actuated by SMA spring through electric stimuli.

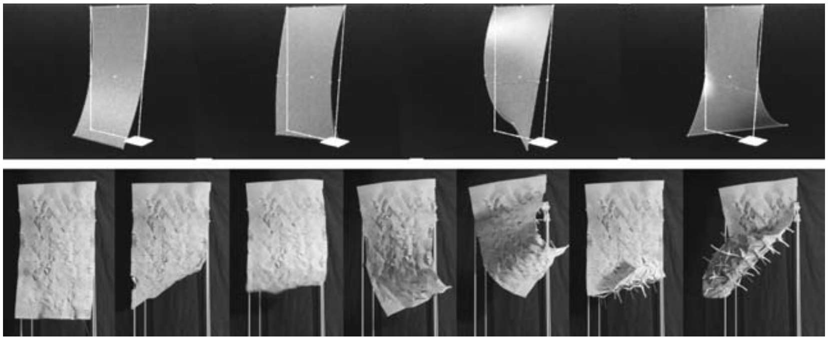
Referencing the characteristics of the human skin for the design of an architectural surface and envelope as the *'second skin'* of a building, became one of the core areas of the research into responsive architecture. The skin metaphor is not new; however, this approach still holds a lot of potential to develop responsive architectural skins especially in terms of lightweight and passive design implementation. Foam is used for the skin surface in the initial approach to elasticity to explore its behaviour when actuated by the tensegrity skeleton and SMA wire (Figure 9).

► Figure 9: The contraction and expansion of foam skin actuated by the tensegrity structure and SMA springs.

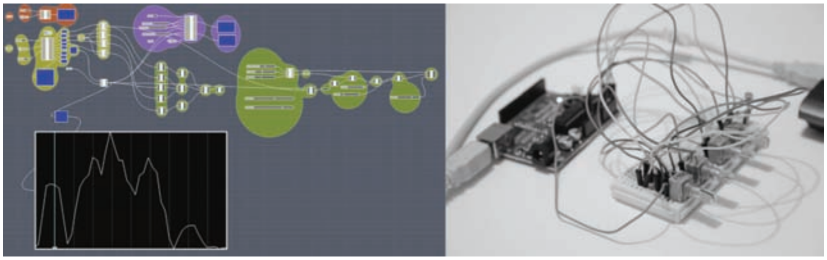


Curtain includes a study of the dynamic properties of the form-changing materials used to materialise the concept EMS. These materials introduce a simple type of physical material transformation: *expansion and contraction*. This transformation allows the actuation to take place in any three-axis configuration resulting in complicated morphing performance of the transformable tensegrity skeleton and skin. The constraints on the movement and change of this continuous morphing skin provide the possibilities and limitations to the morphological transformation. The global surface curvature of *Curtain* is modifiable. It allows contraction and expansion while it maintains the continuous topology of any undulating or flat surface. It can respond to various functional drivers to manipulate sun shading and shadow casting (Figure 10).

► Figure 10: Top: Experimentation in *morphological transformation: bending* and *twisting* in digital SAA process. Bottom: Physical implementation of the tensegrity modules to test *Curtain's* response to the direction of light.

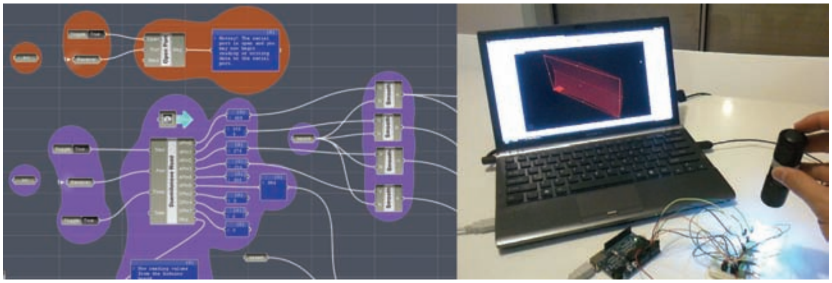


A parametric design tool is used to construct a full-scale responsive digital simulation. In the digital simulation, the prototype system is applied to an existing building as the *'Second Skin'* that creates a climatic envelope for *Comfort* purposes. The Sensing-Analysis-Actuation (SAA) model with sensors and actuators is used to make the phenomenon responsive. First, Grasshopper and Firefly parametric software together with an Arduino microcontroller, photo resistors and potentiometers, are used as design tools engaged with this simulation process (Figure 11). Second, an SMA spring serves as an actuator. The goal of this parametric model is to be an elastic tensegrity skin actively responding to the environment with a series of features like flexibility, unpredictability and non-linear transformation that constitute important facets of what architectural morphing skins might ideally manifest.



◀ Figure 11: Left: SAA system process – parametric design tool included Grasshopper and Firefly software. Right: Firefly integrated with Arduino microcontroller, photo resistor and potentiometers to test the initial '*adaptability*' of the EMS.

The *morphological transformation* of the overall surface responds to the direction of the sun to achieve maximum natural light penetration during winter and minimum heat gain during summer. It serves the goal of optimal comfort conditions within the existing space. The initial empirical experiment used a photo resistor and torchlight to mimic the path of sunlight. This process embodies the essence of *Comfort*: the digital and physical responsive surface models are stimulated to adopt various morphological states for optimal performance as a sunlight modulator (Figure 12).



◀ Figure 12: Left: Responsiveness: The data input schema. Right: SAA system process set-up morphological transformation of *Curtain*.

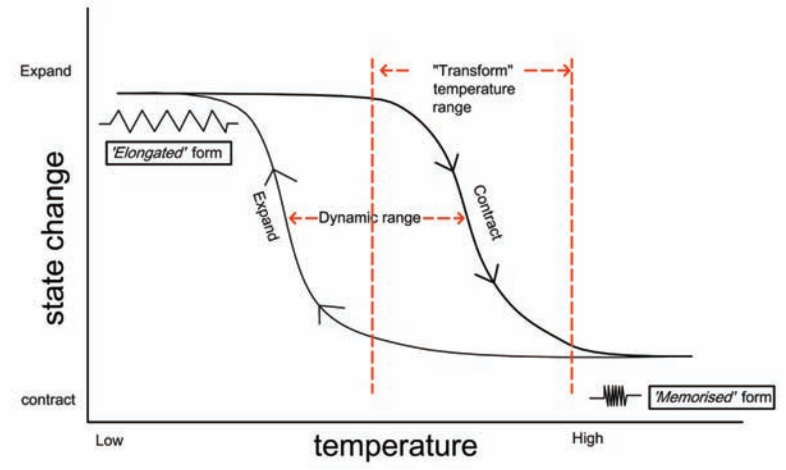
3.3. Design Experiment 3: Form-changing materials-Blind

The initial success of implementing the *tensegrity* skeleton in Design Experiment 2 led to reflection followed by further investigation of kinetic materials for a viable skin surface. In this third design experiment, called *Blind,* we extend the skin to exhibit *Visual Patterns* and *Communication*.

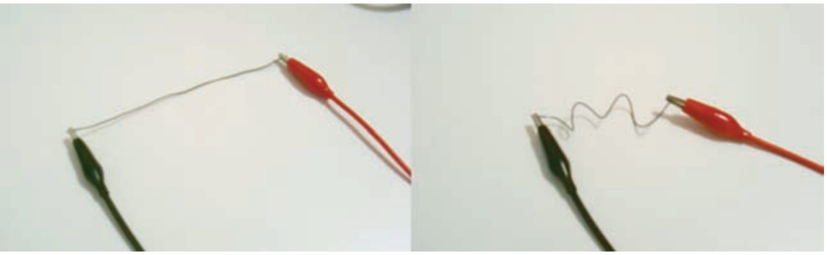
As a result of comparing multiple form-changing materials (Table 1), we found that shape memory alloy (SMA) is the most suitable material for designing elastic modular system (EMS). Although EAPs (Electro Active Polymers) have been used widely in robotic research, EAPs-based actuators are still exhibiting low force below their efficiency limits, are not robust, and are not available as commercial materials for practical application in this type of experiment [20]. Furthermore, they require a high activation field

(>150V/um) close to the breakdown level. Since the 1960s, SMAs have been the most accessible form-changing materials in the present market, and there are many applications in the aerospace and automobile sector [11]. They are commonly used in a wire or spring form that contracts in length when heat is applied; the heating can be done directly via electricity to give electrical actuation. SMAs expand by as much 8% when heated and cooled. The typical expansion of SMA in relation to temperature is graphed in Figure 4. When the SMA is below the *'transform'* temperature (60 degrees) the material takes on an *'elongated'* and neutral form, but if heated it contracts and returns to the *'memorised'* form. This process creates a dynamic range in the way that the SMA wire expands and contracts for various state changes (Figure 13).

► Figure 13: Form property of SMA is stretchable by applied force and will return to its 'memorised' form when heated by electric stimuli.

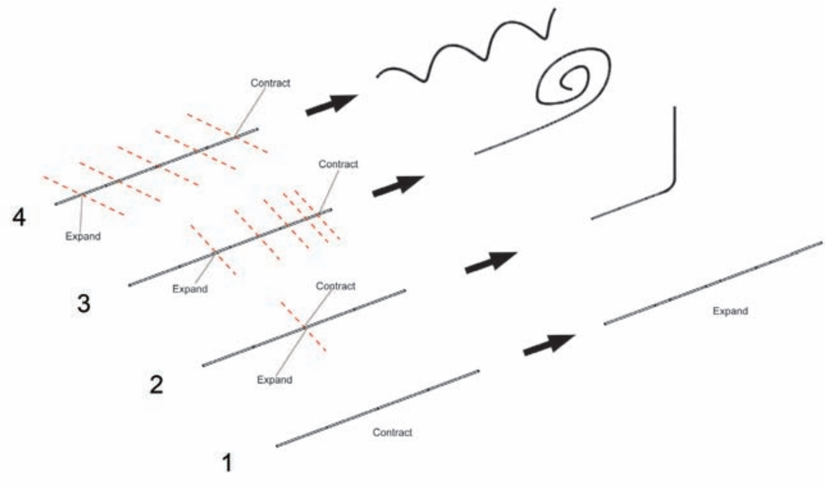


Ordinary metal alloys have an internal structure that is not altered by small temperature or electric current changes. Electrical stimuli create heat causing the atoms of the metal to vibrate faster and this makes it easier to bend when an external force is applied. The molecular form of the metal is not normally altered by heating. However, form-changing materials such as SMAs (shape memory alloys) are, by nature, dynamic and deformation occurs under electrical stimuli in this experiment, using: 5V for a 3 amp current (Figure 14). There are two stable crystalline states in their structures. When a temperature change occurs, a triggering from one crystalline form to the other occurs. Thus, SMAs are selected to implement in this research and develop further because of their accessibility, reliability and low electric current usage. This form-changing process produces expansion and contraction which can be harnessed for actuation of the whole kinetic system.

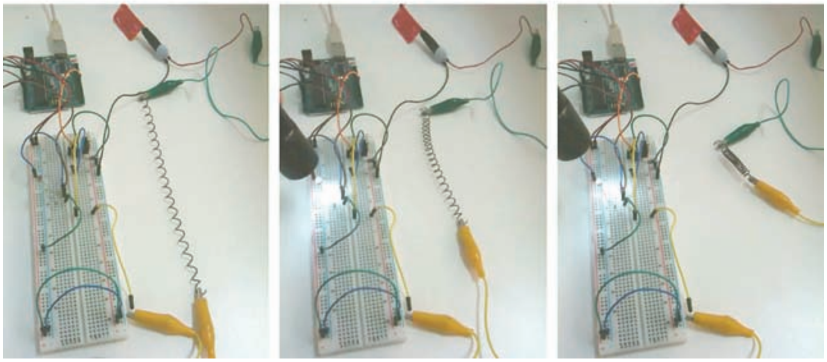


◀ Figure 14: Left: 'Stretch' SMA wire in room temperature. Right: Deformation of SMA wire occurred when heated by electric stimuli.

Figure 15 shows four potential profiles for *'Soft'* actuation based on the process of *Expansion* and *Contraction* in specific parts of the SMA wire (Figure 15). While profile one and two show the potential for the *pull* and *push* actuation, profile three and four functioned as the spring system that can actuate greater distance and force. They demonstrate that an alternative actuation system can be embedded in the overall tensegrity structure. Profiles one and four are selected for use to actuate the transformation of *Blind* . They are chosen for their robustness and stronger pulling force (Figure 16).

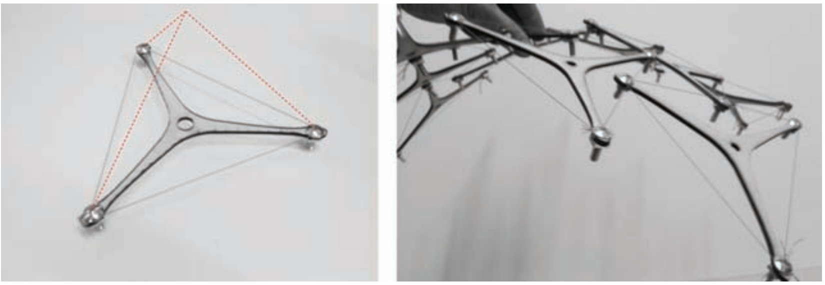


◀ Figure 15: Four potential profiles for '*Soft*' actuations of SMA wire.



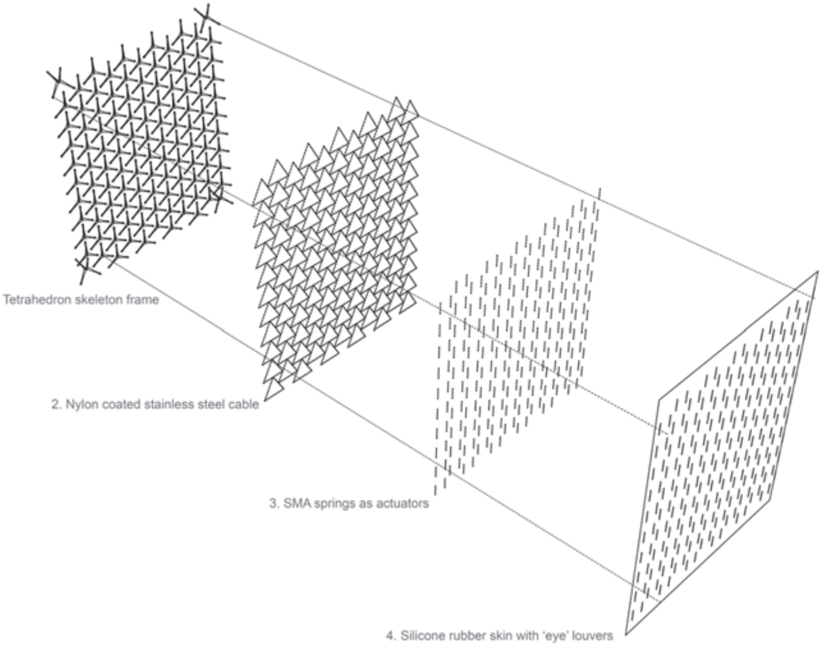
◀ Figure 16: Early test of the *expansion* and *contraction* of the SMA spring (Profile four) responding to light through a Photo resistor for the purpose of *porosity transformation*.

The materials used for assembling the skeleton of *Blind* included ABS (Acrylonitrile Butadiene Styrene) as the primary lightweight, strong material for a *'reduced'* version of the tetrahedron skeleton. This was integrated with stainless steel wire as the tension component. The tensegrity tetrahedral module was fabricated with reduced components to be assembled as the exoskeleton structure (Figure 17).

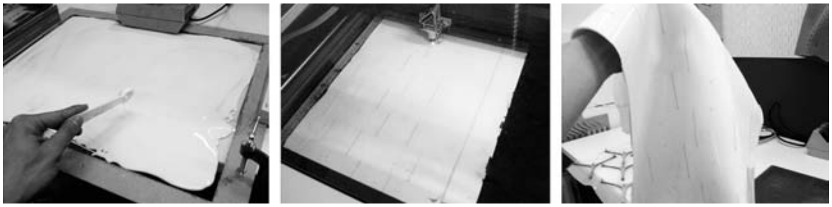


► Figure 17: Left: '*Reduced*' version of tetrahedron module for lightweight purpose. Right: Tetrahedral modules formed the elastic tensegrity skeleton of *Blind*.

With the multilayer skin of *Blind,* we explored the responsiveness to light through changing porosity (Figure 18). The elastic material used for this experiment is silicone rubber and it forms the basic non-load bearing membrane surface for the architectural envelope. The skin surface of *Blind* is fabricated using silicone rubber because of its heat resistance and elastic capacity (Figure 19).

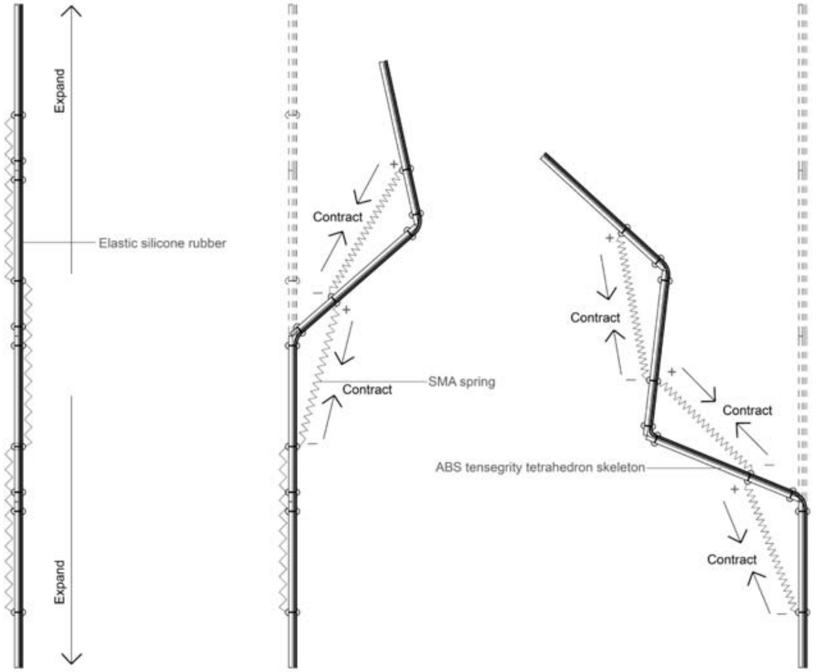


► Figure 18: Exploded layers of *Blind* to individual component and function.



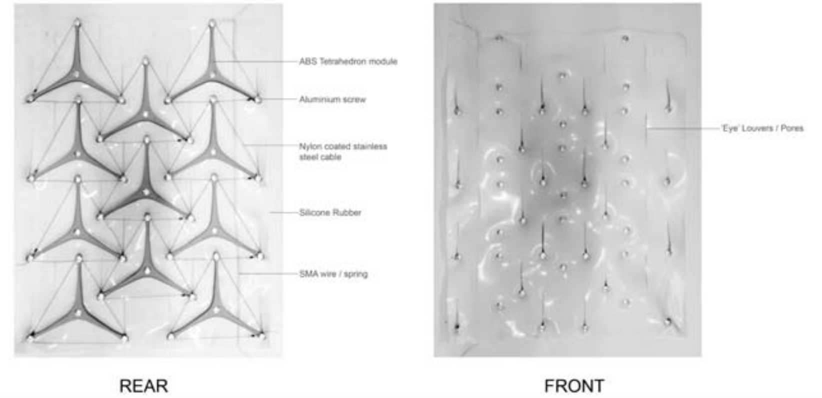
◀ Figure 19: Left: silicone rubber in the mould. Middle: Laser cutting the openings of '*eye*' apertures with embedded SMA wires. Right: Modular silicone skin.

In general, silicone rubber offers good resistance to extreme temperatures from -55 to 300 degree Celsius. Under extreme temperatures, the properties in terms of the elongation, compression, tear and tensile strength are far superior to conventional soft and elastic materials. Conventional organic rubber has a carbon to carbon backbone which can make it susceptible to UV, heat, ozone and other ageing factors that silicone rubber can withstand even in many extreme environments [21]. Thus, this high-heat-resistance material property makes silicone rubber a suitable material to integrate with SMAs to form morphing skin, addressing elasticity and actuation respectively (Figure 20). In addition, the skin itself serves as part of the actuation as well as structural component of the overall modular tensegrity system (Figure 21).



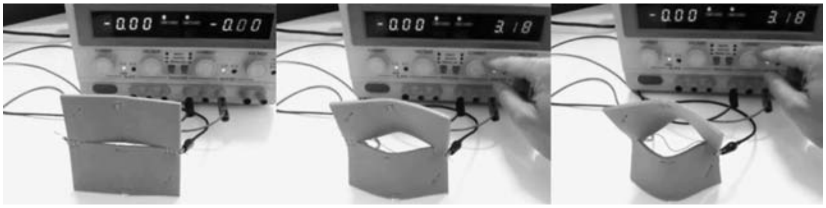
◀ Figure 20: 'Integrated' approach of SMA springs and silicone rubber to *contract* and *expand* to actuate *morphological transformation* through electrical stimuli.

► Figure 21: Left: Integration of tensegrity tetrahedral modules and silicone rubber skin. Right: Outer side of the *Blind* with '*eye*' apertures.



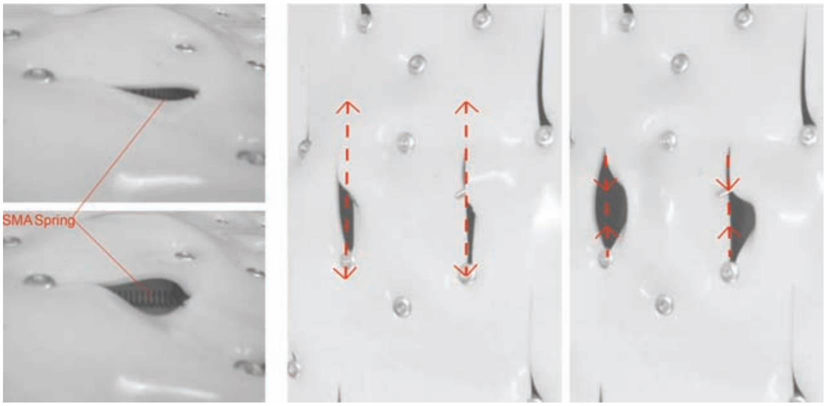
The focused transformation of *Blind* is named *porosity transformation;* the changing form of the *'soft'* opening on the surface facilitates change between multiple possible *visual patterns*. This real-time analogue media effect controls the appearance of the skin surface. The new building envelope is in constant flux as part of a 'dialogue' with the environment and occupant interacting with it. This effect, applied to provide the translucency of the surface is generated by the individual porous openings that respond to sunlight penetration and shadows cast (Figure 22). This transformation is designed to improve the spatial conditions of interior and exterior spaces through the dynamic communication between the two.

► Figure 22: Early stage of the experiment with individual modules of the '*eye-like*' aperture actuated by SMA wire through DC electric power supply regulator.



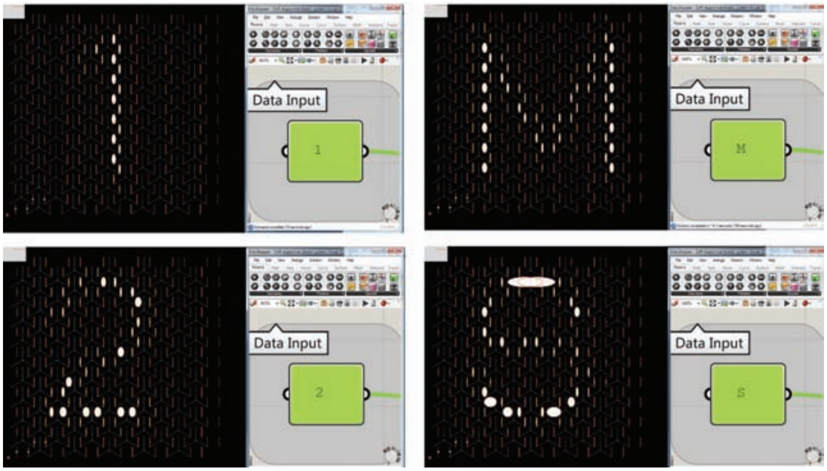
The initial geometry of the membrane porosity or openings is inspired by the performance of the eye. This analogy of an *'eye-like'* permeable aperture functioned as a skin muscle mechanism in the eye which allows various changing porous patterns on the skin (Figure 23). The *'eye-like'* apertures in the geometry are determined by their relative curvature on the responsive undulating silicone rubber surfaces and actuated by SMA wires and springs.

The application of the adaptability of *Blind* is as an analogue media screen for visual communication, which can also be responsive to ambient conditions or live data streaming. It addresses the application termed *Communication*.



◀ Figure 23: Left: '*Eye-like*' apertures open and close actuated by SMA spring. Middle: The elastic nature of silicone rubber 'closes' the '*eye*' apertures when SMA spring not heated. Right: SMA spring 'opens' the '*eye*' apertures to allow light penetration.

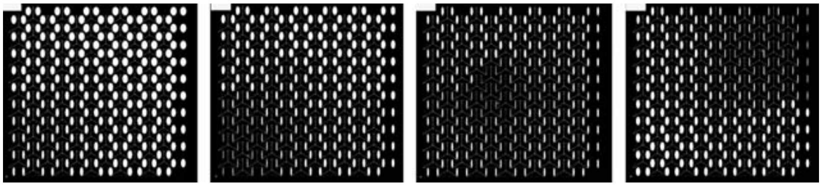
Since *Blind* serves as the *analogue media skin,* it performs communicative adaptability to display binary images and motion graphics using the perforation process of the soft surface composed by the *'eye-like'* permeable apertures. This visual intervention demonstrated in digital simulation creates a new layer of communication between the existing building skin and the surrounding urban fabric through its constant malleable porosity activated by the input of real-time information (Figure 24).



◀ Figure 24: Left: Light penetrates through the '*eye*' apertures to form the numeric text on surface. Right: Other textual *visual patterns* formed by light spots penetrating through the '*eye*' apertures.

The shadows cast into the existing interior space under the *Blind* screen provide a morphing patterned atmosphere that suggests a continued relationship between exterior and interior by shadow casting and modulation of the direct sunlight (Figure 25). This is an alternative approach to the conventional digital media screen, the design of which generally lacks the consideration of its effect on the interior condition especially in porosity and permeability.

► Figure 25: The animated sequential *visual patterns* of the '*eye*' apertures respond to reduce the direct sunlight penetration.



4. CONCLUSION AND FUTURE WORKS

Architecture is built to last. Hence, the idea of having building envelopes constructed from soft and elastic material does not seem intuitively to be feasible since soft materials do not generally possess robust structural properties. However, advances in soft, and form-changing material technology have revealed their relevance to architecture, especially when integrated with other composite materials such as those used in the aerospace technology, for examples, Aramid and carbon fibre. Current technology on aircraft morphing wing design indicates some of the potential of these materials to be implemented in architectural morphing skins. It is timely to investigate how smart materials can now be applied to designing architectural morphing skins.

This research investigates new possibilities for applying *'elasticity'* in modular systems for architectural skins that respond to various environmental conditions. It does this through a series of design experiments using kinetic models that combine digital and analogue techniques. In this paper, the evaluation of the three design experiments, *Tent*, *Curtain* and *Blind,* reveal the possibility for elastic modular systems to be applied to architectural morphing skins. The design experiments demonstrate the opportunities for a shift from a hard to a soft material and mechanical system approach. They also develop a method to study soft responsive architectural morphing skins from different perspectives in order to improve the quality of future experiments. One of the related technologies presented in this paper is the elastic modular system using the passive and active form-changing materials, silicone rubber and shape memory alloy. Here they are applied in the novel context of architectural morphing skins. These design experiments while in an early stage, extend the current repertoire of kinetic brise-soleil to introduce alternative design methods. They point to the potential for full-scale architectural applications.

Future work will include further experiments that explore the scalability of the elastic modular system and implement it in an actual site context. This approach aims to develop a novel design method and a feasibility study for designing full scale responsive architectural morphing skins with current technologies. A further investigation also aims to design *'adaptive'* form-changing materials as synthetic composites which have kinetic matter embedded and computational process integrated in the architectural morphing skins.

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Chin Koi Khoo, Flora Salim and Jane Burry

RMIT University
Spatial Information Architecture Laboratory (SIAL)
GPO Box 2476, Melbourne, Victoria 3001, Australia

chinkoi.khoo@rmit.edu.au; flora.salim@rmit.edu.au; jane.burry@rmit.edu.au