C. M. Herr, N. Gu, S. Roudavski, M. A. Schnabel, *Circuit Bending, Breaking and Mending: Proceedings of the 16th International Conference on Computer-Aided Architectural Design Research in Asia,* 143-152.

DESIGNING ELASTIC TRANSFORMABLE STRUCTURES

Towards Soft Responsive Architecture

CHIN KOI KHOO[1] and FLORA DILYS SALIM[2]
RMIT University, Melbourne, Australia
1. mosphosis@hotmail.com, 2. flora.salim@rmit.edu.au

Abstract. This paper discusses the issues of designing and building environment involving spatial conditions that can be physically reconfigured to meet changing needs. To achieve this architectural vision, most current research focuses on the kinetic, mechanical systems and physical control mechanisms for actuation and structural transformation. Instead of the *'hard'* mechanical joints and components, there is an unexplored *'soft'* approach using lightweight elastic composite materials for designing responsive architectural skins and structures. This paper investigates the new possibilities for the manipulation of various architectural enclosures using 'soft' and elastic transformable structures, in response to environmental, communication and adapting to various contexts. This approach intends to minimise the mechanistic actuations and reduce weight for such operations. Therefore, this research introduces two modules (a tetrahedron and a cube) as responsive spatial models to test the potentials and limitations for the implementation of elastic materials with responsive capability towards reconfigurable architectural enclosure. Despite their individual differences, these experiments identify a trajectory for new possibilities for elastic architectural components that are more appropriate for *'soft'* responsive architecture. We argue that this approach can provide an early hypothesis for design responsive architecture with a mix of passive and active design strategies.

Keywords. Elastic; transformable; soft; responsive.

1. Transformable structures for responsive architecture

"Responsive architecture" was coined by Nicholas Negroponte in the mid seventies (Soft Architecture Machines) when spatial design problems were explored in responsive space (Sterk, 2003). There are precedents for responsive architectural spaces that can be transformed and reconfigured to accommodate different usage. The first precedent: Villa Girasole, the rotating house built by the engineer Angelo Invernizzi in 1929-35 Marcellise, a completely revolutionary idea of a rotating building designed to constantly capture sunlight and the use of eco-compatible energy source. In addition, Gerrit Rietveld used sliding partitions to allow spaces to be responded to different uses in his Schroeder House, 1924 (Butler and Oudsten, 1989). Recently, Shigeru Ban's 9 Square Grids House has a similar approach, a contemporary interpretation of the conventional Japanese house with sliding partitions as large cabinets to store blankets and mattresses during the day and provide privacy at night (Ban, 1998). However there are several shortcomings to these approaches that have restricted their implementation. In general, there are only limited possible configurations, and while the partitions are produced as lightweight as possible to allow inhabitants to move them manually, making them poor thermal and sound insulators, the process of reconfiguring a space is fairly labor intensive (Weller and Do, 2007).

In parallel, computationally generated transformable structures have also been a focus of current digital era. When we consider responsive architecture composed by transformable structure, we are forced to confront issues of human power, space control, environmental manipulation, material economy, operational effectiveness, and energy investment (Sanchez-del-Valle, 2005, p.137). Furthermore, contemporary responsive architecture in general is built on the convergence of embedded computation (intelligence) and a physical counterpart (kinetics) that satisfies adaptation within the contextual framework of human and environmental responsiveness (Fox, 2009, p.381). The integration of these two areas will provide the environment that is capable of reconfiguring itself and automating physical change to respond, react and be adaptive. This metaphor will lead to a purpose that structure can be reduced for space-making through the ability of a singular system to facilitate multi-uses via transformative adaptability.

2. Soft Responsive Space

Recently, the work of dECOi: Aegis Hyposurface has attempted to integrate two facets of architecture: responsiveness and transformable structure, to create and investigate responsive architectural facades and installations using high-tech mechanical solutions. However, this solution involving *'hard'* mechanical components like multiple pistons to actuate transformation always comes with high energy consumption and complex mechanism. Is there an alternative to this approach? There is a need to further explore a new possibility to address the *'soft'* elastic architectural components like elastic strings, textile and silicone latexes towards responsive architecture.

Since the *'soft'* approach of architecture introduced during 60s and 70s, there is not much progress in this experiment and research area of architecture (Negroponte, 1975). However, in order to achieve this architectural vision, further exploration of kinetic mechanism and materiality is needed. Instead of investigation towards the conventional mechanistic approach, this research explores for the use of day-to-day *'soft'* elastic materials for constructing kinetic and responsive architectural model. The purpose of this investigation takes the position that a more organic versus mechanistic approach to transformable structures, one that capitalises on material properties rather than technologies of connections, provides an opportunity to holistically address both performance and aesthetics in soft responsive architecture (Khan, 2009). Although works by ONL and HRG, such as project Muscle (Oosterhuis, 2003) aimed to demonstrate a soft responsive space, the pneumatic mechanisms are highly power consuming and less consider the potential of elastic memory of the soft structure for passive actuation and surface porosity. On the other hand, the work of Omar Khan: Gravity Screens provide an alternative approach that the surface constructions form results from gravity's effect on their elastic material patterning. These elastic mutable screens provide possibilities for responsive space that can mutate from circulation corridors to room clusters (Khan, 2009). However, Khan's work just provides a starting platform for soft responsive architectural idea and it is still unexplored territory to expand this potential of responsive architecture, from *'hard'*, to *'soft'* approach.

There is a need for low-tech passive design strategies which can generate responsive architectural prototypes without complex mechanical actuations. Thus, this research aim to explore the application of elastic transformable structures, such as exhibited in elastic material systems, for fabricating low-tech and soft responsive spatial modules. 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 premise of energy and maintenance of this application are concerns in this research, they are not included in the scope of this paper. We argue, as an early hypothesis of this research, that elastic transformable structure can provide designers with a mix of passive and active design strategies for manipulate soft responsive space through the testing of scaled spatial modules. Therefore, this paper will expands the repertoire of responsive architectural design solutions using accessible *'soft'* component such as elastic materials integrated contemporary digital sensing devices and parametric design tool.

3. Design Process

The purpose of the design process presented in this section is to design elastic transformable structures using the soft approach of manipulating responsive space. The whole process undergoes iterations of physical and digital modeling and fabrication (Figure 1). Through each step of the process, digital data is exchanged between digital and physical models. This process is called form fostering, which bridges the physical and digital through exchanges of digital data (Salim et al, 2011). Parametric models can be associated with real time data from sensors, which stream data from physical environment, as input to drive the parametric variations in the model (Salim et al, 2011). The parametric model becomes the platform for simulating the behaviours of the elastic transformable structures in the design stage. In general, the design process of elastic transformable structures consists of four factors as listed in subsections 3.1-3.4.

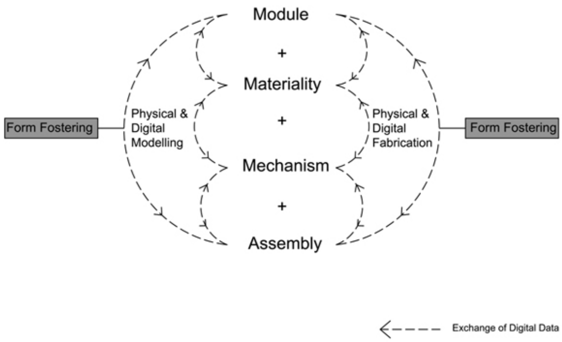

Figure 1. Diagram of design process in four areas towards form fostering.

3.1. MODULES

The first stage of the design requires modular components to be sketched, modeled, and fabricated. They are represented in the form of parametric models as part of experiment process.

3.2. MATERIALITY

It investigates day-to-day, accessible and affordable elastic materials such as rubber band, elastic spring and balloon for physical implementation.

3.3. MECHANISM

Mechanism is looks at the new possibilities of these elastic materials to produce simple mechanisms like joints, actuators and hinges that could become an alternative toolkit compared to conventional mechanical approach.

3.4. ASSEMBLY

The last process is the assembly of the modules in order to achieve transformable structure that displaying elastic properties to respond digital and physical adaptation. The following section discusses form fostering experiments which include two different modules – an Elastic Tetrahedron and adaptive Cube, which are presented to demonstrate some experiments which include the proof of the early concept for elastic transformable structures that are simulated by computational methods for their active and passive modes responding to changes in the environment.

4. Experiments

4.1. THE ELASTIC MODULE

In general, initial idea of the elastic module has the ability to reconfigure itself - to automate physical change to respond, react and adapt. However, this idea needs further exploration especially in terms of energy and weight. When we argue a structure that moves in whole, or in parts, is like a machine. A machine applies energy to do work and energy use is unavoidable. Thus, this section demonstrates two experiments that address this issue by using lightweight orientated and accessible transformable structure with elastic ability to reduce energy and weight that respond to stimuli by changing their form. It aims to test this hypothesis on two modules. The intention of these modules is to propose general directions to be applied to solve the 'soft' technical responsive design and energy issues for future works. The Elastic module discussed these issues focus on the new possibilities of elasticity towards soft responsive architecture in the following areas:

- **Elasticity as structure.** The structure of architectural components such as roofs, ceilings and walls can be contracted and expanded to increase flexibility in the use of existing internal or external architectural space.
- **Elasticity as membrane.** A *'soft'* architectural surface will be explored through harnessing elastomer (elastic polymer) properties for the feasibility of implementation such as passive amorphous building membrane harvesting kinetic energy through wind or sunlight.
- **Elasticity as actuation.** This research and design looks at the new approach of elastic material as actuator for it lightweight and minimising the use of mechanistic joints and piston. For instance, pneumatic air harnessing balloon

or muscle for global actuation and reduce weight and fiction between part.

4.2. ELASTIC TETRAHEDRON MODULE

4.2.1. Materiality

The module of Elastic Tetrahedron is using accessible elastic string as a primary material and hollow straws fabricate the Elastic Tetrahedron module used as supportive structure.

4.2.2. Mechanism

It is to form an elastic skin for existing building to response proximity through pneumatic air balloons actuation in order to contract and expand parameter to manipulate the interior spatial condition. It is capable of changing various states while force applied and return to the original state if force released (Figure 2). This behaviour provides the opportunities to minimise the energy for local actuation and attempt to develop a low-technological approach to performance structures that possess adaptive and evolutionary personality related to environmental stimuli.

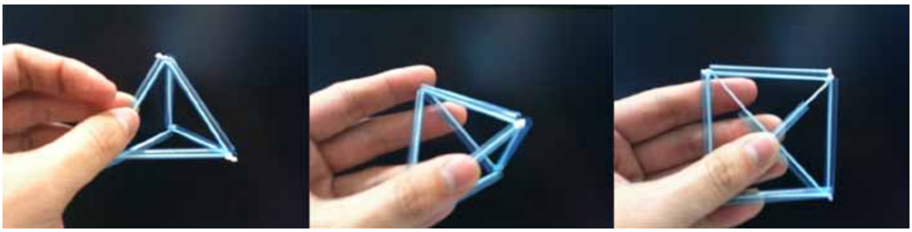

Figure 2. Elastic Tetrahedron is formed by elastic string and plastic hollow straws for their lightweight and flexible purpose.

4.2.3. Assembly

Furthermore, the combination of individual module will form the *Elastic Space-Frames* that assembling more complex formation of elastic structures and behaviour in bigger scale. This experiment is mimicking a simple living organism that responds to human interaction to form a responsive *Shelter*. Therefore, in order to achieve this responsive phenomenon, form fostering technique composed of sensors and actuators is necessary that roughly simulates the biologic behaviour. Firstly, Grasshopper and Firefly parametric software together with Arduino microcontroller and proximity sensors are used as design tools engaged with this simulation process (Figure 3). Second, the actuation is involved through the use pneumatic air balloon serves as actuator to reduce mechanistic components as mentioned in the section *Elasticity as actuation*. The goal of this parametric model is to be an elastic skin actively responds to the environment with a series of features like flexibility, unpredictability and non-linear transformation that constitute important facets of what soft responsive architecture should manifest (Figure 4).

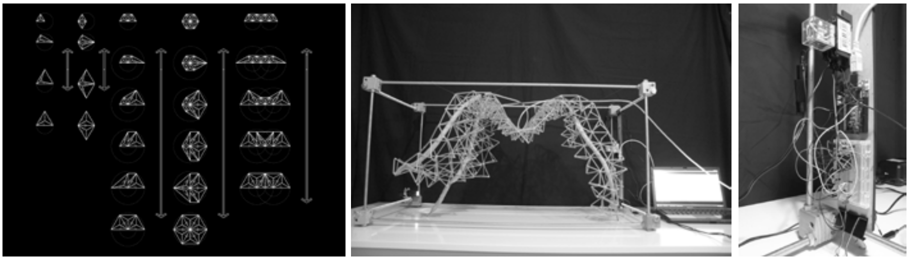

Figure 3. The formation of Elastic Space-Frames (left); The complete module of Shelter (middle); A setup included Arduino microcontroller, relays and breadboard (right).

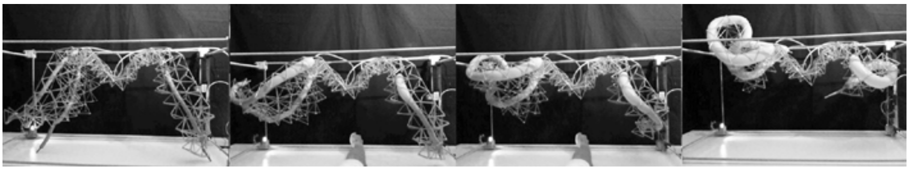

Figure 4. The Shelter contracts and expands responds to the proximity of human intervention and population through the pneumatic balloon as elastic actuator.

4.3. ADAPTIVE CUBE MODULE

4.3.1. Materiality

The elastic and adaptation capability of the structure configuration is the initial goal for this *Cube* module development process. This *Cube* structure model basically is assembled by two components, a hard hollow aluminium tube and soft elastic string for theirs lightweight and accessibility, to minimise the energy required for actuation, and be able to be continuously flexed along each joint to connect them together.

4.3.2. Mechanism

Furthermore, the actuation system will be a similar approach to the Elastic

Tetrahedron module previously and the pneumatic air balloon is ‘embedded’ in-between two hard and soft materials for actuation in order to adapt various environment conditions. For example, each corner of the *Cube* structure is embedded a sensor to detect the proximity of object or surface and it extends the length of the structure until it reaches the stable state (Figure 5).

4.3.3. Assembly

The purpose of this experiment is to test the new possibility for assembling automated adaptability in architectural structure for unpredictable calamity events such as earthquakes and floods to minimise damage and provide protection.

In addition, the design of this module opens up opportunities to develop of architectural configuration that responds and adapts for uncertainty (Figure 6).

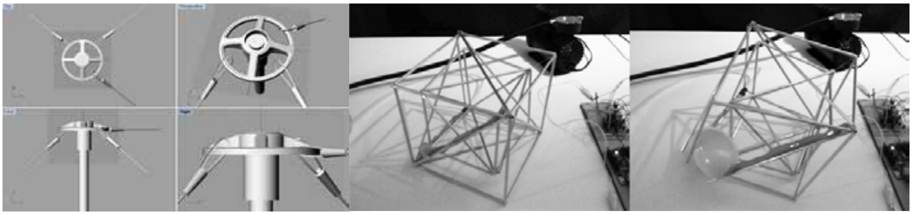

Figure 5. Digital detail of elastic joint that minimise fiction (left); Physical Cube structure with sensors and embedded pneumatic air balloon to detect proximity of surface until reaches its stable state (right).

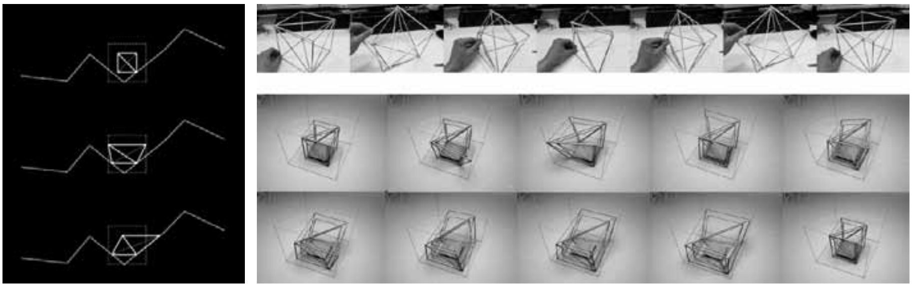

Figure 6. Adaptive Cube structure for unpredictable environment (left); Early stage of physical study of the elasticity (above); Adaptability of the elastic Cube structure (below).

5. Conclusion and future work

The research presented in this paper introduces the new design possibilities of elastic transformable structures that adapt and respond to environment in order to manipulate dynamic reconfigurable space. By using the two elastic modules as experiments to test, the aim of these experiments allow new ideas emerge from performing physical and digital modeling. One of the fundamental investigations for this research is testing the *'soft'* approach of elastic structures provide alternative to conventional kinetic approach using mechanical components to achieve responsive architecture. We argue that the *'soft'* and elastic components such as elastic strings, latexes and fabrics demonstrate more appropriate approach for responsive architecture in terms of actuation and deformation as demonstrated in precedent works by ONL and also experiments described in this paper. This approach has been tested by the two responsive parametric models discussed in section 4 and presented the great potential for full-scale implementation in future research. In addition, when applying the computation design tools for the parametric model; the multiple analogue inputs information flows to the responsive algorithm to activate the *'soft'* elastic actuator for the flexibility, versatility and adaptation in transformable structures. The further development of this research attempts to refine this method and explore the simpler and robust prototypes using elastic, lightweight, form-changing materials as structure in order to achieve the dynamic reconfigurable space for functional environmental aspects.

On the other hand, since the property of elastic material makes it problematic as a self-supporting structure, the introduction of embedded pneumatic air muscle as stretchable actuator shown in two modules cause it to stiffen and hence solve certain level of the structural integrity. This design approach is leading to the lightweight structure that allows *'soft'* elastic architectural skin to transform from thresholds to enclosures. This approach implemented in the process of designing holds significant potential for further exploration towards the form-changing materials as platform of convergence in-between transformable structure and responsive space. The form-changing materials such as Ethylene Tetrafluoroethylen (ETFE) embedded with photovoltaic cell, Shape Memory Alloy (SMA) and Electro-Active Polymer (EPA) that respond to environmental and communication stimuli will provide the potential for full scale architectural applicability of elastic transformable structures; and harvesting energy for self-sustainability while reducing mechanistic components. They also enable real time manipulation of elastic capabilities for transformation demonstrated by the two modules that ultilise the novel design framework proposed in section 3. This future research is offered a practical methodology for conceiving a responsive architectural envelope system that synthesizes passive design concerns with the feasibility factors of fabrication and construction goals. Thus, in relation to the hypothetical experiment, the purpose is to find a range of possible integration of responsive skins and structures that can be applied to various architectural components such as facades, walls and roofs in general to complete the actual design solution for the future work. These transformable components will eventually serve as second skins for existing buildings intended to potentially improve the interior and exterior spatial conditions.

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