

Designing with Biomaterials for Responsive Architecture

A soft responsive “bio-structural” hydrogel skin

Chin Koi Khoo¹, Jae-Won Shin²

¹IDEA Lab, Deakin University ²Sculpting Regeneration Lab, The University Illinois at Chicago

¹chin.khoo@deakin.edu.au ²shin.jw@uic.edu

Synthetic biomaterials are not only widely explored in tissue engineering, but also present important opportunities in responsive architecture, especially soft structures and skins. In this paper we present how water-containing hydrogels can be adapted to digital fabrication techniques to design a soft responsive skin with integrated skeleton and surface. This research project details preliminary investigation into how tough hydrogels with different material properties can be designed and incorporated into laser-cutting and 3D printing methods typically used in architectural design. The outcome of this research produces an early prototype of thermally sensitive, tough hydrogel skin that responds to environmental stimuli such as temperature and moisture. Our work provides initial insights into how a soft responsive “bio-structural” architectural skin can be designed by integrating actuation, structure, and skins.

Keywords: Biomaterials, digital fabrication, hydrogel, responsive architecture

INTRODUCTION

For centuries, materials were subordinate to architecture that followed the form, structure and function of buildings. Although building technologies and construction methods were improved, building materials used in architecture remain traditionally rigid (Konarzewska 2017). Advanced responsive materials offer radical changes in architectural design because of novel properties and functions (Aksamija 2016). Some of these materials have been shown to respond to different stimuli such as light and temperature and undergo structural changes (Ritter 2007). While a number of material systems were investigated previously in architecture such as shape memory alloy for Blanket (Khoo 2012), most of them are not capable of

interfacing with biological matters, since they do not contain water.

In this paper we aim to explore hydrogels, synthetic biomaterials that contain water to prototype a soft skeleton that can be potentially used in responsive and kinetic architecture. Hydrogels have been widely used in tissue engineering and biotechnology industries, but their applications in architecture and built environment have been rarely explored (Rotzetter et al. 2012). While hydrogels are traditionally known to be brittle, recent advances have led to new formulations that may be more suitable for architectural purposes, such as tough hydrogels where materials can be both soft and durable (Sun et al. 2012). To motivate this investigation, we used

moulding and 3D printing technologies guided by a parametric design principle. The outcomes demonstrate a designed hydrogel skeleton with structural deformation and heat sensitivity capabilities, which can be potentially applied to responsive architectural structures and skins. The skeleton can also be applied to augment functions of existing buildings.

SOFT RESPONSIVE STRUCTURES AND SKINS IN ARCHITECTURE

The concept of soft architecture was first introduced decades ago (Negroponte, 1975). The climatic skin of the Biosphere at the Montreal Expo of 1967, designed by Buckminster Fuller, sets the first precedent for soft architecture. It is considered a pioneering use of soft materials (fabrics) in the design of the shutters for geodesic dome steel structure (Bonnemaïson 2008). More recently, Omar Khan’s “Gravity Screens” shows an envelope fabricated by patterning soft and elastic synthetic rubber, which deform in response to gravity (Khan 2009). While these projects show promising

directions for the field of soft architecture, it has yet to leverage recent advances in novel materials.

BIOMATERIALS IN ARCHITECTURAL DESIGN

Advanced materials have been recently implemented in architecture for different applications especially in responsive building façade and surface design (Konarzewska 2017). Biomaterials have been considered in architecture because they have potential to interface with living matters (Gazit 2016). Projects such as The “Organic Mushroom-Brick Tower” by The Living [1] and “Grow Brick” by bioMASSON [2] introduce the novel use of biomaterials to synthesize bricks directly in buildings (Larson 2010). However, biomaterials have been rarely considered as construct for soft architecture.



Figure 1
A series of trial hydrogel formulations with a composite (interpenetrating network) of alginate, polyethylene glycol-methacrylate, and poly(N-isopropylacrylamide) polymers.

Figure 2
The stretchable and
flexible hydrogel.

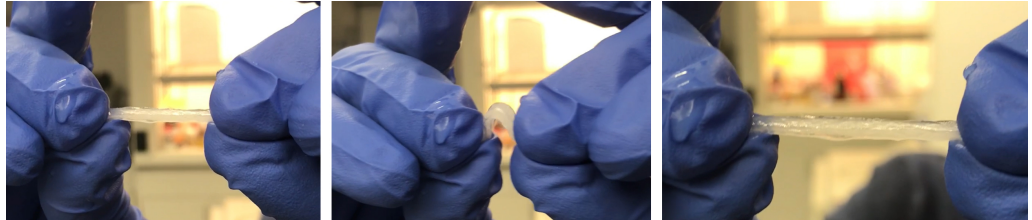


Figure 3
Left: A strip of
PNIPAM in room
temperature. Right
PNIPAM is
undergoing
deformation in
response to heat
(boiling water).

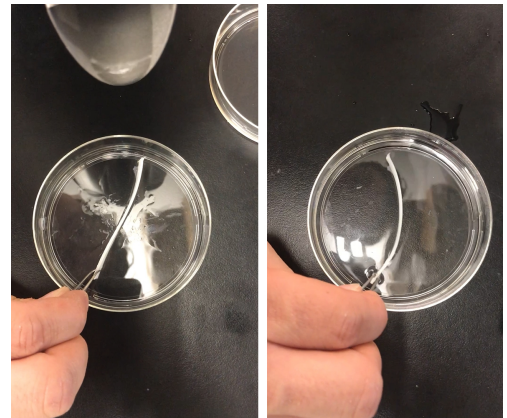
RATIONALE: HYDROGELS IN RESPONSIVE ARCHITECTURE

Hydrogels have emerged as novel materials of interest in the field of architecture and design due to their responsive abilities with low-energy consumption and cost, and the possibility of interfacing with biological matters with active or ‘smart’ properties ranging from DNA to cells at the architectural scale. For example, the project “Hydroceramic” exploits hydrogels to respond heat and water by leveraging its ability to evaporate, which enables temperature regulation of the interior space [3]. This project introduces a passive system to balance humidity and temperature of an interior space to achieve a human comfort-zone. While most previous studies have focused on utilizing intrinsic, chemical properties of hydrogels, structural design aspects of hydrogels in responsive architecture remain largely unexplored. Understanding design principles behind how hydrogels can be designed and fabricated for architecture will be an important goal to realize integrated skeletons and skins that can perform multifunctional tasks such as sensing, actuation and illumination with minimum active and passive energy.

METHODS

This project-based research was conducted in two Stages. In Stage 1, we explored different formulations and fabrication of hydrogels to achieve a range of mechanical and structural properties, such as stiffness, toughness, and sensitivity to heat. In Stage 2, we digitally fabricated a structure consisting of multiple types of hydrogels with distinct properties and performances by moulding. A 3D printing technique

was used to demonstrate whether it is possible to print the materials across different scales in cm and mm. Various samples and mock-ups were produced in the centimetre scale to evaluate the feasibility of physical hydrogel structures.



PHYSICAL DESIGN IMPLICATION AND FABRICATION

To identify polymer formulations that show toughness (fracture energy per cross-sectional area) with tuneable control of stiffness and thermosensitivity, we created a series of rectangular cuboid hydrogels by mixing alginate, polyethylene glycol-diacrylate (PEG-DA), and poly(N-isopropylacrylamide) (PNIPAM) in different ratios and crosslinking them (Figure 1). Alginate undergoes ionic crosslinking in the presence of divalent cations (e.g. Ca^{2+}), while PEG-DA is crosslinked covalently upon UV exposure in the pres-

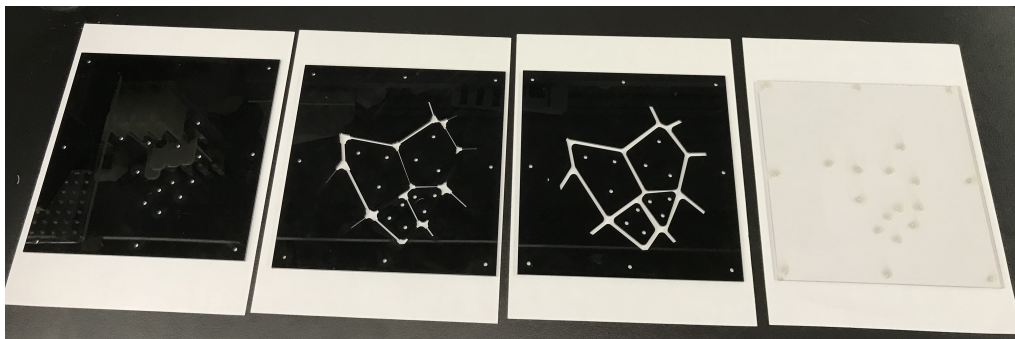


Figure 4
The mould of the hydrogel structure consists four layers of laser-cut panels.

ence of photoinitiator. Mixing alginate and PEG-DA during crosslinking leads to toughness of hydrogels (Sun et al. 2012) (Figure 2). Crosslinking of PNIPAM occurs in the presence of bis-acrylamide, and is further enhanced in the presence of UV. PNIPAM hydrogels undergo deformation in response to heat (Figure 3). We proceeded Stage 2 with select formulations.

In Stage 2, a laser-cut mould with four different layers was designed and used to produce a hydrogel structure in the cm scale (Figure 4). The mould is mimicking a typical leaf structure pattern that was derived from a natural structure to achieve the system of “minimum inventory for maximum diversity”. This system is a modular structural system can achieve a wide variety of patterns from a small variety of parts (Perce 1978). Three different types of hydrogels were used to fabricate the structure: stiff, soft, and thermal-sensitive hydrogels. Figure 5 presents a material mapping for the different types of hydrogels that were deposited in different parts of the mould for various stiffness of the overall structure. The hydrogels were deposited in different parts of the mould (Figure 6) guided by parametric design.

The structure is durable and actuates in response to temperature, since the joints become rigid and deformed in hot water, while they are reversed in cold water (Figure 7). We also demonstrate that the same materials can be used to fabricate a structure in the millimetre resolution using stereo-lithography based 3D printing technology (Figure 8).

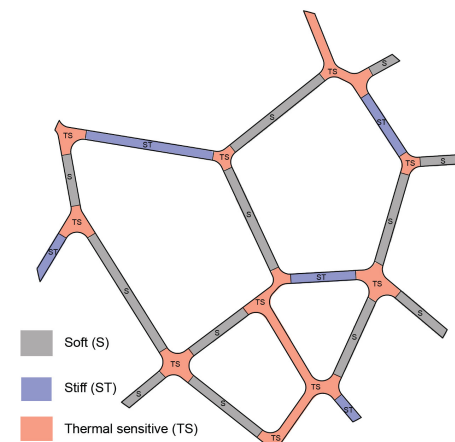


Figure 5
The material mapping of hydrogel structure with different properties: stiff, soft, and thermal-sensitive.

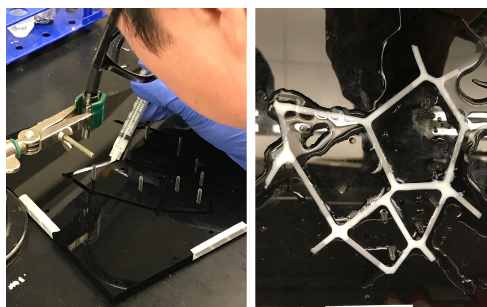


Figure 6
Left: The hydrogels were deposited in different parts of the mould for various stiffness of the overall structure. Middle: The hydrogel structure formed in the laser-cut mould. Right: Hydrogel structure soaked in water.

Figure 7
Left: The bio-structural hydrogel skeleton in cold water. Right: The bio-structural hydrogel skeleton deformed in hot water.

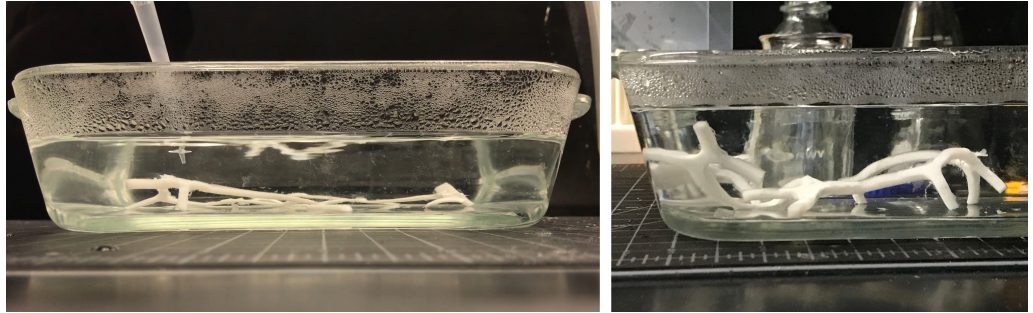
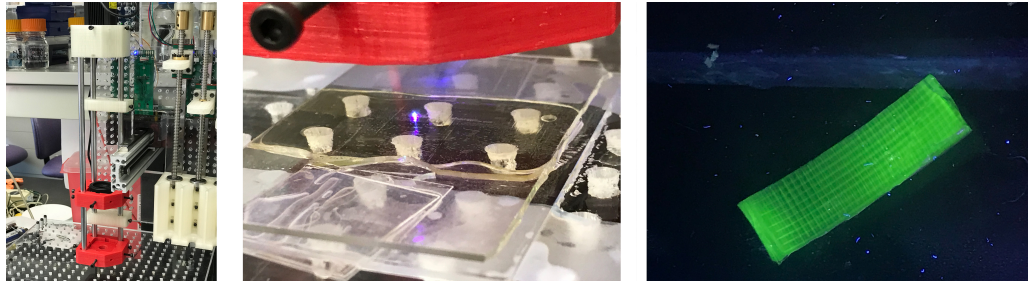


Figure 8
Left: The 3D printer equipped with stereo-lithography. Middle: 3D microprinting for hydrogel. Right: Hydrogel structure is 3D printed using stereo-lithography technique.



These physical outcomes demonstrate a promising potential of parametrically designed hydrogel-based structures with multiple physical properties that can be manufactured through different techniques.

POTENTIAL APPLICATIONS AND DEVELOPMENTS

The preliminary outcome is a very encouraging demonstration to design hydrogels for responsive and kinetic architectural applications and implementations. By appropriately placing hydrogels with different mechanical properties, it is possible to actuate and deform the structure with minimum passive energy such as heat from sunlight. This outcome serves as a proof of concept for an integrated hydrogel structure. Three directions have been identified for potential architectural applications and developments enabled by our approach:

- Reciprocal intervention: Adaptive architectural intervention to improve the performance and responsiveness of existing building components such as glazing and window with phase-changed and thermotropic shading capabilities
- Environmental skeleton: Novel type of architectural skeletons for existing built environment to regulate temperature and humidity for building exteriors and interiors
- Soft responsive skin: Responsive and multi-functional soft architectural skins to perform structural, sensing and actuation capabilities

Reciprocal intervention

One of the potential applications of our bio-structural hydrogel is to develop a shading system with passive thermotropic properties to improve the

existing windows and openings with enhanced environmental responsiveness and adaptability. Since PNIPAM in our hydrogel becomes opaque in heat, materials that can convert light into heat, such as graphene oxide (Kim et al., 2015) can be incorporated into our system to realize a photothermotropic capability.

Thermally sensitive glazing in hydrogels was initially developed in the 90s to construct a simple composite structure using a viscous hydrogel and conventional type of substrate sheet glass (Watanabe 1998). Figure 9 demonstrates a conceptual model of hydrogel structure as a leaf pattern that can serve as thermotropic shading between two substrate sheet glasses. Temperature change can impact opacity of the retrofitted thermotropic hydrogel (Figure 10). This system has great potential to both shade light and enhance the aesthetic and appearance of existing façade and surface of buildings through the kinetic movement and thermotropic effect of the structural hydrogel pattern.

Environmental skeleton

Our bio-structural hydrogel presents another architectural design possibility to improve structural performance of existing architectural elements and components such as curve glass surface. The proposed skeleton can serve as a retrofitted soft skeletal pattern in the internal surface of a hypothetical glass dome (Figure 11). The hydrogel skeleton can perform as a secondary structure to provide additional flexible structural support and to potentially reduce heat gain and energy consumption of existing building surfaces. This approach could apply to almost any architectural surface with any form and shape.

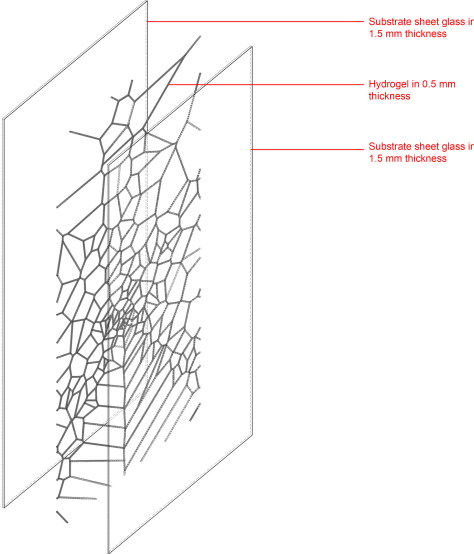


Figure 9
The components of the proposed thermotropic hydrogel glazing with appropriate thickness

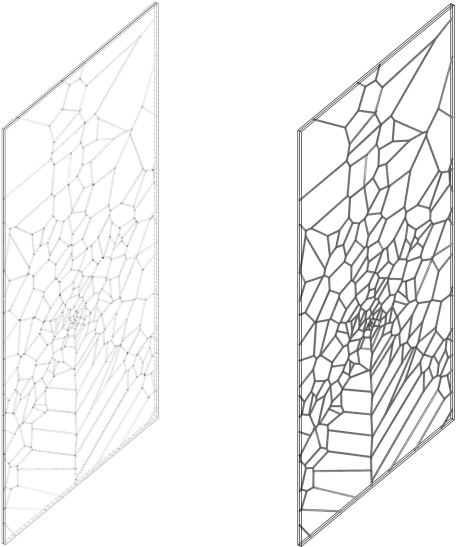


Figure 10
The transparent and light scattering phases of the thermotropic hydrogel glazing with high and low temperature.

Transparent phase
(lower temperature)

Light scattering phase
(Higher temperature)

Figure 11
The proposed
secondary structure
the as retrofitted
soft environmental
hydrogel skeleton
on the surface of a
glass dome.

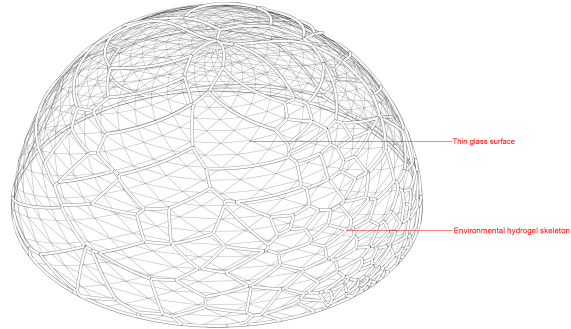
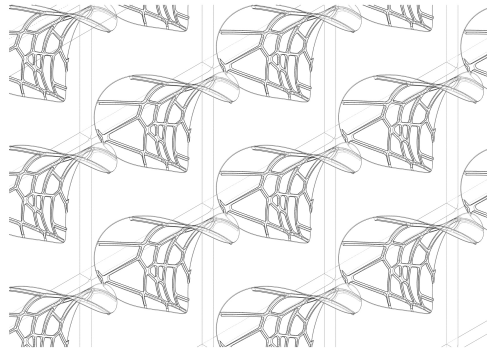
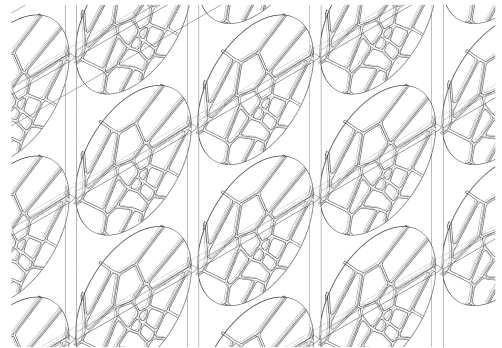


Figure 12
Left: Soft hydrogel
skin contracted in
low temperature.
Right: Soft hydrogel
skin expanded in
high temperature.



Low temperature



High temperature

Soft responsive skin

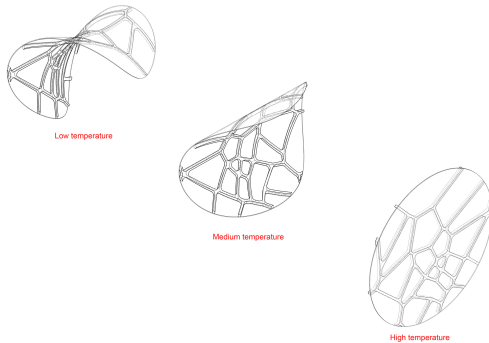
The bio-structural hydrogel combines skeleton, skin and actuator as one integrated entity will enable to form a soft responsive architectural skin for building facades. This integrated system is represented as a circular leaf-like module that eventually form a soft responsive hydrogel skin with passive sensing and adaptive shading functions. This soft skin can be applied to existing glass façade that can serve as responsive shading to passively respond and actuate in response to environmental stimuli (Figure 12). Each leaf-like hydrogel module can contract under low temperature to allow fenestration for sunlight. When heated by direct sunlight, the hydrogel modules can expand to serve as a blind by scattering direct sunlight and heat (Figure 13). This design

approach will potentially produce a soft responsive skin, which can not only enhance the environmental performance of existing building facades, but also impact aesthetics of an overall building appearance with media and communication functionalities.

CONCLUSION AND FUTURE WORK

Synthetic hydrogels with mechanically robust and tunable properties present opportunities for designers to digitally fabricate responsive structures and skins in architecture, which can potentially interface with biological matters. The low cost and accessibility of hydrogels encourage architects and designers to explore new design possibilities with them by implementing kinetic, adaptive and performative capabilities.

The heat-sensitive stretchable hydrogel skeleton developed in this paper demonstrates an early stage proof-of-concept with novel fabrication techniques and initial physical implementations for the soft kinetic architecture. The prototypical outcome of our “bio-structural” hydrogel skeleton and skin not only indicates potential implications of hydrogels in responsive architecture, but also introduces feasible moulding and 3D printing methods to manufacture novel architectural materials equipped with different performative properties.



To fabricate the proposed large-scale products in the section of Potential Applications and Developments, future studies will be done to enhance toughness and durability of parametrically designed hydrogel skins and skeletons. For instance, a kinetic hydrogel skeletal skin with thermal and light responsive capacities may serve as an active reciprocal retrofit to enhance energy efficiency of existing buildings and built environments. Further user studies will also be included to evaluate the aesthetic and applicability of bio-structural skins. Importantly, the use of hydrogels in architecture enables direct incorporation of active biological matters into built structures, which can potentially lead to exciting possibilities to interface synthetic and living matters at the architectural scale.

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- [2] <https://biomason.com/uses-impact/#architect>
- [3] <http://www.iaacblog.com/programs/hydroceramic/>

Figure 13
The transformation of the leaf-like hydrogel module through different temperatures.