SMP Prototype Design and Fabrication for Thermo-responsive Façade Elements

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Abstract

The aim to attain sustainability in the built environment introduced the innovative application of advanced material technologies for low-energy, but aesthetically intriguing, building design strategies. Adaptive and responsive building skins as embedded and intrinsic control systems can be delivered with smart materials, and thus have the potential to minimise the energy consumption of buildings by maximising the natural and passive adjustment of façade components for shading, air-flow, daylight, and view. The dynamic smart material façade, adaptable to changing outdoor environments, is considered to be a holistic design approach that integrates the behavioural performance effects with the appearance and aesthetics of kinetic ability provided by smart materials acting as actuators, by adjusting their properties according to external stimuli. Of the various environmental inputs sensed by, and actuating, active and dynamic building façade systems, this research focuses on temperature as the stimulus to activate a dynamic shading device with the mechanism of opening and closing, specifically considering Seoul's climate. Among currently available thermo-responsive smart materials, the shape memory polymer (SMP) is investigated as an activator of shading devices to be implemented to adaptive building skin strategies. As the first stage of SMP prototype design and fabrication study toward the thermo-responsive building façade elements, SMP prototypes are proposed in cell types. Among the general thermo-mechanical cycle of thermo-responsive SMP, only programming of the permanent shape via additive manufacturing and recovery at the activation temperature are focused upon in this research. This study proposes a design-to-fabrication workflow integrating computational tools, 3d printing and recalibration of relevant variables in digital design process, G code generation, and manufacturing using commercially available SMP filaments. To verify the 3d printing process, and to demonstrate the shape-changing behaviour of SMP actuators, reproduction of a referenced prototype was conducted, in addition to fabrication experiments of SMP surfaces with various thicknesses and SMP hinges with customised rotating angles. In addition, a base-line prototype combining the static ABS plate and the active SMP hinge is developed to set up the heat test and a digital motion simulation from data of shape changing behaviour acquired from a hands-on model test. After the demonstration of the baseline prototype in design and additive manufacturing process, various SMP prototypes were designed with reference to kinetic prototype researches, but with the consistent 100mm-diameter circular surface, in a scale of 1:3. They were also fabricated with a 3d printer for both open and closed positions to testify to their constructability, and thus to comparatively evaluate the design and fabrication outcomes. Furthermore, after conducting radiation and thermal simulation analysis, shading performance validation is noted for selecting potential prototypes. Lastly, the needs to further develop reversible reiterative shape-changing materials or systems are briefly discussed.

Keywords

thermo-responsive, building skin, shape memory polymer (SMP), 3d printing

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1 INTRODUCTION

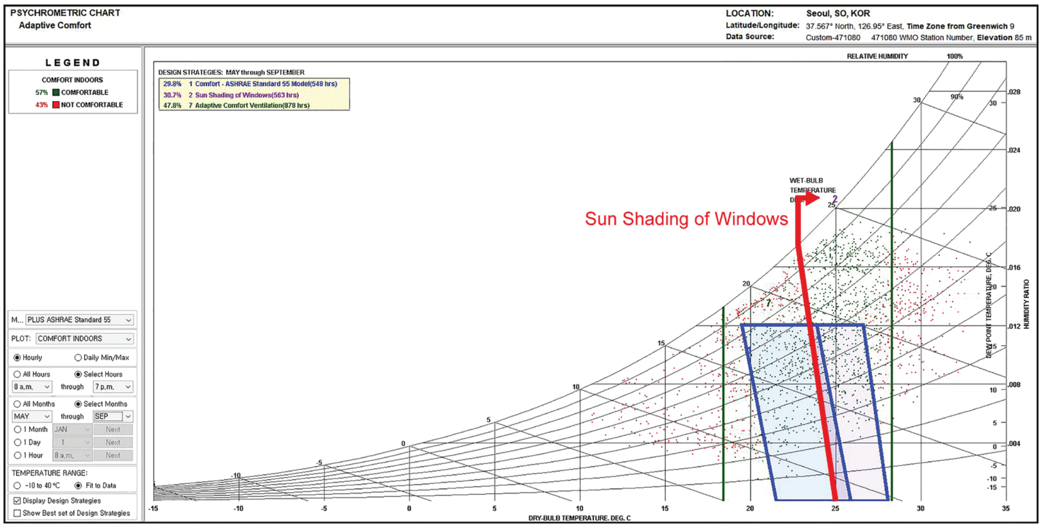
Smart adaptive, or dynamic skin, façades have been considered a promising and efficient strategy to enhance the internal lighting and thermal comfort in modern buildings, especially in terms of the impact of the target of nearly zero-energy (Boldini, Colangelo, Pilla, Tavanti, & Mariani, 2017). Despite high-tech kinetic and responsive building skin developments, low power consumption through autonomous adjustments has been a dilemma in applying responsive building skins. Among the various concerns involved in the design of high energy-performance buildings, the control of daylight and environmental conditions is of primary importance (Fiorito et al., 2016). The aim to enhance the level of sustainability in the built environment introduced innovative applications of advanced material technologies to achieve low-energy but aesthetically intriguing building design strategies. A concept to integrate the conflicting requirements by superimposing a passive structure with an active structure is proposed and developed by researchers and architects. The passive approach does not consume energy since it adapts in an autonomous way to changes in environmental factors to attain the zero-energy impact. The active system can be actuated to counteract or mitigate the action of the passive system, thus consuming energy only in specific circumstances (Boldini et al., 2017).

Of the various energy efficient state-of-the-art technologies in architecture, adaptive and responsive building skins as embedded and intrinsic control systems can be delivered with smart materials, having huge potential to reduce the energy consumption of buildings by minimising the mechanical system operation and maximising the natural and passive adjustment of façade components for shading, air-flow, daylight, and view. The intrinsic properties of smart materials include the ability to change physical properties or shape without any energy source (Al-Obaidi, Ismail, Hussein, & Rahman, 2017). Addington and Schodek (2005) have classified smart features in terms of immediacy, selectivity, transiency, self-actuation, and directness. The dynamic smart material façade, adaptable to changing outdoor environment, is considered a holistic design approach that integrates the behavioural performance effects with the appearance and aesthetics of kinetic ability provided by smart materials acting as actuators, by adjusting their properties according to external stimuli. Recent work on responsive architecture has capitalised on functional integrity, soft architectural components, and material properties, as opposed to highly mechanistic components, by highlighting kinetic materiality leading to advancements in this domain (Abdelmohsen et al., 2018)

Currently, designers are moving towards a nature-inspired approach in search of the underlying principles of morphogenesis and materialisation inherent to biological entities (Naboni, Kunic, Breseghello, & Paoletti, 2017). Researchers also incorporate the biomimetic approach and research by design method into their projects (Mungenast, 2017), in order to attain façade functions such as thermal separation, natural light control, heat gain control, and natural ventilation through layers, shadings, and openings. Al-Obaidi et al. (2017) list the most common types of materials inspired from nature by categorising, and argue that adaptive dynamic movements derived from plants, with special features such as responding to changing environments, including temperature, making them an inspiration for adaptive movements (López, Rubio, Martín, & Ben Croxford, 2017). Motions and surface structures of plants can be learned in three ways: morphological, physiological, and behavioural. Studies have shown that plants blur mechanism, material, and structural borders, with elastic movement, reversible snapping motion, smart opening-closing, orientation and folding based on temperature sensitivity, and folding inward as a reaction to contact. From biomimicry-based research, the functions of adaptive architectural envelopes have been identified as regulating environmental factors such as temperature, light intensity, humidity, and air quality (López et al., 2017; López, Rubio, Martín, Croxford, & Jackson, 2015).

Above all, smart materials that change and react in response to external stimuli resemble organisms that can change specific characteristics and parameters in response to a series of mechanical, chemical, spatial, and temporal information in different environmental conditions (Al-Obaidi et al., 2017; Lurie-Luke, 2014).

As such, the thermo-responsive building skins can adopt the dynamic mechanisms from plants with material and structure from thermo-responsive Shape Memory Polymer (SMP). The initiative, 'A Study on a Sustainable Energy-efficient Envelope applying Thermo-responsive Smart Materials', of which this research forms a part, seeks to exploit thermo-responsive smart material façade systems. Of the various environmental inputs sensed by, and actuating, active and dynamic building façade systems, the initiative focuses on temperature as the direct stimulus to activate a dynamic shading device to control the indoor climate with the mechanism of opening and closing, from the specific perspective of implementing the consequent study in Seoul. Analysis of the psychrometric chart and adaptive comfort from Climate Consultant software with EnergyPlus climate data demonstrates that sun shading of windows can be adopted as one of key measures to achieve strategic indoor climate control (Yoon, 2018). Also, as shown in Fig.1, the ideal baseline temperature of activation would be between 22℃ and 25℃, where the sun shading of windows is demanded.


PSYCHROMETRIC CHART
Adaptive Comfort

LOCATION: Seoul, SO, KOR
Latitude/Longitude: 37.567° North, 126.95° East, Time Zone from Greenwich 9
Data Source: Custom-471080 471080 WMO Station Number, Elevation 85 m

LEGEND
COMFORT INDOORS
57% 🟩 COMFORTABLE
43% 🟥 NOT COMFORTABLE

DESIGN STRATEGIES: MAY through SEPTEMBER
29.8% 1 Comfort - ASHRAE Standard 55 Model(548 hrs)
30.7% 2 Sun Shading of Windows(563 hrs)
47.8% 7 Adaptive Comfort Ventilation(878 hrs)

M... PLUS ASHRAE Standard 55
PLOT: COMFORT INDOORS
● Hourly ○ Daily Min/Max
○ All Hours ● Select Hours
8 a.m. through 7 p.m.
○ All Months ● Select Months
MAY through SEP
○ 1 Month JAN Next
○ 1 Day 1 Next
○ 1 Hour 8 a.m. Next
TEMPERATURE RANGE:
○ -10 to 40 °C ● Fit to Data
☑ Display Design Strategies
☐ Show Best set of Design Strategies

FIG. 1 Psychrometric chart: Adaptive comfort resulted from Climate Consultant with EnergyPlus Data of Seoul

A preceding research (Yoon, 2018) included climate-adaptive building skin typologies and design-driven research process to identify adaptive façade strategies with various thermo-responsive smart materials, specifically focusing on implementation in Seoul. The research summarized four differently categorised adaptive façade strategy types identifying kinetic actuating capabilities of Shape Memory Alloys (SMAs) and SMPs. As part of the aforementioned initiative, SMPs are investigated as façade elements in this research.

Both SMAs and SMPs are common shape memory materials. The main characteristics of shape memory materials in general are that they show a plastic deformation as a temporary shape when an external stimulus is applied and can recover to their original shape from the temporary shape. This is also called 'shape memory effect' (Huang, Ding, Wang, Zhao, & Purnawali, 2010). Shape memory materials possess the unique characteristic of memorising, during appropriate training processes, while also having shapes that can be recovered through the application of external stimuli, such as temperature, light, and moisture (Leng, Lan, Liu, & Du, 2011). However, SMAs have disadvantages among other types of shape memory materials, such as high manufacturing cost, toxicity, limited recovery, and complicated surgical problems (Ratna, & Karger-Kocsis, 2008; Bengisu, & Ferrara, 2018). SMPs have been preferred in recent times for their advantages compared to SMAs (Arun, Chakravarthy, Arochiakumar, & Santhosh, 2018).

SMPs have particularly useful properties for building technology. Among currently available thermo-responsive smart materials, SMPs offer extensive opportunities of investigation and design interpretation due to their reaction temperatures, deformations and stains, shape-changing behaviours, variety of surface shapes and forms, and possible manufacturing processing (Beites, 2013; Lelieveld, 2013; Ge et al., 2016; Bengisu & Ferrara, 2018). SMPs are programmable, exhibit variable stiffness, undergo extremely large deformation without fatigue damage, and require a minimal actuation force to change shape. In building technology applications, SMPs can morph to several pre-programmed shapes, effectively using smart material to reduce system complexity by lowering reliance on external sensors, wiring, electronics, and digital computation (Clifford et al., 2017). In addition, SMPs have low thermal conductivity in comparison to SMAs, which can be useful for application as insulation materials, with relatively lower cost than SMAs. Therefore, keeping in mind the long-term successive researches and prototype developments, SMPs are targeted as the thermo-responsive materials to be implemented in adaptive building skin strategies. Additionally, in this paper, as the first stage of SMP prototype design and fabrication study of the thermo-responsive building façade elements, SMP is investigated as an activator of shading devices, a climate mediator of thermo-responsive building façades, in a cell type.

The inspiration of the basic form derives from the simple geometry and dynamism implemented in RMIT Design Hub Façade, but with SMP introduction into the system. The initial results of experiments will be presented, concentrating on SMP application for cell components of building skin with rotating movement and bending deformation, inspired from the kinetic façade of RMIT Design Hub having the simple mechanism but elegant look. It investigates the transfer of smart material techniques, low-tech mechanism, and digital 3d printing technologies for applications in building skin elements. The main objective of this research would be the SMP prototype design using 3d parametric design software and scaled-down model fabrication to testify the 3d printing feasibility of different kinetic SMP cell types, and to examine their shape-changing behaviours by heat. In addition, the further research tasks to be carried out for validation of SMP applications and their performances toward the actual implementations are discussed, following the experiment results.

2 METHODOLOGY

The research is conducted in intuitive design propositions and their verifications through experiments of hands-on manufacturing and digital simulation. In experiments, the passive structure is meant to be driven by SMPs according to their activating temperature (Boldini et al., 2017), and changes between open and closed positions of the building skin are assumed to be triggered by a combination of the material behaviour and momentary counteracting of the active mechanism into the reverse condition, but ideally by two-way SMPs. From the similar motivation and objective of the research, Clifford et al. (2017) addressed the challenges of designing adaptive façade systems with dynamic or smart materials. They presented a series of self-shading building tiles that apply the attributes of a class of polymers with shape memory characteristics. The smart material, adaptive, and reconfigurable tiles are designed to wrinkle and reposition themselves in response to incoming solar radiation to shade building surfaces and lower thermal transmission, with the additional mechanism of pneumatic system.

To design SMP components, the fundamental behavioural properties of SMPs should be understood. The thermo-responsive SMPs have high elastic deformations, and the elastic modulus changes largely at the temperature below and above Glass Transition Temperature (T_g). If SMP is heated with no external force from a low temperature to a temperature higher than T_g, it eliminates the strain, resulting in the recovery of its original shape. SMP allows the maximum strain to be applied up to 400%, which means that SMPs have a shape recovery property of up to 400% of the plastic strain. Between the glassy and rubbery states of SMPs, large reversible changes of elastic modulus can be observed as high as 500 times.

In addition to the behavioural properties, the principle of having the memorised shapes above T_g should be also considered as a progression from the design phase to the manufacturing process. The general thermomechanical cycle of thermo-responsive shape memory polymers consists of three steps at a macroscopic level; (1) programming, (2) storage, and (3) recovery. The shape-shifting behaviour of SMP can be programmed to fix one temporary shape and subsequently recover back to its permanent shape upon heating. The temporary shape is usually defined by applied force during the shape fixing step. Accordingly, this step is also called a programming step (Zhao, Qi, & Xie, 2015). The programming needs the combination of a reversible switching mechanism and a structure. From a design point of view, with materials and morphologies, thermomechanical behaviour should be investigated together with the material properties. As has been realised by many researchers, the shape memory effect is a response of materials under a special set of thermomechanical loading conditions, rather than a material property. Therefore, shape memory effect is determined not only by material properties, but also by complicated thermo-mechanical loading conditions. In many cases, the latter complicates the evaluation of shape memory performance as well as material design (Zhao et al., 2015). In this paper, the entire programming process would not be targeted because it not only needs an extrinsic active mechanism other than by SMP, but also requires a design-driven approach to conceal ancillaries. Rather, this paper focuses on the programming of the permanent shape via manufacturing and recovery at T_g as an activated shape-changing behaviour.

After all, this paper studies a design-to-fabrication workflow for the conception of responsive skin systems that integrates the use of computational tools, 3d printing, and material experiments. As a novel innovative material, the thermo-responsive SMP is known to be easy to process and applicable to moulding or extrusion as a format of pellet or resin. Processing polymers into certain shapes is a necessary step towards their eventual uses. Fabricating SMP components in the relevant and potentially complicated shapes is important given the fact that their functions are much more tightly and uniquely bound to the shapes. In many SMP applications, the involved materials cannot provide the intended functions without being processed into proper 3-dimensional shapes or micro-structured surfaces. In addition to traditional polymer processing methods, such as injection moulding and potting, used to produce relatively simple shapes, several methods that lead to new SMP design, capability, and highly complex shapes have emerged (Zhao et al., 2015). To achieve rapid manufacturing and promote prompt feedback between design and fabrication, experimental 3d printing is undertaken to fabricate SMP components in this research by using an FFF (Fused Filament Fabrication) 3d printer, Cubicon Single Plus. The maximum nozzle temperature reaches 260 ℃ and the maximum heating bed temperature reaches 120 ℃.

From the research on current states of commercially available smart material products and manufacturers, it was found that a widely-used polyurethane (PU)-based SMP was developed by

Mitsubishi Heavy Industries (Erkeçoglu, Sezer, & Bucak, 2016), and the SMP used in this research was acquired from SMP Technologies, led by Dr. Shunichi Hayashi, formerly of Mitsubishi Heavy Industries. Following an inquiry to SMP Technologies, SMP filaments, jointly developed by SMP Technologies and Filament KO-BO, were employed with the 3d printer.

To verify the 3d printing processing in SMP fabrication, the SMP prototype developed by Beites (2013) was reproduced as in Fig.2. While Beites manufactured the prototype with injection-moulded SMP actuator and Polypropylene (PP) panels, the tested model (Fig.2) was created with 3d printed SMP actuator and ABS panels, to demonstrate the shape-changing behaviour of the same prototype with different processing methods. The rotating movement and bending deformation pattern of SMP hinges can be interpreted as mechanisms of opening-closing shading devices, which are the main principles of shape-changing behaviours.

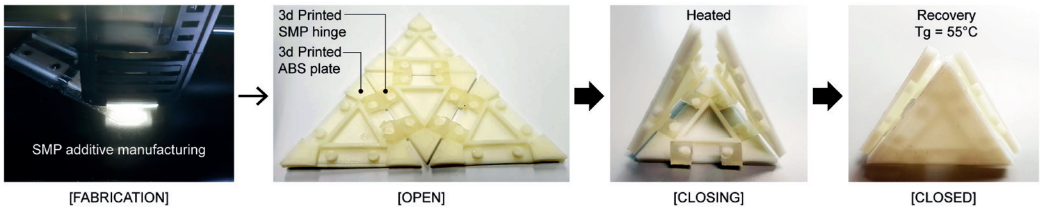


FIG. 2 Shape-changing behaviour demonstration of 3d Printed SMP hinges by reproducing Beites' prototype *(Beites, 2013)*

As previously mentioned, to focus on simple behavioural principles in the first stage of prototype design and fabrication, this paper limits the scope of the skin morphology into circular components. In the field of architecture, cellular solids are constructions based on assembly of cells with solid edges or faces packed together to fill a space (Gibson & Ashby, 1997). In the manufacturing process, the infill density of 3d printed cells should be defined appropriately to maintain the structure, shape, and behaviour (Naboni et al., 2017). This study starts from homogeneous cells with a solid state of high density based upon the stability of fabrication, material behaviour, and expected movement outcomes. To implement experimental building skin systems based on SMP application, the computational design tools, hands-on scale-down model, and 3d printing manufacturing are used in parallel.

This research provides a foundation for kinetic SMP applications in cell-type shading devices of building skins with a focus on the prototype design and 3d printing fabrication to demonstrate adaptability with activation temperature, cell morphology, scale, cell material behaviour, controlling mechanism, movement and deformation pattern, subsequent opening and closing effect, and reversible reiteration pattern. Within the field of architecture, the shift from prototyping to direct manufacturing is mainly connected to material improvement, which, in comparison to product design, is more complicated to achieve. Material characteristics and behaviour, mechanical properties, and dimensional requirements are key elements in evaluating the use of digital fabrication. Therefore, the exploration of a material system should be held to understand the way it can be exploited, with a rigorous multi-scalar analysis of the material coupled with the fabrication system that will be used. This process starts with analysing the materialisation process through fabrication experiments and the observation of their geometrical and mechanical characteristics (Naboni et al., 2017). The research starts with applying SMP as an activator to input heat and output movement or deformation in very simple circular cells.

This study introduces novel materialisation processes of SMP additive manufacturing. Logics of sustainability and efficiency that are typical of mass-production are no longer applicable. Taking inspiration from the multiple references, a design methodology which adapts to the thermal environmental changes with various surface shapes and structures, hinges as activators, and opening-closing mechanisms is developed. The outcome of this process is an impetus for the thermo-responsive building envelope system, which allows for the creation of adaptive façades with smart materials. This experimental approach challenges current design paradigms of mechanically active architecture. The research develops a system for responsive building envelopes based on SMP properties and behavioural design concepts. The design process is inspired by the external shielding formation in autonomous response to temperature conditions. The opening-closing mechanism, which allows visual permeability as well as light transmission by exhibiting the constructive geometry of cell surfaces or actuating components, is a required performance in SMP building skin applications.

SMPs have wide range of T_g from −70°C to +100°C. Since they have a wide range of glass transition temperatures, their stiffness can be tailored. For example, SMP Technologies provides 7 different glass transition temperatures (T_g) of 25, 35, 45, 55, 65, 75 and 90℃, in four different types of pellet, resin & hardener, solution, and filament. Pellets are processed by injection moulding, and resin should be cured in specific conditions with a vacuum oven. Therefore, for the rapid production and testing, the 3d printing filament was selected for the fabrication method. The 3d printing filament is only available with T_g at 55 ℃, made of MM5520, although 25℃ would be the optimal activation temperature to examine the climate-adaptability of SMP façade elements in Seoul. MM 5520 shows almost no definite property difference from MM2520, which is the target to be applied in the long-term research, as shown in Table 1. In the future experimentation, SMP pellets with activation temperature at 25℃, MM 2520 would be examined for 3d printing, as Yang used MM 4520 pellets from SMP Technologies (Yang, Chen, Wei, & Li, 2016), but probably with different settings for the 3d printer and the controlled experiment environment.

ITEM	UNIT	SMP TECHNOLOGIES MM 2520		SMP TECHNOLOGIES MM 5520	
		Glass Region	**Rubber Region**	**Glass Region**	**Rubber Region**
Hardness	H_DD	78	26	77	27
100% Modulus	MPa	-	3	-	2.1
TS (Tensile Strength)	MPa	45	12	48	13
Elongation	%	30-50	>600	30-50	>600
B M (Bending Modulus)	MPa	2450	-	2150	-
B S (Bending Strength)	MPa	90	-	80	-
T_g (Glass Transition Temperature)	°C	25		55	

TABLE 1 SMP Material Properties (SMP Technologies)

The main hypothesis is that defined cell types from deductive and analogical interpretation and design process, using Rhinoceros and Grasshopper, are fabricated and tested using achievable materials – ABS for non-activating parts and SMP for activating parts, and simplified details to verify the design-to-manufacturing workflow from 3d design process to 3d printing for the further study of a full-scale prototype of the dynamic cell skin typology in the near future, to analyse performative possibilities and the aesthetic behavioural properties of actual building skin designs. Specific logics pertaining to rotating activators and bending deformation of SMP, such as thicknesses, hinge angles, activating directions, and stretchable textures are tested to examine the material, morphological, and mechanical behaviour patterns. This experiment involves the iterative workflow to generate and materialise cell components combined with proper activators and surfaces. Fig.3 indicates the overall research workflow scheme involving computational tools, 3d printing fabrication, and simulation for performance validation, focusing on SMP cell components composed of simple activators and surfaces with rotating movement and/or bending deformation.

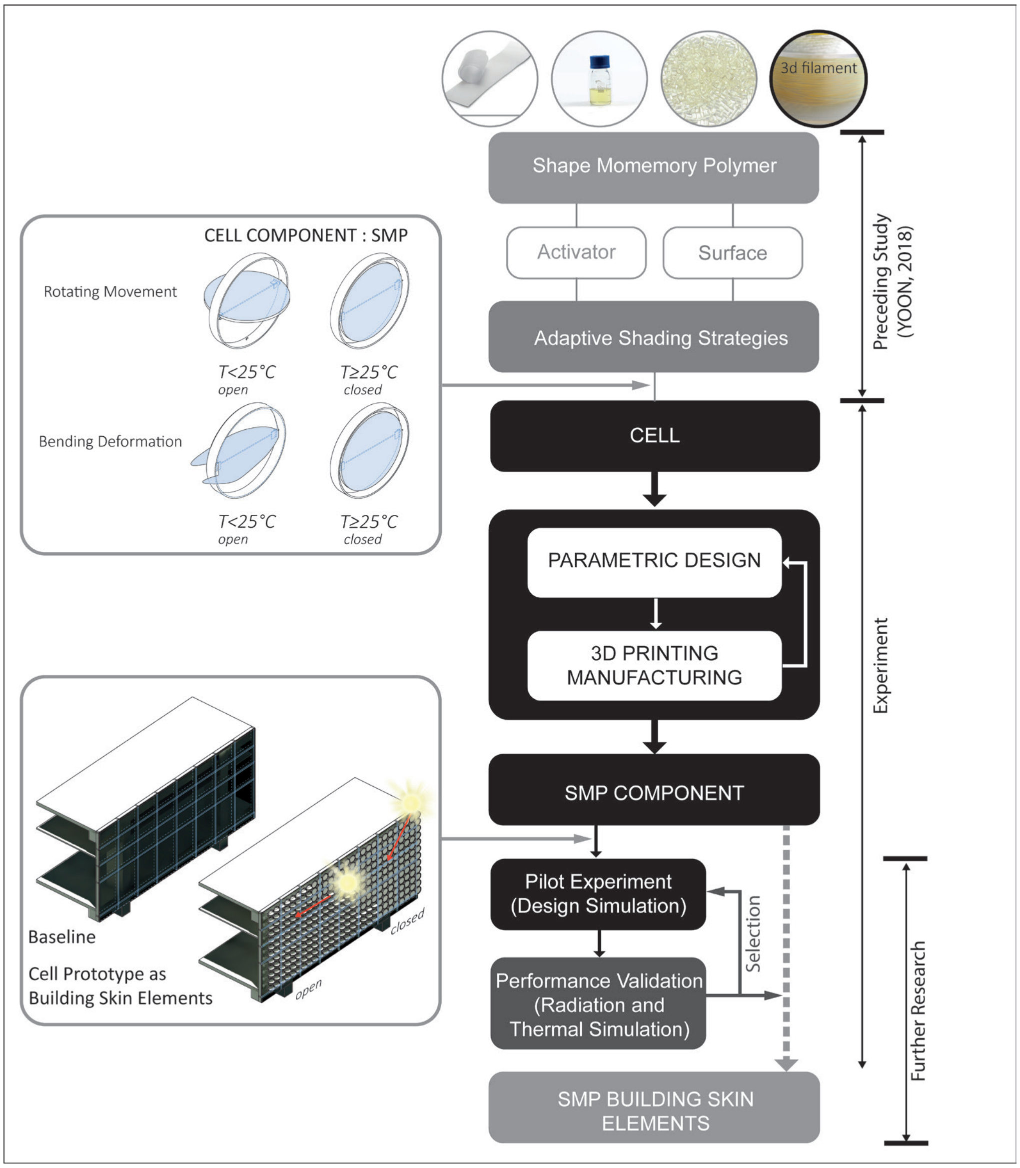


FIG. 3 Overall Research Workflow Scheme, involving computational tools, fabrication, and performance validation

The computational design and 3d printing fabrication experiments were carried out to tackle the prototype design and fabrication feasibility. Through the fabrication experiments, difficulties and opportunities to develop the initially proposed SMP cell components into the kinetic façade elements can be evaluated in consideration of structural and performative optimisations.

Furthermore, performance simulations of building skins with tested SMP prototypes were conducted to validate the performance as shading devices and climate-adaptive building skins after applying

SMP prototypes to a pilot project, located in Seoul, in design simulations. As the beginning stage of performance validation setup, solar radiation and thermal simulations using Rhinoceros and Grasshopper with plug-ins such as Honeybee and Ladybug were conducted to analyse the results to verify the possibility of energy performance evaluation to select the optimal prototypes. From the performance simulations, prototypes demonstrating more efficacy in solar radiation reduction and thermal impact can be sorted out for further development in the next stage of the research. The complex and elaborate workflow including parametric design and energy simulation would allow feeding productive information into the workflow as proposed in Fig.3. Therefore, this paper discusses the opportunities of such procedures as well as the limit of current experiment and further fabrication issues to be studied.

3 RESULTS

3.1 FABRICATION EXPERIMENTS OF SURFACES AND ACTIVATORS

To determine the design parameters, including the minimum surface thickness, perforation, and programmed shape angles, a series of experiments were set up. First, SMP components based on the selected cell morphologies and movement mechanisms were fabricated and tested, starting from circular disc samples of 100mm diameter, at a scale of 1:3, with a variety of thicknesses – 0.15, 0.2, 0.3, 0.5, 0.75, 1.0, 3.0mm, as shown in Fig.4. To compare the surface finishes and stability, ABS surfaces were 3d printed as control groups. These samples contributed to the definition of an optimal fabrication thickness. The thicknesses less than 1.0mm had issues with printing quality and bending in a neutral state. In addition, this test is intended to ensure the best compromise between production precision and printing speed, with an average production time of 3 to 5 hours.

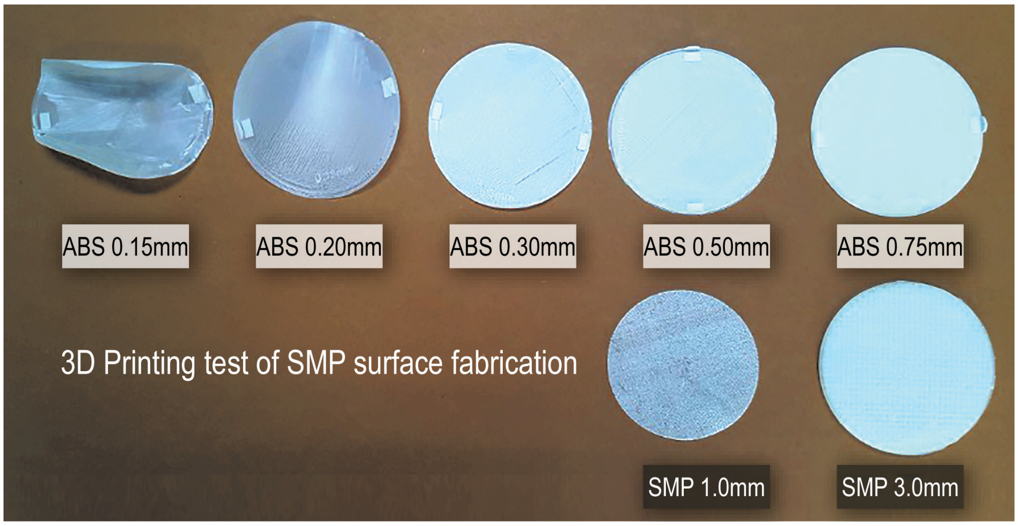


FIG. 4 Fabrication experiments of SMP surfaces in comparison with ABS surfaces

Second, in the process of manufacturing, SMP hinged activators for the prototype in Fig.2, the quality of finishing, and creating perforations in vertically printed plates used as joinery holes, created difficulty in additive manufacturing. To adjust the primary parameters in 3d printing by focusing only the completeness of the construction, perforations were omitted. As the extruder temperature (T_e) was set higher than T_e for ABS 3d printing, the quality improved as shown in the second pictures of Fig.5. However, at T_e higher than 250℃, SMP outputs are burnt brown when extruded. After a series of errors and tunings, and adopting references (Yang, Chen, Wei, & Li, 2016) and correspondence from Clifford (Clifford et al, 2017), the 3d printer setting was finalised as shown in Table 2. Consequently, the final 3d printed outcome could be generated, even with perforations on both horizontal and vertical surfaces.

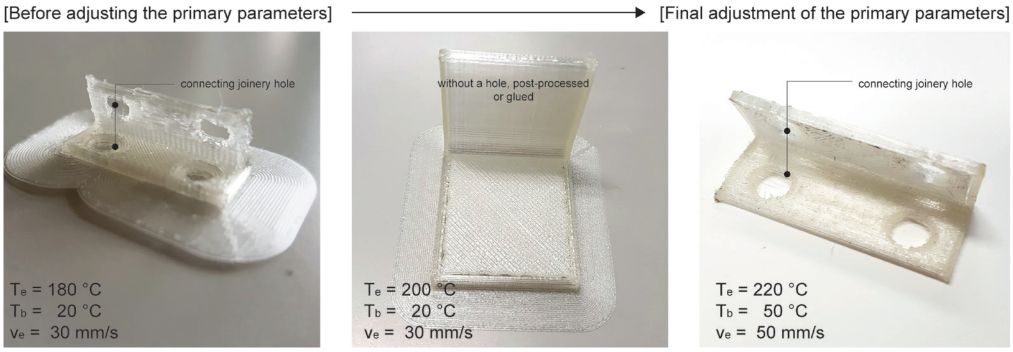


FIG. 5 Fabrication experiments of SMP hinges as joints and activators with various 3d printing parameters

PARAMETERS	VALUES			
	Yang (2016)	**Clifford (2017)**		**Yoon (2018)**
Extruder Temperature T_e (°C)	220	210		215 ~ 220
Bed plate temperature T_b (°C)	45	48		50
Speed while extruding v_e (mm/s)	$30 < v_e < 60$	25 (Perimeter)	30 (Infill & Support)	50
Speed without extruding v_t (mm/s)	150	30		150
Gap between nozzle tip & build layer d (mm)	0.3	(No information)		0.3
Retraction Distance (mm)	-	-		3~10
Printing Infill percent (%)	100 (vibration issue)	Custom 0.3 (Triangles) Infill overlap 0.06mm		30 ~ 100

TABLE 2 Comparison of primary parameters of 3D printing machine by Yang and Clifford with the finalized parameters

Yang et al. (2016) note that there is no previous report about process studies on the 3d printing of SMP materials. The FDM (Fused Deposition Modelling) 3D printing process is similar to a moulding process, as they both include melting and reshaping of material. 3D printing quality is managed by controlling the quality of SMP filament and the bubble content in the filament extrusion process, and by setting up the process parameters related to the FDM printing process, such as nozzle temperature, scanning speed, and part cooling. Yang et al. (2016) used the MM-4520 pellets with a Makerbot Replicator 2X. However, Clifford (2017) used MM-5520 Filament, i.e. the same as used in this research, with a Creator Pro machine, and the fabrication setup parameters are acquired by inquiry.

Table 2 shows a set of 3d printing parameter values for SMP material. In addition, several matters require attention, including the extruding flow amount adjustment, transfer from the printed SMP to the ambient air, surface roughness, and the retraction distance calibration. Furthermore, from continued studies, additional parameters including layer height at 0.3mm, quantity of wall line at 3, flow ratio at 50%, retraction speed at 100mm/s, support structure type as raft, and infill type as zigzag were additionally set up for better printing quality. However, in the 3d printing process, the unexpectedly high ambient temperature of the work environment caused many troubles in producing good-quality outcomes, resulting in air bubbles in the extruded SMP and the obstruction of the extruders with SMP lumps.

The design of shading systems can be developed to meet adaptivity principles based on two approaches of activators and surfaces. SMP activators allow the kinetic behaviours through intrinsic material properties directly affected by changes of temperature. SMP surfaces are actuator-embedded envelopes which show surface deformations and configuration changes through the dynamic motion mechanisms. The SMP layer of shading devices will react to different input of heat, opening and closing accordingly in an autonomous way. A critical phase in the development of cell type building skin is the definition of the baseline cell. This implies that the geometry constraints of SMP are first to be taken into account in this evaluation. For example, to figure out the restorative behaviour and force with the marginal angles in recovery of hinge rotation, hinges can be differently shaped and programmed to result in customised rotating movements, as in Fig.6. To programme rotating angles other than 90°, the support structures between plates should be adequately set for 3d printability to stably acquire the outcome without falling down in the fabrication process and detachability to obtain clean final products. However, the rotating behaviours tend to be degraded after the first recovery in multiple reiterative operations (Bae, Choi, & Yoon, 2018), by 20 to 40%. In this research, the recovery fatigue was not considered in design process, but later in developing the installation design with a certain expectation of kinetic movements, the recovery fatigue should be counted.

FIG. 6 Programming of rotating angles by 3d printing the customised angled hinges

3.2 BASELINE CELL PROTOTYPE FABRICATION AND KINETIC SIMULATION

As the baseline cell prototype, a prototype in an ABS circular plate with a SMP hinge is considered (Fig.7). The idea is simply to rotate the ABS plate with forces caused by SMP hinges. However, the pulling force by the SMP hinge folding is insufficient to rotate the ABS plate and the position after rotating is not sustained. By repositioning the SMP hinges to the ABS tester, it was discovered that the centre of gravity can be translated by rotating SMP hinges and the fixed shape of SMP activator can hold the ABS plate position. To testify shape-changing behaviour activated at 55℃, five different devices were devised and examined: (1) hot plate, (2) warm water basin, (3) insulated box with electric heating cable and thermostat, (4) insulated box with higher-temperature electric heating cable and thermostat, and (5) heating cabinet. Direct wiring with heat cables was avoided, considering the heat would be transferred to SMP components through the ambient temperature. At the beginning, using a warm water basin was enough to observe the thermal behaviour of SMP, but SMP shows weak moisture-resistance and after several handlings of SMP in the basin, the original shape was deformed too much. In other test settings with a hot plate and electric heating cables, the ambient temperature didn't reach 55℃. After all, the heating cabinet provides the best testing environment in more stable conditions. Therefore, the following experiments at 55℃ are conducted using the heating cabinet.

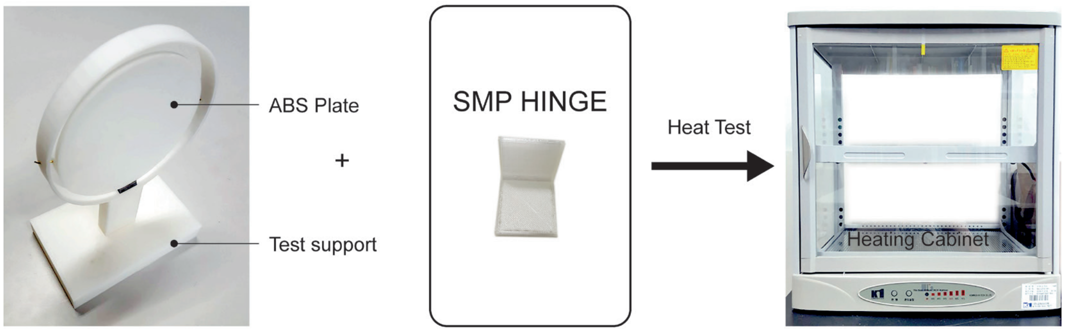
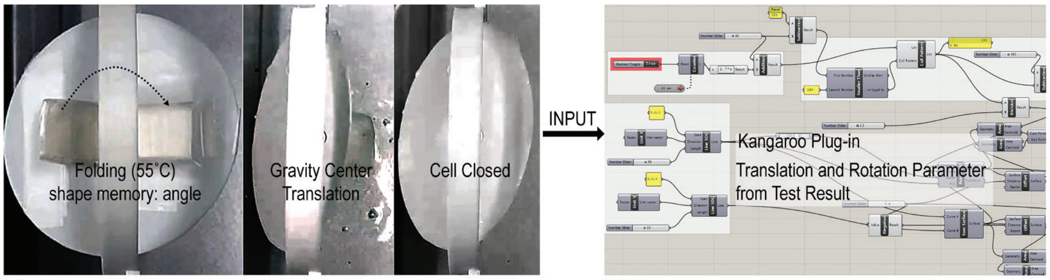


FIG. 7 Baseline prototype and heat test setup

With the baseline prototype combining the ABS plate and the SMP hinge, the digital motion simulation was studied. Grasshopper with Kangaroo Plug-in is selected as a live physics engine for kinetic simulation directly within Grasshopper and Rhinoceros. The purpose of kinetic simulation is to demonstrate the dynamic movement of prototypes and to find an aesthetically pleasing prototype design. Furthermore, it is assumed that the kinetic adaptability to the specific temperature can be modelled and imported to the energy simulation software. However, the physics and the relation between SMP elasticity, gravity centre translation, and rotational movement of the prototype could not be achieved, due to the unknown value of each variable. Also, from the research (Bae et al., 2018), it was found that the recovery pattern is not maintained at an equal level at all times. Therefore, the simulation setup was determined to follow the empirical results.

From the hands-on model test, the shape-changing behaviour is examined to measure the bending angle of the hinge, the rotation angle of the plate, and the time taken for hinge bending and plate rotation. The acquired movement data is input to Grasshopper with a simplified control of parameters to simulate the motion mechanism of rotating and bending. As the relative effects by the bending hinge, the rotation of plate occurs, and the shading device is closed. The demonstration of the SMP activator with the ABS circular cell disk is provided in Fig.8. The activation by temperature is programmed as Boolean logic at this stage. The simulation setup should be further developed to include the activation by temperature with climate data to demonstrate the actual performance of a prototype as well as more precise relations among all kinds of influence factors after collecting their values from measurement experiments. To exemplify the model-driven programmable matter design approach in the future and to tailor the thermo-responsive behaviour of SMP for the design and construction of a shape-changing façade element, physical parameters controlling the morphing behaviour and response time (Abdelmohsen et al., 2018) of SMP to T_g should be explored.



❶ Hands-on Model Test

❷ Grasshopper Parametric Algorithm with Kangaroo

❸ Simulation Model

FIG. 8 Baseline model test and motion simulation

3.3 DESIGN AND FABRICATION OF CELL PROTOTYPES

After the demonstration of the baseline prototype in the design and additive manufacturing process, various SMP prototypes were designed with reference to kinetic prototype researches using SMA, biomimetic design approaches, and 4d printing from disciplines other than architecture (Al-Obaidi et al., 2017; Coelho & Zigelbaum, 2011; Ning, Wang, Zhang, Yu, Choi, Zheng, & Rogers, 2018), but with the form and size restrained to the circular cell of 100mm diameter, at a scale of 1:3. In the prototype design process, each cell was intended to be manufactured entirely with SMP as the activator-embedded surface, and to reduce the additional complexities by joints and connections for further applications involving installation details. The challenge in designing thermo-responsive building skins with SMP is to evaluate and expect transformation behaviours between two different pliability statuses before and after reaching T_g. Both rigid and elastic bodies are able to perform mechanical movements (Fiorito et al., 2016) but in dissimilar ways. With the combined mechanism of rotating and bending in addition to connections and joints, movement patterns can become more complicated and broken down to swivel, revolve, swing, flap, lever, and slide, which should be further explored in continued study. In case of the baseline prototype, the SMP activator and the ABS plate were attached with Cyanoacrylate-based glue.

The design of thermo-responsive building skin cells involves the design of programming SMP to determine the permanent shape above 25℃ activated by heat and to control heat gain and natural light. Based upon the opening-closing mechanism given the circular cell types, by borrowing the surface structure from references (Coelho & Zigelbaum, 2011; Ning et al., 2018), five cell component types are proposed for experiment. To conduct morphology study, 3d geometry production and G code generation for 3d printing, Rhinoceros with Grasshopper and Cubicreator were used. Five cell components were designed by programming the closed surface, shown in Fig.9. The big difference between it and other kinetic structures is that the activated phase of mechanism is closing, while most kinetic façade installations have the opening condition as the activated phase. However, to compare the effects of kinetic movement from opening to closing, open surface models were also additively manufactured. This process includes creating both open and closed models in Rhinoceros, exporting to STL files, importing STL files in Cubicreator to finally acquiring G codes ready for 3d printing.

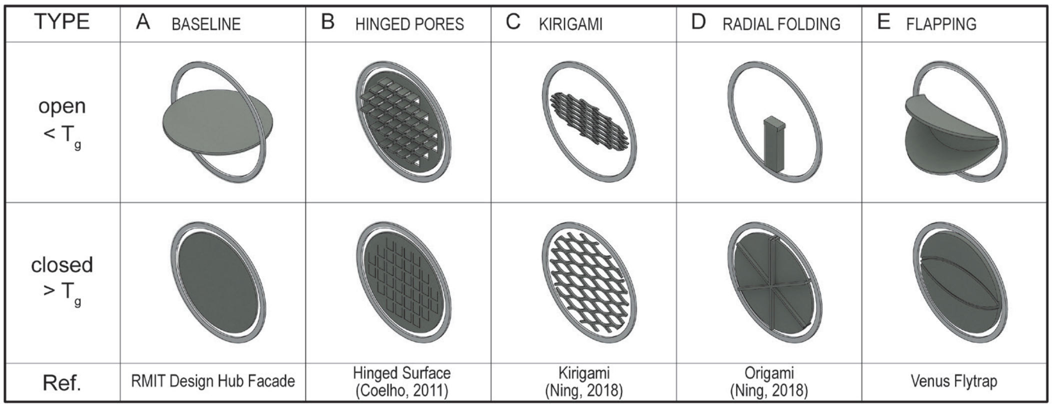


FIG. 9 Five cell component types and their morphologies

To define an optimal configuration, two main parameters of formability and responsive outcome are considered. The employed material, thermo-responsive SMP, demonstrated compatibility with 3d printing fabrication for actuators and bending surface components by setting up the optimised printing parameters such as nozzle temperature, bed temperature, nozzle speed, extrusion amount etc. as previously discussed, which enables various morphology studies.

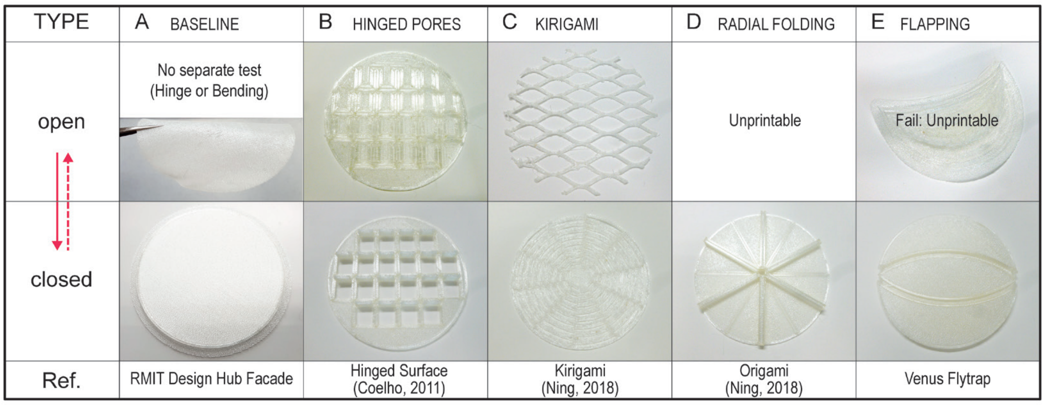


FIG. 10 Cell component 3d printing results

SMP prototype components were 3d printed and, iteratively, the designs and G codes were revised to control the outcomes. The best final outcomes after several tests are shown in Fig.10. For Type B, the sizes of hinged pore, the minimum spacing between pores, and openings between the hinged surface and spacings were variables tested for design decisions. For Type C, the minimum thickness and width of structure, and spacing between structures, were edited for 3d printing feasibility and quality control. For Type D and E, the design process and G code acquisition proceeded smoothly, but the open position models could not be printed. In case of Type D, the spacings between folded surface and structure are not achievable with the precision of the used 3d printer. In addition, to hold the angled surface stacking, supports are required under the folded surface, but they are too small to be printed. In the case of Type E, the open flap could not be supported in vertical stacking. While the angled SMP hinges were produced as in Fig.6 with multiple tests, the bended curvature with bigger sizes are obstacles to successfully fabrication in 3d printing. Additionally, pliability of SMP in extruding moment makes it very difficult to sustain the vertically built-up surfaces and complicated surfaces. Through the 3d printing process, SMP filament softens when it heats after printing, thus memorising the customised shapes. This unique process and material property provide not only the opportunities of kinetic elements but also the major barriers to manufacturing SMP components. The 3d printing process and the observed result of thermo-responsive behaviour would affect the next step of integrating geometries, functions, and reversing programming.

Regarding the responsive outcomes, all of the fabricated prototypes showed prompt responses at the activation temperature with good performances, as shown in Fig.11. The response lead time varies depending on the morphology, the thickness of surface, the scale of a transformed part, and rotating or bending angles, but the general response lead time with the tested prototypes are within a maximum of 4 minutes.

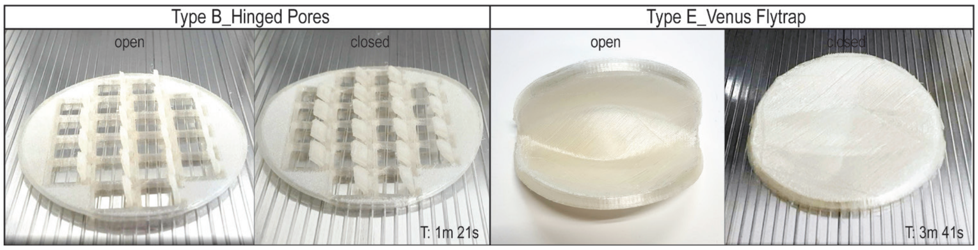


FIG. 11 Heat test result of Type B and Type E

However, after recovering to the permanent shape, the pliability of SMP yields its shape to other external forces, or simply to gravity, depending on SMP shell thickness. Thus, the strain fatigue becomes an obstacle to implementing the SMP component on a building skin that should resist various external loads. In addition, the sensitivity of the mechanical properties of SMPs to humidity is pointed out and it requires a covering structure that protects them from possible harsh environmental conditions (Boldini et al., 2017). This research excludes integrated solutions for solving these issues at this stage and assumes that the temperature in the building is mainly controlled by using a double skin façade.

The evaluation of design and fabrication test results is made by a matrix, as in Table 3, to find out which prototypes and which combination of mechanisms will be further developed in more detail in future studies. The evaluation index includes structural optimisation, performative optimisation, material dependency, morphological dependency, autonomous activation, and reversibility friendliness in the process of closed positions to open positions of the five tested prototypes. Structural optimisation means compatibility with the fixing framework. In case of type A and B, the circular surface forms and the central axis are maintained in spite of shape-changing, gravity translation, bending deformation, and rotation movement. Therefore, these types can be easily installed with a simple framework. Type C is difficult to hold within a consolidated framework due to the stretching of its entire surface and its perimeter deformation. Types D and E can be structurally optimised to the framework with points. Performative optimisation indicates the shading effects by closed and open positions of prototypes. Except for Type C, which has permeability in both closed and open positions, four other prototypes show obvious surface closings reducing light and heat transmission. Material dependency is the index evaluating the inherent materialisation of SMP, which is not substituted by SMA. Morphological dependency is the shape-changing behaviour determined by SMP surface geometries and structural shapes. Each type can be autonomously activated by the proper temperature. The reversibility friendliness means the shape programming from the closed position to the open position. Types A and E can be easily reverted to their permanent shapes with one-directional force. Types B and D need multiple forces to be reverted. Type C needs delicate operations of forces to be programmed in order for it to be returned to its original and consistent position and shape. From this evaluation, Types B and E are considered to be the most effective for their design, fabrication, and operation.

TYPE	EVALUATION INDEX					
	Structural Optimisation	Performative Optimisation	Material Dependency	Morphological Dependency	Autonomous Activation	Reversibility Friendliness
A	+	+	0	-	+	+
B	+	+	+	0	+	0
C	-	-	+	+	+	-
D	0	+	0	+	+	0
E	0	+	+	+	+	+

TABLE 3 Evaluation matrix of the results

+: Good/High | 0: Average/None | -: Bad/Low

However, in this experiment, the heat tests with prototype models were tested in a laboratory setup using a heat cabinet. Thus, their implementations in operative conditions of buildings would require further development of the consistent and stable material behaviours and optimised additive-manufacturing techniques with SMP activated at 25℃, as previously mentioned. Additionally, further development of SMP with T_g at 25℃ would require mock-up tests in the adequately controlled environment through a full-scale architectural demonstrator, where a wider set of evaluative criteria are to be measured and assessed.

3.4 PILOT SIMULATIONS AND SHADING PERFORMANCE VALIDATION

For pilot simulations and shading performance validation, the façades with studied prototypes were modelled with Rhinoceros and Grasshopper. The façades are assumed to face south in an office building located in Seoul, integrating a glass curtain wall façade and SMP shading devices. In the pilot studies, required criteria of energy use set points and average heat coefficients of the total building envelope should be employed. The average thermal transmission coefficient requirement shall be set at 1,500 $W/m^2{\cdot}K$ for glazing as a baseline.

To evaluate and validate the system, energy simulation shall be incorporated into the design process. Merla, Diaferia, & Dibari (2016) discussed a comparison of several integrated software suites. Combined use of Ladybug and Honeybee would demonstrate the pros by performing very detailed and reliable parametric analyses. As presented in Fig.12 and Fig.13, the radiation simulation and thermal simulation were conducted for all the prototypes in order to verify the effectiveness of SMP shading mechanisms and to discuss further agendas to be studied in the next stage of the research in relation to holistic analysis of SMP building skins. In order to proceed and acquire simulations within a reasonable rendering time, as well as to identify the effect of SMP in activating, the simulations were done between May 1st and September 30th (Lim & Yun, 2017), when the average high temperature ranged from 23℃ to 30℃ (Yun, Kong, & Kim, 2012) with the pilot project facing south.

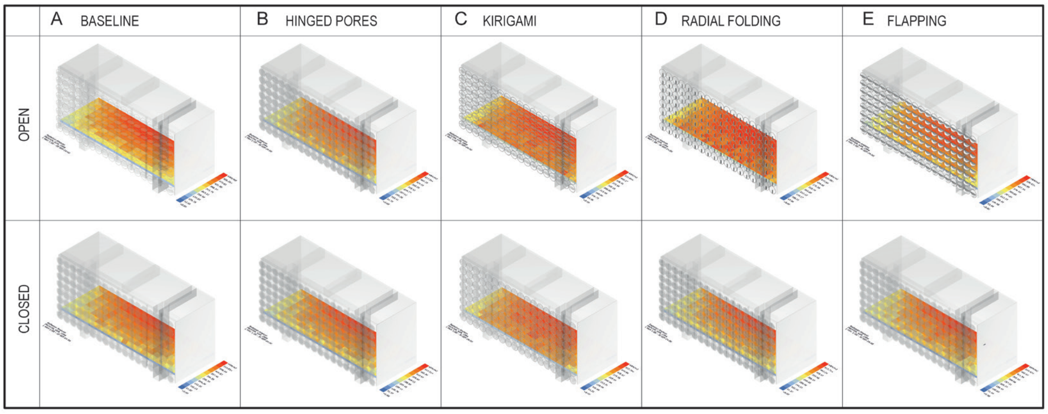


FIG. 12 Radiation simulation results of SMP cell building skins

To achieve the precise radiation simulation results and deduce the quantitative effects of direct solar radiation reduction, the dynamic kinetic transformation of SMP building skin elements, depending on the ambient temperature, should be input into the algorithm. However, in this research, to roughly estimate the effects of radiation reduction, two radiation simulations of each type at both open and closed positions were undertaken, and the big radiation difference between open and closed positions is interpreted as the most evident radiation reduction effect of SMP building skins. However, as shown in Fig.13, with the generally applied thermal simulations, the analysis results failed to verify the thermal impacts by shading devices between closed and open positions of designed prototypes. Further energy simulation algorithms with more detailed information should be developed to validate the performance by SMP kinetic shading façades.

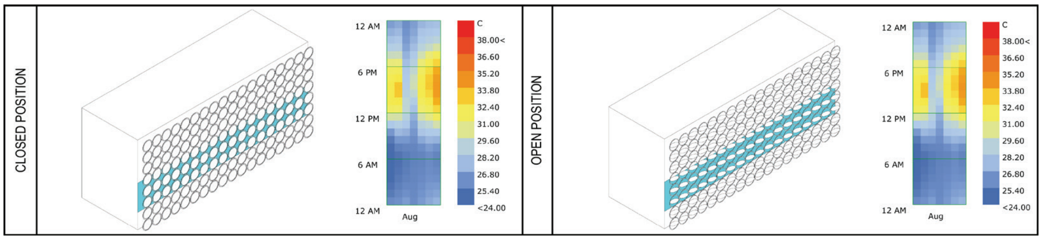


FIG. 13 Thermal simulation results of SMP cell building skin type A (baseline)

Nevertheless, to roughly evaluate the effects of reducing direct radiation by SMP cell mechanisms, differentials between the radiation simulations at open and closed positions are visualised in Fig.14. The differentials are represented in colour, and a colour with a higher hue and saturation indicates a wider radiation difference, which means more distinct radiation reduction effects. From the figure, Type D and Type E show more apparent colours than the other types. From radiation simulations, the radiation levels between May 1st and September 30th are estimated approximately between 371.39 to 530.56 kWh/m^2 at the open position of Type D, which has the lowest façade coverage at the open position among five types and their positions. When it is closed, the perimeter area has a radiation between 256.85 and 308.23 kWh/m^2. In the case of Type E, the radiation ranges between 320.65 and 534.42 kWh/m^2 at open position, and the radiation reduces to between 257.21 and 514.43 kWh/m^2 at closed position. Regarding Type C, the radiation ranges between 320.18 and 533.64 kWh/m^2 at open position while it ranges between 319.97 and 533.29 kWh/m^2. Although the radiation reduction effect of Type C is more evident than Types A and B, the effect is not distinctly advantageous in considering the complexity of cell structure accompanying the perimeter deformation. If the framework to hold the dynamic kirigami structure and the activator system to provide the distributed forces to contract the cell structure into the closed position are devised, Type C can be explored, but in this research, to strategically search for simpler application methods, Type C is excluded from the further development.

However, Type B shows distinctive solar radiation effects. From Fig.14, and based on the fundamental assumption of radiation reduction by closing the cell with the SMP actuating, it can be concluded that Type B does not verify the radiation reduction so as to reduce energy load. Due to its porous surface condition, Type B has a radiation level from 258.77 to 517.54 kWh/m^2 when it is open, which is as low as solar radiation amounts of other prototypes at their closed positions, while the radiation level of closed Type B is between 256.85 and 513.71 kWh/m^2. Therefore, it would be difficult to state that Type B doesn't have an environmental impact from this analysis. In addition, other factors such as thermal comfort, daylight, and natural ventilation, which should be measured to discuss about energy performance, have not been reviewed in this research.

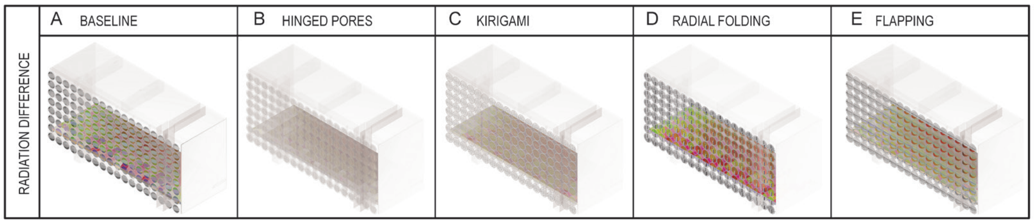


FIG. 14 Differentials of radiation simulation results between open and closed positions

4 DISCUSSIONS

4.1 REVERSIBLE REITERATION OF SHAPE-CHANGING

Besides securing the recovery strength, and scaling up the prototype production, the critical issue is acquiring the reversible reiteration of shape-changing. Within a one-way shape-memory cycle, the shape recovery step can only go from the temporary shape to the permanent shape. Unless the SMP is mechanically deformed again via a re-programming process, the recovered permanent shape cannot revert back to the temporary shape by altering the external stimulus only (Zhao et al., 2015). By now, there are no commercial two-way SMPs, which have instead been produced in a laboratory for research reasons. Therefore, previous researches (Boldini et al., 2017) selected other materials as alternatives to two-way SMPs for the actuation of the passive system in the prototype, since it presents other promising features such as a multi-way shape memory effect, and an electrical triggering. Additionally, in many cases, the actuation mechanism was obtained with two counterposed one-way SMA springs. This solution allows an enhanced movement control of the actuator, but considerably increases the complexity of the feedback design, easily resulting in a wired and distracted unattractive system. Therefore, a considerate design approach that minimises the counteracting mechanism parts, and incorporates it into a simple system, should be steadily studied.

Therefore, two-way reversible SMP is desirable for building skin applications, as such for actuators, artificial muscle, sensors, and self-locomotion robotics (Li, Liu, & Leng, 2014). Such polymers may vary between two distinct shapes when they are exposed to stimuli creating the opposing conditions, such as heating and cooling. But two-way SMPs are harder to achieve and have become the most desired shape memory materials due to their unique properties (Wang, Jia, & Zhu, 2017). The future developments of two-way SMPs will permit a more practical functioning of the system. The reduction of the cost of SMPs is then supposed to promote a real implementation of the proposed concept (Boldini et al., 2017). Ideally the interdisciplinary and collaborative research between engineers developing two-way SMPs and architects would shift the paradigm and territory of thermo-responsive adaptive façades.

4.2 FURTHER SMP PROTOTYPE DEVELOPMENT

Beyond this research, advanced foreseen versions of responsive systems exhibit further surpassing conventional and mechanistic dynamic motion by generating reactions according to responses from the environment (Abdelmohsen et al., 2018). As presented in the experiment result and discussed with shading performance validation, Types B, D, and E, among proposed prototypes, are sought to be exploited for further prototype development.

As visualised in Fig. 15 with simple 3d modelling, there are wide ranges of issues to be tackled through the prototype development with Types B, D, and E. From the economic and efficient use of SMP, the active and responsive parts, and the static and passive parts of prototypes can be separated in materials such as SMP and ABS but shall be integrated into one cell to preserve the dynamic and kinetic effects as experimented in this research. Also, to further develop the prototypes into façade elements, the optimum size of each cell should be defined in terms of its behaviour, performance, and beauty. Lastly, the attachment and framework details, in addition to controlled SMP behaviour in reiterative and reversible pattern, should be tailored.

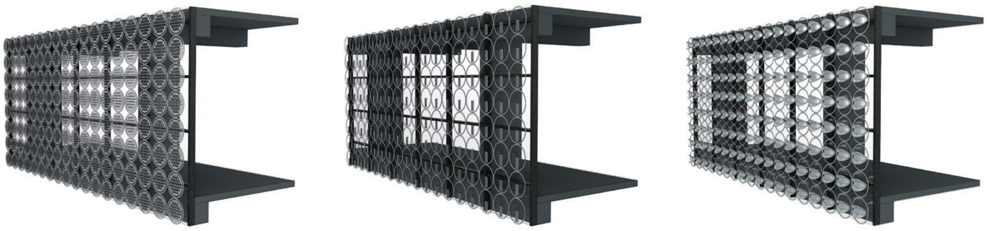


FIG. 15 Further research direction: Prototype development with Type B, D, and E at open positions

5 CONCLUSION

The paper aims to summarise the coordination process of SMP material programming, design, and fabrication, focusing on simple circular cells, and their opening and closing mechanism resulting from SMP bending deformation and/or rotating movement. The design and G code generation was conducted with a process combining Rhinoceros, Grasshopper, and Cubicreator. The kinetic movement of a tested prototype could be simulated using Rhinoceros, and Grasshopper with

Kangaroo plugin, but with the simplified interpretation and algorithms of data obtained from the hands-on model test. The iterative process of additive manufacturing with reference reviews led to the optimal parameter setting for 3d printing. The further SMP prototype design studies, which borrowed morphologies from precedent references, were fabricated to review their constructability in 3d printing. Within the constrained surface geometry and size of circle, the 3d printing feasibility is related to thickness, required finishing precision, vertical additivity with proper supports, and geometric complexity. Manufactured outcomes were reviewed with a focus on material morphing behaviour, structural and performative optimisation, material and morphological dependency, autonomous activation, and reversibility friendliness. The results of this research project developing SMP prototype design and fabrication show a great opportunity for the goal of applying novel smart materials in adaptive and responsive building skins by user-friendly manufacturing methods with easily accessible materials. However, the use of SMP, which shows instabilities depending on the manufacturing and operating environments, is still a challenge.

Moreover, performance analysis of the proposed prototypes was briefly conducted with Ladybug and Honeybee. Radiation simulation led to the ruling out inefficient prototypes, However, more detailed material information of SMP and behavioural relations of variables should be acquired from experiments in order to have more precise and adequate simulations and validations of kinetics and performances of SMP applications. The morphology, kinetic mechanism, and fabrication method of proposed SMP prototypes can be considered to be simple if undertaken with optimal design and 3d printing parameter settings. However, reiterative reversible movement designs and performance validations, with numerous material and behavioural property studies, should be developed in the direction of thermo-responsive SMP façade implementation, as well as material improvements to achieve reiterative shape-changing and stability by scientists and engineers in other disciplines.

Acknowledgements

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