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RESEARCH ARTICLE

The Use of Smart Materials in Architecture: Nitinol-based Foldable Façade Systems

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ABSTRACT
The built environment accounts for a significant portion of global energy consumption and carbon emissions. The generation of kinetic facade systems that can adapt to the changing environmental conditions has gained even more importance for this reason. This study focused on the use of shape memory alloys (SMA) and folding techniques to create heat-active systems and explores the potential of using smart materials in architectural design. The methodology of this research consists of two main stages as undertaking physical experiments and generating a computational design model of the system. Physical experiments involved shaping and programming Nitinol wire as a type of SMA, and creating foldable units based on flat and curved folding techniques. The computational design process includes transferring the physical behavior of Nitinol wire and foldable units by the use of design and simulation tools in an algorithmic modeling environment, in order to create a kinetic building envelope model. The study discusses the potential use of responsive folding techniques to create facade elements that can change shape through the use of SMA actuators without additional mechanical devices and energy use.

Keywords: Climate-adaptive façade, smart materials, shape memory alloy, folding

1. Introduction

Today, we confront difficult goals such as limiting global warming and the use of fossil fuels by maximizing energy efficiency. The built environment contributes significantly to the human carbon footprint, accounting for 30% of the global energy demand and 55% of global energy consumption. As the part of the building that connects to the outside world, the facade is a key part of how well the building uses energy (Schneider et al., 2020). For this reason, the evolution of facade systems that are responsive to environmental conditions has also acquired relevance. Innovative concepts such as "Adaptive Building Facades" will play a key role in the near future since the energy performance of buildings can be maximized through dynamic design (Ergin & Girgin, 2020). New generations of facade systems are becoming more flexible and multifunctional (Boer et. al., 2011). The research conducted by Fiorito et al. shows that using "smart materials" that can control themselves or make their own adjustments can help solve problems with overcomplicated designs, maintenance, and recycling for facade systems (Fiorito et al., 2016). Today, apart from a few groups of smart materials, which are divided into more than twenty groups, their use in architecture is still being researched. These materials contribute to the adaptation of buildings to environmental conditions with their unique behavior patterns. Shape memory alloys (SMA), which belong to the group of smart materials that alter shape and form in response to environmental stimuli, have the inherent capacity to perceive and directly adapt to changing environmental circumstances through a variety of motions.

Kinetic facade systems, which exhibits dynamic behavior against environmental conditions, contributes positively to the energy performance of buildings. However, traditional kinetic facade systems employ a large number of linked, movable components to achieve movement. But, facade systems that use SMAs as a component have the ability to move without any external elements or forces. This reduces the system's complexity and, most importantly, its energy consumption. Furthermore, the geometry of the elements that make up the system and the way they move are the main factors affecting energy consumption and efficiency. Various solutions are being sought to save the system from complexity and minimize the amount of energy. As a solution, the kinetic behavior of Origami geometries can reduce the overall amount of energy required for movement by the system. Due to the self-folding nature of Origami geometries and the shape memory behavior of certain alloys, it is possible to create a component for adaptable facade systems that does not require external force and energy. Combining smart materials such as SMA with different

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folding methods can produce unique solutions for kinetic or adaptable facade systems.

In recent years, kinetic facade systems have been a way to make interior spaces more comfortable by blocking the sun, controlling how much light gets in, and blocking out noise (Karaseva & Cherchaga, 2021). These systems are also responsible for energy consumption and the efficiency of buildings. However, today's built environment requires more innovative solutions to increase the energy efficiency of buildings. Smart facade systems that include intelligent and interactive elements present a new solution for kinetic facade design. According to this typology, a kinetic facade is a system that adjusts the geometry or position of the whole facade and/or its components in response to external inputs. (Boer et. al, 2011). Their ability to respond directly to environmental stimuli using little or no energy makes SMA-based facades advantageous over facade systems with mechanical control systems. Various facade designs have emerged that use SMAs as the system itself or as a subcomponent. Developed by Rift Architecture, the Air Flower project includes independent SMA- based components that provide air flow and temperature control without using electric energy. These components provide interior comfort by opening when the SMA reaches its activation temperature. With the reduction in temperature, the SMA-based components close and airflow stops (Payne & Johnson, 2013). Another project that uses SMAs as facade elements is Living Glass, conducted by S. Yang and D. Benjamin in 2005 The project uses electrical stimuli that activate SMAs to control the amount of CO2 in the interior. When the CO2 level reaches higher levels, the electrical stimuli activate SMAs to open facade elements. When the CO2 level of the interior is equal to that of the exterior, the SMAs return to their initial state by closing the facade elements (Ergin & Girgin, 2020). The Blind Project, developed by K. Khoo, F. Salim, and J. Burry, aims to create a media facade by embedding SMA springs beneath an elastic membrane with perforations like eyes (Khoo et. al., 2011). By investigating state-of-the-art works, this paper aims to contribute to the field by introducing alternatives for kinetic facade systems using combinations of different folding patterns and shape memory alloys.

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This study particularly focuses on the use of SMA and folding techniques to create heat-active facade systems. It also draws attention to the alternatives offered to kinetic facade systems by examining the combination of different folding patterns and shape memory alloys.

1.1. Shape Memory Alloys

The discovery of martensite in steel by Adens Martens in the 1890s was an important step towards the development of future shape memory alloys (Gamal & Mowafy, 2018). Although the first shape memory effect was observed in the Au-Cd alloy in the 1930s, the most important development occurred in 1962, when Buehler and Wang discovered the phase transformation and the associated shape memory effect in the Ni-Ti (Nitinol) alloy. Shape memory effect materials are preferred in many practical and advanced applications today. These materials are used in industrial and medical applications such as machinery, equipment, building materials, medical devices, and vehicles. They are also used in advanced applications such as electronic devices and spaceships. Moreover, a few projects, such as The Harvest Screens, AIR Flower, and the Flea Tower mentioned earlier, are architectural examples that use shape memory alloys in the building envelope.

Shape memory alloys and polymers are materials that have the ability to regain their original shape when heated after being deformed. SMA has shape memory and super elasticity. The shape memory effect is the ability of alloys to return to their original form (austenite phase) when heated to phase transformation temperatures. Super elasticity, on the other hand, is the property of returning to its original form after the load applied on it is removed (Figure 1) (Chu et al., 2012).

1.2. Nitinol as a Shape Memory Alloy

Nitinol, a shape memory alloy, was employed in this work to construct adaptable components in response to environmental stimuli due to its relatively rapid movement capabilities and low cost. These two qualities make it ideally suited for energy-efficient kinetic facade systems.

Nitinol is a group of intermetallic compounds based on nickel and titanium. Due to the thermoelastic martensitic transition, it exhibits shape memory and superelasticity (Wadood, 2016). The nitinol wires utilized in this research are flexible at room temperature, but when heated above the transition temperature, they return to their "recorded form" (Won et al., 2017). This change was used to create an actuator for adaptable movement. To save a specific shape, the Nitinol wire has to be fixed in the desired position and heated between 400 °C and 800 °C for around 5 minutes, then immediately cooled down (programming of Nitinol). The programmed wire can be deformed as desired, and then returned to the programmed shape with the activation temperature.

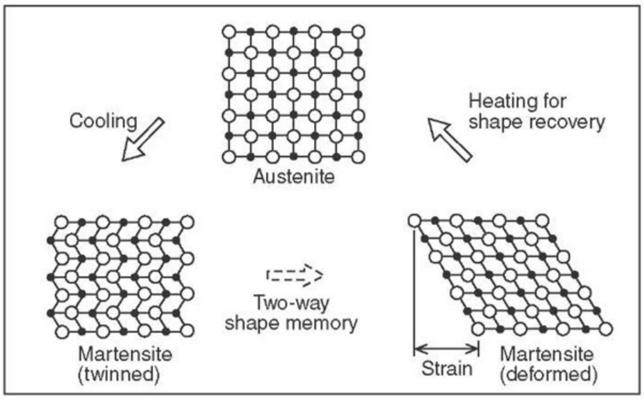

Figure 1. Principle of shape memory alloy (Chu et al., 2012).

The amount of titanium contained in it determines the transformation temperature of the wire to return to the programmed shape. This study uses wires with a conversion temperature of 45 degrees Celsius and a diameter of 1 mm, among Nitinol wires with a conversion temperature of 30, 45, and 60 degrees.

2. Methodology

This study examines the use of geometries created by shape memory alloys and origami folding techniques in heat activated facade designs. The methodology of the study consists of two basic steps: physical experiments and computational design. Physical experiments involve shaping and programming Nitinol wire, which is a kind of SMA, and creating foldable units based on flat and curved Origami folding techniques. Then, the study examines folding techniques to create kinetic systems and considers its transformation into kinetic structures through simulations and prototypes based on the two main variations, flat and curve folding techniques.

The second stage includes computational design, which transfers the physical behavior of Nitinol wire and foldable units into a digital environment by using Kangaroo add-ons operated by the Grasshopper (GH) algorithmic modeling environment. The second stage includes computational design, which transfers the physical behavior of Nitinol wire and foldable units into a digital environment by using Kangaroo add-ons that work with GH. The Kangaroo Engine simulates the folding behavior of paper and Nitinol wire with the help of an algorithmic flow in a digital environment. The folding geometries created in a physical environment transform parametrically in a digital environment. Then, two different folding geometries that can move parametrically are transformed into components for heat-active kinetic facades. Finally, using the Ladybug, Honeybee, Butterfly, and Kangaroo add-ons, the behavior of the heat-activated facade system has been simulated.

2.1. Physical Experiments

This study uses wires with a conversion temperature of 45 degrees Celsius and a diameter of 1mm. Criteria such as thermal reaction range and conversion rate are effective in the selection of the wire. Different types of nitinol programming methods have been utilized for different surface folds. The Nitinol wires, which were originally straight, have been fixed on wooden pieces with nails in the arc, zigzag, and flatform, which are appropriate shapes for transformation. The fixed wires are baked in a 500°C oven for approximately 5-7 minutes to be programmed into their given shape. The wire, which passes into the austenite phase at this temperature, has gained shape memory in the form in which it was fixed. Then, the wire has been manually shaped in order to realize the surface folding motion. In order for the folding movement to be carried out properly, the shaped wire is heated until it reaches the reaction temperature (40–45 °C). When it reaches the reaction temperature, the wire transforms into the shape it was first programmed into, thanks to its shape memory feature, and provides surface folding. Nitinol wires with a length of 10cm are programmed for each folding geometry and movement. Figure 2 illustrates the programming process for Nitinol.

After the programming experiments with Nitinol wires have been completed, the process of modeling foldable elements has started. Origami has faceted surfaces, fold lines, and joints. These parameters are important to understand the transformation of geometry. The fold lines and joints created on the surface define the form of the 3D geometry. Geometric transformations of patterns from 2D to 3D depend on the mathematical understanding behind folding types. The study handles flat fold and curve

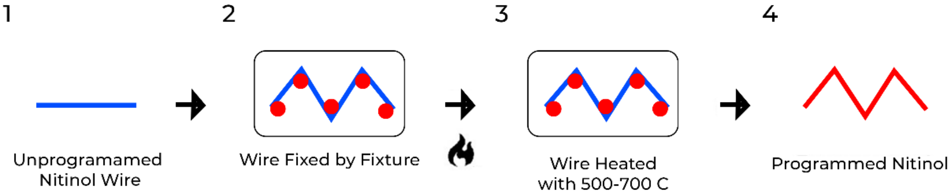

Figure 2. Nitinol programming process

fold patterns from the origami models Lang grouped in 2018 (Table 1) to produce physical prototypes (Lang, 2017).

Table 1. Lang's origami categorization (Lang, 2017).

Model	Description
Flat- Foldable Origami	All faces are flat and coplanar; creases have fold angle of 0 or 180 degree; paper has zero thickness
Polyhedral Origami	Facets are flat, creases are straight, but fold angles can vary continuously; paper has zero thickness
Curved Origami	Facets and creases can be curved; paper has zero thickness
Thick Origami	Paper thickness is explicitly included

In both folding techniques, fold lines are drawn on paper, and manual folding is performed. Then, the movement directions of the surfaces are determined, and an idea is obtained about how the Nitinol wire can be programmed and where it would be located. In order to generate geometry, the shapes of the wires before and after activation gain importance. For each folding operation, wires with a length of 10cm are programmed to exhibit appropriate folding behavior. It is then placed in its predetermined position, where it will transform the paper correctly (Figure 3).

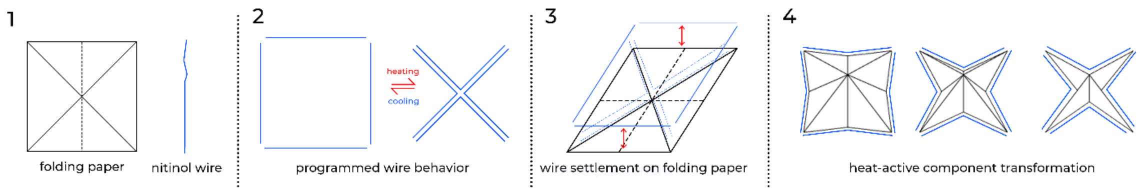

Figure 3. Physical Experiment Process

Figure 4 shows all alternative component models generated by Nitinol wire and paper in a physical environment. It also shows the fold lines of the surfaces created by the curved and flat folding techniques, the Nitinol wire geometry before and after folding, and the 3D physical model of the surface after transformation.

In the next step, patterns 3 and 4 in this table were used as moving parts for heat-activated facade systems and analyzed in a digital environment by the use of GH add-ons.

2.2. Computational Design Model

Since changes in ambient temperature trigger SMA, the relationship between ambient temperature and time is crucial. With the help of a systematic compilation of relevant weather data, ideal locations and suitable SMA activation temperatures for different scenarios can be identified. The aim is to design a structure for a self-sufficient operation, activated only during essential time periods such as temporary exposure to high direct solar radiation. For this purpose, physical models have been translated into computational design models. First of all, Pattern 3, as indicated in Table 1, which gives the maximum surface area change and surface opening before and after folding, has been chosen for the thermally active ventilation surface element. The 3D models

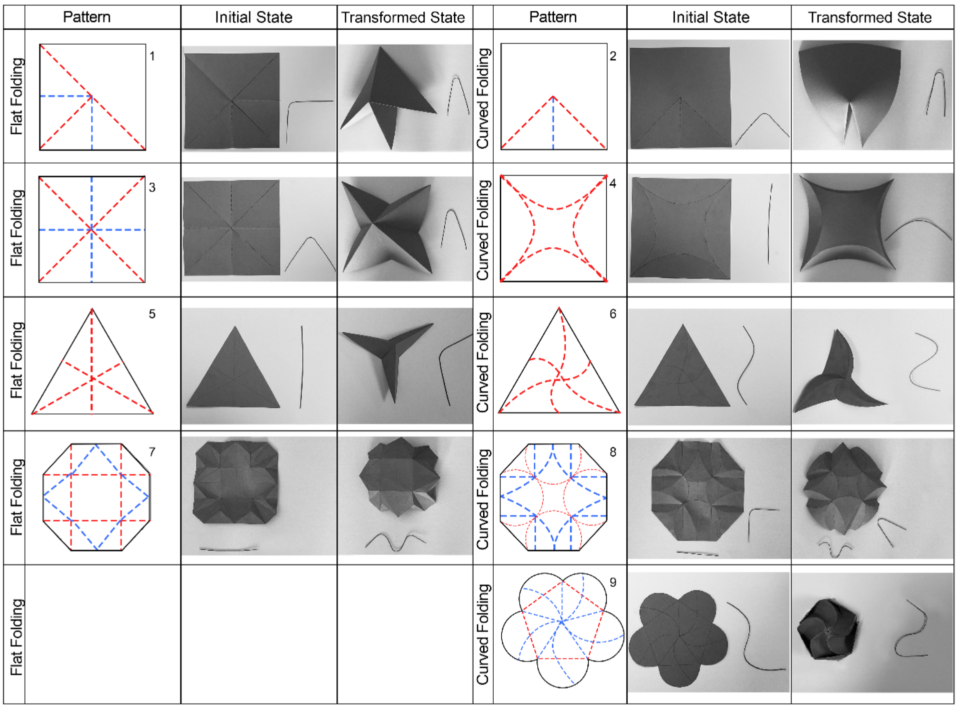

Figure 4. Folding patterns and model transformations with Nitinol wires

based on Pattern 3 have been modeled with Rhino and Grasshopper tools, and the Kangaroo plugin has been used for folding simulation of the model.

The first step for creating a foldable-facade element in a digital environment is to draw a base square plane. The plane has 10 x 10cm dimensions. Then, the fold creases are generated on this plane according to the folding behavior. As a second step, the points that determine the start and end of the folding are determined on the square plane, these points refer to the hinge component in the Kangaroo Engine. These hinge points also represent the locations of Nitinol wires in the physical environment. With the help of the parameter added to the hinge points, the folding angle of the surfaces is defined. The maximum and minimum rotation angles of the folding points have been parametrically defined in the range of 0–120 degrees based on physical experiments. Then, with the help of the forces applied to the hinge points, the surfaces are folded. The applied forces represent the bending forces that occur when the Nitinol wire is activated by the effect of temperature in the physical environment. After modeling a kinetic facade element, a curved facade layout is generated to observe the temperature difference on the surface. Afterwards, foldable and heat-activated composite panels are implemented on the designed facade. Figure 4 shows the modeling process of a heat-active facade element in the Grasshopper environment.

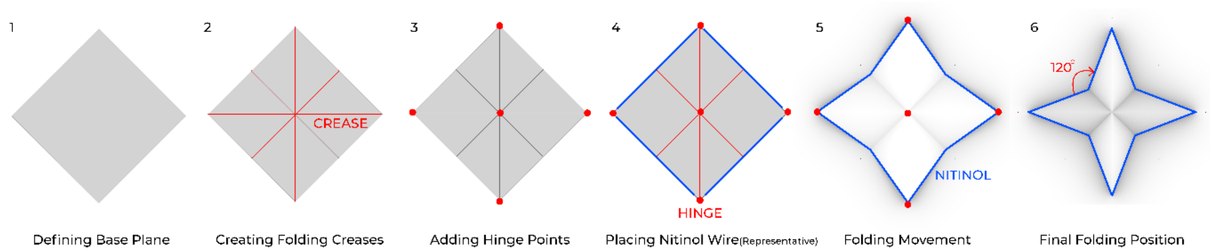

Figure 5. Digital Modeling Process of Heat-Active Panels

To test the behavior of a heat-activated façade system for ventilation, location data of a Mediterranean climate zone with suitable daily temperatures for the activation of Nitinol wires was used. Solar radiation analysis of the façade was made with Ladybug add-ons; facade elements were activated in areas where the surface temperature was sufficient and passive ventilation was provided. Then the Butterfly plugin was used to analyze the ventilation efficiency.

As a second scenario, a curved facade layout has been designed to better observe the temperature difference on the surface, similar to the first scenario. Pattern 4, as indicated in Table 1, which creates a curved surface when folded, has been chosen for the thermally active shading panel. Contrary to the previous facade system, the Nitinol elements on this façade are programmed to expand when heated and placed in the crease of the composite elements. However, similar component modeling processes to the previous one have been conducted. Solar Radiation Analysis and Grid View Illuminance Analysis have been performed on the surface by means of the Ladybug and Honeybee add-ons. The schematic workflow of computational model actions is shown in Figure 5.

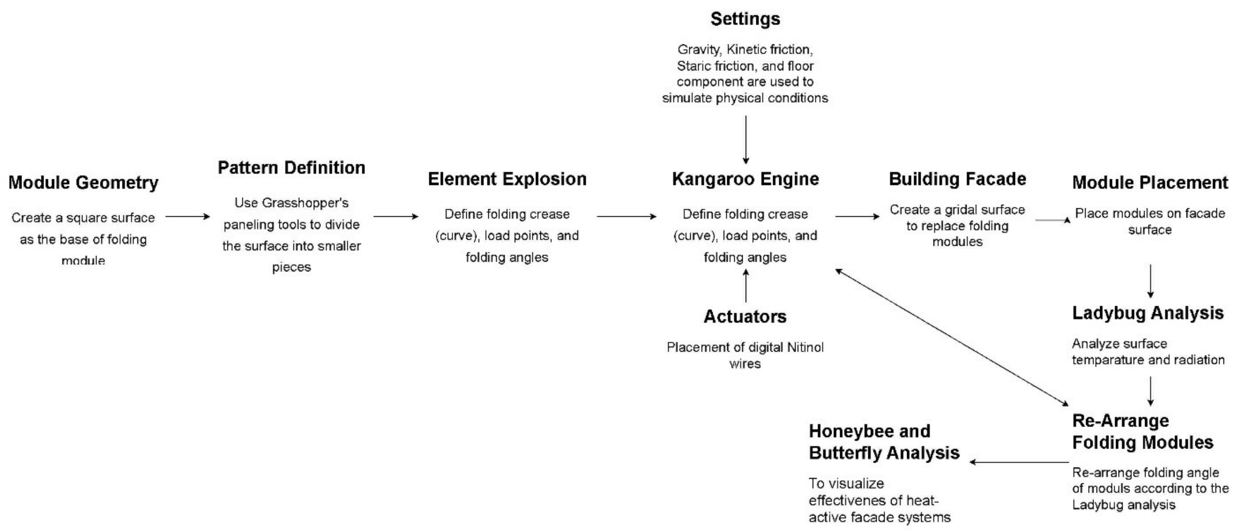

Figure 6. Schematic description of the proposed digital workflow

3. Results & Discussion

The facade generated by the use of the proposed methodology was analyzed with the help of the geological location data of the Mediterranean climate zone that represents appropriate daily temperatures for the activation of Nitinol wires. Figure 6 shows the hourly temperature data for the selected zone. When the temperature reached 40 °C, the facade panel responded in accordance with the Nitinol's behavior. While the red areas represent high temperatures, the blue areas represent low temperatures.

The resulting surface created by Pattern 3 models showed that facade elements exihibit kinetic behavior when the Nitinol wires reach the transformation temperature. In areas where the temperature reached a level that could activate Nitinol (above 5 kwh/m2 or 40 Celcius), the composite elements shrank and formed ventilation gaps on the surface. According to the climate data of the selected location, half of the Nitinol-based façade elements on the whole system were activated. Activated façade elements were compressed according to the nitinol behavior, creating gaps on the façade and providing air circulation between the interior and exterior. Ventilation analysis with the Butterfly plugin showed that the indoor air flow occurred at an average pressure of 30Pa, and the proposed facade system obtained effective ventilation. Figure 7 shows the results of the solar radiation analysis of the heat-activated facade surface and the ventilation analysis of the interior space ventilated to the heat-activated facade system.

The second model made by Pattern 4 showed that when the temperature reached the transformation temperature of Nitinol

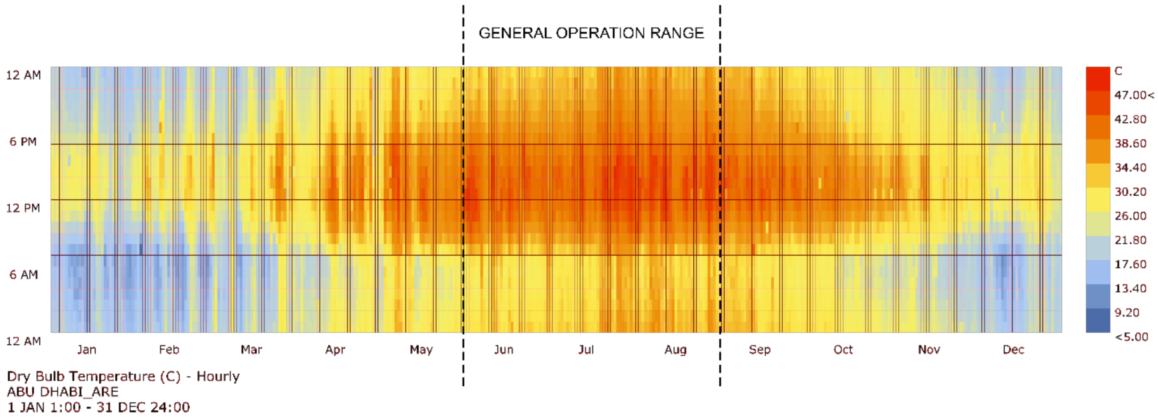

Figure 7. Hourly Dry Bulb Temperature of Selected Work Area

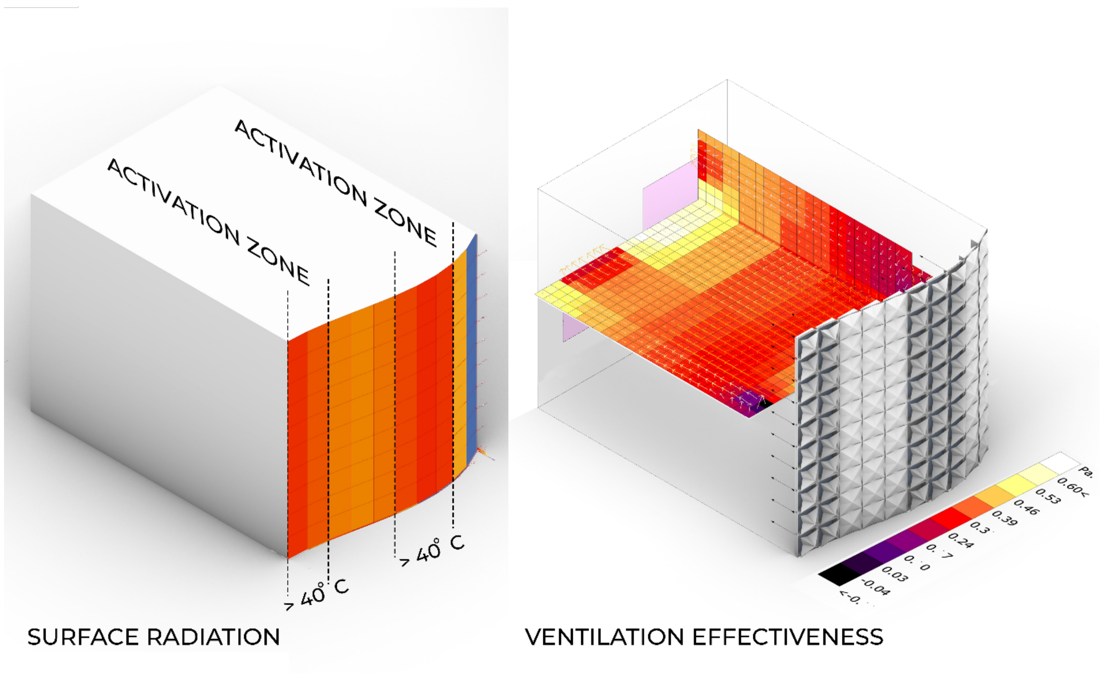

Figure 8. Results of base surface radiation analysis and ventilation analysis results of the heat-activated facade based interior

(above 5 kwh/m2 or 40 Celcius), the initially closed composite panels expanded with the expansion of Nitinol and shaded the area. According to the climate data for the selected location, forty percent of the nitinol-based facade elements on the whole system were activated. Nitinol didn't reach the activation temperature in the blue regions; therefore, no expansion movement was observed in the foldable composite panels. In the red regions, Nitinol reached the activation temperature, and the panels expanded with the action of Nitinol and provided maximum shading. According to the results of Daylight Illumination Analysis, the proposed heat- activated facade system gave positive results when compared to the passive facade system consisting of the same elements. According to the analysis carried out on the passive facade system, the indoor illumination level reached a maximum of 1000 lux and a minimum of 252 lux. In the heat sensitive facade system, when the indoor illumination value reached a maximum of 800 lux in areas close to the passive surface elements, it reached a minimum value of 112 lux in the regions where the elements provided active shading. Figure 8 shows the shading analysis of the heat sensitive active facade and passive facade systems in the interior space.

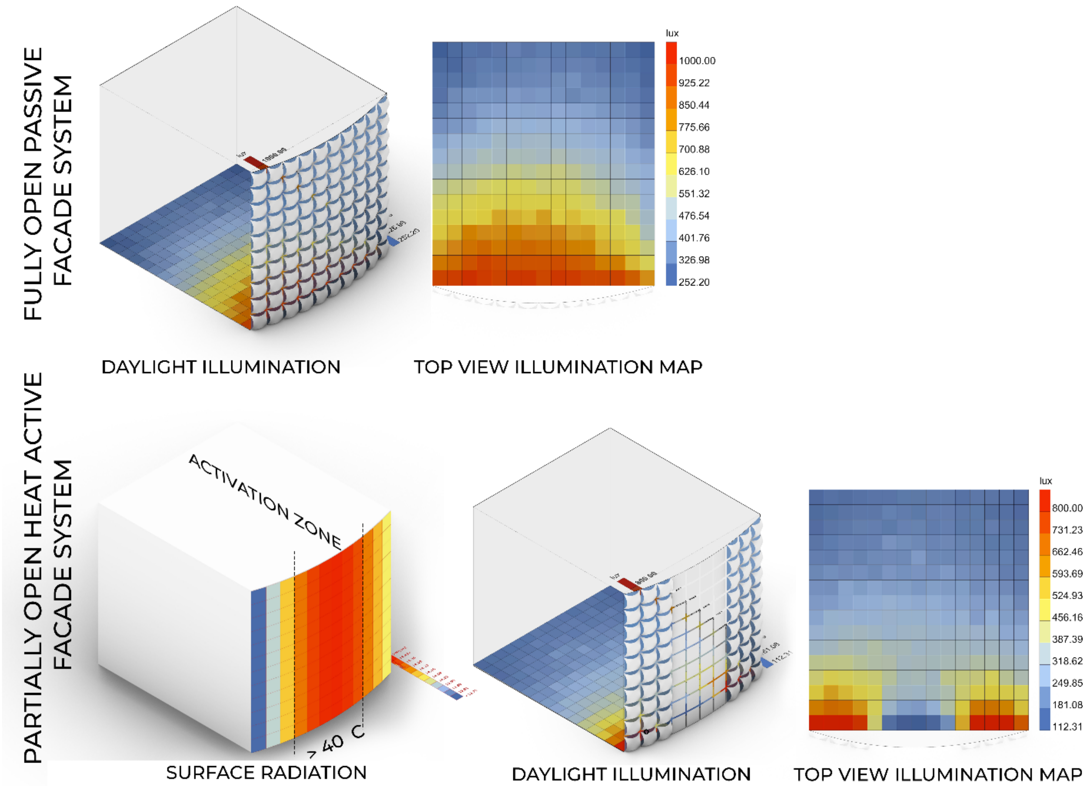

Figure 9. Passive facade based indoor shading analysis results and shading analysis results of heat-active facade based interior

The design proposal was undertaken experimentally. Even though the research began with basic analog models, a detailed interpretation of the material behavior and folding geometries has greatly aided the investigation of the methodology. After exploring the potential of Nitinol's behavior, different alternatives were tried in the process that was transferred to the digital environment. These alternatives were developed by considering the scale issue since the transformation movement of Nitinol wire would be affected according to the scale. In this direction, the process has progressed over composite facade elements, which have the same dimensions as the analog model (10 x 10 cm) and heat-active properties. Analyses were made on two different models to provide active ventilation and shading, and possible alternatives were illustrated (Figures 7 and 8).

The findings of this research showed that smart materials can be successfully incorporated into the design of kinetic building surfaces. Utilizing smart materials on the facade reduced building energy consumption, unlike other dynamic facade systems, which do not use smart materials but require mechanical and electronic components instead. In this study, dynamic systems using smart materials was developed as an alternative to other systems.

4. Conclusion and Future Work

The main purpose of this study is to understand the behavior of smart materials and contribute to the sustainability of the built environment. As mentioned previously, problems such as global warming and excessive resource use, sustainability and efficiency issues have started to gain more importance in all disciplines. This study focused on the use of SMA and folding techniques to explore the potential of using smart materials in architectural design. While physical experiments in the methodology involved shaping and programming Nitinol wire, the computational design process included transferring the physical behavior of this material and foldable units to the algorithmic modeling environment. The combined use of SMA actuators and responsive folding techniques will provide the potential to create shape-changing façade elements without the use of additional mechanical devices or energy.

The results of the study demonstrated that smart materials may be used for the design of intelligent systems. It also provides opportunities for further research and study in several domains. Various alternatives for facade systems can be developed by conducting experiments using different smart materials such as Al-Mn and Fe-Ni-Co-Al alloys or by creating various folding patterns and techniques such as polyhedral folding.

The scale of the material system used in both physical and digital models was relatively small compared to the components used on a building's facade. Thus, the proposed facade design should be considered as an experimental one by translating the behavior of the Nitinol from product to building scale. For further stages of the research, the scale issue should be further investigated and resolved by implementing the system at the building scale. It is expected that the use of smart materials in buildings will become widespread in the future with the help of similar research.

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Peer Review: Externally peer-reviewed.
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