An Approach to Using Shape Memory Alloys in Kinetic Facades to Improve the Thermal Performance of Office Building Spaces

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Abstract This paper presents a study focused on reducing cooling loads and enhancing shading efficiency in office spaces using kinetic façades with shape-memory materials. The research addresses the limitations of mechanical methods commonly employed in kinetic façades by exploring the application of Nitinol, a shape-memory alloy that serves as both an actuator and sensor without requiring external power or complex mechanical components. The study consists of four stages: preparation, material test, design, and model test. In the preparation stage, suitable materials are carefully selected based on factors such as durability, strength, maintenance, corrosion resistance, and flexibility. Nitinol is chosen for its silent operation and reduced susceptibility to malfunctions, while polycarbonate is selected as the sunscreen material due to its lightweight nature and transparency. The specific characteristics of the office space, including orientation and building specifications, are taken into consideration. The material testing stage involves evaluating the effectiveness of Nitinol in moving loads under different temperatures and loads. The weights of the polycarbonate sunscreen are determined to assess their compatibility with the movement capabilities of the smart material. In the design stage, a 1:1 scale kinetic sunscreen unit is implemented, revolving around a horizontal axis at variable angles through thermal stimulation of Nitinol using a parabolic trough solar collector. In the model test stage, the behavior of the kinetic façade is monitored, and opening angles are measured under various climatic conditions. Simulation programs are utilized in the monitoring stage to predict the thermal performance of the kinetic façade. Cooling load measurements are conducted, and the results are compared to those of traditional unshaded glass façades, determining the percentage reduction achieved during summer months. The principal findings demonstrate that implementing kinetic façades with Nitinol can significantly reduce cooling loads in office buildings, with up to a 55% decrease in cooling consumption. While the study acknowledges its limitations regarding scale and specific environmental conditions, it contributes valuable insights to the field. Moreover, the research promotes energy conservation, and improved thermal comfort in office spaces, with potential social implications for creating greener built environments

Keywords Smart Materials, Responsive Facades, Adaptive Buildings, Shape-Memory Alloy, Kinetic Facades, Thermal Performance, Office Buildings

1. Introduction

The thermal performance of office buildings is one of the most crucial factors for the successful design of the building where employees spend a significant portion of the day at work, so the amount of thermal comfort inside the workplace has a significant impact on employees' health and state, which in turn affects how well they perform and complete their work.

Building's façade is regarded as one of the most significant contributors to the energy budget and comfort requirements of any building, given that it insulates the interior environment from the exterior. The goal of this research is to employ a kinetic façade to increase the shading efficiency of highly vitrified facades, creating a thermally pleasant environment for building occupants while lowering cooling and heating energy usage, without resorting to the mechanical methods that usually cause breakdowns. That is through using smart material.

The research addresses a theoretical study of the kinetic facades in office buildings and smart materials, their definition and the reason for choosing them in moving the kinetic facade, and an experimental study of scalable model 1:1 of a kinetic facade that is moved using smart materials and then measuring the thermal performance of the facade by honeybee tool in grasshopper and comparing results before and after the façade enhancement in office space to achieve the research goal.

2. Background

2.1. Office Building Façades and Egyptian Climate

Due to the operational performance of buildings, which is the widespread use of air conditioning systems and the increase in demand for cooling, Egypt has witnessed a rapid growth in energy consumption in the buildings sector in recent years. Hanna [1] indicated that more than 60% of the total electricity consumption in Egypt is attributed to residential, commercial and office buildings. In the office buildings in particular, it is found that the consumption resulting from air-conditioning and lighting equipment represents 38% and 33%, respectively, of the total annual energy; i.e., more than two-thirds of the electricity consumption is in the office buildings sector in Egypt. This means that most of the façades of the office buildings fail to perform their function as a climate responsible for softening the atmosphere inside the building, as the façades of buildings in desert climates such as Egypt are responsible for more than 45% of the cooling load [2]. However, the Egyptian government has worked hard to improve the energy efficiency of buildings and address greenhouse gas emissions. In this sense, the development of the Egyptian Code for Energy Efficiency Improvement has been a critical first step [1]. Nevertheless, there is little indication of a change in general design practices in Egypt towards improving energy efficiency. It is noted that the office buildings in Egypt imitate the Western buildings. The complete glass office buildings have appeared, which causes an increase in the level of solar radiation penetrating into the interior and a rise in temperatures in the summer, leading to their dependence on electrical air-conditioning systems in a country that already suffers from a lack of energy. Priority, here, is given to the form more than the surrounding climatic conditions [3]. Also, most of the climate solutions on which the façades depend are fixed and traditional and not suitable for climate changes that we are witnessing today.

2.2. Kinetic Façades and Their Role in Thermal Performance in Office Buildings

Improving thermal performance can help to lessen energy use and to lessen the impact of the energy crisis, environmental pollution, and climate change caused by excessive energy use in buildings. The thermal performance of a building, according to Nayak & Prajapati, is "the process of modeling energy exchange between the building and the surrounding environment, and the magnitude of the temperature difference between the building and its surroundings is the main driver of energy flow throughout the building" [4]. Previous studies have proven the effectiveness of kinetic façades, which directly contribute to reducing the energy consumption of cooling loads by up to 40% [3,5]. The first generation of traditional kinetic façades was mainly based on CPU-driven (mechanical, hydraulic, or pneumatic) actuators, which respond to climatic conditions [6,7,8,9]. Traditional façades can bring benefits such as energy efficiency improvement, user comfort improvement, and aesthetically appealing design. Yet, they usually require a complex system configuration and multiple mechanical and electronic components, making them bulky, heavy, and difficult to maintain. Traditional actuators also require external power sources to operate which increases their power consumption and operating costs [10,11,12]. For example, at the Arab World Institute (1987), an adaptive solar shading system, inspired by the traditional Arab mashrabiya, was designed to control the amount of sunlight entering the building and reduce energy consumption for cooling. The system consisted of 30,000 individual mechanical light-sensitive control membranes between two glass panels of the southwest façade. The membranes were controlled by actuators connected to a central computer, allowing them to open and close based on the level of sunlight and temperature [18]. Despite the innovative design and functionality, these façades have been criticized significantly due to the failure of their kinetic shutters to respond to the environmental conditions resulting from mechanical problems and the need for constant maintenance. This highlights the importance of considering the long-term maintenance and practical application of innovative systems before implementing them in large projects [13].

2.3. Smart Materials and Their Role in the Operation of Kinetic façades

To address these challenges, research has begun to study the possibility of integrating smart materials into modern kinetic façades that can interact intelligently with external factors, and reshape the kinetic façade [14,12]. Smart materials are defined as “a material that has a built-in or internal sensor (devices), actuator(motors) and control mechanism(s), which is capable of sensing a stimulus, responding to it in a pre-determined manner and extent, in an appropriately short time and returning to its original state once the stimulus is eliminated" [15]. These materials are characterized by their response to ambient weather conditions according to temperature, humidity, light, and stimuli. They also contribute to reducing energy consumption, avoiding mechanical complications, and significantly reducing many maintenance problems and economies related to the operation and maintenance of the kinetic façade. Examples of these materials are: magneto restrictive materials, piezoelectric materials, shape-memory polymers, phase-change materials, photochromic glasses, and shape-memory alloys [16].

However, it is found that there is a lack of studies that conducted tests on smart materials in real environmental conditions to figure out their capabilities and the most important limitations resulting from their use and their economic feasibility in order to determine the possibility of applying them to the kinetic façades at the total range.

2.4. Shape Memory Alloys (SMA): Definition, Reasons for Selection

SMAs are active, multipurpose materials that are widely used in numerous commercial engineering applications in the civil, automotive, electrical, and aerospace industries [17]. Shape Memory Alloys are kinds of smart materials characterized by their ability to restore their original shapes when heated [18]. When the shape-memory alloys are at low temperatures, their yield strength decreases, which facilitates their formation and transformation into any new form. This state is called (Martensait). They retain this shape until they are heated, and then they regain their original shape (Austenite), and this is known as the mother state [19]. They are characterized also by high durability, low energy consumption, high strength, precise control, corrosion protection and flexibility [20]. These properties make SMA ideal for creating dynamic designs in kinetic systems, while also being able to withstand loads and motions and consuming low energy. As a result, SMA has become a popular material choice for architects and engineers in the design and construction of kinetic facades in various types of buildings [21]. Christina Koukelli et al [22] argue that using shape-memory Alloys can demonstrate a certain degree of climatic sensitivity and can react to harsh thermal fluctuations in an energy-saving way as a viable method, in order to lower a building's energy usage. This paves the way for the development of responsive technologies on a large scale, including passive adaptable dynamic façade systems. The real-time response to dynamic and unanticipated environmental changes, which serve as a barrier between the building and the outside environment, makes these systems popular. Hannequart et al [23] developed prototypes of SMA-based sun protection devices that have silent actuation and fewer mechanical elements, but energy consumption requires further comparison. Formentini and Lenci [21] used SMAs as thermal sensors and actuators for a sustainable façade that responds to temperature fluctuations without using electricity. Grinham et al. [24] developed the first full-scale commercially viable application of a programmable Nitinol-based system for passive shading and irradiative insulation. SMAs can improve the architectural and energetic performance of buildings and be implemented and tuned for each climate zone. This literature review summarizes studies investigating the potential of using shape-shifting materials in building envelopes to improve energy efficiency and indoor environmental conditions. Studies explore the use of shape memory alloys (SMA) and other smart materials for adaptive building skins, solar protection and solar shading systems, and kinetic shading devices. However, the scalability, durability, stability, energy consumption and weather resistance of these materials require further validation. The review indicates that future research should focus on exploring the thermal performance of shape-shifting materials for building facades to improve energy efficiency and their scalability to apply them to façades in real environmental conditions.

3. Materials and Methods

To achieve the study's goal, the research investigates the use of kinetic façades with shape-memory materials, specifically Nitinol, in order to reduce cooling loads and enhance shading efficiency in office spaces applying methodology consists of four main stages as follows:

The first stage is the preparation stage and is divided into several sections as shown in Figure 1.

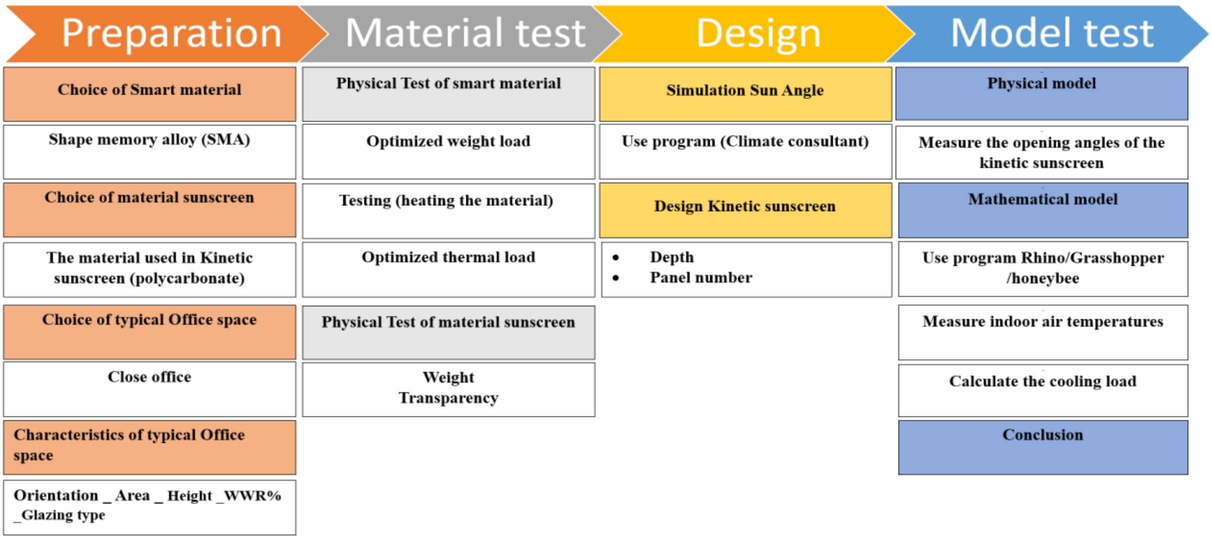


Figure 1. Research approach of using SMA in Office space (By Authors)

The first section is concerned with selecting the smart material that operates as an actuator and sensor at the same time, based on several factors such as durability, strength, maintenance, corrosion resistance, and flexibility. Based on these factors, Nitinol material, which is a shape memory alloy, was selected, and it is characterized by silent operation and is less prone to malfunctions. The second section is concerned with selecting the material to be used for the sunscreen, and polycarbonate material was chosen due to its lightweight and transparency. In the third section, the type of office space being studied is determined, a closed plan space was chosen and south-oriented, and its building characteristics were specified. The second stage is the physical testing stage of the smart material, it was tested at different temperatures with several loads to determine its ability to move loads. Consequently, the weights of the sunscreen made of polycarbonate were determined to identify their effectiveness in moving using the smart material. The third stage is the design stage of the kinetic sunscreen based on the sun's angles and the weight specified from the physical testing of the material. A kinetic sunscreen unit was implemented with dimensions of 1 m length × 0.30 m width in real environmental conditions. Kinetic sunscreen is used. They revolve around a horizontal axis at variable angles, moving by heating the Nitinol using a parabolic trough solar collector. This increases the sensitivity of Nitinol to solar radiation and moves the kinetic façade. The behavior of the kinetic façade was monitored and the opening angles were determined under different climatic conditions, The fourth stage is monitoring the behavior of the kinetic sunscreen and determining the opening angles under different climatic conditions. This is a prelude to stimulation using the rhino program with using grasshopper plugin and the honeybee tool, The values of the angles extracted from the experimental study are entered into the simulation program to predict the thermal performance of the kinetic façade of an office room, by measuring cooling loads and finding out the resulting reduction percentage in the summer months compared to a traditional unshaded glass façade.

3.1. Reasons for Chosen Material

(NiTi shape memory alloys (Nitinol))

SMA can be used to achieve specific types of motion in building façades, such as sliding, rotation, folding and twisting [25]. In this study, Nitinol was used as the basis for the shading system. Nitinol is a type of alloy that consists of 55% nickel and 45% titanium and is known for its shape memory alloy. It is a well-known material that is resistant to corrosion, can be stretched without breaking, and has high strength [21]. Additionally, it can interact with solar radiation and temperature, as it relies on thermal sensing and is capable of responding to even small thermal changes. Raw or end products made from SMAs currently available include Wires, rods, Sheets, Strips, and Springs made from SMAs. Compression or tension SMA springs are available; they can be fastened at one or both ends, directed through their centers, or encased in a sleeve [26]. In this study, a one-way tension coil spring was used.

Figure 2 shows the Nitinol can be deformed (up to about 19cm) when cold (Martensite), and will return to its original shape 2.5cm long with an (Austenite) transition temperature of ~50°C . This shape recovery can be repeated 200,000 cycles [27]. The physical characteristics of the material fluctuate greatly between the austenite and martensite phases. The material is strong and hard in the austenite phase, yet soft and ductile in the martensite phase [28]. As shown in Figure 3, Austenite has a basic body-centered cubic structure, whereas martensite has a more complicated rhombic structure. Figure 4 shows temperatures for martensite beginning (Ms), martensite ending (Mf), austenite beginning (As), austenite ending (Af), austenite maximum temperature (Amax)

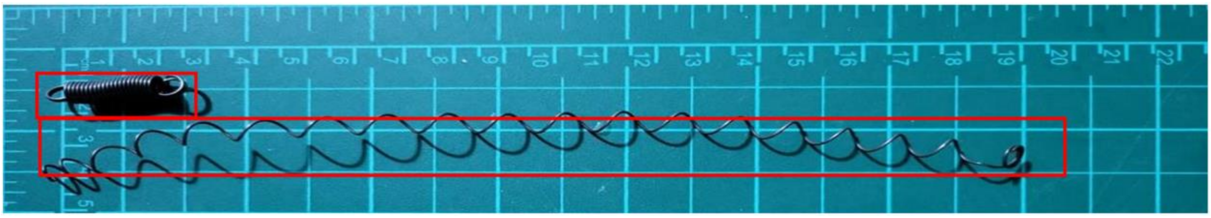


Figure 2. Nitinol when martensite and austenite (By Authors)

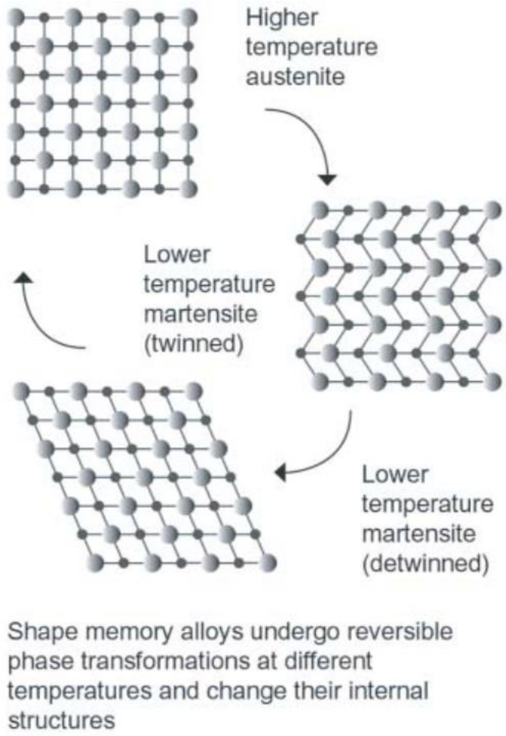


Figure 3. Shape memory alloys (e.g., Nitinol) that exhibit thermally induced shape memory effects [28]

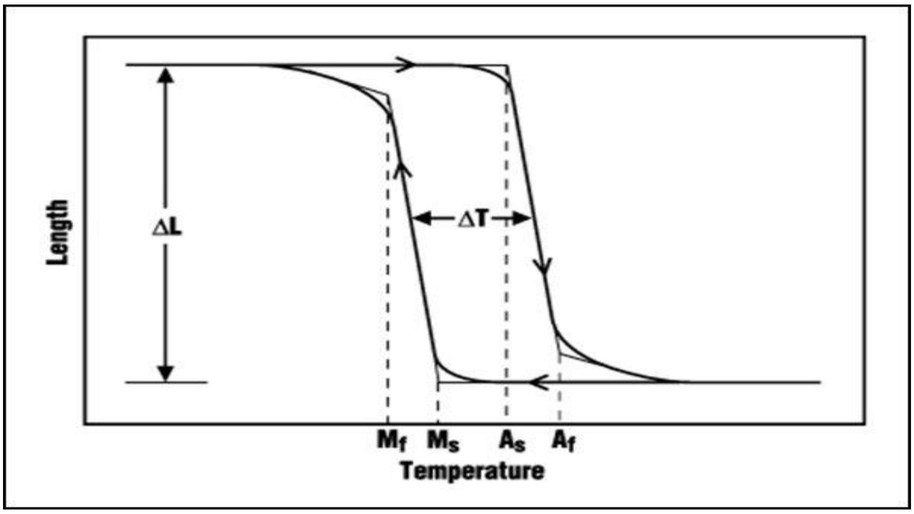


Figure 4. The typical temperature-transformation curve of a NiTi alloy [29]

The spring has an outer diameter of 6.5mm, the number of coils is 21, and the wire diameter is 0.75mm. This type is commercially available on eBay item number 254747805745 the Country/Region of Manufacture is Belgium, and the Brand Flexmet, but it can be manufactured to take different sizes and shrink at lower or higher temperatures.

Experiment for Evaluating Forces in the Nitinol Tension Spring

Figure 5 shows thermal analysis experiments carried out with varying loads. Δ=deflection due to load W Δr= resid.

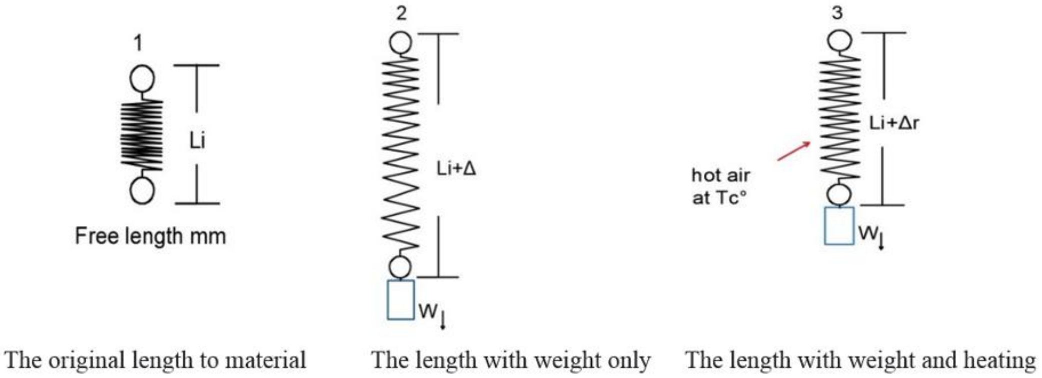


Figure 5. The length of material at different air conditions at the experiment. (By Authors)

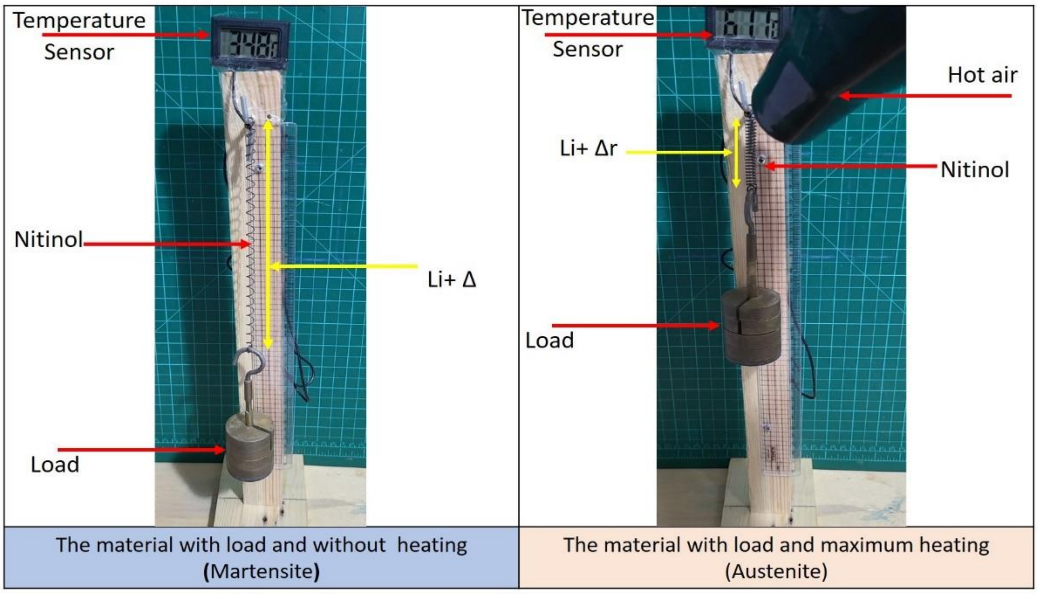


Figure 6. The practical experiment of loading the weights of Nitinol with temperatures. (By Authors)

Figure 6 shows the length of Nitinol after loading several different loads in the order (465, 365, 265, 165) gm at air temperature (Li + Δ) (martensite phase). After that, the length of the material was measured when exposed to high temperatures (Li + Δr) (austenite phase), in order to find out the maximum load that the Nitinol could lift without distortion in its shape, as well as the effect of these loads on the martensite and austenite phases. This is a prelude to the experimental study of the kinetic façade to figure out the maximum load of the façade and the possibility of movement when the temperature rises .

3.2. Experimental Study and Testing

The experimental study includes the preparation of a model of an iterative kinetic façade unit at a scale of 1:1 with dimensions of 0.80m length * 0.30m width. The unit consists of 7 kinetic horizontal suncreens rotating around a horizontal axis with an opening angle from 3° (in the case of closing the façade) to an angle 90°, which is the maximum opening of the sun-screen. The material of the sunscreen is polycarbonate sheets with a thickness of (6mm) and weighs 45g. The façade also consists of a single Nitinol spring actuator; a bias spring works in the opposite direction to the force of Nitinol to ensure the façade opens when the temperature decreases. There is a wire to connect the sunscreen with Nitinol. It is noted that many complexities and links have been avoided in order to avoid mechanical faults. Figure 7 shows a simple operating system with springs (helical SMA and bias spring) installed on two fixed sides [30]. It is also noted that a bias spring has been used, as Nitinol requires a force to return it to the martensite phase due to the hysteresis phenomenon [31].

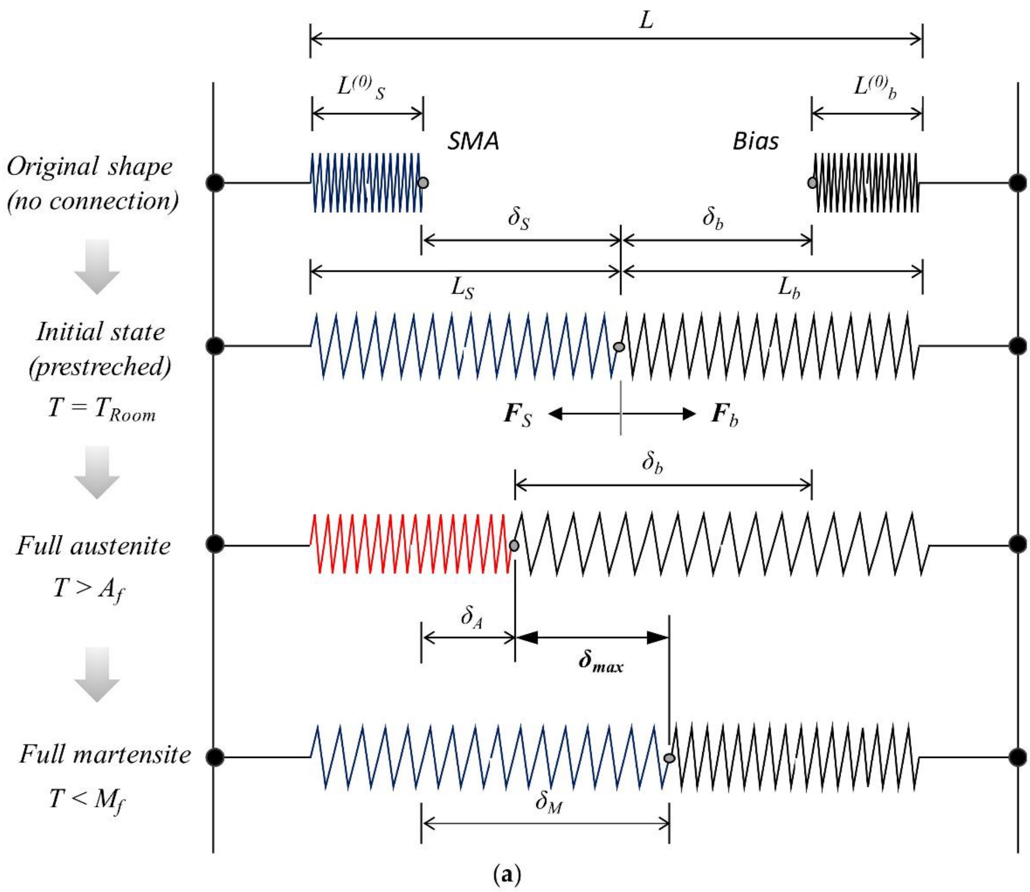


Figure 7. The effect of the bias spring on the Nitinol spring in the austenite and martensite phases [30]

Figure 8 shows the design of the prototype of the kinetic façade unit, scale 1:1. The sunscreen is moved by Nitinol by stimulating it thermally using a parabolic trough solar collector to increase the sensitivity of Nitinol to solar radiation by focusing solar radiation on it to move the kinetic façade. As shown in Figure 9, the proposed smart actuator consists of a curved reflective surface (mirror), and a smart material (Nitinol) inside a glass tube located at the pivot point. Figure 10 shows the pivot point using a laser device. The mirror plate was installed on the condenser in a bending manner by dividing the mirror plate every 3cm, 11 times. The condenser moves the sunscreen at temperatures starting from 29°C by focusing the solar radiation on the Nitinol and raising its temperature. The commercially available Nitinol begins to transform from martensite to austenite at temperatures ranging from 45°C to 50°C, which is a relatively high temperature. The use of bending mirrors can be eliminated if Nitinol, which shrinks at temperatures of 30°C, is manufactured.

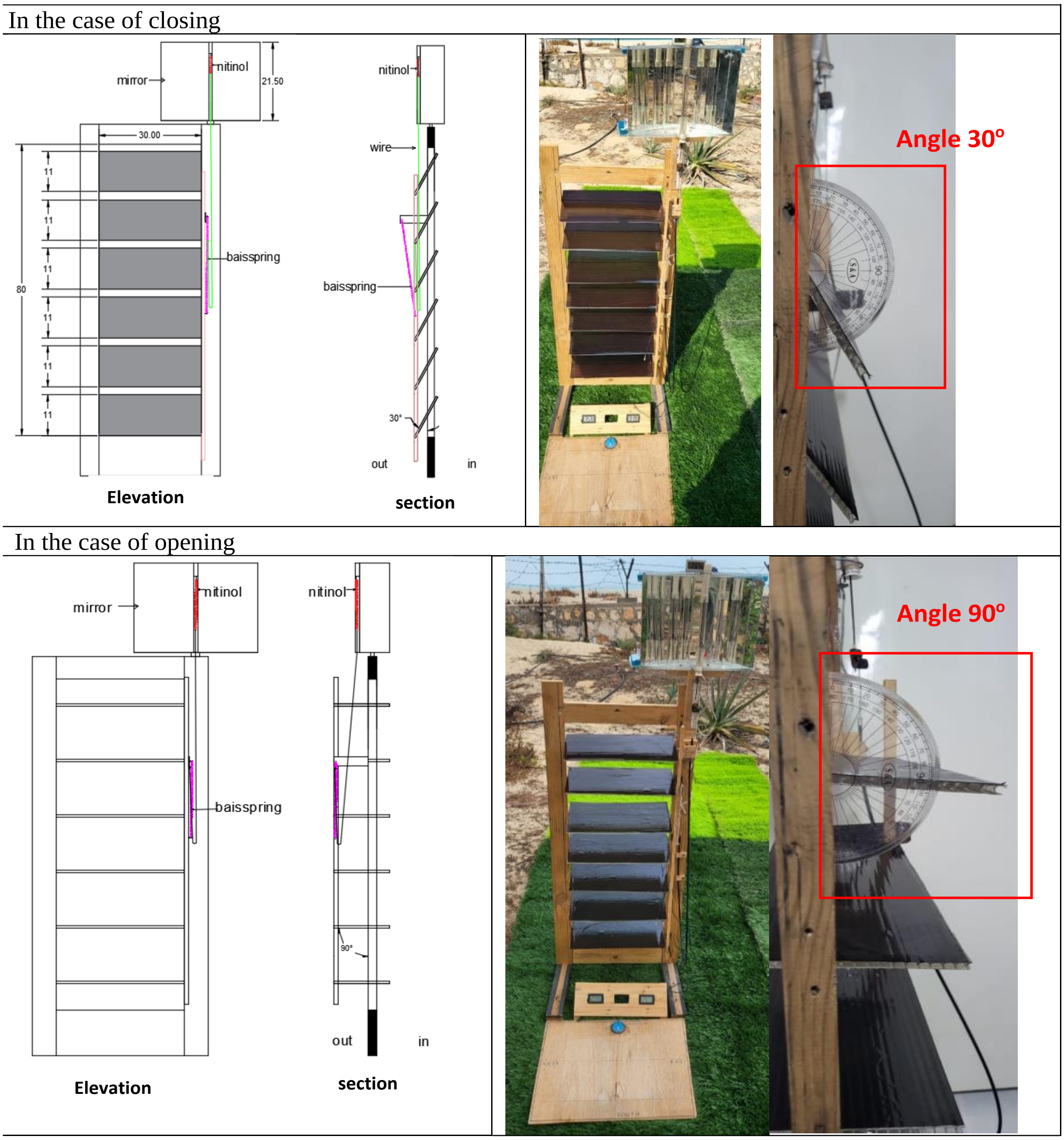


Figure 8. Dynamic façade model in the case of opening and closing. (By Authors)

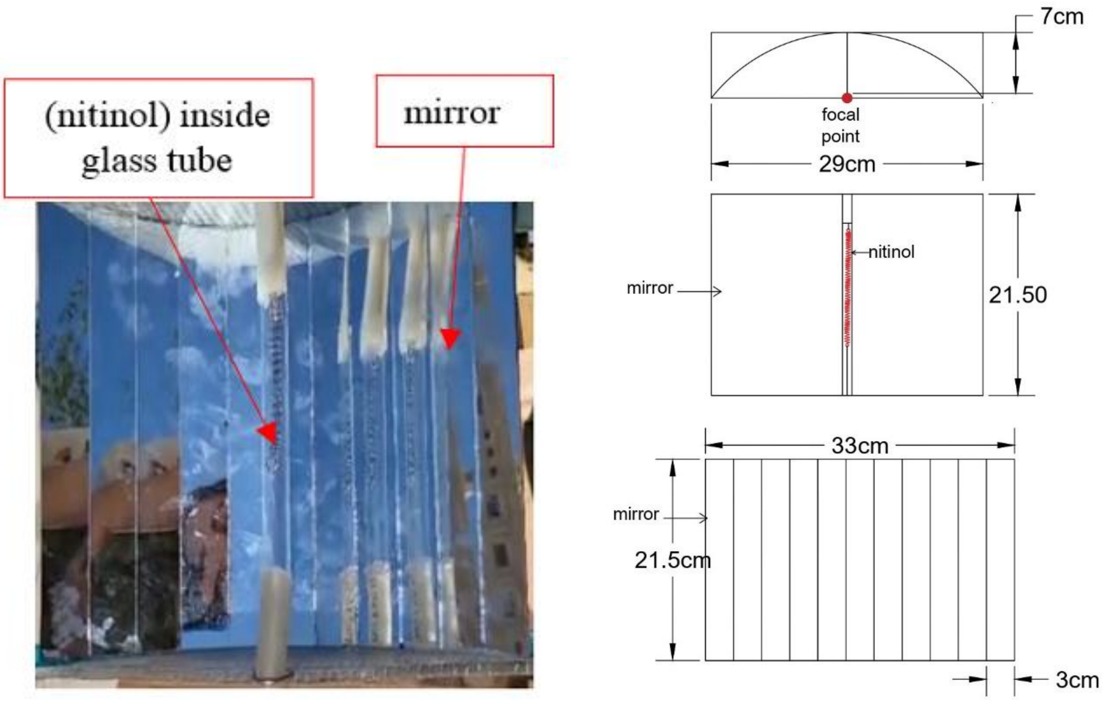


Figure 9. Smart materials(nitinol) and parabolic trough solar collector. (By Authors)

Figure 10. Focal point. (By Authors)

The operation mechanism includes monitoring the behavior of the proposed kinetic façade with the surrounding climatic conditions and their impact on the kinetic façade oriented to the south and measuring its performance and opening angles at different times. The angles were measured every hour from 9:00 to 17:00 over several days in the summer to determine the average opening angles resulting from the temperatures and solar radiation throughout the day, in order to measure the performance of the façade movement during daylight hours in preparation for simulating the thermal performance of the proposed kinetic façade on the office buildings.

3.3. Modeling Office Space

Firstly, the location of the office was selected in Al-Arish, Egypt. It is located between latitudes 29° 00 and 31° 10ʹ N - 33° 05ʹ and 34° 40ʹE Its Köppen climate classification is hot desert (BWh), Although the region's temperatures are moderated by the Mediterranean winds, like the rest of Egypt's northern shore [32] An air-conditioned office space model has been made by using the Grasshopper plug-in for Rhino. The office area is 32m^2, the office is oriented towards the south. The percentage of the glass is 75% (single glass). Ayegbusi et al.'s study [33], which employed dynamic modeling software (Energy Plus/Design Builder) as a tool, produced results showing that the annual heat transferred through the building's east orientation is higher than that through all other orientations. Therefore Office Room No. 3 was selected because of the lack of research that conducted simulation tests on the last floor and it is the most exposed to heat due to solar radiation from the ceiling and the eastern and southern sides, as shown in Figure 11. Table 1 shows the requirements of the office space. Table 2 shows the characteristics and dimensions of the window. Tables 3, 4, and 5 show the construction characteristics of the office space.

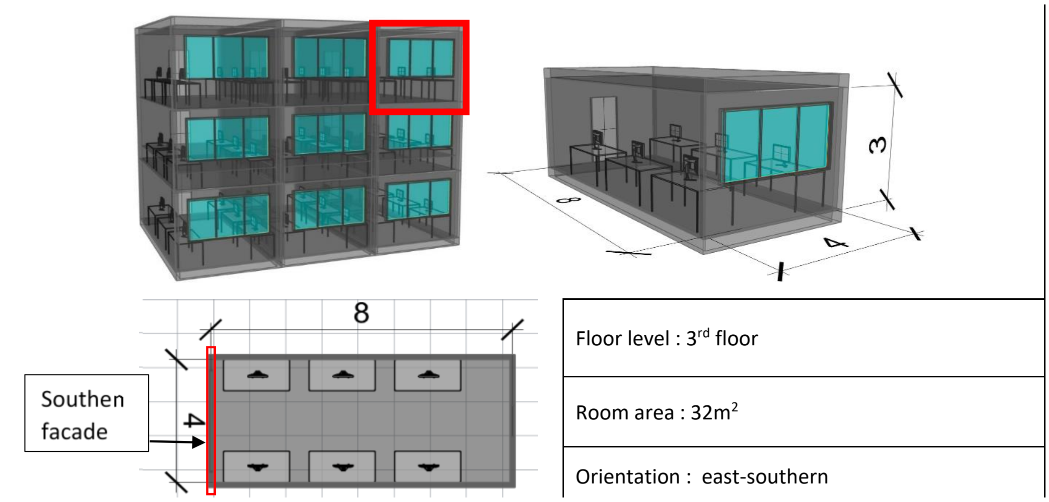


Figure 11. Office space parameters. (By Authors)

Table 1. Office space requirements. (By Authors)

Program	Medium Office Closed Office
Table of occupations	The hours chosen by the table of occupations —between 9:00 and 12:00 for five days—are typical for many private businesses in Egypt.
Lighting	[8.0 W/m^2]
Electric Equipment	[9.4 W/m^2]
Infiltration	[0.000227 m^3/s-m^2]
Ventilation	0.000305 m^3/s-m^2
Setpoint	[heating: 21°C]
	[cooling: 24°C]

Table 2. Window of office space Parameters. (By Authors)

Window Parameters	
Name	U 1.7 SHGC 0.55 Simple Glazing
Window size	3m by 1.5 m
U-factor {W/m^2-K}	9.6526
(SHGC) Solar Heat Gain Coefficient	0.55
(VT) Visual transmittance	0.6

Table 3. The characteristics of construction materials in exterior wall. (By Authors)

Material name	Roughness	Thickness {m}	Conductivity {w/m-k}	R-value (m^2-k/w)	Density {kg/m^3}	Specific heat {j/kg-k}	Thermal absorptance	Solar absorptance	Visible absorptance
1 in Stucco	Smooth	0.025**3**	0.690		1851.00	836.46	**0.9**0	0.70	0.92
8 in concrete HW Refbldg	Rough	0.20**00**	1.310		2240.00	836.26	0.90	0.70	0.70
Typical Insulation-R7	Medum Smooth	1.232**0**	0.900	1.232			0.90	0.70	0.70
½ in Gypsum, Smooth	0.0127	0.012**0**	0.159		784.90	829.46	0.90	0.40	0.40

Table 4. The characteristics of construction materials in exterior roof. (By Authors)

Material name	Roughness	Thickness {m}	Conductivity {w/m-k}	R-value {m^2-k/w}	Density {kg/m^3}	Specific heat {j/kg-k}	Thermal absorptance	Solar absorptance	Visible absorptance
Roof Membrane	Very Rough	0.0095	0.159		1121.2**0**	1459.05	0.90	0.70	0.70
Typical Insulation-R22	Medium Smooth		0.900	3.87**0**			0.70	0.70	0.70
Metal Roof Surface	Smooth	0.0008	45.240		7824.01	499.67	0.90	0.70	0.70

Table 5. The characteristics of construction materials in Interior Wall. (By Authors)

Material name	Roughness	R-value {m^2-k/w}	Thermal absorptance	Solar absorptance	Visible absorptance
Adiabatic Material	Medium Rough	1760.93	0.90	0.70	0.70

Second, the proposed kinetic façade model has been designed using the Grasshopper program. In the program, the angles of the sunscreen are changed according to the angles proposed by the experimental study from the experimental measures linked to the temperatures and solar radiation. The kinetic façade of the office room includes 14 kinetic iterative units, i.e., the single office room requires 14 Nitinol actuators. Figure 12 shows the office room before and after the installation of the kinetic façade.

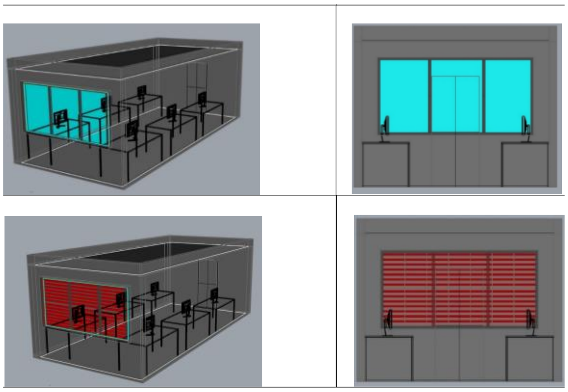


Figure 12. Office space before and after kinetic façade. (By Authors)

Third, a simulation is used to model the kinetic façade behavior and predict its cooling load performance for the proposed model office space in the summer months. This is due to the fact that heating loads are highly converged after the addition of the dynamic façade with the suggested opening ratios, which encourages thinking practically about how to use sunlight to lighten interior spaces during the winter months (Dec.- Jan.- Feb.- Mar.). The higher the opening ratio, the greater the benefit ratio from sunlight inside the space [34]. This simulation was carried out to measure the shading angle efficiency resulting from the SMA material of the proposed kinetic façade, in order to improve the thermal performance inside the office. For this purpose, the percentage of reduction in cooling loads was measured under different scenarios and conditions during office working hours (9:00 to 17:00). Figure 13 shows the steps of simulating the kinetic façade using Honeybee in Grasshopper to find out the cooling loads resulting from the use of the kinetic façade with the Nitinol opening ratios proposed from the experimental study and compare it with a traditional glass façade to figure out the percentage of reduction in cooling loads.

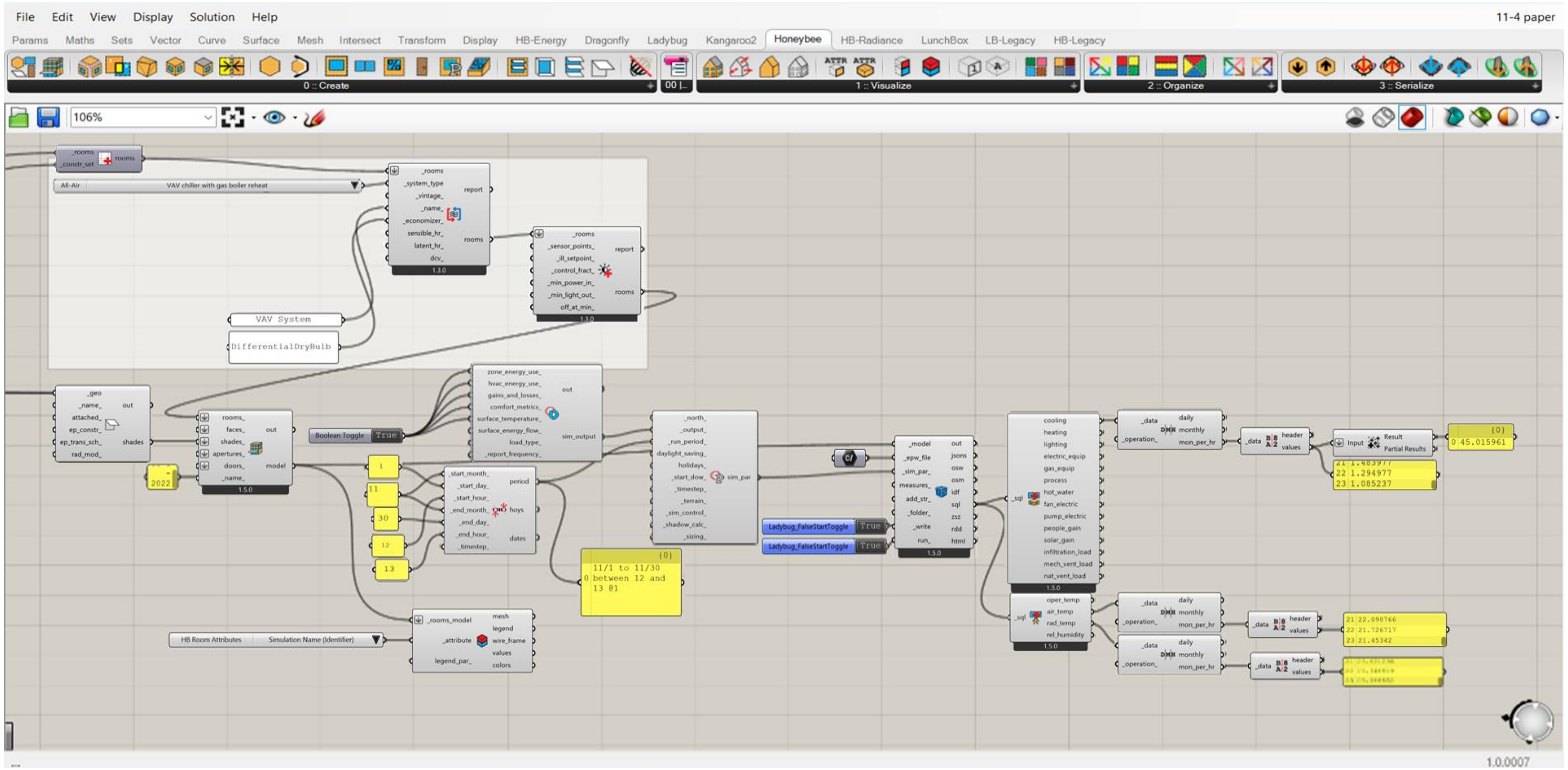


Figure 13. Grasshopper screenshot for window of office space simulation in honeybee. (By Authors)

4. Results and Discussion

4.1. Results and Discussion of Nitinol Behavior with Different Loads

It appears that nitinol undergoes strain when subjected to weight at normal temperatures, and shrinkage when subjected to weight at maximum temperatures in space as explained in Figure 14. Furthermore, the behavior of nitinol differs between austenite (shrinkage) and martensite (strain) under the same load. The length ratio of nitinol is affected by the load and temperature, with the maximum length observed at weight 465 gm. It is the maximum weight that the material can bear, after which it deforms and does not return to its original shape, and the minimum length observed at weight 165 gm in both austenite and martensite cases. The length of nitinol increases with increasing load and decreases with increasing temperature. Overall, that nitinol is a smart material that exhibits unique behavior under different conditions, and has potential applications in kinetic façade.

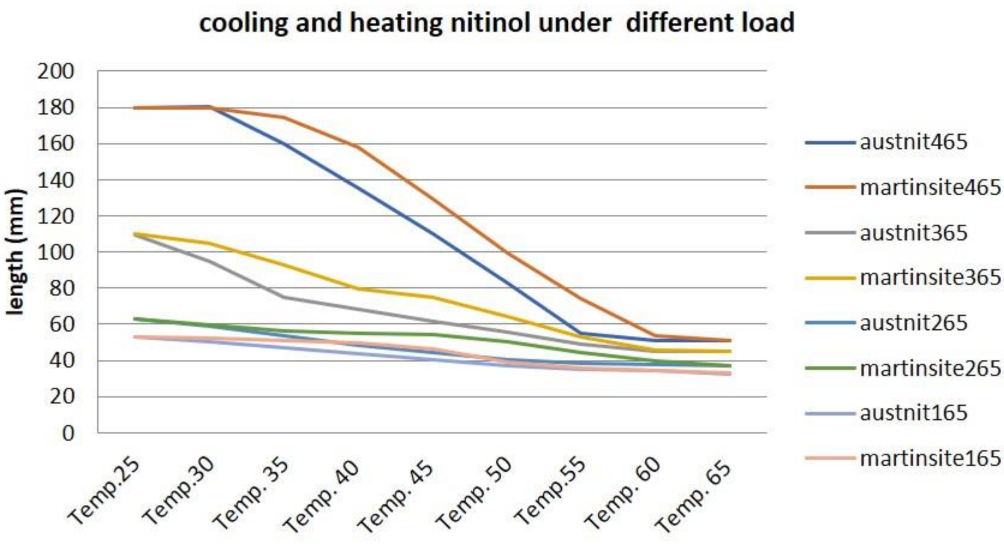


Figure 14. The cooling(martensite) and heating(austenite) nitinol under different load. (By Authors)

4.2. Results and Discussion of Experimental Study and Testing

To close the facade, we observe that the parabolic trough solar collector raises the temperature of nitinol to reach 45°C and more by concentrating solar radiation, and thus nitinol shrinks and returns to its original state, the austenite phase, causing a tensile force of 3.5N and closes the facade at noon as shown in Figure 15. And when going into the stage of martensite, the tension spring (bias spring) works with a counter force to open the façade. the nitinol material expands to 11.5cm at low temperatures in the afternoon.

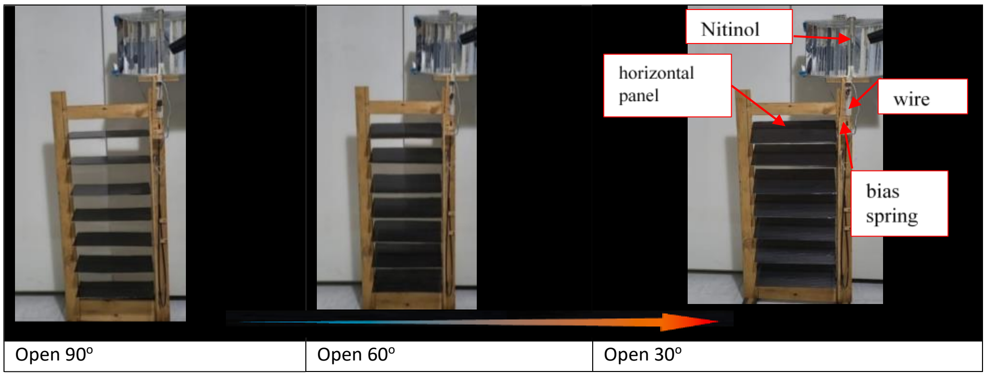


Figure 15. Heating (martensite to austenite) (By Authors)

Table 6 shows the monitoring of the movement of Nitinol with temperatures during working hours (9:00 to 17:00), its effect on the kinetic façade, the percentage of solar radiation, and the temperatures in front and behind the proposed kinetic façade. This study was conducted on three different days in the summer months.

Table 6. The length and temperature of Nitinol and its effect on the façade movement throughout the day. (By Authors)

Day	Case		Time	Nitinol length Cm	Angle °	Temperature °C			Solar radiation w/m^2	
						Out	In	Nitinol	Out	In
Day1		Austenite	9:00	10.2	80°	28.0	28.0	26.0	100	70
			10:00	10.0	78°	29.0	29.0	29.0	126	79
			11:00	9.4	73°	33.0	31.0	46.0	897	345
			12:00	8.4	67°	35.0	32.0	57.0	923	329
		martensite	13:00	9.0	71°	36.0	32.0	43.0	801	286
			14:00	9.5	74°	35.0	32.0	40.0	588	231
			15:00	9.8	76°	32.0	31.0	34.0	196	75
			16:00	11.2	89°	29.0	29.0	27.0	72	29
			17:00	11.4	90°	27.0	27.0	24.0	04	03
Day2		Austenite	9:00	10.5	88°	28.0	28.0	26.0	100	70
			10:00	10.2	80°	34.0	28.0	39.0	697	375
			11:00	8.5	70°	37.0	31.0	56.0	842	321
			12:00	7.5	60°	35.0	30.0	60.0	886	376
		Martensite	13:00	8.0	65°	37.0	31.0	43.0	598	268
			14:00	8.5	70°	35.0	30.0	37.0	460	259
			15:00	8.5	70°	33.0	29.0	33.0	291	97
			16:00	10.3	81°	29.0	27.0	28.0	39	31
			17:00	11.5	90°	28.0	26.0	24.0	05	05
Day3		Austenite	9:00	10.2	80°	28.0	28.0	26.0	100	70
			10:00	9.4	73°	33.0	31.0	46.0	897	329
			11:00	6.5	50°	34.0	30.0	67.0	931	381
			12:00	6.2	43°	37.0	33.0	51.0	990	389
		Martensite	13:00	7.2	55°	35.0	31.0	42.0	858	279
			14:00	7.4	60°	35.0	31.0	36.0	451	281
			15:00	7.7	62°	33.0	29.0	33.0	263	118
			16:00	8.2	65°	29.0	26.0	29.0	30	19
			17:00	11.4	90°	28.0	26.0	26.0	6	5

Figure 16 shows on day one the Nitinol length has been decreased between 9:00 and 12:00 with a ratio of 17.6%. Also, the Nitinol length has been increased between 12:00 and 17:00 with a ratio of 26.3%. According to that, the minimum of the Nitinol length is 8.4cm at the peak hour of 12:00. Additionally, the maximum of the Nitinol length is 11.4cm at 17:00 o'clock.

On day two, the Nitinol length has been decreased between 9:00 and 12:00 with a ratio of 28.5%. Also, the Nitinol length has been increased between 12:00 and 17:00 with a ratio of 34.78%. According to that, the minimum of the Nitinol length is 7.5cm at the peak hour of 12:00. Additionally, the maximum of the Nitinol length is 11.5cm at 17:00 o'clock.

On day three the Nitinol length has been decreased between 9:00 and 12:00 with a ratio of 39.21%. Also, the Nitinol length has been increased between 12:00 and 17:00 with a ratio of 45.6%. According to that, the minimum of the Nitinol length is 6.2cm at the peak hour of 12:00. Additionally, the maximum of the Nitinol length is 11.4cm at 17:00 o'clock

Figure 17 shows that on day one the kinetic façade angel has been decreased between 9:00 and 12:00 with a ratio of 16.2%. Also, the kinetic façade angle has been increased between 12:00 and 17:00 with a ratio of 25.5%. According to that, the minimum of the kinetic façade angle is 67° at the peak hour of 12:00. Additionally, the maximum of the kinetic façade angle is 90° at 17:00 o'clock. Finally, the kinetic façade closes at the peak hour.

On day two the kinetic façade angle has been decreased between 9:00 and 12:00 with a ratio of 31.8%. Also, the kinetic façade angle has been increased between 12:00 and 17:00 with a ratio of 33.33%. According to that, the minimum of the kinetic façade angle is 60o at the peak hour of 12:00. Additionally, the maximum of the kinetic façade angle is 90o at 17:00 o'clock. Finally, the kinetic façade closes at the peak hour.

In day three the kinetic façade angle has been decreased between 9:00 and 12:00 with a ratio of 46.2%. Also, the kinetic façade angle has been increased between 12:00 and 17:00 with a ratio of 52.2%. According to that, the minimum of the kinetic façade angle is 43° at the peak hour of 12:00. Additionally, the maximum of the kinetic façade angle is 90o at 17:00 o'clock. Finally, the shatter closes at the peak hour.

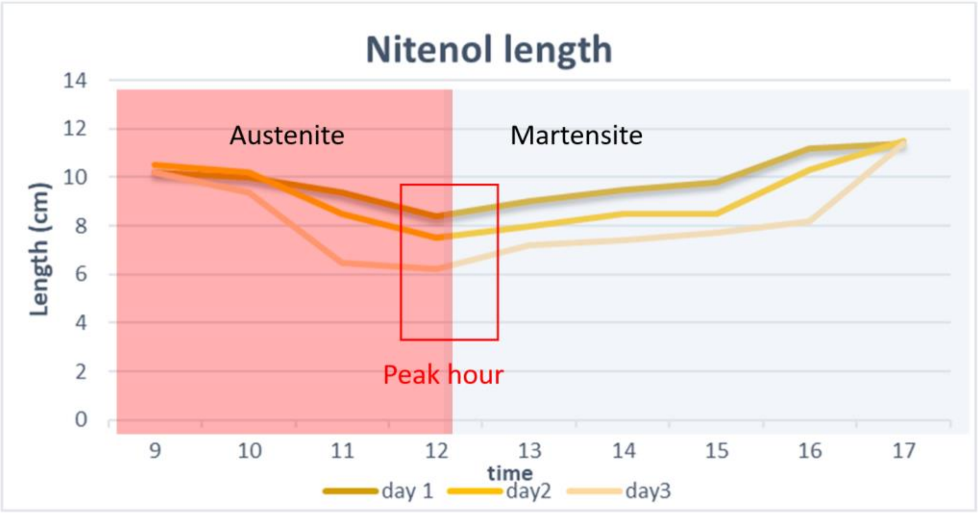


Figure 16. The length of nitinol material at different time in three days. (By Authors)

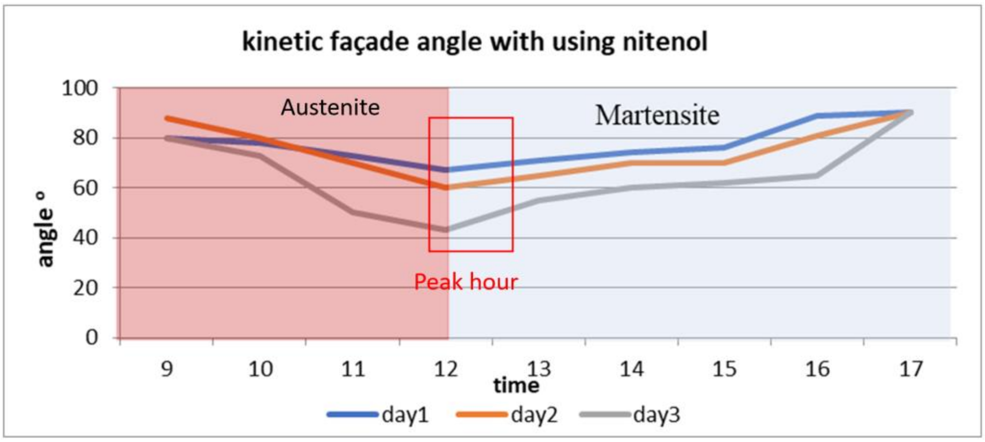


Figure 17. The shatter angel at different time during use nitinol material. (By Authors)

In Figure18, it is observed that the rate of shutter opening increases to approach 90° degrees as nitinol expands, indicating that when temperature decreases, the shutter opens to let in light and ventilation.

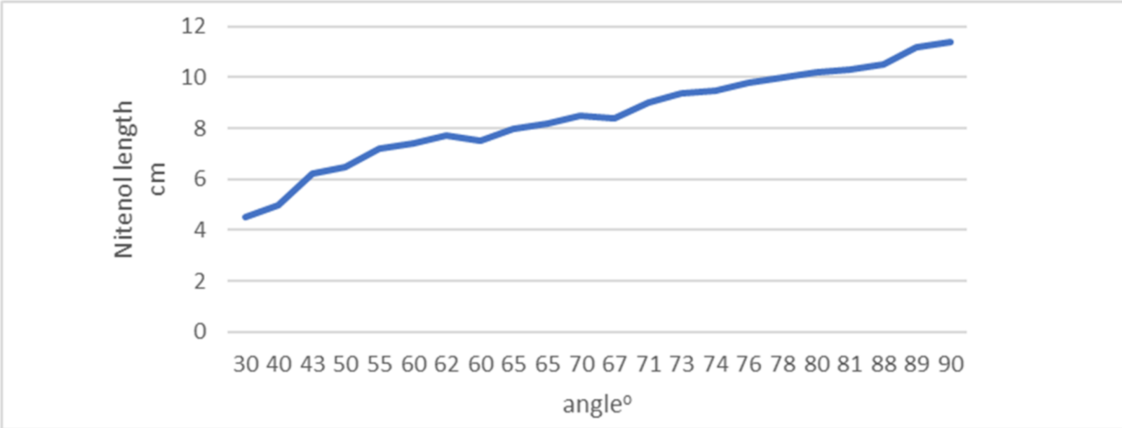


Figure 18. Curve between nitinol length and kinetic façade angle. (By Authors)

When nitinol shrinks, the opening rate decreases to 30° degrees, and this indicates that when the temperature rises, the shutter closes to block the solar radiation while enabling air to circulate inside the building.

Figure 19 shows the kinetic façade with smart material is inversely proportional to the increase in radiation temperature. The kinetic façade closes as Nitinol gains heat from solar radiation and ambient air and opens in the afternoon when Nitinol begins to lose heat as a result of decreasing solar radiation intensity and ambient air temperature

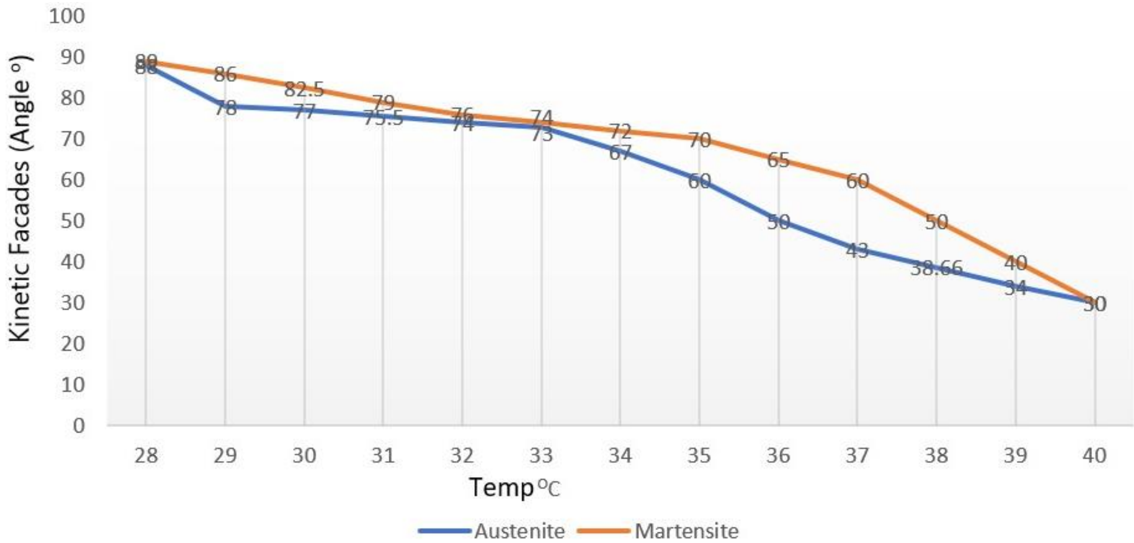


Figure 19. Curve between angle kinetic facade with temperatures using smart materials (Nitinol) and parabolic trough solar collector. (By Authors)

4.3. Results and Discussion of Thermal Performance Simulation

The following table 7, table 8, table 9, table 10, show the efficiency of the thermal performance of the kinetic façade in the summer months (July, August, September and October) by reducing the cooling loads in the selected room No. 3 of the office building with the proposed angles for the kinetic façade of the previous Figure 17 as a result of the response of Nitinol to temperatures throughout the day (from 9:00 to 17:00).

Table 7. Room 3 (Upper East) July Average Cooling Load (kWh). (By Authors)

Time	Average radiant temperatures- °C	Average air temperatures- °C	Kinetic facade angle- Degree	Average radiant temperatures with kinetic façade- °C	Average air temperatures with kinetic façade- °C	Cooling loads for the room with kinetic façade - kWh	Cooling loads for the room with traditional façades- kWh	The reduction compared to kinetic facades with traditional façades- %
9:00	33.0	33.0	73°	31.0	32.0	3.70	4.40	16%
10:00	34.0	34.0	67°	32.0	32.0	4.24	5.35	21%
11:00	35.0	35.0	60°	32.0	32.0	4.68	6.19	24%
12:00	36.0	36.0	50°	32.0	33.0	4.63	6.39	27%
13:00	36.0	37.0	60°	32.0	33.0	5.03	6.66	24%
14:00	36.0	37.0	60°	32.0	33.0	5.18	6.58	21%
15:00	36.0	37.0	60°	33.0	33.0	5.05	6.17	18%
16:00	36.0	37.0	60°	33.0	33.0	4.89	5.74	15%
17:00	36.0	36.0	65°	33.0	33.0	4.10	4.76	14%

Table 8. Room 3 (Upper East) August Average Cooling Load (kWh). (By Authors)

Time	Average radiant temperatures- °C	Average air temperatures- °C	Kinetic facade angle- Degree	Average radiant temperatures with kinetic façade- °C	Average air temperatures with kinetic façade- °C	Cooling loads for the room with kinetic façade - kWh	Cooling loads for the room with traditional façades- kWh	The reduction compared to kinetic facades with traditional façades- %
9:00	35.0	35.0	60°	32.0	32.0	4.30	5.51	22%
10:00	36.0	36.0	50°	32.0	33.0	4.72	6.60	28%
11:00	37.0	37.0	43°	23.0	33.0	5.27	7.83	33%
12:00	38.0	38.0	39°	33.0	33.0	5.21	8.02	35%
13:00	38.0	39.0	40°	33.0	33.0	5.60	8.19	31%
14:00	38.0	39.0	40°	33.0	34.0	5.81	7.93	27%
15:00	38.0	39.0	40°	33.0	34.0	5.63	7.14	17%
16:00	38.0	38.0	50°	34.0	34.0	5.48	6.40	14%
17:00	37.0	37.0	60°	34.0	34.0	4.69	5.39	13%

Table 9. Room 3 (Upper East) September Average Cooling Load (kWh). (By Authors)

Time	Average radiant temperatures- °C	Average air temperatures- °C	Kinetic facade angle- Degree	Average radiant temperatures with kinetic façade- °C	Average air temperatures with kinetic façade- °C	Cooling loads for the room with kinetic façade - kWh	Cooling loads for the room with traditional façades- kWh	Reduction compared to kinetic facades with traditional façades- %
9:00	35.0	35.0	60°	30.0	30.0	3.05	5.30	42%
10:00	36.0	37.0	43°	30.0	31.0	3.44	6.85	49%
11:00	38.0	38.0	39°	30.0	31.0	3.72	7.69	51%
12:00	38.0	39.0	34°	30.0	31.0	3.47	7.39	53%
13:00	39.0	39.0	40°	31.0	32.0	3.82	7.35	48%
14:00	39.0	39.0	40°	31.0	32.0	4.10	7.17	43%
15:00	39.0	39.0	40°	31.0	32.0	4.26	6.59	35%
16:00	38.0	38.0	50°	32.0	32.0	4.35	5.82	25%
17:00	37.0	37.0	60°	32.0	32.0	3.62	4.65	22%

Table 10. Room 3 (Upper East) October Average Cooling Load (kWh). (By Authors)

Time	Average radiant temperatures- °C	Average air temperatures - °C	Kinetic facade angle- Degree	Average radiant temperatures with kinetic façade - °C	Average air temperatures with kinetic façade - °C	Cooling loads for the room with kinetic façade - kWh	Cooling loads for the room with traditional façades- kWh	Reduction compared to kinetic facades with traditional façades- %
9:00	34.0	34.0	67°	27.0	27.5	2.16	4.89	56%
10:00	36.0	36.0	50°	27.0	27.8	2.23	6.03	63%
11:00	38.0	38.0	39°	27.0	28.0	2.42	7.33	66%
12:00	39.0	39.0	34°	26.0	27.0	2.38	7.54	68%
13:00	39.0	39.0	40°	28.0	28.9	2.63	7.29	64%
14:00	39.0	39.0	40°	28.0	29.0	2.65	6.25	57%
15:00	38.0	38.0	50°	28.0	29.4	2.73	5.32	48%
16:00	37.0	37.0	60°	29.0	29.6	2.84	4.58	38%
17:00	36.0	36.0	65°	29.0	28.9	2.48	3.81	35%

Table 11 explains comparing the consumption of the energy for the cooling load inside the space in two cases in four months (July, August, September, and October). Case1, the space includes a roof and three traditional façades. Case2, the space includes a roof and two traditional façades in the north and east direction, and also one kinetic facade with different angles according to time and solar temperature by using smart material. Result that the energy consumption for the cooling load inside the space has been different in four months (July, August, September, and October).

Table 11. Comparison of the energy consumed for the cooling load inside the space in the two cases. (By Authors)

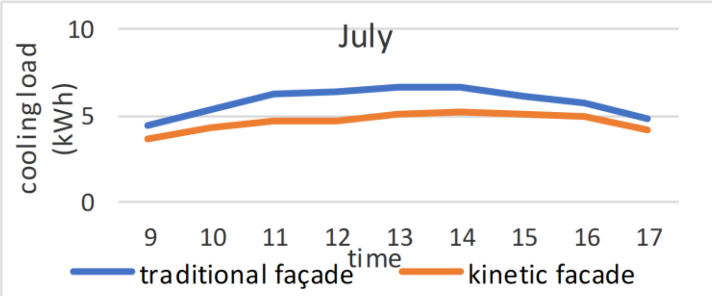
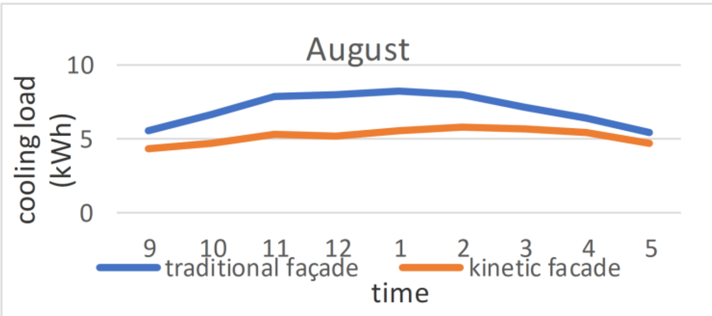
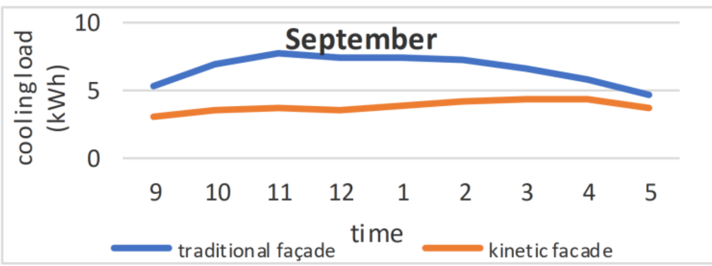
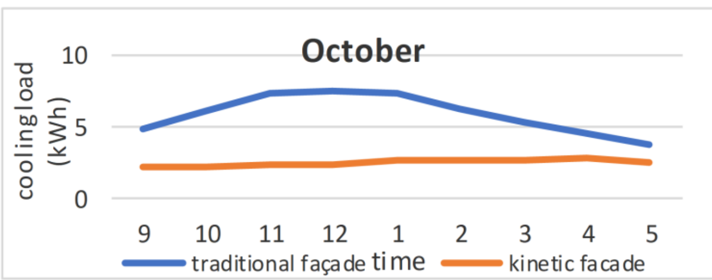
<table>
<tr><td>
</td><td>Case-1 total energy consumed for the cooling load inside the space is 52.24 kWh. While in case-2 total energy consumed for the cooling load inside the space is 41.5 kWh.</td></tr>
<tr><td>
</td><td>Case-1 total energy consumed for the cooling load inside the space is 63.01 kWh. While in case-2 total energy consumed for the cooling load inside the space is 46.71 kWh.</td></tr>
<tr><td>
</td><td>Case-1 total energy consumed for the cooling load inside the space is 58.81 kWh. While in case-2 total energy consumed for the cooling load inside the space is 33.83 kWh.</td></tr>
<tr><td>
</td><td>Case-1 total energy consumed for the cooling load inside the space is 53.04 kWh. While in case-2 total energy consumed for the cooling load inside the space is 22.52 kWh.</td></tr>
</table>

Table 12 compares the solar radiation temperature in the internal space in case of using traditional elevation and dynamic elevation in four months (July, august, September, and October). In July, the ratio of decrease in the solar radiation temperature in the internal space was 8.28%. In august, the ratio of decrease in the solar radiation temperature in the internal space was 11.8%. In September, the ratio of decrease in the solar radiation temperature in the internal space was 18.28%. In October, the ratio of decrease in the solar radiation temperature in the internal space was 25.62%. According to that the solar radiation temperature in the internal space in October was higher than in July.

Table 12. Comparison between the solar radiation temperature in the internal space in case of using traditional façade vs using dynamic façade. (By Authors)

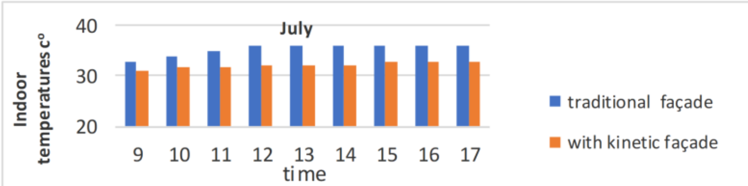
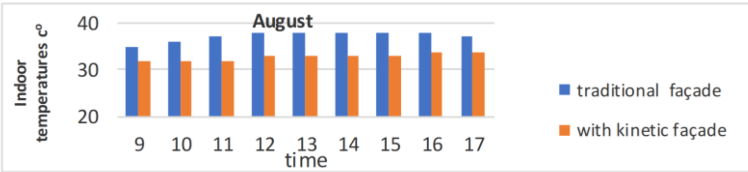
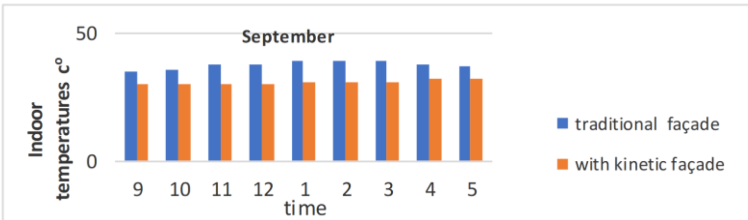
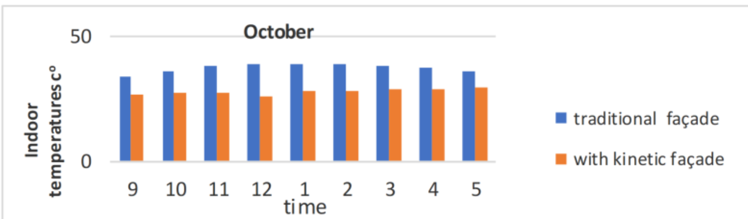
	The average solar radiation temperature in the internal space with the traditional elevation is 35°C and the average solar radiation temperature in the internal space with the dynamic elevation is 32.1°C.
	The average solar radiation temperature in the internal space with the traditional elevation is 37.2°C and the average solar radiation temperature in the internal space with the dynamic elevation is 32.8°C.
	The average solar radiation temperature in the internal space with the traditional elevation is 37.6°C and the average solar radiation temperature in the internal space with the dynamic elevation is 30.7°C.
	The average solar radiation temperature in the internal space with the traditional elevation is 37.3°C and the average solar radiation temperature in the internal space with the dynamic elevation is 27.7°C.

Figure 20 shows the average decrease in the energy consumption for the cooling load inside the space comparing the traditional facade with dynamic facade using smart material is 20.12% in July. The average decrease in the energy consumption for the cooling load inside the space compared to the traditional facade with dynamic facade using smart material is 24.52% in August. The average decrease in the energy consumption for the cooling load inside the space compared to the traditional facade with dynamic facade using smart material is 40.68% in September. The average decrease in the energy consumption for the cooling load inside the space compared to the traditional facade with dynamic facade using smart material is 55.09% in October. This suggests that the kinetic facades using Smart materials are effective in reducing building temperatures, leading to lower energy consumption and improved thermal comfort

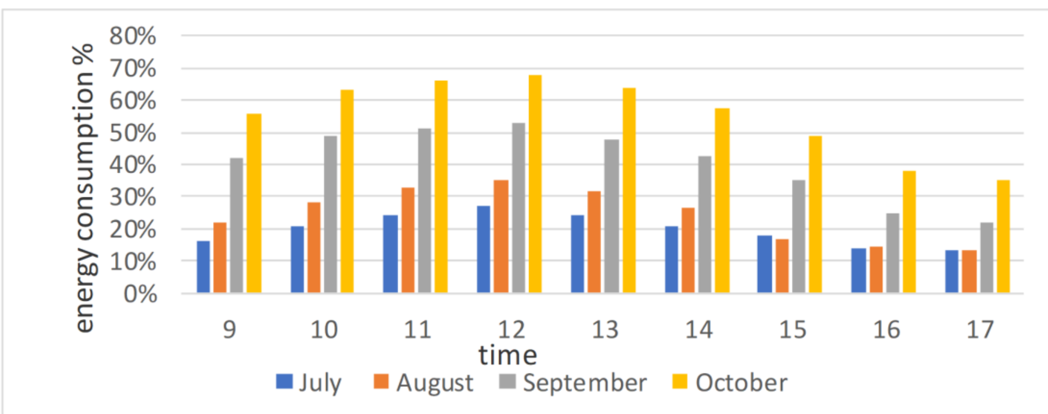


Figure 20. Reduction rate of energy consumption due to cooling load. (By Authors)

5. Conclusions

Nitinol is a smart material that exhibits unique behavior under different conditions. The use of nitinol in the design of a facade system that can open and close in response to changes in temperature demonstrates. This experimental study shows that the kinetic facade using smart materials can effectively improve the thermal performance of a building.

The length of nitinol increases with increasing load and decreases with increasing temperature .The Nitinol length decreased between 9:00 and 12:00 with a ratio of 28.43%. Also, the Nitinol length increased between 12:00 and 17:00 with a ratio of 35.56%. According to that, the minimum Nitinol length is 7.36cm at the peak hour of 12:00. Additionally, the maximum Nitinol length is 11.4cm at 17:00 o'clock.

The use of a 1:1 prototype allowed for the evaluation of the performance of the kinetic facade under real environmental conditions. The system is able to adapt to changing environmental conditions by adjusting the angle of the shutter to control the amount of solar radiation and ventilation entering the building. In the case of using Nitinol material in the kinetic façade, the shatter angle has decreased between 9:00 and 12:00 with a ratio of 31.4%. Also, the shatter angle has been increasing between 12:00 and 17:00 with a ratio of 36%. According to that, the minimum shatter angle is 56.6 ^{o} at the peak hour of 12:00. Additionally, the maximum of the shatter angle is 90^{o} at 17:00 o'clock. Finally, the shatter closes at the peak hour. By utilizing the parabolic trough solar collector, the facade can raise the temperature of nitinol, causing it to shrink and close, and when it reaches the stage of martensite, the facade can open again with the help of the tension spring.

In the case of a space that includes a roof and three traditional façades, the total energy consumed for the cooling load inside the space is the highest in August and the lowest in July. In the case of the space includes a roof and two traditional façades in the north and east direction, the total energy consumed for the cooling load inside the space is the highest in August and the lowest in October. In the case of comparing the solar radiation temperature in the internal space in the case of using traditional elevation and using dynamic elevation, the solar radiation temperature in the internal space in October was higher than in July. The dynamic facade was able to decrease the solar radiation temperature in the internal space by an average of 8.28% to 25.62% compared to the traditional facade. Moreover, the energy consumption for cooling load inside the space was reduced by an average of 20.12% to 55.09% in the four months studied (July to October).

In conclusion, the experimental study provides evidence that nitinol material can be used to create a dynamic facade that responds to changing environmental conditions, such as temperature and solar radiation. The proposed facade design has the potential to reduce energy consumption in buildings by controlling the amount of solar radiation that enters the building and providing shading during the hottest part of the day.

Further research is needed to optimize the design and control of kinetic facade systems using smart materials and long-term performance. Investigate their energy savings potential and user acceptance, analyze the cost-benefit ratio and scalability for real-world building projects, and explore integration with other building systems such as lighting and ventilation.

Nomenclature

SMA	Shape Memory Alloys	NiTi	Shape memory alloys (Nitinol)	BWh	Warm desert climate
kWh	kilowatt hour	SHGC	Solar Heat Gain Coefficient	VT	Visual transmittance
Δr	residual strain elongation of nitinol	Δ	deflection due to load	W	load
m2-k/w	meters squared Kelvin per Watt				

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