REPLACING DYNAMIC SHADING IN ARCHITECTURAL FACADES WITH SHAPE MEMORY ALLOYS (SMA) AS A NEW APPROACH IN SHADING SYSTEMS

MONA MOHAMED SALEH

ASSISTANT PROF IN THE DEPARTMENT OF ARCHITECTURE, THE HIGHER INSTITUTE OF ENGINEERING EL SHOROUK, EGYPT

EMAIL: DR_MONA.SALEH@YAHOO.COM.

ABSTRACT

The architectural facades play a major role in controlling energy consumption and how to efficiently used in the building. Recently, the adaptive buildings have become more feasible due to their efficient energy consumption and the rapid technological development. The building skins aim to control the transfer of heat to and from the building. With the advent of smart materials and their new properties, the architects have decided to incorporate such properties into the architectural engineering to benefit from them in new buildings.

This paper sheds light on the change of shading system strategy in the dynamic facades of buildings; as a material that responds to environmental influences and changes that occur outside the building, namely shape memory alloys (SMA), was chosen as a smart material that can be used to create a new shading system for architectural facades, an alternative to dynamic facades, and an energy saving system for the movement of such facades.

KEYWORDS: Adaptive Facade-Kinetic installations- Shape memory alloy (SMA)- Smart material - Sustainable design.

1. INTRODUCTION

Recently, various technological innovations have supported the sustainable design of the buildings so as to modify the indoor environment and mediate the outside conditions. Moreover, the outer envelope of building always plays the main role in such environmental control. The main functional task of facade is to keep the external environment away from the internal one in order to protect it against external the conditions such as rain, wind, or intense solar radiation. Thus, the different components shall be integrated in the façade to perform the environmental control applications.

Also, double skin facades were emerged to incorporate passive design strategies, such as: ventilation, glazing and shades. These systems were transformed to an active design equipped with sophisticated system of wiring and controls that include ventilation, thermal controllers and electricity generators. Therefore, the facade is transformed from a static, conventional state into a dynamic controller of the environment with the aim to reduce energy consumption. The adaptive facades are adaptable to environmental changes through their adjustable properties. This can be achieved, for example, by integrating sensors, actors and controller, in addition to regulating the amount of solar radiation or air passing through the adaptive facades. As a result, the energy demand can be reduced, but it is necessary to have ideas and mechanisms regarding the temperature and how it interacts with it in the adaptation process. Accordingly, the role of temperature in activating the dynamic shading device has been studied, as it turns on/off automatically under high and low temperatures. The research has focused on the development of a new concept of dynamic facades concerning smart materials; as the power required to move the shading panels on the dynamic facades is high-cost electrical one. Meanwhile, the building can be provided by smart materials to form new features capable to create movement on the facade without consuming energy; as the energy saving is strategic matter and may give the building a new architectural character. The smart materials can sense the environmental changes, or act according to them, in order to represent a new strategy in shading systems without consuming energy. Such materials can be emerged in the facade, especially memory alloys, to benefit from their smart properties and their interaction with the surrounding environment without the need for electrical energy. The shape-memory alloys (SMA) are classified as smart materials known to have two unique characteristics: The shape-memory effect is the ability of alloys to revert to their initial shape upon being heated until they enter their phase transformation temperature and super elasticity is where the alloys exhibit comparatively large recoverable strain. Hence, the use of smart materials on the façade can lead to have dynamic sustainable facades with no need to provide a source of energy for movement on the facade, which can be considered as a new direction towards the new energy saving strategies and reaching responsible shading systems.

2. **RESEARCH PROBLEM** The dynamic facades have become the latest trend of the era, but they consume much energy while reaching adaptability towards the surrounding environment in form of environmental control. At the same time, smart memory alloys are considered as smart materials that can be integrated into the facades of buildings as an alternative dynamic facade able to reduce the building's electricity consumption. In contrast, there isn't enough research about the efficiency of using such smart alloys, especially SMA, in the scope of sustainability.
3. **RESEARCH OBJECTIVE** The research aims to study the adaptive fabric facades by integrating the shape memory alloys (SMA) into the architecture as a new approach that produce a building adapted to the environment and save energy, as the solar shading of such alloys enhances the energy performance of building in the surrounding environment. The research also aims to enhance the large use of the application of this material on the facades of buildings; as the electricity is not necessary to adapt to the external environment. Furthermore, the application of this idea in smart buildings can cope with the strategies of sustainable cities.
4. **RESERCH METHODOLOGY This research is divided into three parts:**

First: Theoretical Framework It includes the definition of smart materials, how to be integrated with the architecture, how to be used in new architectural trends, definition of shape memory alloys and the grounds for selecting them as a dynamic tool used in shading parts of architectural buildings.

Second: Analytical Framework It shows examples of international architectural buildings that used shape memory alloys in their facades for the purpose of shading or controlling the quantity of light penetrating the building. **A building was displayed** BLOOM - DO|SU STUDIO AND COMPANY DECKER YOEADON and the cost of this material when used on part of the building was also studied, while their analyses and ways to maintain it in the future were identified.

Third: Deduction: The results of research indicate a new methodology in the process of dynamic shading of architectural facades in an energy-saving and non-electricity consuming manner, by using the Shape Memory Alloys as a smart material on the facades of architectural buildings.

5. **SMART MATERIALS IN ARCHITECTURE** The smart materials and structures can sense environmental acts, process sensory information, and then affect the environment. There are three primary material classes: metals, ceramics, polymers and composites, the last one being the combinations and variations of the three first ones. The smart materials are substances that receive, transport, or manipulate stimulus and response by producing a beneficial effect, which can be demonstrated by changing the color, resizing, changing the distribution of strains, or changing the refractive index. This ability to produce a beneficial effect is aimed to respond to incentives. Smart materials are considered as beneficial materials for architectural design as the buildings are always faced with changing conditions. Considering the properties of smart materials, it is found that they are directly focused on working acts, predictability, and the immediate response to environmental conditions **[1].**

5.1. RESPONSES IN MATERIALS

For the building to adapt to the environment, the architect should inspire his design from the behavior of natural organisms that adapt to, and integrate with, the environment. Thus, the designers seek to employ new building materials to improve, and adapt to, the sustainability of the environment. For example, if we look at the (rhododendron leaves) plant and identify its adaptation to the environmental changes and its response to the external stimuli, namely light and heat, we find that this plant has become a source of inspiration for engineers to use smart materials that work in the same way, adapting to the environment and its stimuli **[2].**

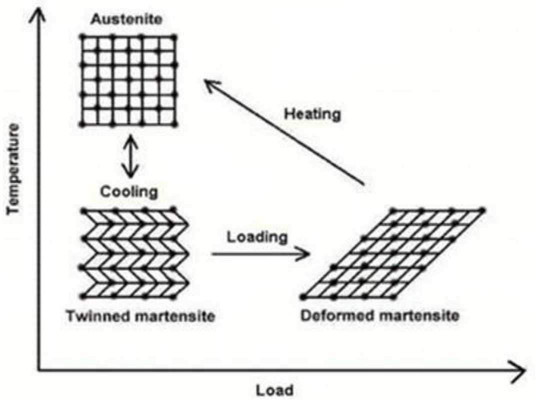
This wonderful plant is characterized by the movement of its leaves, which occurs under the changing temperature of the surrounding environment. Its margins wrap around the midrib and bend flexibly. This movement is considered as a part of its response to the environmental changes, then it returns to normal state again after the disappearance of external influence, which is the low temperature. The temperature here is the external stimulus of such plant. There are also smart materials that work in the same way and are changed based on the surrounding stimuli.

.

Figure (1) Shape of a plant (rhododendron leaves) when it twists due to the low temperature of external environment and returns to its original state under the normal temperature [3].

The temperature is the motivator of such smart materials, as, while exposing to different temperatures; the response depends on the molecule configuration in a material or the connections between different materials in a combined structure. As the heat of material can be increased, the atoms are excited by the heat energy. As a result of the absorption of such energy, its movement increases causing the material to expand. The magnitude of this expansion depends on the material's sensitivity to heat and its volumetric heat capacity. The heat can also trigger chemical reactions within the material transforming into new molecular configuration. This change within the material structure alters the properties of material and can be both permanent and temporary; recovering to the initial state as the temperature returns to the starting point. This smart material is a shape memory alloy (SMA) **[3].**

5.2. SHAPE MEMORY ALLOYS (S.M.A): The Shape Memory Alloys (SMAs) are one of the recent achievements in the world of metals and alloys and are called one of the coolest materials in materials science. An alloy is a mixture of two or more metals that keep the shape or the appearance. These alloys are unique due to their properties that differ from any other alloy or metal. What is distinctive about such alloys is their ability to return to their original shape when subjected to forming; (Formation is a permanent change in shape such as bending or twisting) under normal temperatures. These smart alloys return to their original shape by the effect of temperatures. For example, if a piece of wire made of a shape-memory alloy formed as a spiral and then heated, the wire will return to its original shape as a straight form, as these Shape memory alloys are generally composed of 55% nickel and 45% titanium. **[4].**



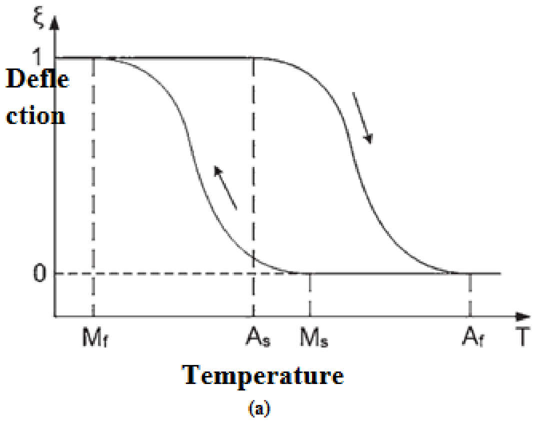
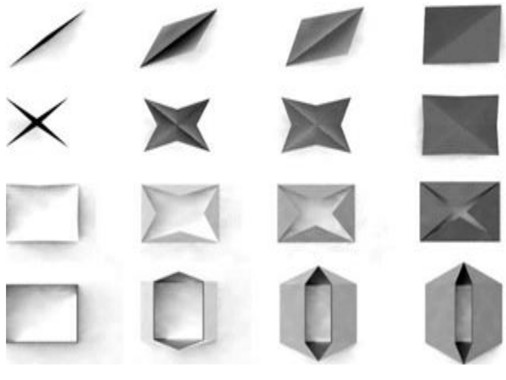


Figure (2) Temperature-induced phase transformation of an SMA without mechanical [5].

In general, the shape Memory alloys have many distinctive properties, such as: high ductility flexibility, oxidation resistance (rust), and good electrical conductivity. In metallurgy, the shape-memory alloy (SMA) is subject to be deformed if it gets cold, but it can return to its pre-deformed ("remembered") shape if re-heated. It can also be referred to as muscle wire, smart metal, smart alloy, memory metal, or memory alloy. **[5]**

5.2.1. Shading unit concepts in SMA: The shading unit is a simple geometric strip inspired by nature. They are interconnected with each other using paper models or computer simulations **[6].** These strips can be folded and unfolded in response to the external environmental influences. This spreading and folding movement results in a range of shading factors that control the passage of light and air through it **[7].**



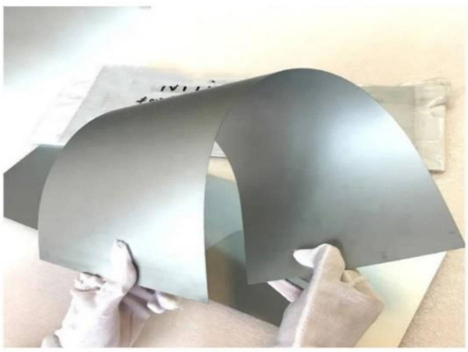


Figure (3) Shading unit concepts based on origami folding [7].

The (SMA) actuators are forged to operate in environmental temperature, allowing the shading system to respond to climate conditions. The proposed unit shape can be changed from the conventional shape to the modern one, which affects both the user's perception and the façade's form, regardless of the quantity of sunlight which penetrates the building. The shading system modules size can be related.

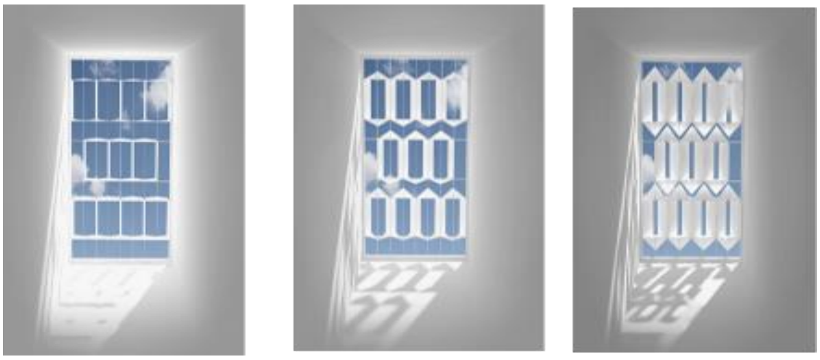


Figure (4) 3D renderings of the shading unit's transformation. [8]

To meet the sunlight needs of each space, which forms interesting patterns on the building's façade, a different folding shape offering a wide shading factor range were explored. **[8]** Thermo-bimetals are composite materials made of two alloys connected to each other. The laminated sheet coils in different directions when heated or cooled, predictably and repeatedly, without being degraded; as both metals expand at different speeds. The system is composed of of bimetal parts that are placed on a stainless-steel network grid and is intended to be sealed inside the cavity of an insulated glass unit. The individual bimetal bits shall be warmed up and start to curl as sunlight enters the window, flipping into a new orientation that shields the direct light. **[9]**

Large glass facades in office buildings need to be efficiently protected against the sun rays, which is sometimes designed to change its direction during the day, but common mechanical systems like electrical motors are not fully satisfied in architecture. The scientists are exclaiming if the material expansion or shrinkage can put sunshades into motion in reaction to a temperature change. The researchers aim to explore the potential of shape memory alloys (SMA) in building facade systems, especially in double glazing facades.

Figure (5) Adaptive facades act as smart materials (shape memory alloys) as a shading solution [10].

In such a way, the façade configuration can be kept smart as its regularity and its architectural shape will be maintained without adding any other systems that can make a load in its form. These materials shift and move according to the outside air temperature like a flower which opens for sunlight and closes its petals at night. The new high-tech smart materials (SMA) have allowed this idea to thrive and develop; as Ezio Manzini says in his book (The Material of Invention) that many smart materials are intrinsically linked to change and movement. The metals and plastics can be bent and deformed, but they quickly return to their original shape once heated **[10].**

6. APPLICATIONS OF SHAPE MEMORY ALLOYS (SMA) IN ARCHITECTURAL FIELDS:

6.1. BLOOM - DO|SU STUDIO ARCHITECTURE The structure (BLOOM) was designed by the architect (Doris Kim Sung), an engineer at the University of Southern California. She is specialized in biology, then became an architect, which has influenced her architectural design, as she was benefited from the adaptation of living things to the environment to create environmentally friendly designs. This structure is found at the Materials and Applications Expo in Los Angeles. It is composed of smart metal chips. These metal chips are assembled and fastened together with aluminum screws. These slices are characterized by their light weight and flexibility, and no slice of this structure is similar in properties and the extent of their influence by external influences. The structure is made up of 1,400 metal strips used as a shell for such structure. These smart mineral facts are characterized by the fact that they generate movements evolved from the movements of plants through the behavior of materials in thermal expansion and contraction. These metal sheets are winkled once exposed to the sun's heat, allowing air and light to pass into the building. Then, it regains its original form after the disappearance of the sun's rays, thus regulating the entry of heat and light into the building.(Doris Kim Sung) has conducted research on these slices to identify their characteristics and behavior under the sun, and to study the place, time, and temperature needed by each slice needs to wrinkle and perform its role in the shading process, and, thus, better regulate the temperature **[11].**

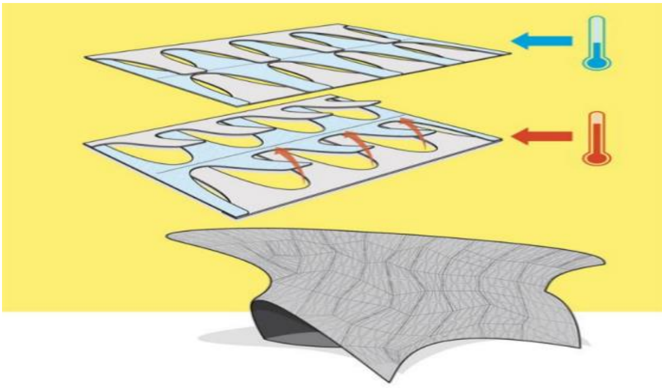


Figure (6) Two layers of metal that react differently to heat [11].

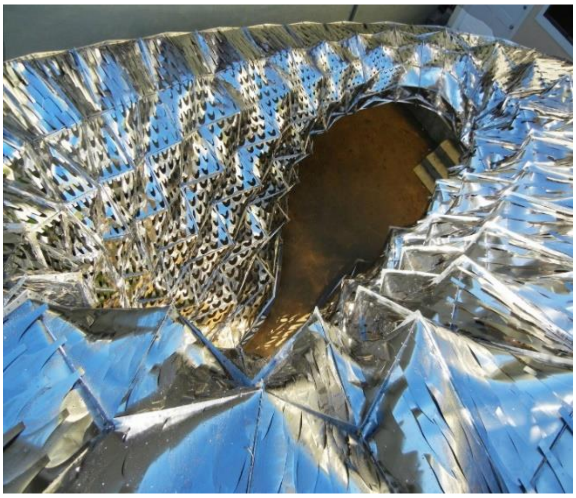


Figure (7) Self-regulating ventilation, proof of concept (Doris Kim Sung) [12].

7. COMPANY DECKER YOEADON -BIMETAL SYSTEMS

DECKER YOEADON Architectural Materials Technology Company in New York has designed a double-glazed facade system covered with smart metal. It can be closed and opened in response to the change of environment and temperature. The work's idea is inspired by the muscles of human body. The facades consist of two layers of glass equipped with smart metals between each other. A bimetal is a laminate of two different metals together (a manganese, nickel alloy and a darker manganese iron), which may be wrinkled based on the external environmental influences, thus working to control heat loss and save energy inside the building.

Once exposed to heat, the slats expand to form a shadow on the interior of the building. Once the temperature is decreased, such slats contract to allow the greatest amount of light to pass into the building. This process is called self-regulation and reduced energy consumption. This high degree of control is particularly beneficial to contemporary architecture, whose contemporary goal is to reduce energy consumption and associated emissions **[13].**

Figure (8) The difference between the shape of material when exposed, or not exposed, to high temperature and heat [13].

8. AVAILABILITY AND COST OF MEMORY ALLOYS IN THE GLOBAL MARKET:

The alloys are available in the form of sheets of different thicknesses ranging from .5 mm to .23 mm. These panels are sold and weighed by the ton. The Nickel Titanium Shape Memory Alloy (Nitinol Shape Memory Alloy) is a functional titanium alloy with shape memory effect. It may be deformed by force at a certain temperature. After the removal of external force, it still maintains the shape after deformation, but it can automatically regain the original shape before being deformed at a higher temperature. This phenomenon is known as the shape memory effect. The Titanium-Nickel Shape Memory Alloy Titanium and nickel is an intermetallic compound with equal atomic fraction (Ti50Ni50), and the practical composition of the alloy is Ti - (49-51) percent Ni (atomic fraction). The Titanium-Nickel metal composite is ductile and can be hot and cold, with a cold working rate of 10 percent to 25 percent and a recrystallization temperature of 500 to 600 degrees. The Titanium and Nickel Alloys have excellent corrosion resistance under the high temperature and good damping under the low temperature, while the unique memory properties and superior flexibility are existed in the phase change region. **[14].**

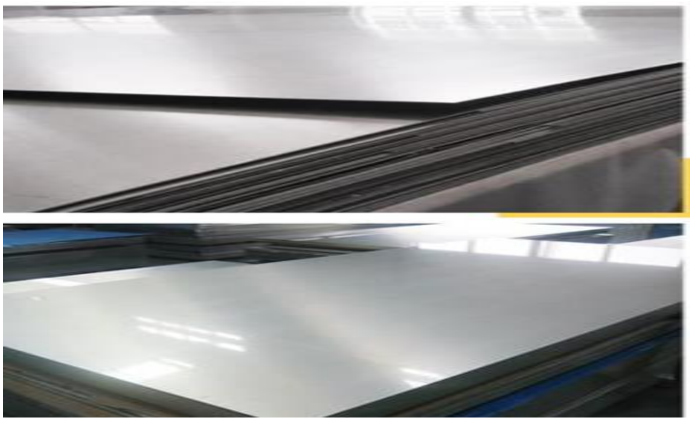


Figure (9) Cost of shape memory alloy boards in the market [14].

9. SMA alloys as cost efficiency: These panels are sold by weight as shown in the Alibaba website, as one kilogram of the panels is estimated at approximately 30- 100 dollars [15].

9.1. Maintenance of Shape Memory Actuator Systems:

These metals are of simple structure and the condition monitoring system must provide a device that measures the condition of the ingot and gives its state data. The aim is to develop a concept of maintenance in a way that guarantees the permanent functionality and efficiency. Then, the customer shall measure the SMA-AS resistance from time to time. The measured resistance shall be saved and compared with the initial resistance in order to identify the change of behavior, which is an indicator of the alloy's breakdown. A warning message is given.

The customer should send this message to the company's specialists to set an appointment for maintenance. The SMA ship shall be replaced or renewed according to the situation and the results of the measured resistance. As for the companies experienced in the SMA industry, they can predict the time needed by the alloys for fatigue and lack of sensing. Accordingly, A periodic maintenance schedule shall be set **[16]**. Every material has its specification label or catalogue shown in **table (1).**

9.1.1. Specification of Nitinol Material as SMA

Name	Nitinol
Category	Shape Memory Alloy
Expansion Rate	more than 20%
Alloys	NiTi, Cu NiTi, Fe NiTi
Types	Superplastic and Shape Memory Available
Description	The Nitinol is a special shape memory alloy whose plastic deformation can automatically regain its original shape at a certain temperature. Its damping characteristics are 10 times higher than that of ordinary springs, and its corrosion resistance is better than the best medical stainless steel. Thus, it can meet the needs of various engineering and medical applications. It is a very excellent functional material. In addition to its unique shape memory function, the memory alloy also has excellent characteristics such as wear resistance, corrosion resistance, high damping, and super elasticity. [**16**]

Table (1) Description Nitinol is a shape memory alloy.

9.2. Enhancing the life cycle behavior of shape memory alloy.

After the numerous research and support provided by the Center for Advanced Equipment, it was discovered that the behavior of SMA alloys can be improved, and their life cycle can be affected once the Mn is added to Cu-Al-Nie. The morphological, structural, and thermal characteristics were analyzed to determine the effect of manganese on the ductility of the alloys, but it was not determined. Distance. **[17]**

10. THE FUTURE VISION OF THE POSSIBILITIES AND RESULTS OF USING SHAPE MEMORY ALLOYS IN FACADE SHADING (SMA)

10.1. Adaptive technologies aim to create a sustainable natural environment and access to smart materials (memory alloys). They have increased the electricity saving rates; as it turns on or off automatically once exposed to high or low temperatures without using any electrical systems. This makes it the best solution to save electricity and also achieve cooling and heating for the interior spaces of buildings. However, the developments will not stop there; as the capacitors can also be placed on the facades exposed to high temperatures and covered with (SMA) with the aim to collect sunlight and convert it into electrical energy that serves the rest of the building, including the operating devices and others.

10.2. The scientists aim to evaluate the energy performance of the shading structure and to achieve a full- size model; as the shape memory can be integrated and the shading system actuators can eliminate power consumption and reduce the total cost.

10.3. Reducing the cost of shape memory materials in the future shall be considered; as this prototype aims to encourage the architects to be interested in the non-mechanical and seamless design, while experimenting the shape memory alloys.

10.4. Further optimization of the prototype can include exploring more shading aspects and the material of the structure and shape of the unit. The shading system shape can be analyzed with respect to the environmental factors, such as wind speed and the design improvement possibility.

10.5. A futuristic vision by replacing the dynamic & energy-consuming facades to operate and control the kinetic elements with smart sensing materials, in addition to highlighting and integrating (SMA) with the facades of architecture in sustainable cities to achieve the thermal balance and environmental adaptation.

10.6. Developing new strategy of shading (textile shading) using intelligent heat- sensitive materials.

10.7. There are additional factors regardless of the shading factor, such as: solar gain, incandescence and exploring the possibilities of incorporating passive or active solar systems that can increase the energy. The future project works may include optimization of the actuator by studying the shape potential of memory polymers. In such way, every building serves itself. If it is used in sustainable cities as well, the electricity can be saved.

10.8. Shape memory material can be used in countries that are exposed to high temperatures. Once this material is used to cover building facades, it can provide the appropriate climate and achieve the highest benefit of energy saving and material saving.

11. RESULTS AND CONCLUSION

In this research, a kinetic facade is proposed that is operated using shape memory alloys and aims to shade and improve the architectural and vital performance of architectural buildings without the need to electricity of energy source to activate this movement. It is resulted from the alloy’s sensing of the forest environment heat. Thus, such alloy’s sensing of the external environment and the control of passing light and air into the building results in the achievement of a sustainable facade with thermal climate changes.

The shape memory alloys represent an efficient dynamic shading that controls the amount of light and heat passing through the building and makes the building environmentally adaptable. They comply with the concept of the dynamic buildings especially the hyperbolic configurations; as, their panels can be formed in various sizes. At the same time, they need no electricity to motivate its workability as it works directly once exposed to temperature. This is considered as a new trend of a dynamic shading strategy using smart sensors for the surrounding environment in order to produce an environmentally adaptive and energy saving building. At the same time, it has an adequate cost and maintenance applications and can be enhanced by several additions capable of summarizing the shape memory alloy, as an efficient material in building shading systems.

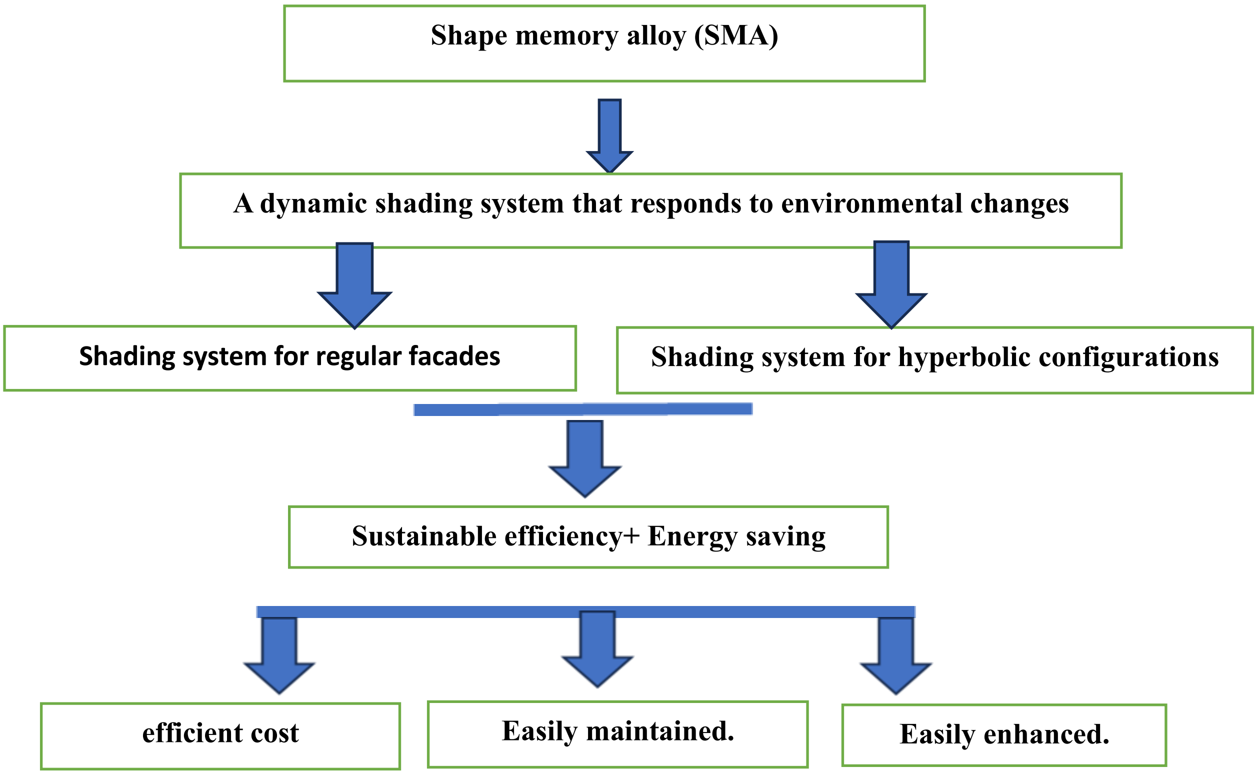


Figure (10) Diagram of the shape memory alloy as an efficient material in building shading systems.

12. REFERENCES

(1) Crano, John C. – Guglielmetti, Robert J., "Organic Photochromic and Thermochromic Compounds, Kluwer Academic Publishers, New York,2002.

(2) W. T. Sheikh and Q. Asghar, "Adaptive biomimetic facades: Enhancing energy efficiency of highly glazed buildings," Frontiers of Architectural Research, vol. 8, no. 3, pp. 319–331, Sep. 2019, doi: 10.1016/j.foar.2019.06.001.

(3) H. Wang, E. T. Nilsen, and M. Upmanyu, "Mechanical basis for thermonastic movements of cold-hardy Rhododendron leaves," J R Soc Interface, vol. 17, no. 164, Mar. 2020, doi: 10.1098/rsif.2019.0751.

(4) http://olom.info/forum/index.php?topic=17432.0

(5) Cederstrom, J., Van Humbeeck, J. "Relationship Between Shape Memory Material Properties and Applications", (1995).

(6) M. Addington and D. Shodek., "Smart Materials and New Technologies for Architecture and Design Professions", Architectural Press, 2005, pp. 105-107.

(7) https://www.researchgate.net/figure/Shading-unit-concepts-based-on-origami-folding_fig2_280708390

(8) Paper of Adaptive Textile Facades Through the Integration of Shape Memory Alloy

(9) https://www.architectmagazine.com/awards/r-d-awards/award-invert-self-shading-windows-flip-energy-efficiency-on-its-head_o

(10) https://priedemann.net/en/projects/project_db/adaptex.html

(11) https://www.archdaily.com/tag/decker-yeadon

(12) https://www.architectmagazine.com/awards/r-d-awards/2012-r-d-awards-honorable-mention-bloom_o

(13) https://www.anthropocenemagazine.org/conservation/2013/03/homeostatic-building-facade/

(14) https://ar.bjplftitanium.com/nitinol-sheet/nitinol-shape-memory-alloy-sma-plate/nickel-titanium-shape-me9mory-alloy-plate-and.html

(15) https://www.alibaba.com/product-detail/Superelastic-NiTi-Two-way-Shape-Memory_1600696483657.html?spm=a2700.7735675.0.0.44e530eePiimmV&s=p

(16) Maintenance of Shape Memory Actuator Systems - Applications, Processes and Business Models, ScienceDirect, 2015, Pages 84-89

(17) Enhancing the life cycle behavior of Cu-Al-Ni shape memory alloy bimorph by Mn addition, ScienceDirect