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The Usage of Shape Memory Alloys and Shape Memory Polymers in Architecture

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1. Introduction

Smart materials have become a type of material that attracts attention in the field of architecture with the development of technology nowadays. These materials, which have many advantages, allow the construction of more functional, aesthetic and sustainable structures by using them in different areas of architectural design. Shape memory alloys (SMA) and shape memory polymers (SMP), which are frequently used in the architectural construction process in recent years, are also among the smart materials. Shape memory alloys are particularly obtained from metals such as nickel and titanium. These materials can return to their original shape when heated or subjected to stress. Thanks to this feature, it allows the structural elements easily adapt to environmental conditions such as temperature and mechanical effects. Shape memory polymers are a type of thermoplastic polymer. These materials can be deformed when heated or exposed to an environmental effect and return to their original shape when cooled. Due to its aforementioned features, it provides ease of application to architects with the possibility of usage in various areas such as building envelopes and roofs.

In this study prepared with a focus on the mentioned subjects, the usage areas of shape memory alloys and shape memory polymers, which are among the smart material types, in architectural applications were examined. In the study conducted using a literature-based analysis method, a conceptual framework regarding the topics of "smart materials", "shape memory alloys" and "shape memory polymers" was analyzed through readings conducted on literature. First, the emergence process, properties and classification of smart materials are explained. The nature of shape memory smart materials and the discovery phase are briefly mentioned. Then, shape memory alloys and shape memory polymers are discussed, respectively. The properties of these smart materials have been investigated and their usage in architecture has been examined through examples. In line with the findings obtained, the necessary syntheses were made, and the scientific outputs of the study were created. Finally, the study was completed by turning the research outputs into conclusions.

2. Smart Materials

The concept of smart material used in the field of architecture expresses an understanding of material that adapts to the environmental conditions by reacting to the stimuli in the environment instead of struggling with the conditions surrounding a building. In this approach, "smartness" encompass the appropriate design of building elements or components using smart materials (Addington & Schodek, 2005; Yağlı, 2019). Brownell (2006), on the other hand, defined smart materials as materials that can be physically transformed based on environmental stimuli. This concept includes a sequential relationship from materials to technologies and environments. In other words, there is a process that starts with the usage of smart materials, and this process progresses to technological developments and environmental factors (Albayrak, 2020).

2.1. The Emergence Process of Smart Materials

The progress of humanity has led to changes in the usage of building materials. While these changes took place slowly until the Industrial Revolution, they accelerated significantly after this period. In previous eras, simple conditions such as functionality and accessibility were the primary considerations in material selection, but with the Industrial Revolution, these criteria came to the forefront as structural and aesthetic changes in architecture. Nowadays, the advancement of technology has combined both the change in material diversity and properties and the desire for flexible and environmentally compatible building design to contribute to architectural design (Sevinç, 2023).

The history of smart materials goes back about 65 years. However, its applications in architecture, engineering and commercial fields can be considered a new trend. Interest in smart materials began in the late 19th century. Following the discovery of the fascinating properties of natural materials like quartz and Rochelle salt by the Curie siblings, it continued with Donald Stookey's invention of a product known as "Corning glass" in the early 1960s. The glass that Stookey discovered was light sensitive, darkening when exposed to light and reverting to its original state when the exposure ended. By the 1970s, National

Aeronautics and Space Administration (NASA) began researching materials that could predict potential faults, fatigue, or overvoltages that may occur in structural materials (Geiser & Commoner, 2001; Leo, 2007).

The concept of responsive architecture was first put forward by architect Negroponte in 1970. This concept was initially based on the idea of integrating sensors within the building, which would gather external stimuli and be evaluated by computers, allowing the building elements such as the shell and structure to respond through integrated movement mechanisms. However, with the usage of smart materials, it has become possible to produce structures in which smart materials are used as sensors and/or actuators without the need for computers (Negroponte, 1970). One of the first examples of responsive architecture is the Institut du Monde Arabe, designed by Jean Nouvel in Paris in 1987. In the facade of the building, a dynamic and adaptable cladding material has been used. This facade, through an automated system that adjusts based on the amount of light, contracts and expands to prevent excessive heating in the interior and contributes to controlling the impact of heat (Yağlı, 2019) (Figure 1).

Figure 1. Facade and mechanical diaphragm detail of Institut du Monde Arabe Building (Peutz, 2023; Winstanley, 2011)

2.2. Properties of Smart Materials

A class of materials known as "smart materials" stands out from conventional materials due to their unique dynamic properties. These materials have the ability to exchange energy, change their properties, change in different sizes and positions, and recycle, as well as respond to environmental factors by perceiving them. Even at the molecular level, one may witness these properties of smart materials. But, as can be seen in examples such as the expansion of metals with temperature or the reaction of wood to moisture, materials that are not included in the smart materials group may also contain some of these abilities. There are specific properties that are present in all smart materials that can be used to identify them as such (Ürkmez, 2019).

Smart materials are described as having directness, immediacy, selectivity, self-actuation and transiency by Addington and Schodek (2005). The material can be referred to as smart if it possesses all of these qualities; otherwise, this label cannot be used. Immediacy necessitates a real-time response from smart materials, which makes them temporal. They frequently switch between states or instantly transform energy. They are transient, which means they can alter in response to shifting environmental factors. The changes brought about by various environmental states must be reproducible and reversible to be considered direct. Selectivity is the ability to respond subtly to environmental changes and to be dependable in order to manage unpredictability. Self-actuation refers to a substance that activates itself based on its own molecular programming, composition, assembly, or chemical qualities (Addington & Schodek, 2005; Ürkmez, 2019).

According to Newnham and Ruschau (1998), the most important property of smart materials is the ability to remember. Shape memory materials are an exemplary type of this. When subjected to an external load, these materials can deform greatly, yet when the load is removed, they regain their previous shape. Shape memory materials have the ability to perceive and respond quickly and repeatedly (Newnham & Ruschau, 1998).

2.3. Classification of Smart Materials

Classification of smart materials has been done in studies prepared by Addington and Schodek (2005), Ritter (2007) ve Casini (2016). Addington and Schodek (2005) divided smart materials into two groups, Type 1 and Type 2 (Figure 2). Type 1 materials are those that are self-regulating and can modify their optical, chemical, magnetic, electrical, mechanical or thermal properties in response to a change in the environment. Materials with these properties are called “property-changing smart materials”. Materials belonging to the type 2 group are those that change energy from one form to another in order to arrive at the desired outcome. Materials exhibiting this behavior are called "energy-exchanger smart materials" (Addington & Schodek, 2005; Topal & Arpacıoğlu, 2020).

Ritter (2007), on the other hand, classified smart materials into three categories: those that change property-changing, those that energy-exchanger, and those that matter-exchanger (Figure 3). In this classification, materials that quality-changing are divided into sub-headings as materials that color and optics changing, adhesion modifying and shape shifting materials. In the subtitle of smart materials that energy- exchanger, there are materials that light emitting, electricity generating and phase changing materials (Ritter, 2007; Sevinç, 2023).

Casini (2016) also analyzed smart materials in three categories as those that property-changing, energy-exchanger and energy-exchanger bidirectionally (Figure 4). While making classification, he defined factors such as light, temperature, chemical, magnetic field, electric field, UV light, pressure, as trigger factors for smart materials (Albayrak, 2020; Casini, 2016).

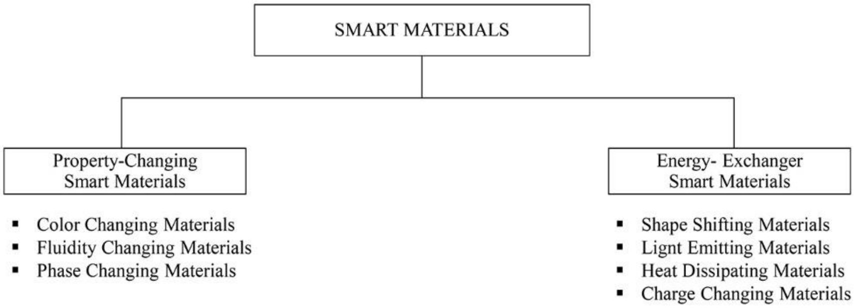

Figure 2. Classification of smart material (Edited using the Addington & Schodek, 2005; Casini, 2016; Ritter, 2007 sources.)

Within the scope of the study, shape shifting materials, which are in the energy-changing smart materials category, will be emphasized.

2.4. Shape Memory Smart Materials

Shape memory materials are a group of materials included in the group of shape-shifting materials. This family of materials known as "shape memory materials" are capable of returning to their original shapes after being momentarily deformed by an external stimulus. Any stimuli, including changes in the environment's temperature, electric current, magnetic field, pH, UV radiation, or certain compounds, might cause shape recovery. Gold-cadmium (Au-Cd) alloy materials were the first to exhibit the shape memory effect in 1932 and 1951, followed by brass (copper-zinc) alloy materials in 1938. At the US Naval War Research Laboratory, Buehler et al. discovered the nickel-titanium (NiTi) alloy in 1962, which contributed to the advancement of the shape memory effect (Addington & Schodek, 2005; Bedeloğlu, 2011) (Figure 3).

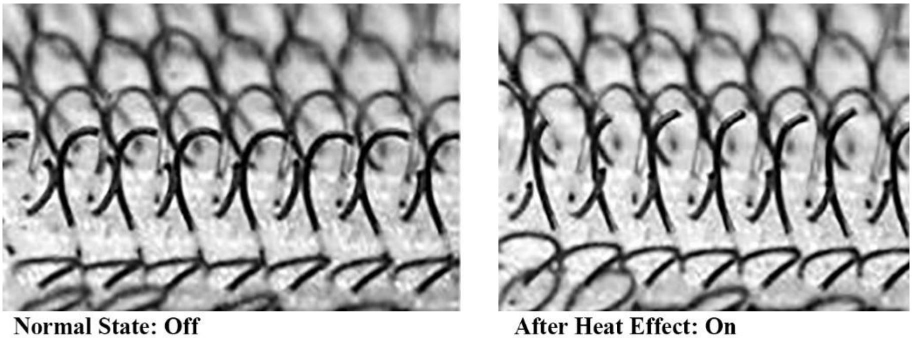

Figure 3. Changing shapes of Ni-Ti alloy hooks with excitation (Ritter, 2007)

Shape memory materials can be classified as organic or inorganic based on their components. Organic shape memory materials include polymers and gels. Inorganic shape memory materials include metal alloys, ceramics and glasses. Shape memory alloys and polymers are among the most widely usage materials. These materials can sometimes be used together because of their properties (Bedeloğlu, 2011; Sevinç, 2023).

3. Shape Memory Alloys (SMA)

Shape memory alloy (SMA) is defined as group of alloys that, when heated, can transform back into a certain shape or dimension. Shape memory alloys can be easily deformed to a new shape in the martensitic state. However, the alloy has the property of remembering its previous shape when heated above its austenite transformation temperature. Cu-based SHAs (CuAlNi, CuZnAl), Ni-Ti (also known as 'Nitinol') SHAs, iron-based SMA (FeMn) can be given as examples of SMA. Among all these shape memory alloys, Ni-Ti based alloys are widely used due to their excellent mechanical properties, flexibility, high deformation recovery ability, corrosion resistance and biological compatibility (Kurt & Orhan, 2003; Yi et al., 2020).

3.1. Properties of SMA

The main features of SMA are that they can have different crystal structures and shapes above and below certain temperature values. Although a material is deformed at low temperatures (martensitic), it can revert to its pre-deformation shape at higher temperatures (austenitic) because of the effect of temperature change on the material's internal structure (Albayrak, 2020; Ritter, 2007) (Figure 4).

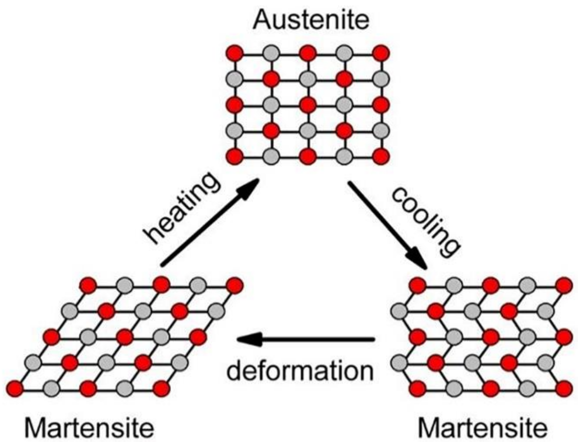

Figure 4. Transformation of SMA's Structure (Ürkmez, 2019)

Shape memory effect has two different types, unidirectional and bidirectional. Alloys with a one-way shape memory effect remember their shape only when heated. However, duplex alloys can remember their shape at high and low temperatures, meaning they can also regain their shape when cooled. However, bidirectional shape memory alloys are not commercially common because they require special training, and they tend to degrade, especially at high temperatures. For this reason, one-way SMA accepts more economical and considered safer (Auricchio, Marfia, & Sacco, 2003; Costanza, Tata, & Calisti, 2010; Stöckel, 1995; Ürkmez, 2019; W & Toh, 2000).

SMA have superelasticity. These features contribute positively to their ability to return to their original form after the applied load is removed (Ergin & Girgin, 2019).

The process of forming the memory alloy is called "programming" and is performed as long as heat is used to determine the shape. Materials usually have a programming temperature of 500°C, which is below the melting point, but can vary depending on the composition of the material. Heating treatments of SMA can be done by two common methods. The first is inductive heating. In this method, heating is carried out using the heat supply. The second method is resistive heating. In this technique, heating is carried out using electricity (Ürkmez, 2019).

The deformation of shape memory alloys varies depending on many factors. For example, the alloy composition and prior heat treatments affect the phase changeover temperature. The properties of the components and the proportions of the components can cause critical differences in behavior. In addition, the shape and thickness of the material are among the factors affecting the deformation. For example, a thick material may have a high activation force. However, as the thickness increases, the resistance decreases accordingly and the power consumption for activation increases (Ürkmez, 2019).

The useful life of shape memory alloys is about 30 years. The size and processing of these materials has a decisive influence on cost. It is quite costly compared to other building materials. Cost reduction is considered an important criterion for large-scale designs (Ayvaz, 2019). SMA are used in many fields including aerospace, robotics, automotive industries, medical instruments, bioengineering, optometry, dentistry, pharmaceuticals, construction industries and engines. In the construction industry, it can be applied to plastic, metal, ceramic, glass, gel, film surfaces as a surface, and to flooring, roof and wall as a building element (Ayvaz, 2019; Çakmak & Kaya, 2017).

3.2. SMA Applications in Architecture

The reason why SMA are preferred in architecture is their low activation energy and their ability to respond directly to changing conditions. Three of the samples used shape memory alloys in architectural structures have examined.

- *Iconic SKIN:* The SKIN project is structured on a network of implanted muscle fibers that change shape when an electric current pass through them. It consists of small-scale prototypes of an adaptable kinetic surface capable of spatial modulation and responsiveness to environmental stimuli (Ergin & Girgin, 2019) (Figure 5).

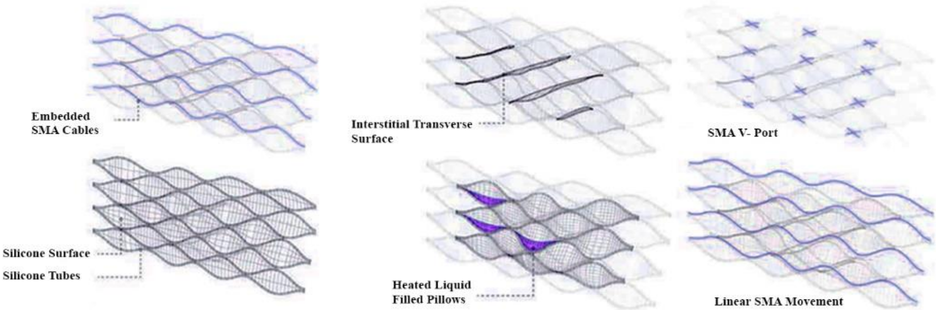

Figure 5. Detail representations of SMA used in the project (Ergin & Girgin, 2019)

Wire mesh provides surface transformations with smooth and muscle-like movements. Within the composite construction, the material system generated around the wire mesh modifies its thickness, stiffness, or permeability. Variability in the material system produces different behavior within the surface regions; it modifies the movement's speed and range, alters the transparency of the surface, and enables additional levels of performance, such as the ability to trap and release heat produced by the muscle fiber within the surface regions (Ergin & Girgin, 2019) (Figure 6).

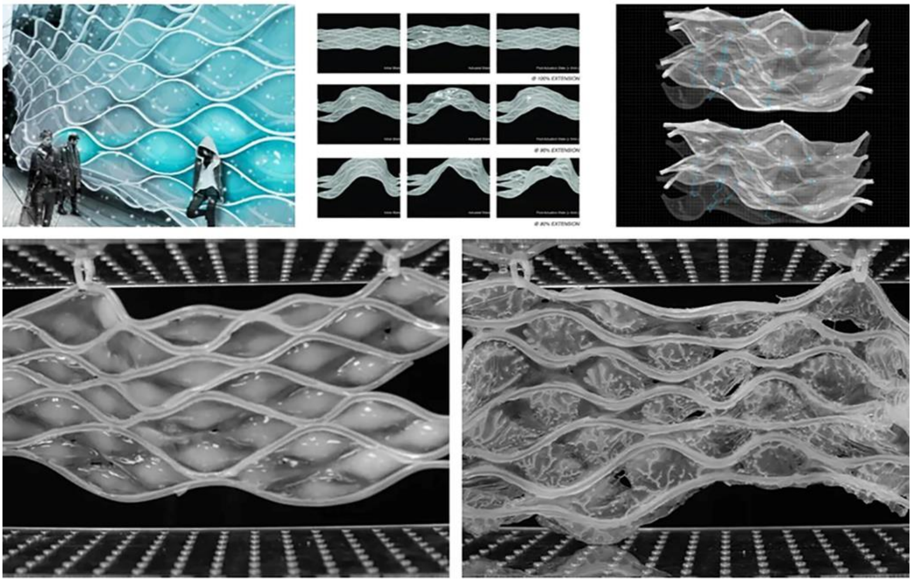

Figure 6. Changes in velocity, degree, and surface rigidity and transparency of movement (Ergin & Girgin, 2019)

- *Basilica of San Francesco:* The structure, which was built in Italy in 1253, was restored after it suffered great damage in the 1997 earthquake (Figure 7). While the building was being restored, shape memory alloys were used on the roof. SMA component was used to split and then reattach the sloping wall at the edge of the roof. Superelastic shape memory alloys are utilized in the connection between the roof and the wall to lessen the seismic forces transmitted to the vault. Distinct horizontal forces cause the shape memory alloy device to exhibit distinct structural characteristics. To prevent collapse under heavy horizontal stresses, the shape memory alloy's hardness rises (Ayvaz, 2019; Castellano, Indirli & Martelli, 2001) (Figure 7).

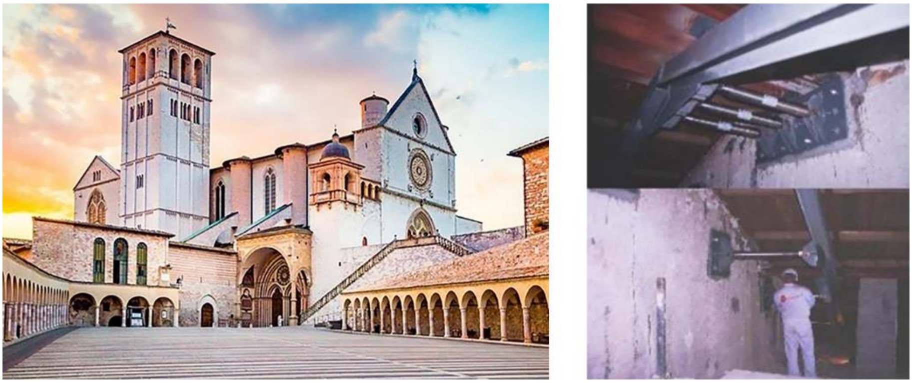

Figure 7. The Basilica of San Francesco and the usage of SMA on the roof (Castellano et al., 2001; Ytur, 2023)

- *The Air Flow(er):* The Air Flower project was designed by LIFT Architecture. The project was inspired by the thermonastic response of the Yellow Crocus plant in nature (Figure 8). The dynamic response of plant structure to temperature variations is known as thermonasty (Lift, 2023).

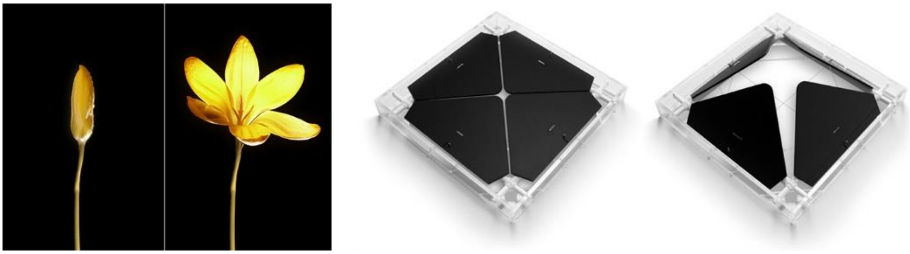

Figure 8. Behavior of yellow crocus against heat and its prototype (Lift, 2023)

In the project, it is aimed to keep the indoor quality in balance by providing indoor and outdoor air flow through shape memory alloy wires without the need for a power source. Accordingly, a thermally active ventilation system was established (Lift, 2023) (Figure 9).

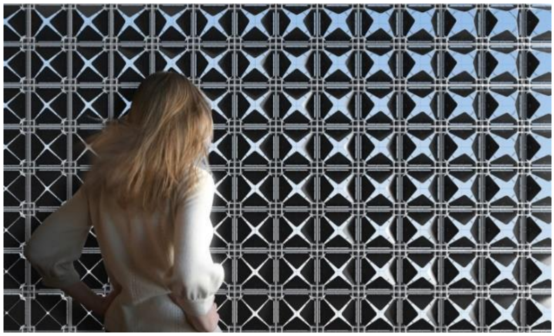

Figure 9. A double or single skin facade system of air flow(er) (Lift, 2023)

The temperature of the prototype is brought to approximately 65°C (150°F) using a heat gun. With this effect, the wires are shortened, and the panels widen, opening up like a yellow crocus plant. As the temperature decreases, the wires begin to expand, and each panel slowly returns to its closed position (Ergin & Girgin, 2019) (Figure 10).

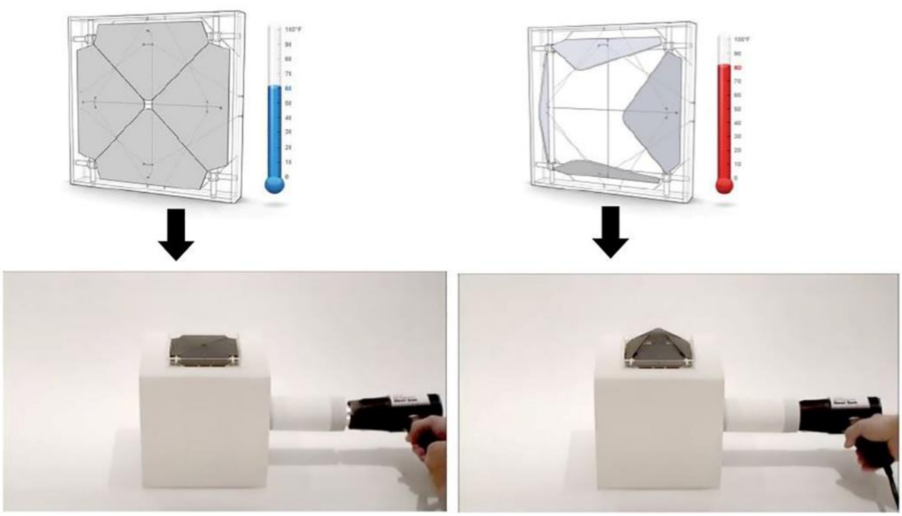

Figure 10. The experiment of opening the panel by shortening the SMA wires with increasing temperature (Edited using the Lift, 2023 source.)

4. Shape Memory Polymers (SMP)

Shape memory polymers (SMP) are a class of active polymers with the ability to have dual shape properties. They are smart polymeric materials that can revert from their deformed temporary shape to their original and permanent shape when triggered by an external stimulus such as chemicals, pH level, temperature, after being converted to SMP (Figure 11). There are two important factors for obtaining shape memory of a polymer. One of these factors is that it has a stable and stable structure. The other is that it changes shape when stimulated by environmental factors and returns to its original state when the stimulation is over. Although SMP has a memory feature like SMA, it has a completely different mechanism (Ege, Surmen, & Güneş, 2019; Tür, 2020).

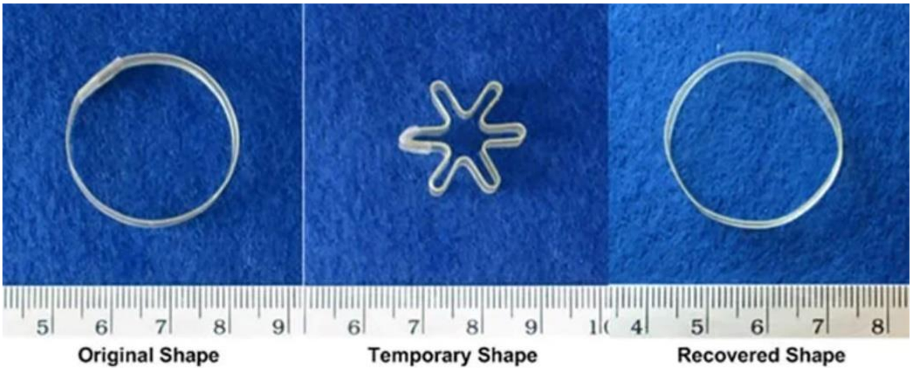

Figure 11. Shape memory polymers (Huang, 2012)

4.1. Properties of SMP

Shape memory polymers have been widely used in recent years with their wide range of shape recovery temperatures, easy processability and high recoverability. In addition to these, they also have properties such as high elastic deformation, low density, low cost, biodegradability and biocompatibility. However, despite such good extensibility and shape memory, voltage and load memory are low. In these cases, Shape Memory Polymer Composites are produced by increasing the stress and load strengths with the help of composites (Memiş & Kaplan, 2018; Mib, 2020).

Heat sensitive SMP has high elastic deformation ability and its elastic modulus differs above and below the Glass Transition Temperature (Tg). When the SMP is heated from a low temperature to a temperature above Tg without an external force, it exhibits the ability to recover its original shape by removing the stress (Hu, Meng, Li, & Ibekwe, 2012). According to the structure of the fixed points formed by intermolecular forces and/or covalent bonds, they are divided into two groups as chemically crosslinked SMP and physically crosslinked SMP. Chemically crosslinked SMP is also called "Thermoset SMP", while physically crosslinked SMP is also known "Thermoplastic SMP" (Leng, Lan, Liu, & Du, 2011).

SMP is a polymer class that has emerged with applications covering various areas of daily life. Among the applications of SMP are selfopening solar sails on spacecraft, self-destructing mobile phones, heat-shrinkable tubes for electronics or packaging, smart medical devices, or implants for minimal surgery. It is also possible to benefit from shape memory polymers in products such as foil, tube and cable. In addition, the usage of SMP is also found in various art applications (Behl & Lendlein, 2007; Mib, 2020).

4.2. SMP Applications in Architecture

The reason why SMP is preferred in architecture is that it can easily respond to environmental conditions. It is generally used in buildings built in the kinetic architectural style, which is a design concept that means "moving architecture" in the literature and can realize flexible design approaches (Zuk & Clark, 1970). Two of the samples used shape memory polymers in architectural structures have examined.

- *BalnaeNY:* It was designed by American designer Bryan Boyer in 2003 as a fun bathroom in New York's Soho neighborhood. SMP is used in BalnaeNY to enrich users' experience. It is aimed to make the activities carried out in a certain built area enjoyable through the deformable walls and floors in the project. Boyer proposed a sensor and actuator system that would provide a dynamic response to the various activities taking place during a day at BalnaeNY (Ritter, 2007; Yağlı, 2019) (Figure 12).

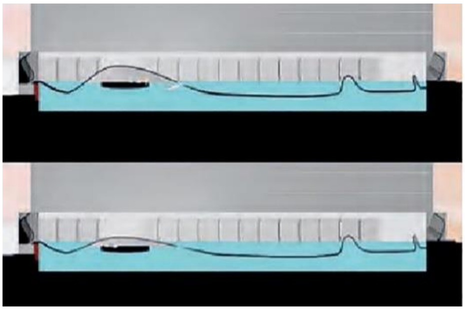
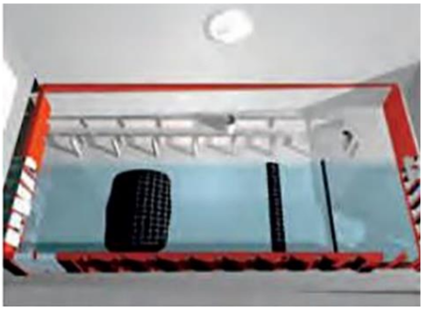

Figure 12. Section and perspective view of the pool (Ritter, 2007)

Electromagnetic radiation produced by humans is collected by electroactive polymers and converted into moving spatial changes. This material is integrated into the areas near the water level of the pool, the walls of the shower enclosures and the façade, the intermediate synthetic rubber floor. To give an example, depending on the time of day, the part where the SMP is located takes the form of waves, rising or falling on the surface of the water, thus creating an appearance as if it were a cave entrance. Shower walls can spiral into a shape to provide privacy or take another shape to function as splash guards. SMP has also been used on the walls forming the sides of the pool, and depending on the activities, they can turn into niches of various sizes. These niches can also be used as individual sauna areas. Niches can be projected onto the street from different angles, allowing them to be seen outside the building if desired (Ritter, 2007; Sevinç, 2023) (Figure 13).

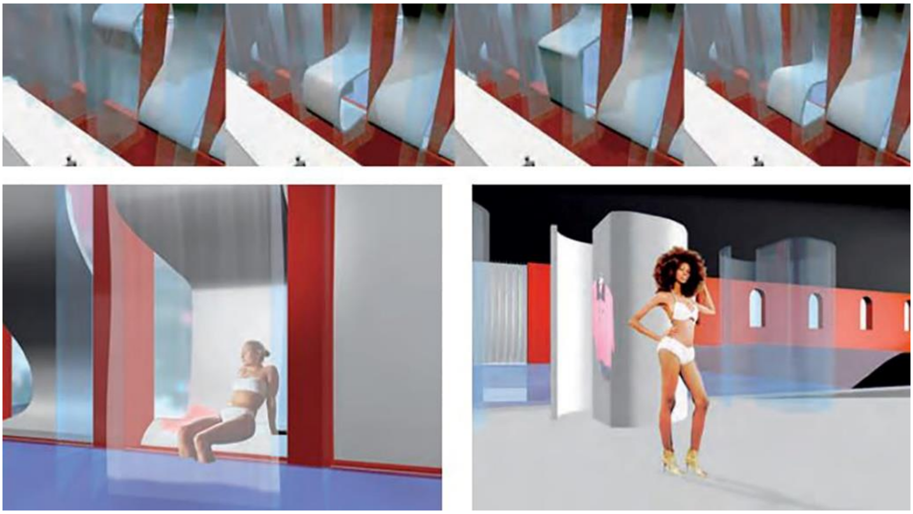

Figure 13. Kinetic wall surfaces made of SMP trips at BalnaeNY (Ritter, 2007)

- *Media-TIC:* Media-TIC was designed by Cloud 9 Architecture Office in Barcelona, Spain, under the leadership of Enric Ruiz Geli (Figure 14). Energy efficiency in the building and SMP are used in the exterior cladding. The facade consists of a building shell with kinetic character based on swelling and deflation (Arkitektuel, 2023).

Figure 14. Media-TIC (Ruiz-Geli, 2023)

The purpose of the SMP used on the facade of the building is to keep the heat and solar energy under control. While these smart materials absorb solar energy in hot weather, they release this energy in cool weather. In this way, the temperature in the interior is balanced. In addition, energy efficiency increases. SMP is also used in the movable partitions designed indoors. Responding to temperature or an environmental stimulus, polymers change shape, separating or joining segments (Arkitektuel, 2023) (Figure 15).

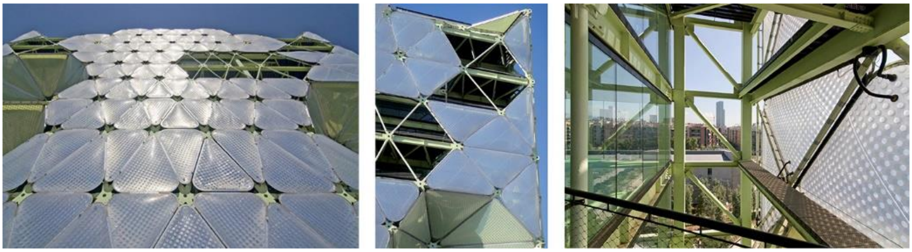

Figure 15. Facade of media-TIC (Ruiz-Geli, 2023)

5. Conclusion and Suggestions

With smart materials, building elements that are suitable for their function and capable of energy conversion can be created. In this way, it is possible to produce structures that have an increased lifespan, support environmental quality, improve energy performance, and occupancy comfort by control daylight and glare. In addition, it contributes positively to the safety and durability of the structure by providing static stress control. SMA and SMP, which are smart material types, have started to attract great attention in the field of architecture in recent years. The structural properties of these materials offer many new opportunities in architectural designs.

SMA has the potential to be applied in many points, from facade design in different forms to the control of air and light permeability from the facade. Having the ability to deform, SMA is used in the creation of movable and dynamic facade elements. Thanks to the panels used in the buildings and produced by making usage of SMA, energy efficiency can be increased by reacting to sunlight and external weather conditions.

SMP, on the other hand, can change shape or return to a predetermined shape by being activated by external factors such as heat and light. Thanks to this feature of polymers, it provides an innovative approach to designers in the field of architecture in various applications such as solar panels or adaptive roof systems. Thanks to the SMP used in the buildings, energy efficiency can be increased by storing solar energy.

The usage of these materials in architecture not only provides energy efficiency in buildings, but also makes a different and positive contribution in terms of aesthetics. It is among the other advantages that their use on the facade contributes to the sustainable building design, as well as having a positive effect on lighting and glare performance. With the effect of developing technology, as the building sector becomes familiar with systems based on smart materials in the coming years, the application area of SMA and SMP in architecture will also become widespread.

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The book section complies with national and international research and publication ethics.

Ethics committee approval was not required for the study.

Author Contribution and Conflict of Interest Declaration Information

All authors contributed equally to the book section. There is no conflict of interest.

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