Application of Smart Materials in Civil Engineering and Architecture

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Abstract. Smart materials are the result of great advancements in material engineering and have different practical applications. This paper presents a review of selected smart materials applied in modern building structures from civil engineering and architecture perspective and determines what advantages they can bring. These benefits include building structure, interior design and façade solution. A very important causative factor resulting from the use of intelligent materials is obtaining a new aesthetic effect. This effect can be achieved through refined patterns, change of shape, presentation of interactive images.

1. Introduction

Stronger energy efficiency requirements and interactivity require modern building structures to be constructed using new materials and solutions. In order to design and build a sustainable structures which fulfil functionality and load bearing capacity under static and dynamic loads application of smart materials is necessary. For that reason, civil engineers and architects are seeking new materials and technologies which are going beyond standard way of thinking and design [1, 2].

Smart materials have the capability to respond to changes in their condition or the environment to which they are exposed, in a useful and controlled manner. The input that cause the change in smart material properties may be in the form of mechanical stress or strain, electrical or magnetic field or changes in temperature, pH, moisture and light. They are used in modern building structures and contribute in increasing load-bearing, control vibration, noise reduction and energy efficiency of structure.

The following types of smart materials can be distinguished [3]: piezoelectric, electroactive, photostrictive, thermostrictive, magnetostrictive, chemosensitive materials and fiber optic sensors. These materials are components of an intelligent structure that is an electronically reinforced with a physical framework. For example, piezoelectric materials can produce electricity under pressure or can change its dimensions under the influence of electricity. Piezoelectric controllable dampers generate friction force by pressing friction materials with actuators. There are other forms of intelligent materials, such as shape memory alloys, which can be applied as temperature sensors in ventilation systems or as actuators in detection devices. The properties of glass can be improved using nanotechnology. There are now self-cleaning systems with antimicrobial activity that can reduce pollution properties. Titanium dioxide represents a type of broad-spectrum bactericide with excellent biocompatibility which create an anti-adhesive coating.
2. Smart Materials in Civil Engineering

A group of intelligent materials that has an impact on the development of building structures and their safety is dynamically developed [4]. Smart concrete occupies an important place in this group [5]. By adding carbon fibres it is possible to add electrical impulses to the concrete structures, making the concrete able to have electrical resistance change in response to damage and deformation. This allows to detect small increases in internal stress. Signs of cracks or increase in stress can be monitored by the material itself. Due to shrinkage and other rheological phenomena which occur in reinforced concrete, cracks cannot be avoided. However, care must be taken to limit the propagation of such cracks. One possibility for minimizing cracking is through the use of fiber reinforcement such as steel, polyvinyl alcohol (PVA) or natural fibers [6]. A recent and more reactive approach is the use of self-healing concrete: once a crack forms, it is autonomously repaired by the material itself. An example of intelligent material that can solve a problem is microbial concrete in which bacteria produce calcite (CaCO₃), filling in the cracks, Fig. 1. In this process, bacteria produce urease which catalyzes the hydrolysis of urea into ammonium and carbonate.

![Figure 1. Schematic of crack healing by bacteria (developed by author on the basis of [7])](image1)

Another approach for reducing concrete cracking caused by thermal effects is incorporation of phase change materials (PCMs) in the concrete mix, Fig. 2. PCMs are a phase change materials that are able to absorb, accumulate and release a large amount of energy in the form of heat. In PCMs, heat is absorbed and released when the material changes its state from solid to liquid. Phase change materials can be divided in three categories: organic paraffin and non-paraffin compounds, inorganic (salt hydrates and metallics) and eutectic (composition of two or more components, each of which melts and freezes congruently forming a mixture of the component crystals during crystallization).

![Figure 2. Different ways of incorporating PCM material into concrete: a) pipes filled with PCM; b) microcapsules with PCM; c) filling concrete surfaces by absorbing PCM; d) lightweight aggregate particles impregnated with PCM (developed by author on the basis of [6])](image2)
Another type of materials widely used in construction engineering are SMA (shape memory alloys) thermobimetals which react to changes in temperature by changing shape [8]. The reversible switching between the high temperature phase (austenitic) and low temperature phase (martensitic) and the associated changes in the electric, thermal and mechanical properties allow for passive control of structures. Due to its excellent deformation behavior and a very good resistance Ni-Ti, Cu-Zn-Al and Cu-Zn-Ni can be successfully used in damping of vibration [9]. Average residual inter-story drifts decreased with the use of SMA bracing system, Fig. 3. Moreover, tube connections elements made from SMA with one-way effect of shape memory could be used in construction of skeletal building elements such as lattice beams. Also, smart concrete beam are developed by taking advantage of the shape memory effect of SMA and characteristics of applying large forces on the resisting member in the transformation of SMA on heating [10]. In this case application of SMA wire allow concrete structure to recover from residual deformation by damaged earthquake after electrically heating the SMA wires. The effectiveness of self-restoration of SMA concrete beams is directly related to the increase in the initial pre-stress of the SMA wire.

Figure 3. Schematic representation of SMA braces for steel building structure (figure by author)

Magnetorheological liquids (MR) are very important intelligent material used to ensure the safety of the structures. MR changes their viscosity, from a thick fluid to almost a solid, under the influence of a magnetic field. This dispersion system is composed of a carrier in the form of mineral or synthetic oil in which ferromagnetic suspension is dispersed. These materials are mainly used in vibration dampers of buildings located in seismic areas or subjected to strong wind action. The dampers are very often integral component of the main-load bearing structure, e.g. MR applied in Nihon Kagaku Miraikan building in Tokyo. An important application of magnetorheological dampers in building structures is also protection against displacement of bridge structures [11]. In structural solutions of suspension bridges they are used to damp cables of structure, Fig. 4. The damping parameters are regulated autonomously in the hydraulic damping element by way of electronic system. A sensor measures the natural frequency, sends data to computer which calculates the desired response force of the damper and sends its result back to the damper by way of electrical impulses [12]. This solution was used in Volgograd Bridge, which is one of the longest in Europe (Volgograd, Russia).

Figure 4. Scheme of vibration damping of the cable suspension bridge (figure by author)
3. Smart Materials in Architecture

A relatively large group of materials, more and more noticeable in architecture, are materials that change color or degree of transparency under the influence of specific factors. These are mainly glass materials [13, 14]. Some of them react to changes automatically, e.g. under the influence of light (photochromic glasses) or solar heat (thermotropic glasses). The most widely used are glasses with controlled variation of optical parameters, controlled by electricity. The most commonly used technologies are:

- **Electrochromic glass**

A special coating is placed between two glass panes filled with crystal particles in liquid form. The laminate consists of two layers of transparent conductors, electrolyte, electrochromic layer (active electrode) and ion storage (passive electrode). The change of the glass color to blue and its shading occurs due to the movement of ions between the electrodes under the influence of the applied voltage.

- **Suspended particle devices (SPD) glass**

The laminate consists of a thin film containing a suspension of elongated particles sandwiched between two sheets of transparent plastic or glass, Fig. 5a. In the case of absence of electrical voltage, suspended particles are arranged in random directions and tend to absorb light so that the glass plate is dark (gray or black). After applying voltage, suspended particles align their position and allow light to transmit. The potential of the applied voltage is controlled manually or automatically to precisely control the amount (and brightness) of light and heat passing through such glass, thus reducing the need for air conditioning in summer and heating in winter. An example of the use of this type of solution is the façade of Indiana University building in Bloomington (USA).

- **Polymer dispersed liquid crystal devices (PDLCD) glass**

The laminate consists of a thin film which contain a dispersion of liquid crystals in a suitably solidified or hardened polymer, Fig. 5b. As a result of a change in the state of polymer from liquid to solid, liquid crystals are separated from the polymer and in the form of droplets remain suspended in the polymer mass. In this system, a liquid crystal film is inserted between two layers of plastic or glass. Films with a thin layer of transparent conductive material bond the whole in the lamination process. In the initial state, the liquid crystals are arranged in a chaotic manner, which causes the glass to become opaque. After applying voltage crystals arrange in an orderly manner, and the glass becomes transparent. The transition from one state to another takes a very short time. An example of the use of this type of solution is the façade of Chanel Headquarter building in Tokyo (Japan).

- **Gas chromatic glass**

In gasochromic glazing technology, the color is determined by the active diluted hydrogen which flow through the void between the layers of the glass. This gas reacts with the active coating WO₃ causing its color. In the passive phase, the glazing is neutral and transparent. In the active phase it
changes color to darkened navy blue. The advantage of this technology is short time of phase change. An example of the use of this type of solution is the façade of Frauenhofer Institute Building in Freiburg (Germany).

- **Micro-blinds**

  Micro-blinds also control the amount of light passing through the glass when the appropriate voltage is applied. Micro blinds consist of many small and thin metal blinds installed on the glass pane. The metal layer is embedded in the magnetron sputtering process and the division into individual blind slats is carried out in the process of laser technique or lithography. The glass substrate contains a thin conductive layer (transparent conducting oxide TCO). Most often it is indium tin oxide (ITO), fluorine doped tin oxide FTO or doped zinc oxide. A thin insulator layer is embedded between a layer of thin metal blinds and a TCO layer. In the absence of voltage, the micro-blinds have rolled slats and light can pass through the structure.

  Another type of activity using the features of intelligent materials can be light emission. After impulse operation, the particles go to a higher energy state, which lasts as long as the impulse works. Part of the energy is released in the form of visible light radiation which is not accompanied by heat radiation. Photoluminescent materials which react to light and electroluminescent which react to electric voltage are the most useful for architecture. They are used in the form of phosphorescent or fluorescent paint coatings, wallpapers or fabrics. LEDs are the best-known product from the group of electroluminescent materials. They are used to create media facades on the surface of which any moving images can be displayed. Initially, these were a grid structures applied to the facade surfaces. In the most modern solutions, the diodes are placed inside the glass pane. New generations of diodes based on polymer semiconductor (OLED) technology are also developed. An example of such a solution may be light-kinetic curtain wall façade in Hotel Habitat in Barcelona (Spain).

  There are materials that are capable of producing electricity as a result of a specific stimuli, e.g. light, temperature, mechanical force or chemical environment. The most common material in this group are photovoltaic cells, obtaining electricity from solar energy. They use semiconductor technology, and their operation is reverse of LEDs. Individual cells are combined into modules and then into serial connection. New generation cells are produced as very thin films that can be bonded to the structure of a glass pane. The most modern products are semi-transparent glasses with PV cells, also colored in a very wide range of colors, and cells suitable for use on surfaces intended for pedestrians. The most effective solutions from an architectural point of view, e.g. semi-transparent cells, achieve lower efficiency.

  Another very important example of intelligent solutions compatible with sustainable design is photocatalytic self-cleaning coating for building façade [15]. This solution incorporates nanometer-scale coating of titanium dioxide on the outer surface of façade. The photocatalytic activity of titanium dioxide is induced by the absorption of ultraviolet radiation. As a result of this process is initiated chemical oxidation of soiling deposits on exposed surfaces. The initial decomposition activated by the coating allows them to be easily washed under the influence of rain towards the façade of the building. Photocatalytic coatings revealed a great potential for air purification and easy cleaning properties. An example of the use of this type of solution is the Manuel Gea Gonzalez Hospital in Mexico.

4. **Summary**

The recently noticeable intensive development of intelligent materials paved the way for the development of building structures and changed the mindset of designers and specialists in the field of construction and architecture. Development of nanotechnology result in increasing number of new smart solutions. Many different functions that smart materials can achieve led to the composition of intelligent material systems that affect the behavior of structures. The potential of new smart materials technologies and material systems can change and improve the design and construction process. As they become more and more integrated with civil engineering and architecture applications they should be considered in the early stages of the design process. In the era of current technology, the development of sophisticated building structure is becoming extremely important because the creation of better
structural solutions should be the driving force behind the development of technology, and not just a projection of what is available.

For example, application of SMA and MR is very effective in improving the response of structures to any extreme loading. Other concepts include self-repairing concrete, phase changing materials which enables create large surface area to improve heat transfer can be very efficient in reducing the cost of repairing and retrofitting of various structures.

Moreover, ecological solutions can be included self-cleaning buildings envelopes or thin polymer films mimicking the function of living skin which are adopted in a building envelope.

The use of intelligent glass allows savings by reducing the costs of heating, air conditioning and lighting, as well as avoiding the costs of installation and maintenance of automation and drives for traditional sun visors, such as blinds or awnings. Glass, which is not transparent in an inactive state, blocks almost all UV transmission through the glass, and thus reduces the fading of fabrics, paints and other products sensitive to UV radiation.

The overall conclusion is that material engineering tends to increase the ability of intelligent materials to shape the comfort of the internal environment, security and energy efficiency of the building, as well as its aesthetic and ecological features.

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