Smart and Nano Materials in Architecture

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Abstract

We describe and analyze the fields of Smart and Nano Materials and their potential impact on architectural design and building fabrication. Distinguishing Smart and Nano materials, Smart Materials perform both sensing and actuating operations, whereas many Nano materials are capable of self-assembly. In general, Smart and Nano materials can perform like living systems, simulating human skin, the body's muscles, a leaf's chlorophyll and self-regeneration. Recognizing that the traditional partition between Materials Science and Architecture is obsolete, our intent is to show how these two fields are intrinsically connected, while growing evermore symbiotic as we progress into the future.

Keeping the designer in mind, our paper begins with the question: "What Nano and Smart materials can be used in future architectural designs?" Outlining what such materials might mean for architectural fabrication and design, we claim that Smart and Nano Materials can imitate living organisms. Effective implementation of these materials will therefore allow designed spaces to operate as active organs within a larger dynamic organism, synthesizing both expressive intent and pragmatic considerations.

This paper is a collaboration between an architect and a materials scientist on the future of materials and their influence in architecture. By giving examples of work already underway we intend to illustrate and suggest directions ranging from the functional to the expressive, from tectonics to morphology. We conclude with a reflection on the importance of future research between our two areas of knowledge.

Introduction

"Architecture should strive to imitate the principles of nature without imitating its forms."
Frank Lloyd Wright

Writing in the first half of the twentieth century, Wright couldn't predict what potentials lie in wait for current designers willing to imitate both the principles and forms of nature. If contemporary field experts in materials science are correct, the near future of science and technology will offer products and procedures which follow the principles of plant and animal growth and regeneration in extraordinary ways. Oddly enough, these large scale changes will rise from the "I.Q." of smart materials and by new uses of the tiniest of forms, such as nano materials. Imitating the principles of the abalone, which self-assemble their own shells atom by atom, scientists and technologists are in the process of creating systems such as minute machines (nano-assemblers) and coding mechanisms, which will imitate the generative processes of nature following nature's growth and manufacturing methods. As the field of materials science predicts, the "I.Q." of smart materials will be determined by the degree of the material's response to environmental stimulus, whereas advanced nano materials will be fabricated by self-assembly. The ramifications of this work will reach out from laboratories into various fields, promising large scale re-inventions to rival the industrial revolution in impact and scope.

Health care, building methods and materials, fashion, technology, transportation, food and drug composition and distribution, and material processing: all of these fields will be changed by the import of smart materials concomitant with nanotechnology and its resultant advancements. Architecture will feel the impact as well, via innovation in materials and construction, but also through the resultant cultural changes that will emerge in the face of new technology. At this important juncture between science, technology and culture, the architectural community will have the opportunity to embrace, question and reject nanotechnological advancements. Without grounded knowledge to do so, however, the import of nanotechnology to the field of architecture will be superficial at best, and at worst, just another inundation of mediatic tricks and flashy painterly building skins. Herein, drawing on the expertise of an architect and a materials scientist, we propose that the interplay between smart materials and nanotechnology can be more than buzzwords in the latest design review: with real knowledge, real impact is possible.

When we consider smart and nano materials in their particular and peculiar characteristics, their design and construction potentials are easily understood. Yet we would be remiss to leave you without a word of caution regarding that same apparent facility. Many times, when seeking new ideas and approaching new concepts, one can make strides in speculative and metaphorical thought while reality lags further and further behind. Eager to embrace new, cutting edge technology, we as designers often let ourselves dream into the future, forgetting the work toward implementation which true creativity entails. To apply many of the ideas discussed here, some technical barriers between scientific discovery and architectural application must be overcome before realizations are complete. To prevent lags between practice and theory, investment in realization must keep pace with the hours invested in written speculation. Second, interdisciplinary research, utilizing the best minds of both architecture and materials science must be encouraged and supported institutionally and professionally. When these objectives are most nearly achieved, we as designers will be best able to ground our discussion in possibilities, not theoretical musings. We hope this paper is a primary step in that grounded direction.

Smart Materials and Nano Materials

What are Smart and Nano Materials?

To critically engage the world of leading science, the architectural community should understand the technological innovations that smart and nano materials are capable of producing. To best do so, we need a working definition for both smart materials and nano materials.

Beginning with "Smart:" Smart Materials are materials with the ability to perform sensing and actuating functions, similar to those in living systems, upon the application of an external stimulus [Newman 1997] . This stimulus can be in the form of light, sound, temperature, electric field, magnetic field and stress. The term "smart materials" gained relevance after the 1960's Naval

Ordonnance Laboratory discovery of Ni-Ti alloys (Nitinol) which were first used for the construction of junction components in F14 aircrafts [Purdy 1961]. If deformed, Nitinol will recover its original shape when subsequently heated above a specific temperature. Since its discovery, this material has been used in many different applications, such as medical implants, dental fixtures and electrical switches.

Over the last 35 years, smart materials have further developed and diversified to include piezoelectric, electrostrictive, magnetostrictive, and shape memory alloys, which have both sensing and actuating functions. Additional materials, such as electrochromic, electroluminscent and photoluminescent, pH-sensitive and photovoltaic are capable of sensing functions. These smart materials also carry the potential to become *intelligent materials*, i.e., besides their sensing and actuating properties, such materials will able to learn and adapt with time [Newman 1997] and may ultimately simulate living systems.

As for "Nano:" Technically, nano materials are materials with a nanometer scale substructure. The term "nano" derives from the Greek word for "dwarf". It is used as a prefix for any unit like a second, or a meter, and it means a billionth of that unit. Hence, a nanometer is a billionth of a meter, which is 1000 times smaller than the thickness of a human hair. The eventual objective of nanotechnology is to manipulate and control materials at the atomic level. In other words, we expect to build things the way nature does it, atom by atom and molecule by molecule, i.e., by self-assembly.

In 1959, Physics Nobel Laureate Richard Feynman challenged the scientific community by asking if we could write the 24 volumes of the Encyclopedia Brittanica on the head of a pin [Feynman 1960]. Although Feynman could not predict it, this lecture was a defining moment in the field of "nanotechnology". The phrase "nano-technology" was first used in print in 1974 by Norio Taniguchi [Taniguchi 1974] to refer to the increasingly precise machining and finishing of materials. In the 1980's, K.E. Drexler, described a new "bottom-up" approach, involving the molecular manipulation and molecular engineering in the context of building molecular machines and molecular devices with atomic precision [Drexler 1981, 1986], which eventually popularized the term "nanotechnology".

Types of Smart Materials

Piezoelectric Materials

Piezoelectric materials produce electrical charge when mechanically stressed, and undergo some mechanical deformation when subjected to an electric field. Among the natural materials with this property are human skin and quartz. When used in computers and watches, quartz is subjected to an electric field which causes it to vibrate at a particular frequency, hence sending a signal at precise time intervals.

Piezoelectrics can also be used as resonators in items like watches, and in active noise control systems such as headphones, to detect noise through the generation of electrical signals upon vibrating due to the sound waves. Piezoelectrics are also used in mechanical vibration damping systems, such as high competition skis and tennis rackets. More recently, piezoelectric paints have been studied to detect fissures in walls. Conductive paint is doped with piezoelectric particles that will react to stress/strain by producing an electric current. In this way, piezoelectric materials can also be used as sensors to test material stress/strain in construction.

Electrostrictive Materials

Electrostrictive materials, like piezoelectrics, produce electrical charge when mechanically stressed and generate strain when subjected to an electric field. However, while the strain produced is proportional to the applied electric field in piezoelectric materials, in electrostrictive materials, the strain generated is proportional to the square of the applied electric field. As a result, for the same applied voltage, electrostrictive materials are capable of generating strains that far exceed those of conventional piezoelectric materials. The disadvantage is that the deformation at low applied electric fields is small. Electrostrictive materials have been used as wiper blades, artificial muscles, landing gear hydraulics, and for correcting surface deviations caused by thermal fluctuations.

Magnetostrictive Materials

Magnetostrictive materials change shape when subjected to a magnetic field. Pure elements with high magnetostrictive properties at room temperature are Cobalt and Iron. By adding other elements one can achieve "giant" magnetostriction under relatively small fields [Hathaway and Clark 1993]; this is the case of Terfenol-D. Magnetostrictive materials were first used in telephone receivers and hydrophones. With the discovery of "giant" magnetostrictives further applications have developed, such as ultrasonic cleaners, high force linear motors, medical and industrial ultrasonics for surgical tools and underwater sonar. Magnetostrictive devices are rather robust in terms of wear, and thus may potentially replace piezoelectric materials.

Electrochromic Materials
Electrochromic materials change color upon application of an electrical voltage. An applied voltage initiates a chemical reaction which changes how the material reflects and absorbs light [Hardaker and Gregory 2003]. In some electrochromic materials, the change is between different colors, such as those used in electrochromic windows wherein the material changes between colored (reflecting light of some color) and transparent (not reflecting any light). As a result, electrochromic windows darken when a voltage is applied and become transparent when the voltage is removed. Reflective mirrors are electrochromic as well, reflecting light upon the application of an electrical voltage, instead of absorbing it. Additional potential uses of this technology include rechargeable lithium batteries, sensors, privacy/security glazing areas and high contrast displays.

Shape Memory Alloys
Shape memory alloys are of two types: thermally and/or stress driven (SMA), and magnetically driven (MSM). Thermally/stress driven shape memory alloys, such as Nitinol, undergo a phase change under stress, from a high temperature phase to a low temperature phase, and return to the original high temperature phase when reheated [Newman 1997, Wayman 1993, Schetky 2000] . Magnetically driven shape memory alloys such Ni_2MnGa, on the other hand, undergo a reorientation of the low temperature crystal structure upon the application of a magnetic field [Ullakko 1996, Ullakko et al. 1996]. When the orientation of the magnetic field is reversed, the structure returns to its original shape. MSM alloys show larger strains than traditional SMAs, and seem to be the most promising for future applications. Additionally, MSM alloys can already obtain 50 times greater frequencies (250 Hz) than SMA materials, without a reduction in the output strain, and are capable of attaining several kHz with lower output strains.

Current applications for the thermally driven SMAs include coffeepots, thermostats, vascular stents, hydraulic fittings or airplanes. MSM alloys will be used in loudspeakers, joysticks, ink-jets, robots and air foils to control drag and turbulence.

Biomimetic Materials
The term "biomimetic" has origin in the Greek words "bios" and "mimetikos", which mean "life" and "imitate", respectively [Newman 1997]. Hence, "biomimetic" means "to imitate life". Biomimetic biosensors are used to convert a biological response into an electrical signal. In nature there is a wide spectrum of cases where smart bio systems are utilized. Fish, for example, contain a number of fibers that vibrate as they swim and act as sensors for flow noise. Simulated transducers can then be used to talk to fish. Frogs communicate by emitting a low-frequency and a high frequency tone through dual-tone transducer as well.

Types of Nanoscale Materials

Nanoparticles

Nanoparticles, also called "zero dimensional nano materials", do not possess any dimension outside the 1-100 nm range. Although nanoparticles can have different shapes, crystal structures and compositions, their small scale induces a change in fundamental properties. A good illustration of this phenomenon can be found in the properties of quantum dots, such as CdSe, which are nanocrystalline particles containing only a few hundred atoms. Because electrons in a quantum dot are confined to widely separated energy levels, as particle size decreases, the dots emit only one wavelength of light when excited. Thus, CdSe nanocrystals in solution, and exposed to incident light, emit radiation of a particular color [Dabbousi et al. 1997]. Accordingly, quantum dots can be used in the design of road reflectors and any other reflective surface that will be exposed to incident light.

Magnetic nanoparticles can be used to detect particular biological entities, such as microorganisms that cause disease. In these applications, magnetic nanoparticles are attached to antibodies which bind to a target. When binding occurs, the magnetization vector of each nanoparticle is parallel, thus inducing a strong magnetic signal. On the other hand, antibodies which do not recognize the target do not bind and display randomly oriented magnetization vectors, with no strong net magnetic signal [Reed and Tour 2000].

Nanowires and Nanotubes

Nanowires and nanotubes are materials created with one non-nano dimension. These materials tend to have one long axis (above 100 nm), and a cross-section that is within the 1-100 nm range. The best examples of these structures are the widely publicized carbon nanotubes [Iijima 1991, 1994]. These nanostructures are composed of carbon atoms that assemble into cylinders a mere 1.4 nm in diameter, and a few micron in length (Figure 1). A single-wall carbon nanotube has extremely good electrical properties (conducting electricity better than copper) and very good mechanical properties (its tensile strength is much higher than steel). A multi-wall carbon nanotube, on the other hand, has semiconductor properties, such as nanowires of ZnO, GaN and SnO_2 [Yang 2005], which are attractive to the microelectronic industry.

In 1998, the idea of using carbon nanotubes to fabricate simple minute gears evolved by bonding rigid chemical ligands onto the external surfaces of carbon nanotubes to produce 'gear teeth'. Each gear is made of a 1.1 nm diameter nanotube with seven benzyne teeth. Computer simulation results show that the gears can operate up to 70 GHz (70 billion times a second) in vacuum at room temperature without overheating or slipping [Han et al. 1997].

There are many applications for which nanotubes and nanowires may become important, in particular electronic and opto-electronic devices, magnetic storage, and composite materials with very high strength-to-weight ratios.

Nano Films

Nano films are materials that have two non-nano dimensions. Typically, nanofilms are used as a surface treatment when composition or/and mechanical properties need to be altered, or as coatings when a different material is deposited to create a new surface. In some cases, thin coatings with a nanocrystalline structure are formed in selected substrates, through a dispersion of nanoparticles. In other cases, the films are so thin that their thickness is within the 1-100nm range. The most recent nanofilms are just a few molecules thick, having been built up by self-assembly, i.e., atom-by-atom or molecule-by-molecule [Kotov 2001].

Nanofilms are stable and able to cover larger areas. Once applied, they are easy to manipulate using standard processes and tools. Potential applications of nanofilms include the development of scratch-resistant plastic coatings, low friction coatings, and materials with a very low or negative refractive index. Nanofilms are useful in the microelectronic industry, data storage industry, solar energy area, optical devices and medical equipment.

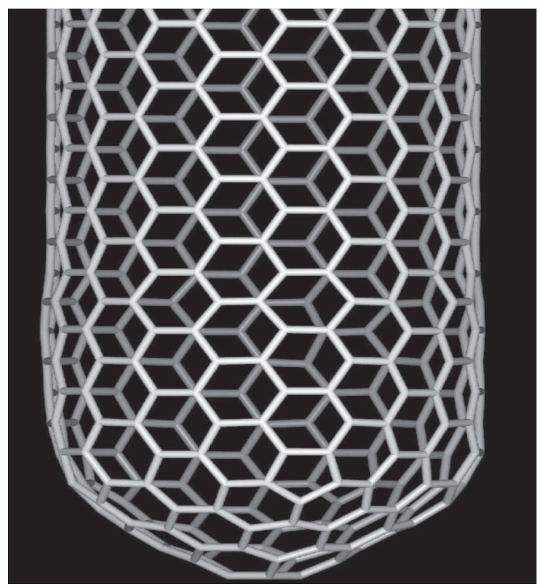

Figure 1. *Single-wall carbon nanotube with a diameter of 1.4nm. These carbon nanotubes can be thought as wrapped sheets of graphite*

Bulk Nanomaterials

Bulk nanomaterials are materials that have macrodimensions in 3-D, but exhibit a nanoscale substructure. Currently, there are two main processes used to achieve bulk nanomaterials : 1) production of nanoparticles in powder form, followed by high-pressure compaction and subsequent high temperature sintering to consolidate the powder, and 2) high angular extrusion or high pressure torsion, where relatively small metal work pieces (of the order of cm) are highly deformed to produce a nanoscale substructure. Current research in field of mechanical behavior demonstrates a broad range of fascinating properties for bulk nanomaterials, namely a significant increase in hardness [Sanders et al. 1997], yield stress (up to five times higher) [Chokshi et al. 1989] and, in some cases, ductility [Kock et al. 1999]. The disadvantage of these materials thus far is that they are difficult to produce in large scales.

Bulk nanomaterials have potential for applications where high strength-to-weight ratios, high strain rate and low temperature superplasticity and ductility in usually brittle ceramics. These fantastic mechanical and physical properties make bulk nanomaterials attractive for advanced applications in medical, construction, space, sporting goods, and transportation industries.

Smart Materials and Nano Materials in Architecture

An architect seeking new and better ways of building is often driven by a thirst to develop new forms and express new ideas of space. Architectural history is built of such developments as the 'newest' and the 'boldest' of building forms and construction advancements illustrate. We believe that new smart and nano materials have the potential to open a new era in architectural design and construction, enabling architects a higher level of intricacy which will span from the smaller scales of a molecule to the larger concepts of society.

In this vein, advancing scientific areas are now, as they have often been, the ideal scavenge site for designers eager for new solutions to their technical problems, and looking for better ways to express emerging design concepts. As novel Smart and Nano materials research is no exception, architects must look ahead for the impact these novel cutting edge materials will have in the constructible world. New concepts of materiality emerging from Nano and Smart materials can allow architects to further respond and engage our present – connected, fast paced, organic, plastic, responsive, consumable, volatile, media-centric, and tech-centric. In response Nano and Smart materials can further point architecture towards the ideal of a systemic organism; wherein a material or construction can respond in action and reaction to its environment. Furthermore, emboldened by these new material technologies architects may find new ways to question Aristotelian notions of separation and causality, expressive necessity and the demands of function. [Kalay 1999]. These dichotomies, epitomized in the famous statement by Louis Sullivan that "form follows function" [Sullivan 1934], may dissolve as technological innovation and expression reach toward new unities. Resulting new concepts of materiality can then allow designers to break from 'function or form' into a new cyclic concept, and a new paradigm, that creates one body of 'function and form'.

Below we discuss the impact that both Smart and Nano materials can procure in the realms of architecture, construction and design. It is our goal to describe how these materials will not only allow for new and better responses to the performance needs of today's most efficient buildings but will also allow for the shift in architectural thought regarding materiality and the qualities of materials in architecture.

Intergraded Functionalities

"Making familiar products from improved materials will increase their safety, performance, and usefulness. It will also present the simplest engineering task. A greater change, though, will result from unfamiliar products made possible by new manufacturing methods."(Drexler)

Drexler's vision was strong though his urgency is only now reaching the world of architecture. Alluding to layered structures and manufacturing processes with multiple capabilities, Drexler's vision was to push science and society toward greater efficiency, with amplified results at lower costs. In line with Drexler's vision, material scientists are now drawing inspiration and data from the bat biosonar, shark-skin denticles and whale songs to develop Smart materials. In parallel, a wide effort has been invested in emulating mitochondrias in plant cells, sea shells, spider webs, protein synthesis, as well as other living nanoscale machine-like matter to create nano materials. Strains of molecular manufacturers are working to create nanoscale machines (nano-assemblers) and structures which will be able to build, program, record and transmit information, and ultimately self-replicate to produce identical structures to carry out the same tasks. Building at these levels can lead to materials with greater strength-to-weight ratios, multi-tasking materials that reduce material and labor costs, ultimately making architecture more affordable, sustainable, and more accessible.

In the past few years we have witnessed an exponential increase in building designs that can perform in an environmentally responsive manner. In regards to performance of the building we have what is many times termed green design, or sustainable architectural design. These design approaches focus on the creation of high performance sustainable buildings – wherein high-performance is defined as an economic sound, efficient, and conscious employment of resources in the creation of living, working and playing environments [Hawkes et al 2001]. Norman Forster's recent buildings strive far toward these standards as he works to seamlessly intertwine design integrity with sustainability and environmental performance issues throughout his buildings' envelopes [Foster 2003]. Thus, while 'material smartness' is already in play, (i.e., in materials wired to sensors can be found throughout newly constructed buildings relaying security, temperature data, and accomplishing many disparate environmental task), truly Smart materials are only now reaching points of possible employment.

Through the use of Smart materials, as defined in the previous section, new processes of integrating multiple functions into one material will offer alternative construction methods allowing for a decrease in material and construction costs while offering state of the art technology and its secured benefits. For example, novel structural construction materials which are light-weight but exhibit higher strength can reduce the total mass built and offer the possibility of higher, larger, and ultimately safer structures. The events of 9/11, the collapse of the Charles de Gaulle 2E terminal, recurrent natural disasters and simple economic principles of material efficiency have made high strength-to-weight ratios a pressing concern. Yet, while architecture continues to employ the so-called modern materials of concrete, steel and glass, current materials science research has made great strides toward improving the strength-to-weight ratio through the use of composite materials and more recently nano materials. For example, aluminum alloys with nanocrystalline grain sizes are expected to exhibit yield strengths close to 1GPa. Yet in the face of these and other materials discoveries, the work of A.G. Evans [Evans et al. 2001] confirms, by plotting the strength versus density of common materials, that the strongest building materials are, to date, also the heaviest. In this regard, novel nano materials with high strength-to-weight ratios could, when properly introduced, be in high demand.

While improving one existing material characteristic is a notable achievement, manufacturing composites with nanostructured components and integrating these composites as building materials can go further still to conceivably surpass many existing building properties. For example, acoustic and thermal insulation and strength could be incorporated in one sole material: composite materials made from cork dust reinforced with carbon nanotubes could be capable of achieving high tensile strengths and significant ductility, while acting as acoustic and thermal insulators: cork and carbon nanotubes, melded into one single material will help reducing man hours by eliminating construction layers due to functional integration within one single material.

As shown in Figure 2, material layering can often increase efficiency. For example, the above pictured envelope could also be coated with a photosensitive color layer, such as an electrochromic material. This material could be engineered to change color as a function of temperature, shifting from one color to another to better reflect or absorb heat as required (figure 2). In addition, multi-layered smart materials could combine to create a wall that can 'breathe' in response to interior and exterior temperatures. This system could be engineered to react at certain temperatures, opening or closing micropores controlled by smart shape memory alloys embedded in the overall wall structure. In this 'breathing' wall assembly the smart material itself possesses functional capabilities; much like human skin porosity is not controlled by the brain but rather by its intrinsic functional characteristics (Figure 3).

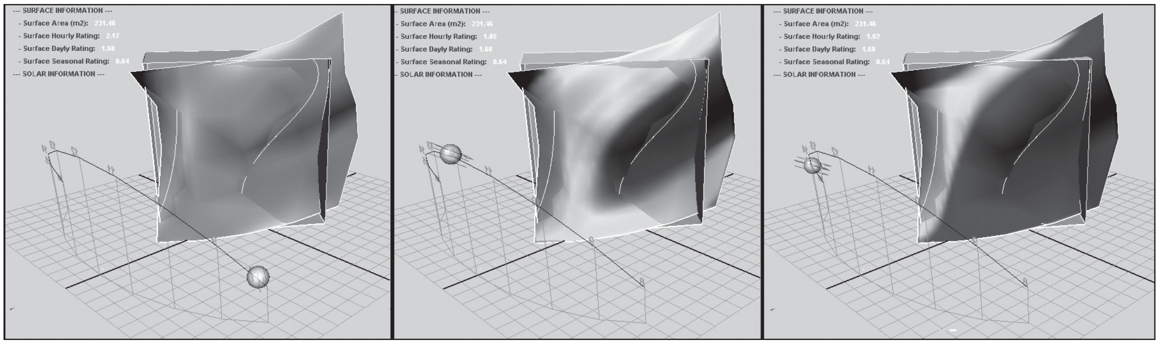

Figure 2. *Simulation of a building surface with color changing paint. (8:am, 12pm, and 4pm) [DaVeiga and LaRoche 2002]*

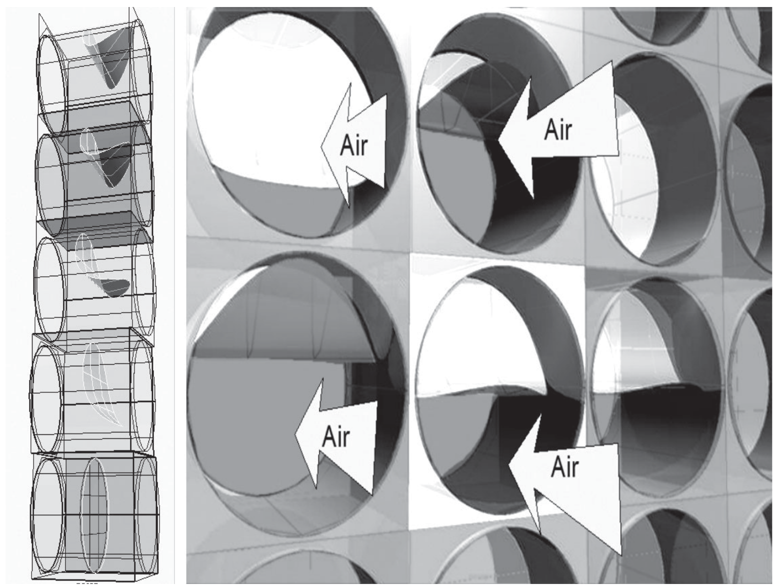

Figure 3. *Smart shape memory alloy membranes at micropores for air circulation through wall*

From the examples above we can see how, when materials contain several functional capabilities, current construction methods will benefit from increased simplicity. Though these are simply a few relevant scenarios, they are based on real material capabilities, waiting only for architects and materials scientists to invent the means to express their inherent potential. Designers, in order to keep pace and create standards, must be informed about such material processes and develop expert knowledge concerning their applications.

Advancements in Manufacturing

"Nanotechnology is fundamentally changing the way materials and devices will be produced in the future. The ability to synthesize nanoscale building blocks with precisely controlled size and composition and then to assemble them into larger structures with unique properties and functions will revolutionize materials and manufacturing."

Using smart materials concomitant with nanotechnology, the future of material selection and manufacturing will be both custom and dynamic. As aforementioned, the incorporation of nano materials will prove a new and innovative engineering, construction, and architectural tool. Materials can now be manufactured in ways that permit the dynamic manipulation of characteristics such as texture, color, and duress. Materials which shift their properties can be applied for aesthetic or functional purposes. For example, a wall covering made of a smart material could conceivably change its surface texture depending on temperature, electric current and other actuating elements. These chameleon-like properties can also be explored in functional areas such as the duress of a material; in which case a material could change its strength or flexibility in response to contact depending on the amount of force applied. If and when these materials can be grown on-site, like plants by self-assembly, architecture must be prepared for the ramifications of such innovation.

Scientific processes have now located the potential for Nano controllers as well as assemblers to self-replicate and, once again imitating nature's processes. As these potentials leave the lab and enter the living room, contractors must learn to 'grow' foundation structures rather than build them. In such a scenario, atomic sized controllers can be programmed, under an architect's guidance and specifications, to grow walls and foundations, in much the same way as genetic material programs the growth of mammals. As in the abalone, with which we started this paper, proteins which fill and expand like water balloons in place can be stacked like bricks. A complex procedure of nourishing rather than constructing these protein walls can lead to structures that grow to reach pre-programmed specifications. Through growth, rather than construction, Eric Drexler looked to a day when the self-assembly and self-growth of residential and office structures would drastically reduce labor costs, enabling both architect and client further creative freedoms that are currently bound by bottom line restraints.

While Drexler wrote out dreams in line with the above fusion of materials research and architecture in the 1970's, the direct usage of novel materials, specifically designed for architecture has not yet occurred. Historically new materials have played an important role in the reformulating of new ideas. For example, Corbusier would have not been as successful in questioning the idea of lightness and heaviness at Ronchamp if it were not for the use of a material perceived as heavy (reinforced concrete). With this paper, a step has been taken in that direction, and we hope that in the present and the near future, architects will begin to employ the knowledge and skills of materials development, through the help of material engineers, in order to custom make materials according to their needs and predicted uses.

Conclusion

Materials performing multiple functionalities embedded in the 'skin' of the building will reduce man hours by eliminating construction layers and complex building control systems. This will happen as novel Smart and Nano materials can act without the assistance of computational methods of sensing and actuating and because when the material is placed in-situ it will be operative in the environment. However, the examples herewith outlined, if embraced and employed, will bring about a new design paradigm. The material capabilities now offered by the forefront of materials science will require a new kind of understanding and cooperation between disciplines. Whilst a computationally manipulated system (i.e. HVAC) can be adjusted to fit most building designs as a unit independent from the design; the use of smart and nano materials will require a deeper understanding in design and material science. As explained the new possibilities require collaboration between architects and material scientists to solve design specific demands on materials. In a sense, the process of creating new buildings will come closer to that of advanced systems in which every part of the building has an operative nature dependent on more than mere aesthetic purpose.

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